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A Comparative Analysis of Naval Hydrofoil and Displacement Ship Design

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Hydrofoils are smaller, carry more payload relative to their size, and are faster than conventional displacement ships. The hydrofoil's performance advantage is achieved by incorporating design standards which save weight and space throughout the ship. Differences in the design standards of hydrofoils and displacement ships are described for the main propulsion, electrical and auxiliary systems, structure, habitability, and other ship systems by analyzing two hydrofoils, PHM and HOC, and two displacement ships, PG-84 and FFG-7. The design standards of the hydrofoils result in significant weight and volume savings at the expense of decreased ship operability. A displacement ship designed to hydrofoil design standards shows a remarkable improvement in calm-water speed and payload capacity. The comparison of the resultant high-performance displacement ship with the hydrofoil reveals that the high-performance displacement ship has superior range and endurance at slow speeds and payload capacity, but inferior speed and motion characteristics in high sea states. The principal conclusion of the paper is that differences in subsystem design standards must be taken into account in any vehicle assessment since the subsystem standards have a first-order effect on the vehicle characteristics as well as on the overall performance.

Introduction

IN THE PAST TEN YEARS, advanced marine vehicles such as the hydrofoil, surface effect ship (SES), air cushion vehicle (ACV), and small waterplane area twin-hull (SWATH) ship have reached sufficient technical maturity to attract serious consideration for military applications. As a result of this interest, there has been an increased amount of effort directed to develop means of comparing different types of vehicles for the purpose of determining which vehicles truly improve the capabilities of the Navy.

From their experience as ship designers and operators of naval ships, the authors have observed that there are a number of major differences in performance capabilities and design standards between conventional displacement ships and the new family of advanced marine vehicles frequently referred to as "high-performance ships." As a group, the high-performance ships are smaller, faster, and carry more payload relative to their size than conventional displacement ships. One of the purposes of this study was to identify the principal design differences between conventional displacement ships and high-performance ships and to relate these design differences to the disparity in such basic performance features as speed and payload capacity.

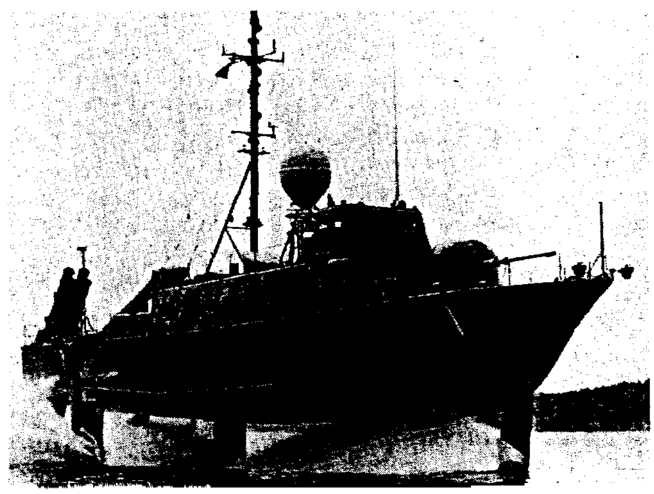

Fig. 1 231-ton NATO hydrofoil, PHM

At the outset of the study it became apparent that the conventional displacement ship incorporated design standards which appeared to be conservative in many respects when compared with those characteristic of the high-performance ships. Because weight is more critical to the high-performance ships, a greater weight-consciousness is evident in their design standards. This observation leads to two important questions: What has the high performance ship designer traded off in order to achieve this weight savings? How would a displacement ship perform if designed to high-performance ship standards?

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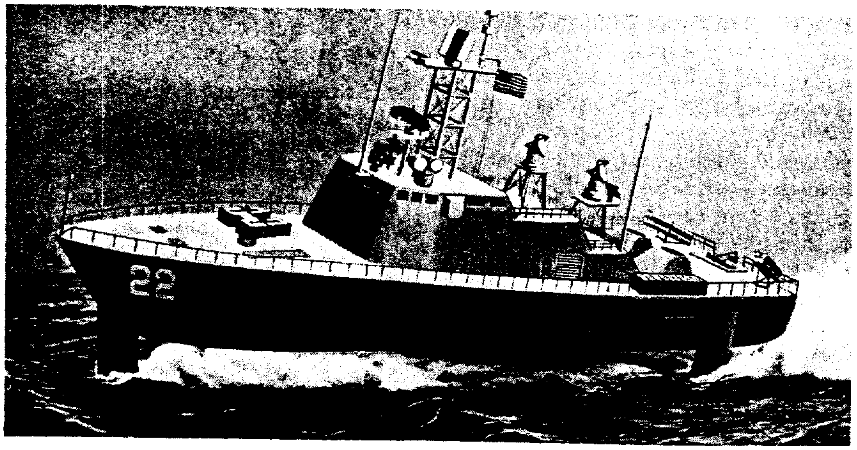

Fig. 2 Proposed **1275-ton** Hydrofoil Ocean Combatant, HOC

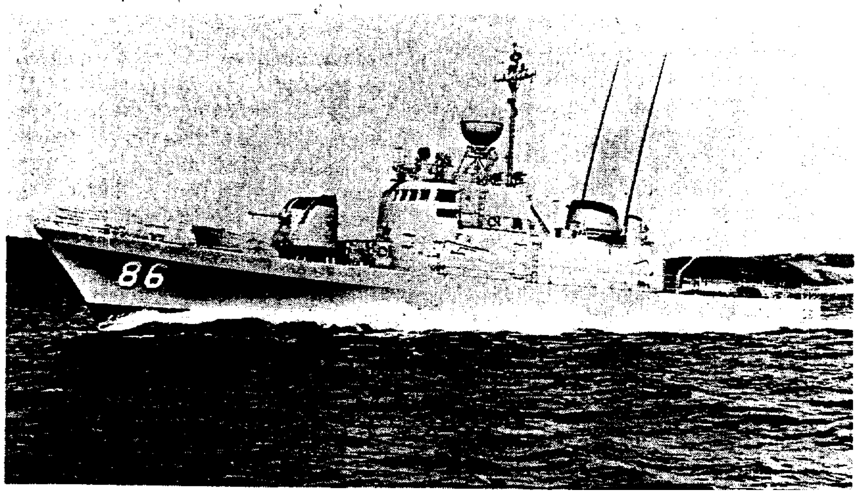

Fig. 3 **242-ton** PG-84 Class patrol gunboat

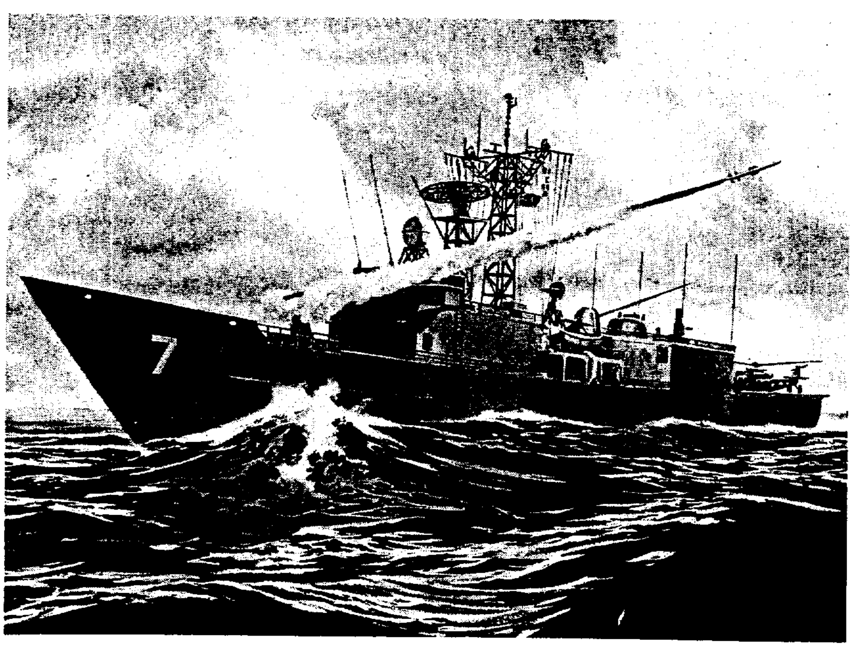

Fig. 4 **3585-ton** guided-missile frigate, FFG-7

Based on these preliminary observations, the authors established the following objectives for the study:

- To investigate the principal tradeoffs associated with the design practices of high-performance **and** conventional displacement ships; that is, to determine the impact of design differences on the naval architectural features (such as weight and space) and the overall performance of naval ships.
- To present a comparison of the conventional displacement ship, high-performance ship, and displacement ship designed to high-performance standards.
- To demonstrate the importance of taking differences in design standards into account when assessing the military worth of different types of vehicles.

Small surface combatants were selected to represent the conventional displacement ship design practices, since they come closest to high-performance ships in size and mission. Two ships were analyzed: the 242-ton PG-84 class patrol gunboat and the 3585-ton guided missile frigate, FFG-7. Hydrofoils were selected to represent the high-performance ship design practices primarily because of the lack of design data available **for** any other type of advance marine vehicle configured as a warship. Two hydrofoil designs, the existing 231-ton NATO hydrofoil, PHM, and the proposed 1275-ton Hydrofoil Ocean Combatant, HOC, were analyzed. Figures 1 through 4 depict these four ships.

In order to accomplish the foregoing objectives it was first necessary to develop analytical procedures to identify design differences in naval ships in a consistent and quantitative manner. Toward this end, a set of design indices was developed which not only provided an indication of the design standards but also provided a means of estimating the weight and internal volume impact of these standards. With these indices, a conventional displacement ship was "redesigned" to high-performance ship standards. The resultant "high-performance" displacement ship was then compared with the conventional displacement ship and the hydrofoil and major design tradeoffs were identified.

This paper provides a condensation of the material contained in references [1][4] and [2], and therefore will only highlight the principal findings. First, the analytical approach used in identifying and then determining the impact of design differences of displacement ships and hydrofoils is described, followed by the results of the analysis. Differences in design standards related to seven features (main propulsion, electrical and auxiliary systems, ship structure, habitability, ship systems, and other ship operation systems) are presented. An analysis of these features reveals that the hydrofoils have incorporated design standards which result in substantial weight and space savings at the expense of decreased ship operability. The characteristics of a high-performance displacement ship (displacement ship designed to hydrofoil standards) are then presented and compared with those of conventional displacement ships and hydrofoils. Finally, the conclusions of the study are summarized.

It should be pointed out that the paper does not address the impact of the design differences on ship acquisition or life-cycle costs. Reliable cost data were not available to the authors to permit this. The paper also does not present a quantified comparison of the seakeeping performance of hydrofoils and displacement ships. Although the differences in hydrofoil and displacement ship basic performance capabilities and design standards are presented, the authors make no attempt to draw conclusions as to which vehicle is "better." A complete system analysis based on established operational scenarios would be required to make such an assessment.

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

Analytical approach

Overall approach

As mentioned in the Introduction, an analytical technique was required to identify and then determine the impact of design differences between naval hydrofoils and displacement ships. The overall approach involved three steps:

- Identification of design differences by use of a set of quantitative design indices.
- Analysis of the tradeoffs between hydrofoil and displacement ship design practices and the selection of hydrofoil design standards which could be applied to the high-performance displacement ship.
- Redesign of the displacement ship to hydrofoil design standards.

Each of these steps is discussed in the following sections.

Identification of design differences

The identification of design differences was accomplished by developing a set of design indices which described the important design features of naval surface combatants. In developing this set of design indices, the following three factors were considered:

- Indices must be quantitative.
- Indices must provide a meaningful indication of the ship's operational performance requirements, design philosophy, and design standards/criteria.
- Indices must be relatively simple to calculate and analyze.

Numerous design indices/parameters have been developed by ship designers to describe the physical characteristics and performance of ships. The indices discussed in this paper represent a set of parameters which were developed for the specific purpose of analyzing design differences between two types of naval ships. After first determining the design features of naval ships to be analyzed in **this** study, the authors developed indices which could be placed in the following six categories:

- Gross *characteristics*. Gross characteristics describe the size and shape, the mobility, and the payload features of the ship, and provide an indication of the type and capacity of some of the more important ship features. This category of design index provides the overall description of the physical characteristics and top-level operational capabilities of the ship and is certainly familiar to ship designers. Examples of gross characteristics include:

  Full load displacement, Δ
  Total internal volume, ∇
  Maximum sustained speed, V_s
  Range, R
  Complement, M
  Listing of major weapons

A complete list of the design indices referred to as gross characteristics is presented in the Appendix.

- *Functional allocation.* A ship designer often divides a naval ship into a number of functions for the sake of focusing his attention on ship features which have similar purposes. A common technique used in comparing one ship with another is to determine the weight and space allocated to these functions as a percentage of total ship weight and internal volume. The allocation of weight and space to the various functions provides an indication of the relative priorities of these functions. Figure 5 presents the functional breakdown used in this study. Typical examples of weight and volume fractions include:

  Payload weight fraction, W_P/Δ
  Payload volume fraction, ∇_P/∇
  Structural weight fraction, W_H/Δ

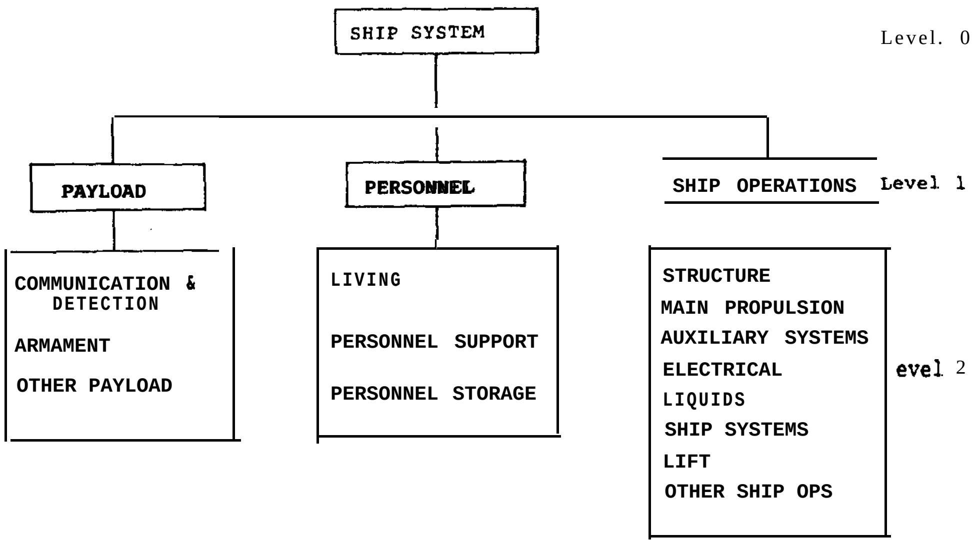

Fig. 5 Functional breakdown of naval ship

W_P, W_H = payload and structural weights
∇_P = payload volume
Δ, ∇ = full-load displacement and total internal volume

The Appendix contains a detailed listing of the weight and space groups which were considered part of each function as well as a tabulation of all of the weight and volume fractions used in this study.

• ***Weight density.*** It is well known that the size of certain ships is governed by weight (weight-limited ships) and the size of others by internal space (volume-limited ships). The weight density of the ship and of certain ship functions provides insight into whether a ship is weight or volume limited and which features are dominating the design. In addition, weight densities are convenient parameters for checking that there is a balance between the weight and space requirements of ship features. Some of the weight densities used in this study include:

Ship density, Δ/∇
Payload density, W_P / ∇_P
Main propulsion plant density, W_{MP}/∇_{MP}

where

W_P, W_{MP} = payload and main propulsion weights
∇_P, ∇_{MP} = payload and main propulsion internal volume
Δ, ∇ = full-load displacement and total internal volume

A complete listing of weight densities is provided in the Appendix.

• ***Specific ratios.*** A good indication of the design standards/criteria which were applied to certain ship features can be provided by analyzing design indices referred to as specific ratios. In general, specific ratios represent the "cost" associated with a ship feature divided by the "capacity" of the feature. In this study the direct weight and volume requirements of the features were used to quantify the cost of incorporating the feature into the ship. The capacity, of course, varies with each feature. Following are a few examples of specific ratios:

Main propulsion specific weight ratio, W_{MP}/SHP
Main propulsion specific volume ratio, ∇_{MP}/SHP
Personnel specific volume ratio, ∇_M/M
Auxiliary systems specific weight ratio, W_{AX}/∇

where

W_{MP}, W_{AX} = weights of main propulsion plant and auxiliary systems
∇_{MP}, ∇_M = internal volumes allocated to main propulsion plant and ship's personnel
SHP = installed propulsive power
M = ship's complement
∇ = ship's internal volume

In each case the capacity of the feature is represented by the parameter which most directly drives the weight and volume requirements of the feature. In several cases, the ship's internal volume is such a parameter. The Appendix provides a complete listing of specific ratios used in this study.

