MARTYN REEVES

Also Historical Perspective #12
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C. S. Draper Laboratory

HYDROFOIL LECTURE DAY

8 July 1975

INTRINSIC HYDROFOIL CHARACTERISTICS

Lecture 2

C. T. Ray

THIS IS IT!

INTRINSIC HYDROFOIL CHARACTERISTICS

INTRINSIC HYDROFOIL CHARACTERISTICS

Lecture 2

"By examining the obvious I have gained a new, deeper and marvelous insight." Auguste Comte 1832

1.0 INTRODUCTION

The calm water speeds of displacement ships have reached a near-limit. This is due, in the main, to the sharp rise in wave drag associated with increased speeds on one hand coupled with practical limiting values of specific power (HP/ton) and resultant cost and volume requirements on the other (Figure 1). At the same time hull form modifications, coupled with active stabilization devices, although improving rough water behavior in destroyer class ships, have not produced that quantum increase in open sea performance necessary for a combatant ship of the future. The hydrofoil ship designer has two major objectives as a consequence of these presently limiting conditions:

- Increase the continuous operating speeds of Fleet units at least 25% in calm water and at least double it in statistically probable realistic year-round open-sea conditions. At the same time,

- Achieve seakeeping performance in 200 to 2000 ton ships exceeding that of the best dynamically stabilized large destroyer-class displacement ships.

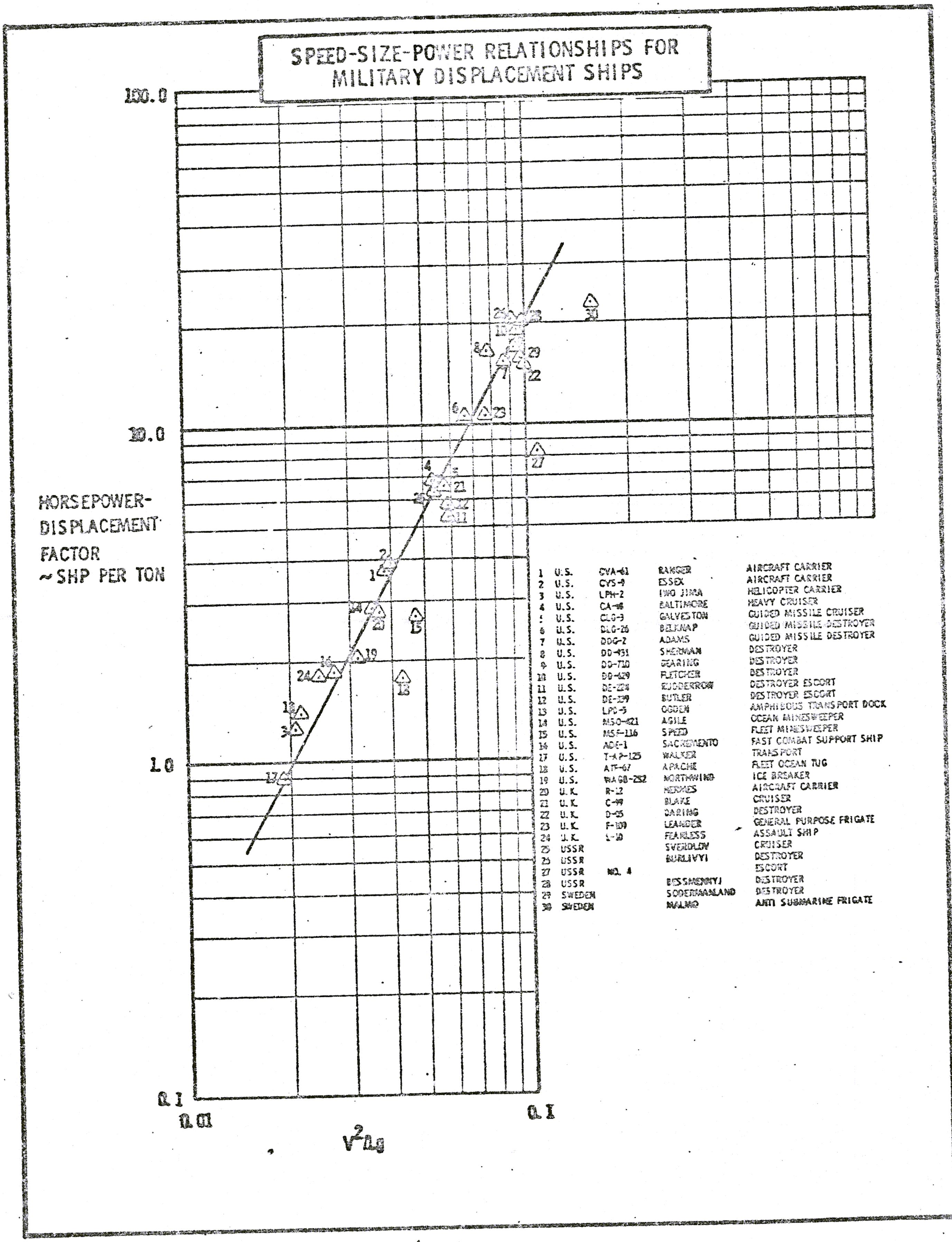
SPEED-SIZE-POWER RELATIONSHIPS FOR MILITARY DISPLACEMENT SHIPS
100.0
10.0
1.0
0.1
0.01
0.1
HORSEPOWER-DISPLACEMENT FACTOR ~SHP PER TON
V²Δg
1 U.S. CVA-61 RANGER AIRCRAFT CARRIER
2 U.S. CVS-9 ESSEX AIRCRAFT CARRIER
3 U.S. LPH-2 IWO JIMA HELICOPTER CARRIER
4 U.S. CA-16 BALTIMORE HEAVY CRUISER
5 U.S. CLG-3 GALVESTON GUIDED MISSILE CRUISER
6 U.S. DLG-26 BELKNAP GUIDED MISSILE DESTROYER
7 U.S. DDG-2 ADAMS GUIDED MISSILE DESTROYER
8 U.S. DD-931 SHERMAN DESTROYER
9 U.S. DD-710 GEARING DESTROYER
10 U.S. DD-629 FLETCHER DESTROYER
11 U.S. DE-224 RUDDERROW DESTROYER ESCORT
12 U.S. DE-339 BUTLER DESTROYER ESCORT
13 U.S. LPD-5 OGDEN AMPHIBIOUS TRANSPORT DOCK
14 U.S. MSO-421 AGILE OCEAN MINESWEEPER
15 U.S. MSF-116 SPEED FLEET MINESWEEPER
16 U.S. AOE-1 SACRAMENTO FAST COMBAT SUPPORT SHIP
17 U.S. T-AP-125 WALKER TRANSPORT
18 U.S. ATF-67 APACHE FLEET OCEAN TUG
19 U.S. WAGB-282 NORTHWIND ICE BREAKER
20 U.K. R-12 HERMES AIRCRAFT CARRIER
21 U.K. C-99 BLAKE CRUISER
22 U.K. D-35 DARING DESTROYER
23 U.K. F-109 LEANDER GENERAL PURPOSE FRIGATE
24 U.K. L-10 FEARLESS ASSAULT SHIP
25 USSR SVERDLOV CRUISER
26 USSR BURLIVYI DESTROYER
27 USSR NO. 4 ESCORT
28 USSR BESSMENNYI DESTROYER
29 SWEDEN SODERMANLAND DESTROYER
30 SWEDEN MALMO ANTI SUBMARINE FRIGATE

FIGURE 1

DRAG BREAKDOWN

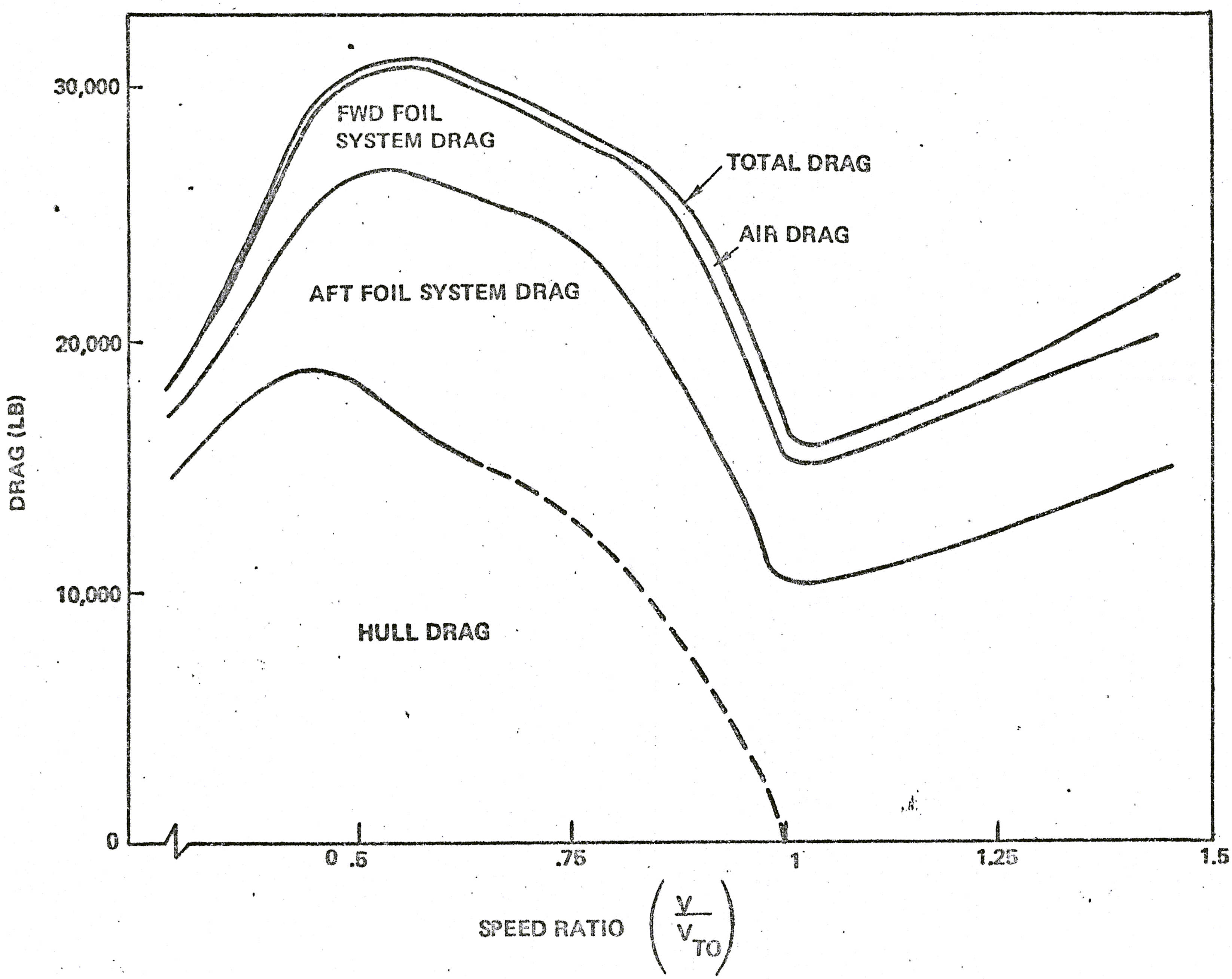

FIGURE 2

VEHICLE POWER USE

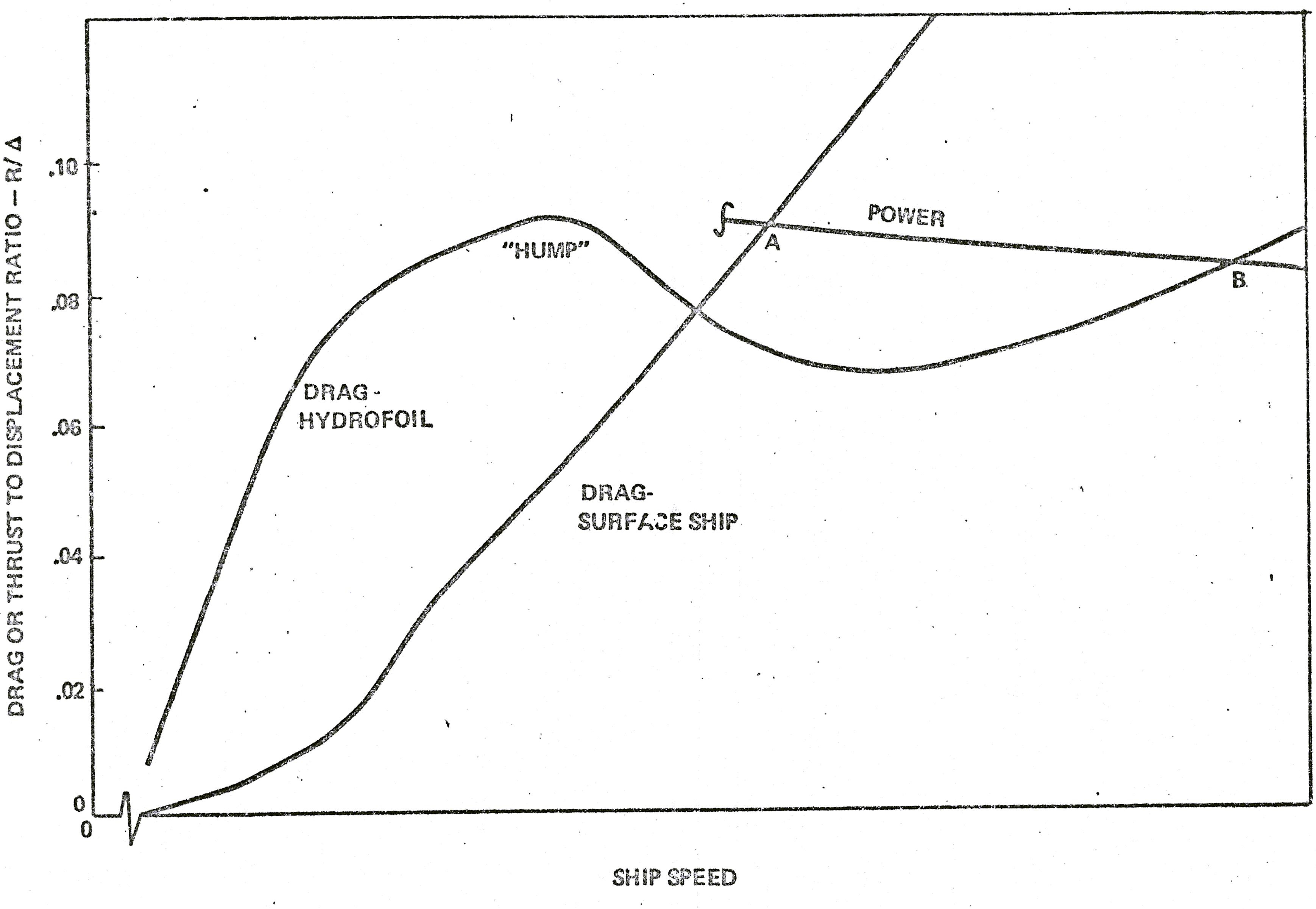

FIGURE 3

2.2 ROUGH WATER EFFECTS

The preceeding performance characteristics, and ultimately limits, are generated considering the sea as a perfectly smooth surface. In fact the sea is rarely calm and unfortunately not too much is known, in systematic engineering terms, about the influence of a confused seaway on the hydrodynamic drag of ships. Figure 4 shows data obtained from a surface ship model towed against regular "long" waves in a tank. The increment in the average total drag is moderately high and this increment is suggested by several investigators to be proportional to the product of beam times wave height. However, particularly note that in a comparatively narrow speed range, the time average resistance is roughly doubled and may increase to a still higher factor in other combinations of ship form and seaway. In this range, the frequency of wave encounter is in synchronism with the natural pitch and heave motions of the ship. As a function of the predominant wave length, therefore, any surface ship has a critical speed at which not only the resistance is significantly increased but also the structural strength and the efficiency of crew and equipment is considerably affected. At this speed the drag increment is predominantly of the wave making category and is characteristic of the motions associated with plunging in and out of the water. The only recourse in this situation is to increase power, to steam at a speed above the critical resonant conditions or, more probably after "falling out of step" with the wave train, reduce speed to a value acceptably below the critical range.

Much work has been done to identify means of modifying "clean" hulls to improve seakeeping. An example of a progressive application of available alternatives to a fine destroyer-type hull is shown in Figure 5. The modern naval displacement ship, if dynamically stabilized, probably represents the technological limit of the well balanced and well developed art of Naval Architecture as regards roll motions. Unfortunately with regard to pitch and heave motions and the associated hydrodynamic drag increment, the capabilities for improvement are not so striking. Once a hull length is established, the options to increase seakeeping capability further or reduce drag in rough water are severely limited.

