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78-725

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AIAA/SNAME ADVANCED MARINE VEHICLES CONFERENCE

San Diego, California/April 17-19, 1978

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BALANCING MISSION REQUIREMENTS AND HYDROFOIL DESIGN CHARACTERISTICS

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Abstract

Achieving the proper balance between "technology push" and "requirement pull" is an important aspect in the orderly development of advanced vehicles such as hydrofoil ships. All too often top level requirements are based on what is technically achievable without full realization of their effect on ship design. This paper quantifies the relationship between mission requirements and hydrofoil ship design characteristics, so that top level requirements can be established with fuller awareness of their impact. Mission related parameters such as payload weight, range, maximum speed, sea state, complement, and mission duration are varied and their effect on design characteristics are presented. In contrast to the usual parametric approach, this study, through the use of the hydrofoil computer-aided design tool, HANDE, reaches a level of integrated analysis and design detail heretofore not available. The technology constraints used in the study are presented and reflect the current hydrofoil ship state-of-the-art. The study reaffirms the need for a cost model more directly sensitive to ship design parameters.

Introduction

The operational community depends on data supplied by the design community when setting mission requirements* for naval vehicles. All too often the design community tends to emphasize what is technically feasible rather than presenting trade-off data in a form which permits the Navy to assess the impact of mission requirements on platform characteristics and thus on cost. This situation is further aggravated in the case of advanced vehicles such as hydrofoil ships. In contrast to conventional ships, the Navy is confronted with a more limited data base for advanced ships to aid in relating mission capability and ship size. Furthermore, advanced vehicles have a greater weight and size sensitivity to mission requirements. In the current cost-conscious climate there is a greater need to be capable of determining the minimum size platform that will do the job effectively.

The purpose of this paper is to demonstrate the ability to address the interrelationships that balance hydrofoil ship operational requirements and platform characteristics. The paper has two specific objectives. First, to quantify the tradeoffs between requirements and characteristics over a spectrum of hydrofoil operational capabilities. Secondly, to provide a context in which the state-of-the-art of hydrofoil technology can be expressed in terms of operational parameters.

Methodology

General

Four notional military payloads of 30, 60, 120, and 240 tonnes were selected to accomplish the objectives of the study as detailed above. These payloads are intended to encompass the spectrum of envisaged hydrofoil carried weapons suites that represent capabilities ranging from single mission to multi-mission with air-capability. The warfare areas and weight and volume breakdown that might be appropriate to each payload are shown in Table 1.

Table 1 Baseline military payload characteristcs.

MILITARY PAYLOAD, TONNES		30	60	120	240
CAPABILITY	SUW	●	●	●	●
	ASW		●	●	●
	AAW			●	●
	AIR CAPABILITY (2) HELO'S				●
WEIGHTS (TONNES)	COMMAND & SURVEILLANCE	7.5	37.6	50.4	54.1
	ARMAMENT	9.5	12.3	22.0	75.6
	MISSILES & AMMUNITIONS	13.0	10.1	47.6	110.3
	TOTAL PAYLOAD WEIGHT	30.0	60.0	120.0	240.0
VOLUMES (M^3)	COMM, DETECT & EVAL	135	476	629	668
	WEAPONS	7	14	521	422
	AVIATION	0	0	0	1260
	TOTAL PAYLOAD VOLUME	142	490	1150	2350

For each of the above payloads an appropriate manning level was established using existing hydrofoil ships and design study data. Many of these design studies have had extensive analyses conducted to establish a realistic manning level. Figure 1 shows crew sizes for each of the selected payloads as a function of military payload.

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*mission or operational requirements (used interchangably in this paper) are those platform performance parameters directly related to fulfilling a military role.