• ***Capacity/ship size ratios.*** It is frequently more meaningful to indicate the "capacity" of a ship feature in relationship to the size of the ship rather than in absolute terms. Capacity/ship size ratios provide insight into how much of a certain feature the designers *were* willing to incorporate into the ship relative to its overall size. Examples of capacity/ship size ratios include:

Manning ship size ratio, M/Δ
Main propulsion ship size ratio, SHP/Δ
Electrical ship size ratio, KW/Δ

where

M = ship's complement
SHP = installed propulsive power
KW = installed electrical power
Δ = full-load displacement

• ***Overall vehicle performance.*** Nearly every paper on the subject of vehicle comparison makes reference to the paper by Gabrielli and von Karman [3] in which the authors presented the parameter now known as the transport efficiency. The transport efficiency and the closely related lift/drag ratio were used in this study to compare the hydrodynamic performance of hydrofoils and displacement ships. These parameters are defined as follows:

Transport efficiency, $\Delta V/SHP$
Lift/drag ratio, L/D

where

Δ = full-load displacement
V = vehicle's speed
SHP = propulsive power (including lift power) required at speed, V
L = vehicle lift equal to total weight
D = total drag force of vehicle

A very large number of indices may be defined in the manner outlined in the foregoing paragraphs. In order to take full advantage of these indices, it is necessary to analyze them in steps, focusing attention on particular ship features in a systematic manner. The first step in this study consisted in analyzing the Level 1 indices of each type. This overview provided the first indication of design differences and pointed the way to areas which required further investigation. The second step consisted of a reorganization of the indices by ship features. The Appendix lists the design indices considered for the eight features which became the focus of the study; namely, main propulsion, electrical, auxiliary systems, personnel, payload, ship structure, ship systems, and other ship operations. In this step more detailed design indices were often defined and quantified to identify the cause of the design differences. See the Appendix for a complete listing.

Since the result of analyzing these indices for two displacement ships and two hydrofoils are presented later, no further explanation of the methodology for interpreting them is presented. The discussion of the results serves as an example of the application of this analytical approach and thus provides further insight into the methodology.

Analysis of design tradeoffs

After identifying differences in the design of hydrofoils and displacement ships by means of a set of design indices, the next task consisted of analyzing the major tradeoffs associated with these differences. In almost every case, the hydrofoil design standards resulted in a savings in weight and internal volume. The weight and space savings associated with each design difference were estimated by taking the difference of the appropriate specific ratio and multiplying by the associated displacement ship capacity parameter. For example, the weight saved by incorporating the hydrofoil's electrical plant design standards into the displacement ship was estimated as follows:

Electrical plant weight savings

$$= [(W_E/KW)_D - (W_E/KW)_H]KW_D$$

where

$(W_E/KW)_D$ = conventional displacement ship's electrical specific weight
$(W_E/KW)_H$ = hydrofoil's electrical specific weight
KW_D = conventional displacement ship's installed electrical capacity

Judgment was used in selecting the values for the hydrofoil specific ratios to be applied to the displacement ship. In some cases a more conservative value was used, reflecting differences in displacement ship geometry or mode of operation. On the other hand, lower values of specific ratios were selected to reflect the fact that the displacement ship did not require certain systems associated directly with the foil system. As was noted in the Introduction, the "cost" impact of incorporating hydrofoil standards was only expressed in terms of ship weight and internal volume. Neither acquisition nor life-cycle costs were addressed in a quantitative manner.

The performance impact of incorporating hydrofoil design standards into a displacement ship was not as straightforward as the weight and volume impact and could not be accomplished in a quantitative manner, In nearly all cases it was felt that the hydrofoil design approach could produce the required "basic" performance of the particular feature in question. In most cases, however, it was felt that the high-performance standards reduced the operability of the ship. In this study the word "operability" was used to include the following:

- Reliability, maintainability, availability
- System flexibility
- Ease of operation by crew
- Specialized support requirements
- Specialized crew training
- System lifetime
- Noise and vibration impact on ship
- System compatibility and ease of integration with the ship

Operability is not a performance area which can be easily quantified, and consequently its impact on overall ship performance was addressed only in a subjective fashion in this study. Because of the difficulty of addressing operability, most vehicle assessments ignore this performance feature. However, anyone with first-hand experience of operating naval ships at sea realizes that the operability of a ship is often more important to overall mission effectiveness than the basic performance features such as maximum speed or weapon firepower. One of the primary conclusions of this study is that operability is a ship performance feature which cannot be ignored in vehicle assessments.

A basic assumption made by the authors is that the operability of a ship feature is directly proportional to the weight and space allocation, provided similar types of equipment are utilized. To illustrate the validity of this assumption, take an electrical plant design using gas turbine prime movers which provides an installed capacity of 1000 KW, weighs 15 tons, and occupies 6000 cu ft of internal volume. If the weight and space budget of this 1000-KW gas turbine plant were increased significantly, the designer could

- Select a more lightly loaded electrical generator with higher inherent reliability and longer lifetime.
- Increase the redundancy of ancillary equipment and enhance reliability and system flexibility.
- Provide additional access space around the generator to enhance maintainability and ease of operation.
- Provide for more on-board repair parts and special tools and thus enhance maintainability.
- Provide sound and vibration isolation mounts to reduce ship noise.

No quantitative analysis was performed in this study to verify the assumption that operability is directly proportional to the weight and space allocation. As every designer knows, however, design is tradeoff, and therefore the assumption that performance for systems with similar component types is bound to decrease as the weight and space budget is decreased would appear to be valid. 'This assumption would then lead to the conclusion that the operability of hydrofoils is less than that of displacement ships. It remains to be shown, however, whether the hydrofoil designers or displacement ship designers have achieved the proper compromise between basic system performance and operability.

Design of high-performance displacement ship

After determining which hydrofoil design practices appeared to be feasible and attractive if applied to a displacement ship. the conventional displacement ship was then redesigned to the hydrofoil design standard. The resultant high-performance displacement ship represented what a displacement ship would

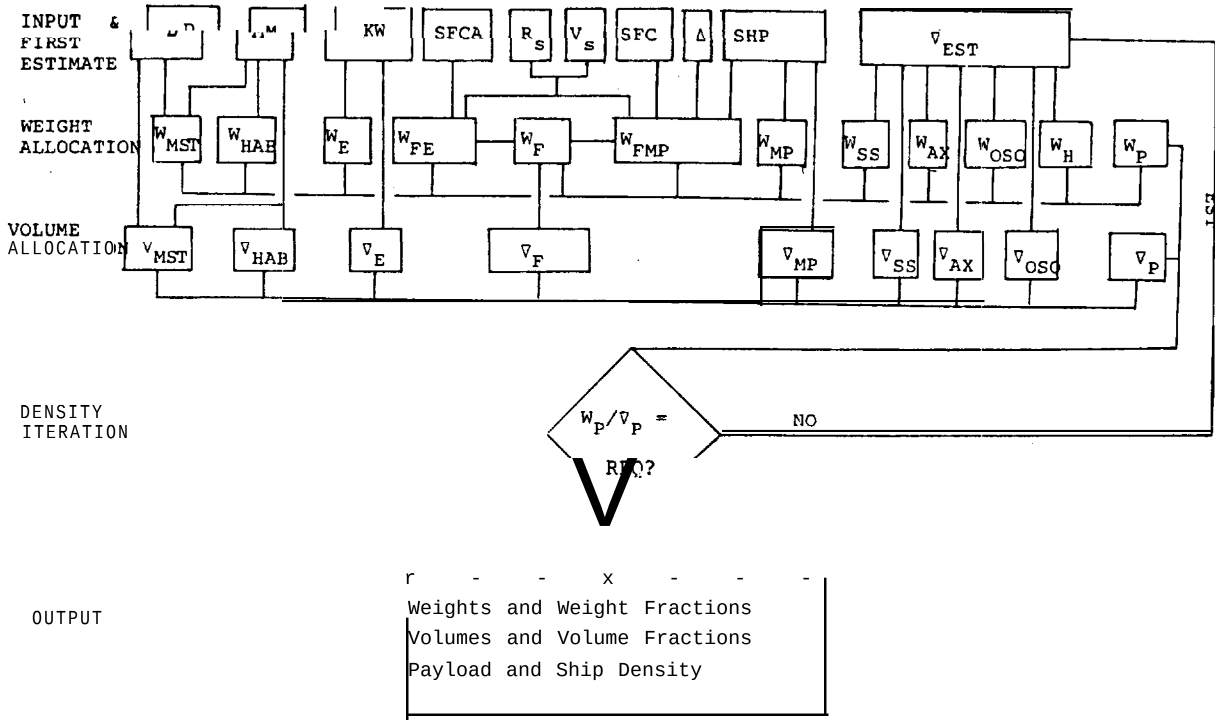

Fig. 6 Parametric model flow diagram

look like if designed to the same standards as typical high-performance ships. Through a comparison with both the hydrofoil and original conventional displacement ship, the overall impact of the differences in design approach was determined.

The model used to redesign the displacement ship was not a design model but a parametric model which altered the weight and volume allocation of a ship of fixed gross characteristics as design standards were varied. Figure 6 presents the flow diagram of this model.

The input to the model was the ship's gross characteristics:

Stores endurance, D (days)
Complement, M (men)
Installed electrical power, KW (kilowatts)
Electrical plant specific fuel consumption rate, $SFCA$ (lb/hp hr)
Range at maximum sustained speed, R_s (nautical miles)
Maximum sustained speed, V_s (knots)
Propulsion plant specific fuel consumption rate, SFC (lb/hp hr)
Full-load displacement, A (long tons)
Installed propulsive power, SHP (horsepower)

and the design standards quantized by 15 specific ratios and 3 weight densities:

Personnel/stores specific weight ratio, W_{MST}/MD (lb/man-day)
Habitability specific weight ratio, W_{HAB}/M (lb/man)
Electrical specific weight ratio, W_E/KW (lb/KW)
Main propulsion specific weight ratio, W_{MP}/SHP (lb/SHP)
Ship system specific weight ratio, W_{SS}/∇ (lb/cu ft)
Auxiliary system specific weight ratio, W_{AX}/∇ (lb/cu ft)
Other ship operations specific weight ratio, W_{OSO}/∇ (lb/cu ft)
Structural specific weight ratio, W_H/∇ (lb/cu ft)
Personnel stores specific volume ratio, ∇_{MST}/MD (cu ft/man-day)
Habitability specific volume ratio, ∇_{HAB}/M (cu ft/man)
Electrical specific volume ratio, ∇_E/KW (cu ft/KW)
Main propulsion specific volume ratio, ∇_{MP}/SHP (cu ft/SHP)
Ship system specific volume ratio, ∇_{SS}/∇ (cu ft/100 cu ft)
Auxiliary specific volume ratio, ∇_{AX}/∇ (cu ft/100 cu ft)
Other ship operations specific volume ratio, ∇_{OSO}/∇ (cu ft/100 cu ft)
Fuel density W_F/∇_F (lb/cu ft)
Payload density W_P/∇_P (lb/cu ft)
Ship density A/V (lb/cu ft)

After making the initial estimate of total internal volume from the relationship

$$\nabla_{EST} = A \cdot V/A$$

the weights of the ship functions were calculated from the following relationships:

Stores weight, $W_{MST} = W_{MST}/MD \cdot M \cdot D$
Habitability weight, $W_{HAB} = W_{HAB}/M \cdot M$
Electrical weight, $W_E = W_E/KW \cdot KW$
Electrical fuel weight,

$$W_{FE} = \frac{KW \cdot SFCA \cdot R_S}{V_S} \times \left(\frac{1.34}{2240}\right)$$

Main propulsion fuel weight,

$$W_{FMP} = A[1 - \exp(-R_s \cdot SHP \cdot SFC/A \cdot V_S \cdot 2240)$$

Total fuel weight, $W_F = (W_{FE} + W_{FMP})/TLPE$
Main propulsion weight, $W_{MP} = W_{MP}/SHP \cdot SHP$
Ship system weight, $W_{SS} = W_{SS}/\nabla \cdot \nabla_{EST}$
Auxiliary system weight, $W_{AX} = W_{AX}/\nabla \cdot \nabla_{EST}$
Other ship operations weight, $W_{OSO} = W_{OSO}/\nabla \cdot \nabla_{EST}$
Structural weight, $W_H = W_H/\nabla \cdot \nabla_{EST}$

The payload weight carrying capacity of the ship was then computed by subtracting the sum of the weights of the above functions from the full-load displacement.

The internal volume requirements of the ship functions were calculated in a similar manner from the relationships:

Personnel stores volume, $\nabla_{MST} = \nabla_{MST}/MD \cdot M \cdot D$
Habitability volume, $\nabla_{HAB} = \nabla_{HAB}/M \cdot M$
Electrical volume, $\nabla_{E} = \nabla_{E}/KW \cdot KW$
Fuel volume, $\nabla_{F} = \nabla_{F}/W_F \cdot W_F$
Main propulsion volume, $\nabla_{MP} = \nabla_{MP}/SHP \cdot SHP$
Ship system volume, $\nabla_{SS} = \nabla_{SS}/\nabla \cdot \nabla_{EST}$
Auxiliary system volume, $\nabla_{AX} = \nabla_{AX}/\nabla \cdot \nabla_{EST}$
Other ship operations volume, $\nabla_{OSO} = \nabla_{OSO}/\nabla \cdot \nabla_{EST}$

The internal volume which can be devoted to payload was then computed by subtracting the sum of the volume requirements of the foregoing functions from the estimated total ship volume.

The calculations were iterated until suitable ship and payload weight densities were obtained. The hydrofoil's payload density or ship density could be held constant or values could be selected to represent a reasonable compromise in between the two. The output of the model contained the new functional weights and volumes, functional weight and volume fractions, and densities. The height of the center of gravity of the payload was estimated keeping the ship's original vertical center of gravity and the center of gravity of each of the ship functions unchanged.

The model is extremely simple in concept and application and is based on a number of simplifying assumptions. In order to appreciate the limitations of the model, the following points deserve some discussion:

- The model does not differentiate among tankage, arrangement space, and large object space and assumes that a satisfactory internal arrangement can be achieved provided sufficient internal volume has been allocated to each function.
- The mode1 does not calculate the longitudinal weight distribution and ignores the impact of such on the longitudinal center of gravity and structural loading.
- The model does not design any of the subsystems or ship functions but merely estimates their weight and volume requirements by means of appropriate specific ratios. Thus it is assumed that the weight and space requirements for all of the ship features are continuous rather than discrete functions.
- The model assumes that the underwater hull dimensions and shape of the high-performance displacement ship are the same as those of the baseline ship. Thus the powering requirements are not affected.
- The support requirements (electrical power, auxiliary systems and manning) for the original design payload are taken into account by the input characteristics and specific ratios. Any payload weight or volume increase over the original design payload must include the support requirements for this increase. For example, if a SO-ton increase in payload was achieved, this 50 tons must be allocated to military payload plus the personnel and support systems required by this payload. This is an important assumption since the systems comprising military payload require support whereas the "inert" ship features such as structure and fuel do not.
- The model assumes that weight and internal volume can be interchanged among any ship feature. This perhaps is the most important assumption and the one which most severely limits the validity of the model.

As explained later, the authors are fully cognizant of the fact that the foregoing model does not guarantee that the resultant characteristics of the high-performance ship are completely feasible. Further studies are required first to determine the hydrofoil design standards which realistically can be applied to the displacement ship. Secondly, a new design must be synthesized from the established performance requirements and design standards. The ship design process is far too interrelated in character to permit the production of a ship design by means of parametric models.

Study results

The principal results of the study carried out in accordance with the analytical approach previously outlined are presented in this section. First, the most significant design differences between hydrofoils and conventional displacement ships are discussed. Next, the potential weight and internal volume impact and the expected effect on ship operability associated with these design differences are presented. Finally,. the high-performance displacement ship is described and compared with the original hydrofoil and conventional displacement ship, and the most important observations are summarized.

