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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

SPD-517-03

SUMMARY OF DEVELOPMENT FOR LNG TANK DESIGN ACCELERATION RULES

by

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SHIP PERFORMANCE DEPARTMENT

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SUMMARY OF DEVELOPMENT FOR LNG TANK DESIGN ACCELERATION RULES

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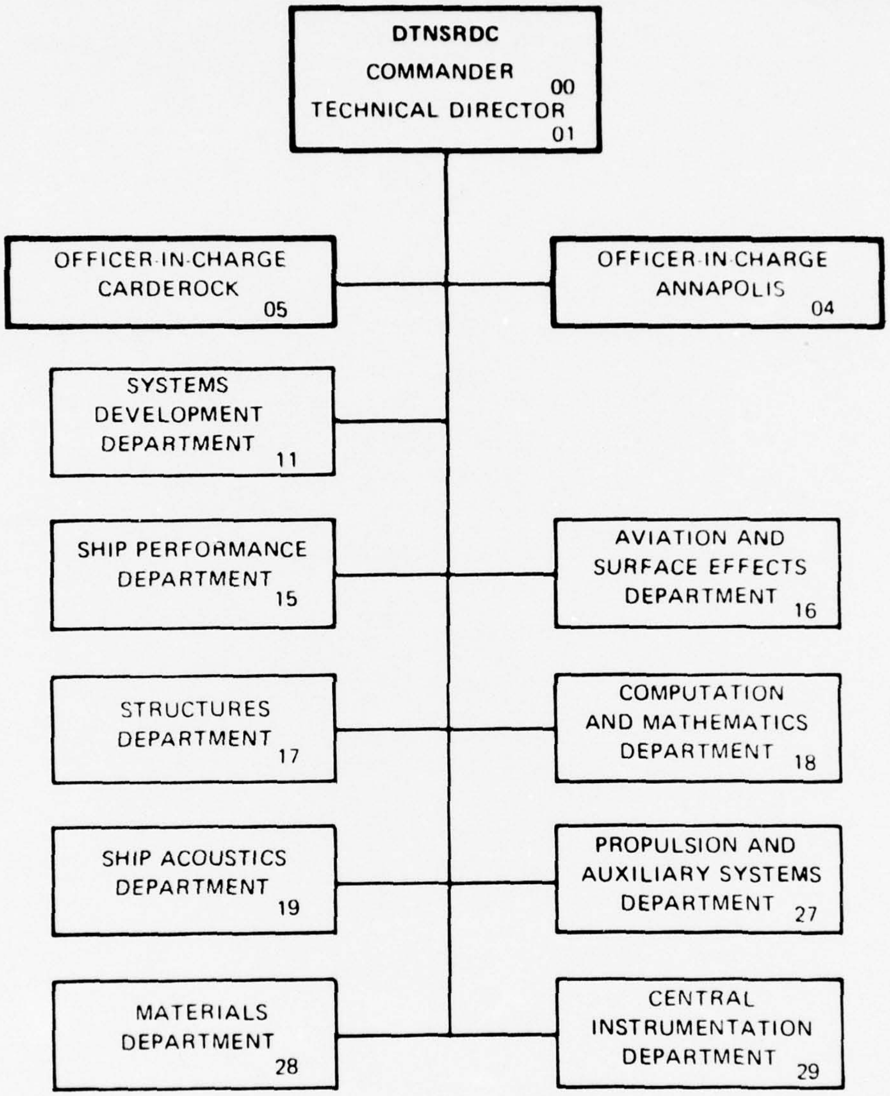

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*(Liquid Natural Gas)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Progress and results are offered from a two year research project devoted to LNG* tank design guidelines. The work was undertaken by the Naval Ship Research and Development Center and sponsored by the U.S. Coast Guard for assistance in its regulatory program. Five LNG tank vessels were examined ranging in capacities from 29,000 to 200,000 m^3 (cu. m.), including spherical and membrane tank systems.

Extreme accelerations and motions are developed by applying short term → next page

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statistics to hull responses predicted for severe sea conditions. Historical data from ocean areas serving LNG shipping routes provides the sea input.

Design accelerations are selected from the extreme values by applying operator strategies in storms. This involves speed reduction, heading change to limit vessel motions, most likely headings, etc. The accelerations selected in accordance with a Worst Heading, James Speed Loss strategy are considered to be most appropriate for LNG Tank design.

Vertical acceleration is the single most important acceleration component which determines the design pressures. Lateral and longitudinal accelerations do not appreciably affect design pressures.

The vertical accelerations are strongly dependent upon ship length with the shorter ships having substantially higher design accelerations than the longer ships.

The predicted accelerations tend to be somewhat conservative. In order to improve the accuracy of these predictions better speed loss models are required for the shorter ships and better extreme wave data is required for the longer ships.

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NOTATION

A	Bretschneider spectral amplitude parameter
a_x	Longitudinal Inertia force in x direction $a_x = -\ddot{L}_0$
a_y	Lateral Inertia force in y direction $a_y = -\ddot{L}_A$
a_z	Vertical Inertia force in z direction $a_z = -\ddot{L}_V$
$\underline{a}_x$	Extreme longitudinal ship acceleration magnitude
$\underline{a}_y$	Extreme lateral ship acceleration magnitude
$\underline{a}_z$	Extreme vertical ship acceleration magnitude
B	Bretschneider spectral phase parameter
C_T	Confidence factor
$\|DV\|$	Magnitude of Design Vector
GM	Transverse metacentric height
KG	Height of center of gravity above baseline
$\ddot{L}_A$	Lateral acceleration
LNG	Liquid Natural Gas
L_{pp}	Ship Length
$\ddot{L}_0$	Longitudinal acceleration
$\ddot{L}_V$	Vertical acceleration
RMS	Root mean square, square root of variance
$S_\zeta(\omega)$	Extreme sea wave spectra
T	Time variable
T_{0E}	Modal response period, period corresponding to peak of encountered response spectrum
T_0	Modal wave period, period corresponding to peak of wave spectrum
X	Extreme response surface
α	Exceedance probability
ε	Bandwidth parameter of ship response
ζ_{obs}	Wave height visually observed
$(\zeta_w)_{1/3}$	Significant wave height - average of one-third highest double amplitudes
θ	Pitch angle
λ	Wavelength
μ	Ship's heading in degrees, 180° is head seas, 0° is following seas

NOTATION

σ	Root mean square (RMS) ship response
ϕ	Roll angle
ω	Wave frequency
T, T	Angle tau in YZ plane between design vector and vertical axis of tank
Υ	Angle upsilon or upslon in XZ plane between design vector and vertical axis of tank

ABSTRACT

Progress and results are offered from a two year research project devoted to LNG tank design guidelines. The work was undertaken by the Naval Ship Research and Development Center and sponsored by the U. S. Coast Guard for assistance in its regulatory program. Five LNG tank vessels were examined ranging in capacities from 29,000 to 200,000 m^3, including spherical and membrane tank systems.

Extreme accelerations and motions are developed by applying short term statistics to hull responses predicted for severe sea conditions. Historical data from ocean areas serving LNG shipping routes provides the sea input.

Design accelerations are selected from the extreme values by applying operator strategies in storms. This involves speed reduction, heading change to limit vessel motions, most likely headings, etc. The accelerations selected in accordance with a Worst Heading, James Speed Loss strategy are considered to be most appropriate for LNG Tank design.

Vertical acceleration is the single most important acceleration component which determines the design pressures. Lateral and longitudinal accelerations do not appreciably affect design pressures.

The vertical accelerations are strongly dependent upon ship length with the shorter ships having substantially higher design accelerations than the longer ships.

The predicted accelerations tend to be somewhat conservative. In order to improve the accuracy of these predictions better speed loss models are required for the shorter ships and better extreme wave data is required for the longer ships.

ADMINISTRATIVE INFORMATION

This work was conducted at the Naval Ship Research and Development Center (NSRDC) upon request of the U. S. Coast Guard (USCG), MIRP Z-70099-3-30922. It is identified as Work Unit Number 1-1568-004.

INTRODUCTION

The objective of this report is to develop realistic tank design accelerations for LNG carrying ships. The general approach was presented in a recent paper[1*] as applied to a single ship. This report applies the approach to a series of five ships considered representative of current and future LNG ships entering or leaving United States (U.S.) harbors.

The procedure to predict the design values is broken into basically four distinct steps. The first three steps, described in detail in Reference 1 consist of developing a data base of extreme responses which contains the design accelerations as a small sub-set. The relationship between the three components of the extreme responses X is shown by

$$X = \sigma \cdot (\tilde{\zeta}_w)_{1/3} \cdot C_T \qquad (1)$$

σ represents the root mean square (RMS) ship response in short crested irregular seas for a specific ship load condition, speed, heading, and location on the ship. $(\tilde{\zeta}_w)_{1/3}$ is the significant wave height for the extreme seas considered appropriate for design. C_T is a factor which relates the RMS response to a probability level not to be exceeded in a specified ship exposure time to the extreme seas. Strictly speaking, the three components of extreme response are not independent as shown in equation 1. However, the factors which relate the three components have such a small effect that the assumption of independence is considered valid for engineering purposes.

The fourth step of the procedure consists of selecting the proper design accelerations from the data base determined by equation 1. In this context, "proper" implies that such unavoidable factors as both speed reductions and the worst possible ship headings in the extreme seas are appropriately considered.

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*A list of references is given on page 67.

An important addition to the procedure of Reference 1 has been developed and is also presented in this report. That is, a method for specifying a total acceleration design vector containing both the static and dynamic components* of acceleration is developed. The method is applied to select regions of the data base to examine conditions where vertical acceleration is maximum.

This report is divided into several major topics, each of which will now be discussed:

1. Series Description
2. Extreme Response Procedure
    a. RMS Responses and Associated Periods
    b. Extreme Seas, $(\tilde{\zeta}_w)_{1/3}$
    c. Confidence Factor, C_T
3. Design Accelerations
    a. Selection Strategies
    b. Speed Loss
    c. Tank Location
4. Design Acceleration Vector
5. Assumptions and Uncertainties
6. Recommendations and Conclusions

SERIES DESCRIPTION

The United States Coast Guard (USCG) is responsible for regulating all ships carrying hazardous cargo which enter or leave U.S. ports. A series of five ships, representative of current and future U.S. LNG traffic, have been selected for this work. The ships range in length from about 600 to 1000 feet and in LNG capacity from about 29,000 to 200,000 m^3. Ships with spherical as well as ships with membrane tanks are included. Figure 1 and Table 1 give the particulars of the five ships.

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*Static refers to the gravity component, dynamic refers to the component due to motions of the ship.

The ship/load conditions are taken as full or near full LNG capacity. In order to determine the effect of load variations on predicted ship responses (accelerations), KG (GM) variations are included for Ships B and C. This simple load variation is considered more appropriate than combined draft, trim, displacement, and GM variations because current full-scale ballasting procedures maintain LNG ships at essentially a constant draft without regard to the LNG cargo load status.

EXTREME RESPONSE PROCEDURE

As stated in the Introduction, the extreme responses are determined by the building block procedure of Reference 1,

$$X = \sigma \cdot (\tilde{\zeta}_w)_{1/3} \cdot C_T \tag{1}$$

Each component of equation 1 is now discussed.

RMS UNIT WAVE HEIGHT RESPONSE SURFACES, σ

Reference 2 provides the data base of RMS responses for calculation of design accelerations in this report. Briefly, the RMS data base consists of response surfaces for heave, roll, pitch, and longitudinal, lateral, and vertical accelerations at the center of the forward tank for each ship/load case, for each speed 0, 5, . . ., 20 knots. The surfaces are computed for short crested seas using Bretschneider two-parameter wave spectra with modal (peak) periods of 7, 9, . . ., 21 seconds and significant wave heights of 1 foot. Ship headings with respect to the waves are taken as 0, 15, . . ., 180 degrees. By definition, 0 degrees is following seas and 180 degrees is head seas. Figure 2 provides sample RMS surfaces for the five series ships.

In summary, the RMS unit wave height surfaces characterize ship responses in irregular, short crested seas for all possible sea conditions and ship headings at each ship/load condition and speed. The usefulness of the presentation of the responses in a surface format is further discussed in Reference 2.

PERIODS ASSOCIATED WITH RESPONSES, T_{OE}

Due to repeated USCG requests for the periods associated with the ship responses, a procedure has been developed to provide such information. Reference 2 provides the details of the procedure as well as validation of the results using both simulated and measured full-scale ship responses. In brief, the period, T_{OE}, associated with the responses is taken as the modal (peak) period of the encountered response spectra and is related to the period of the cycle of maximum response in the time domain. The periods, T_{OE}, for the LNG ships are given in Reference 2 and Figure 3 shows a sample of the RMS response versus period data presentation. The usefulness of this figure in examining resonant conditions, envelopes of extrema, etc. is discussed in some detail in Reference 2.

EXTREME SEAS, $(\tilde{\zeta}_w)_{1/3}$

The prediction of design accelerations is considered to be the prediction of ship accelerations in an extreme storm. Thus, it is appropriate to use the highest measured or observed sea conditions for the predictions. Figure 4 presents the design sea conditions used within this work.*

These sea conditions, denoted by the open circles on the figures, e.g. o, represent the highest observed values reported by Hogben and Lumb[4] for the North Atlantic area as defined in Reference 1. As the ship RMS responses were computed for evenly spaced modal wave periods of 7, 9, ..., and 21

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*Before the main text of this report was written, the results of this work were employed to examine the LNG Tank design accelerations required by the existing 1974 rules. The design rules were intended to cover LNG ships traversing all areas of the world rather than just the transatlantic Trade Route 1 of Figure 4, specified by the USCG for this and earlier LNG work. Thus a new literature search for reported extreme sea conditions was conducted. Reference 3 applies these newer, world-wide extreme seas to the LNG ship response data base. The determination of the world-wide extreme wave heights appropriate for LNG Tank design is discussed in Appendix A, though they are not directly used in this report. Figure 7 presents in tabular form the Trade Route 1 design seas, TR #1; the world-wide extreme design seas, WW; as well as a third set of design seas suggested by USCG staff and designated as the constant 40-ft significant wave height, CONST. WH.

seconds, the design sea conditions were actually obtained by linearly interpolating the wave heights between the reported modal wave periods.

As the determination of appropriate design sea conditions was both the most complicated and the most time-consuming aspect of the project, Appendix A has been prepared to give the details of the process. The Appendix is broken into several major sections including:

1. Representation of Extreme Seas
2. Philosophy of Selection of Design Wave Parameters
3. Selection of LNG Trade Routes
4. Worldwide Extreme Sea Data Sources

CONFIDENCE FACTOR, C_T

As was noted in equation 1, the extreme accelerations are related to the RMS accelerations and the extreme wave heights by a so-called confidence factor, C_T. Strictly speaking, C_T is derived from the distribution of the wave heights and is related to the exposure time of the ship to the extreme seas, T, to the probability of exceeding a specified value α, as well as the zeroth and second moments of the ship response. Practically speaking, however, C_T is dependent only on T and α. Figure 5 presents, for a 3 day exposure time, at three levels of probability, the range of C_T for all ships, all load conditions, and all ship responses. It was considered that the small range in the C_T values for these variables allow the selection of a single C_T value for the entire LNG ship series. As per agreement with the U.S. Coast Guard, a C_T value that corresponds to a probability α of 0.01 has been used in this work. The arithmetic average of the C_T values, for all ships, e.g. $C_T = 5.413$, is the value used.

EXTREME RESPONSE SURFACES, X

Figure 6 presents a typical extreme response surface. The surface is found by taking the product of the RMS response surface, see Figure 2, the design significant wave heights as a function of modal wave period, see Figure 4, and the appropriate confidence factor, $C_T = 5.413$, see Figure 5. Exactly as for the case of the RMS unit wave height responses, one such surface exists for each ship/load condition, ship speed, and response type. The collection of all the extreme response surfaces is referred to as the extreme response data base.

DESIGN ACCELERATION PROCEDURE

SELECTION STRATEGIES

Design accelerations are considered to be those values selected when a realistic, yet conservative, strategy is applied to the extreme response data base. In this context, the word "strategy" means ship operator procedure in extreme seas. Three basic strategies were considered in this work:

1. The Worst Heading Strategy assumes that the ship operator selects the worst possible heading for each of the six ship responses.
2. The Most Likely Heading Strategy assumes that the operator considers the extreme seas as endangering the survivability of his ship and thus heads the ship directly into wind and sea. In applying this strategy, all headings less than 150 degrees, e.g. 0 through 135 degrees, were eliminated from the data base.*
3. The Average Pitch Strategy limits speed by avoiding pitch angles in excess of 3 degrees. This strategy is reportedly presently employed by the operator of two LNG tankers, and was interpreted here simply to mean that the operators would attempt to limit ship motions by heading changes when average pitch angles in the extreme seaways exceed 3 degrees.

The Worst Heading Strategy is considered the preferred strategy for selecting design values due to the as yet unknown consequences of large LNG spills. Clearly, this strategy represents the limiting case of ship response levels as the worst value for each response type is selected independently of all other response types. In reality, of course, these selected extreme responses can never occur simultaneously, e.g. the worst heading for roll is not the worst for pitch. Since ship operator behavior is not entirely predictable, and in the absence of other limiting conditions,

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*Data were available for discrete headings at intervals of 15 degrees.

the worst heading strategy appears to be the only safe one to employ in selecting design values.

The other two strategies (Most Likely Heading M, and Average Pitch AP), are so-called voluntary operator strategies and have been included in this work because they show the potential for reduced acceleration loads when prudent operator procedures are employed. It is expected that operators will become increasingly reliable in minimizing ship responses in extreme seas as accelerometer and hull strain gauge readouts on the bridge will become available during the lifetimes of these ships.

The optimization of both speed and heading changes made on the basis of minimizing ship trip time has not been considered in this work as such a process is also rational, voluntary strategy and therefore not appropriate for design work.

SPEED LOSS

Involuntary speed loss due to the increase in ship resistance with wave height is regarded as another limiting condition that, together with the Worst Heading Strategy, should be applied to the extreme response data base. Unfortunately, the capability for predicting this involuntary speed loss from purely theoretical considerations is not, at this time, sufficiently developed to allow its use during the course of the present LNG project. Since the impact of speed loss in extreme seas is regarded to be of great importance in developing realistic LNG design accelerations, it was decided to use the empirically collected speed loss data of James, see Reference 5. This data is currently in use by the U.S. Navy Fleet Numerical Weather Service for ship routing and is regarded as being the best available speed loss data that might be applied for ships such as the LNG tanker series. Better statistical/empirical speed loss data may exist within large commercial tanker fleets, but at this time such data are not available. Of the James speed loss data available for 15 ships, only a single ship appeared to adequately represent any of the ships in the LNG series--this is a C4A-A1/B1 cargo ship (Mariner-type ship) with a 17 knot design speed. The speed loss for this ship was applied uniformly to all LNG ships. Figure 7 presents these reduced speeds as indicated by James.

DESIGN ACCELERATIONS

Table 2 presents the responses selected for each ship when all three of the operator strategies, both with and without the James speed loss criteria, are applied to the extreme response data base. The periods associated with these selected extreme responses are also included. The Table 2 results thus provide lifetime extreme motion and acceleration data for the LNG ships operating on the transatlantic Trade Route 1 of Figure 4. Ship A, for example, would be expected to undergo a ± 47.6 foot heave cycle with a 10.1 second period once during its lifetime if the ship were operated under the Worst Heading, James Speed Loss Strategy on Trade Route 1. There is a one percent chance that a greater heave would occur.

Figures 8 and 9 were prepared to illustrate the sensitivity of such lifetime extreme ship accelerations to various heading, speed loss, and trade route (sea conditions) assumptions. These figures present accelerations and associated periods (from Table 2) of the ships arranged in order of increasing ship length for various combinations of assumptions. Accelerations are denoted by $\ddot{L}_V$ for vertical, $\ddot{L}_A$ for lateral, and $\ddot{L}_0$ for longitudinal. Though the Worst Heading Strategy, combined with the James speed loss criterion, W. J., is considered most appropriate for design, the lowest values for the two voluntary strategies, AP, MJ, are also shown in the table and these figures. The maximum accelerations shown for each ship in Figure 8a and 9 are, of course, the worst accelerations for all headings, speeds, and sea conditions. Although these worst accelerations are not physically realizable* they are useful because they represent the upper bound of the accelerations.

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*The highest speed thus considered, and consequently the worst acceleration, is too high because involuntary speed losses due to the added drag in waves and the loss in propulsive efficiency in waves were not considered.

Figures 8a and 8b are, of course, based on the Trade Route 1 design sea conditions of Figure 4. Figures 8c and 8d were constructed with a constant forty foot significant wave height across modal wave period suggested by the USCG staff. It is to be noted that this alternate set of design sea conditions is greater than the Trade Route 1 seas at all modal periods except for the 11 second period case. The 40 foot design sea is unrealistically high at periods greater than 19 seconds and less than 8 seconds, and unrealistically low compared to the world-wide extreme sea data of Figure 7. Nevertheless, the Trade Route 1 to 40 foot height sea comparison demonstrates the sensitivity of design accelerations to variations in design seas.

Figure 9 has been prepared to demonstrate the influence of speed loss on design acceleration. By means of arrows, the figure also denotes the heading angles at which the most extreme accelerations occur.

Upon examination of Figures 8 and 9, several observations can be made:

1. Load variations which consist of nothing more than simple GM (KG) changes do not affect design accelerations.
2. The range of periods associated with the accelerations is generally one second or less for vertical acceleration which, because it is so much larger, can be considered the most important of the three accelerations. The periods associated with lateral and longitudinal accelerations vary substantially more -- the largest variation in periods occurs for the least important acceleration (longitudinal).
3. The longer ships are more significantly affected by variations in the design seas than the shorter ships are. This tendency is particularly noticible when speed loss is not considered. These results suggest that the design accelerations of longer ships are likely to be increased as more and better wave data becomes available.
4. By far the greatest impact of speed loss on accelerations is for the shorter ships. For example, for the shortest ship, Ship A, the vertical acceleration is reduced by nearly 35 percent. Similarly, the reduction for Ship B, is 25 percent, for Ship C 13 percent, and for Ships D and E is less than 10 percent.

5. Speed reduction does not appear effective in reducing, or in any way affecting, either lateral or longitudinal accelerations. Rather, it is more effective for the more important vertical accelerations.
6. Extreme accelerations occur at different headings for the three types of accelerations, though they tend to occur in bow seas when speed reduction is considered; when no speed reduction is applied, the extremes tend to occur in head seas for the shorter ships.