HYDRODYNAMIC DRAG

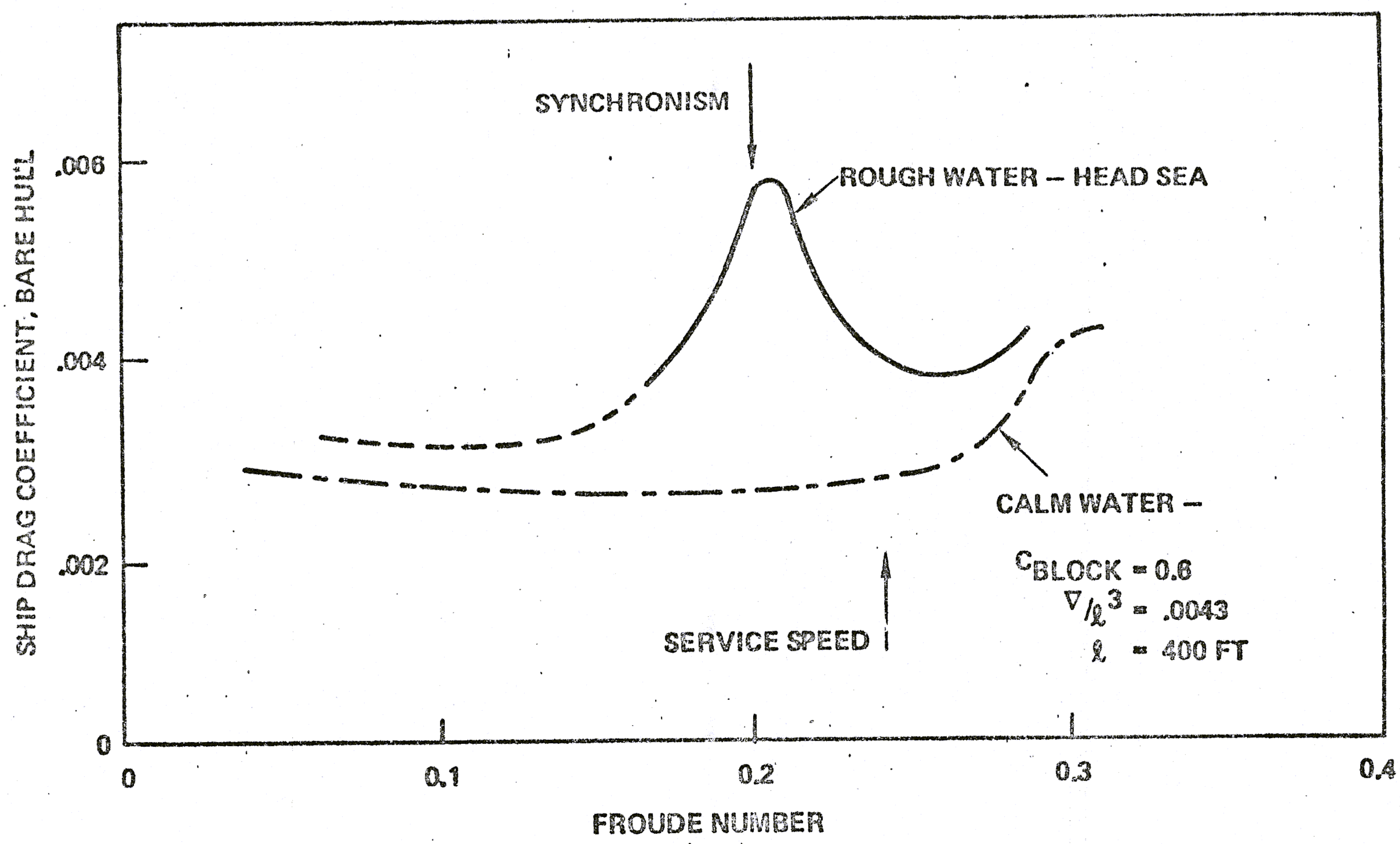

FIGURE 4

DISPLACEMENT SHIP — ROLL EXCURSIONS

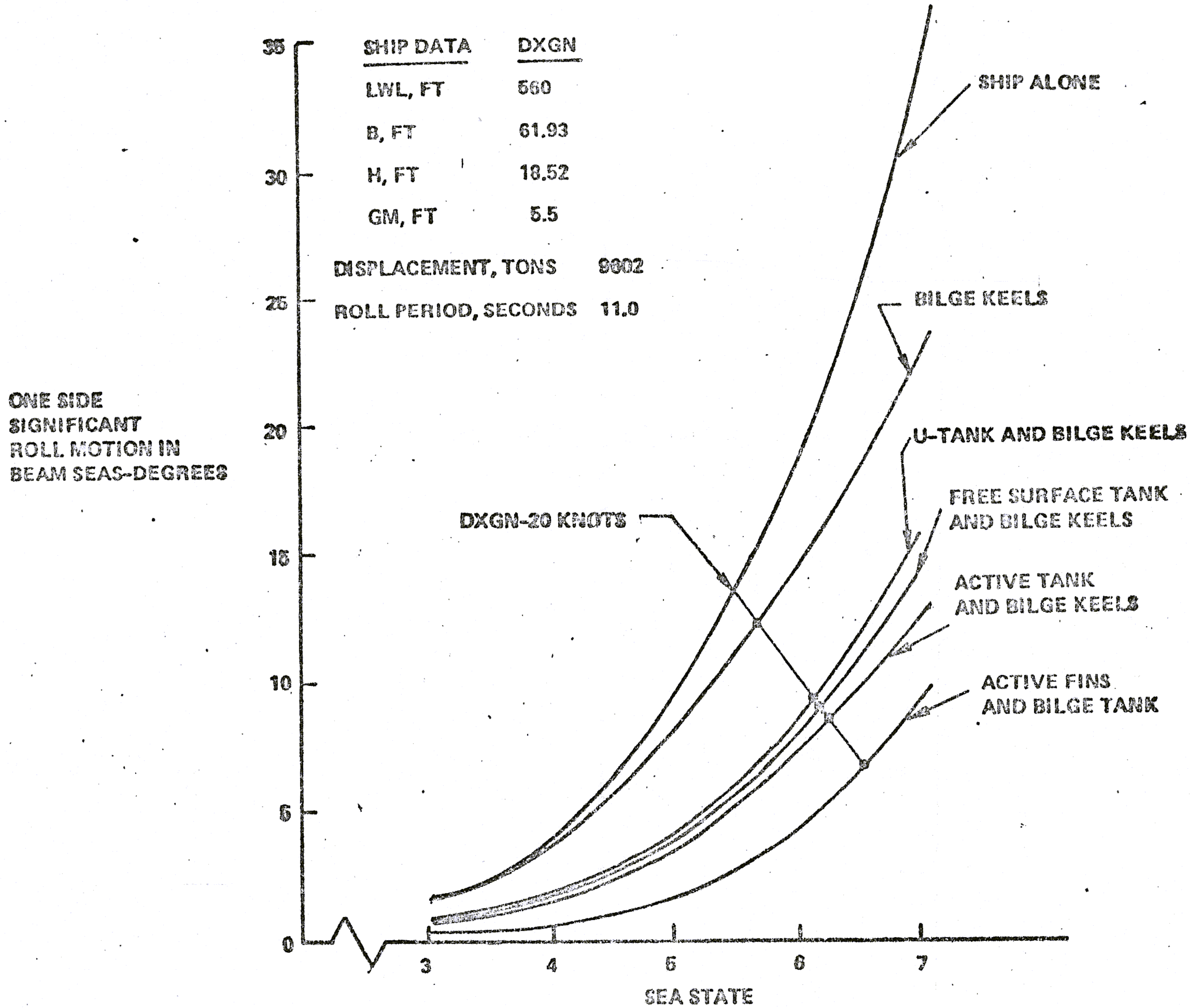

FIGURE 5

Kehoe (Naval Institute, November 1973) recently contributed significantly by presenting data on US and USSR destroyer performance with a systematic evaluation of "end result" data. He did not attempt to make an element analysis of drag or motion values but did make some pointed observations with regard to slamming and deck wetness as they require reduction in steaming speed. Figure 6, from his treatise, shows average rough water speed as a function of hull length as well as differentiating between bulbous and non-bulbous bow forms. One additional point not made in the context of the paper was that the emergence of sonar domes per se represented a limit on speed that undoubtedly occurred before either a slamming or deck-wetness boundary condition was reached. This negates the ability of the ship to perform an essential element of ASW explicit in unporting the forefoot of the ship on one hand and certainly degrading sonar performance in the process of re-wetting upon re-entry on the other.

As stated previously systematic rough water data, in engineering terms, is difficult to obtain for displacement types and virtually impossible for some other Advanced Vehicles. On the other hand, hydrofoil ships used for industrial, commercial and Naval development and operation are probably the most completely characterized of vehicles with the possible exception of commercial and military aircraft. Before examining these data, an important digression into the fundamentals of the open sea environment is in order.

ROUGH WATER SPEED IN HEAD SEAS VS. LENGTH

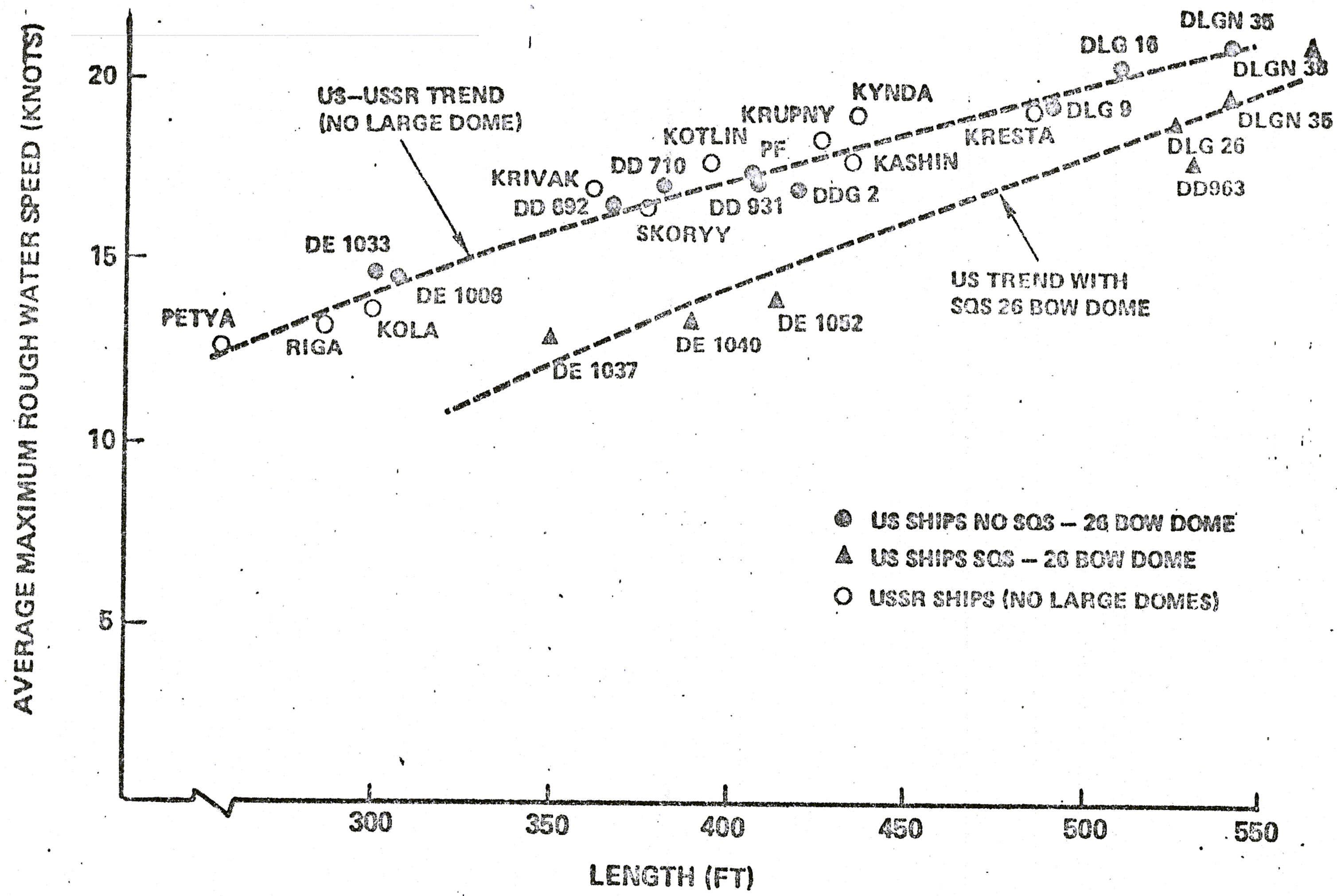

FIGURE 6

3.0 BASIC SEAKEEPING AND LOADS

Ship motions, accelerations, and loads result from forces and moments induced in the ship by individual waves in rough water. In turn, the wave induced forces derive from two distinct wave properties:

- Changes in water surface contour (wave height)
- Wave orbital particle velocities

Figure 7 depicts these characteristics for a long crested sinusoidal wave train. The surface characteristics are defined by H_w (wave height), λ (wave length) and C (wave celerity) which is the velocity of propagation of the wave crest. The wave orbital particle velocities decay exponentially with depth in accordance with the relationship:

$$V_D = V_o \, e^{\frac{-2\pi D}{\lambda}}$$

It is recognized that this simplistic wave model is not by itself representative of the realistic random environment in which ships operate. Never the less, by examining the ship response to simple sinusoidal wave trains we can gain a basic insight into ship responses to waves.

3.1 SURFACE SHIP BEHAVIOR

The hull-down ship, supported by hull buoyancy, is obviously going to tend to rise or fall, pitch and roll as the ship traverses the waves. In small waves where the wave length is less than the hull length, the heaving forces tend to be self-balancing along the length of the hull. In yet smaller waves, the pitching and rolling moments due to the waves will tend to be neutralized by one wave action cancelling another. For the large dominant waves however, the surface ship tends to be a wave profile follower in large or small degree.

The surface piercing hydrofoil ship, although its lifting surface is under the water, also tends to be a surface follower in that the lift on a hydrofoil increases with immersed area and, as the wave front passing a surface piercing foil rises more and more on the foil more and more lift

SEA PROFILE

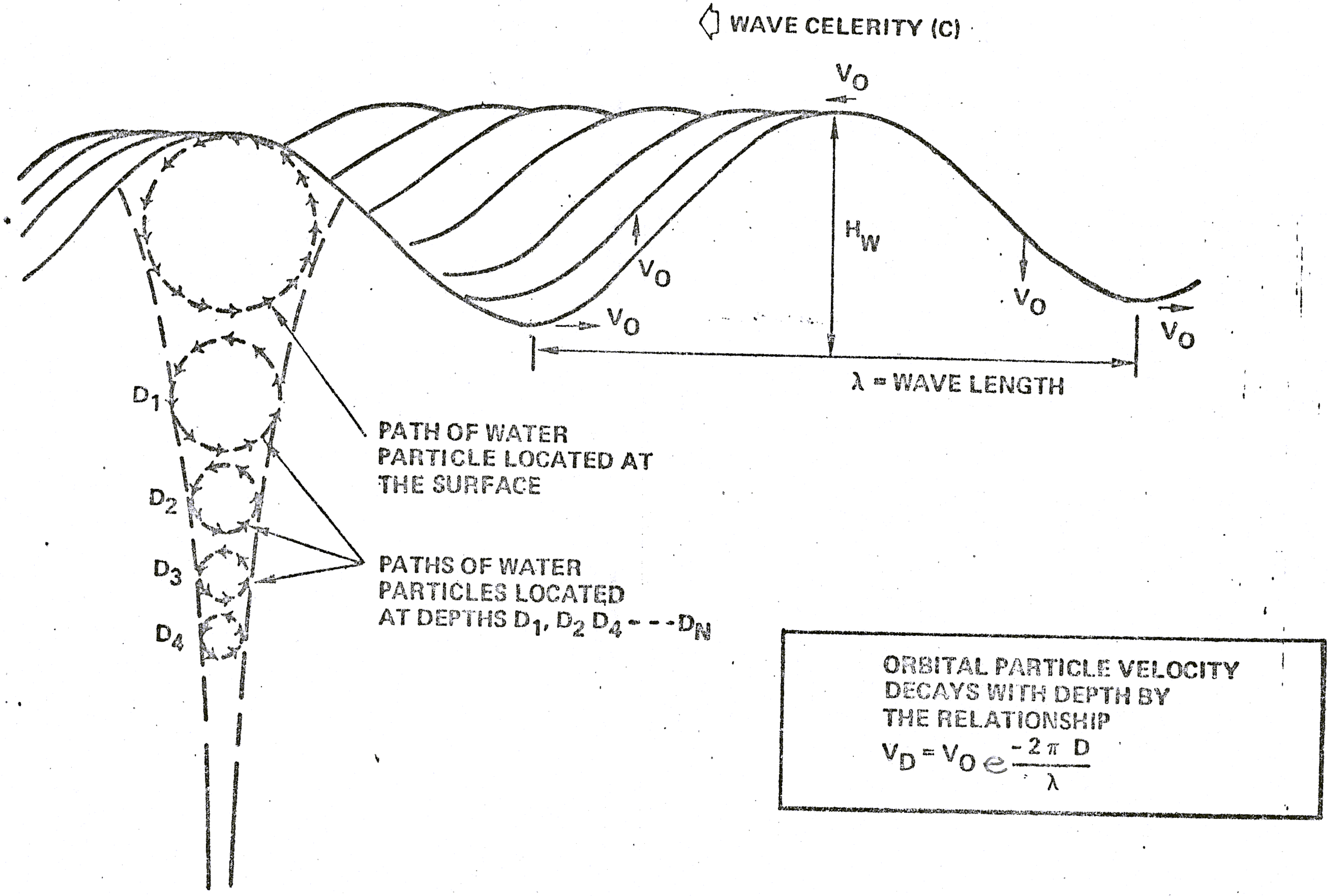

FIGURE 7

from the foil results. Thus the surface piercing foil tries to seek a constant immersion as the wave passes through the foil arrangement.

Air Cushion Vehicles also tend to be surface followers, although a major effort has been directed toward eliminating this characteristic in the SES by containing the air cushion between two rigid side walls which knife through the surface. There still exists, however, a major wave contour effect which results in a variation in the entrapped air volume as the wave crest or wave trough passes by. This increasing and decreasing volume and change in pressure in the captured air bubble has been termed "wave pumping". It has been found, if untreated by plenum venting, to be a major degrading factor in ride quality of the SES. An informed discussion of these characteristics is left to other lecturers.

3.2 SUBMERGED HYDROFOIL SHIPS

The submerged foil hydrofoil ship receives its primary wave disturbances from the wave orbital particle velocities as opposed to the surface contour. This is a significant advantage as the forces due to these orbital particle velocities are relatively small compared to hull or body forces on a surface ship. Additionally, other benefits accrue from operating the lifting and control surfaces at a distance below the water surface by taking advantage of the orbital particle decay with depth. For example, a wave with 100 foot length and 5 foot height would have an orbital particle velocity at the surface of 3.6 ft/sec while at a depth of 10 feet that value is reduced to 1.9 ft/sec, or 53% of the surface value.

The reduction in orbital particle velocities at foil operating depths is a dominant factor in the lower wave length (higher frequency) waves but this reduction is minor-to-insignificant in the larger long period waves. Figure 8 depicts a typical orbital particle velocity spectrum at the surface, and a second spectrum for a nominal foil depth of 10 feet. The reduction in orbital particle velocities and hence the foil disturbances, at the higher frequencies is readily seen.

ORBITAL PARTICLE VELOCITY SPECTRA FOR FULLY ARISEN SEA STATE 4.