Considerable thought went into the selection of the ships to be analyzed to insure that the authors would not bias their findings. The first criterion was that the ships should have been designed as combatants as opposed to test beds for research and development purposes. This limited the hydrofoil population significantly. It was also recognized that differences in ship size would influence the ship comparisons, At the small end of the spectrum, the 231-ton NATO hydrofoil (PHM) was chosen. The.PHM is a small, gas-turbine-powered ship with

Nomenclature

W_n = weight of a functional category, where n is a subscript defining the category
V_n = volume of a functional category
A = full-load displacement of ship, tons
D = stores endurance period, days
KW = installed electrical generation capacity, kilowatts
M = total crew size
NA = number of installed armament systems
PC = propulsive coefficient
R_s = range at maximum sustained speed, nautical miles
SFC = specific fuel consumption rate of main propulsion machinery, pounds of fuel/SHP-hr
$SFCA$ = specific fuel consumption rate of electric plant, pounds of fuel/HP-hr
SHP = installed propulsive power
$TLPE$ = tailpipe allowance for fuel requirements
V_s = maximum sustained speed, knots
V = total enclosed volume of ship, cu ft

Subscripts

A = armament
AX = auxiliaries
CD = communications/detection
E = electrical
F = fuel
FE = electric plant fuel
FMP = main propulsion fuel
H = hull structure
HAB = habitability
L = lift systems
M = personnel
ML = personnel living
MP = main propulsion
MS = personnel support
MST = personnel storage
OP = other payload
OSO = other ship operations
P = payload
SO = ship operations
SS = ship systems

Table 1 Comparison of characteristics

	PC-84	PHM	FFG-7	HOC
Size				
(tons)	242	231	3,585	1,275
(ft^3)	48,600	45,500	514,900	227,100
Structural material				
Hull	aluminum	aluminum	steel	aluminum
Deckhouse	fiberglass	aluminum	aluminum	aluminum
Personnel				
Complement	24	21	176	87
Stores endurance, days	14	7	45	30
Mobility in calm water				
V_s (knots)	-40	40+	28+	40+
Range @ V_s (NM)	-500	700+	-2,000	-2,400
Range @ V (NM)	~2,000@20	1,700+@9	~4,500@20	3,500+@ 15
Propulsion machinery				
Type	CODAG	CODAC	GT	COGOG
SHP	14,750	17,340	40,000	47,000
Payload				
Weapons	one 3-in./50	one 76-mm	one 76-mm	two standard launchers
	two 50 cal	two standard launchers	one MK13 GMLS	two vertical launchers
	one 40-mm		two lamps	one NATO Sea Sparrow
			two MK 32 TT	two MK 32 TT
			one 20-mm CIWS	
Year operational	1964	1976	1977	1985 (estimated)

a small crew and limited endurance configured primarily for a mission of surface warfare. The lead ship of this class is currently undergoing test and evaluation by-the U. S. Navy. For a larger ship, the Hydrofoil Ocean Combatant (HOC) was selected. The HOC is a 1275-ton multimission ship with an endurance sufficient for ocean area operations. The HOC is only in the conceptual design stage and therefore only a limited amount of design detail was available.

Having selected the hydrofoils to be examined, the candidates for displacement ships to use as yardsticks for comparison *were* examined. Two displacement ships of similar size and military mission and designed in approximately the same period of time as the PHM **and** HOC were desired.

The PG-84 class of patrol boat was selected for comparison with the PHM. A 242-ton ship capable of calm-water speeds of approximately 40 knots, it provided a close match to PHM in both size, speed, and military mission.[5] However, the PG-84, built in the period between 1960 and 1970, does reflect a 10-years-older technology. The U. S. Navy does not have a more recent design in this size range.

Selection of the counterpart for the HOC was not as straightforward as there are no recent U. S. Navy designs in the 1300-ton range. The smallest current displacement ship design is the new guided missile frigate (FFG-7) presently under construction. This multimission ship displaces approximately 3500 tons or nearly three times that of the HOC and has a maximum sustained speed which is considerably slower than the HOC. This disparity in size and speed for the same general mission requirements provides a visible indication of the differences in design practices between these two types of vehicles. Since the FFG-7 is under construction and the HOC is only in the conceptual design phase, there is about a 7-year difference in design periods. As pointed out later, the lack of detail in the HOC design documentation hindered the comparison. These four ships are pictured in Fig. 1 through 4 and their principal characteristics are listed in Table 1.

Identification and analysis of design differences

The first step in the analysis consisted in the identification of design differences between the hydrofoils and displacement ships. First, the most significant differences observed after comparing the Level 1 design indices of each category are discussed. The results of the analysis of **seven** ship functions, including main propulsion, electrical, auxiliary system, structure, personnel, ship systems, and other ship operations, are then presented. In order to conserve space, only the results of the main propulsion comparison are presented in any detail. In addition, the design differences which lead to savings in ship weight receive more attention than those impacting on ship internal volume since high-performance ships are weight limited. After identifying the principal design differences for each of the seven functions, the impact on ship weight and space and on ship operability is discussed.

Overall design differences. A review of the principal characteristics (Table 1) 'of the two hydrofoils and two displacement ships leads to the following observations:

- The PG84 and PHM are similar in size whereas the FFG-7 is a ship of nearly three times greater displacement than the HOC.
- The complements of the displacement ships are larger, and the stores' endurance longer, than the corresponding hydrofoil.
- The PHM has a moderate speed advantage in calm water over the PG-84, and the HOC a very substantial speed advantage over the FFG-7.[6] In high sea states this speed advantage for the hydrofoils would be even greater.
- The displacement ships have significantly longer range at their economical speed whereas the hydrofoils have a longer

[5] The PG-84 has a planing hull. However, in this study it is considered to be a conventional displacement ship.

[6] In order to keep the paper unclassified, no specific data are presented relative to the maximum speed and range of these vehicles.

Table 2 Comparison **of** design **indices**

Index	Units	PG-84	PHM	FFG-7	HOC
Weight allocation					
W_P/Δ	%	12.2	14.3	9.3	10.9
W_M/Δ	%	6.1	4.7	5.7	4.3
W_H/Δ	%	21.5	23.9	36.7	20.3
W_{MP}/Δ	%	18.2	10.9	7.9	5.3
W_{AX}/Δ	%	3.7	4.5	6.9	1.3
W_E/Δ	%	2.6	2.3	4.6	2.7
W_F/Δ	%	16.4	18.1	18.2	32.1
W_{SS}/Δ	%	9.8	7.4	8.3	3.7
W_L/Δ	%	0	12.5	0	18.5
W_{OSO}/Δ	%	3.6	1.4	2.2	0.9
Volume allocation					
∇_P/∇	%	15.8	18.2	19.0	25.4
∇_M/∇	%	27.4	22.6	21.3	22.2
∇_{MP}/∇	%	23.7	16.7	12.4.	20.8
∇_{AX}/∇	%	8.5	14.1	12.3	2.9
∇_E/∇	%	5.7	5.4	4.7	3.3
∇_F/∇	%	4.6	6.2	6.5	9.1
∇_{SS}/∇	%	7.4	2.3	12.0	5.7
∇_{OSO}/∇	%	6.9	13.6	11.8	9.6
∇_L/∇	%	0	0.9	0	1.0
Densities					
Δ/∇	lb/ft^3	11.1	11.4	15.6	12.6
W_P/∇_P	lb/ft^3	8.6	9.4	7.6	5.4
W_M/∇_M	lb/ft^3	2.5	2.3	4.1	2.5
W_{MP}/∇_{MP}	lb/ft^3	8.5	7.3	9.9	3.2
W_{AX}/∇_{AX}	lb/ft^3	4.8	3.9	8.7	5.7
W_E/∇_E	lb/ft^3	5.0	4.9	16.1	10.2
W_F/∇_F	lb/ft^3	39.6	33.3	43.7	44.4
W_{SS}/∇_{SS}	lb/ft^3	14.7	36.7	10.8	8.2
W_{OSO}/∇_{OSO}	lb/ft^3	5.8	1.2	2.9	1.2
W_L/∇_L	lb/ft^3		158.3		233.1
Specific ratios					
W_A/N_A	tons/=	6.7	9.5	40.0	11.9
W_M/M	tons/man	0.62	0.51	1.2	0.68
∇_M/M	ft^3/man	555	490	624	580
W_H/∇	lb/ft^3	3.1	2.7	5.7	2.6
W_{MP}/SHP	lb/SHP	6.7	a.2	15.8	3.2
∇_{MP}/SHP	ft^3/SHP	0.78	0.44	1.6	1.0
W_{AX}/∇	lb/ft^3	0.41	0.52	1.07	0.17
W_E/E	lb/KW	69.2	30.4	97.1	51.8
∇_E/E	ft^3/KW	13.8	6.2	6.0	5.1
W_{SS}/∇	lb/ft^3	1.1	0.84	1.29	0.47
W_{OSO}/∇	lb/ft^3	0.40	0.16	0.35	0.11
Capacity ship size ratios					
N_A/Δ	=/1,000 tons	12.4	13.0	1.9	5.5
M/Δ	men/100 tons	9.9	9.1	4.9	6.8
SHP/Δ	SHP/ton	61	75	11.2	36.8
E/Δ	KW/ton	0.83	1.7	1.1	1.2
Overall					
$\Delta V/SHP$ @ V		5+@40	7+@40+	20+@28+	9+@40+
L/D @ V		8+@40	13+@40+	30+@28+	15+@40+
W_PV/Δ @ V	knots	4.9@40	6.4@40+	2.7@28+	4.9@40+
W_PR/Δ	NM	61	107	186	262

range at the maximum sustained speed.

- All four ships utilize gas turbines for their primary main propulsion power. Both of the small ships (PC-84 and PHM) have diesels for cruising, and the HOC employs two small gas turbines for cruising. All ships employ propellers for propulsors except the PHM, which is designed with waterjets.
- The PG-84, being an older design, is armed only with guns whereas the PHM has both missiles and guns for its primary mission of surface warfare. The most significant difference between the payloads of the two larger ships is that the FFG-7 is an air-capable ship carrying two helicopters.
- Both of the hydrofoils reflect more recent technology as indicated by their year of introduction into the fleet.

The Level 1 design indices for the four ships are listed in Table 2. Figures 7 and 8 graphically display a comparison of the weight and volume allocations and Figs. 9-12 compare the more important specific ratios for these ships. Since a more detailed discussion of the seven ship features follows, only a few observations are made at this time based on these figures:

- Both of the hydrofoils have larger payload weight and payload' volume fractions than the corresponding displacement ships. This is especially significant when one observes that the PHM and HOC carry a 12.5 and 18.5 percent weight "overhead" resulting from the foils and struts, and are smaller and faster than the displacement ships. All three of these factors would tend to depress the payload-carrying capability of the hydrofoils.
- The'hydrofoils have larger fuel weight and volume fractions and also larger useful loads (payload, personnel, and fuel).

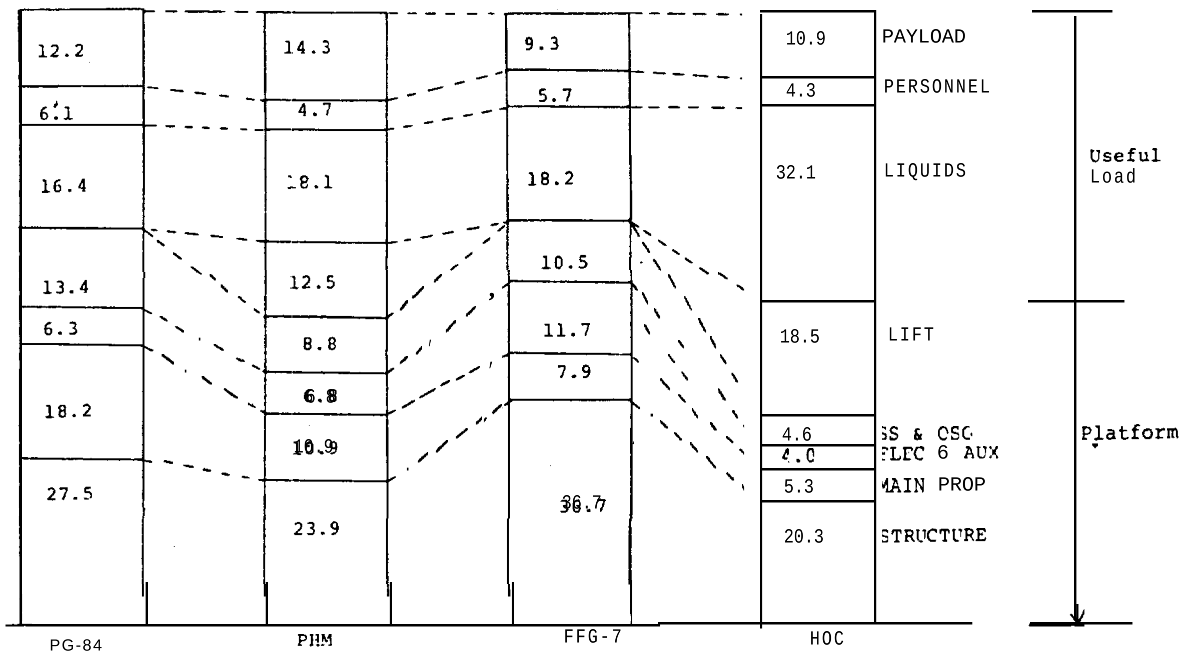

Fig. 7 Comparison of weight allocation

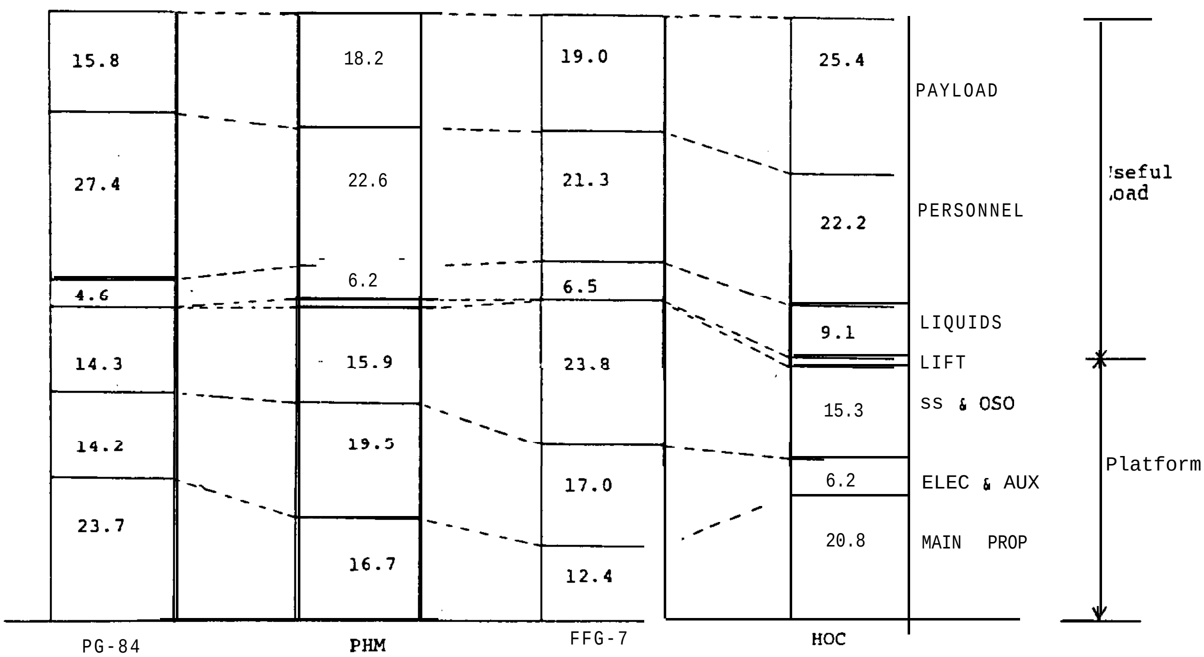

Fig. 8 Comparison of volume allocation

- The structural, main propulsion, personnel, and combined electrical, auxiliary, ship systems, and other ship operations weight fractions are all larger on the displacement ships.
- The ship densities of the two small ships are almost identical, whereas the FFG-7 is 20 percent more dense than the HOC.
- The specific weight and volume ratios for nearly all of the features are significantly less for the hydrofoils as compared with the displacement ships.
- The capacity/ship size ratios indicate that the hydrofoils carry a larger number of weapon systems, a larger complement, more propulsive power, and more electrical power per unit size than the displacement ships.