In summary, Figure 10 presents the accelerations and associated periods considered most appropriate for design if the ships are restricted in service to Trade Route 1. Reference 3 elaborated on design accelerations in seas representative of world-wide worst! The values are derived by applying the Worst Heading Strategy and James speed loss criteria to the extreme response data base generated by applying equation 1. Lines are drawn between values for adjacent ships on the figure only to suggest general trends, and should not be interpreted as acceleration curves across ship length. The main reason for this is, of course, that the location of the center of the forward tank is not in the same place relative to each ship. Also the lines do not account for changes in tank geometry due to tank type, e.g. the vertical distance of the center of the tank above the baseline.

Several conclusions can be drawn from Figure 10:

1. The largest, and hence most important design acceleration, vertical acceleration, is strongly dependent on ship length.
2. Design accelerations generally occur at 10 knots, though for more severe seas than those of Figure 4, the speed will decrease.
3. Only small variations in the periods, e.g. less than 2 seconds, associated with a given design acceleration type occur across the series ships. Variations in period across all three design acceleration types is less than 4 seconds.

TANK LOCATION

The extreme ship accelerations presented in this report are predicted for the center of the forward tank of each ship, though the designer may find it useful to know the accelerations for other tanks along the ship. Reference 2* presents a brief examination of the influence of spatial variations along the ship in which point location, as well as GM, speed, and heading were allowed to vary. The conclusions of this examination are briefly repeated here:

1. Vertical acceleration is constant along any vertical line through the ship. Similar rules hold for lateral and longitudinal accelerations.
2. Only the large spatial variations in the longitudinal direction drastically alter ship responses, e.g. vertical and lateral accelerations; longitudinal and lateral accelerations are so much smaller in magnitude than vertical accelerations that any changes that do occur in these two appear rather insignificant.
3. Load (GM) variations do not further affect response variations for a given heading.
4. Heading variations do affect responses with response variations being higher in bow seas (135 degrees) and less in quartering seas (45 degrees).
5. Speed variations do not further affect response variations for a given heading.

DESIGN VECTOR

A LNG tank must be designed to withstand the maximum force exerted by the liquid natural gas on the sides and bottom of the tank at any given

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*Reference 2 contains response trend-with-spatial variation plots which can be used to translate the forward tank extreme accelerations to other locations in the ship.

instant in time. A major component of this force* is directly proportional to the magnitude of the forces acting on the LNG along the direction of this force or acceleration** vector. The maximum value of this force vector in the lifetime of the ship is regarded as the design force or acceleration vector. This vector consists of the inertia forces due to the accelerations of the ship and the force or acceleration due to gravity. The calculated ship accelerations were derived in a coordinate system that remains perpendicular to the earth's gravity. As a result neither the vertical accelerations nor the lateral and longitudinal accelerations include gravity.

Since tank design procedures require the magnitude and direction of the design force or acceleration vector it is necessary to combine the acceleration related inertia forces and gravity. The magnitude of the resultant design vector, henceforth denoted as the design acceleration vector may be written in terms of the inertia forces*** a_x, a_y, a_z which are equal to but of opposite sign to the corresponding ship accelerations $\ddot{L}_0$, $\ddot{L}_A$, and $\ddot{L}_V$ and the force due to gravity.

$$|DV| = \sqrt{a_x^2 + a_y^2 + (a_z - 1)^2} \qquad (2)$$

were a_x is the longitudinal force,
a_y is the lateral force,
a_z is the vertical force,
1 is the acceleration due to gravity.

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*Vapor pressure in tank and sloshing loads represent the other major components of the tank design loads as noted by R. L. Bass et. al. in their 1976 Ship Structures Report SSC-258 Table VI.

**The terms forces and accelerations are used interchangeably since they are equal when forces are calculated on a per unit weight basis and accelerations are calculated on a per unit gravity basis as is the convention adopted for this work.

***See Figure 11. It should be noted that the distinction between inertia force and acceleration was not appropriately made in the earlier work of reference 3.

The direction of the design vector is referenced to the tank by two angles, T and T in the YZ and XZ plane of the tank, see Figure 11. T is defined as

$$T = \left\{ \arcsin \left(\frac{a_y}{|DV|} \right) \right\} - \phi \qquad (3)$$

and T is defined as

$$T = \left\{ \arcsin \left(\frac{-a_x}{|DV|} \right) \right\} - \theta \qquad (4)$$

Thus both T, and T reference the design vector to the vertical axis of the tank, which in turn moves with the roll and pitch of the ship. The tank axis is thus referenced to the local earth vertical using roll and pitch.

It becomes immediately apparent upon inspection of equation 2 that there are two fundamentally different methods by which the design acceleration vector, DV, may be determined, i.e., DV may be considered as a time dependent vector, DV(T) given in equation 2, or a time independent scalar DV(TI).

If DV is time independent, the three inertia force components, a_x, a_y, a_z are determined independently. That is, DV is composed of gravity nondimensionalized by g and by the absolute value of the extreme accelerations $L_{\ddot{O}}$, $L_{\ddot{A}}$, and $L_{\ddot{V}}$ which represent the maximum possible a_x, a_y, and a_z. This time independent design vector has a magnitude

$$|DV(TI)| = \sqrt{\bar{a}_x^{\,2} + \bar{a}_y^{\,2} + (\bar{a}_z + 1)^2} \qquad (5)$$

where $\bar{a}_x$ is the absolute value of extreme longitudinal ship acceleration,

$\bar{a}_y$ is the absolute value of extreme vertical ship acceleration without gravity,

$(\bar{a}_z + 1)$ is the absolute of extreme vertical ship acceleration including gravity.

To examine the difference between DV(T) and DV (TI), ship responses, wave height and DV(T), in accord with equation 2, were calculated in time history form for a series of representative conditions. The resultant maximum values of the accelerations as well as the time dependent and the independent design acceleration vector are presented in Tables 3-6. These calculation conditions included situations where pitch and vertical acceleration predominated as well as other situations where roll and lateral accelerations predominated. The time history expansions were performed using, essentially, the procedures detailed by Zarnick[32] and Withrington[33]. All of the time history expansions were made for realistic short crested seas using a $\cos^2$ spreading function. Figure 12a presents an example of the time histories of DV(T) and the associated ship responses for Ship A in a condition where vertical ship responses predominate. Although these response syntheses were made for Ship A operating for 30 minutes in 40 foot significant wave height seas, Figure 12a shows only the 30 second time interval which included the extreme vertical ship responses. Figure 12b shows similar results for conditions where relatively large lateral accelerations occur.

In summary, the magnitude of the vertical acceleration which includes the earth gravity determines the magnitude of both DV(T) and DV(TI) irrespective of a_x and a_y. Thus, the vertical acceleration term a_z is the dominant term which specifies the magnitude of the design acceleration vector. In other words, for design purposes

$$|DV(T)| \cong |DV(TI)| \tag{6}$$

Table 3b summarizes the results of this brief set of calculations. It may be seen from this table for example, that the DV(TI) varies, by 6 percent or less from DV(T) at headings where design accelerations are attained. The a_x and a_y terms, along with pitch and roll, serve to define the angles T, T, which the design vector DV(T) makes relative to the vertical axis of the ship or tank. These angles in turn are generally 8 degrees or less when DV(T) is a maximum. It is noted however, that when DV(T) is less than a maximum the angles reach values up to 17 degrees.

ASSUMPTIONS AND UNCERTAINTIES

The major assumptions in the prediction of the design accelerations are as follows:

1. Ship responses are assumed to be linear for the extreme seas employed, though roll motion is treated as a special case as described below.
2. Extreme seas are assumed to be appropriately represented by two-parameter wave spectra defined by observed extreme wave heights and wave period pairs.
3. The wave height distribution function is regarded as a Rayleigh distribution.
4. The worst extreme acceleration, modified by speed loss, and not to be exceeded 99 percent of the time in a three day ship exposure to the extreme seas is the appropriate design value.

With these assumptions in mind, a certain so-called uncertainty can be associated with the design accelerations of Figure 9. For example, each component of

$$X = \sigma \cdot (\tilde{\zeta}_w)_{1/3} \cdot C_T \tag{1}$$

as well as the selection of design values from the extreme response data base has its own individual uncertainty associated with it. Each of these four stages of the building block procedure are now examined.

σ UNCERTAINTIES

The uncertainties associated with the RMS unit wave height responses, σ, are associated with the use of the linear superposition principle for large values of ship responses. It has been known for some time that as ship motions tend to reach limiting values in extreme seas, the limiting values are not necessarily accurately predicted by use of linear superposition. As reported in Reference 2, a technique was developed to treat roll motion, the most nonlinear ship response. Briefly, a roll reduction factor which implies increased roll damping in extreme seas has been developed and applied to the LNG series ships.

Experimental verification of the accuracy of the predicted three components of acceleration are given in Reference 1. It was shown in that reference that the RMS ship responses are overpredicted within an accuracy of 10 percent. Thus the predictions are on the conservative side of reality.

$(\tilde{\zeta}_w)_{1/3}$ UNCERTAINTIES

Two basic uncertainties are inherent in the determination of extreme sea conditions. The first is in the shape or frequency content of the extreme sea energy spectrum. The second is the actual height of the extreme sea. Reference 1 demonstrated that the shape of North Atlantic Extreme Sea Spectra can be approximated by single peaked Bretschneider spectra. The use of these spectra resulted in uncertainties (overpredictions) in the predicted extreme responses of up to 10 to 12 percent. Figure 13 is adopted from the Reference 1 work. The top row of graphs shows the measured Atlantic spectra at Station India (59°N, 19°W) and the corresponding predicted Bretschneider spectra. The bottom row of plots shows the resulting response spectra for Ship A at 135 degrees and 10 knots. Percent variations in RMS response values vary from 4.7 percent (first graph) to 12.0 percent (last graph).

Subsequent to this earlier work, the fit of Bretschneider spectra to North Pacific extreme seas has been investigated by use of measured spectra at Station Papa (50°N, 145°W). The results of this comparison are shown in Figure 14. The use of the Bretschneider spectra for the extreme sea cases (first four columns) results in response overpredictions up to about 5 percent. The fifth column of graphs is included only to illustrate that higher modal period seas do exist in the Pacific, although the available spectra are for moderate seas. In this case, the response is overpredicted by about 8 percent.

In summary, the shape of extreme sea spectra can be represented by the Bretschneider spectral form. The uncertainty in predicted extreme ship response due to this choice of spectral shape is about a 12 percent overprediction. The second uncertainty associated with the extreme seas, e.g. the height of the sea, is not so easy to quantify.

The difficulty in establishing realistic extreme wave heights is due to a scarcity of extreme sea data. A further element of uncertainty is that associated with the calibration of visual wave height data. As shown in Reference 1, the uncertainty in proper calibration results in up to a 22 percent variation in extreme wave height. It is regarded that this 22 percent uncertainty is equally applicable to the uncertainty in the expected occurrence of the wave, i.e. the quantity of available extreme sea data is scarce and the resulting reliability of their probability of occurrence is poor.

C_T UNCERTAINTIES

Uncertainties in design accelerations resulting from the selected confidence factor C_T are associated with the length of the exposure time to the extreme seas and the wave height distribution function. For the sake of conservatism, the ship exposure to the extreme seas used throughout this work has been taken as three days. When exposure time is computed for a 20 year ship life directly, on the basis of occurrence* of the extreme seas, ship exposure times on the order of three hours to twelve hours result. Thus, the use of a three day exposure time is up to three times as long as the exposure time indicated by the existing wave data. If C_T is considered for a somewhat less conservative exposure time than three days, for instance 40 or even 20 hours, a reduction in the predicted extremes ranging from about 4 to 8 percent results. This rather low reduction in the predicted extreme with substantial exposure time reductions suggests great accuracy in the estimation of the exposure time of the ship to the extreme storms is not required.

Another factor of conservatism inherent in the use of C_T values is the validity of the wave height distribution factor which we have assumed

---

*Unreliable due to scarcity of data.

for a large number of waves, i.e., the use of the Rayleigh distribution. The results of Reference 6 suggest that C_T may overpredict the extreme ship responses by 9 percent when 20,000 cycles of waves are encountered.

Reference 6 presents results of an experimental model study of extreme ship motions and bending moments for very long time periods in irregular seas. Based on the results of this work, it is clear that the use of our C_T values and the associated assumption of the Rayleigh wave height distribution will tend to produce conservative estimates of the extreme design accelerations. Specifically, the results of Reference 6 indicate that C_T overestimates the true value of the extreme by "at least" a factor of $(1 - \varepsilon^2/2)^{\frac{1}{2}}$ where ε corresponds to the bandwidth parameter of the ship response. If this assessment of the error associated with C_T due to spectral bandwidth is assumed to be valid, the consequences of the assumption of the Rayleigh wave height distribution may be quantified. The evaluation of ε for a typical range of ship responses indicates that ε varies from about 0.3 to 0.7. This, in turn, corresponds to overpredictions of the true extremes by up to 9 percent. Figure 15 shows that estimated overpredictions of the worst heading extreme accelerations is from about 2 to 9 percent. Though this measure of the degree of conservatism in the predicted extreme response may not be entirely valid, it still suggests that a substantial degree of conservatism is inherent in the use of the series C_T values of Figure 5.

In summary, it appears quite certain that the C_T values are associated with 10 to 20 percent overprediction of extreme responses.

DESIGN SELECTION UNCERTAINTIES

The last major uncertainty associated with the design accelerations is due to the procedure employed to select design values from the extreme response data base. For example, if speed loss is not considered in the selection process, the vertical accelerations may be overestimated by up to 35 percent for the shorter ships, see Figure 16 adopted from Figure 9. For ships with lengths in excess of 800 feet, the uncertainty of design vertical acceleration associated with speed loss decreases to negligible values of 8 percent or less. In general, speed loss has little effect on the less important design accelerations in the lateral and longitudinal directions.

SUMMARY

The uncertainties associated with each of the four steps of the building block procedure have been discussed and are summarized on Figure 17. In all cases, the uncertainties are on the conservative side which, in this context, indicates a percentage overprediction. By far, the most influential of the four steps of the building block procedure on the shorter ships is the design selection (speed loss) procedure. For the longer ships, the height of the extreme seaway is more critical to the design, e.g. vertical, acceleration than the loss of speed due to the extreme seas. The effects of ship response prediction accuracy, wave spectral shape, ship exposure time to the extreme seas, and assumed Rayleigh distribution of the extreme wave heights vary from 8 to 12 percent design acceleration overpredictions and hence are not so important as speed loss and wave height.

RECOMMENDATIONS AND CONCLUSIONS

In view of the unknown consequences of LNG spills, it is considered that conservative tank design acceleration rules must be retained at the present time. Thus, design accelerations have been presented based on the worst heading assumption both with and without voluntary speed loss criteria. Due to the great effect of speed loss on design acceleration levels, e.g. for the smaller ships, it is strongly recommended that an involuntary speed loss criteria, e.g. due to added drag in extreme waves, be developed and adopted to the building block procedure.

For the smaller ships, the voluntary speed loss criteria used is the single most important factor in determining the design accelerations. However, for the larger ships, the height of the extreme seaway is by far the most important factor.

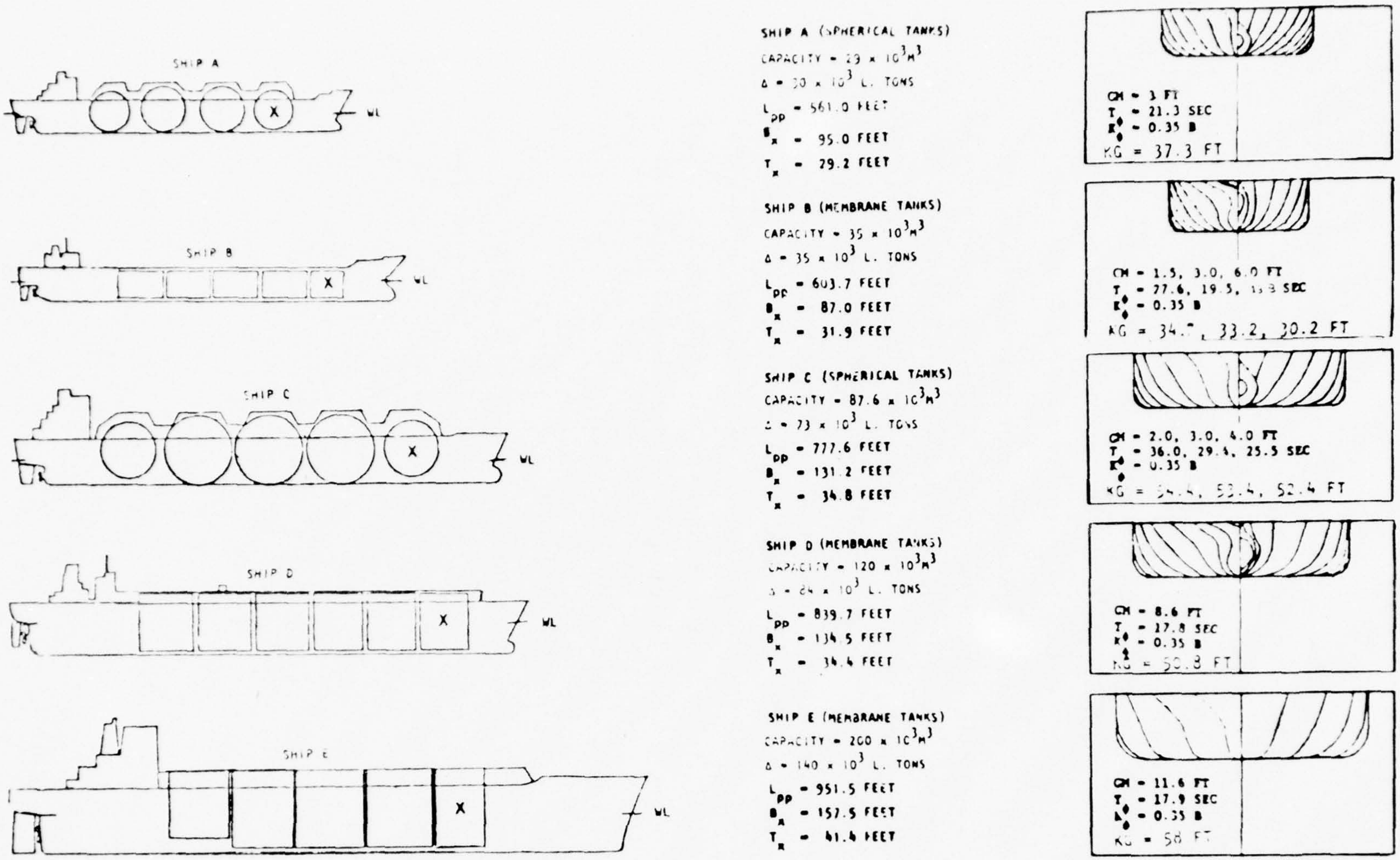
Design vertical acceleration is considered the most important acceleration for design because it is so much larger than either lateral (by at least a factor of 2) or longitudinal (by at least a factor of 10) design accelerations. The dominance of vertical acceleration in determining the magnitude of the design vector and hence the tank design pressure is accentuated when gravity is properly considered. Design vertical acceleration is strongly dependent on ship length though periods associated with it are not. For each ship in the series, design vertical acceleration occurred in bow seas.

It is expected that as more extreme sea data becomes available, the design sea conditions will change (increase). As more data becomes available, e.g. for the North Pacific, it is expected that the wave heights will increase for the higher modal period groups. Thus, the larger ships will have larger responses at these higher periods than in the present work.

Finally, it is recommended that the LNG ship series response data base be updated regularly to reflect increases in extreme seas, newer speed loss criteria, and potential to reduce extreme ship responses by reliable operator strategies. The data base is stored on magnetic bcd tape so such access will be relatively easy to accomplish on any computer systems of the future.

ACKNOWLEDGMENT

The authors express their appreciation to Dr. W. R. McCreight of DTNSRDC for his efforts in fitting Weibull distributions to the observed North Atlantic wave data of Hogben and Lumb.



SHIP A (SPHERICAL TANKS)
CAPACITY = 29 x $10^3 M^3$
Δ = 30 x 10^3 L. TONS
L_{PP} = 561.0 FEET
B_x = 95.0 FEET
T_x = 29.2 FEET

SHIP B (MEMBRANE TANKS)
CAPACITY = 35 x $10^3 M^3$
Δ = 35 x 10^3 L. TONS
L_{PP} = 603.7 FEET
B_x = 87.0 FEET
T_x = 31.9 FEET

SHIP C (SPHERICAL TANKS)
CAPACITY = 87.6 x $10^3 M^3$
Δ = 73 x 10^3 L. TONS
L_{PP} = 777.6 FEET
B_x = 131.2 FEET
T_x = 34.8 FEET

SHIP D (MEMBRANE TANKS)
CAPACITY = 120 x $10^3 M^3$
Δ = 84 x 10^3 L. TONS
L_{PP} = 839.7 FEET
B_x = 134.5 FEET
T_x = 34.4 FEET

SHIP E (MEMBRANE TANKS)
CAPACITY = 200 x $10^3 M^3$
Δ = 140 x 10^3 L. TONS
L_{PP} = 951.5 FEET
B_x = 157.5 FEET
T_x = 41.4 FEET

GM = 3 FT
T_ϕ = 21.3 SEC
K_ϕ = 0.35 B
KG = 37.3 FT

GM = 1.5, 3.0, 6.0 FT
T_ϕ = 27.6, 19.5, 13.8 SEC
K_ϕ = 0.35 B
KG = 34.7, 33.2, 30.2 FT

GM = 2.0, 3.0, 4.0 FT
T_ϕ = 36.0, 29.4, 25.5 SEC
K_ϕ = 0.35 B
KG = 54.4, 53.4, 52.4 FT

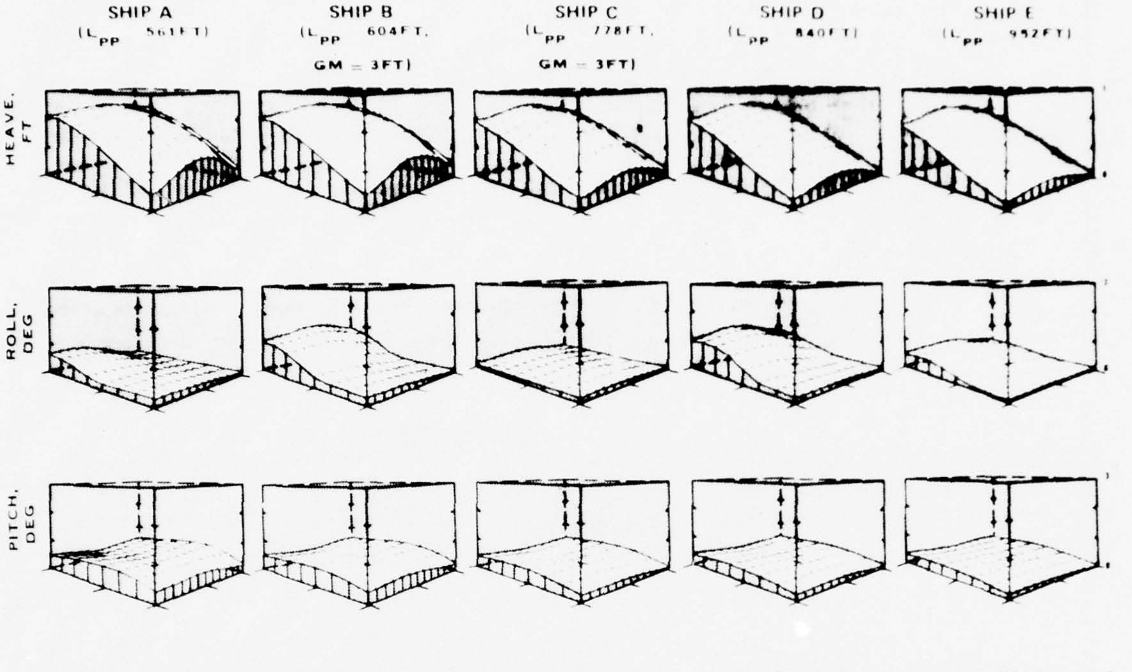
GM = 8.6 FT
T_ϕ = 17.8 SEC
K_ϕ = 0.35 B
KG = 50.8 FT

GM = 11.6 FT
T_ϕ = 17.9 SEC
K_ϕ = 0.35 B
KG = 58 FT

NOTES: 1. **X** IS LOCATION OF CENTER OF FORWARD TANK FOR WHICH SHIP ACCELERATIONS ARE PREDICTED.
2. SHIP PROFILES ARE NOT TO SAME SCALE AS SHIP BODY PLANS.
3. T_ϕ IS APPROXIMATE ROLL PERIOD. K_ϕ IS ROLL RADIUS OF GYRATION.