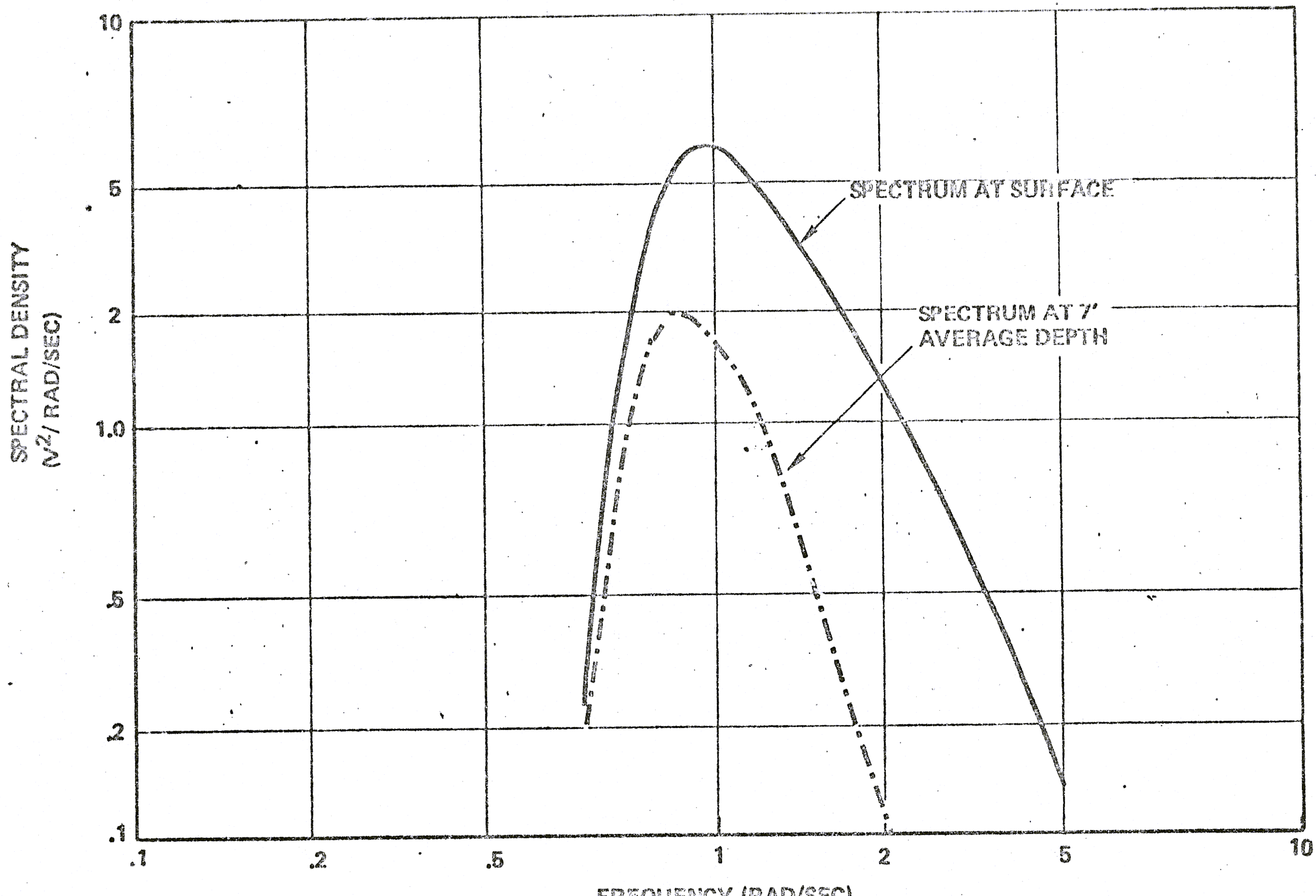

FIGURE 8

From these relationships one can begin to appreciate the significance of criteria for selection of hydrofoil strut length. Figure 9 shows a typical sinusoidal wave train with a hydrofoil craft superimposed. As long as the strut length exceeds the wave height the ship is effectively isolated from surface contour variations; hence its response to the seaway is dominated by the orbital particle velocities of the wave. Most other marine vehicles being surface followers are not concerned with orbital particle velocities. Hull down ships, surface piercing hydrofoils, and air cushion vehicles (ACV, SES, etc.) all are strenuously influenced and tend to follow the surface contour because the dominant forces and moments are introduced into the hull by the varying surface contour and not what happens below the wave surface.

Referring again to Figure 8, the decay of the orbital velocity with depth is significant in one other sense. Because of the natural attenuation of these higher frequency disturbances with depth, the hydrofoil automatic control system is relieved of the requirement to provide ride smoothing at high frequencies, which in turn allows the use of a fairly low band pass control system. This low band pass requirement in turn allows the control system to do a better job of controlling and ride smoothing in the larger low frequency waves.

Thus two particular characteristics of the fully submerged hydrofoil craft are dominant in its seakeeping characteristics:

- Isolation from surface contour variations by the use of relatively long struts which separate the hull from the lifting surfaces.
- Disturbance inputs are limited to those from wave orbital particle velocities and these are minimized by the depth of operation of the lifting surfaces.

3.3 DYNAMIC RESPONSE TO WAVES

A third element of the fully submerged hydrofoil system which is paramount in producing its exceptional seakeeping characteristics is its relatively flat response to wave inputs. Conversely surface ships have a very peaked

TYPICAL HYDROFOIL IN WAVES

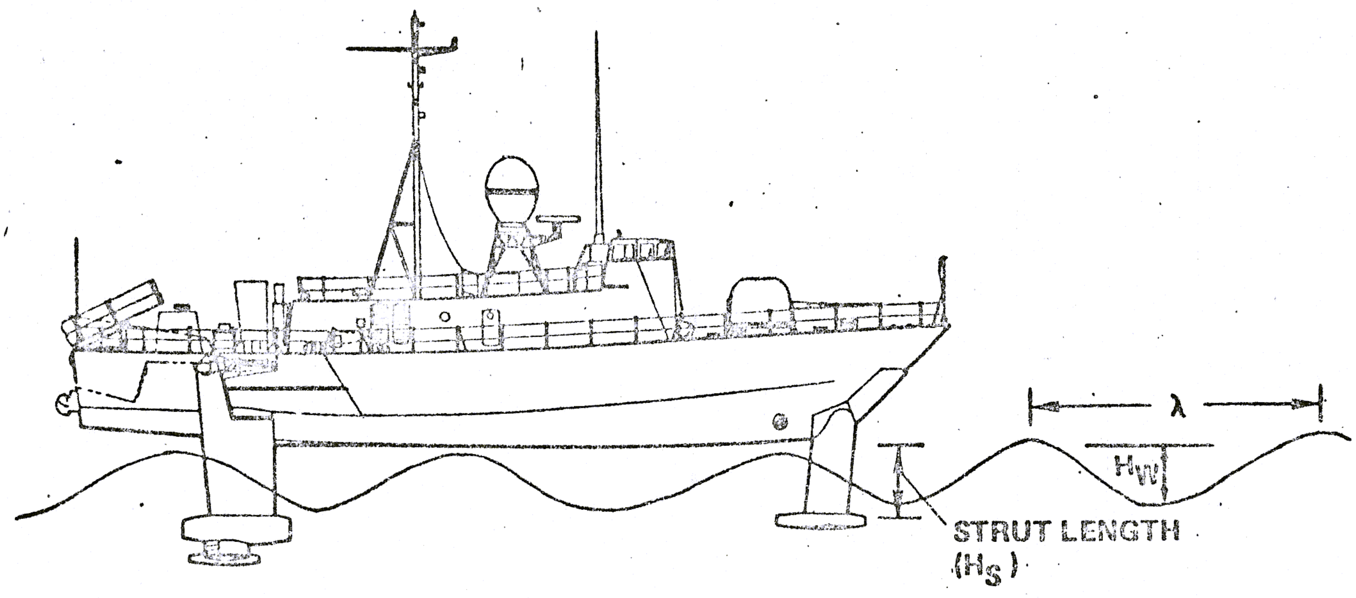

FIGURE 9

response characteristic at the hull resonant frequency. Before proceeding, let us examine the question of resonances in more detail. Starting with a simple model of a surface ship on a smooth water surface, let us assume the hull were some how displaced downward 1 foot and then released. The restoring forces (buoyancy and dynamic lift) would then cause the ship to move upward and, with characteristic light damping, the ship would over shoot its nominal smooth water point, peak out, fall back, pass the steady state point going downward, and with gradually decreasing amplitude the ship would oscillate up and down about its steady state operating depth until it finally settles out. What we have is the classic under-damped second order response of a spring-mass system. Likewise, similar pitch and roll response characteristics exist, and to a lesser degree a similar yaw response.

Each of these basic modes will have a resonant frequency which is the point at which the response peaks as shown in Figure 10. Thus there are a multiplicity of ship resonant modes which may be closely coupled or well isolated from each other. The point being that when the ship encounters waves at the particular frequency of one of these modes the ship tends to over-respond to the disturbance in the manner shown by the Figure 10 transfer functions. At this point, recall our previous discussion of what happens to the drag of the entire ship system as a result of this type of response (Figure 4).

A hydrofoil ship supported by underwater foils without an active control system is subject to the same basic response characteristics, except that the restoring forces due to a change in depth, pitch angle, or roll angle tend to be small, and the damping forces associated with the foils tend to be large; hence the response is better damped (less peaking in the response curve) than surface craft responses. Also, the magnitude of the responses is lowered all accross the frequency band due to the lesser input disturbances.

For the hydrofoil there is also a specific syncronous pitch condition associated with waves and the distance between the foils. When the wave

TYPICAL SHIP RESPONSES TO WAVE SURFACE

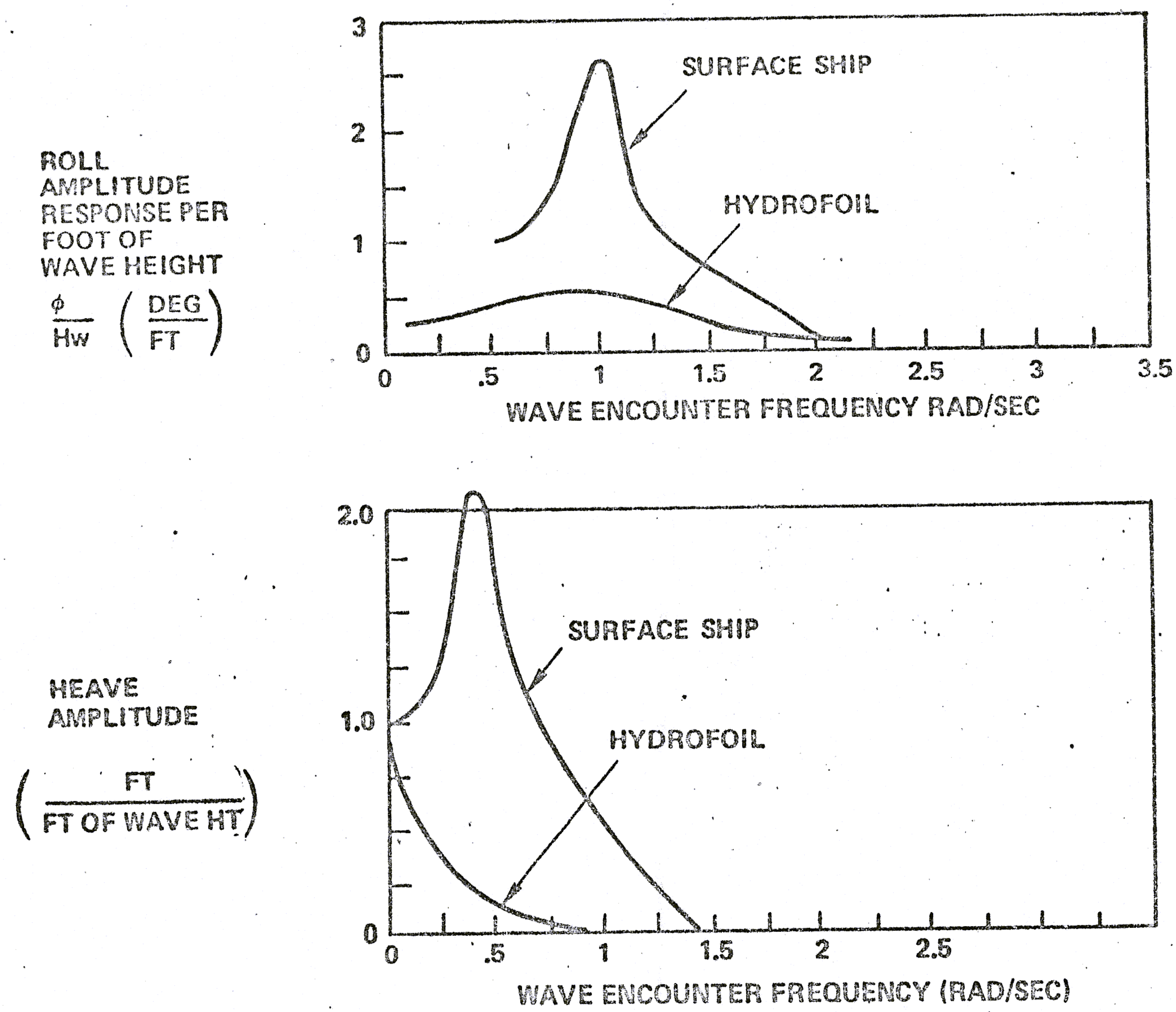

FIGURE 10

length is twice the distance between the foils the pitching moments due to the forces on the forward and after foils are additive; hence pitch motions tend to peak at that wave length. A similar situation exists in roll and yaw.

While granting the mechanisms for under damped response exist in the hydrofoil in much the same manner as for a surface follower, but to a somewhat lesser degree; the use of a full time automatic control system in the hydrofoil allows the designer, through the use of conventional feedback control methods, to compensate for the under damped resonant characteristics. Thus the resonant peaking characteristic which is of major importance in surface craft seakeeping and speed characteristics in a seaway has no counterpart in the fully controlled hydrofoil as is shown in Figure 10.

Additionally, it is basic that the resonances of surface craft will lie within the range of operating spectra and hence they must be lived with. Figure 11 shows the range of wave encounter frequencies which would be encountered by any ship operating in a single sea state. (10 foot significant wave height.) As can be seen, a slight change in heading can cause an appreciable change in frequency content. Although the commercial ship may be able to afford the luxury of course changes and at least locally cicuitous routings to avoid a critical encounter frequency at a given speed in a given sea, this solution can be a crucial disadvantage to any warship.

3.4 AUTOMATIC CONTROL CONSIDERATIONS

Finally in the area of ship response characteristics, the Hydrofoil Automatic Control System (ACS) is also used to provide additional ride smoothing, and motion reduction through the use of position, rate, and acceleration feedbacks, which further enhance its seakeeping characteristics. Over the years the improvements in seakeeping attained through the ACS have been dramatic to say the least. Figure 12 shows pilot house vertical accelerations for 5 hydrofoil ships. The earlier ships, HIGH POINT (Mod 0)