Main propulsion. The design indices related to main propulsion are listed in Table 3. Some of the more significant differences between the propulsion design practices of hydrofoils and conventional displacement ships are as follows:

- The hydrofoils have a faster maximum sustained speed than do the displacement ships. The explanation for this lies in the following relationship:

$$V = \frac{W_{MP}/\Delta \cdot PC \cdot L/D}{W_{MP}/SHP}$$

where

V = maximum speed

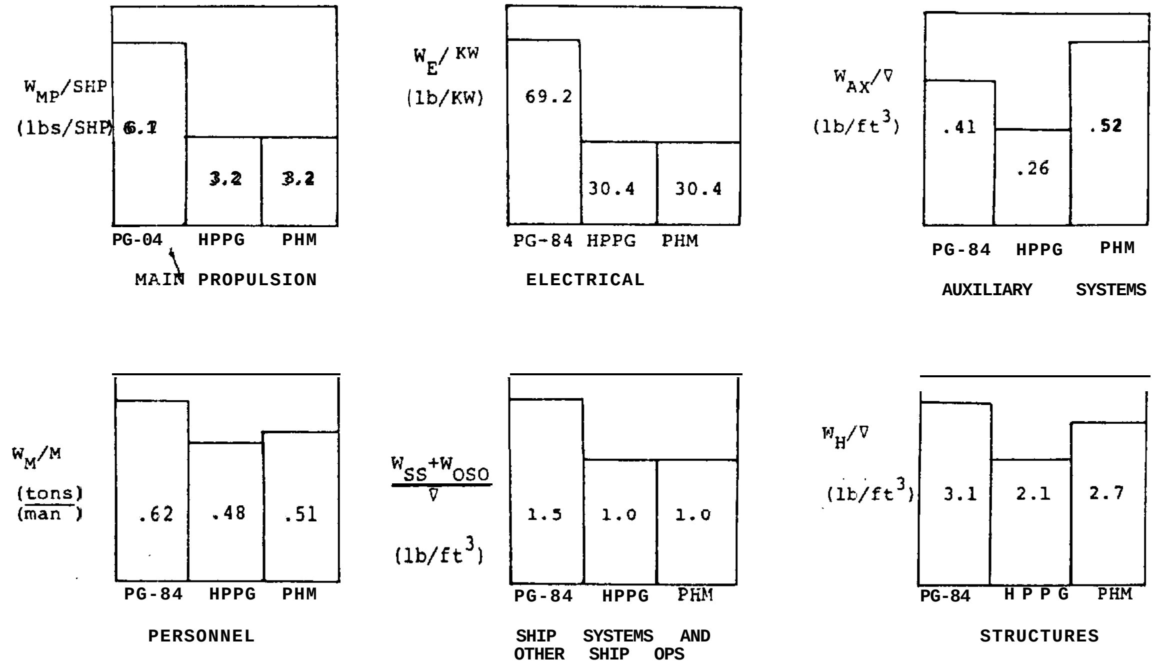

Fig. 9 **Small-ship** **weight** specific ratios

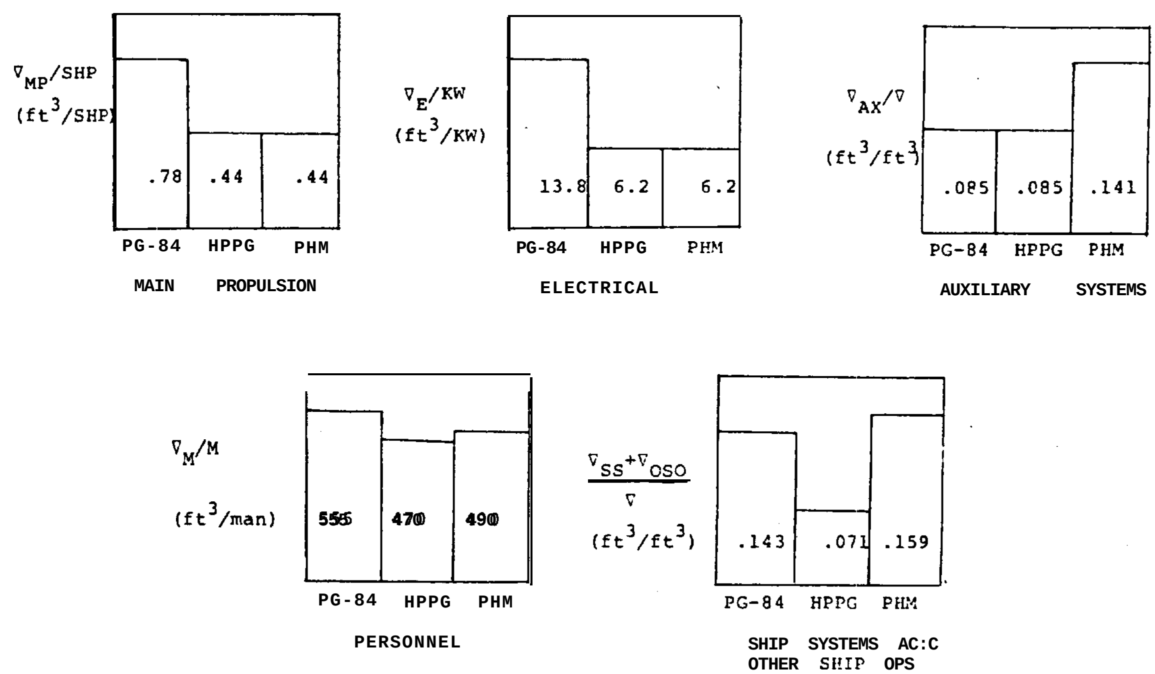

Fig. 10 **Small-ship volume specific ratios**

W_{MP}/Δ = **propulsion weight fraction**
PC = **overall propulsion coefficient**
L/D = **lift/drag ratio at** V
W_{MP}/SHP = **propulsion specific** weight

The hydrofoils achieve their faster speed despite smaller propulsion weight fractions and propulsive coefficients because of their higher lift/drag ratios and lower propulsion specific weight. The lift/drag ratio is a hydrodynamic parameter which has been used often as an index of vehicle performance.

The lift/drag ratios at 45 knots for these ships has been estimated as follows:

	PG-84	PHM	FFG-7	HOC
L/D @ 45 **knots**	7+	13+	14+	15+

The PHM's lift/drag ratio is greater than the PG-84's, as should be expected. Resistance data at 45 knots were not available for the FFG-7 and thus the lift/drag ratio for this ship was estimated from reference [4]. It is felt that the lift/drag ratio of the FFG-7 at 45 knots would be only slightly lower than that

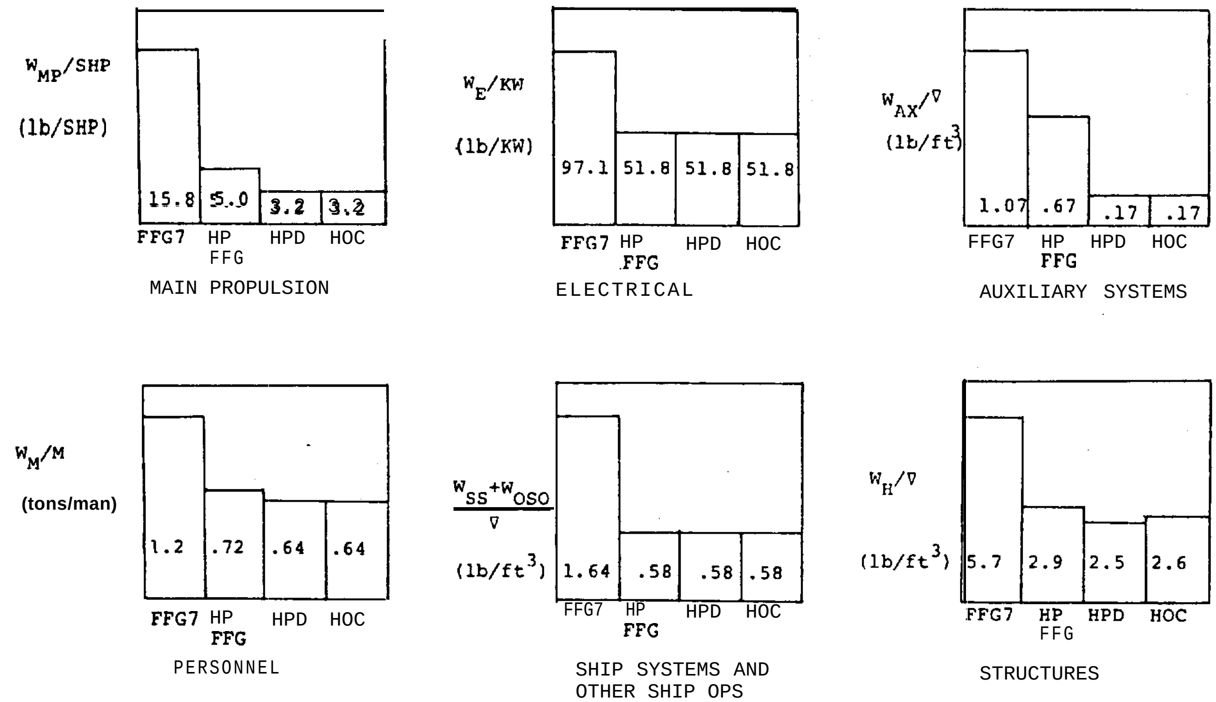

Fig. 11 Large-ship weight specific ratios

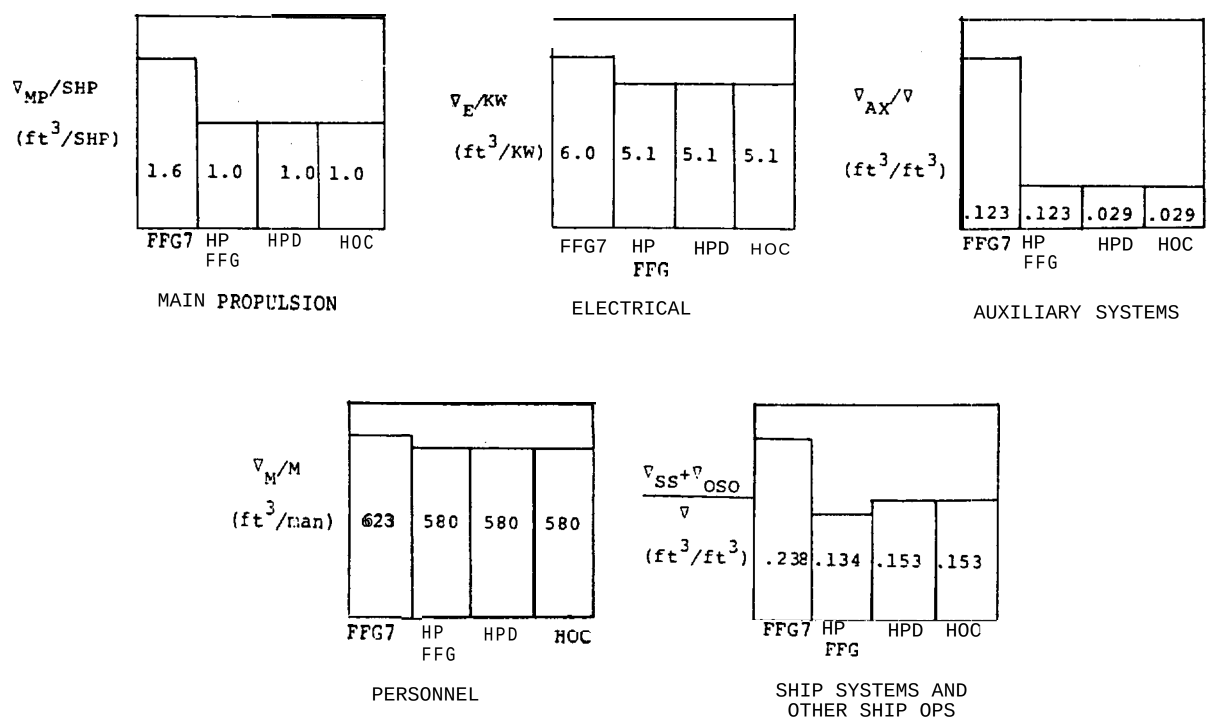

Fig. 12 Large-ship volume specific ratios

of the HOC at 45 knots. Thus the primary reason for the hydrofoil's higher speeds (especially for the larger ships) is the lower propulsion specific ratios. It should be noted that this important observation was made 15 years ago by Mandel [5] when he concluded that the slow speed of displacement ships was not due to a low lift/drag ratio but rather to propulsion plants with very high specific weights. The attention therefore in this discussion will be focused on a comparison of hydrofoil and displacement ship propulsion specific ratios.

- Both the propulsion specific weights and specific volumes are significantly less for the hydrofoils as compared with the displacement ships:

	PG-84	PHM	FFG-7	HOC
W_{MP}/SHP, lb/SHP	**6.7**	**3.2**	15.8	3.2
∇_{MP}/SHP, cu ft/SHP	0.78	0.44	1.6	1.0

Table 3 Comparison of main propulsion indices

Index	Units	PG-84	PHM	FFG-7	HOC
Main engine *SHP*	*HP*	13,100	16,000	40,000	40,000
Cruise engine *SHP*	*HP*	1,650	1,340	...	7,000
Total SHP/Δ	HP/ton	61	75	11.2	36.8
L/D @ 45		7+	13+	14+	15+
V_s	knots	-40	40+	28+	40+
PC		0.60	0.53	0.65	0.625
SFC	lb/*HP* hr	0.48	0.43	0.43	0.43
W_{MP}/Δ	%	18.2	10.9	7.9	5.3
∇_{MP}/∇	%	23.7	16.7	12.4	20.8
W_{MP}/∇_{MP}	lb/ft³	8.5	7.4	9.9	3.2
∇_{MP}/SHP	ft³/*SHP*	0.78	0.44	1.6	1.0
W_{MP}/SHP	lb/*SHP*	6.7	3.2	15.8	3.2
$W_{Prime\ mover}/SHP$	lb/*SHP*	1.5	1.3	3.5	0.9
$W_{Transmission}/SHP$	lb/*SHP*	3.4	1.1	7.7	1.6
$W_{Support\ \&\ fluids}/SHP$	lb/*SHP*	1.8	0.75	4.6	0.7
$W_{Main\ engine}/SHP$	lb/*SHP*			0.92	0.93
W_{Module}/SHP	lb/*SHP*	...	...	1.3	...
W_{Gear}/SHP	lb/*SHP*	1.4	0.4	3.1	0.8
$W_{Shaft\ \&\ prop}/SHP$	lb/*SHP*	2.1	0.8	4.7	0.8
Type		CODOG 1 LM 1500 GT 2 Cummings N12 diesels 2 CRPP	CODOG 1 LM 2500 GT 2 MBBV 331 diesels waterjet	GT & Aux. 2 LM 2500 GT 1 elec. propulsor 1 CRPP	CODAG 2 LM 2500 GT 2 TFMO GT 2 CRPP

Since the high-speed ‘capability in calm water of the hydrofoils is so closely linked with their low propulsion specific ratios, it is important to determine how these specific ratios were achieved.

- The next level of breakdown of the propulsion specific weights reveals the following:

	PG-84	PHM	FFG-7	HOC
Prime mover specific weight, lb/*SHP*	1.5	1.3	3.5	0.9
Transmission specific weight, lb/*SHP*	3.4	1.1	7.7	1.6
Support and fluids specific weight, lb/*SHP*	1.8	0.75	4.6	0.7

The specific weights of the prime mover for the PC-84 and PHM are quite similar. However, the specific weight of the prime mover of the FFG7 is four times that of the HOC, This may seem startling when one recalls that both of these ships are propelled by two LM 2500 gas turbines. The weight of the transmission system per shaft horsepower is over three times lighter on the hydrofoils. There is also a great disparity in the area of propulsion support and fluids.

- There are two reasons for the FFG having a larger prime mover specific weight than the HOC. The FFG-7’s two LM 2500’s are encased in two large modules, similar to small box cars, which are located inside the ship’s manned engine room. However, the HOC’s LM 2500’s have no such modules. The impact of this module is significant, as shown by the following numbers:

	FFG-7	HOC
Main engine (LM 2500) specific weight, lb/*SHP*	0.92	0.93
Main engine module, lb/*SHP*	1.3	0
Total main engine specific weight, lb/*SHP*	2.2	0.93

The second reason for the high prime mover specific weight of the FFG-7 is the heavy auxiliary propulsor (17.9 tons) which is used for emergency propulsion and slow-speed maneuvering.