Figure 1 - LNG Series Ship Particulars and Geometry

LNG SERIES
ROOT MEAN SQUARE RESPONSE SURFACES
UNIT SIGNIFICANT WAVE HEIGHT
5 KNOTS



NOTE: T_O IS MODAL WAVE PERIOD IN SECONDS.
μ IS SHIP HEADING IN DEGREES, 180 DEGREES IS HEAD SEAS.

Figure 2 - RMS Response Surfaces of LNG Series, 5 Knots

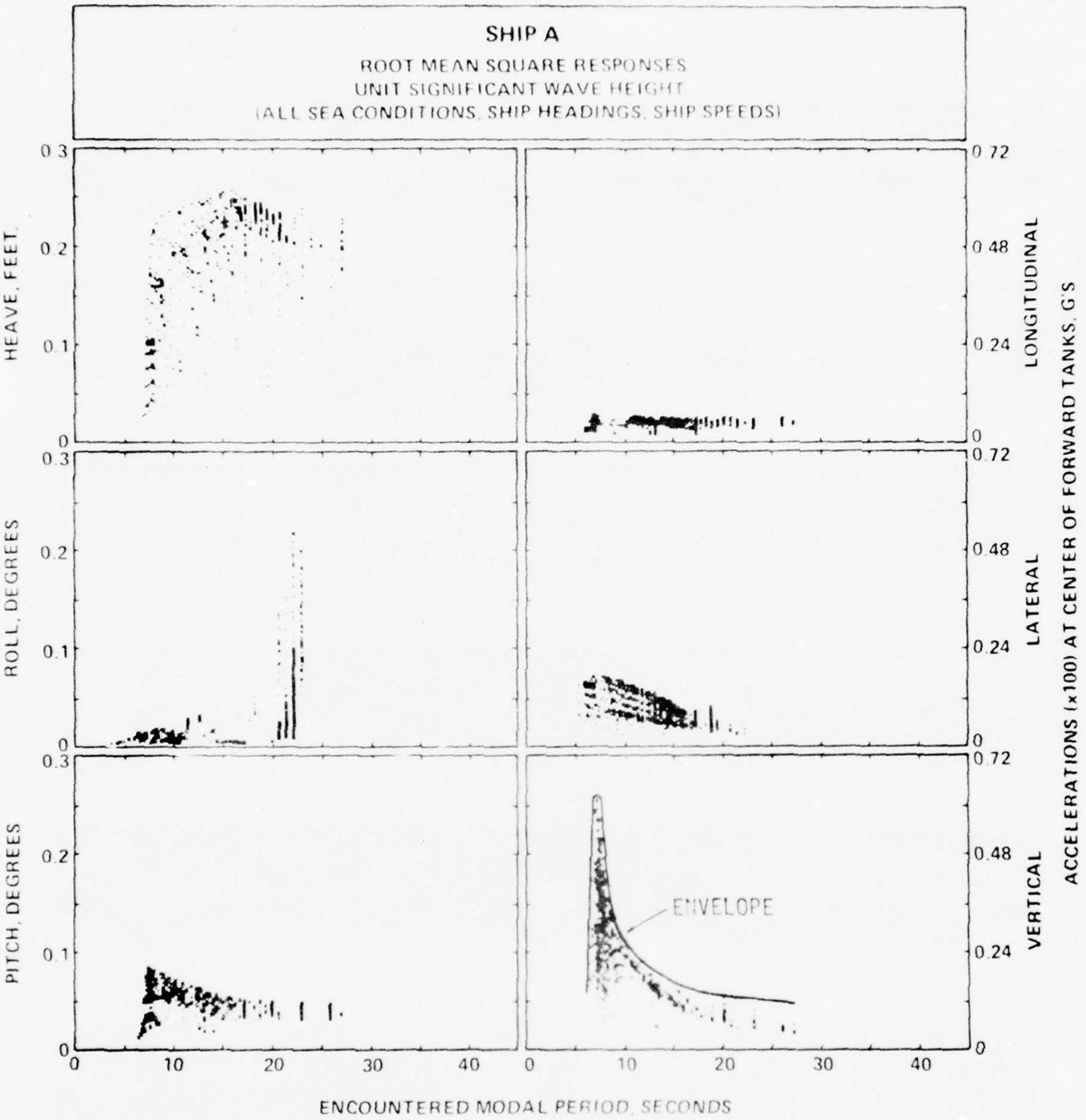


Figure 3 - Ship A, Root Mean Square Responses versus Encountered Modal Periods

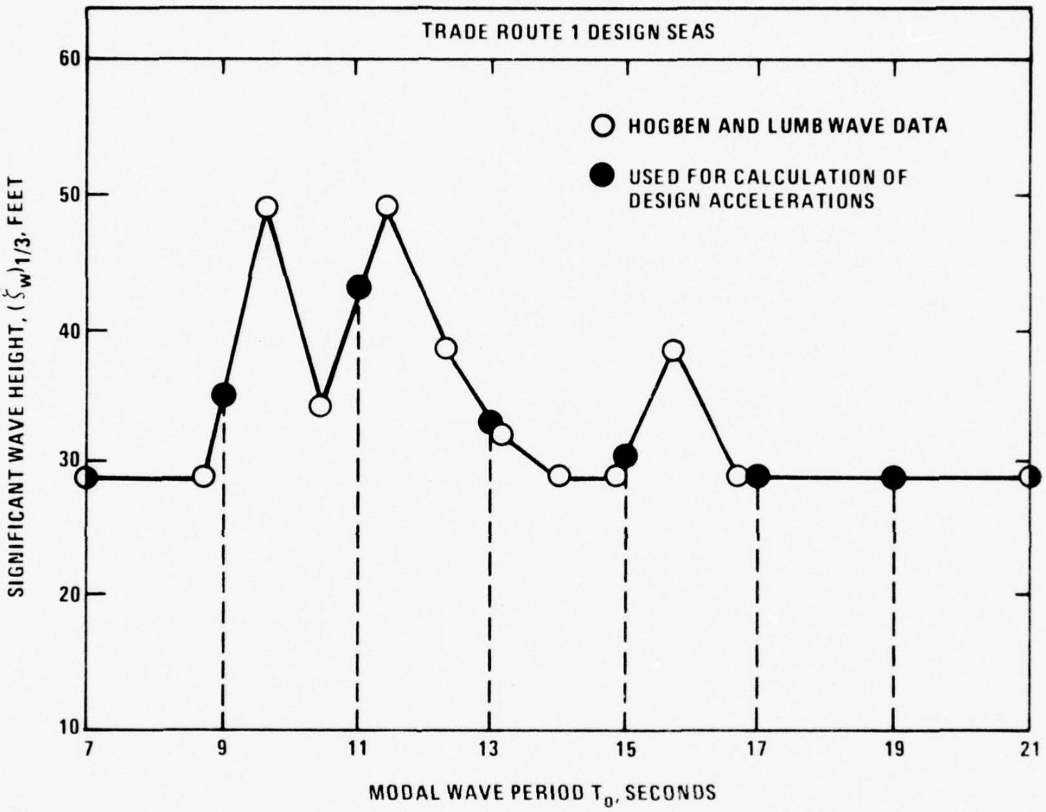


Figure 4 - Design Sea Conditions

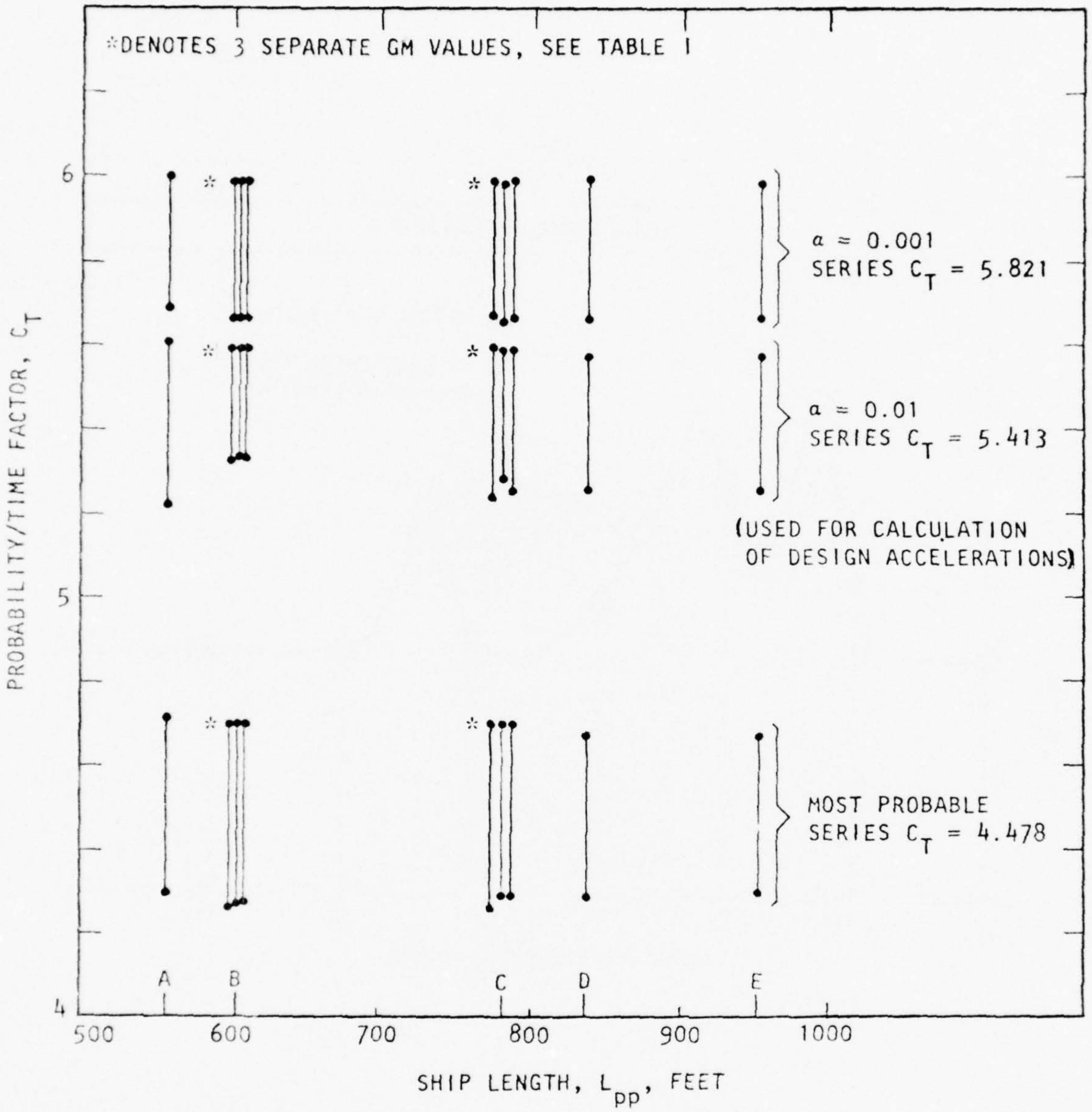
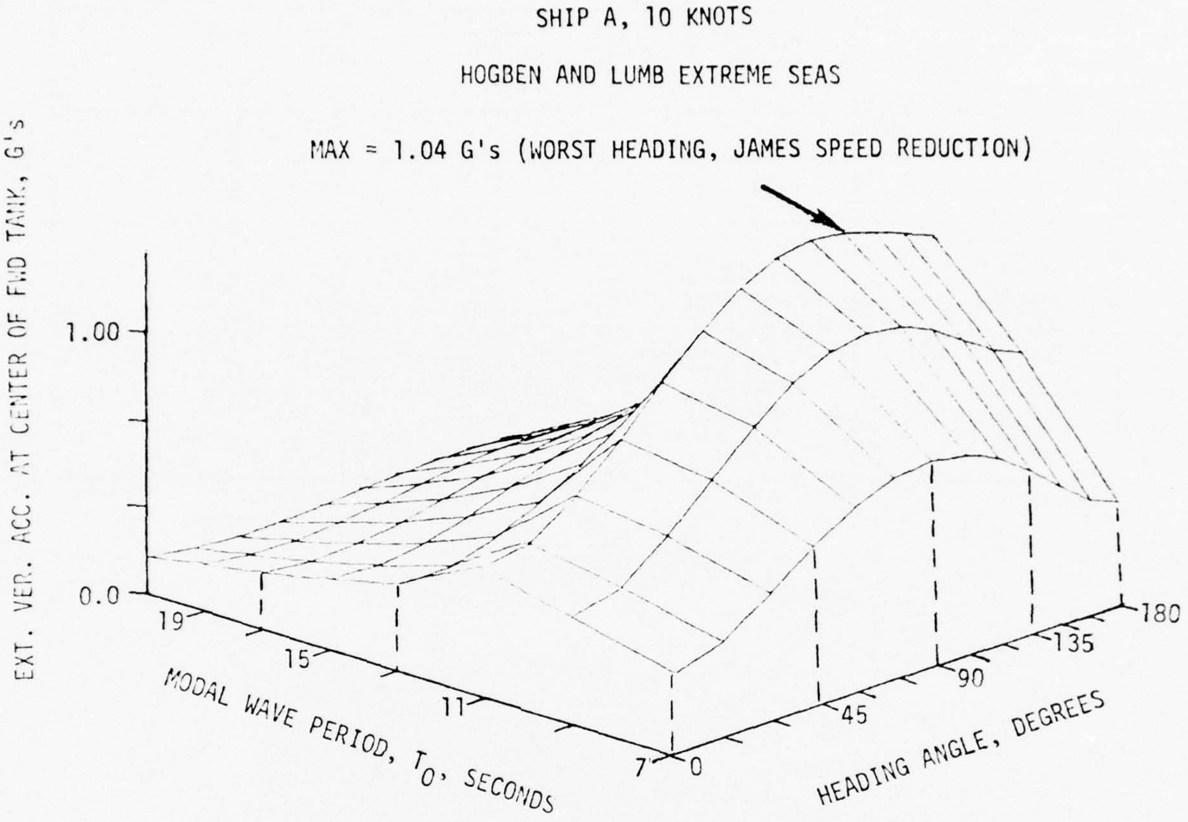


Figure 5 - LNG Series Probability/Time Confidence Factor: C_T



SHIP A, 10 KNOTS

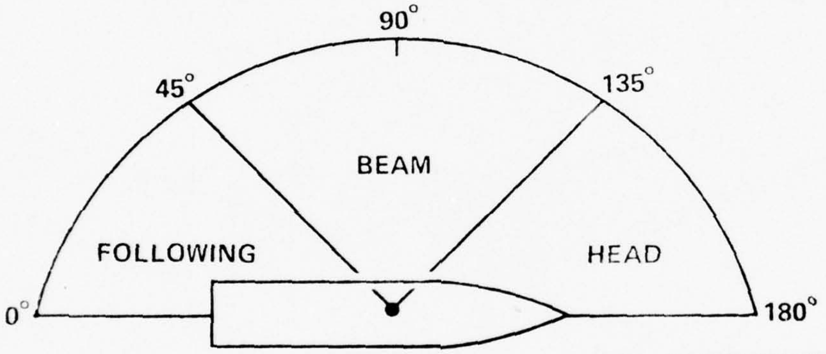
HOGBEN AND LUMB EXTREME SEAS

MAX = 1.04 G's (WORST HEADING, JAMES SPEED REDUCTION)

(NOTE: 180° ~ HEAD SEAS)

Figure 6 - Extreme Response Surface for Vertical Accelerations

SIG. WAVE HT., FEET	JAMES SPEEDS FOR C4-S-A1/B1 HULL (KNOTS)		
	FOLLOWING SEAS	BEAM SEAS	HEAD SEAS
28.9	14.2	11.0	8.6
30.0	13.9	10.7	8.2
32.6	13.6	9.9	7.3
35.0	13.2	9.3	6.7
43.8	11.9	6.9	4.0
45.5	11.8	6.4	3.4
48.5	11.6	5.6	2.4
52.0	10.9	4.6	1.3
54.8	10.6	3.8	0.6
54.9	10.6	3.8	0.6
55.0	10.5	3.6	0.5



FOR CALCULATION OF DESIGN VALUES:*

FOLLOWING SEAS: 0 - 45°
BEAM SEAS: 60 -135°
HEAD SEAS: 150 -180°

DESIGN SEA CONDITIONS FOR 3 DIFFERENT TRADE ROUTES. SIGNIFICANT WAVE HEIGHTS (FEET)

T_o	WW	TR#1	CONST.WH
7	28.9	28.9	40'
9	45.5	35.0	40'
11	52.0	43.8	40'
13	54.8	32.6	40'
15	54.9	30.0	40'
17	55.0	28.9	40'
19	48.5	28.9	40'
21	28.9	28.9	40'

---

*Data Base covered only discrete headings at 15-degree intervals.