WAVE AMPLITUDE SPECTRA - 22 KNOT WIND SPEED

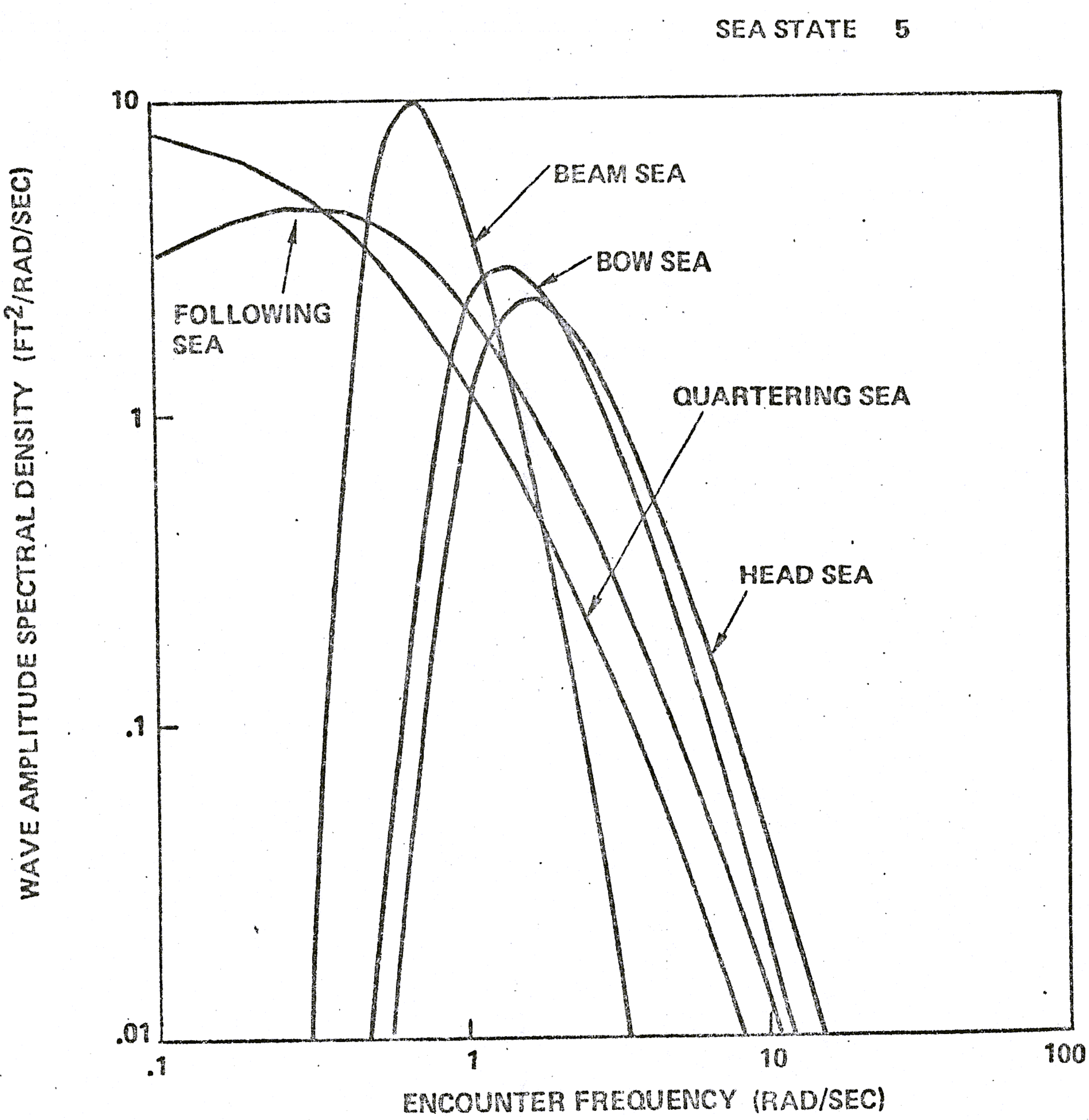

FIGURE 11

PILOT HOUSE VERTICAL ACCELERATIONS
COMPARISON OF VARIOUS HYDROFOIL SHIPS

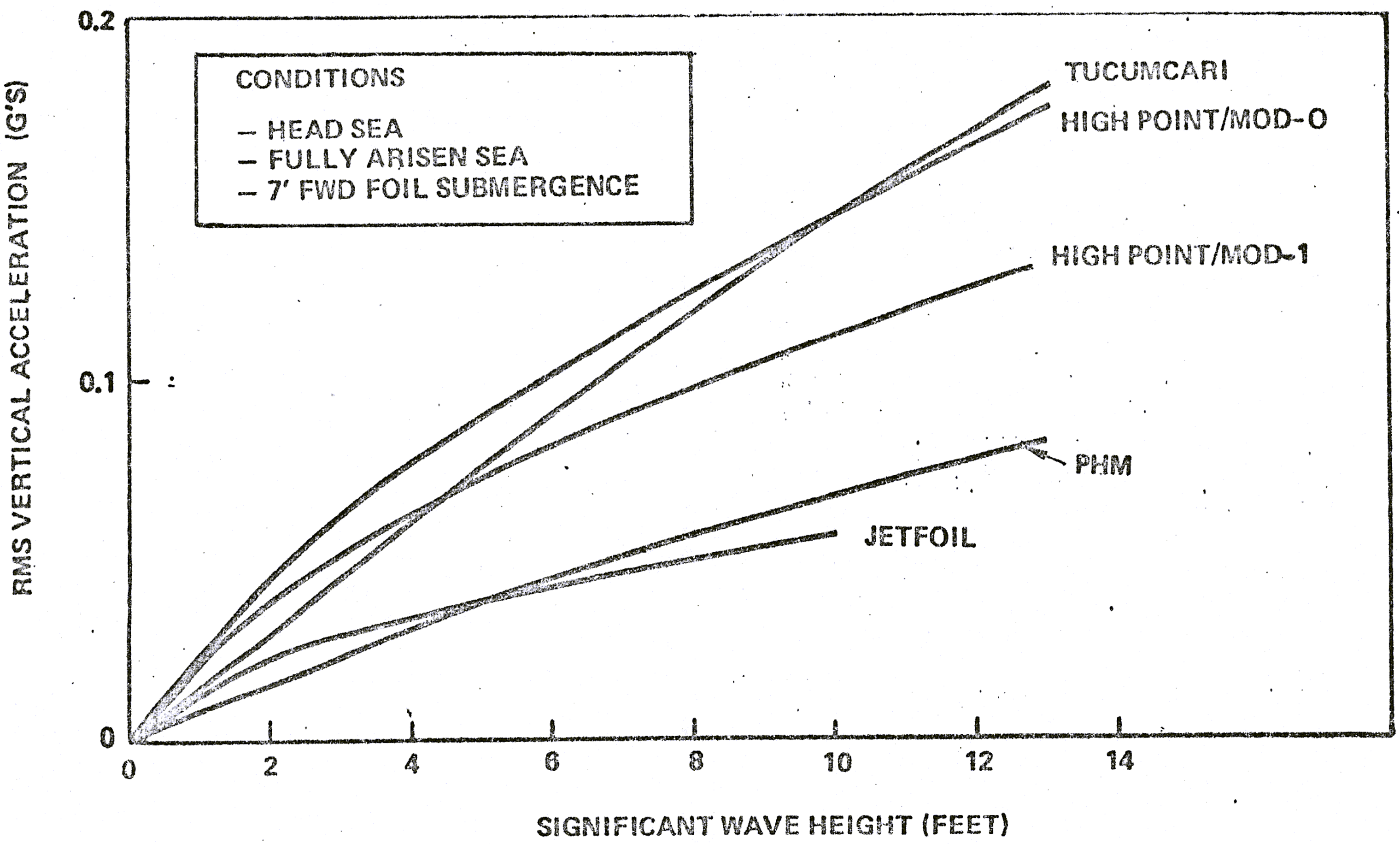

FIGURE 12

and TUCUMCARI have higher levels of acceleration for almost any significant wave height. And the newer ships (JETFOIL and PHM-1, PEGASUS) show marked ride improvement, which is almost totally due to improved control systems.

We now are in a position to add two additional sources of superior seakeeping quality to those introduced on page 16:

- Isolation from surface,
- Orbital velocity decay with increasing depth, and shorter wave lengths,
- Lack of peaked response characteristic and
- Acceleration and motion reduction via the automatic control system.

4.0 ANALYTIC APPROACH TO SEAKEEPING PREDICTIONS

While it is interesting to philosophize and generalize on the seakeeping characteristics, attributes and problems associated with various ship types, one must eventually depart from the abstract and turn instead to the very serious business of quantitizing responses to the seaway. When the specific vehicle or system responses to specific sea conditions are quantized, then and only then, can meaningful evaluations be made. In the following paragraphs an analytical approach to prediction of ship responses to the seaway is outlined. There is no short cut, or quick answer to developing quantitative vehicle responses to the sea. However, by carefully developing, in a step by step manner, quantitative analysis techniques we can eventually arrive at a realistic set of response data which are representative of ship operation.

4.1 REGULAR WAVES

The first step in the development of seaway responses is the development of mathematical models of the sea. Since any ship response is the aggregate of the responses to the many individual waves encountered, the analytical method must start with the individual wave. The wave picture shown in Figure 7 is representative. Briefly, the wave data needed are:

- Wave length (λ) ft
- Wave height (H_W) ft
- Orbital particle velocity (V_W) ft/sec
- Wave Celerity (C) ft/sec

Given a wave train of any wave length (λ) the frequency at which the wave crests pass a fixed point is simply the ratio of wave celerity to the wave length:

$$f_o = \frac{C}{\lambda} = \text{(Hertz)} \qquad \frac{ft/sec}{ft} = \frac{1}{sec} = \text{Hertz}$$

Wave celerity (C) according to wave theory is given by:

$$C = \left(\frac{g\lambda}{2\pi}\right)^{\frac{1}{2}}$$

ft/sec² x ft = $\sqrt{\text{ft}^2/\text{sec}^2}$ = ft/sec = velocity

hence it is seen that the fixed point encounter frequency (f_o) is a function of wave length only.

The orbital velocity vector at the surface can be divided into two components, the vertical component and the horizontal component. The vertical component is simply the first derivative of wave height variations:

$$V_{ov} = \frac{d}{dt} h_w .$$

the horizontal component has the same peak magnitude as the vertical component, but shifted 90° in phase:

$$V_{oH} = \frac{d}{dt} (h_w + \phi) \qquad \text{where } \phi = 90°$$

As a vehicle moves across the water surface, the encounter frequency is changed due to the ships velocity relative to the wave train velocity. Hence for a moving vehicle the wave encounter frequency must be translated to account for ship speed and heading relative to the wave. This translation is given by the relationship:

V = c

$f_o = \dfrac{\sqrt{\frac{g\lambda}{2\pi}}}{\lambda}$

$$f_e = f_o + \left(f_o^2 \frac{U_o}{g}\right) \text{Cos } \psi$$

$f_o^2 = \dfrac{\frac{g\lambda}{2\pi}}{\lambda}$

$f_o = \sqrt{\;}$

U_o, is ship forward velocity
g, is gravity constant
ψ, is ship heading relative to the direction to the wave
    ψ = 0° for head sea dirction
    ψ = 180° for following sea direction

Thus with the accomplishment of frequency translation to account for ship heading and speed we have all the classical wave data necessary for the development of craft responses.

H_w - Wave height

V_w - Orbital particle velocity

f_e - Encounter frequency

4.2 RANDOM WAVES

Observations readily verify that a seaway is random in nature, not a train of regular waves as discussed previously. Hence, we must next turn our attention to the statistical development of the sea.. In this statistical domain the primary descriptor is the wave amplitude spectrum. Neumann, Pierson, Bretschneider and others have formulated analytic expressions for ocean waves spectra based on statistical concepts of continuous random events.

At this time in our technological development, the ISSC adaptation of the Bretschneider spectrum is most suitable for design purposes because of its universal application to all types of sea conditions, be they fully arisen, decaying swell, or steep-rising seas. Most other spectra developed have been for fully developed, wind blown seas, formulated in terms of wind velocity. The ISSC/Bretschneider spectrum on the other hand is defined in terms of the significant wave height and the significant wave period. Hence the spectrum is defined in terms of two statistical measurements of the sea without regard to the factors involved in generating the sea. The ISSC/Bretschneider spectrum is given by:

$$\left[H(\omega)\right]^2 = 0.11 \left(\frac{2\pi}{T_s}\right)^4 \cdot H_s^{\,2} \cdot \omega^{-5} \cdot e^{\left(-0.44 \left(\frac{2\pi}{\omega T_s}\right)^4\right)}$$

ft²

where:

$H(\omega)$ = energy density spectrum of the long crested seaway – ft² sec ft²/cycle/sec

(ω) = wave frequency in rad/second

T_s = significant wave period in seconds

H_s = significant wave height in feet.

But for performance we also need wind speed → air drag

Again, as in the case of the regular wave train, we have the problem of translating encounter frequency as a function of craft velocity and heading relative to sea.

To preserve the energy content of the spectra in this transformation it can be shown that the transformed spectrum is given by:

$$\left[H(\omega_\varepsilon)\right]^2 = \frac{\left[H(\omega)\right]^2}{\left|1 + 2V_0\ \omega/g\ \mathrm{Cos}\ \psi\right|}$$

Figure 11 shows five resultant spectra for a fully arisen sea state 5 ($H_s \doteq 10$ feet, and $T_s = 6.75$ seconds) for a craft travelling at 45 knots. The beam sea spectrum is the fixed point spectrum. The head and bow sea spectra are translated to a considerably higher frequency domain due to craft velocity, while the quartering and following sea spectra are translated to a lower frequency domain, which effectively encompasses zero frequency. Energy to the left of zero frequency simply respresents those waves which are overtaking the ship.

4.3 SHIP RESPONSES TO THE SEA

The craft response to a seaway is made up of the aggregate of all the responses to the individual waves, be they big waves, little waves, long waves, or short waves. In the analytical process we make the assumption that the craft response is <u>linear</u>. While this assumption may bother some there is considerable precedent for it. Researchers including Bernicker and Jasper have found that ship responses tend to be linear to a large extent and that linear analyses techniques can be used effectively to predict the seakeeping characteristics of ships and hydrofoils, in a non-linear domain. Boeing studies utilizing extensive non-linear simulation of hydrofoil craft in a seaway have confirmed that predictions based on linearized theory result in essentially the same responses as the non-linear simulation up to the point where the hull is piercing the oncoming wave crests, or the foil broaches (comes out of the water) in the trough of the wave. More will be said on these grossly non-linear regimes in a later section. In the meantime, for the bulk of hydrofoil analysis the linearizing assumption can be accepted with confidence.

4.3.1 Transfer Function

In developing linearized craft responses we must first develop a frequency response characteristic of the craft. By assuming a unity wave height distrubance, craft frequency response characteristics similar to Figure 13 can be developed for any craft motion, velocity, or acceleration. In this case we have chosen to show the craft vertical acceleration at the steering station response as a function of frequency to a 1 foot high wave. (This is commonly known as a transfer function.)

4.3.2 Response Spectrum

Combining the craft response characteristic of Figure 13 for a given heading with the head sea spectrum of Figure 11 gives a resultant craft response spectrum. Figure 14 shows the craft acceleration spectrum for head sea operation for the sea state 5 example.

The acceleration response spectrum is at the same time very informative and very cumbersome; and we quickly reach saturation in our ability to comprehend the resultant differences in response due to different sea conditions, headings, speeds, etc. Hence, we must find a shorthand notation that simply represents the spectrum.

4.3.3 Standard Deviation

The integral under the spectrum for any stochastic process is known as the variance, and the square root of the variance is the standard deviation commonly designated sigma (σ). When the mean value of the variable is zero the standard deviation becomes the rms value which is the more commonly understood form.

Thus the next step in the analytical process is to find the rms value of acceleration for the given spectrum. We now have a single summary value of acceleration due to a specific sea condition, craft velocity and craft heading. If we repeat the calculations for other sea conditions or operating conditions, we can then develop summary ship response characteristic to seaway disturbances. One of the more useful displays of craft

STEERING STATION VERTICAL ACCELERATION
RESPONSE CHARACTERISTICS

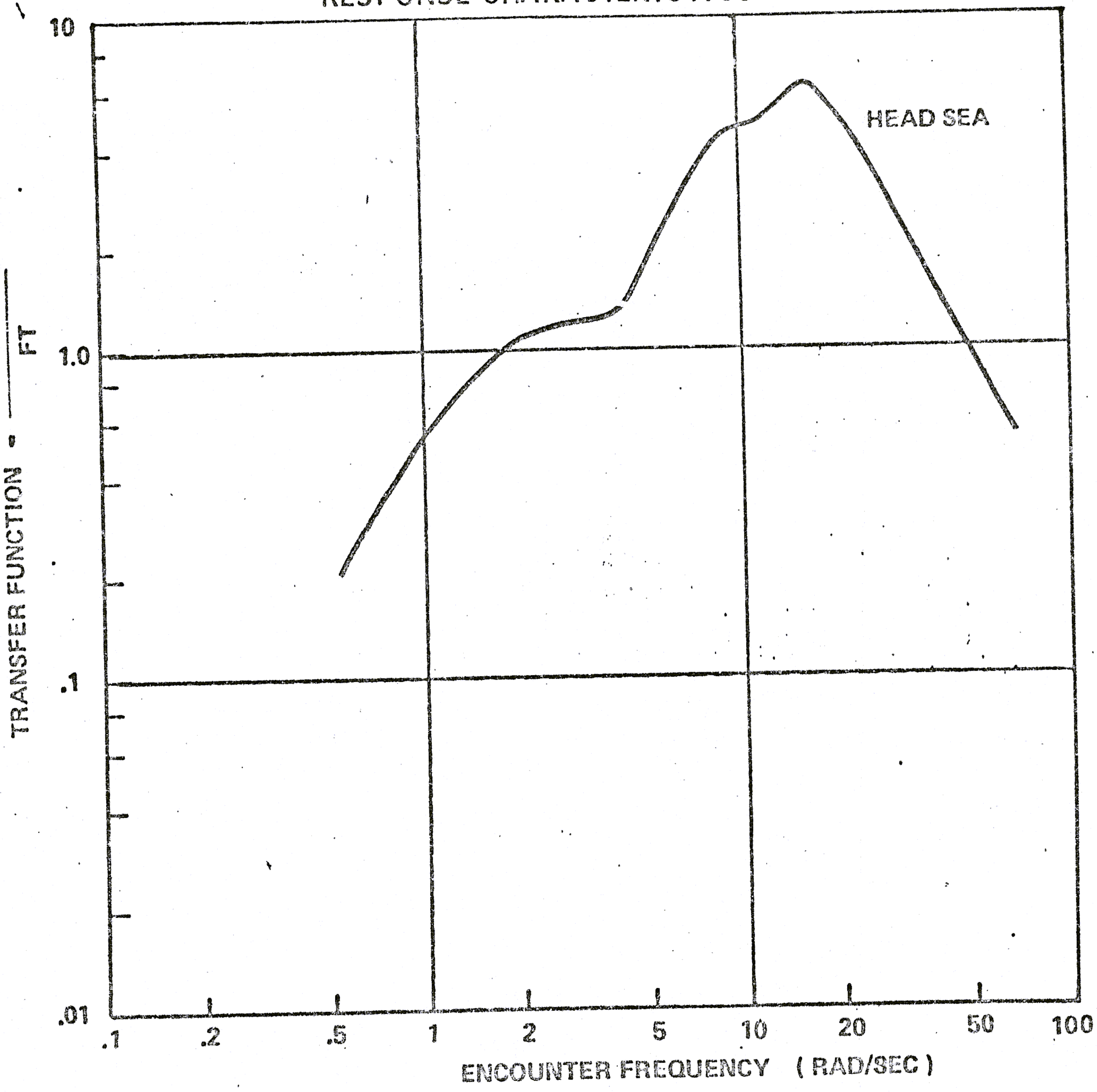

FIGURE 13

RESPONSE SPECTRUM

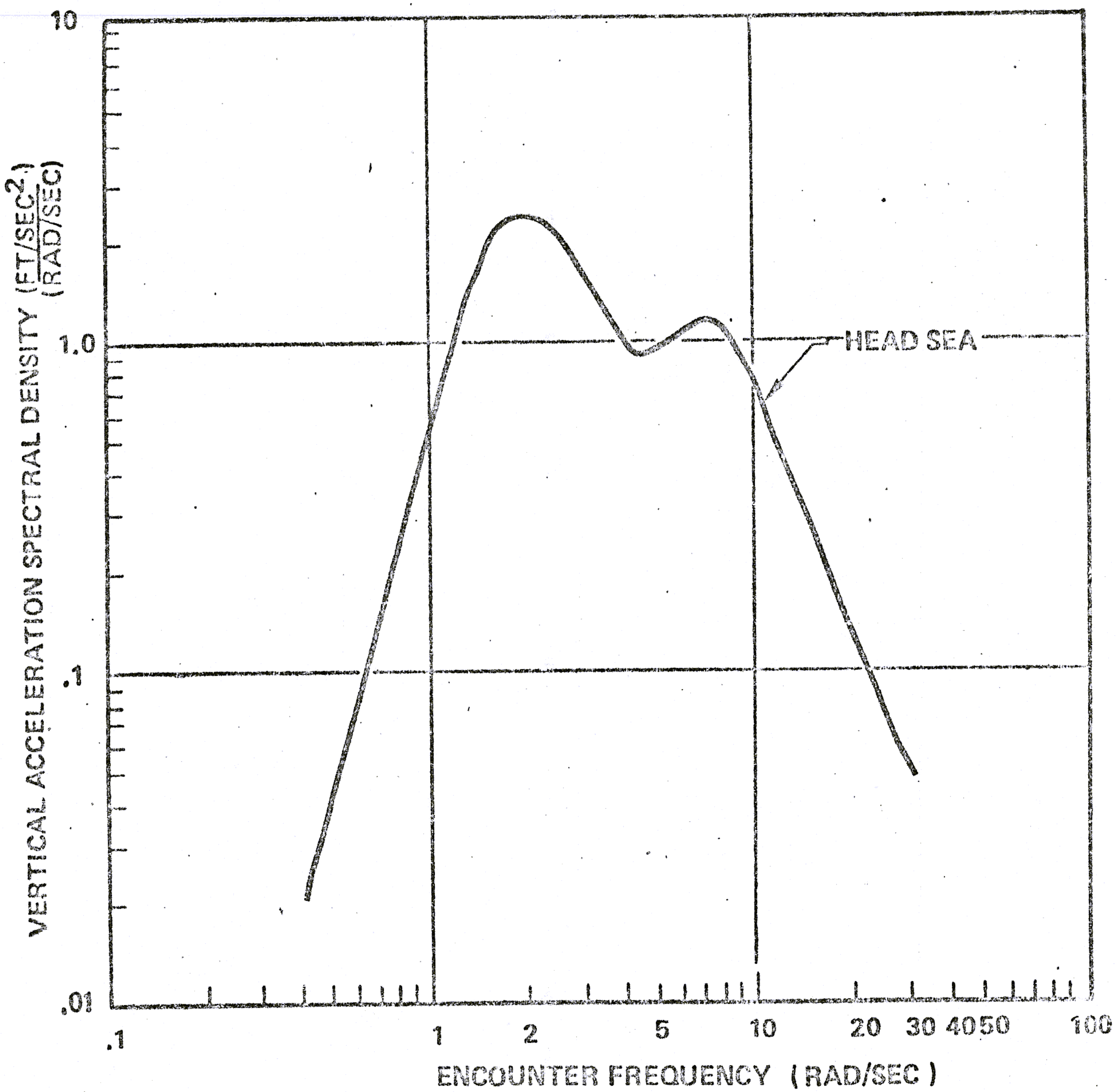

FIGURE 14

responses is to plot rms accelerations, motions, etc. versus significant wave height.