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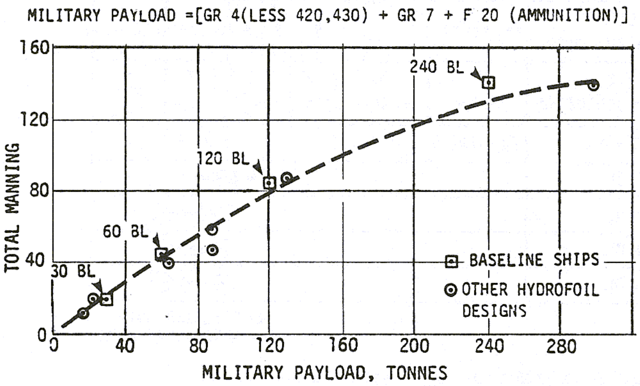


Fig. 1 Hydrofoil manning as a function of military payload.

For each of the military payloads and manning levels, realistic operational requirements were set for foilborne range, design foilborne speed, foilborne sea state capability, mission duration, and hullborne speed. It must be stressed that these operational requirements, although arbitrarily selected, are thought to be representative of the capabilities appropriate to each weapon suite. These operational requirements along with crew size are shown in Table 2.

Table 2 Operational requirements for baseline ships.

MILITARY PAYLOAD (TONNES)	30	60	120	240
FOILBORNE RANGE, NM	1500	2000	2500	3000
DESIGN FOILBORNE SPEED, KTS	50	50	50	50
FOILBORNE SEA STATE CAPABILITY, $H_{1/3}$, m [FT]	3[10]	4.6[15]	4.6[15]	4.6[15]
CREW SIZE, PEOPLE	21	45	84	140
MISSION DURATION, DAYS	10	20	30	30
DESIGN HULLBORNE SPEED, KTS	15	15	15	15

It should be noted that no hullborne range requirement is addressed. The hullborne range is treated as a dependent variable and is determined by the fuel carried to meet the foilborne range requirement. A concept which is presented in this study is that of achieving a speed of advance (SOA) by using a "mixed-mode" operation, i.e. mixing foilborne and hullborne operations in appropriate proportions. In the Discussion of Results section a method is presented whereby a foilborne range requirement can be determined from a specified SOA and range.

Having selected the operational requirements for each of the four military payloads, four "baseline ships" were designed. (These are designated 30 BL, 60 BL, 120 BL and 240 BL). Each baseline ship is an integrated design carried out with the aid of the Hydrofoil ANalysis and DEsign (HANDE) Program. A description of the HANDE Program can be found in Reference 1 and an overview of its capabilities is presented in Appendix A. It should be stressed that the HANDE Program allows the designer to converge on both weight and enclosed volume. The resulting characteristics of the four baseline ships are presented in Table 3.

Table 3 Baseline ship characteristics.