Figure 7 - Speed Loss and Design Sea Conditions

$\alpha = 0.01$ T = 3 days, $(\tilde{\zeta}_w)_{1/3}$ = TR #1 of Fig. 4 and 7

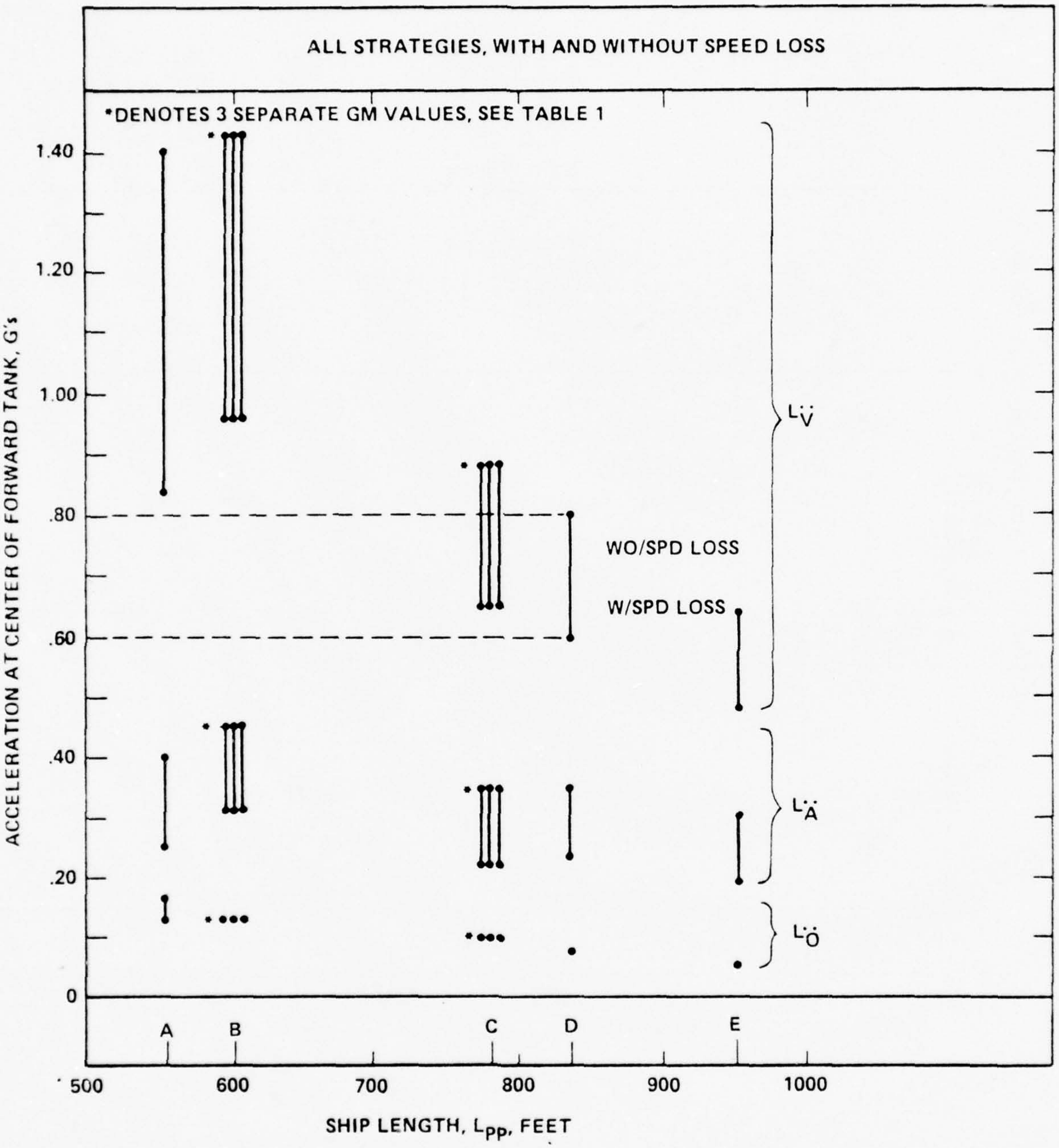


Figure 8a - LNG Series Extreme Accelerations

$\alpha = 0.01$ T = 3 days, $(\tilde{\zeta}_w)_{1/3}$ = TR #1 of Fig. 4 and 7

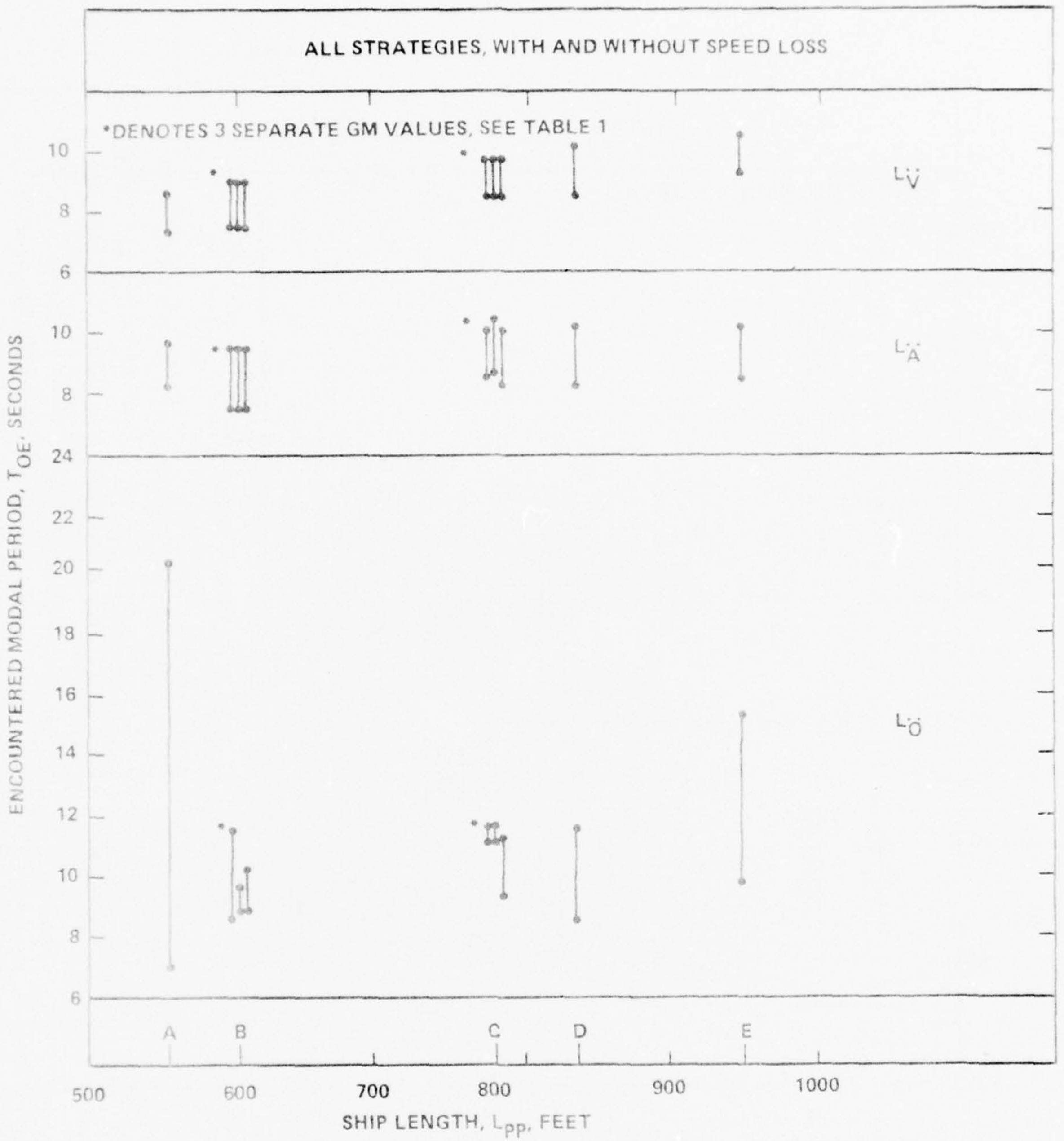


Figure 8b - LNG Series Periods Associated with Extreme Accelerations

$\alpha = 0.01$ T = 3 days, $(\tilde{\zeta}_w)_{1/3} = 40'$ of Fig. 7

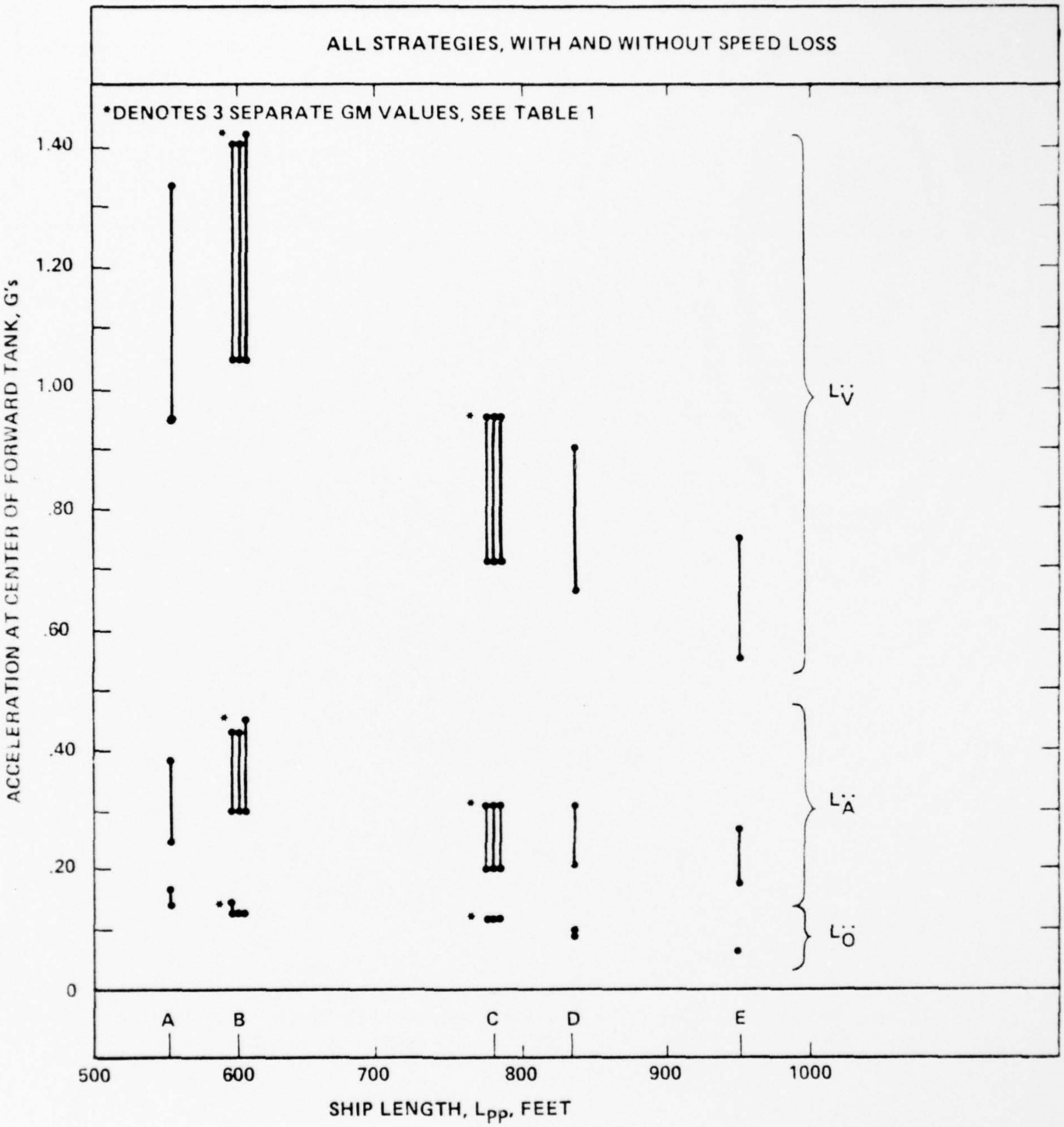


Figure 8c - Influence of Alternate Constant 40 Ft Design Sea Conditions on Extreme Accelerations

$\alpha = 0.01$ T = 3 days, $(\tilde{\zeta}_w)_{1/3}$ = 40' of Fig. 7

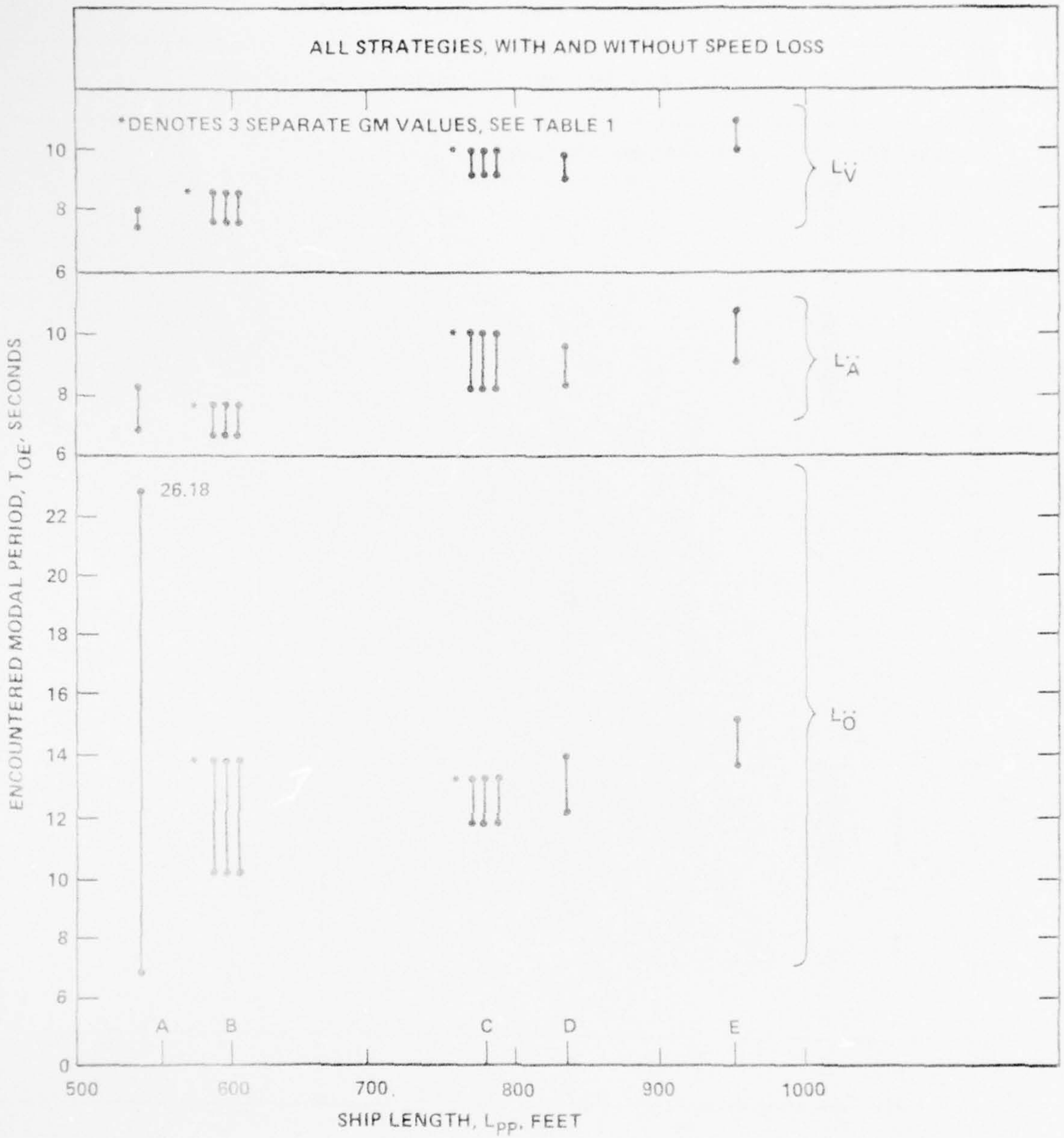


Figure 8d - Influence of Alternate Constant 40 Ft Design Sea Conditions on Periods Associated with Extreme Accelerations

$\alpha = 0.01$ T = 3 days, $(\tilde{\zeta}_w)_{1/3}$ = TR =1 Fig. 4 and 7

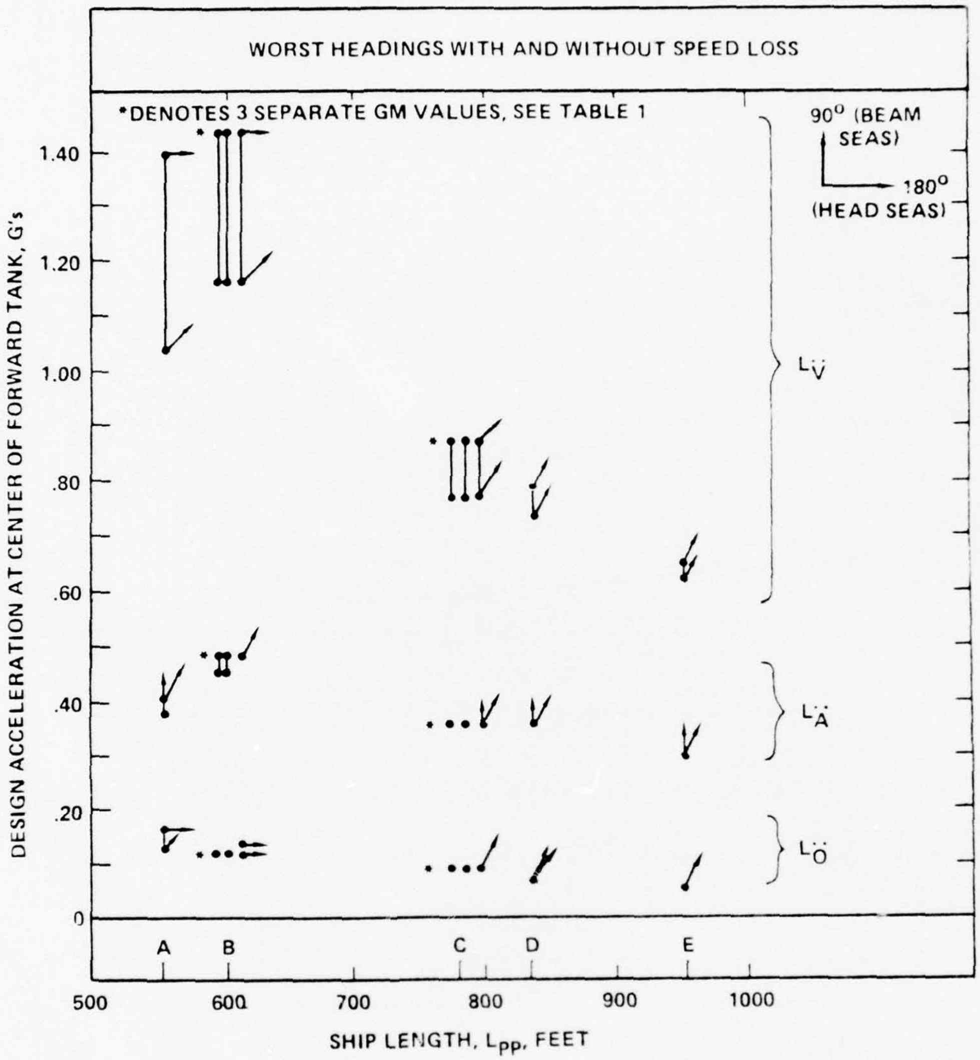


Figure 9 - Influence of Speed Loss on Extreme Accelerations

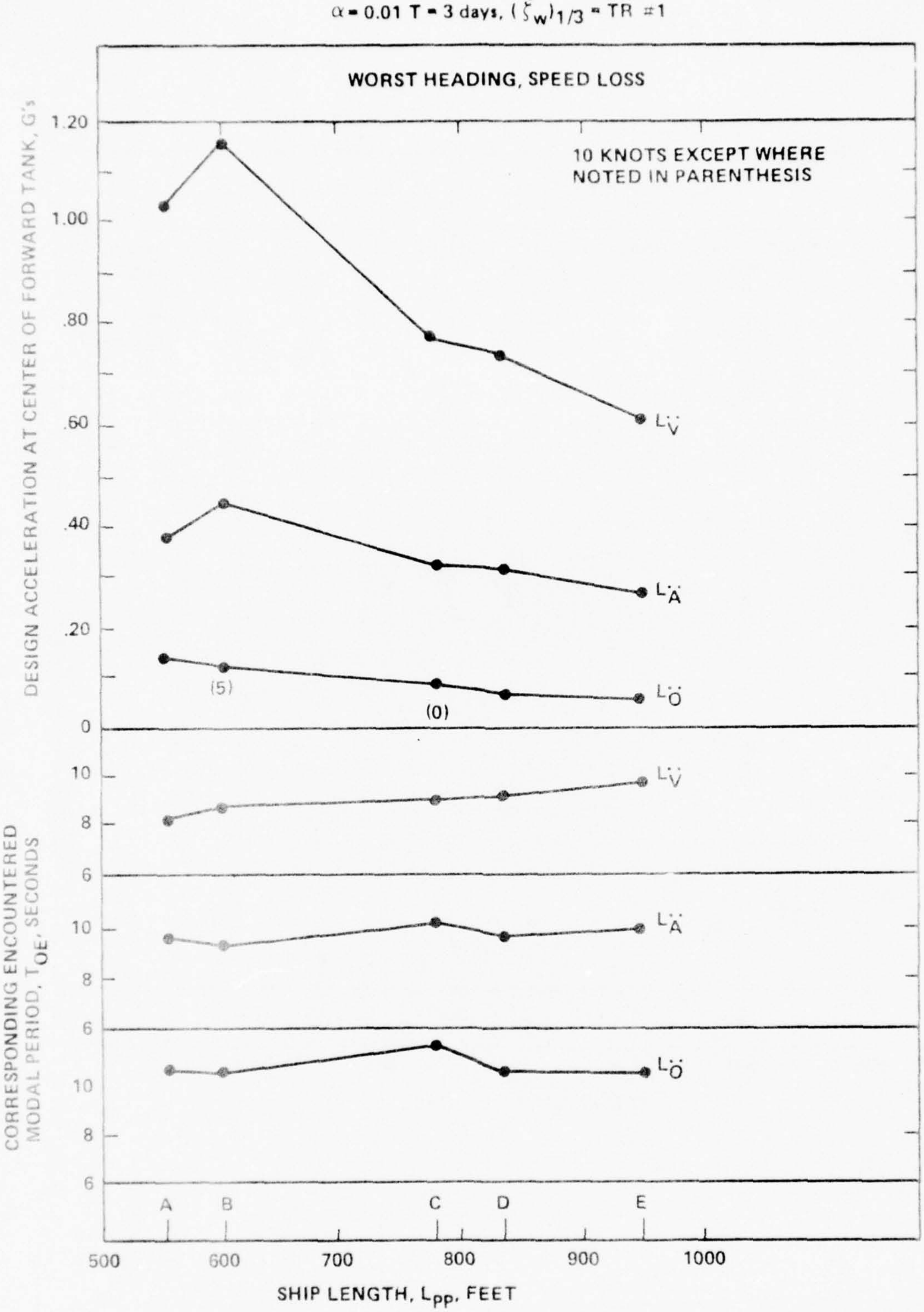
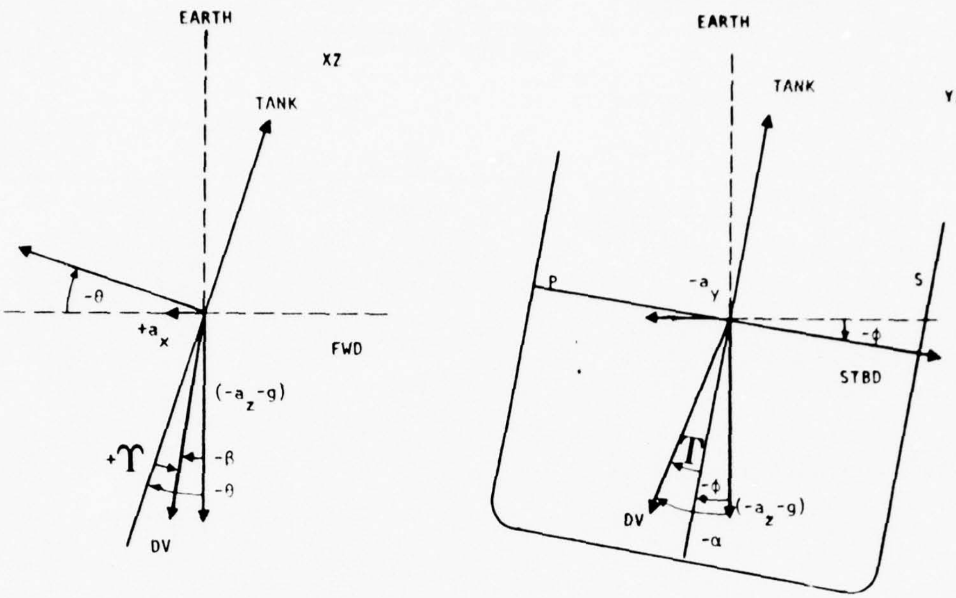


Figure 10 - Recommended Design Accelerations and Corresponding Encountered Modal Periods of LNG Ship Series



$$\mathrm{T} = \alpha - \phi, \quad \alpha = \arcsin\left\{a_y / \left[a_y^2 + (a_z - 1)^2\right]^{1/2}\right\}$$

$$\Upsilon = \beta - \theta, \quad \beta = \arcsin\left\{-a_x / \left[a_x^2 + (a_z - 1)^2\right]^{1/2}\right\}$$

$(a_x, a_y, a_z)\ \underline{\Delta}$ Inertia forces due to ship accelerations $(\ddot{L}_0, \ddot{L}_A, \ddot{L}_V)$

$a_x = -\ddot{L}_0, \ a_y = -\ddot{L}_A, \ a_z = -\ddot{L}_V$

DEFINITION OF ANGLES	XZ PLANE	YZ PLANE
Earth* to tank	θ, pitch pos. CCW from ref.	ϕ, roll pos. CCW from ref.
Earth* to DV	β, beta pos. CCW from ref.	α, alpha pos. CCW from ref.
Tank* to DV	Υ, upsilon pos. CCW from ref.	T, tan pos. CCW from ref.