Figure 15 is such a plot showing typical rms accelerations versus significant wave height for 5 different headings relative to the sea.

4.4 COMPARATIVE SEAKEEPING DATA

In the initial paragraphs a qualitative case was built that suggests the fully submerged hydrofoil craft would be superior to other types of craft due to 4 factors:

- Isolation from the wave surface,
- Reduction of orbital particle velocity disturbances by foil depth,
- Flat response characteristic, and
- Ride smoothing by the automatic control system.

Subsequently the analytical processes for predicting responses in a seaway were developed showing methods for computing rms accelerations, motions, etc. versus sea state, or in this instance significant wave heights for fully developed seas.

Let us now examine this premise that the hydrofoil has superior seakeeping. Figure 16 shows rms accelerations versus significant wave height for a 200 ton hydrofoil, a conventional destroyer, and a high speed planing hull craft, the German S143 patrol craft. The comparisons speak for themselves. Finally Figure 17 shows typical hydrofoil measured responses in the same format as Figure 16. Hence it can be seen that the responses measured are in agreement with the analytical predictions.

4.5 NON-LINEAR CONSIDERATIONS

In earlier paragraphs the assumption of linear response was imposed. This must bother some for indeed ship operation in a seqway in non-linear, be it a surface ship, a hydrofoil or an ACV. For the hydrofoil ship such as depicted in Figure 9, there was genuine concern in the early days

TYPICAL ACCELERATION RESPONSES TO ROUGH SEAS

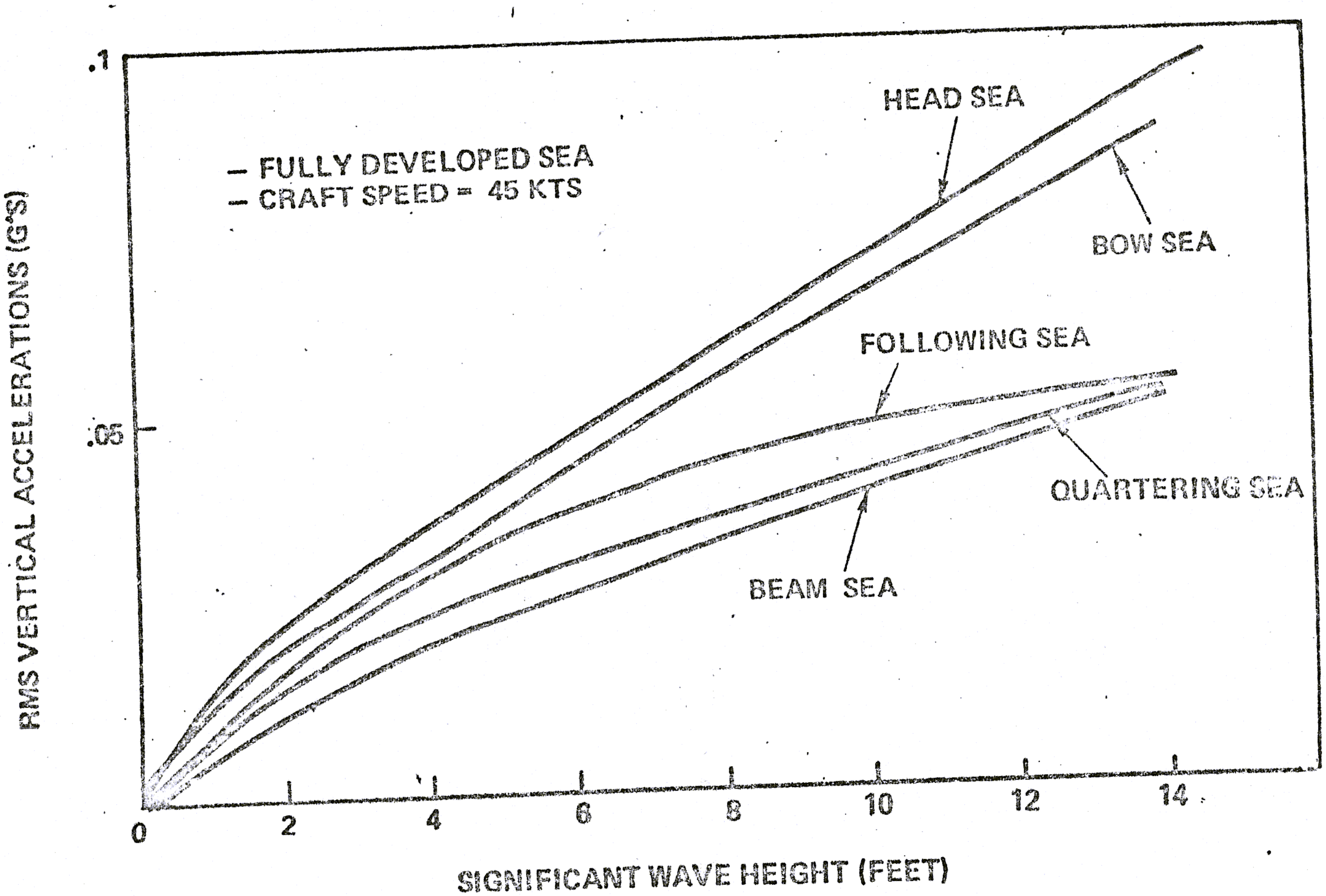

FIGURE 15

COMPARATIVE SEAKEEPING DATA

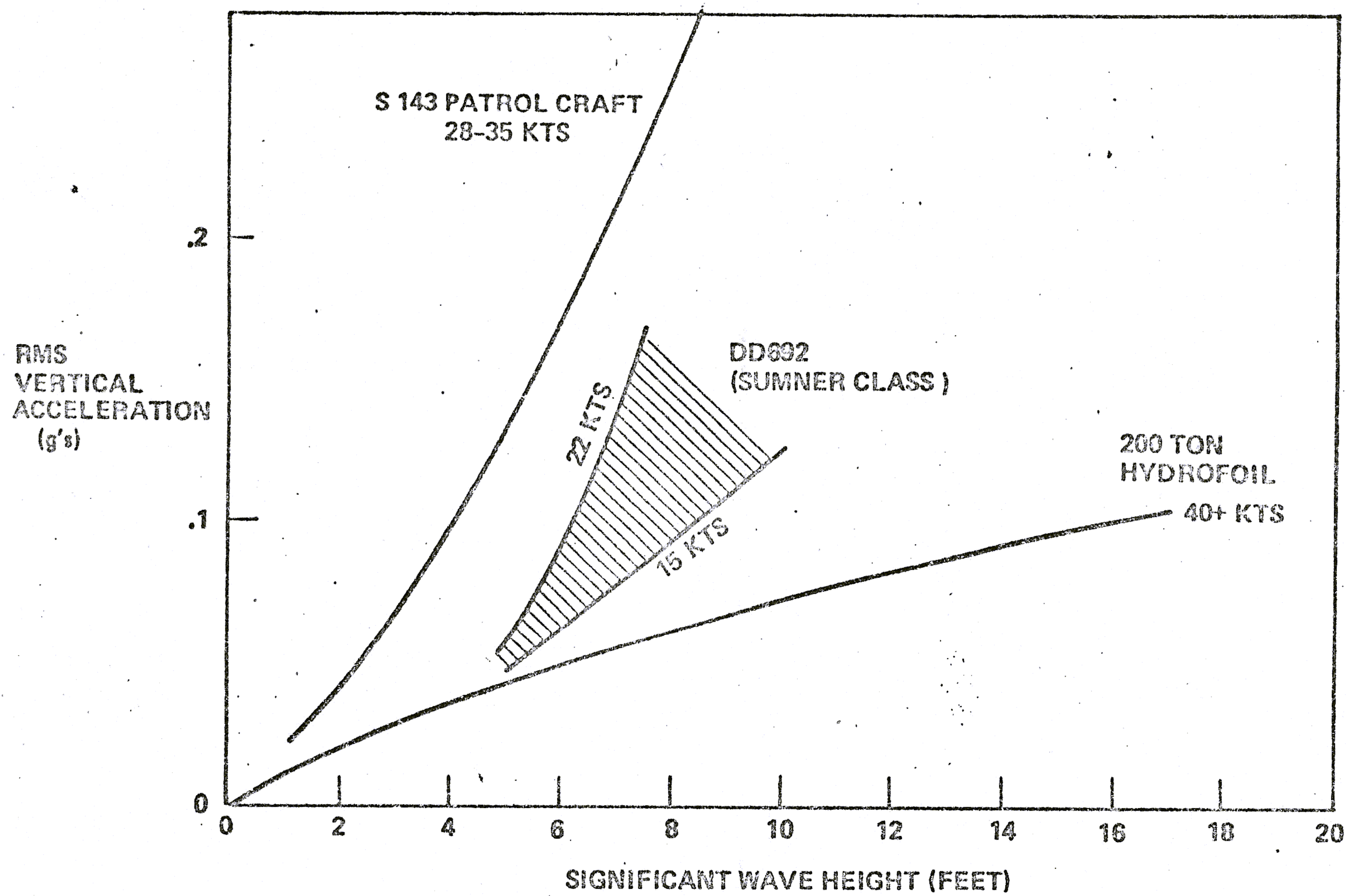

FIGURE 16

MEASURED ACCELERATIONS FOR VARIOUS HYDROFOIL SHIPS

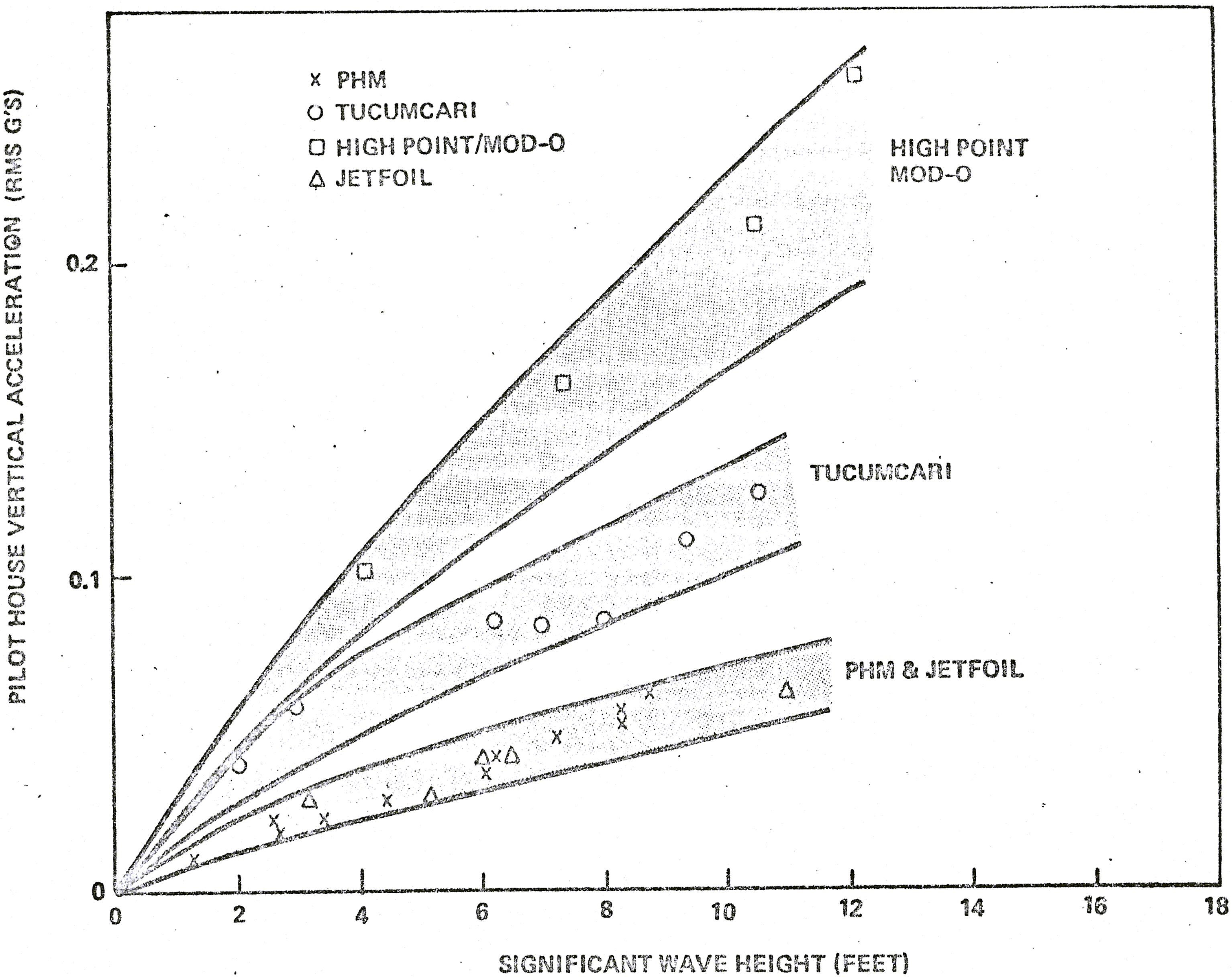

FIGURE 17

that when the seas became sufficiently large that the foils broached the surface or the hull came in contact with the waves, operation would have to revert to the hullborne mode due to the slamming accelerations and loads envisioned. That supposed hard limit, or "cliff" has not materialized for canard confugured hydrofoil ships, and indeed routine operation of hydrofoil ships in seas where wave cresting[1], foil broaching[1], and subsequent hull slamming[1] occur has been demonstrated repeatedly with both HIGH POINT (PCH-1) and TUCUMCARI (PGH-2). Figure 18 shows acceleration distributions due to broaching, cresting, and slamming for TUCUMCARI operating in head seas of significant wave heights between 6 and 11 feet. (TUCUMCARI strut length was 7.5 feet.)

This discussion is not intended to show that non-linearities do not matter, but rather that operation continues in spite of the non-linearities. At the same time the motions and accelerations due to broaching and slamming tend to be much larger than those ordinarily occurring during rough water operation where boraching, slamming and cresting are not present. For example the 1 σ value of acceleration in 10 foot significant waves for TUCUMCARI was 0.13 g's. Extending this value to the 90% of all peak using the Raleigh distribution, reveals that only 10% of all peaks would be greater than 0.28 g's. At the same time 10% of the peaks associated with broaching and slamming exceeded 0.8 g's.

Finally on the subject of non-linearities, it should be said that when the seas are sufficiently <u>beyond</u> the design point that <u>frequent</u> foil broaching and hull slamming are present then the predictions based on linear methods discussed previously tend to breakdown. But keeping a

---

1 - A foil broach occurs when the foil becomes fully or partially unwetted due to penetration or near penetration of the water surface.

- A hull slam is the contacting of the hull with the water surface following a foil broach.
- Wave cresting is defined as a hull contact that occurs while foilborne at a time other than immediately following a foil broach.

VERTICAL ACCELERATION PEAKS DUE TO BROACHING, SLAMMING & CRESTING – TUCUMCARI

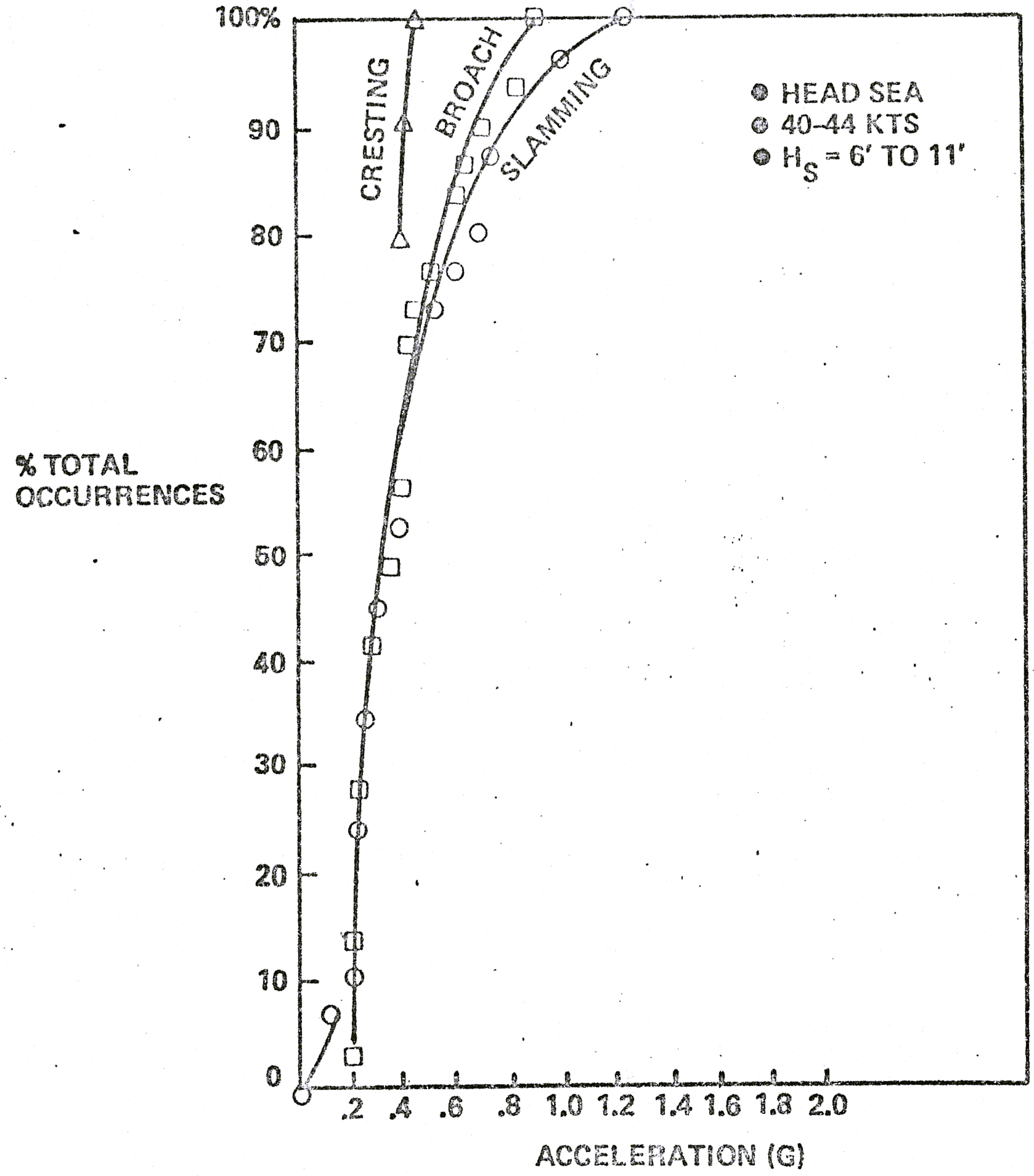

FIGURE 18

proper perspective we must recognize that for the vast majority of cases the assumption of linearity provides us with efficient methods for design and predictions of performance, and since the significant non-linearities are associated with waves whose height exceeds the effective strut length, we know the areas to single out for additional non-linear studies.