PAYLOAD, TONNES	30	60	120	240
PHYSICAL CHARACTERISTICS				
LBP, METERS [FEET]	39[129]	52[170]	69[225]	82[270]
HULL BEAM, MAXIMUM, m [FT]	9.7[32]	11.6[38]	14.6[48]	16.1[53]
FOIL SPAN, MAXIMUM, m [FT]	13.1[43]	18.6[61]	26.2[86]	36.0[118]
DRAFT, FOILS DOWN, m [FT]	7.5[25]	10.4[34]	11.4[38]	12.6[41]
HULL DRAFT, FOILS UP, m [FT]	2.0[6.7]	2.7[8.8]	3.4[11.0]	4.2[13.9]
FULL LOAD DISPLACEMENT, TONNES	298	674	1350	2618
TOTAL ENCLOSED VOLUME, m^3 [FT^3]	1305	2591	5069	8637
[FT^3]	46,100	91,500	179,000	305,000
FOIL LIFT DISTRIBUTION, FWD/AFT, PERCENT	33/67	40/60	40/60	40/60
CREW SIZE				
OFFICERS	5	6	10	14
CHIEF PETTY OFFICERS	4	5	6	12
ENLISTED	12	34	68	114
TOTAL	21	45	84	140
PAYLOAD, TONNES	30	60	120	240
PERFORMANCE (SEA STATE 0)				
MISSION DURATION, DAYS	10	20	30	30
DESIGN FOILBORNE SPEED, KNOTS	50	50	50	50
FOILBORNE RANGE @44 KNOTS, NM	1500	2000	2500	3000
SPECIFIC RANGE @44 KNOTS, NM/FUEL TONNE	21.5	10.9	6.61	3.51
ENDURANCE @ 44 KNOTS HOURS	34	46	57	70
MAXIMUM HULLBORNE SPEED, KNOTS	15	15	15	15
HULLBORNE RANGE @12 KNOTS, NM	2560	4030	5650	8050
SPECIFIC RANGE @ 12 KNOTS, NM/FUEL TONNE	36.6	22	14.9	9.5
RANGE @ 21.5 KNOTS, NM (30% TIME FOILBORNE)	1814	2527	3240	4061
ENDURANCE @ 21.5 KNOTS, HOURS (30% TIME FB)	84	117	150	188
ENVIRONMENTAL				
FOILBORNE SEA STATE CAPABILITY, $H_{1/3}$, m [FT]	3[10]	4.6[15]	4.6[15]	4,6[15]
PAYLOAD, TONNES	30	60	120	240
POWER DATA				
FB INSTALLED PWR.(MAX CONTINUOUS),METRIC HP	12,600	27,300	62,000	101,000
HB INSTALLED PWR., METRIC HP	2470	4030	5820	9220
ELECTRICAL INSTALLED POWER, KW	431.3	840.3	1144.0	1612.6
WEIGHT DATA				
HULL STRUCTURE WEIGHT, TONNES	53.9	105.3	208.3	318,0
PROPULSION SYSTEM WEIGHT, TONNES	25.2	56.0	109.8	239.5
ELECTRICAL SYSTEM WEIGHT, TONNES	8.6	16.1	22.9	33.1
COMMAND AND CONTROL (GROUP 400), TONNES	11.4	43.1	59.3	67.8
AUXILIARY SYSTEMS, LESS FOIL-STRUT, TONNES	17.2	45.3	95.5	167.4
FOIL AND STRUT SYSTEM, TONNES	34.9	83.1	175.7	242.9
OUTFIT AND FURNISHINGS, TONNES	18.3	38.6	74.2	125.1
ARMAMENT, TONNES	9.5	12.4	22.0	75.6
MARGINS (15% ON LIGHTSHIP), TONNES	26.9	60.0	114.8	205.0
LIGHTSHIP, TONNES	(205.9)	(459.8)	(880.6)	(1574.0)
CREW AND EFFECTS, TONNES	2.7	5.3	9.7	16.0
MISSILES AND AMMUNITIONS,TONNES	13.6	10.1	47.0	110.3
PROVISIONS, TONNES	0.9	4.0	11.3	18.8
FUEL, TONNES	71.2	187.0	385.8	870.8
LUBE OIL, TONNES	0.7	1.7	3.3	6.4
FRESH WATER, TONNES	3.1	6.7	12.5	20.8
TOTAL LOADS, TONNES	(92.2)	(214.8)	(469.6)	(1043.1)
FULL LOAD DISPLACEMENT, TONNES	298.1	674.6	1350.2	2617.1

As mentioned in the introduction, the main thrust of the paper is not to present a number of hydrofoil ship designs, but rather to demonstrate the interrelationships that balance operational requirements with platform characteristics. The method chosen to accomplish this objective was to vary each of the following mission requirements while keeping the remainder at their "baseline ship" value:

- Foilborne Range
- Design Foilborne Speed
- Foilborne Sea State Capability
- Crew Size
- Mission Duration

To ensure that meaningful trends could be established, two variations of each of the above operational requirements for all four baseline ships were examined. For consistency, each variation was designed to the same level of detail as the baseline ships. As there are five mission requirements for each baseline ship, this involved redesigning 10 ships per baseline ship or 40 ships in all. It was also decided to examine the weight sensitivity of each baseline ship. Although not an operational requirement per se, weight sensitivity influences decisions concerning vulnerability and survivability or the development and use of lightweight ship subsystems. This involved another 8 designs, bringing the total number of variations to 48. The range of operational requirements presented below are felt to span the spectrum of interest.