*Reference

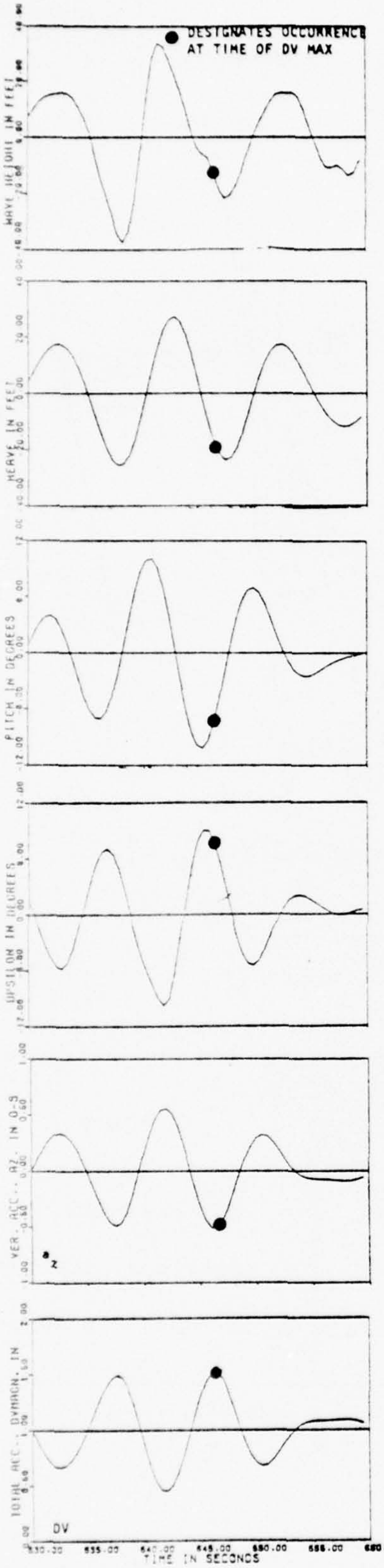
$$|DV| = |\text{DESIGN ACCELERATION VECTOR}| = \sqrt{a_x^2 + a_y^2 + (a_z - 1)^2}$$

Figure 11 - Total LNG Tank Design Acceleration Vector

SHIP A, 135 DEGREES, 10 KNOTS, 30 MINUTES
IN SEAWAY CHARACTERIZED BY SIG. WAVE HT. OF
40 FEET AND MODAL WAVE PERIOD OF 13 SECONDS.

TIME AND VALUE OF SHIP RESPONSE AT DV AND MOTION MAXIMA

Response	At Max DV		At Max Response	
	Value	Time	Value	Time
Wave Ht.	-12.3	646.5	-37.5	638.5
Heave	-17.7	646.5	27.2	643.0
Roll	0.2	646.5	- 1.1	121.5
Pitch	- 7.5	646.5	-10.2	645.5
a_x	-0.00	646.5	0.09	970.5
a_y	-0.04	646.5	- 0.18	356.0
a_z	-0.51	646.5	0.56	642.0
DV Magn.	1.51	646.5	1.51	642.5
Upslon	7.7	646.5	- 9.8	642.0
Tau	-1.8	646.5	12.7	642.5



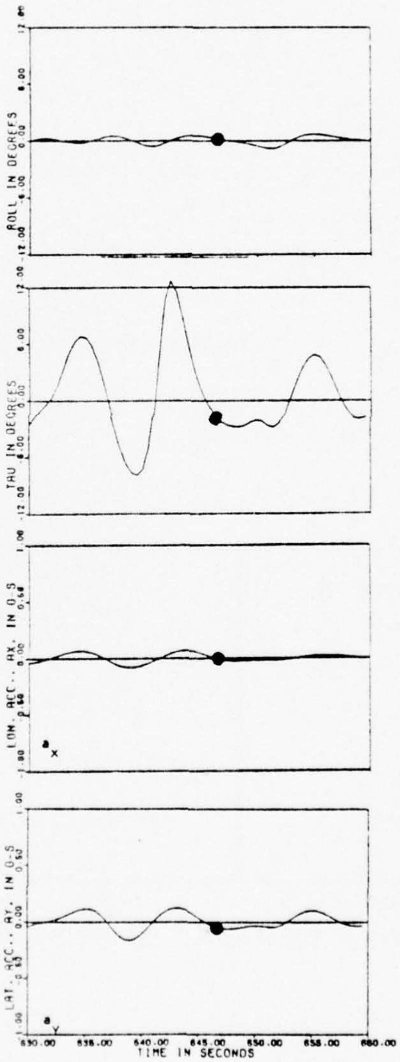
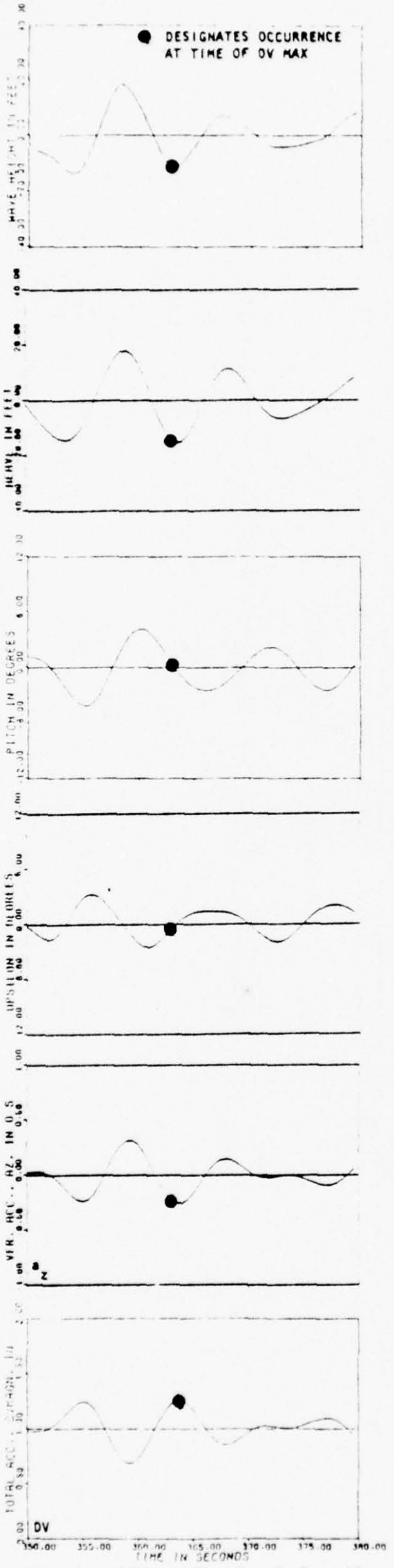


Figure 12a - Typical Predicted Short Crested Wave and Ship Response Time Histories in Bow Seas



SHIP A, 45 DEGREES, 10 KNOTS, 30 MINUTES IN SEAWAY CHARACTERIZED BY SIG. WAVE HT. OF 40 FEET AND MODAL WAVE PERIOD OF 13 SECONDS.

TIME AND VALUE OF SHIP RESPONSE AT DV AND MOTION MAXIMA

Response	At Max DV		At Max Response	
	Value	Time	Value	Time
Wave Ht.	-11.2	363.5	30.79	878.0
Heave	-15.3	363.5	20.77	88.5
Roll	- .6	363.5	- 3.88	199.0
Pitch	- .4	363.5	8.13	92.0
a_x	.01	363.5	- .08	91.0
a_y	.02	363.5	- .18	356.5
a_z	- .26	363.5	.32	359.5
DV Magn.	1.26	363.5	1.26	363.5
Upsion	.1	363.5	5.16	577.0
Tau	1.3	363.5	10.54	360.5

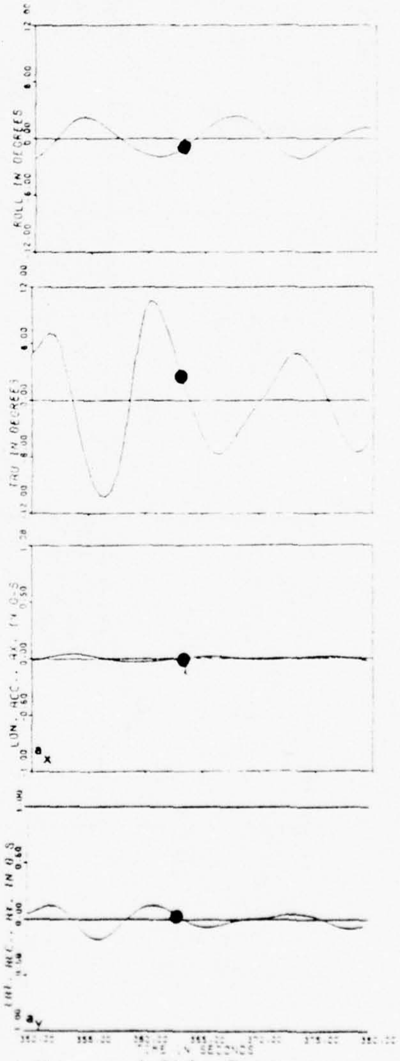


Figure 12b - Typical Predicted Short Crested Wave and Ship Response Time Histories in Quartering Seas

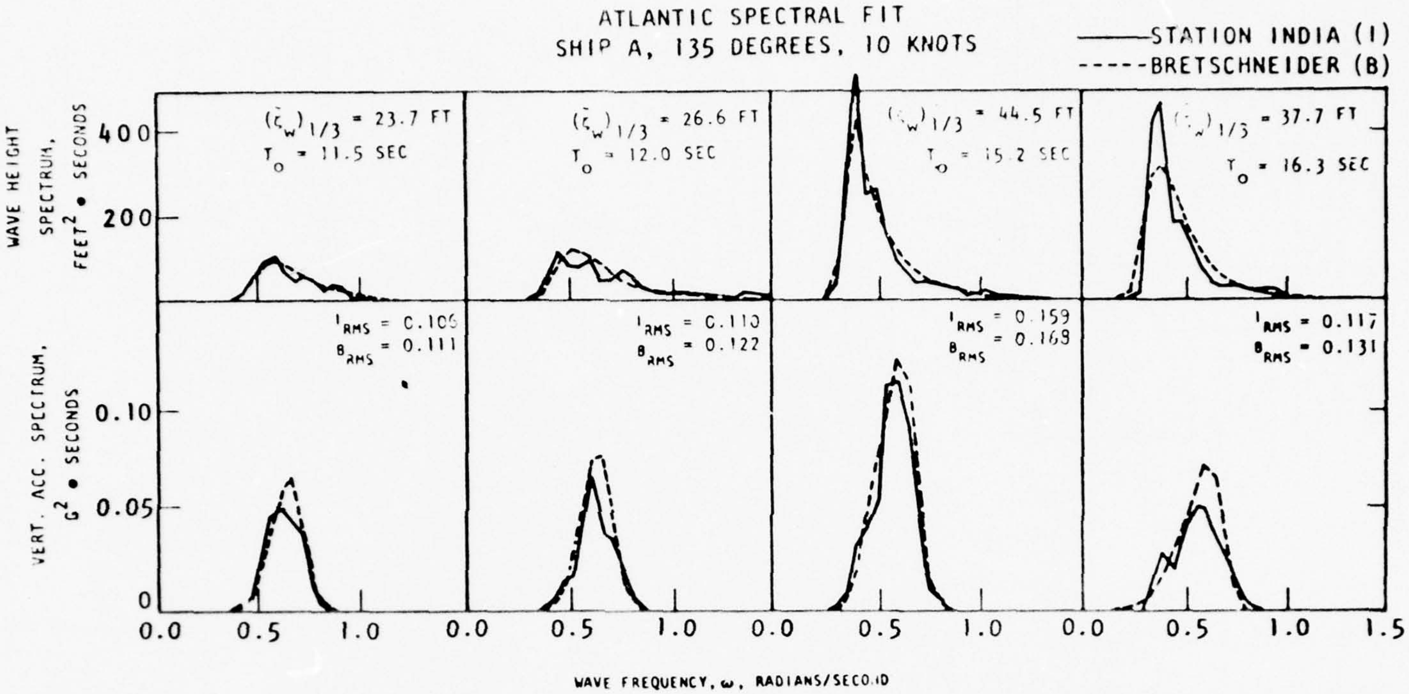


Figure 13 - Validation of Atlantic Spectral Fit for Extreme Seas

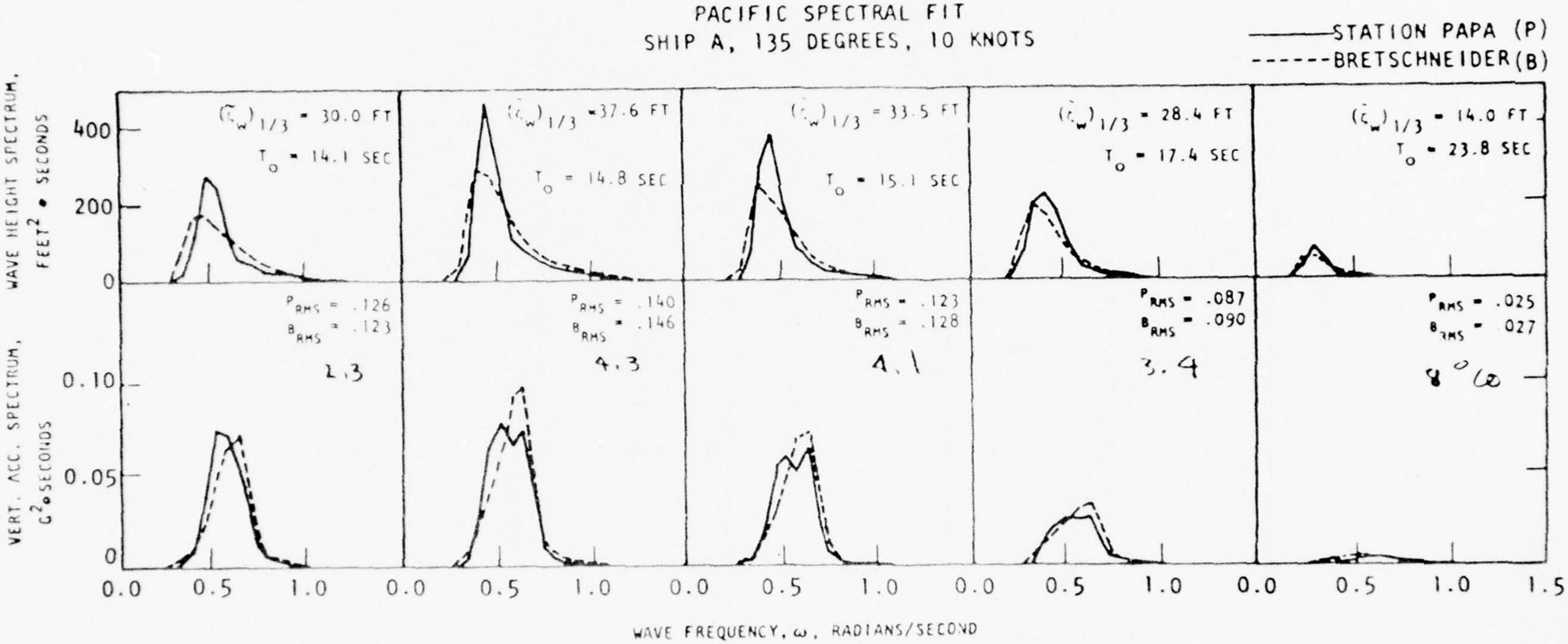


Figure 14 - Validation of Pacific Spectral Fit for Extreme Seas

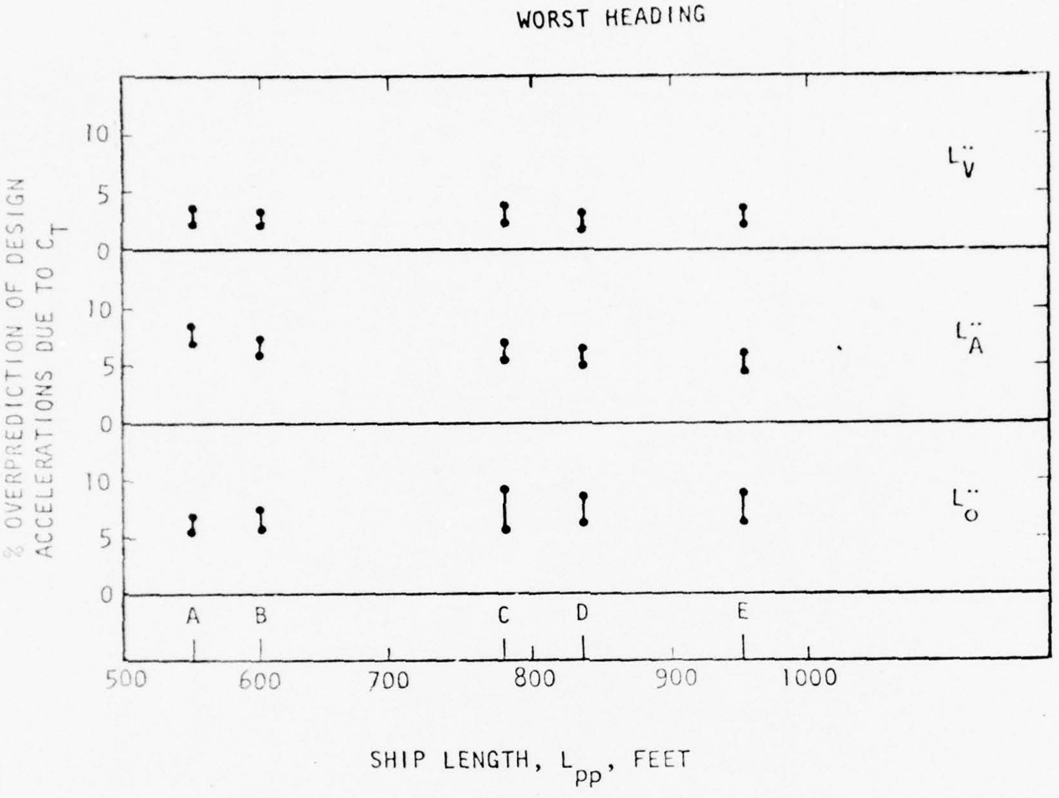


Figure 15 - Illustration of Overprediction in Design Acceleration Due to C_T

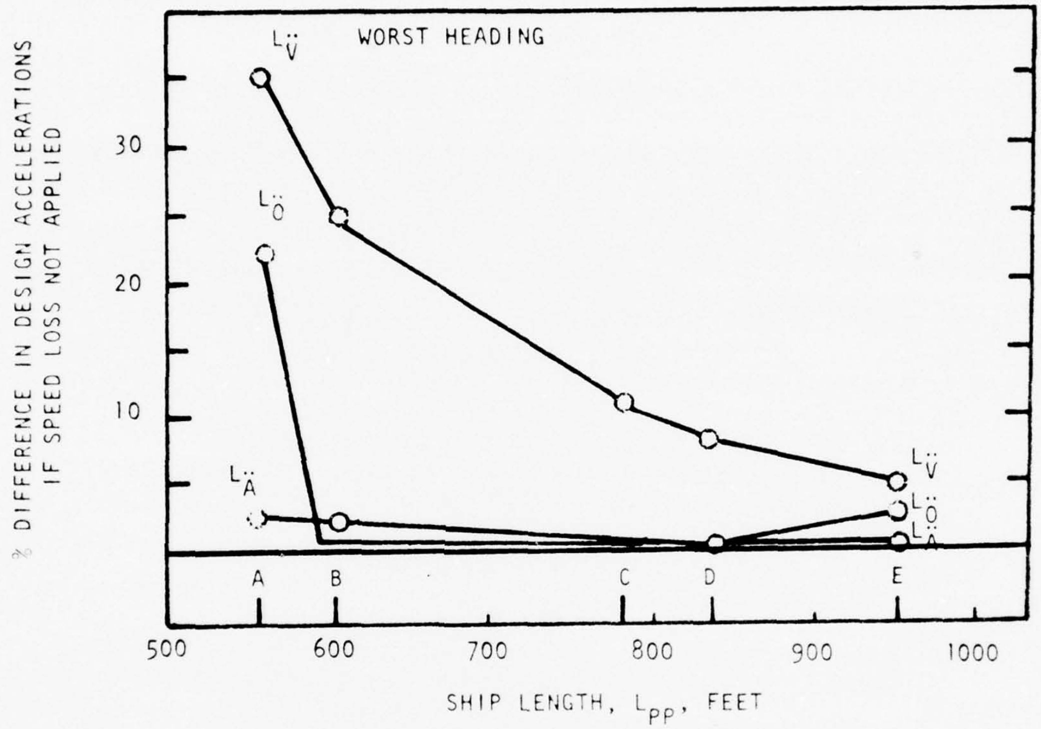


Figure 16 - Speed Loss Effect on Design Accelerations

BUILDING BLOCK PROCEDURE:

SELECT DESIGN VALUE FROM DATA BASE OF EXTREME VALUES, X,

$$X = \sigma \cdot (\tilde{\zeta}_w)_{1/3} \cdot C_T$$

STEP	UNCERTAINTY		
σ	0 to + 10%		
$(\tilde{\zeta}_w)_{1/3}$	0 to 12% DUE TO SPECTRAL SHAPE		
	0 + 22% DUE TO SPECTRAL HEIGHT		
C_T	0 + 8% DUE TO SHIP EXPOSURE TIME TO EXTREME SEAS		
	0 + 9% DUE TO ASSUMED RAYLEIGH DISTRIBUTION FOR EXTREME WAVES		
DESIGN SELECTION* (VERTICAL ACCELERATION)	+ 5%	L_{PP} = 951 FT	DUE TO SPEED LOSS
	to + 35%	L_{PP} = 561 FT	

*WORST HEADING IS ASSUMED ONLY APPROPRIATE STRATEGY FOR DESIGN.