- The transmission specific weights were broken down into two categories as follows:

	PG-84	PHM	FFG-7	HOC
Reduction gear specific weight, lb/*SHP*	1.4	0.4	3.1	0.8
Shafting and propulsor specific weight, lb/*SHP*	2.1	0.8	4.7	0.8

The lower weight of the hydrofoils’ reduction gears is due to the use of highly loaded planetary gears. The PHM’s waterjet propulsor shows a substantial weight savings as compared with the PG-84’s propellers. The HOC’s right-angle drive and supercavitating propellers are significantly lighter than the FFG’s conventional shafting and propeller arrangement.

- The propulsion support and fluids category is made up of the propulsion controls, cooling system, fuel service system, lube oil system, inner casing of uptakes, repair parts, and operating liquids in the systems. The specific weights in each of these categories were not calculated; however, their net effect is significant.

From the foregoing discussion, the authors concluded that because of similarities in ship size and power requirements, the PHM's propulsion design indices could be applied to the high-performance PC (HPPG). However, because of the size differences between the HOC and FFG-7, there was some reservation in applying the HOC's propulsion specific weight of 3.2 lb per shaft horsepower. A value of 5.0 lb per SHP was selected for the high-performance FFG (HPFFG) to reflect a more conservative transmission design.

If the foregoing values for the propulsion specific ratios were incorporated into the high-performance displacement ship designs, the following weight and internal volume savings could be realized:

	PG-84	HPPG	FFG-7	HPFFG
W_{MP}/SHP, lb/SHP	6.7	3.2	15.8	5.0
∇_{MP}/SHP, cu ft/SHP	0.78	0.44	1.6	1.0
SHP	14,750	14,750	40,000	40,000
Weight change, tons	B	-22	B	-193
Volume change, cu ft	B	−5000	B	-24000

(Note: B implies baseline.)

The significance of these weight and volume savings due to incorporating the hydrofoil's propulsion design standards is evident when one compares them with the weight and volume of the original payload of the PG-84 and FFG-7.

	PG-84	FFG-7
Payload weight, tons	30	330
Payload volume, cu ft	7700	97,800

Clearly, the application of high-performance ship propulsion design standards to displacement ships would have a dramatic impact on their payload carrying capacity.

If the propulsion system weight and internal volume were held constant and the high-performance standards applied for the purpose of increasing the installed power and thus the speed, the following results are indicated:

	PG-84	HPPG	FFG-7	HPFFG
W_{MP}/SHP, lb/SHP	6.7	3.2	15.8	5.0
∇_{MP}/SHP, cu ft/SHP	0.78	0.44	1.6	1.0
SHP-weight limited	14,750	30,880	40,000	126,400
SHP-volume limited	14,750	26,150	40,000	64,000
V_s-weight limited, knots	-40	54	-29	45
V_s-volume limited, knots	~40	51	-29	35

These speed estimates were based on reference [4] and the assumption that the propulsive coefficient was independent of speed. Although it is felt that the foregoing estimates are optimistic, the authors are certain that a substantial increase in calm-water speed can be realized by incorporating hydrofoil propulsion design standards in displacement ships.

Although it is feasible to decrease the disparity between hydrofoil and displacement ship maximum sustained speed in calm water, the hydrofoil will retain a significant speed advantage as sea state is increased. This high-speed performance capability at high sea states is a unique advantage of the hydrofoil and one which must not be forgotten in a vehicle assessment study. The authors did not address sea state performance quantitatively because of the lack of reliable data on these four ships. One of the important shortcomings of the present study is the lack of this analysis.

Much of the propulsion system weight and space savings predicted in the foregoing analysis could be transferred to military payload, resulting in a high-performance displacement ship with a more capable combat capability. On the other hand, the maximum sustained speed could be increased. Of course, the advantage of incorporating the high-performance standards could also be applied to increase other basic ship performance features such as range and endurance or any combination of these basic performance features. Two questions must be answered before a design team rushes into this high-performance displacement ship design: "What would be the impact on the 'operability' of the ship?" and "How would the overall performance of the ship be. effected by this change in ship operability?"

It is unfortunate that the scope of this study did not permit a detailed analysis of the impact on ship operability which might result if high-performance propulsion design standards were incorporated into a displacement ship. The foregoing discussion has pointed out a number of design differences between the propulsion design standards of hydrofoil and conventional displacement ships, and one might wonder what would be the impact on conventional displacement ship operability of the following:

- A gas turbine prime mover installed in the engine room without an isolation module.
- A planetary reduction gear instead of a conventional lock-train double-reduction gear.
- A highly loaded supercavitating propeller and lightweight shafting system.
- A decrease in the redundancy and inherent reliability of the propulsion plant's ancillary and support systems.

A detailed study of the operability of high-performance propulsion plants is strongly recommended.

Electrical. The comparison of the design features of the electrical plants of the hydrofoil and displacement ships resulted in conclusions similar to those for the propulsion plants. As indicated in the Introduction, the results of the analysis of the electrical system and the other ship features are only briefly summarized. References [1] and [2] provide a more detailed presentation, and the design indices related to the electrical plant are listed in Table 4. The following observations were made:

- Although the hydrofoils have a greater electrical plant capacity relative to their size, the electrical design standards result in lower electrical weight and volume fractions.
- The hydrofoils' electrical specific weight and volume are significantly lower than those of the displacement ships:

	PG-84	PHM	FFG-7	HOC
W_E/KW, lb/KW	69.2	30.4	97.1	51.8
∇_E/KW, cu ft/KW	13.8	6.2	6.0	5.0

- The lower specific ratios of the hydrofoils were achieved by using gas turbine generators and a 400-Hz electrical system (PHM only) as opposed to diesel generators and 60-Hz systems on the displacement ships.
- There appears to be no reason why the design standards of the hydrofoil's electric plant cannot be applied to displacement ships. However, since the gas turbine generators have a higher specific fuel consumption, the increase in fuel for the electrical power generators must be taken into account.

The weight and space impact of incorporating the hydrofoil's electrical design standards can be summarized as follows:

	PG-84	HPPG	FFG-7	HPFFG
W_E/KW, lb/KW	69.2	30.4	97.1	51.8
∇_E/KW, cu ft/KW	13.8	6.2	6.0	5.0
$SFCA$, lb/HP/hr	0.50	0.85	0.44	0.82
Installed electrical power, KW	200	200	4000	4000
Electrical plant weight change, tons	B	-3.47	B	-80.9

Table 4 Comparison of electrical indices

Index	Units	PG-84	PHM	FFG-7	HOC
KW	KW	200	400	4,000	1,500
KW/∇	K W/ton	0.83	1.7	1.1	1.2
W_E/Δ	%	2.6	2.3	4.8	2.7
∇_E/∇	%	5.7	5.4	4.7	3.3
W_E/∇_E	lb/ft³	5.0	4.9	16.1	10.2
W_E/KW	lb/KW	69.2	30.4	97.1	51.8
∇_E/KW	ft³/KW	13.8	6.2	6.0	5.1
$W_{Generator}/KW$	lb/KW	58.9	22.7	52.1	37.8
$W_{Switchgear}/KW$	lb/KW	7.7	7.2	10.5	6.1
$W_{Degaussing}/KW$	lb/KW	0	0	6.8	0
$W_{Support}/KW$	lb/KW	0	0	22.4	0
W_{Fluids}/KW	lb/KW lb/HP	2.5 0.50	0.85 0.4	0.44 5.4	7.9 0.82
Type		diesel 60 Hz	GT 400 Hz	diesel 60 Hz	GT 60 Hz

Table 5 Comparison of auxiliary systems indices

Index	Units	PG-84	PHM	FIFG-7	HOC
W_{AX}/Δ	%	3.7	4.5	6.9	1.3
∇_{AX}/∇	%	8.5	14.1	12.3	2.9
W_{AX}/∇_{AX}	lb/ft³	4.8	3.7	8.7	5.7
W_{AX}/∇	lb/100 ft³	40.7	51.5	107.1	16.7
$W_{Climate\ control}/W_{AX}$	%	12.6	15.6	19.4	12.4
$W_{Saltwater}/W_{AX}$	%	3.4	0	4.4	6.6
$W_{Distiller}/W_{AX}$	%	4.5	12.8	2.5	0
$W_{Gas\ fluid}/W_{AX}$	%	2.3	21.7	8.0	57.3
$W_{Steering}/W_{AX}$	%	48.2	8.9	27.9	0
$W_{Deck\ aux.}/W$					23.7
$W_{Fluids}/x./W_{AX}$	%	10.2 18.8	41.2 0	25.7 17.1	0
$W_{Climate\ control}/\nabla$	lb/100 ft³	5.1	8.0	20.7	2.1
$W_{Salt\ water}/\nabla$	lb/100 ft³	1.4	0	4.8	1.1
$W_{Distiller}/M$	lb/man	37.3	143	78.4	0
$W_{Gas\ fluid}/\nabla$	lb/100 ft³	0.9	11.2	8.6	9.6
$W_{steering}/\Delta$	lb/ton	39.4	9.0	42.9	0
$W_{Deck\ aux.}/\Delta$	lb/ton	15.4	41.8	39.5	7.0
W_{Fluids}/∇	lb/100 ft³	4.2	0	12.9	0

	PG-84	HPPG	FFG-7	HPFFG
Electrical plant volume change, cu ft	B	-1520	B	-4000
Electrical plant fuel weight change, tons	B	+0.59	B	+71.1
Electrical plant fuel volume change, cu ft	B	+39	B	+3590
Net electrical plant weight change, tons	B	-2.88	B	'9.8
Net electrical plant volume change, cu ft	B	-1481	B	-410

As can be seen, there is still a favorable weight and space impact of the high-performance electrical design standards in spite of the fuel penalty associated with the lightweight gas turbine generators.

It is difficult even to speculate concerning the impact of the high performance electrical design standards on ship operability. Because of the differences inherent in gas turbines and diesels, it is not possible to make the assumption that the lower electrical specific ratios infer that operability has been compromised. However, the smaller allocation of weight and volume to electrical plant support would have an adverse effect on operability.

Auxiliary systems. Before discussing the comparative analysis of the auxiliary systems, it is important to note that the hydrofoil's lift system (foil and struts) was placed in a separate functional category. However, the foil support systems (hydraulics and retraction equipment) remained in the category of auxiliary systems. As will be seen, the foil support systems have a large impact on the hydrofoil's auxiliary system.

The design indices associated with the ships' auxiliary systems are listed in Table 5.. The following observations were made:

- The PHM has larger auxiliary weight and volume fractions than the PG-84. The cause of this is the higher auxiliary specific ratios:

	PG-84	PHM
W_{AX}/∇, lb/100 cu ft	40.7	51.5
∇_{AX}/∇, cu ft/100 cu ft	8.5	14.1

- The HOC, 'however, has much lower auxiliary weight and volume fractions than the FFG7. The extremely low auxiliary system specific weight is the cause for the lower weight allocation. It is felt that this low value is partially due to an underestimation in HOC's conceptual design. The specific ratios for the two large ships are as follows:

	FFG-7	HOC
W_{AX}/∇, lb/100 cu ft	107.1	16.7
∇_{AX}/∇, cu ft/100 cu ft	12.3	2.9

- The Level 2 breakdown of auxiliary systems includes climate control, saltwater systems, distilling plant, gas and fluid systems, steering and maneuvering, deck auxiliaries, and op-

Table 6 Comparison of structural indices

Index	Units	PG-84	PHM	FFG-7	HOC
W_H/Δ	%	27.5	23.9	36.7	20.3
W_H/∇	lb/ft³	3.1	2.7	5.7	2.6
$W_{Basic\ hull}/\Delta$	%	20.4	12.9	26.5	14.1
$W_{Superstructure}/\Delta$	%	3.2	1.8	3.1	1.8
W_{Masts}/Δ	%	1.9	1.8	2.1	. . .
$W_{Foundations}/A$	%	1.9	3.4	4.0	4.3
$W_{Flooding\ liquids}/\Delta$	%	0	4.0	1.0	
$W_{Superstructureure}/\nabla_{Superstructure}$	lb/ft³	1.8	0.88	3.0	0.74
$W_{Basic\ hull}/\nabla_{Hull}$	lb/ft³	2.9	1.9	4.9	2.6
$W_{Foundations}/W_{LS-Gpl}$	lb/ton	83.7	150	224	222
A/V	lb/ft³	11.1	11.4	15.6	12.6

·erating liquids. As shown in Table 5 the weight allocated to each of these systems compared with the overall auxiliary system weight varies significantly between the hydrofoils and displacement ships. The most dramatic differences are in the areas of gas and fluid systems and deck auxiliaries, which comprise over 60 percent of PHM's auxiliary weight and 80 percent of HOG's auxiliary weight. On hydrofoils these two systems are dominated by the hydraulic and handling equipment associated with the foil retraction and control mechanisms.

- Specific ratios were computed for the Level 2 breakdown of auxiliary systems using the appropriate capacity parameter. This capacity parameter varies with the particular auxiliary system. The PHM has higher specific weights in the areas of climate control, distilling plant, gas and fluid systems and deck auxiliaries than the PG-84. The higher specific weight for the latter two systems can be attributed to the requirements of the foil system. The high distilling plant specific ratio represents a tradeoff with a much lower potable water stowage capacity. The PHM has lower specific ratios for the saltwater systems, steering systems and operating fluids. The PHM's extremely low steering system specific weight can be attributed to the steerable wateriet system.
- The HOC's gas and fluid system specific weight is higher than that of the FFG-7. All other specific weights for the HOC are lower than those for the FFG-7 and in fact are lower than those for the two small ships as well. The HOC's auxiliary system design lacked sufficient detail for a comprehensive comparison.

It is difficult to estimate reasonable values for the specific ratios which could be applied to the high-performance displacement ship. As has been pointed out, the contribution of the auxiliary system directly related to the foils can be deleted. As-a result of this consideration and the realization that the HOC's auxiliary system design was suspect, the following specific ratios were selected for the high-performance ship and the ship impact estimated:

	PG-84	HPPG	FFG-7	HPFFG
W_{AX}/∇, lb/100 cu ft	40.7	25.5	107.1	67
∇_{AX}/∇, cu ft/100 cu ft	8.5	8.5	12.3	12.3
V	48,600	48,600	514,900	514,900
Weight change, tons	B	-3.3	B	-92
Volume change, cu ft	B	0	B	0

The auxiliary systems on a ship, since they support operations throughout the ship, are vital to a successful execution of a ship's mission. The decrease in weight allocations to this function is bound to have an adverse effect on the operability of the overall ship.

Ship structure. There is a large potential for weight savings in the area of ship structures due to differences in materials and fabrications techniques. Based on the design indices listed in Table 6, the following observations were made:

- The structural weight fractions of the hydrofoils are significantly less than those of the displacement ships. The structural weight fraction of a ship is dependent on the structural specific weight and ship density.

$$W_H/A = \frac{W_H/\nabla}{\Delta/\nabla}$$

. The primary reason for the small structural weight fractions for the hydrofoils is the low structural specific weights as indicated in the following:

	PG-84	PHM	FFG-7	HOC
W_H/∇, lb/cu ft	3.1	2.7	5.7	2.6
W_H/A, percent	27.5	23.9	36.7	20.3

The structural specific weights of the basic hull and superstructure are both less on the PHM as compared with the PG-84.

	PG-84	PHM
$W_{Basic\ hull}/\nabla_{Hull}$, lb/cu ft	2.9	1.9
$W_{Superstructure}/\nabla_{Superstructure}$, lb/cu ft	1.8	0.88

Since the hull of both the PG-84 and I'HM are constructed of aluminum, it appears that the PHM has obtained the lower hull specific weight by incorporating a more efficient structural design. (This ignores any differences in structural loads between the two ships.) Because the PG-84 was the first combatant displacement ship over 200 tons to be constructed of aluminum, the conservatism is understandable. The difference between the PC-84 and PHM superstructure specific weight is probably attributable to the different materials used; aluminum in the PHM and fiberglass in the PG-84.

- The disparity in structural weight fractions and specific weights are even more dramatic in the case of the FFG-7 and HOC.

	FFG-7	HOC
W_H/A, percent	36.7	20.3
W_H/∇, lb/cu ft	5.7	2.6

A breakdown of the structural weights for the basic hull and superstructure reveals the following:

	FI'G-7	HOC
$\frac{W_{Basic\ Hull}}{\nabla_{Hull}}$, lb/cu ft	5:5	2.6
$\frac{W_{Superstructure}}{V_{Superstructure}}$, lb/cu ft	3.0	0.74

The large difference in hull specific weight is primarily due to the FFG using steel and the HOC aluminum as the material for the hulls. There also is a large difference in the superstructure specific weights. As both of the ships have aluminum superstructures, the difference must be caused by either a more efficient structural design or lower loadings.