Foilborne Range

The span of maximum foilborne range requirements considered are shown in Figure 2. It should be noted that these ranges are achieved at speeds of 40 knots or greater.

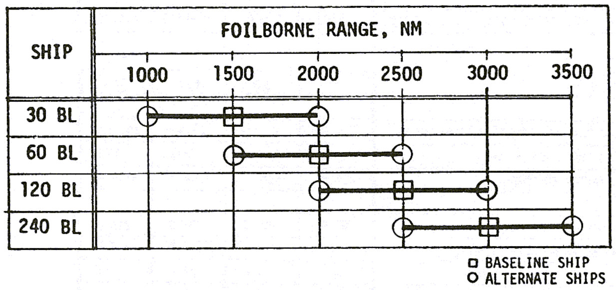


Fig. 2 Foilborne range requirement variations.

Design Foilborne Speed

The span of maximum design foilborne speed considered was from 40 to 55 knots. The upper design speed of 55 knots is essentially the limit of subcavitating foils.

Foilborne Sea State Capability

The span of foilborne sea state capability examined is shown in Figure 3. These are expressed as the maximum significant wave height (average of the one-third highest waves) that the ship can operate foilborne while meeting the ship motion requirements outlined in Appendix B.

Crew Size

The crew size was varied plus and minus 25% from the baseline values. The distribution of officers, CPO's, and enlisted men were held constant for the two larger payloads. For the two smaller payloads most of the crew change occurred with the enlisted men because a minimum nucleus of officers and CPO's is always required.

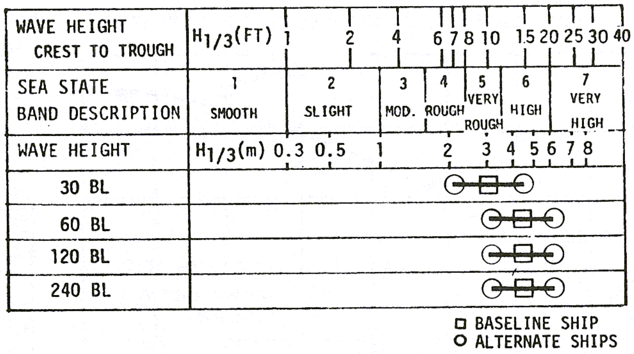


Fig. 3 Foilborne sea state capability variations.

Mission Duration

Mission duration is defined as the maximum mission length that would normally be demanded of a naval vehicle. Figure 4 shows the span of mission duration requirements examined.

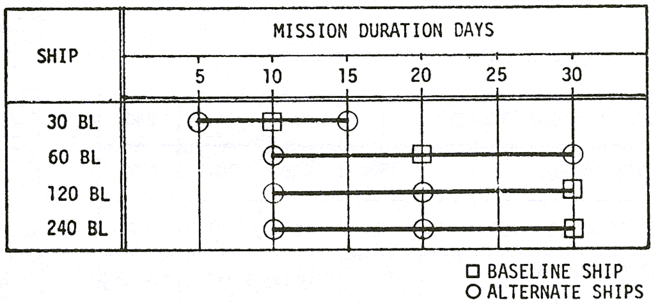


Fig. 4 Mission duration variations.

Weight Sensitivity

To determine this sensitivity, weights corresponding to one-quarter and one-half of each military payload were added to each baseline ship.

Design Program

A significant end product of the Hydrofoil Advanced Development Program is the development of tools that provide feasibility and conceptual designs in a time frame useful in the decision making process. This capability is manifested in the HANDE Program which was developed by The Boeing Company under a U.S. Navy contract over a 5½-year period. Its objective is to provide a fast, consistent, and easily-used tool for integrating all the technologies necessary for designing hydrofoil ships to meet specified mission requirements.

A description of the HANDE Program can be found in Reference 1 and an overview of its capabilities is presented in Appendix A.

Design Constraints

Hydrofoil ship subsystem parameters were kept within the state-of-the-art on the ships designed in this study. The assumptions and constraints used in this study and their justification are described in Appendix B.