Figure 17 - Summary of Uncertainties for Extreme Accelerations

TABLE 1 - LNG SERIES SHIP PARTICULARS

LIQUID NATURAL GAS (LNG) SHIP SERIES																				
Ship	Loaded Condition	Number of Tanks Design	LNG Capacity ($10^3 \cdot M^3$)	Speed (Knots)	*Displacement* (10^3 L. Tons)	L_{pp} (Feet)	B_X (Feet)	T_X (Feet)	C_B	C_X	C_P	KG (Feet)	GM (Feet)	T_{AP} (Feet)	$T_{\oplus}$ (Feet)	T_{FP} (Feet)	T_ϕ (Sec)	K_ϕ % B_X	K_θ % L_{pp}	K_ψ % L_{pp}
A	Full Bunkers, Tanks 99% Ethylene, Arrival	4, Spherical	29.0	19.7	30	561.0	95.0	29.2	0.68	0.98	0.69	37.3	3.0	1.4	29.2	29.0	21.3	0.35	0.25	0.25
B	Methane Loaded	5, Membrane	35.0	23.0	35	603.7	87.0	31.9	0.73	0.98	0.74	34.7, 33.2, 30.2	1.5, 3.0, 6.0	4.4	31.9	31.7	27.6, 19.5, 7.3	0.35	0.25	0.25
C	Tanks 98, 99, 99, 99, 40% Propane, Dep., Fuel 6000 naut. mi.	5, Spherical	87.6	19.0	73	777.6	131.2	34.8	0.72	0.99	0.72	54.4, 53.4, 52.4	2.0, 3.0, 4.0	0.0	34.8	34.4	36.0 29.4, 25.5	0.35	0.25	0.25
D	Fully Loaded	6, Membrane	120.0	19.0	84	839.7	134.5	34.4	0.75	0.99	0.76	50.8	8.6	3.2	34.4	33.7	17.8	0.35	0.25	0.25
E	Fully Loaded Methane Departure	6, Membrane	200.0	18.8	140	951.5	157.5	41.4	0.79	0.98	0.80	58.0	11.6	0.0	41.35	41.04	17.9	0.35	0.25	0.25

NOTE: L_{pp} is length between perpendiculars, B_X is maximun beam, T_X is maximum draft,
C_B is block coefficient, C_X is *maximum section coefficient*, C_P is *prismatic coefficient*, KG is vertical center of gravity above baseline,
GM is transverse metacentric height, T_{AP}, $T_{\oplus}$, T_{FP} are the draft at the aft perpendicular, midships, and the forward perpendicular, T_ϕ is the
roll period approximated by $T_\phi = 1.108\,(K_\phi)/\sqrt{\overline{GM}}$, and K_ϕ, K_θ, and X_ψ are the radii of gyration for roll, pitch, and yaw

TABLE 2 - EXTREME RESPONSE/T_{OE} VALUES

(FOGBEN AND LUMB WAVE DATA)

SHIP A

	Heave	Roll	Pitch	Lon. Acc.	Lat. Acc.	Ver. Acc.
W	50.76/8.3	43.27/23.3	18.75/7.5	.16/7.0	.40/9.0	1.40/7.3
M	44.97/7.9	3.38/20.9	18.75/7.5	.16/7.0	.29/8.1	1.40/7.3
AP	46.06/10.5	43.27/23.3	12.95/19.0	.12/20.3	.37/9.8	.92/7.5
WJ	47.60/10.1	25.56/20.9	16.99/9.5	.13/9.0	.39/9.8	1.04/8.1
MJ	36.47/17.0	3.38/20.9	16.99/9.5	.13/10.5	.26/9.5	.85/8.5

SHIP B, GM 1.5

	Heave	Roll	Pitch	Lon. Acc.	Lat. Acc.	Ver. Acc.
W	53.15/8.3	65.05/29.9	14.72/9.0	.12/8.7	.46/9.0	1.43/7.7
M	48.14/8.3	2.70/11.2	14.72/9.0	.12/8.7	.34/7.5	1.43/7.7
AP	53.15/8.3	65.05/29.9	12.97/8.3	.12/11.6	.46/9.0	1.29/7.9
WJ	49.75/9.5	65.05/29.9	14.09/9.8	.12/10.5	.45/9.2	1.15/8.5
MJ	36.22/19.0	2.70/11.2	14.09/9.8	.12/10.5	.31/9.5	.96/9.0

SHIP B, GM 3.0

	Heave	Roll	Pitch	Lon. Acc.	Lat. Acc.	Ver. Acc.
W	53.18/8.3	44.70/20.3	14.74/9.0	.12/7.7	.46/9.0	1.43/7.7
M	48.17/8.3	17.03/20.9	14.74/9.0	.12/7.7	.34/7.5	1.43/7.7
AP	53.18/8.3	44.70/20.3	12.98/9.5	.12/12.1	.46/9.0	1.29/7.9
WJ	49.76/9.2	44.70/20.3	14.72/9.8	.12/10.5	.45/9.2	1.16/8.5
MJ	36.22/19.0	17.03/20.9	14.72/9.8	.12/10.5	.31/9.5	.96/9.0

SHIP B, GM 6.0

	Heave	Roll	Pitch	Lon. Acc.	Lat. Acc.	Ver. Acc.
W	53.22/8.3	45.83/15.0	14.80/9.0	.13/7.3	.46/9.0	1.43/7.7
M	48.24/8.3	29.84/15.0	14.80/9.0	.13/7.3	.34/7.5	1.43/7.7
AP	53.22/8.3	45.83/15.0	12.98/10.1	.12/7.1	.46/9.0	1.30/7.9
WJ	49.78/9.2	44.60/15.0	14.16/9.8	.12/10.5	.46/9.5	1.16/8.5
MJ	36.22/19.0	29.84/15.0	14.16/9.8	.12/10.5	.31/9.5	.96/9.0

SHIP C, GM 2.0

	Heave	Roll	Pitch	Lon. Acc.	Lat. Acc.	Ver. Acc.
W	42.41/9.5	22.10/37.0	9.97/9.8	.09/11.6	.34/8.7	.88/8.7
M	37.46/17.4	3.19/12.1	9.97/9.8	.09/11.2	.24/8.3	.87/8.7
AP	42.41/9.5	22.10/37.0	9.97/9.8	.09/11.6	.34/8.7	.88/8.7
WJ	41.53/10.5	5.35/17.5	9.86/9.5	.09/11.6	.34/10.1	.78/9.2
MJ	34.43/19.0	3.19/12.1	9.83/10.5	.09/11.2	.22/10.1	.65/9.8

SHIP C, GM 3.0

	Heave	Roll	Pitch	Lon. Acc.	Lat. Acc.	Ver. Acc.
W	42.42/9.5	25.28/29.9	9.98/9.8	.09/11.6	.34/8.7	.88/8.7
M	37.47/17.5	3.00/22.4	9.98/9.8	.09/11.2	.24/8.3	.87/9.2
AP	42.42/9.5	25.28/29.9	9.98/9.8	.09/11.6	.34/8.7	.88/8.7
WJ	41.53/10.5	4.96/11.2	9.88/9.5	.09/11.6	.34/10.1	.78/9.2
MJ	34.43/19.0	3.00/22.4	9.84/10.5	.09/11.2	.22/10.1	.65/9.8

SHIP C, GM 4.0

	Heave	Roll	Pitch	Lon. Acc.	Lat. Acc.	Ver. Acc.
W	42.43/9.5	20.38/26.2	9.99/9.8	.09/11.6	.34/8.7	.88/8.7
M	37.47/17.5	3.57/25.1	9.99/9.8	.09/11.2	.24/8.3	.87/8.7
AP	42.43/9.5	20.38/26.2	9.99/9.8	.09/11.6	.34/8.7	.88/8.7
WJ	41.53/10.5	6.71/17.5	9.89/9.5	.09/11.6	.34/10.1	.78/9.2
MJ	34.43/19.0	3.57/25.1	9.86/10.5	.09/11.2	.22/10.1	.65/9.8

SHIP D

	Heave	Roll	Pitch	Lon. Acc.	Lat. Acc.	Ver. Acc.
W	40.08/9.8	43.13/19.6	8.31/10.8	.07/8.7	.34/8.7	.80/8.7
M	35.86/17.5	14.87/19.0	7.92/9.8	.07/8.7	.25/8.3	.78/8.7
AP	40.08/9.8	43.13/19.6	8.31/10.8	.07/8.7	.34/8.7	.80/8.7
WJ	39.26/10.8	43.13/19.6	8.31/10.8	.07/10.5	.34/9.8	.74/9.2
MJ	32.98/19.6	14.87/19.0	7.77/10.8	.07/11.6	.23/10.1	.60/10.1

SHIP E

	Heave	Roll	Pitch	Lon. Acc.	Lat. Acc.	Ver. Acc.
W	36.44/20.3	19.23/19.6	6.93/10.8	.05/10.5	.30/9.0	.64/9.5
M	34.14/18.0	7.31/19.6	6.93/10.8	.05/13.7	.21/8.5	.58/9.5
AP	36.44/20.3	19.23/19.6	6.93/10.8	.05/10.5	.30/9.0	.64/9.5
WJ	35.82/20.3	19.23/19.6	6.85/11.2	.05/10.5	.29/10.1	.61/9.8
MJ	31.36/19.6	7.31/19.6	6.40/12.1	.05/15.3	.19/10.1	.48/10.5

NOTE:

TOE IS ENCOUNTERED MODAL PERIOD IN SECONDS.
HEAVE, ROLL, AND PITCH RESPONSES ARE IN FEET, DEGREES, DEGREES, RESPECTIVELY.
THE ACCELERATIONS ARE IN G'S.

W IS WORST HEADING STRATEGY.
M IS MOST LIKELY HEADING STRATEGY.
AP IS AVERAGE PITCH (1.25) OF 3 DEGREES STRATEGY.
J INDICATES THAT JAMES SPEED REDUCTION IS APPLIED SIMULTANEOUSLY WITH THE W or M STRATEGY.

TABLE 3 - TOTAL ACCELERATION VECTOR AND SCALAR FOR SHIP A, WORST HEADING AND SPEED FOR ROLL

SHIPA SHORTCRESTED WS=1/20 0 DEG 20 KT H3= 40 FT T0= 13 SEC

CHANNEL	MAX	TIME	WAVEHT	HEAVE	ROLL	PITCH	AX	AY	AZ	DVMAGN	UPSLON	TAU
WAVEHT	-31.15	1415.0	-31.1	-14.2	-8.5	-1.6	.03	-.01	-.05	1.05	.0	8.1
HEAVE	14.35	1479.5	15.3	14.4	-2.3	.9	-.02	-.00	.06	.94	.1	2.3
ROLL	-16.32	1765.0	4.2	4.4	-16.3	-4.5	.04	.01	-.01	1.02	2.3	16.7
PITCH	-6.12	1419.0	-9.6	-3.2	4.2	-6.1	.06	-.01	-.06	1.06	2.8	-4.8
AX	-.07	1430.0	14.0	2.6	.1	5.9	-.07	.01	.05	.95	-1.5	.6
AY	.05	596.5	-1.9	-1.8	5.4	.9	-.00	.05	.01	.99	-.8	-2.4
AZ	.08	1481.0	12.9	12.4	-4.7	3.0	-.03	.02	.08	.92	-.9	5.9
DVMAGN	1.08	1417.5	-19.9	-9.5	-.8	-5.3	.06	-.01	-.08	1.08	2.1	.2
UPSLON	2.81	1419.5	-5.1	-.9	5.6	-6.1	.06	-.01	-.05	1.05	2.8	-6.3
TAU	16.84	1597.0	-4.8	-4.4	-15.8	-.7	.01	.02	.01	.99	.0	16.8

DV(T) = 1.08 (VECTOR)
DV(TI) = 1.08 (SCALAR)

Table 3b - Summary

	SHIP	μ	DV(T)	DV(TI)	T(T) UPSLON	T(T) TAU	T (TI)	T (TI)
20 KTS	A	0°	1.08	1.08	2.1	0.2	2.8	16.8
10 KTS	A	45	1.26	1.33	0.1	1.3	5.2	10.5
	A	90	1.45	1.54	2.3	-1.1	7.8	16.0
	A	135	1.51	1.57	7.7	-1.8	9.8	12.7
10 KTS	D	45	1.21	1.25	0.9	-3.2	2.8	11.8
	D	90	1.33	1.34	2.4	-4.9	3.6	14.1
	D	135	1.37	1.38	3.3	-3.7	4.2	10.2

MAX

TABLE 4 - TOTAL ACCELERATION VECTORS AND SCALARS FOR SHIP A AND D, 135 DEGREES, 10 KNOTS

SHIPA SHORTCRESTED 135 DEG 10 KT H3= 40 FT T0= 13 SEC

CHANNEL	MAX	TIME	WAVEHT	HEAVE	ROLL	PITCH	AX	AY	AZ	DVMAGN	UPSLON	TAU
WAVEHT	-37.53	638.5	-37.5	-24.9	.2	.6	-.08	-.15	-.37	1.38	2.7	-6.7
HEAVE	27.25	643.0	22.3	27.3	.3	.7	.06	.12	.40	.62	-6.3	11.4
ROLL	-1.11	121.5	-.0	6.6	-1.1	-3.7	-.01	-.10	-.21	1.22	4.3	-3.6
PITCH	-10.20	645.5	-6.9	-3.2	.4	-10.2	.03	.01	-.44	1.44	9.0	-.1
AX	.09	970.5	10.9	15.6	.2	-3.5	.09	.10	.18	.84	-2.4	6.6
AY	-.18	356.0	-16.9	-11.9	-.6	-1.0	-.03	-.18	-.23	1.25	2.3	-7.6
AZ	.56	642.0	32.5	22.4	-.2	7.0	.02	.08	.56	.45	-9.8	10.7
DVMAGN	1.51	646.5	-12.3	-17.7	.2	-7.5	-.00	-.04	-.51	1.51	7.7	-1.8
UPSLON	-9.83	642.0	32.5	22.4	-.2	7.0	.02	.08	.56	.45	-9.8	10.7
TAU	12.68	642.5	27.8	26.3	.1	4.1	.04	.11	.51	.51	-9.0	12.7

DV(T) = 1.51 (VECTOR)
DV(TI) = 1.57 (SCALAR)

SHIPD SHORTCRESTED 135 DEG 10 KT H3= 40 FT T0= 13 SEC

CHANNEL	MAX	TIME	WAVEHT	HEAVE	ROLL	PITCH	AX	AY	AZ	DVMAGN	UPSLON	TAU
WAVEHT	31.39	1398.5	31.4	17.0	-.0	1.3	.01	.06	.28	.72	-2.1	4.7
HEAVE	-20.23	1278.0	-21.3	-20.2	.0	1.0	-.00	-.02	-.13	1.13	-.8	-.9
ROLL	2.58	963.0	12.3	6.1	2.6	1.5	.01	.02	.16	.84	-2.3	-1.4
PITCH	4.22	1495.5	14.8	2.8	.6	4.2	-.02	-.05	.21	.80	-2.9	-4.5
AX	-.04	500.0	-8.3	-8.2	-.2	.7	-.04	-.03	-.09	1.09	1.5	-1.7
AY	-.15	428.0	-16.0	-12.3	1.0	-.2	-.02	-.15	-.14	1.15	1.3	-8.6
AZ	-.37	1164.0	-24.9	-14.9	.1	-3.1	-.00	-.08	-.37	1.37	3.3	-3.7
DVMAGN	1.37	1164.0	-24.9	-14.9	.1	-3.1	-.00	-.08	-.37	1.37	3.3	-3.7
UPSLON	-4.23	503.5	13.4	9.2	.1	2.6	.02	.04	.26	.75	-4.2	3.1
TAU	10.19	1160.0	13.1	11.3	.2	2.4	.02	.12	.34	.68	-4.0	10.2

DV(T) = 1.37 (VECTOR)
DV(TI) = 1.38 (SCALAR)

TABLE 5 - TOTAL ACCELERATION VECTORS AND SCALARS FOR SHIP A, 45 AND 90 DEGREES, 10 KNOTS

SHIPA SHORTCRESTED 45 DEG 10 KT H3= 40 FT T0= 13 SEC

CHANNEL	MAX	TIME	WAVEHT	HEAVE	ROLL	PITCH	AX	AY	AZ	DVMAGN	UPSLON	TAU
WAVEHT	39.79	878.0	30.8	15.8	-1.5	.4	-.02	.00	.12	.88	.7	1.6
HEAVE	20.77	88.5	29.8	20.8	.7	-1.1	-.03	-.03	.12	.88	2.9	-2.5
ROLL	-3.88	199.0	4.8	6.5	-3.9	5.9	-.05	.05	.17	.83	-2.4	7.5
PITCH	8.13	92.0	-9.3	-4.0	-2.9	8.1	-.08	.04	.08	.92	-3.4	5.5
AX	-.08	91.0	1.9	6.1	-1.8	7.0	-.08	.03	.16	.85	-1.6	3.9
AY	-.18	356.5	3.7	3.1	.9	-2.9	-.00	-.18	-.09	1.11	3.0	-10.3
AZ	.32	359.5	13.9	16.6	-1.5	3.8	-.03	.06	.32	.69	-1.3	6.9
DVMAGN	1.26	363.5	-11.2	-15.3	-.6	-.4	.01	.02	-.26	1.26	.1	1.3
UPSLON	5.16	577.0	3.8	-3.2	.7	-6.5	.03	-.08	-.22	1.23	5.2	-4.5
TAU	10.54	360.5	6.2	9.2	-1.9	4.1	-.02	.12	.22	.79	-2.4	10.5

DV(T) = 1.26 (VECTOR)
DV(TI) = 1.33 (SCALAR)

SHIPA SHORTCRESTED 90 DEG 10 KT H3= 40 FT T0= 13 SEC

CHANNEL	MAX	TIME	WAVEHT	HEAVE	ROLL	PITCH	AX	AY	AZ	DVMAGN	UPSLON	TAU
WAVEHT	35.04	1670.5	35.0	22.2	-.0	-.3	.01	-.04	.25	.75	-.5	-3.4
HEAVE	28.53	1407.5	27.1	28.5	-.3	.4	.00	-.02	.26	.74	-.8	-1.0
ROLL	-2.56	93.0	-12.7	-12.9	-2.6	8.3	-.06	-.01	.04	.96	-4.9	1.9
PITCH	-8.95	972.5	-7.9	1.1	1.1	-9.6	.04	.01	-.28	1.28	7.3	-.7
AX	-.08	91.5	-12.4	-9.1	-1.6	5.9	-.08	-.02	-.03	1.04	-1.4	.4
AY	-.25	356.0	-10.0	-7.8	.6	-3.8	-.01	-.25	-.30	1.33	4.3	-10.9
AZ	.52	359.0	28.7	24.3	-.3	4.4	-.01	.08	.52	.49	-3.5	9.3
DVMAGN	1.45	363.5	-24.5	-22.8	-.2	-2.0	-.01	-.03	-.45	1.45	2.3	-1.1
UPSLON	7.80	973.0	-8.9	-2.3	1.1	-8.6	.02	-.00	-.32	1.32	7.8	-1.3
TAU	16.04	360.0	15.1	20.1	-.2	3.8	.00	.16	.42	.60	-4.1	16.0

DV(T) = 1.45 (VECTOR)
DV(TI) = 1.54 (SCALAR)

TABLE 6 - TOTAL ACCELERATION VECTORS AND SCALARS FOR SHIP D, 45 and 90 DEGREES, 10 KNOTS

SHIPD SHORTCRESTED 45 DEG 10 KT H3= 40 FT T0= 13 SEC

CHANNEL	MAX	TIME	WAVEHT	HEAVE	ROLL	PITCH	AX	AY	AZ	DVMAGN	UPSLON	TAU
WAVEHT	-34.44	241.5	-34.4	-12.1	3.9	-2.1	.03	.01	-.15	1.15	.6	-3.3
HEAVE	-20.99	1278.5	-25.1	-21.0	2.3	.6	.01	.01	-.15	1.15	-1.0	-1.7
ROLL	9.07	944.5	-3.7	-5.0	9.1	.8	.01	-.02	-.02	1.02	-1.4	-10.0
PITCH	-4.64	547.5	-7.4	-6.9	6.3	-4.6	.06	.01	-.13	1.13	1.8	-6.0
AX	.06	547.5	-7.4	-6.9	6.3	-4.6	.06	.01	-.13	1.13	1.8	-6.0
AY	-.13	550.5	22.2	8.9	1.0	-2.0	.01	-.13	-.05	1.06	1.4	-8.2
AZ	.24	554.5	13.8	15.7	-4.7	4.5	-.04	.05	.24	.76	-1.5	8.6
DVMAGN	1.21	414.5	-10.6	-8.9	1.8	-1.1	.00	-.03	-.21	1.21	.9	-3.2
UPSLON	2.81	406.0	6.0	2.6	-1.2	-3.2	.01	-.11	-.13	1.14	2.8	-4.5
TAU	11.84	556.0	-7.1	7.0	-4.8	4.0	-.03	.10	.16	.85	-1.8	11.8

DV(T) = 1.21 (VECTOR)
DV(TI) = 1.25 (SCALAR)

SHIPD SHORTCRESTED 90 DEG 10 KT H3= 40 FT T0= 13 SEC

CHANNEL	MAX	TIME	WAVEHT	HEAVE	ROLL	PITCH	AX	AY	AZ	DVMAGN	UPSLON	TAU
WAVEHT	33.96	1272.5	34.0	24.5	-.2	-.9	.00	.02	.14	.87	.7	1.6
HEAVE	-28.18	1278.5	-39.3	-28.2	1.7	.7	-.00	-.03	-.23	1.23	-.7	-3.0
ROLL	-7.00	953.5	27.4	12.7	-7.0	-.1	.01	.06	.10	.90	-.7	11.1
PITCH	4.29	555.5	-.4	7.9	-3.2	4.3	-.02	.12	.28	.73	-2.6	12.6
AX	.05	548.5	1.9	.2	4.2	-2.8	.05	.01	-.03	1.03	.2	-3.6
AY	-.17	428.0	-10.2	-9.8	1.7	-.2	-.02	-.17	-.11	1.13	1.0	-10.4
AZ	-.33	414.5	-22.7	-13.0	1.4	-2.9	.01	-.08	-.33	1.33	2.4	-4.9
DVMAGN	1.33	414.5	-22.7	-13.0	1.4	-2.9	.01	-.08	-.33	1.33	2.4	-4.9
UPSLON	-3.64	1294.0	2.3	2.0	2.6	2.6	.01	.06	.21	.79	-3.6	2.0
TAU	14.12	994.0	13.1	12.3	-2.6	2.2	.00	.15	.28	.74	-2.5	14.1

DV(T) = 1.33 (VECTOR)
DV(TI) = 1.34 (SCALAR)

APPENDIX A

DESIGN SEA CONDITIONS

This Appendix will describe the procedure used to select design sea conditions for a given trade route, compare these selected design seas with worldwide extreme seas, and describe in general the philosophy of determining design sea conditions. The selection of design sea conditions is considered to be the most important element in the four step building block approach to design accelerations. The reason for this is that the sea selection has associated with it the greatest degree of variability or uncertainly of the four steps.* The development of design seas consists of four distinct steps:

1. Representation of Extreme Seas
2. Philosophy of Selection of Design Wave Parameters
3. Selection of LNG Trade Routes
4. Worldwide Extreme Sea Data Sources

Each of these is now discussed. The method for representing extreme seas will be discussed first because both the selection of the geography (Trade Route or Routes) and the extreme sea data sources depend on the basic extreme sea representation.