4.6 STRUT LENGTH SELECTION

By now we have come full circle and must now address the question of strut length quantitatively. As depicted in Figure 9, if the waves are small relative to the strut length then the hydrofoil ship is effectively isolated from the sea; however, if the waves are large, relative to the sturt length then some basic non-linear characteristics (broaching, slamming and cresting) start to come into play which tend to degrade the basicly superior seakeeping characteristics of the hydrofoil. While the degradation tends to be gradual and the results of foil boraching and hull slamming are far from catastrophic, they nevertheless can impose a ship operating limit wherein the operator would voluntarily slow down or land. This voluntary change in operation could result either from a people oriented ride quality standpoint or from a fear of equipment damage. The same type of voluntary change in operation is common to surface ships, where, for example, bow slamming and deck wetness on Destroyers tends to limit speed.

The selection of strut length for a hydrofoil ship should then depend upon the sea conditions in which the ship will be expected to operate; and since as we have previously discussed the seaway can only be defined in a statistical way we must turn to statistical parameters to develop a realistic strut length selection.

Typical practice is to select the strut length such that in the "Design Sea" no more than 8% of the wave heights exceed the effective strut length. Since the distribution of wave heights follows the Rayleigh distribution this can be restated in terms of the effective strut length and significant wave height as:

$$l_{Eff} \geq H_s \quad (1.1)$$

where: l_{Eff} = effective strut length[1]

H_s = significant wave height

Using this criteria we would then conclude that a ship designed to operate in seas up to 10 feet significant wave height should have an effective strut length of at least 11 feet.

All this needs to be put into perspective however by the inclusion of the probabilities or statistics associated with encountering seas greater than a given value. To do this we turn to long term distributions of sea conditions for given areas. Fortunately oceanographic data have been gathered for many years which allow us to construct long term distributions of sea conditions for most ocean areas of the world. Figure 19 shows long term distributions of significant wave height for the North Atlantic Ocean and for the North Sea.

If we arbitrarily select 95% of all sea conditions as the acceptable operating boundary then we would find the strut length should be greater than 13 feet for North Sea operation and 19 feet for North Atlantic operation.

One final note on strut length selection, the length of struts will not continue to grow with ship size as has been noted in the past due to the fact that there is a realistic upper limit to the sea conditions in which the ship would be designed to operate. Realistically the North Atlantic represents a reasonable upper range of seas for hydrofoil operation and it can be seen that for 95% of days the significant wave height will be less than 5.25 meters (17.2 feet) and for 98% of days the significant wave

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1 Effective strut length may differ from actual strut length and in general it is defined as actual strut length plus allowable hull immersion in wave crests minus minimum foil depth required to prevent foil broaching.

YEAR AROUND DISTRIBUTION OF WAVE HEIGHTS

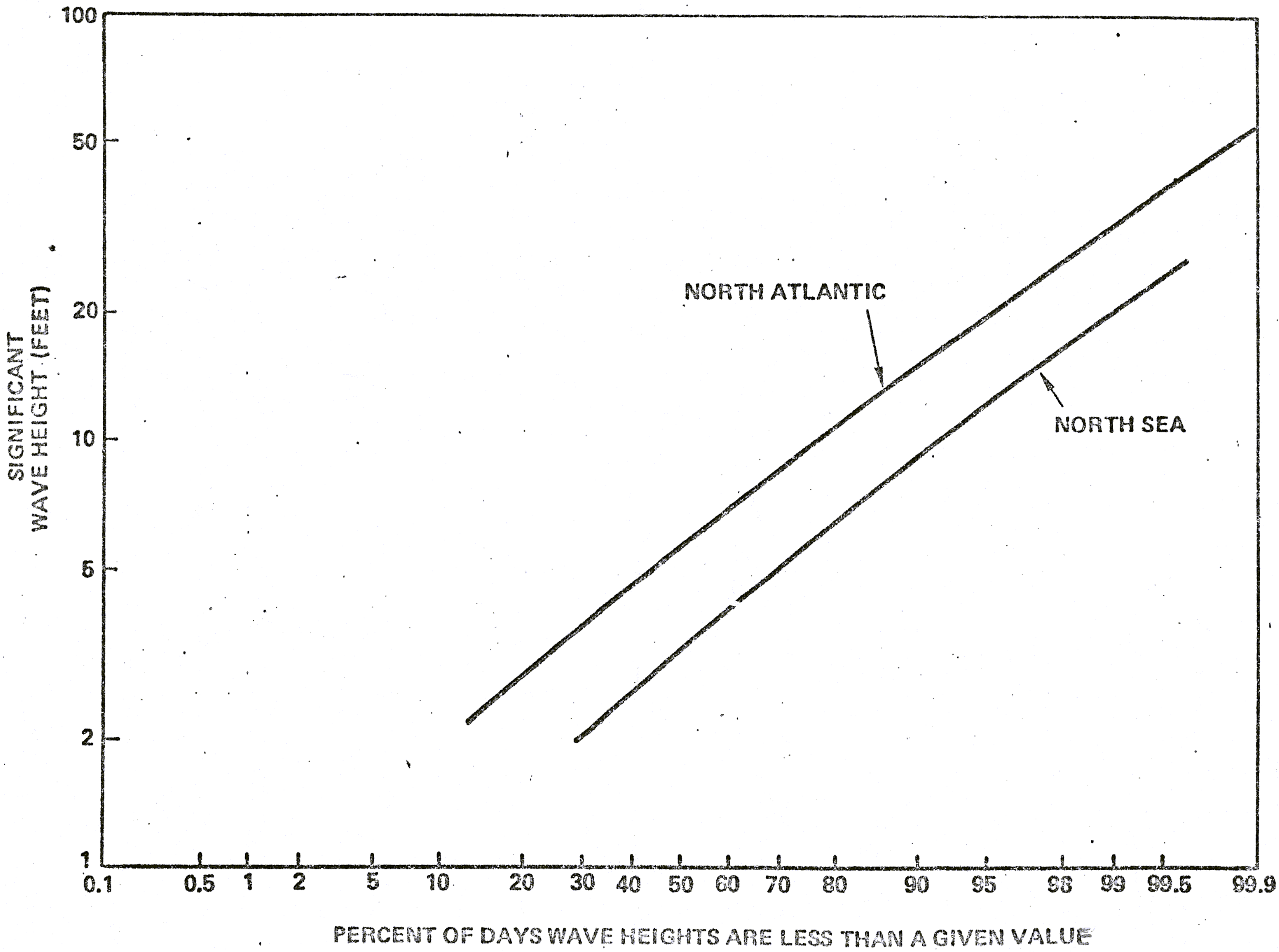

FIGURE 19

height will be less than 6.8 meters (22.3 feet). Thus as hydrofoil ships increase in size the strut length should logically increase to 19 to 24 feet, and then remain relatively constant regardless of the size of the ship.

4.7 HUMAN FACTORS

The old expression "one hand for the Navy and one hand for me" is graphically descriptive of the situation that has been accepted by officers and men since time immemorial when a ship is underway in heavy seas. All appropriate ship's work must continue but at best at reduced efficiency and at worst with hazard to men and materiel. However, although physical tasks somehow continue to get done, the requirements for those kinds of tasks requiring mental alertness, psyco-motor effectiveness and visual or aural acuity have risen extremely sharply in recent years and continue apace. In order to maximize the effectiveness of this type of human function, increasing attention is properly being placed on the environmental conditions in both working and living spaces. To do this the ship designer is provided with lengthy and explicit specifications on subjects as varied as the permissable sound level in a CIC as a function of frequency to the best paint colors on bulkheads in messing spaces. It remains ironic however that the two environmental factors primarily responsible for degradation of command and operation efficiency have not yet found a leading position in our specifications - motion and acceleration.

As we discussed previously, the Naval Architect has been responsible for measurable evolutionary success in the attenuation of these two factors but their ultimate treatment in statistical probable seas results in major reductions of steaming speed or diversion from a planned course or both if ship safety and even minimum crew effectiveness are to be assured. Hydrofoil ships on the other hand, have been specifically designed to produce an optimum environmental situation without suffering either of these disadvantages and, more importantly, have already demonstrated this capability in actual trials in relatively small ships.

In order to place this discussion in a context of engineering terms Figure 20 is most descriptive. The points shown represent a very low fraction of

HUMAN TOLERANCE BOUNDARIES
INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

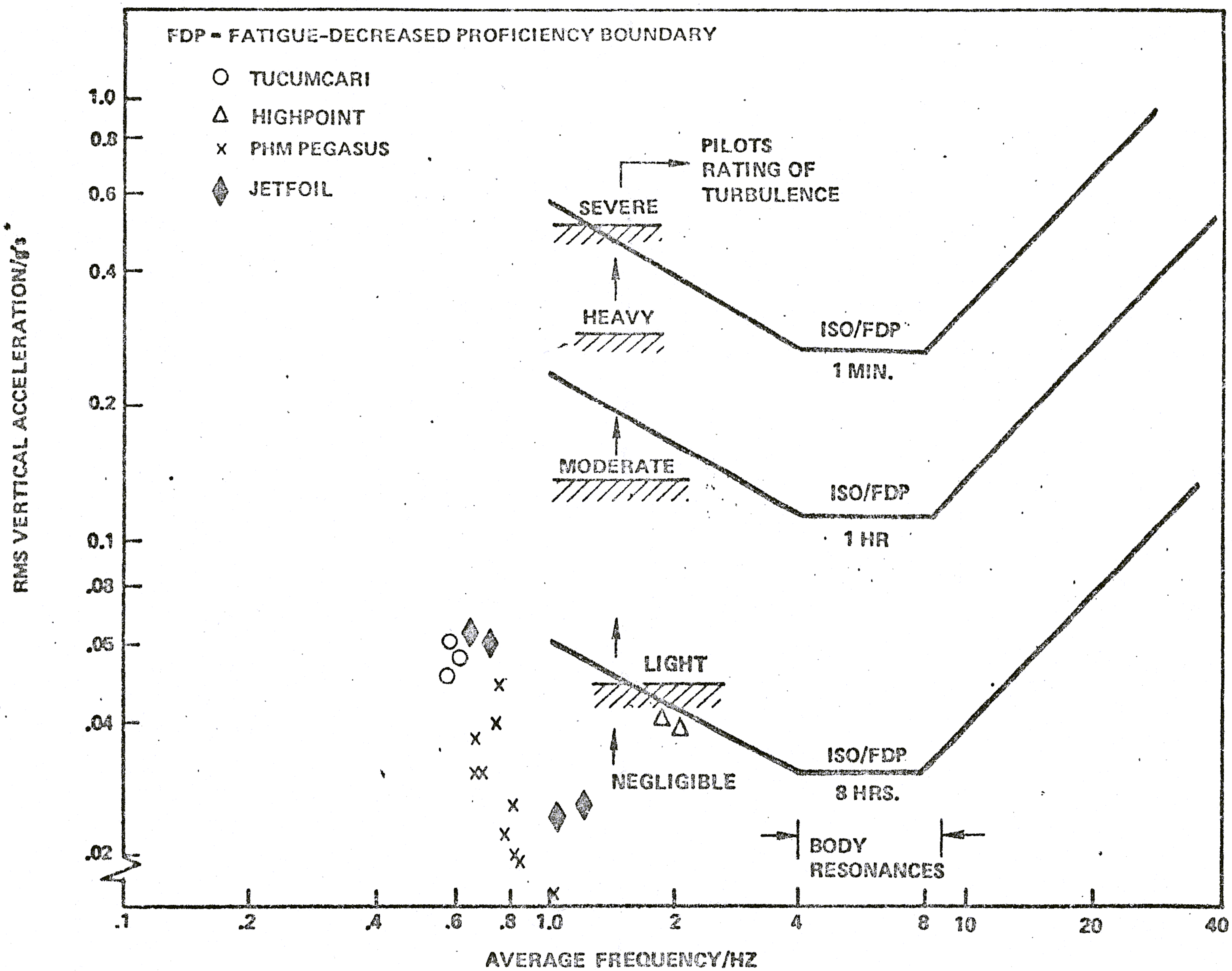

FIGURE 20

total body of data obtained from both Naval and Industrial underway trials. The points nearest the upper limit of the "negligible" boundary represent maxima for the several ships in or near appropriate fully developed design sea states.

Two points should be made in concluding this section:

1. Within reason, hydrofoil ship seakeeping, in statistically probable open sea conditions, is not dependent on size. The Naval planner, therefore has the ability to postulate a wide range of ship sizes based solely on the military factors of endurance and installed payload.

2. The hydrofoil ship will provide a motion and acceleration environment while underway at 40-50 knots in her design sea vastly superior to most displacement ships; equivalent to that of a large (10,000 ton) dynamically stabilized ship; and measurably better than any other Advanced Ship option.

5.0 SHIP PERFORMANCE

To this point our discussion has focused on hydrofoil ships characteristics presented in comparison to those of surface ships. In presenting and discussing the speed-power-payload related aspects of hydrofoil performance, our basis for comparison will be changed. Performance comparisons will be based on the characteristics of a group of hydrofoil ships. This group, or family, is comprised of past and present operational hydrofoils and larger ships which have been defined through extensive design studies. Ship weight has been chosen as a common basis for the presentation of the performance data.

The speed-power performance of a hydrofoil craft can be evaluated from two basic positions; its speed capability and its endurance and payload capability. Craft speed, as a major advantage of hydrofoil ships, has been discussed in the previous sections of this study. However, it is desirable at this time to elucidate a subtle point. Speeds of 40 to 50 knots are common to every member of the hydrofoil group to be reviewed. This condition results from a conscious decision on the part of the US Navy to limit Advanced Development to sub-cavitating hydrodynamic technology and is not a ship size related factor. There is no inherent relationship between the size of a hydrofoil ship and its speed capability in calm water, or in its design sea state. Therefore, maximum speed trends will not be considered further in discussion of the effects of size on hydrofoil ship performance.

The conclusion was reached in previous discussions that the size and the seakeeping qualities of a hydrofoil ship were not related. Seakeeping capability is a function of strut length. With this being the case, the mission or endurance requirements applied to a ship design are the only remaining factors which determine ship size. Since ship size is fixed by the necessity to carry a specific payload or sufficient fuel to achieve specified endurance, range-payload considerations provide a basis for the evaluation of ship performance. In point of fact, ship range equations such as that given below contain all of the principle elements necessary for the evaluation of craft performance.

$$\overset{\text{Range}}{\cancel{\text{Endurance}}} = 325 \left(\frac{W_F}{W}\right) \left(\frac{L}{D}\right) \left(\frac{\eta}{SFC}\right), \text{ Nautical Miles}$$

where:

- 325 = Constant of proportionality
- $\frac{W_F}{W}$ = Fuel Weight fraction
- $\frac{L}{D}$ = Craft Lift-to-drag ratio
- η = Propulsive coefficient
- SFC = Specific Fuel Consumption

The effect of closely related parameters such as craft specific power requirements and propulsion plant weights will be considered. It will be seen that an increase in ship size typically results in an increase in ship performance.

5.1 SIZE OR SCALING EFFECTS

5.1.1 Craft Lift-to-Drag Ratios

Ship lift-to-drag ratio (L/D) is one of the significant indications of overall craft efficiency. The effect of size on L/D is given in Figure 21 for the group of hydrofoil ships considered. These data indicate an improvement in L/D with increasing ship size. It is clear from the range equation that an increase in ship L/D will provide direct increases in craft endurance.