Discussion of Results

General

The results of varying the mission requirements are discussed in this section. Figure C-1 of Appendix C presents an example of how the data were plotted illustrating the effect of changing the six operational requirements on the baseline ships. A brief explanation of this figure is appropriate before discussing, in detail, the effect of each operational requirement perturbation. The figure shows the main ship characteristics of full load displacement, foilborne maximum continuous horsepower, specific range, hullborne maximum continuous horsepower, hullborne range, internal volume, lightship weight, hull system weight, propulsion system weight, and strut and foil system weight. The effect on the baseline ship of altering any of the six mission requirement parameters across the top of the plots can be determined by entering the column containing the parameter of interest and selecting an alternate value of this parameter. By moving vertically a new value of each ship characteristic can then be determined. For example, the effect of increasing the crew on this 30 tonne military payload baseline ship (30 BL) from 21 to 24 is illustrated on the figure. Only one mission requirement change can be examined at a time; the other five remain at the baseline ship value.

The figure can also be used to determine which operational tradeoffs are equivalent by drawing a horizontal line through the six plots for any of the ten ship characteristics such as full load displacement, foilborne maximum continuous horsepower, or strut and foil system weight. In the example given above, if equivalent effects on lightship weight (<u>usually</u> an indication of acquisition cost) are to be examined, it can be seen that the change in crew size from 21 to 24 has the same effect on lightship weight as does increasing the foilborne range from 1500 to 1875 nautical miles, <u>or</u> increasing the design speed from 50 to 53.5 knots, <u>or</u> increasing the foilborne design wave height from 3 to 4 meters (10 to 13.1 feet). The horizontal line fails to intersect the mission duration and additional weight plots. This indicates that changes to these two parameters in terms of an equivalent lightship weight are beyond the range in variations considered appropriate for this payload.

Foilborne Range

Figure 5 shows the full load displacement as a function of military payload for various foilborne range requirements. This plot is useful in approximating full load displacement of a hydrofoil ship to carry a military payload for a specified foilborne range.