REPRESENTATION OF EXTREME SEAS

Spectral Representation of Extreme Seas

Observed and measured seas of all heights or severities represent mixtures of locally wind generated waves and swell from distant storms. The presence of swell in wind generated seas is generally associated with a noticable peak or spike at the lower wave frequencies in the wave spectrum. When large, consistent data bases of measured waves are spectrum analyzed and then examined the presence of relatively few single peaked wave spectra

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* The voluntary speed loss used in the present work is more influential than the design seas on the smaller ships. However, it is expected that when the involuntary speed loss is used this will not be true.

is quite apparent. Thus it is clear that generally realistic seas represent mixtures of sea and swell. However, when the spectral shape of the extreme seas of interest in design are considered, it is noted that the importance of the mixture of sea and swell is much less pronounced. Measured, extreme sea spectra generally consists of spectra which contain only a single, well pronounced peak. It is noted however, that this peak or modal period of the wave spectrum occurs at different frequencies for waves with a constant significant wave height. Based on the above observations of the characteristics of measured extreme sea wave spectra, it was decided to represent extreme seas with an idealized two parameter (wave height and modal period) spectral shape due to Bretschneider. This spectrum is written as

$$S_{\zeta}(\omega) = A\omega^{-5} \exp \left[-B/\omega^{4}\right], \quad Ft^{2} \cdot Sec$$

where

$$A = 483.5 \, (\tilde{\zeta}_w)^{2}_{1/3}/T_o^{4}, \quad Ft^{2} \cdot Sec^{-4}$$

$$B = 1944.5/T_o^{4} \, , \quad Sec^{-4} \qquad (A1)$$

The two parameters of the spectrum are significant wave height, $(\tilde{\zeta}_w)_{1/3}$, and modal wave period T_0. These parameters in turn may be related to the visually observed wave height and period pairs reported by various authors in accordance with relationships due to Cartwright.

$$(\tilde{\zeta}_w)_{1/3} = (.66 \cdot \zeta_{obs} + 2.55) \text{ meters} \qquad (A2)$$

$$T_o = (6.58 + 0.448 \, T_{obs}) \text{ seconds} \qquad (A3)$$

It is to be noted that ship responses were computed for a series of eight wave spectra, each with a one foot significant wave height but with a different modal wave period. These unit significant wave height ship responses were then multiplied by the significant wave height appropriate for a specified modal wave period as determined from the long term wave data bases to yield the extreme ship responses for design. Before discussing the sources of the long term wave data however, the validity of the spectral representation, as well as the basis for establishing the significant wave heights appropriate for design are discussed.

Validity of Two-Parameter Spectral Representation

In Reference 1, the use of the two parameter wave spectra in lieu of measured extreme wave spectra was investigated briefly. The adequacy of the spectral fit was judged on the basis of the differences in ship responses computed using either the measured or idealized two parameter wave spectra. If differences between responses computed in the measured wave spectra and the Bretschneider fit to these spectra were small, i.e. less than 10 percent of the responses in the measured spectra, the spectral fit was adjudged to be good. The fit was judged to be good for the series of cases examined in Reference 1. A more extensive series of cases has now been examined for both severe, measured Atlantic and Pacific wave spectra. The results are presented in Figures 13 and 14. It should be noted that these brief comparisons of vertical accelerations in measured severe wave spectra and the corresponding idealized two-parameter Bretschneider spectra were made at ship conditions which corresponded to the design acceleration conditions for Ship A. In addition, it should be noted that the procedure for matching the idealized two-parameter Bretschneider spectra and the measured spectra are the same ones outlined in Reference 1. It is clear from these limited results that the idealized two-parameter spectral yield somewhat conservative accelerations in comparison to the measured severe sea spectra in both oceans.

In order to more fully investigate the quality of the two-parameter wave spectral fit for extreme seas, vertical accelerations were calculated both for some 200, available wave spectra at the Atlantic Weathership Station India, and the range of two-parameter Bretschneider wave spectra at corresponding wave heights. These results are shown for Ship D traveling at 10 and 20 knots in seas ranging from significant wave heights up to about 44 feet in Figure A1. The results are not intended to imply that Ship D would sustain these accelerations at 20 knots in these seas. It is considered that the involuntary and voluntary speed loss would limit these accelerations. However, the results are intended to establish that the two-parameter wave spectra, when used for a realistic range of modal periods (7 to 21 seconds), see Figure A2, will yield ship response predictions which are equivalent to those based on measured wave spectra.

Figure A3 presents, for all five LNG ships at the design conditions, the vertical acceleration predictions based on measured severe wave spectra with significant heights ranging from 25 to 45 feet, and the two-parameter spectral series responses for the same wave heights. The results strongly suggest that the two-parameter spectral series predictions represent the bounds of the vertical acceleration responses obtained from the extreme or severe measured wave spectra.

PHILOSOPHY OF SELECTION OF DESIGN WAVE PARAMETERS

In order to apply the prediction procedure for design accelerations employed in the current approach, the extreme seas are required in either measured wave spectrum format or in the form of extreme significant wave height and associated modal period pairs. Our approach in determining long-term extreme seas differs from that of several other authors in that statistical models to project the extreme seas are not employed. Instead, it is considered appropriate to base design accelerations on the highest observed and/or measured sea conditions rather than extreme sea conditions based on statistical extrapolations of sea data. Extreme sea conditions which have occurred once may occur again. Mathematically projected extreme seas whose magnitudes exceed or are less than those previously measured or observed are distrusted.

The distrust of mathematically projected extreme seas is based on two specific points, both of which will be discussed at some length. The first point is related to the relatively poor quality of the fit between existing wave data bases and various statistical models such as the Weibull distribution. The second point is related to fact that long-term wave condition variability is not adequately reflected in the length (time span) of the existing wave data bases.

With respect to the first point, Figure A4 was prepared to illustrate the quality of the Weibull distribution fit to the observed wave data for Trade Route 1* of Hogben and Lumb, see Figure A5. The observed results for eight specific reported wave period codes are shown as frequency of occurrence versus wave height histograms. The corresponding Weibull distributions are overlaid on these histograms. The reported extreme wave heights are denoted in these figures by the symbol 0, and the extreme wave heights calculated by means of order statistics (probability level, $\alpha = 0.01$, see Reference 27) and the Weibull wave data distributions are denoted by the symbol W. It is noted that both the observed and the statistically derived extreme heights occur far out in the tail of the wave height distribution where the greatest discrepancies between the actual data and the theoretical distribution occur. Thus, it is concluded that the basic observed wave data base is of insufficient quality to warrant the use of the added layer of sophistication in the treatment of extreme sea data inherent in the use of order statistics or the Weibull fit to this data. Robinson[27] concluded that the distribution for separate wave period groups such as the ones shown in Figure A4 is not well fitted by a Weibull distribution unless areas are combined to increase sample size.

With respect to the second point about the adequacy of time length of the data bases for long-term extreme predictions, the philosophy expressed by Battje[16] that, "The long-term probability structure is a reflection of local and distant climatological features and cannot be dealt with by deductive methods" is considered appropriate. In particular, statistical long-term distributions are regarded as such "deductive methods". The long-term distributions are regarded as procedures** which fit curves to 1, 2, 7 or

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* Trade Route 1 of Reference 1 was designated by US Coast Guard as the most probable and realistic North Atlantic Trade Route. This route and other geographic areas will be discussed in a later section of this appendix.

** Procedures such as the ones used in Reference 12 to establish 100 year extreme design sea conditions from data based on a single year.

10 year's worth of sea data and then extrapolate to obtain the most probable extreme sea in 20 or more years. We regard such extrapolations with apprehension because very little is known about the apparent 18 to 36 year periods associated with yearly extreme sea data from North Atlantic weatherships.[29]

Similar quasi-periodic trends with periods ranging from 12 to 40 years are also noted in other long-term data collections. These data in turn are all correlated with the frequency of occurence of severe sea conditions. These data consist of the frequency of winds greater than 33 knots in the Atlantic[20], the frequency of gale winds (Beaufort 8) and storms[21] in the Gulf of Alaska,[21] as well as frequency of ship collisions,[30] etc. The quasi-periodic nature of such data trends essentially prohibits, in our opinion, the use of statistical extrapolation procedures for use in projecting long-term extreme sea data.

The percentages of wind force 8 data from Reference 21, and the 100 year wave height forecast from two differing years of Reference 26 are cited as examples which serve as warnings as to the use of long-term projections from short or small data bases. The quantity and quality of extreme sea data presently available for use on a worldwide basis is regarded as being too inadequate for the proper application of long-term statistics. We consider it essential to update design sea data on a regular, perhaps yearly, basis as more and more data become available. It is recommended that more extreme wave data, especially for severe sea areas such as the North Pacific, the Capes of Good Hope and Horn and similar areas be collected on a continued basis.

Nolte[26] concluded, as we have also, "That the choice of a statistical model is not as important for extreme wave statistics, as the need for an adequate data base". In our case of course the statistical modal is the actual wave data base from which the highest significant wave height/modal wave periods are selected as the appropriate design sea conditions. It should be mentioned that Nolte compared predicted, North Sea extreme sea conditions obtained from five commonly employed statistical models with visual observations made by a Norwegian weathership from 1959 to 1969.

COMPARISON OF DESIGN WAVE HEIGHTS

The recent work of several authors on deriving extreme wave conditions for design based on the concept of fitting distribution may be referenced as a documented alternative approach for selecting design extreme wave data. The work of Draper, Rence, and Shellard[31] employs instrumented wave measurements and forecast from wind data to develop 50-year design wave heights in the areas surrounding the British Isles. Extreme design wave heights, with a 50-year return period, on the order of 28 to 34 meters (92 to 110 feet) result. Similarly the work of Thom[22] based on visually observed (annual extreme) significant wave heights results in predicted extreme design wave heights with a 25-year return period of 36.6 and 35.7 meters (120 and 117 feet, respectively) for ocean weather stations "I" and "J". These extreme wave heights, based on visual observations, agree well with extreme wave heights developed by Battjes[16] from measured waves at ocean weather stations "I" and "J". Battjes results suggest extreme wave heights of 35 and 32 meters (115 and 105 feet) respectively.

It should be noted that the corresponding extreme wave heights used within this work for Trade Route 1 range from about 74 feet for significant wave heights of 28 feet to 119 feet for significant wave heights of 44 feet for the range of modal wave periods considered. The corresponding extreme wave heights selected from the alternative extreme sea curve, (to be discussed in the next section) see Figure A6, which bounds the reported measured or observed extreme data ranges from 74 feet to 148 feet for the range of modal wave periods considered. If a less conservative confidence factor, C_T, corresponding to the most probable extreme is employed, the Trade Route 1 extreme waves will correspond to wave heights ranging from 61 to 98 feet for the range of modal wave periods; whereas the extremes for the extreme bound curve of Figure A7 will range from 61 to 122 feet. In concluding this section on the selection of design sea conditions it should be noted that very large differences in design sea conditions can occur when different data sources or different statistical models are applied. All approaches, however, share a common shortcoming of very scarce extreme sea data. The importance of differences in design sea conditions is brought out in somewhat more detail in later sections and in References 2 and 3.

SELECTION OF LNG SHIP TRADE ROUTES

Both present and projected future LNG trade routes must be considered when selecting the geography for which design sea conditions are to be established. In addition, the quantity and quality of the wave data available for these trade routes must be considered. Thus, the selection of the geography from which design sea conditions are to be extracted is tempered by the quality of the data available for the appropriate areas.

Since LNG ships once built may be expected to operate on a worldwide basis, the selection of design sea conditions must reflect the extremes of sea conditions found world wide. An extensive literature search on extreme sea conditions revealed no published data (in the significant wave height/modal period form required) which exceeded the extreme sea data for the North Atlantic. As a result, the North Atlantic was considered to be data source for estimating worldwide extreme sea data.

WORLDWIDE EXTREME SEA DATA SOURCES

A total of 17 open literature references present extreme sea data in a suitable format for purposes of the present report. Eleven of these sources referred to the Atlantic and the remaining six presented data for the Pacific. References 4, 8, 9, and 12 present observed Atlantic data, reference 10 presents some measured and observed Atlantic data, and references 13, 14, 15, 16, 17, and 18 present measured Atlantic data. Similarly, references 19, 20, 21, 22, and 23 present observed Pacific data and reference 24 presents measured Pacific data. Other ocean areas known for their severe seas* such as Cape of Good Hope, Cape Horn, and the North Sea did not contribute extreme sea data to the worldwide extreme sea data base represented by the previous references. Only relatively few, primarily visual wave height observations were contained in 4, 25, 26. It is recommended that a wave height measurement

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*Which future LNG tankers are likely to tranverse.

program or at least a concerted effort to locate such data for these areas to be initiated by USCG.

As previously mentioned, very little measured or suitably observed extreme wave data were found in other oceans, or ocean areas outside of the most probable and realistic North Atlantic trade route identified by the USCG as Trade Route 1, see Figure A5. The Trade Route 1 extreme sea data was selected from the largest, available wave data base suitable for the four-step building block prediction procedure employed in the present report.

The wave data base consists of the systematic wave height and period observation tabulations of voluntary ship reports by Hogben and Lumb[4] for the years 1953 through 1961, see Figure 4. The open circles represent the observed height/period pairs converted into significant wave height/modal period pairs in accordance with relationships[2,3] due to Cartwright. The darkened circles in Figures 4 and A7a correspond to the sea conditions for which design ship responses were computed. Since these ship responses were computed for evenly spaced modal wave periods of 7, 9, . . ., and 21 seconds design sea conditions were obtained for these specific periods by linearly interpolating between reported modal periods.

The observed data base of Figure 4, i.e., Trade Route 1, was not extended by the mid ocean weathership D, K and E data of Roll for the years 1951 and 1952 because the extreme, rare wave height/period combinations were not explicitly indicated for the individual weatherships. Nevertheless, Roll's extreme wave height data are almost as high as the extremes selected from Hogben and Lumb. Thus, it appears that the more accurate visual wave observations from weatherships support, in general, the magnitude of the observed extreme sea data selected from the Hogben and Lumb.

The visual observations from the same three weatherships were also reported for the period 1950 to 1960 by Walden.[9] Comparisons of these extreme sea conditions with the ones selected from the far larger (more observations), though possibly less reliable, wave data base of Hogben and Lumb suggest that the two are quite similar. Thus again it may be concluded that the

Trade Route 1 extreme wave data from Hogben and Lumb is representative of the extreme seas that may be expected for this oceanic area.

When the search area for extreme sea data in the North Atlantic or equivalently the world is extended outside of the U.S. Coast Guard specified Trade Route 1, the reported extreme seas become somewhat larger at various modal sea periods than for Trade Route 1. Figure A7b was prepared from the previously mentioned sources to illustrate this fact and to summarize the best available worldwide extreme sea data. For comparison purposes, the Trade Route 1 data is also shown on the same general figure and is designated as Figure A7a. Only data that were presented in suitable wave height/modal wave period form, whether observed or measured, are shown in the figure. It is to be noted that this extreme sea data, with the exception of two visual observations made by Japanese freighters, comes from the North Atlantic for the years 1959 through 1971.

The only measured extreme sea data located for the North Pacific were that of Larsen[24] for the winter of 1972-73. These data, however, are not yet available in spectral format. It is recommended to the USCG that the wave measurement program described in Reference 24 be supported or encouraged to continue on a long-term basis in the future. In addition, it is recommended that an effort be made to obtain the measured, calibrated time history of the top five or six storms reported in the reference.

The extreme observed and measured wave data in Figure 22b exhibit the same erratic behavior as a function of modal wave period as the extreme observed wave data in Figure A7a. A great deal of the erratic scatter is, of course, due to the scarcity of the data. In order to smooth the erratic extreme wave height trends of Figure A7b, it is considered appropriate to employ the outer boundaries of these measured and observed data points to construct a rough curve* of the worldwide extreme seas. This was done in Figure A7c.

Two pronounced physical limits apparent in the data suggest the plausibility of such an approach. These limits appear to roughly shape the scatter of the

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*Such a curve must, of course, be updated on a continual basis as more extreme wave data becomes available.

data. The first limit consists of the theoretical limiting steepness of progressive waves in deep water, i.e., 1/7. This limit applies to short modal periods (less than 9 seconds). Such periods correspond to partially developed wind seas, which are generated as hurricane winds, initially build the seas to their extreme conditions.

Figure A6 presents the worldwide severest observed and measured sea conditions as well as four specific wave steepnesses, $\lambda/h = 10, 20, 25$, and 40. It should be noted that these latter two steepnesses correspond to the significant wave height/modal wave period relationship for partially developed hurricane seas due to Bretschneider and the fully developed wind seas due to Pierson and Moskowitz. Two individual extreme waves quoted by Draper[13] are also shown in Figure A6 to demonstrate the possible steepness of individual extreme waves. It is apparent from these results that the extreme significant wave heights at short modal periods appear to be limited to a corresponding wave steepness of approximately 1/10. In addition, it is noted that these extremely steep, extreme seas were observed visually. If these values are disregarded, the extreme wave data of Pierson[14], as well as Snider and Chakrabarti,[17] appear to represent limiting $(\tilde{\zeta}_w)_{1/3}/\lambda_0$ steepnesses of about 1/15. Thus, $(\tilde{\zeta}_w)_{1/3}/\lambda_0$ steepnesses between 1/10 and 1/15 appear to limit the partially developed extreme seas.

The second limit which shapes the extreme sea significant wave height to modal wave period data is most obvious at the very long modal wave periods (periods > 18.5 seconds). For these longer waves, the height of the observed extreme seas appear to drop sharply. This type of drop in extreme heights with increasing modal period, of course, contradicts the period to height relationships due to Pierson and Moskowitz, Bretschneider or Thom for fully or partially developed seas. Evidence of this long period height limitation is found in many of the more refined joint period/height tabulations in various references.[4,8,9] The wave height at the longer periods are apparently limited by the duration and size of the storms[10,17,21,24] as well as by the constancy of the wind direction and the size of the ocean area. The ocean-to-ocean variations of the variables which govern the extreme wave heights therefore suggest that extreme significant wave height/modal period relations vary from ocean to ocean.

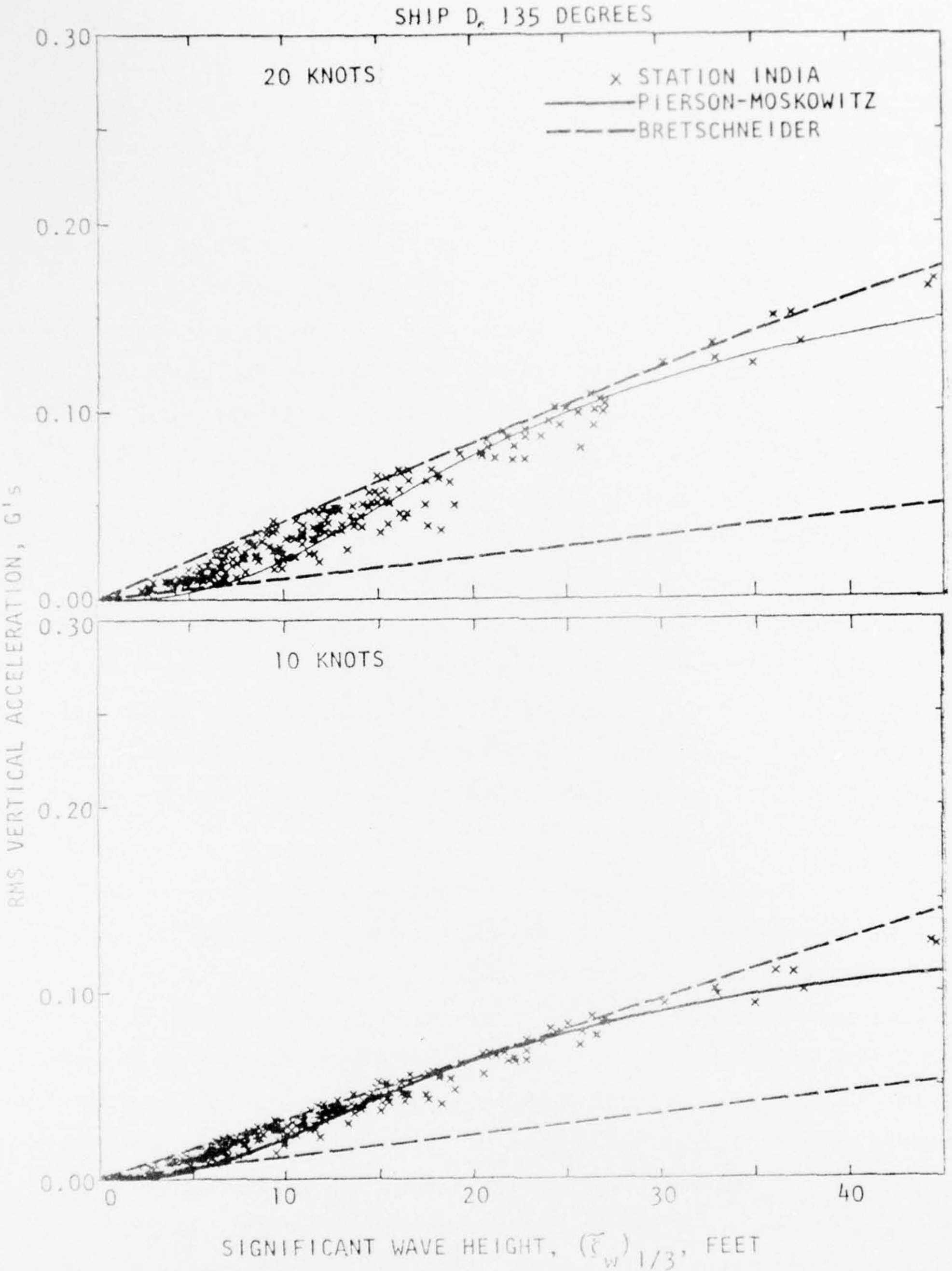


Figure A1 - Validation of Spectral Sea Representation with a Series of Bretschneider Spectra of Different Modal Periods (7-21 Seconds)