- The weight of the foundations are surprisingly high on the two hydrofoils. In fact, the foundation specific weight (based on the light ship weight less structure) is higher for the PHM than the PG-84 and nearly equal for the two large ships.

Table 7 Comparison of personnel indices

Index	Units	PG-84	PHM	FPG-7	HOC
M	men	24	21	176	87
M/Δ	men/100 tons	9.9	9.1	4.9	6.8
W_M/Δ	%	6.1	4.7	5.7	4.3
∇_M/∇	%	27.4	22.6	21.3	22.2
W_M/∇_M	lb/ft³	2.5	2.3	4.1	2.5
W_M/M	tons/man	0.62	0.51	1.2	0.68
∇_M/M	ft³/man	555	499	624	580
W_{Living}/M	lb/man	708	655	948	525
$W_{Support}/M$	lb/man	179	269	444	70
$W_{Storage}/M \cdot D$	lb/man-day	35.5	33.3	26.5	27.8
∇_{Living}/M	ft³/man	455	412	398	437
$\nabla_{Support}/M$	ft³/man	71	43	146	93
$V_{Storage}/M$	ft³/man	2.1	4.9	1.75	1.67
Stores endurance, D	days	14	7	45	30

		PG-84	PHM	FFG-7	HOC
$W_{foundations}/\Delta$,	percent	1.9	3.4	4.0	4.3
$W_{foundations}/\Delta_{LS\text{-}Gp1}$,	lb/ton	83.7	150	224	222

The explanation lies in the requirement for heavy foundations for the foil struts. When designing the high-performance displacement ship, this effect can be discounted.

Since a structural analysis was not carried out on the four ships to determine the relative structural loads, it is not possible to state with certainty that the hydrofoil structural standards could be applied to the displacement ship. However, if it were found that the hydrofoil's structural specific weight (modified to reflect the foil foundation effect) could be applied to the high-performance displacement ship, the following weight savings could be expected:

	PG-84	HPPG	FFG	HPFFG
W_H/∇, lb/cu ft	3.1	2.1	5.7	2.9
∇ cu ft	48,600	48,600	514,900	514,900
Weight change, tons	B	-21	B	-640

For the HPPG this represents a weight saving nearly equal to that due to the incorporation of the high-performance propulsion standards. The weight savings of 640 tons for the HPFFG is 3 times greater than that due to the propulsion standards and represents a weight equal to twice the original payload weight of the FFG-7.

The Navy on several occasions has investigated the feasibility of constructing large aluminum displacement ships. Each time such factors as stability limitations, reduced service life, and the difficulty of reducing the effects of fire have resulted in the rejection of the concept. The foregoing factors would all tend to decrease the operability of the ship. However, with the more advanced technology available today, these disadvantages may very well be able to be overcome.

Personnel. The design indices related to the personnel function are listed in Table 7. The following observations were made:

- The complement on both of the hydrofoils is less than that on the displacement ships.
- The lower personnel weight and volume fractions of the hydrofoils are primarily due to the lower personnel specific weights and volumes.
- Although the habitability standards as indicated by the specific ratios are lower on the hydrofoils, the disparity is not as large as has been found for several of the other features:

	PG-84	PHM	FFG	HOC
W_M/M, ton/man	0.62	0.51	1.1	0.64
∇_M/M, cu ft/man	555	489	624	579

Table 8 Comparison of other indices

Index	Units	PG-84	PHM	FFG	HOC
Payload					
W_P/Δ	%	12.2	14.4	9.3	10.9
∇_P/∇	lb/ft³	15.8	18.2	19.2	25.4
W_P/∇_P		8.6	9.0	7.7	5.4
W_A/N_A	tons/=	6.7	9.5	40.0	11.9
N_A/Δ	=/1,000 tons	12.4	13.0	1.9	5.5
Ship systems					
W_{SS}/Δ	%	9.8	7.4	8.3	3.7
∇_{SS}/∇	%	7.4	2.3	12.0	5.7
W_{SS}/∇	lb/ft³	1.1	0.84	1.29	0.47
Other ship OPS					
W_{OSO}/Δ	%	3.6	1.4	2.2	0.9
∇_{OSO}/∇	%	6.9	13.6	11.8	9.6
W_{OSO}/∇	lb/ft³	0.40	0.16	0.35	0.11

Since the endurance and crew size relative to ship size are reasonably close for both the two small and two large ships, it was felt that the lower habitability standards of the hydrofoils could be applied to the displacement ships. The resultant weight and space savings were estimated as follows:

	PG-84	HPPG	FFG-7	HPFFG
W_M/M, ton/man	0.62	0.58	1.2	0.90
∇_M/M, cu ft/man	555	484	624	605
M	24	21	176	176
Weight change, tons	B	-0.92	B	-45
Volume change, cu ft	B	-1700	B	-3300

Although these weight and volume savings are small in comparison with the savings associated with some of the other features, the impact is still worth considering. Because of the relatively minor decrease in habitability standards, only a small degradation in ship operability would be expected.

It should be pointed out that although the habitability standards, in terms of weight and space allocation per man, are lower on the hydrofoils than on the conventional displacement ships, the superior ride quaky of the hydrofoils in high sea states should result in an environment which would be more pleasurable on the hydrofoils. Additional operational experience will no doubt bear this out.

Other ship features. The remaining features of the ships which should be addressed are payload, ship systems, and other ship operations. Table 8 lists the indices associated with these features. A few of the more important observations which were made are as follows:

- The hydrofoils have larger payload weight and volume fractions than do the displacement ships. (This observation has

Table 9 Input design indices-small high-performance displacement ship

Index	Units	PG-84	HPPG	PHM
Characteristics				
Δ	tons	242	231	231
SHP	SHP	14,750	19,000	17,340
V_s	knots	-40	40+	40+
M	men	24	21	21
D	day	14	7	7
$R @ V_s$	NM@knots	-500	700+	700+
KW	KW	200	200	400
Weight indices				
$W_{MST}/M\cdot D$	lb/man-day	35	33	33
W_{HAB}/M	lb/man	888	834	915
W_E/KW	lb/KW	69	30	30
W_{MP}/SHP	lb/SHP	6.7	3.2	3.2
W_{SS}/∇	lb/ft^3	1.1	0.84	0.84
W_{AX}/∇	lb/ft^3	0.41	0.30	0.52
W_{OSO}/∇	lb/ft^3	0.40	0.13	0.16
W_H/∇	lb/ft^3	3.1	2.1	2.7
Volume indices				
$\nabla_{MST}/M\cdot D$	ft^3/man-day	2.1	2.1	4.9
∇_{HAB}/M	ft^3/man	526	455	455
∇_E/KW	ft^3/KW	13.8	6.2	6.2
∇_{MP}/SHP	ft^3/SHP	0.78	0.44	0.44
∇_{SS}/∇	ft^3/100 ft^3	7.4	2.3	2.3
∇_{AX}/∇	ft^3/100 ft^3	8.5	8.5	14.1
∇_{OSO}/∇	ft^3/100 ft^3	6.9	4.8	13.6
Other indices				
W_F/∇_F	lb/ft^3	39.7	33.1	33.1
SFC	lb/SHP hr	0.48	0.43	0.43
SFCA	lb/HP hr	0.50	0.85	0.85
W_P/∇_P	lb/ft^3	8.6	8.8	9.0

already been made.) It is now known that the greater payload carrying capacity of the hydrofoils is achieved as a result of the **incorporation** of weight and space saving design standards for the other ship features.

- The category "ship systems" is composed of those features which are distributed throughout the ship servicing all other ship functions. Passageways and access represent the volume demand associated with ship systems. From a weight standpoint, such items as cables, lighting system, interior communication system, heating and ventilation ducting, firemain and other fluid systems, hull fittings, compartmentation, and bulkhead and deck coverings which are distributed throughout the ship are included. The specific ratios for ship systems are lower for the hydrofoils than for the displacement ships.

	PG-84	PHM	FFG-7	HOC
W_{SS}/∇, lb/cu ft	1.1	0.84	1.29	0.47
∇_{SS}/∇, cu ft/100 cu ft	7.4	2.3	12.0	5.7

- The final category, other ship operation systems, contains the remaining features of the ships. Included in this category are ship and damage control, offices, tankage, shops, and stores. The specific ratios for other ship operation systems are, on the whole, less for the hydrofoils. The single exception is the larger specific volume on the PHM.

	PG-84	PHM	FFG-7	HOC
W_{OSO}/∇, lb/cu ft	0.40	0.16	0.35	0.11
∇_{OSO}/∇, cu ft/100 cu ft	6.9	13.6	11.8	9.6

Technically there is no reason why the hydrofoil design standards for "ship systems" and other ship operation systems cannot be applied to the high-performance displacement ships. The weight and space impact which would result from this design change is as follows:

	PG-84	HPPG	FFG-7	HPFFG
$W_{SS} + W_{OSO}/\nabla$ lb/cu ft	1.5	1.0	1.64	0.58
$\nabla_{SS} + \nabla_{OSO}/\nabla$ cu ft/100 cu ft	14.3	15.9	23.8	15.3
∇ cu ft	48,600	48,600	514,900	514,900
Weight change, tons	B	-10.8	B	-243
Volume change, cu ft	B	+780	B	-43,800

The impact of incorporating the high-performance standards is surprisingly large. For the HPFFG the weight and volume savings are even greater than the savings associated with the propulsion plant.

The features which have been grouped into the ship systems and other ship operations categories have a major influence on the overall operability of the ship. A decrease in the amount of space and weight devoted to such features as passageways and access, storage, shops, and ship and damage control would certainly have a major impact on how the crew operates and maintains the ship.

High-performance displacement ship

The previous section identified the principal differences between hydrofoil and displacement ship design practices and addressed some of the major design tradeoffs. It certainly appears that if the hydrofoil design practices were incorporated into the displacement ship, the resultant high-performance displacement ship would have both a substantial increase in speed and payload-carrying capability. It should also be evident from the previous section that this increase in "basic performance" would result in a decrease in ship operability.

By applying the parametric model described in the first section, the overall effect of incorporating the hydrofoil design standards in a displacement ship can be estimated. As was indicated in the previous section, some judgment was required in selecting realistic values for the specific ratios to be applied to the high-performance displacement ship. Tables 9 and 10 list the values for the specific ratios and other design indices which were utilized in the "design" of the small high-performance displacement ship based on PG-84 and the large high-performance displacement ship based on FFG-7. Figures 9-12 compare the principal specific ratios in a more graphical fashion. The reasoning upon which these values were based was presented in the previous sections.

Before discussing the results obtained by applying these high-performance design indices to the parametric model, it is important to remind the reader of the objective and limitations of this analysis. The objective was to determine the characteristics of a displacement ship designed to high-performance ship design practices. Because the parametric model was not a design synthesis model and because the design indices for the high-performance displacement ship are not based on a detailed study of the subsystems, the resultant high-performance displacement ship characteristics should be utilized merely as an indicator of the trend that can be expected. The characteristics in this paper would require considerable validation before they could be used in a vehicle assessment.

High-performance PC. The high-performance PC (HPPG) is compared with the conventional PG-84 and PHM in Table 11 and Figs. 13 and 14. Most of the attention has been directed in comparing the HPPG with the PHM. The following observations were made:

- The displacement of the HPPG has been set equal to that of the PHM.
- The HPPG can attain the same maximum sustained speed in calm water as the PHM. As sea state is increased, however, the speed of the HPPG will degrade faster than that of the PHM. The effect of sea state on speed was not calculated in

Table 1 Cl input design indices-large high-performance displacement ship

Index	Units	FFG-7	HPFFG (pay-load)	HPFFG (speed)	1200-ton HPΔ	HOC
ClΔ eristics						
SHP	tons *SHP*	40,000	3,585 40,000	3,585 70,000	50,000 1,276	47,000 1,276
V_s	knots	28+	28+	38	40+	40-t
M	men	176	176	176	a 7	a 7
D	day	45	30	30	30	30
$R@V_s$	NM@ knots	-2,000	-2,400	~2,400	-2,400	-2,400
KW	KW	4,000	4,000	4,000	1,500	1,560
Weight indices						
W_{MSHAB}/M W_{HAB}/M	lb/man lb/man-day	26.5 1,391	26.5 825	825 26.5	825 26.5	594 27.8
W_E/E	lb/KW	97.1	51.8	51.8	51.8	51.8
W_{MP}/SHP	lb/SHP	15.8	5	5	3.2	3.2
W_{SS}/∇	lb/ft^3	1.3	0.46	0.46	0.46	0.46
W_{AX}/∇	lb/ft^3	1.1	0.79	0.79	0.79	0.17
W_{OSO}/∇	lb/ft^3	0.35	0.11	0.11	0.11	0.11
W_H/∇	lb/ft^3	5.7	2.9	2.9	2.5	2.5
Volume indices						
$\nabla_{MST}/M \cdot D$	ft^3/man-day	1.8	1.6	1.6	1.6	1.6
∇_{HAB}/M	ft^3/man	545	530	530	530	530
∇_E/KW	ft^3/KW	6.0	5.0	5.0	5.0	5.0
∇_{MP}/SHP	ft^3/SHP	1.6	1.0	1.0	1.0	1.0
∇_{SS}/∇	ft^3/100 ft^3	0.12	0.06	0.06	0.06	0.06
∇_{AX}/∇	ft^3/100 ft^3	0.12	0.12	0.12	0.12	0.03
∇_{OSO}/∇	ft^3/100 ft^3	0.12	0.08	0.08	0.08	0.10
Other indices						
W_F/∇_F	lb/ft^3	43.8	44.2	44.2	44.2	44.2
SFC	lb/SHP hr	0.43	0.43	0.43	0.43	0.43
SFCA	lb/HP hr	0.44	0.82	0.82	0.82	0.82
W_P/∇_P	lb/ft^3	7.7	19.8	21.0	13.8	5.4

this study and therefore only a qualitative indication is made by the arrow pointing downward, showing that the PC-84 and HPPG would have lower maximum sustained speeds in high sea states. The ability to maintain high-speed operations in high sea states is the dominate advantage of the hydrofoil over the displacement ship.

- The range at maximum sustained speed is equal for the HPPG and PHM. Fuel had to be added to the PG-84 to attain this equalization of high-speed range. Because the displacement ship has a higher lift/drag ratio at lower speeds, the HPPG has a range at 20 knots which is six times greater than that of the PHM. The range was compared at 20 knots because this is the speed used in specifying displacement ship ranges. Since this speed is just below the takeoff speed of the PHM, it places the hydrofoil in a very poor position. At the most economical speed for the hydrofoil, just under 10 knots, the disparity between the displacement ship and hydrofoil range would be decreased. The displacement ship, however, would still have the advantage.
- The stores endurance has been equalized on the HPPG and PHM. Because of the increase in fuel capacity on the HPPG, this ship has a far greater fuel endurance than the PHM.
- The payload carrying capacity has been increased dramatically on the HPPG and is now almost double that of the PHM. The vertical location of the 60 tons of payload on the HPPG is about the same as that on the original PG-84.
- Except in the area of motions in a sea state, the operability of the HPPG should be equal to that of the PHM since the two ships reflect the same design standards. It is felt that the operability of both the HPPG and PHM is less than the' original PG-84. No quantitative assessment was made to validate this conclusion.
- Although no cost analysis was performed, it is felt that the cost of the HPPG platform (ship less payload) would be slightly higher than the cost of the PHM platform (ship less payload) without foils. This statement can be made because the HPPG is, in essence, a PHM with slightly more propulsive power but without foils.