The identification of the source of the craft lift-to-drag ratio improvement with increasing craft size requires further examination. The drag of a foilborne hydrofoil is comprised of drag due to the generation of lift and parasite drag. Induced drag, due to lift, is independent of size and constitutes, during foilborne operation, a relatively small portion of the total. Parasite drag constitutes the major part of foilborne drag and is predominated by drag due to friction. The most effective manner in which craft L/D can be improved is through a reduction in friction drag on the submerged elements of a hydrofoil system. Drag due to friction is typically defined as:

INTRINSIC CHARACTERISTICS – SHIP SIZE BENEFIT

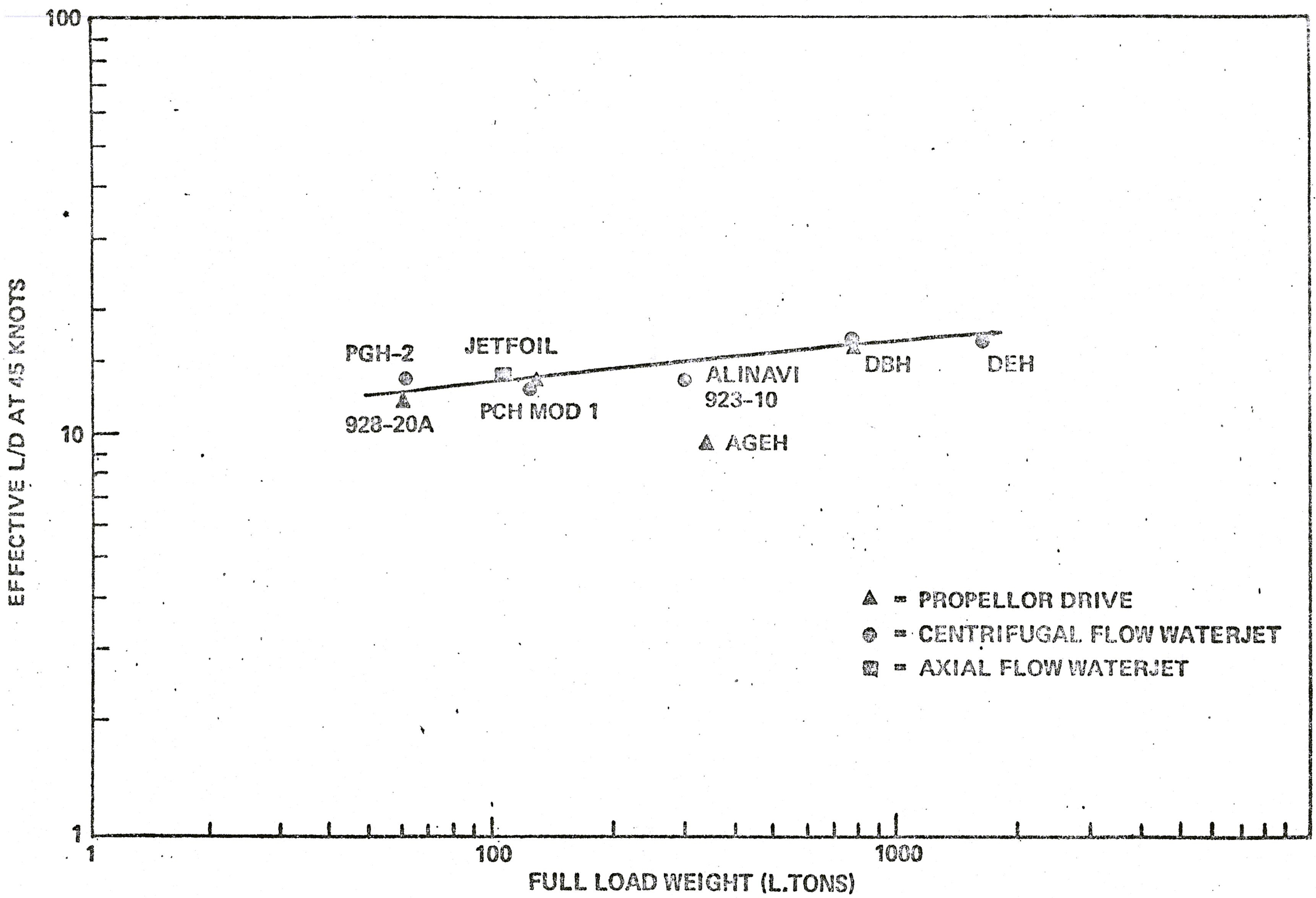

FIGURE 21

$$D_{Friction} = C_F \; q \; S, \text{ pounds}$$

where: C_F = Friction Drag Coefficient

q = Dynamic pressure, $0.5 \rho v^2$

S = Wetted surface area

Within the above relationship the dynamic pressure will remain constant for a given design speed regardless of ship size. In general, for given maximum available foil laoding and ignoring buoyancy factors, the area of a subcavitating foil system will be directly proportional to craft weight. It remains that increases in craft lift-to-drag ratios will only occur with the reduction in friction drag coefficients which result from Reynold's number effect. Reynold's number is defined as:

$$Re = \frac{\text{(Relative velocity over surface) (characteristic length of surface)}}{\text{kinematic viscosity of fluid}}$$

It is apparent that Reynold's numbers will increase with ship size. The extent to which friction drag coefficients will decrease with ship size can be inferred from Figure 22. The reduction in craft drag will reflect directly in improvements in craft range.

5.1.2 Propulsive Efficiency

Propulsive efficiency is a measure of the energy lost by the ship's driving mechanism in propelling the ship. It is generally a function of ship speed. As with any efficiency, propulsive efficiency is a ratio of an input to an output power, the specific terminology being:

$$\eta \equiv \frac{EHP}{SHP}$$

where: η = overall propulsive efficiency

SHP = shaft horsepower of prime mover measured at the engine output shaft

EHP = effective horsepower = $\frac{\text{Drag} \cdot \text{Velocity}}{k}$

k = constant of proportionality

SIZE EFFECT ON PROFILE DRAG

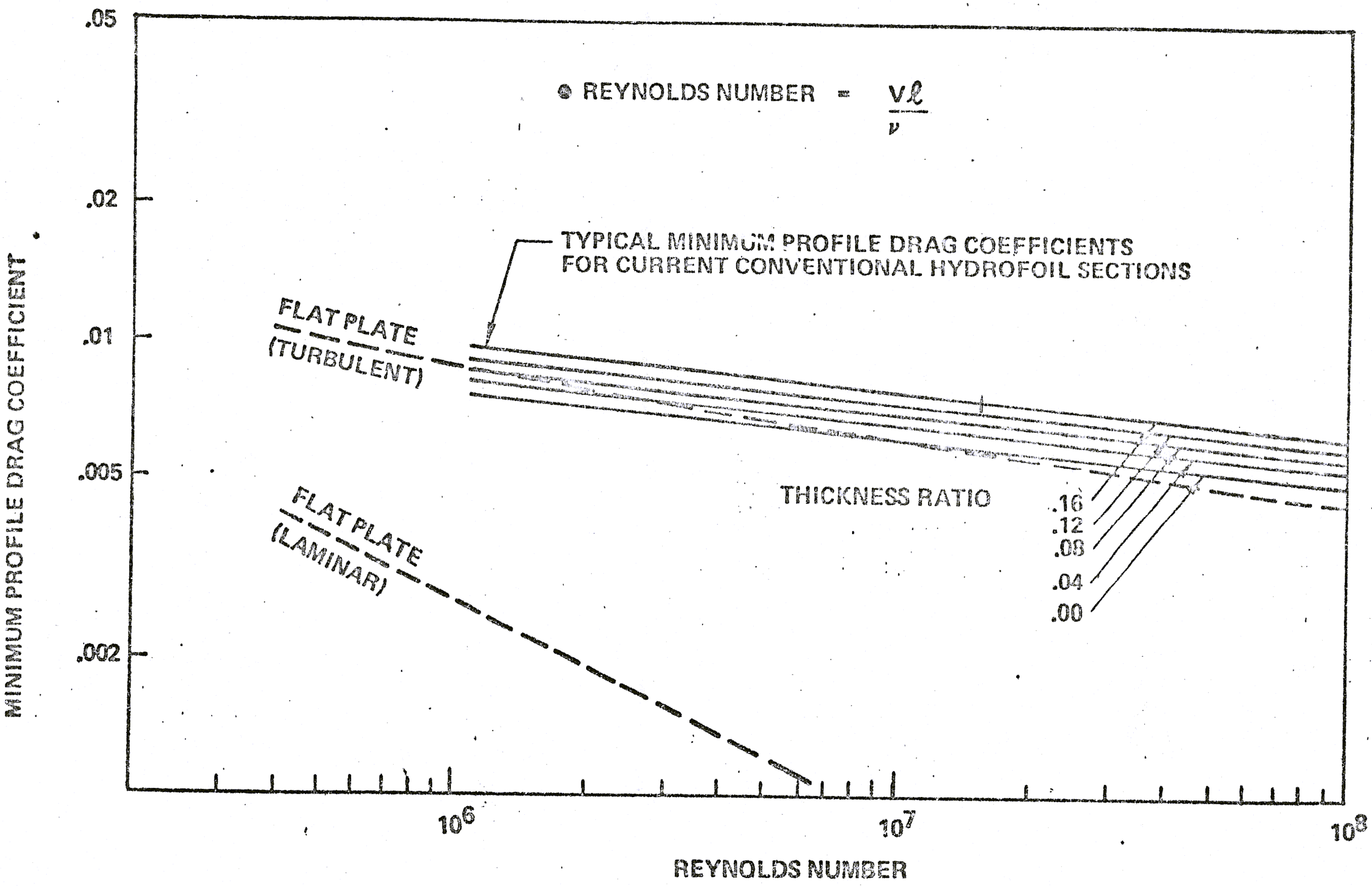

FIGURE 22

Of interest in this discussion is the question as to whether or not the propulsive efficiency of a hydrofoil ship is dependent on ship size. In examining this question the following comments are considered to be effectively valid, if not absolutely true. First, power losses between prime mover and propulsor remain essentially constant for a similar system geometries. This assumes that all sizes of ships would have similar transmission systems with the same number and type of bearings, gear meshes, and flexible couplings, and that the percentage losses in each are equivalent. Second, any size related changes in ship hydrodynamic efficiency would be reflected in both the SHP and EHP terms in the definition of propulsive efficiency. Thus, only a change in propulsor efficiency with size could cause a change in overall propulsive efficiency. Referring to Figure 23, such a change does not occur. Based on the existing family of hydrofoils, overall propulsive efficiency does not change with ship size and thus is neither benefited nor penalized in scaling. This conclusion holds for either waterjet or propeller driven ships, although, as can be seen, the value of propulsive efficiency is different for each propulsor, being about .63 for propeller driven and .50 for waterjet driven vehicles.

5.1.3 Specific Power Requirements

Neither of the previous performance terms, craft L/D or propulsive efficiency, present a description of their combined effect on craft performance. This study aspect can be best considered through the introduction of a specific, or normalized power parameter. Specific power is defined as:

$$\frac{\text{HP}}{\text{TON}} = \frac{\text{Power Output of Prime Mover Measured at Output Shaft}}{\text{Displacement or Weight of Ship}}$$

The benefit of this parameter is found in its ability to combine the aforementioned factors, ship lift-to-drag ratio and propulsive efficiency and in the fact that power ratings are readily related to fuel usage through consideration of SFC terms. This advantage is especially apparent when dealing with trends within a group of vehicles, such as the study

INTRINSIC CHARACTERISTICS – PROPULSIVE EFFICIENCY

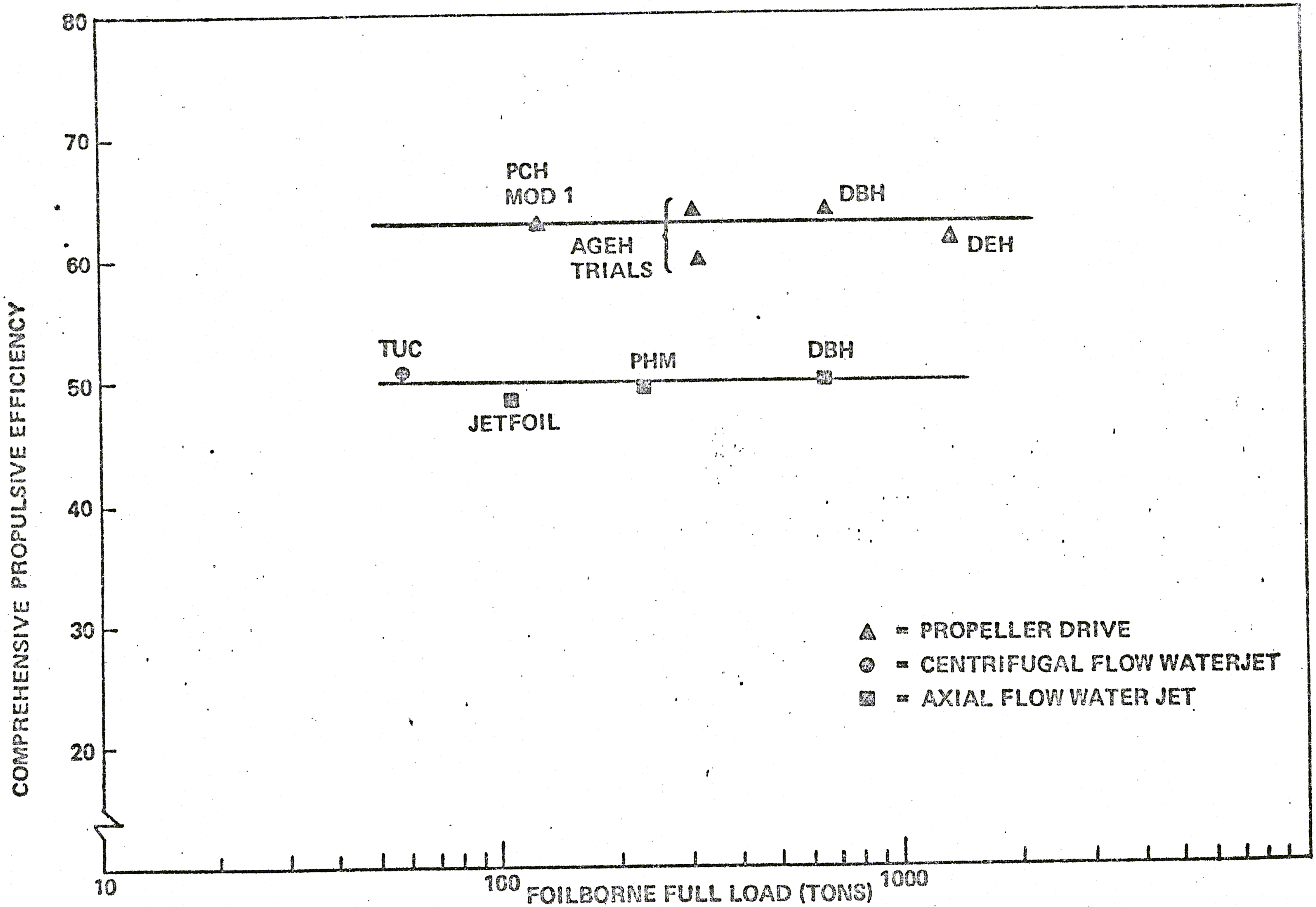

FIGURE 23

group of hydrofoil ships. Figure 24 shows specific power trends which are in full agreement with the previous L/D and propulsive coefficient trends. A decrease in specific power should be expected with increasing hydrodynamic efficiency (L/D) and with, at least constant propulsive efficiency.

Only one characteristic of the curves in Figure 24 differs from the expected; the slope of the waterjet and propeller curves, with constant propulsive efficiency, should be the same since slope is determined by the L/D improvement with ship size. The slopes, in fact, should be equal on this basis. However, the discrete points involved in this particular data survey are sufficiently scattered due to extraneous effects to cause the noted divergence. One anomalous point on the specific power plot deserves additional comment. The AGEH point is typical for that ship. Low foil aspect ratio and the consequent low L/D has caused the specific power for that ship to be higher than what would be considered normal.

5.1.4 Fuel Weight Fraction and Payload

The range of a hydrofoil ship is proportional to the fuel load carried and, to be a useful vehicle, that ship must also carry a payload. In the conceptual design stage, fuel and payload fractions can be traded to achieve the range and mission capability required by ship specifications. The greater the fuel and payload that can be carried by a given ship, the more useful that ship will be, since both range and mission capabilities can be correspondingly increased. In fact, large hydrofoils are of greater value in this regard since the fuel and payload fractions do increase with ship size. These trends are illustrated in Figure 25 which includes useful load information for the study group of hydrofoil ships and in Figure 26 which contains fuel weight fraction information.

Before proceeding with a general discussion of the trends shown in the noted figures, it may be desirable to first dispose of some specific features found in the fuel weight data of Figure 26. Separate trend lines are shown in this figure for propeller and waterjet ships. This separation has been found to result from the greater wet propulsive plant weight fractions which are typical of waterjet systems. Where a ship is