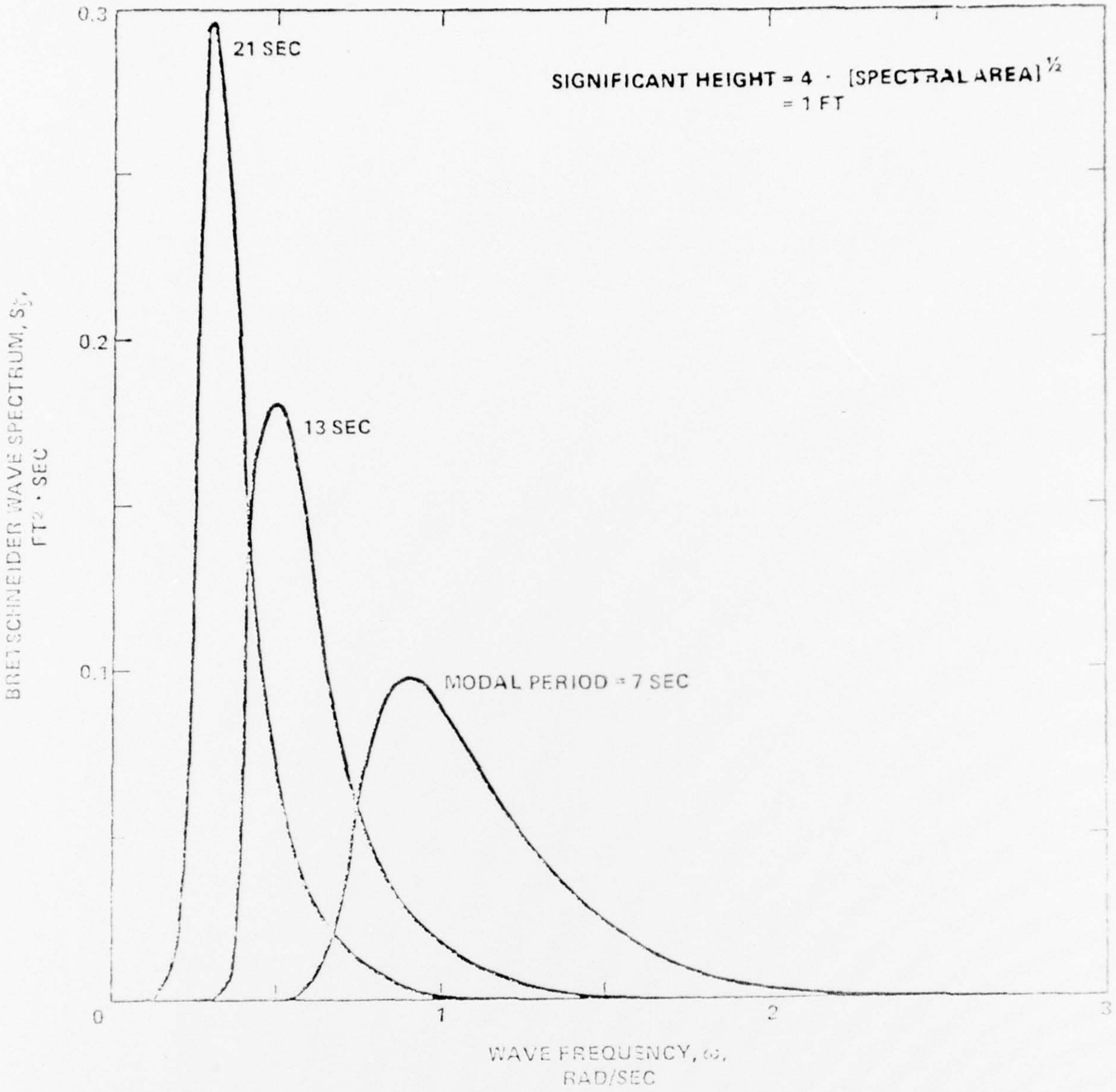


Figure A2 - Bretschneider Two-Parameter Spectral Family

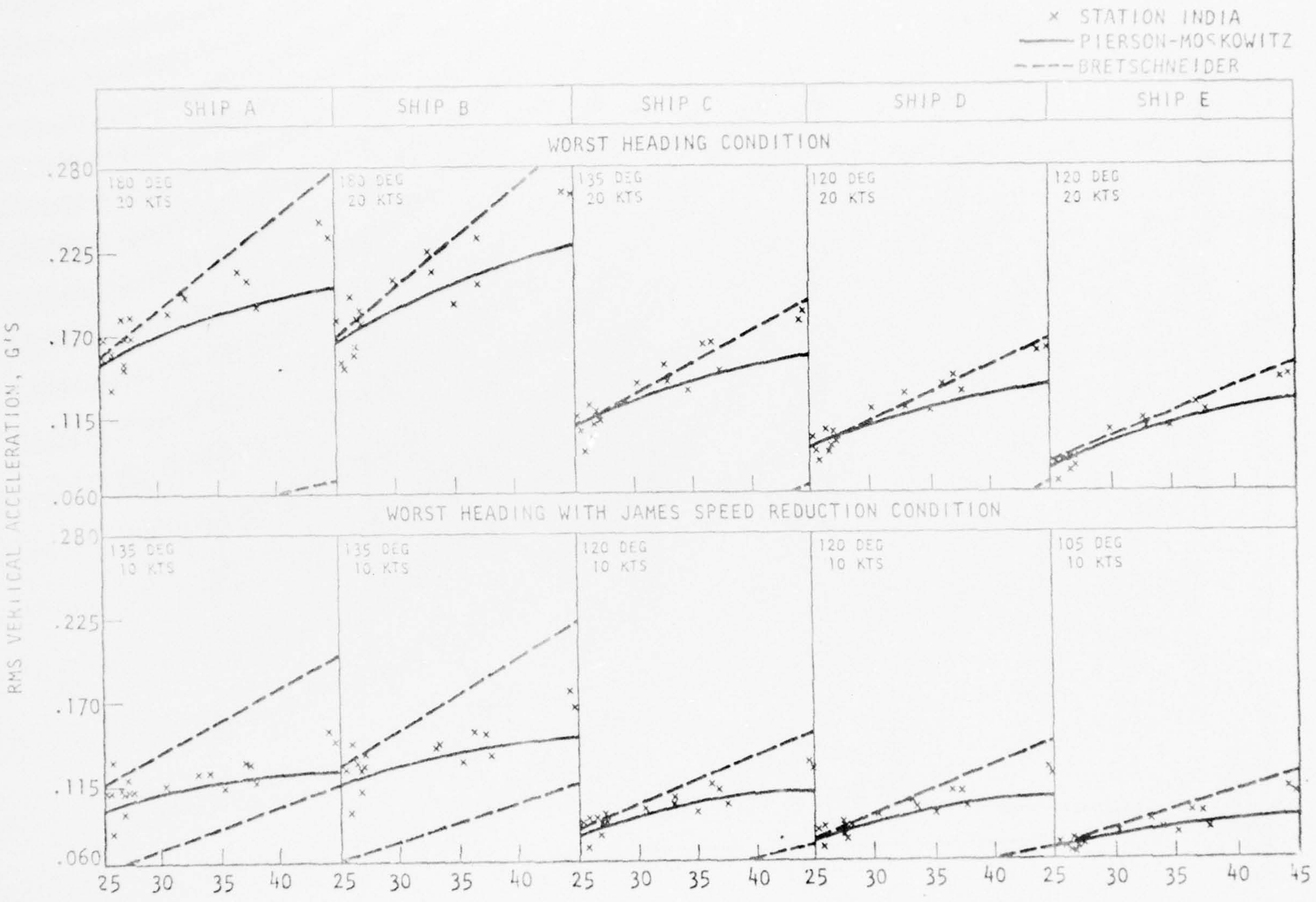


Figure A3 - Validation of Bretschneider Wave Spectral Series For Measured Severe Seas

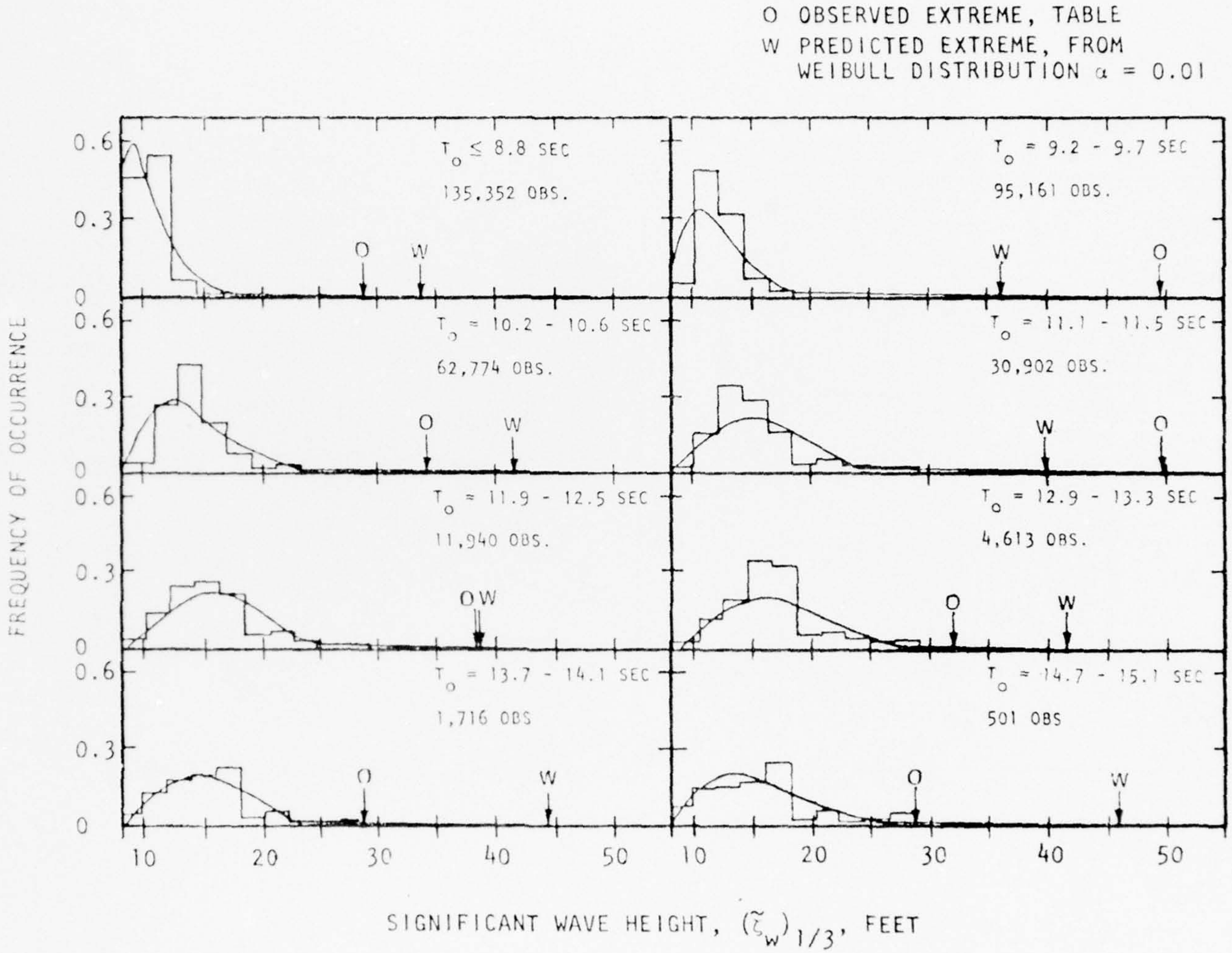
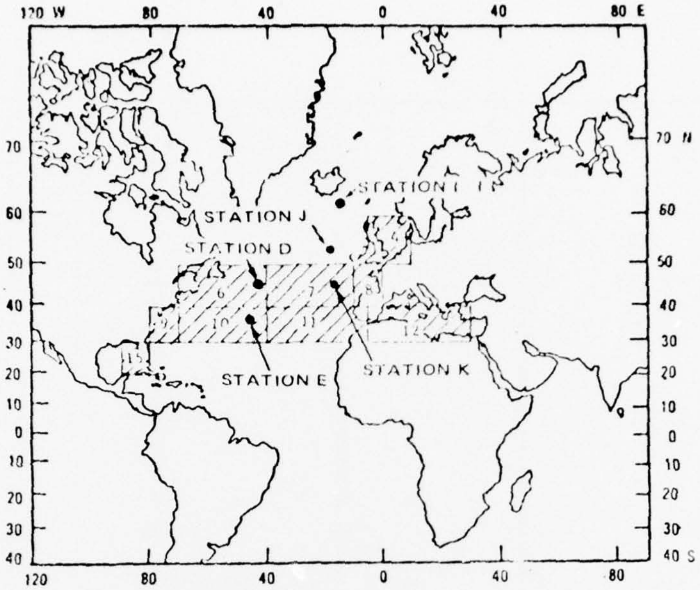
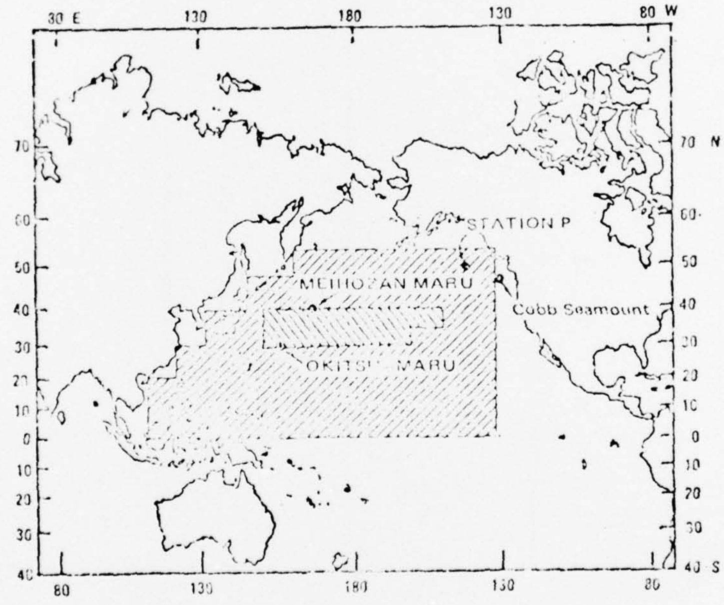


Figure A4 - Weibull Distribution Fitted to North Atlantic Trade Route 1 Wave Height/Period Data



North Atlantic, Trade Route 1



North Pacific, Trade Route 2

Figure A5 - Assumed Trade Routes for North Atlantic and North Pacific

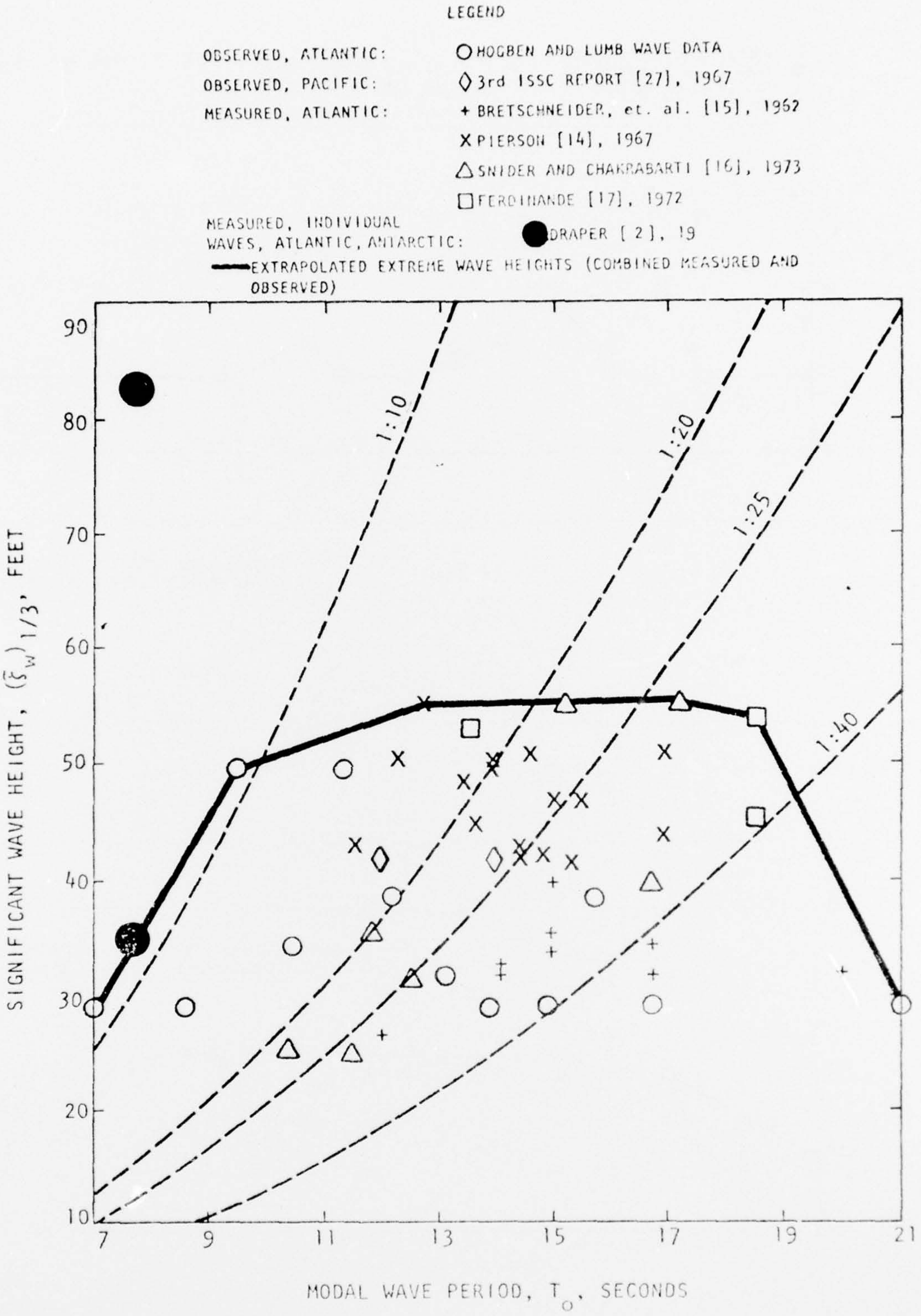


Figure A6 - World-Wide Severest Sea Conditions and Various Wave Steepness and Period to Height Relationships

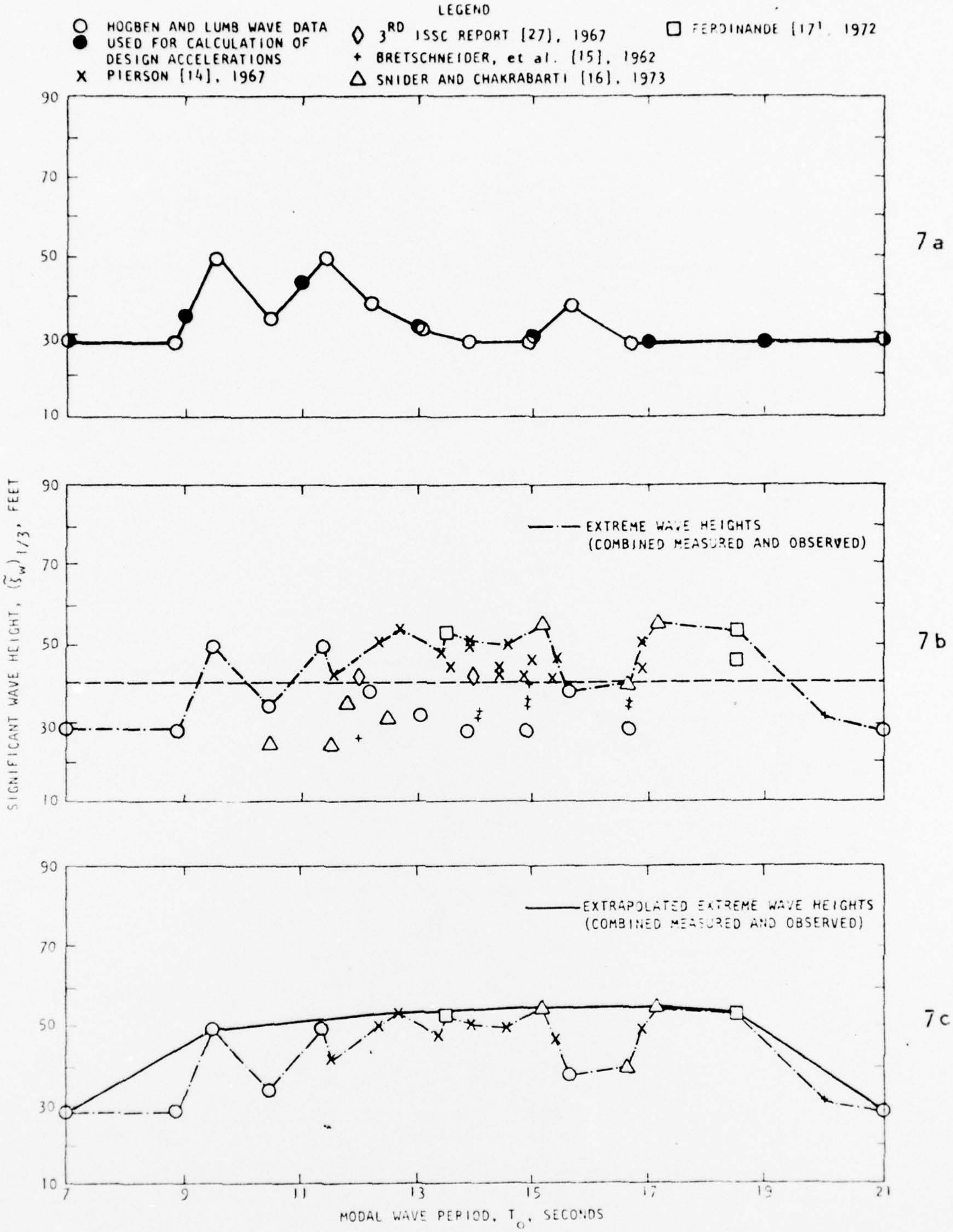


Figure A7 - Worldwide Extreme Wave Heights

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