Table 11 Comparison of small high-performance displacement ship

	PG-84	HPPG	PHM
Size			
Δ, tons	242	231	231
∇, ft^3	48,600	46,350	45,500
Mobility			
V_s (calm water), knots	-40	40+	40+
V_s (sea state), knots	|	↓	B
$R@V_s$, NM	-500	700+	700+
R@ 20 knots, NM	-2,000	4,500	700
Endurance			
Stores endurance, days	14	7	7
Fuel endurance @ V_s, days	0.5	0.7	0.7
Fuel endurance @ 20. days	6.2	9.5	1.6
Payload			
Payload weight, tons	30	60	33
VCG of payload, ft above keel	15.2	15.5	18.8
Payload volume, fts	7,700	15,300	8,300
Operability			
Motions in sea state		1	B
Complement	24	21	21
Habitability standards	.	B	B
Main propeller standards	↑	B	B
Electrical standards	↑	B	B
Auxiliary standards	↑	B	B
Structural standards	↑	B	B
Ship systems & OSO standards	↑	B	B
cost	↓	B'	B

- As is shown in Figs, 13 and 14, the weight and volume of

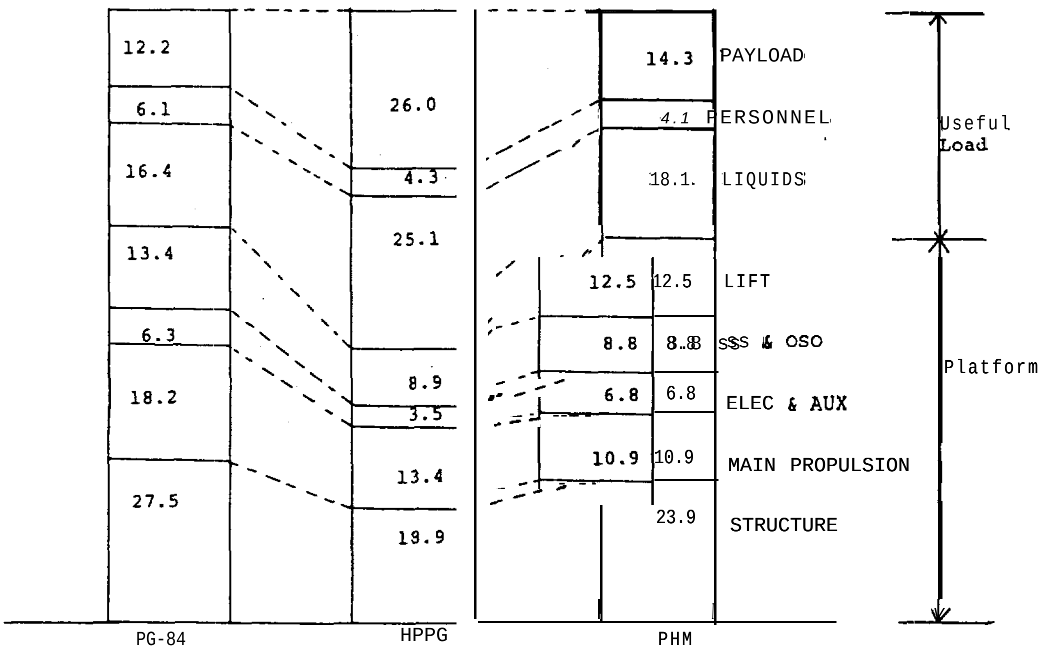

Fig. **13** Comparison of weight allocation-small ships

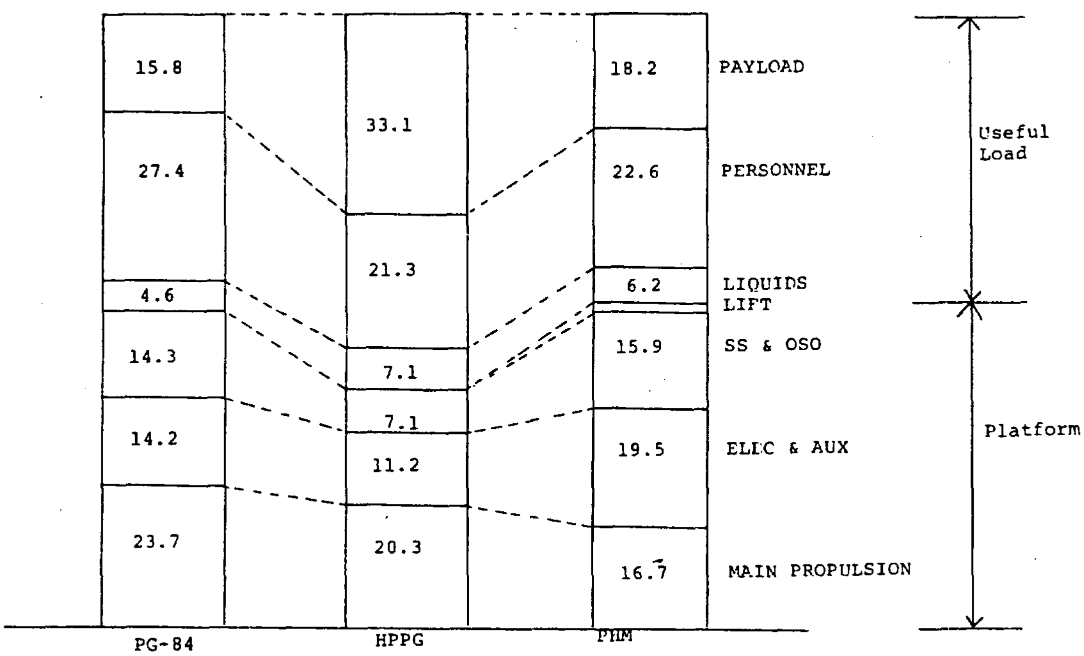

Fig. **14** Comparison of volume allocation-small ships

the HPPG has been drastically redistributed as compared with the original PG-84, resulting in usable loads of 55 percent and a payload of over 25 percent of ship weight.

A final observation should be made concerning the overall assessment of the PG-84, HPPG, and the PHM. In comparing the original PG-84 and PHM with the goal of determining their relative military worth, it would be necessary to consider over a dozen significant differences between these two ships. The analyst would be faced with the task of comparing apples and oranges. However, because the HPPG is designed to the same standards as the PHM, only four significant differences must be analyzed:

Advantages of HPPG	*Advantages of PHM*
Range and endurance at slow speeds	Speed in sea state
Payload capacity	Motion in sea state

These four performance features--range and endurance at slow speeds, payload capacity, speed capability in high sea states, and ship motions in high sea states-should become the focus of a vehicle assessment study between a small high-performance displacement ship and a hydrofoil.

High-performance FFG. Because of the large difference in size between the FFG-7 and HOC, the design of the high-performance FFG (HPFFG) was not as straightforward as that of the HPPG. The parametric model was used to determine the characteristics of two HPFFG's, one designed to maximize speed and the other to maximize payload capacity. The "fast HPFFG" and the "payload HPFFG" are compared with the conventional FFG-7 and HOC in Table 12 and Figs. 15 and 16. Based on these data, the following observations were made:

- The HPFFG displacement was kept equal to the conventional FFG-7 and is almost three times greater than that of the HOC.
- The maximum sustained speed in calm water of the fast HPFFG is substantially greater than that of the FFG7 but still less than that of the HOC. The reason for this is the internal volume limitations on installed shaft horsepower. If the FFG's hull were increased in length to provide more space for propulsive machinery, the propulsive power could he increased to that amount limited by weight, and the lift/drag ratio would be increased. With these modifications, the calm-water speed of the HPFFG could be made equal to that of the HOC. As in the case of the small-ship comparison, the HOC can be expected to have a higher speed in high sea states.
- The range at maximum speed of the HPFFG is equal to that of the HOC. Because of the large addition of fuel required to meet this range requirement and the superior lift/drag ratio at slower speeds, the HPFFG has a marked range advantage over the HOC at 20 knots. Again it should be pointed out that a range comparison at 20 knots is disadvantageous to the HOC, since this speed is close to the hydrofoil's takeoff speed.
- The stores endurance has been equalized on the HPFFG's and HOC. The HPFFG's have a longer fuel endurance.
- The dominant difference between the HPFFG's and the HOC is in payload capacity. The analysis shows that the HPFFG's could carry ten times the payload weight of the HOC. It should be remembered, however, that a significant part of the payload weight quoted for the HPFFG must be allocated to dedicated payload support (crew, electrical power, auxiliary services, etc). The military payload weight of the HPFFG would be less than the values quoted in Table 12 but still significantly greater than the payload on either the FFG-7 or HOC.
- Except in the area of ship motion in heavy seas, the operability of the HPFFG should be approximately the same as that for the HOC. The HPFFG's operability would be substantially less than the conventional FFG-7.
- The weight and volume distributions for the ships, compared in Figs, 15 and 16, indicate exceptionally large usable loads for the HPFFG's. If the essentially "inert" payload predicted by the model were converted to a realistic military payload, the weight and volume allocation to personnel, electrical, auxiliary, ship systems and other ship operations would be increased.

Although the number of different ship features which must be taken into account in making a vehicle assessment has been reduced, the comparison does not reduce to as neat an analysis as that for the small ships. The significant features to be addressed are:

Advantages of fast HPFFG	*Advantages of payload HPFFG*	*Advantages of HOC*
		Small size
		Speed in sea state
		Motions in sea state
Speed in calm water		Speed in calm water
Range and endurance at slow speed	Range and endurance at slow speed	
Payload capacity	Payload capacity	

Since all three of these ships have the same operability, range at maximum speed, and stores endurance, the analysis has been simplified in a way which is quite manageable. A realistic vehicle assessment study between a displacement ship and hydrofoil can now be conducted because one would be comparing similar ships for similar missions.

1200-ton high-performance displacement ship. In recognition of the uncertainties related to the analysis of the 3585-ton high-performance FFG, a high-performance displacement ship of comparable size to the HOC was studied. A Series 64 hull form was selected to approximate the powering requirements of a high-speed displacement ship of this size. The HOC's performance features and design standards and the Series 64 powering estimates served as the input into the parametric model. The resultant characteristics of the 1200-ton high-performance displacement ship (HPD) are compared with those of the FFG-7, HPFFG's, and HOC in Table 12 and Figs. 15 and 16. Based on these data, the following observations were made.

- The HPD displacement is equal to the HOC.
- The maximum sustained speed in calm water of the HPD is the same as that for the HOC. However, the speed capability of the HPD would degrade with sea state more rapidly than the HOC.
- Both the HPD and HOC have approximately equal range and endurance at maximum sustained speed The HPD would have a marked advantage in range and endurance at 20 knots.
- The payload carrying capacity of the HPD is approximately twice that of the HOC.
- Ship motions in a high sea state would be more severe for the HPD than for the HOC. However, in all other areas of operability the two ships would be similar.
- The weight and volume distribution for the two ships is presented in Figs. 15 and 16. The large weight associated with the lift systems in the HOC has been reallocated to payload, fuel, and propulsion in the HPD.

An overall assessment of the HPD with the HOC would be similar to that of the HPPG and PHM. The significant features which are different and which should be considered in evaluating the military worth are:

Advantages of HPD	*Advantages of HOC*
Range and endurance at slow speeds	Speed in sea state
Payload capacity	Motions in sea state

Summary of results

The results of this study can be summarized as follows:

- Hydrofoils are smaller, carry more payload relative to their size, and are faster in both low and high sea states than conventional displacement ships. The hydrofoil's performance advantage is achieved 'by incorporating low ship impact design standards which save significant amounts of weight and space throughout the ship.
- In the following areas, hydrofoils are designed to different standards than displacement ships: main propulsion, electrical and auxiliary systems, ship structures, habitability, ship systems, and other ship operation systems. In all of these areas the hydrofoils have achieved significant weight and space savings at the expense of decreased ship operability. The feasibility of hydrofoils depends on this weight and internal volume savings, and thus the hydrofoil designer has little flexibility in the selection of subsystem design standards. On the other hand, a wide range of design standards can be applied to displacement ships. History has shown that displacement ship designers have taken a conservative approach in subsystem design, leading to

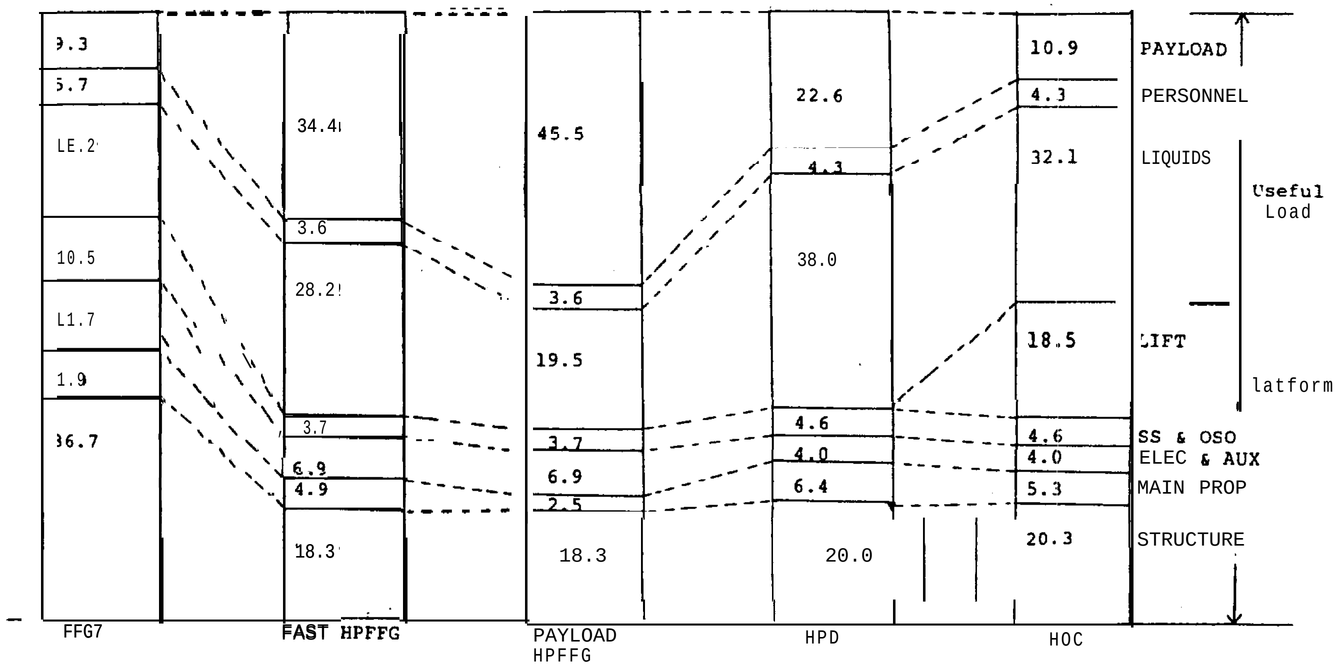

Fig. 15 Comparison of weight allocation-large ships

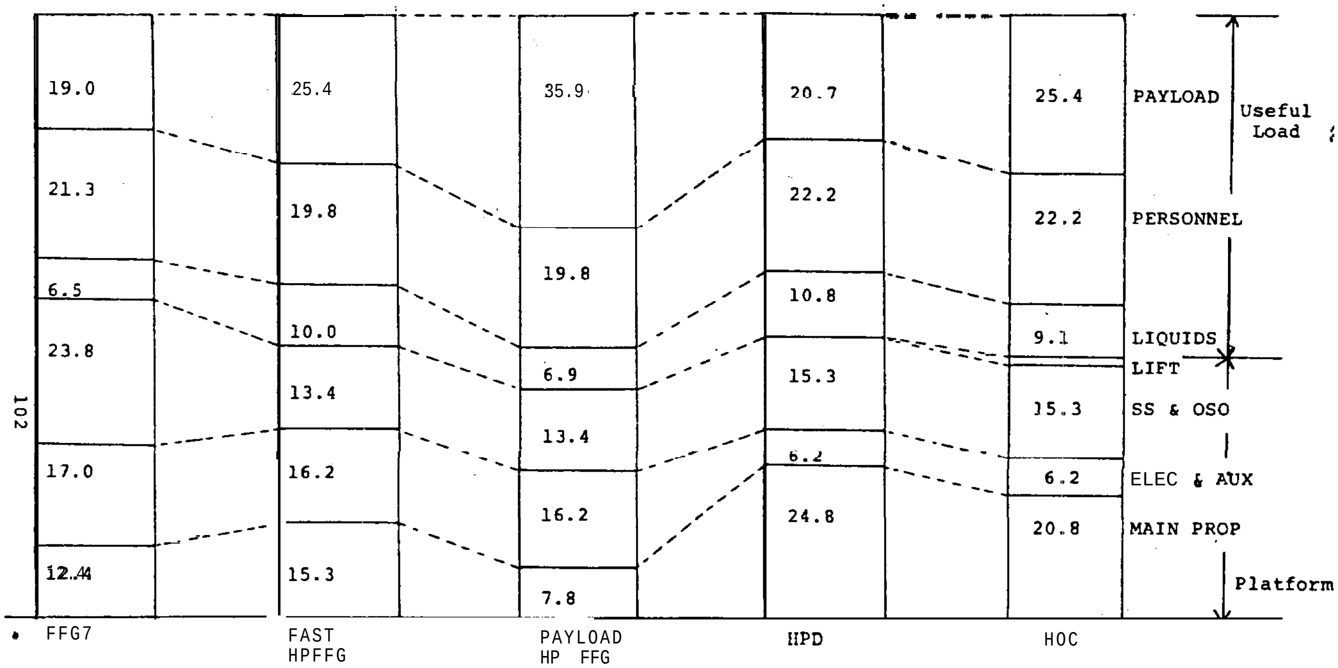

Fig. 16 Comparison of volume allocation-large ships

reduced basic performance but greater operability than the hydrofoil.