INTRINSIC CHARACTERISTICS — CRUISE POWER

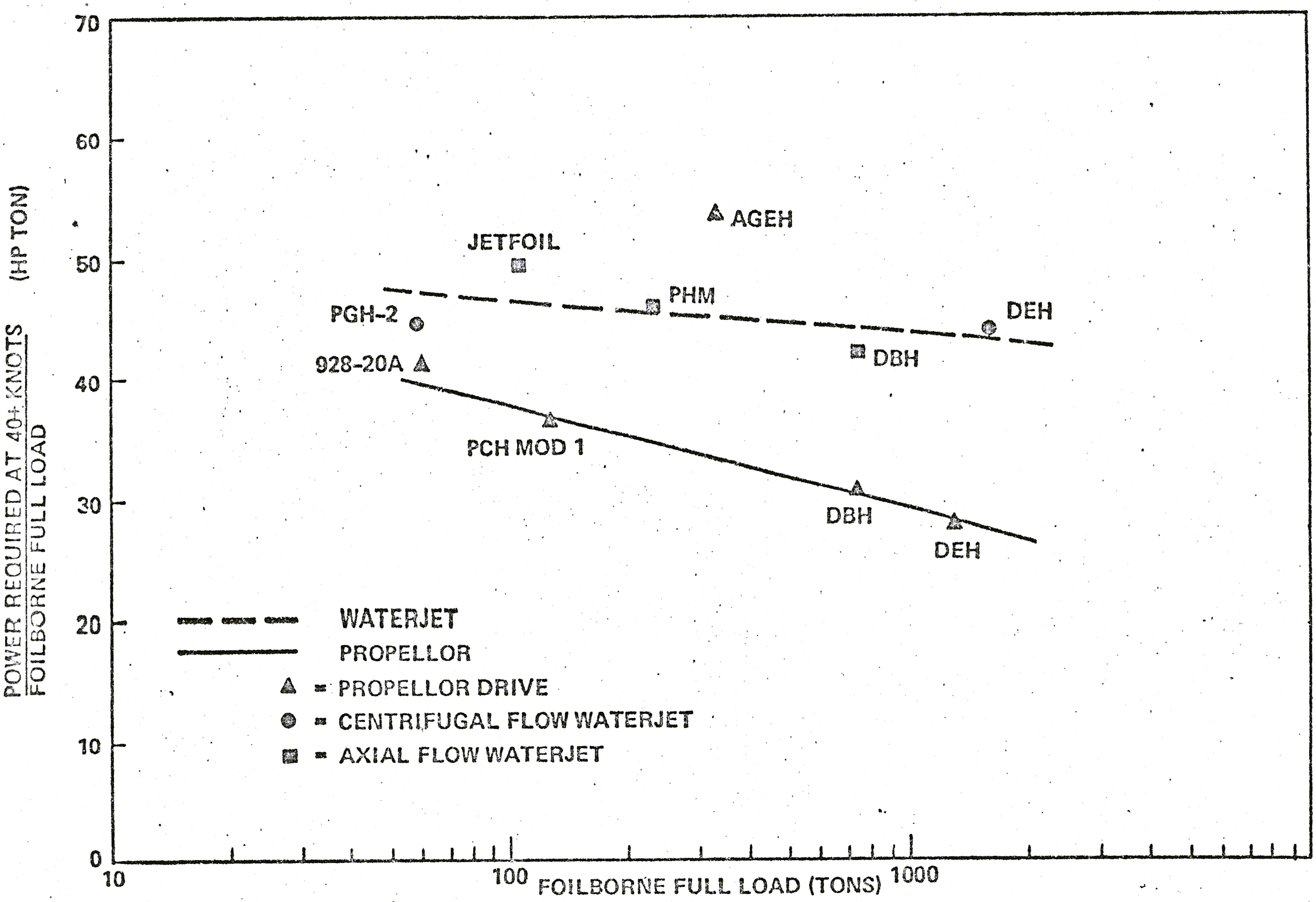

FIGURE 24

INTRINSIC CHARACTERISTICS – USEFUL LOAD

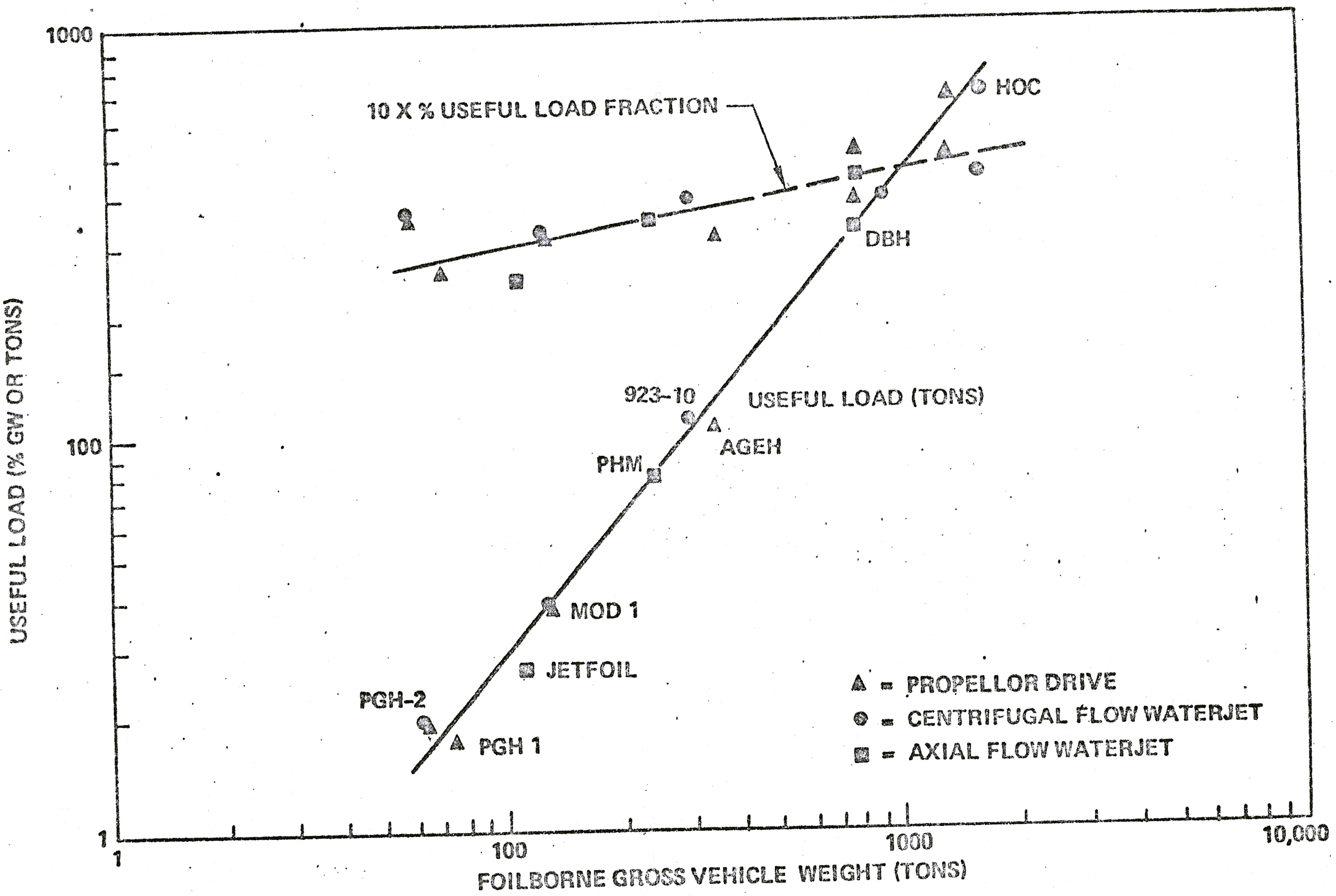

FIGURE 25

INTRINSIC CHARACTERISTICS – FUEL WEIGHT FRACTION

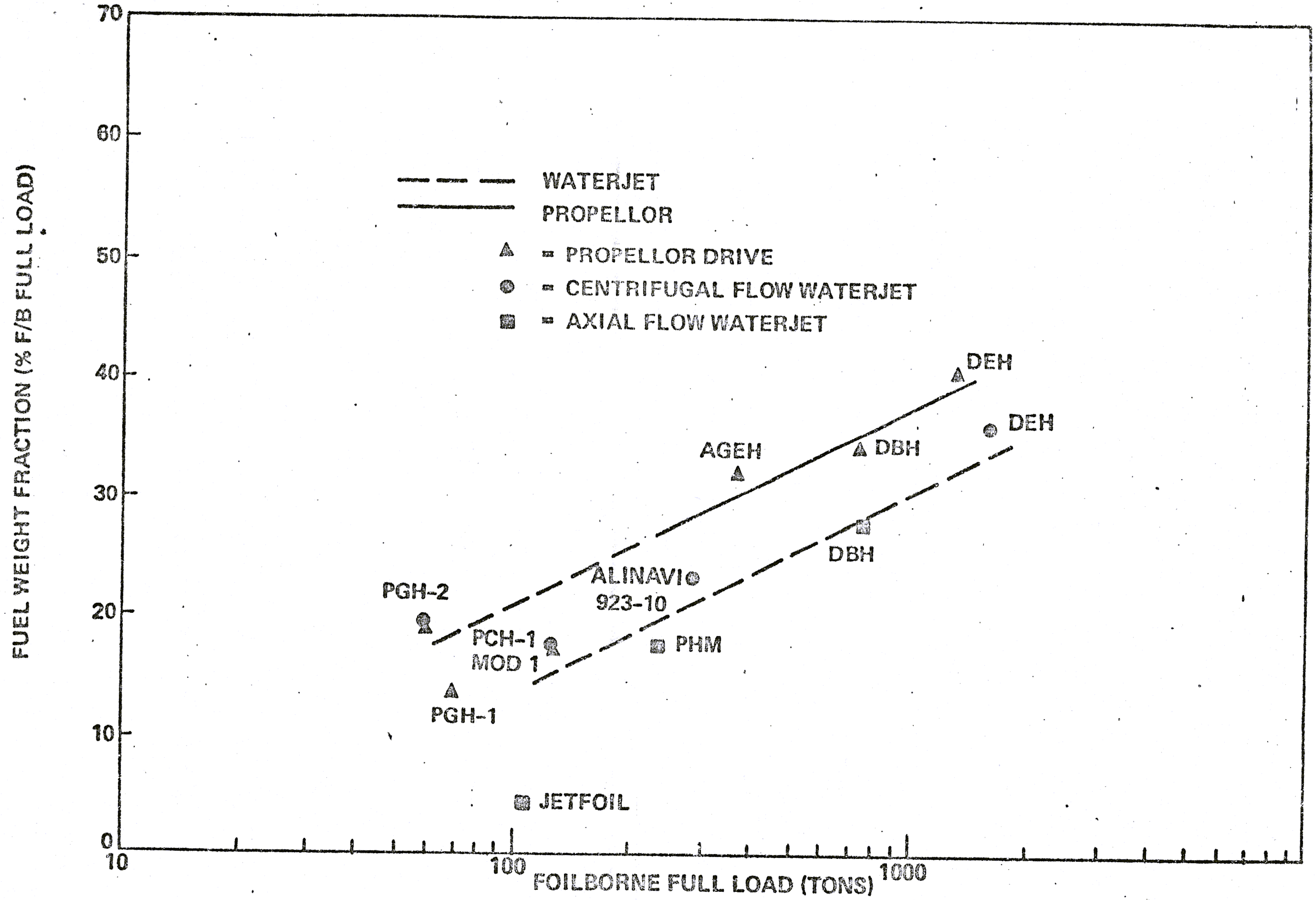

FIGURE 26

designed to a specified weight, increases in fixed systems weight will generally require that variable weights such as fuel or payload be reduced. It is also noted that the JETFOIL data point in Figure 25 is unusually low in comparison with all other craft. This is due to the commercial nature of the ship wherein high endurance is not a high value characteristic as compared to passenger capacity.

The increases in either useful load or fuel load trends with increasing hydrofoil ship size are consistent with the increase in transport efficiency which occurs with increasing size in other ships. It is possible to cite the same factors as general contributors to the increase in fuel or payload weight fraction with ship size. First, and possibly most general, is the increase in ship lift-to-drag ratio with size. Secondly, with the exception of the strut/foil group, most weight groups benefit from "overhead" reductions inherent in increasing ship size.

For propeller-driven ships the propulsive plant weight fraction decreases with ship size. Also, the buoyancy of struts and foils grows. Considering volume-limited designs, more useable tankage volume becomes available as hull structural efficiency increases and propulsion machinery tends to become proportionally smaller with increases in scale. Although the contributions to load carrying ability of these trends may not be dedicated to increasing payload or fuel load in a particular ship design, they are available for such application if desired.

It is recognized that definitive discussion of the effect of fuel weight or payload weight fractions should consider the effect of varying each of these parameters independently. It must also be recognized that in most hydrofoil design instances payload and range requirements are specified design goals. In this sense, fuel and payload weight fractions result from many design trade-offs rather than act as controlling factors in the design process. Meaningful discussion of the impact of such design trades is beyond the scope of this current study. In the present case it is sufficient to state that transport efficiency will increase with increasing hydrofoil ship size. Whether the efficiency increase is used to provide increased craft range or increased payload capacity remain as a design option.

5.1.5 Craft Range

Range or endurance at given craft speed was introduced as a primary measure of overall craft efficiency. The subsequent discussions have considered the effect of ship size on the various parameters which are included within the range equation. Reflecting on the trends noted in the discussion of lift-to-drag ratio, propulsive efficiency and fuel weight fraction, it can only be concluded that the specific range of hydrofoil ships should also increase with size. The specific range data of Figure 27 for the study group of hydrofoil ships support this conclusion. The data support the original contention that hydrofoil ship performance should improve with increasing ship size.

Before continuing with a discussion of other factors which may be of influence in hydrofoil ship performance some additional comments are necessary in regard to the study group data of Figure 27. Trend lines are shown for both waterjet and propeller-driven ships. Comparative studies have shown that the disparity between the two curves is primarily the result of differences in propulsive efficiencies. The AGEH-1 data point is indication of the penalties which must be paid with use of low efficiency foil systems. The PCH-1 data point of Figure 27 summarizes the loss in craft available performance which can occur with either propeller or waterjet propulsion systems when older, less efficient, engines with higher SFC values are installed.

INTRINSIC CHARACTERISTICS – RANGE FACTOR

F/B LOAD AT 0.5 FUEL
40+ KNOT ENDURANCE W/O BURN OFF

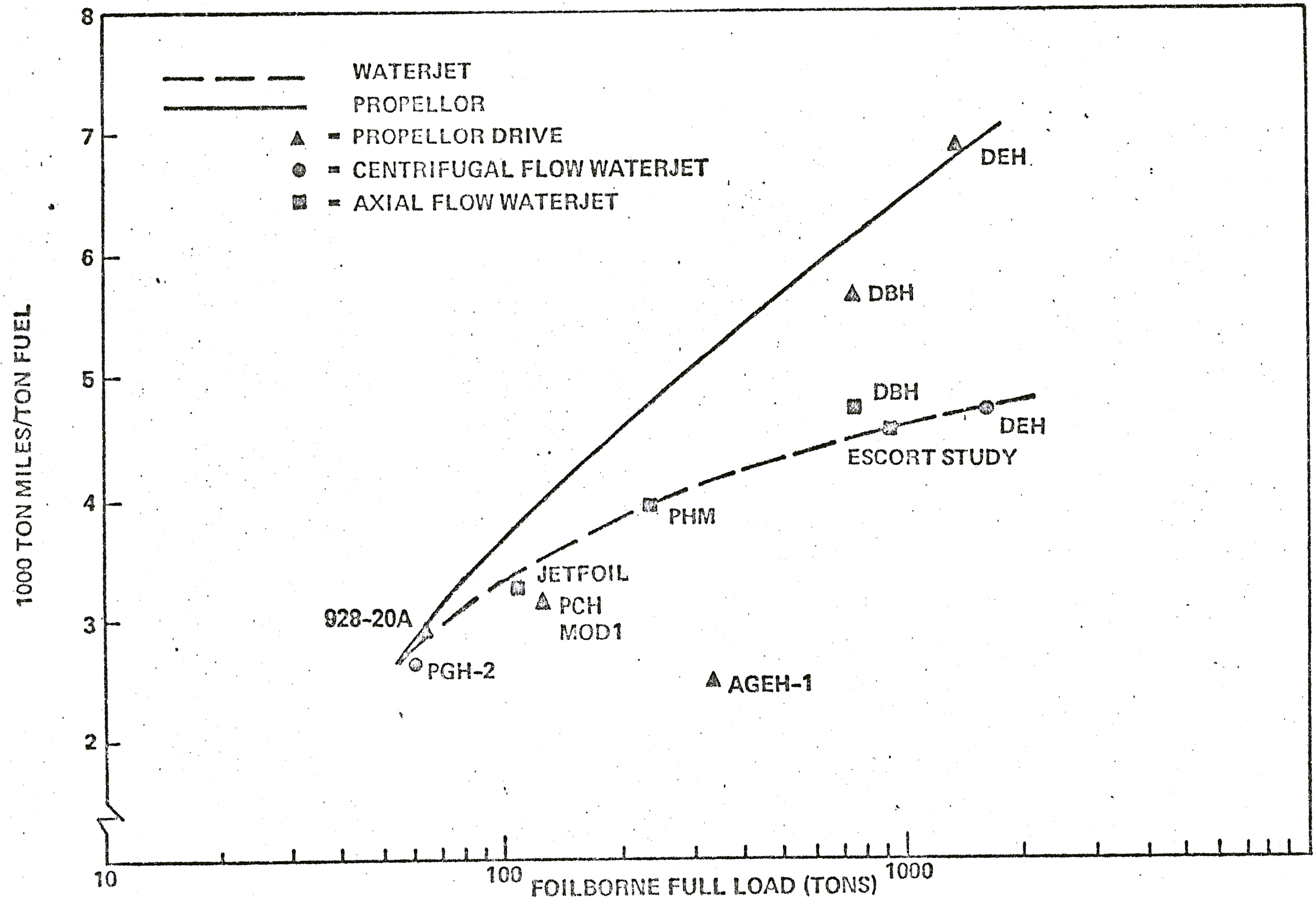

FIGURE 27

5.2 CONCLUDING REMARKS

In the accomplishment of a major advance in ship development designers are faced with an enormous range of ship configurations. In such a situation, the project manager must often choose between exhaustive parametric studies or a point design approach. The range of options is even greater for top level decision people who must compare, on a consistent basis, approaches as varied as say hydrofoil and SES ships. The data discussed in Section 5.1 represents only a small portion of the total data required to describe a ship even at the concept design level if we are to have confidence in our future predictions as they relate to our ship performance.

In order to produce these types of data quickly as well as permitting the designer to examine sensitivities and trades one obviously looks to digital computation techniques as a solution. The U.S. Navy saw the need for such a tool in 1973 and undertook the development of a program called HANDE (Hydrofoil ANalysis and DEsign Program). The first phase of this program, the Initialization Module, has been delivered to the U.S. Navy and has been used satisfactorily by both NSRDC and NAVSEC. This portion of the program employs parametric methods and a digital data bank of existing hydrofoil ship information to determine quickly the gross hydrofoil ship characteristics required to meet the specified mission requirements.

A second phase, the synthesis portion, is expected to be available by the end of the year. This portion of the program employs analytic methods to refine the design and provide a more detailed definition of the ship than has been possible heretofore at this stage of ship design. The approach taken assures that all the diverse technologies involved in ship design are considered, in order to produce a balanced, well integrated design. The use of this tool often discloses effects of one technology on the total system performance that go unnoticed when more insular manual methods are employed. It now becomes possible to consider a much wider range of candidate hydrofoil ship configurations, each at a more detailed level than is possible for other advanced ship types.

It is the opinion of the writer that this program will be of inestimable value in the forthcoming major ship option study recently directed by the Department of Defense. It will also continue to provide a rapid and accurate examination option to operational planning or evaluation personnel to compare like or different advanced ship types.

It should be apparent from the time spent on Sections 3 and 4 in this lecture that the author has very strong feelings on the importance of seakeeping in war ships. Since the writing of this lecture was begun, one milestone event has taken place in that a major seakeeping workshop was held under the auspices of NAVSEA at the Naval Academy in mid June. The purpose of the conference was to develop a multi-year plan for improving the state-of-the-art of technology necessary for achievement of major improvements in seakeeping and integrate these in the ship design process. Formal workshop sessions were held to characterize the environment, define methods for characterization of ship responses to the environment, describe human responses and human performance limits, describe total ship system and subsystem response to the environment, and to characterize ship system requirements and limitations in terms of the environment.

I trust that this work will continue and also become an important part of the Department of Defense analysis mentioned previously. In the meantime one can not help but note that the hydrofoil ship seems to stand alone today, not only in its demonstrated seakeeping capabilities, but also in demonstrated analytical methods for prediction of and design for good seakeeping characteristics. There is today in the hydrofoil data bank, more measured data on hydrofoil responses to the sea environment than possibly exists for all the rest of the ship designs in the U.S. Navy.

Over the short span of intensified hydrofoil development (approximately 16 years) detailed programs have been developed for analtyically predicting ship responses and for designing to minimize these responses to the sea environment. Additionally, a system has been developed to measure the sea environment accurately from onboard the moving ship, and detailed studies have been conducted which assess the degree of correlation between the analytical predictions and actual shipboard measured responses. These studies in turn have led to more sophisticated, more accurate prdiction tools, which in turn lead directly to better seakeeping designs. It is hoped that the entire marine community can soon implement similar programs to the end of a large betterment of design for seakeeping in naval combatant ships.