- The primary reason why large hydrofoils have a significantly higher speed capability in calm water than displacement ships of similar size is not due to superior hydrodynamic performance but rather due to lower propulsion specific weight.
- It is feasible for a displacement ship to be designed to hydrofoil standards. The resultant high-performance displacement ship would have basic performance and operability characteristics similar to those of the hydrofoil except in the following four areas:

Advantages of high-performance displacement ship	*Advantages of hydrofoil*
Range and endurance at low speeds	Speed in high sea state
Payload capacity	Motion in high sea state

These four features-range and endurance at low speed, payload capacity, speed in high sea states, and motions in high sea states-represent the inherent differences between hydrofoils and displacement ships. Other differences between existing hydrofoils and displacement ships are caused by differences in subsystem design standards.

Table 12 Comparison of large high-performance displacement ship

	FFG-7	Fast HP FFG	Payload HP FFG	1200-ton HPΔ	HOC
Size					
A, tons	3,585	3,585	3,585	1,276	1,275
v, ft^3	514,900	514,900	514,900	227,100	227,100
Mobility					
V_s (calm water), knots	28+	38	28+	40+	40+
V_s (sea state), knots	↓	1	↓	1	B
R@ V_s, NM	-2.000	-22.400	-2,400	~ 2,400	-2,400
R@ 20 knots	-4,500	10,900	6,600	6,700	-2,400
Endurance					
Stores endurance, days	45	30	30	30	30
Fuel end @ V_s	2.9	2.9	3.4	2.2	2.2
Fuel end @ 20 knots, days	9.4	22.8	13.9	14.1	5.3
Payload					
Payload weight, tons	333	1.233	1,631	288	139
VCG of payload, feet above keel	29.9	29.5	21.5		35.0
Payload volume, ft^3	97.799	130.200	185,000	46,900	57,745
Operability					
Complement	176	176	176	a 7	a 7
Hab standards		B	B	B	B
Motions in sea state		1	B	1	B
Main propeller standards	↑	B	B	B	B
Electrical standards	↑	B		B	B
Auxiliary standards	↑	B	B	B	B
Structural standards	↑	B	B	B	B
Ship systems and other ship ops standards		B	B	B	B

Summary and conclusions

In this study an analytical approach was developed utilizing a set of design indices to identify and then quantify the differences in design practices between naval hydrofoils and conventional displacement ships. A simple parametric design model was developed to determine the characteristics of a displacement ship designed to hydrofoil standards. From the analysis the following can be concluded:

- There are significant differences in the design of hydrofoils and conventional displacement ships in the areas of main propulsion, electrical and auxiliary systems, ship structure, habitability, ship systems, and other ship operation systems. Hydrofoils incorporate design standards which result in substantial weight and space savings at the expense of reduced operability. Conventional displacement ships are designed in a far more conservative fashion.
- A displacement ship designed to hydrofoil design standards exhibits a marked increase in calm water speed and payload capacity as compared with a conventional displacement ship. A high-performance displacement ship would be superior to a hydrofoil in payload capacity and range and endurance at slow speeds, but would be inferior in seakeeping qualities. All other performance features, including operability, would be approximately the same.
- Because design standards on a subsystem level have a first-order effect on basic performance capabilities (speed, endurance, payload capacity) and on ship operability (reliability, maintainability, availability, service life, system compatibility, flexibility) they should not be ignored in a vehicle assessment study.
- A transfusion of design practices is needed between the designers of high-performance and conventional displacement ships. The conservative design standards invoked in conventional displacement ships should be scrutinized to ensure they reflect the advanced technology which has been incorporated in high-performance ships. High-performance-ship designers should reanalyze their designs to ensure that operability features are viable and that these ships can be operated and maintained in a naval environment.

This study did not address or investigate in sufficient detail several important issues. It is recommended that a complete design study be accomplished for a high-performance displacement ship. This study should compare in detail the operability of a conventional and high performance displacement ship. Acquisition and life-cycle costs, overall military effectiveness, and technical risk should be addressed. The results of this study should then be applied to any assessment of advanced marine vehicles.

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Appendix

The tables in this Appendix define in detail the indices used in the paper. Table 13 defines the functional breakdown used in the study based on the Ship Work Breakdown Structure Weight Classification System [6] and the NAVSEC Space Classification System [7]. Table 14 lists the Level 1 design indices by type. Table 15 lists all the design indices used in the study arranged by feature.

Table 13 **Functional breakdown**

Symbol	Function	Space	Weight
P	Payload		
CD	Communications, detection & evaluation	1.1	410, 440, 450, 460, 471, 472,491 (0.5), 498 (0.51, 499 (0.5). 661*, 663, 665*, 672*
A	Armament	1.2, 1.3	473, 474, 476, 480, 491 (0.5), 492,498 (0.5), 499 (0.5). 522.542.543, 586, 587, 588, 661*, 665*, 672*, 710, 720, 730, 740, 750,760, '780,790, ship ammunition, aviation communication, aircraft, aircraft fuel
OP	Other payload	1.4, 1.5, 1.6, 1.7, 1.8	493, 495, 544, 557, 573, 591, 592, 594, 595, 596, 597, 673, 770
M	Personnel		
ML	Living	2.1	521 (0.2), 528*, 641, 642, 643, 644, crew and effects
MS	Personnel support	2.2	434, 439, 528*, 593,645, 650, 661*
MST	Personnel storage	2.3	533 (0.5), 638, 672*, provisions, stores, potable water,
H	Structure		
	superstructure		150
	masts & stacks		160,170
	foundations		180
	fluids		198
	basic hull		110, 120, 130, 140
MP	Main propulsion	3.12, 3.2	209 (less 299), 513,534, 639.662
	prime mover		
	transmission		
	shafting & propulsor		
	main prop. support		
	main prop. fluids		
AX	Auxiliary systems	3.31 (less spaces dedicated to lift systems), 3.32, 3.53, 3.54	
	climate control		512 (0.5), 514 (0.5), 516, 517
	seawater systems		521 (0.4)
	distilling plant		531
	gas & fluid systems		551 (0.8), 553, 554, 556 (0.8)
	steering & maneuvering		561, 562, 566, 568
	deck auxiliaries		571, 572, 581, 582, 583, 584, 585, 589
	auxiliaries fluids		598
E	Electrical	3.33	
	generator		310
	switchboard		324
	degaussing		475
	electrical support		340
	electrical fluids		398
F	Liquids	3.51	541,545, endurance fuel oil, reserve feed water, lubricating oil
	fuel		
	lube oil		
	feed water		
SS	Ship systems		
	passageways and access	3.7	
	cooling & venting		321, 322, 323, 330, 432 (0.6), 433, 435, 436, 437, 438, 511, 512 (0.51, 514 (0.5). 521 (0.4), 523, 524, 526, 527, 532,
	lighting		
	nonstructural bulkheads		
	painting		

(cont'd)

Table 13 (Continued)

Symbol	Function	Space	Weight
			533 (0.5), 535, 536, 551 (0.2), 552,556 (0.2), 558, 610, 620, 631, 632, 633,634, 635,636, 637, 671, 698
L	Lift systems	spaces dedicated to lift systems	567
OSO	Other shipps control	3.11, 3.13, 3.14	420, 431, 432 (0.4). 494, 555. 661*, 664
	maintenance	3.4, 3.52	199, 299,399, 599, 655*,
	tankage	3.6, 3.8	672*,191,529,699565

Notes:
A number in parentheses indicates the fraction of the weight group assigned to the functional category.
An asterisk identifies a weight group that is distributed among several functional categories in proportion to the deck area of each space.

Table 14 Design indices by type

Index	Units	Definition
1. Characteristics		
Δ	tons	full-load displacement
∇	ft^3	total internal volume
V_s	knots	maximum sustained speed
M	men	complement
R_s	NM	range
D	days	endurance
KW	KW	installed electrical power capacity
2. Weight allocation		
W_P/Δ		payload weight fraction
W_M/Δ		personnel weight fraction
W_H/Δ		structural weight fraction
W_{MP}/Δ		main propulsion weight fraction
W_{AX}/Δ		auxiliary systems weight fraction
W_E/Δ		electrical weight fraction
W_F/Δ		fluids weight fraction
W_{OSO}/Δ		other ship ops weight fraction
W_{SS}/Δ		ship systems weight fraction
W_L/Δ		lift system weight fraction
3. Volume allocation		
∇_P/∇		payload volume fraction
∇_M/∇		personnel'volume fraction
∇_{MP}/∇		main propulsion volume fraction
∇_{AX}/∇		auxiliary systems volume fraction
∇_E/∇		electrical volume fraction
∇_F/∇		fluids volume fraction
∇_{OSO}/∇		other ship ops volume fraction
∇_{SS}/∇		ship systems volume fraction
∇_L/∇		lift system volume fraction
4. Densities		
Δ/∇	lb/ft^3	ship density
W_P/∇^P	lb/ft^3	payload density
4. Densities (cont'd)		
W_M/∇_M	lb/ft^3	personnel density
W_{MP}/∇_{MP}	lb/ft^3	main propulsion density
W_{AX}/∇_{AX}	lb/ft^3	auxiliary systems density
W_E/∇_E	lb/ft^3	electrical density
W_F/∇_F	lb/ft^3	fuel density
W_{OSO}/∇_{OSO}	lb/ft^3	other ships ops density
W_{SS}/∇_{SS}	lb/ft^3	ship systems density
W_L/∇_L	lb/ft^3	lift system density
5. Specific ratios		
W_A/N_A	tons/=	armament specific ratio
W_M/M	tons/man	personnel weight specific ratio
∇_M/M	ft^3/man	personnel volume specific ratio
W_H/∇	lb/ft^3	structural specific ratio
W_{MP}/SHP	lb/SHP	main propulsion weight specific ratio
∇_{MP}/SHP	ft^3/SHP	main propulsion volume specific ratio
W_{AX}/∇	lb/ft^3	auxiliary systems specific ratio
W_{EL}/KW	lb/KW	electrical weight specific ratio
∇_{EL}/KW	ft^3/KW	electrical volume specific ratio
W_{OSO}/∇	lb/ft^3	other ship ops specific ratio
W_{SS}/∇	lb/ft^3	ship systems specific ratio
6. Capacity ship size ratios		
N_A/Δ	=/1000 tons	armament ship size ratio
M/Δ	men/100 tons	personnel ship size ratio
SHP/Δ	SHP/ton	propulsion power ship size ratio
KW/Δ	KW/ton	electrical power ship size ratio
7. Overall		
$\Delta V/SHP$		transport efficiency
$W_P V/\Delta$	knots	productivity index
L/D		lift drag ratio

Table 15 Design indices by feature

Index	Units	Definition
1. Main propulsion		
W_{MP}/Δ	%	main propulsion weight fraction
∇_{MP}/∇	%	main propulsion volume fraction
W_{MP}/∇_{MP}	lb/ft^3	main propulsion density
W_{MP}/SHP	lb/SHP	main propulsion specific weight
∇_{MP}/SHP	ft^3/SHP	main propulsion specific volume
$W_{prime\ mover}/SHP$	lb/SHP	prime mover specific weight
$W_{transmission}/SHP$	lb/SHP	transmission specific weight
$W_{support\ \&\ fluids}/SHP$	lb/SHP	support and fluids specific weight

(cont'd)

Table 15 *(Continued)*

Index	Units	Definition
∇_L/M	ft^3/man	personnel living specific volume
∇_{MS}/M	ft^3/man	personnel support specific volume
∇_{MST}/M	ft^3/man-day	personnel storage specific volume
D	days	stores endurance period
M	men	crew size
6. Payload		
W_P/Δ	%	payload weight fraction
∇_P/∇	%	payload volume fraction
W_P/∇_P	lb/ft^3	payload density
W_A/N_A	tons/=	armament specific weight
N_A/Δ	=/ton	armament capacity ship size ratio
7. Ship systems		
W_{SS}/Δ	%	ship systems weight fraction
∇_{SS}/∇	%	ship systems volume fraction
W_{SS}/∇	lb/ft^3	ship systems specific weight
8. Other ship ops		
W_{OSO}/Δ	%	other ship operations weight fraction
∇_{OSO}/∇	%	other ship operations volume fraction
W_{OSO}/∇	lb/ft^3	other ship operations specific weight

Discussion

Philip Mandel, Member

The senior author deserves the praise of the profession for instigating and inspiring the student theses that led him and them to this paper. While he was dubious about submitting this paper for presentation at this meeting, I urged him to do so because in my opinion the paper presents a very clear-headed view of a complex issue. The Papers Committee of SNAME also deserves great credit for recognizing the merit of the paper amidst its obvious shortcomings.

The paper acknowledges its three major weaknesses; inattention to cost, to seakeeping, and to the quantitative aspects of the broad meaning of operability used in the paper. Nevertheless, by comparing hydrofoils and displacement ships using the same subsystem design standards for both vehicle types, the paper really circumvents the two issues of cost and operability. If the senior author had instigated a third student thesis on the comparative seakeeping qualities of hydrofoils and displacement ships, the third issue could have also been covered.

The issue that aroused the authors to begin this work in 1973-74, the issues that the authors could not address in this paper, as well as the issue of the application of advanced naval vehicles to realistic Navy missions are all now receiving the attention they deserve within the Advanced Naval Vehicles Concept Evaluation (ANVCE) program of the Navy. The issue that aroused the authors three years ago is as follows: Advanced subsystems technologies that promised to make the SES and the hydrofoil vehicles feasible for naval missions were being developed. The authors saw that while, unlike these vehicle types, the surface ship is feasible, useful and attractive without these advanced subsystems, with them its performance would be greatly enhanced. They further recognized the vital principle that any fair assessment of competitive vehicle types must apply the same subsystem design philosophy to all vehicle types. Yet the assessments that were being made three or more years ago and are continuing to this day totally ignored this crucial step. This same issue aroused this discusser and the Panel of which he was a member 15 years ago and gave rise to the current paper's reference [5]. While the current paper is the first attempt in 15 years to openly address this important issue, I trust that it is just the forerunner of a whole series of papers on the issues involved in vehicle assessment.

Peter G. Rainey, Member

[The views expressed herein are the opinions of the discusser and not necessarily those of the Department of Defense or the Department of the Navy.]

The authors are to be congratulated for an excellent paper which illuminates the different design practices and advantages applicable to each of the vehicles discussed.

In the subsection "Analysis of design tradeoffs" the authors make the statement, "it was felt that the high-performance standards reduced the operability of the ship." Further, they state, "A basic assumption made . . . is that the operability of a ship feature is directly proportional to the weight and space allocation, provided similar types of equipment are utilized."

Two points need to be stated in the clearest manner. First, a hydrofoil of the size of the HOC which uses the propulsion specific weight and hull structure specific ratio of an FFG-7 has so little weight left to he allocated that it is totally infeasible. This fact is obvious. Second, if the weight fractions allocated for a hydrofoil design were similar to the FFG-7, payload (as defined by the authors) would be reduced by one-third, range would be reduced by one-half, while all other weights, except lift system, would increase. Thus, using the authors' assumption, the operability would be increased.

Table 16 compares the HOC with the two designs just discussed. Ship (X) is the infeasible hydrofoil; Ship (Y) is the hydrofoil with weight fractions similar to the FFG-7.

Obviously, the main design tradeoffs have been accomplished to attain the desired range of the HOC.

As seen in Table 1.7, examination of just two of the many design indices, SHP/ton and fuel weight fraction, illustrates that high-performance ships have large values of SHP/ton and large fuel weight fraction.

These two design indices are related. By taking a first-order approximation to the authors' equations for total fuel weight, one obtains

$$\text{Fuel weight fraction} = (R_S/V_S)(SHP/\text{ton})\ SFC/2240$$

Until major technology advances can be made to reduce the specific fuel consumption, high-performance vehicles will re-