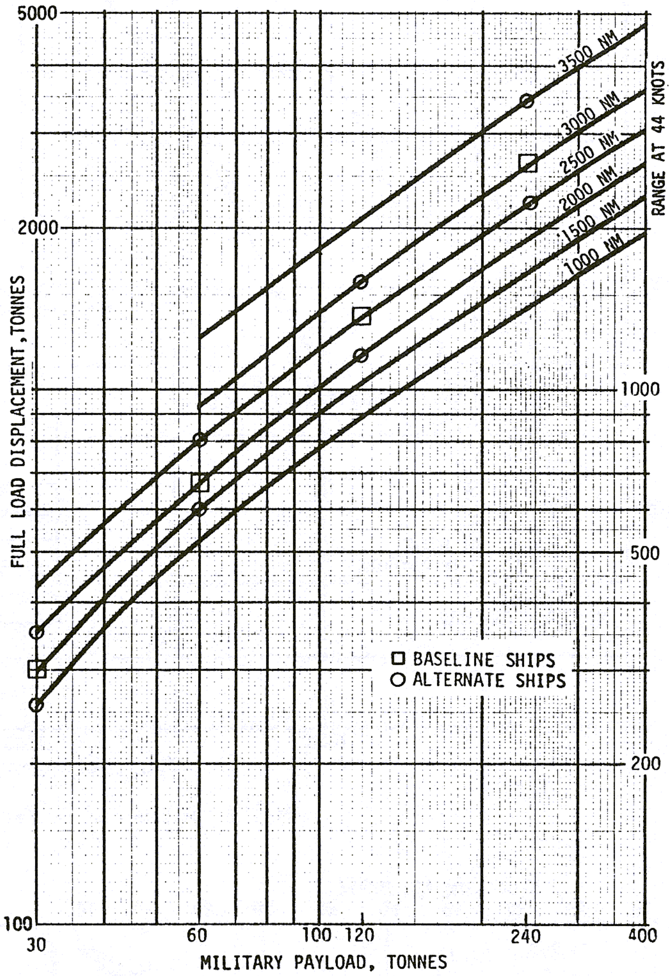
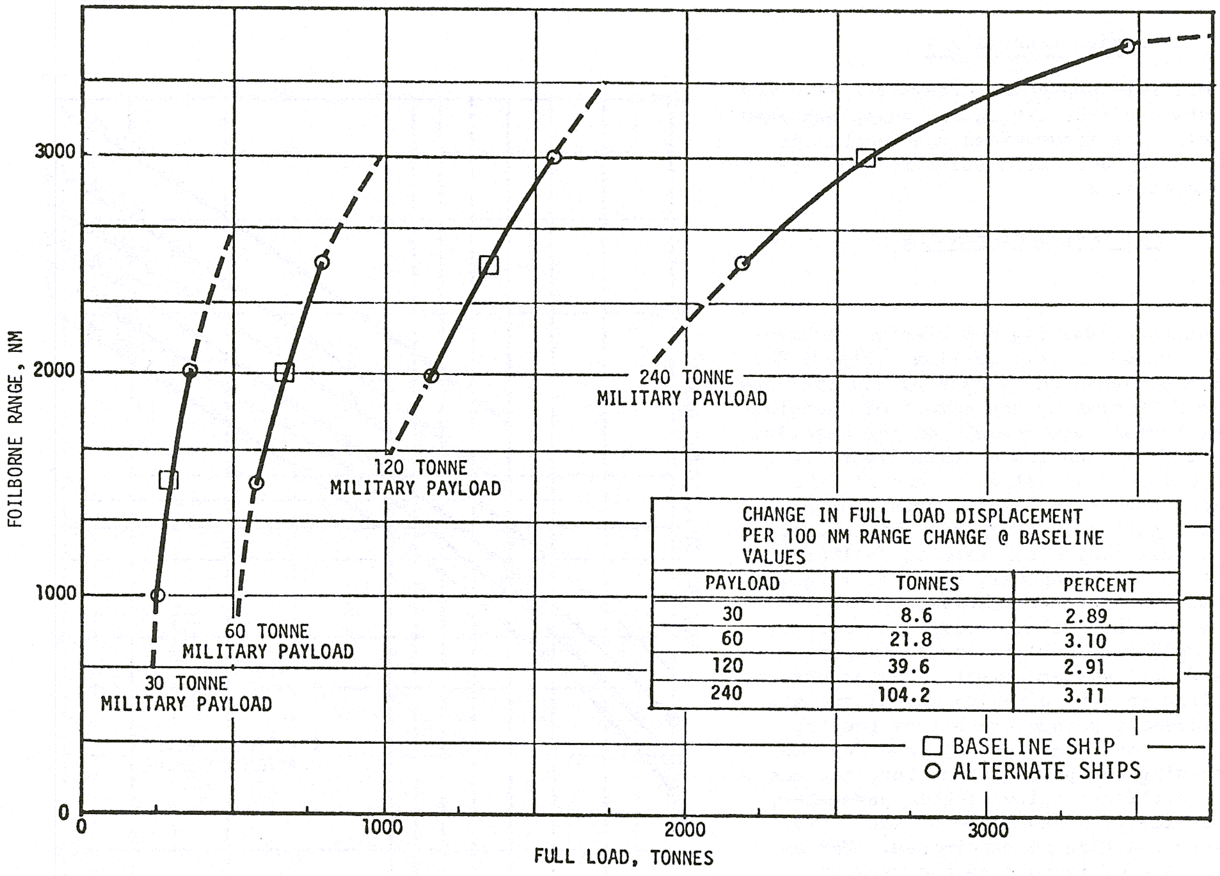


Fig. 5 Full load displacement as a function of military payload for various foilborne ranges.

Figure 6 shows how the sensitivity of changes in the foilborne range requirement varies with ship size. This sensitivity about the baseline values in terms of full load change per 100 nautical mile change, is tabulated on the figure. It can be seen that when the payload, along with the crew required, reaches a certain size, additional range becomes expensive. There appears to exist a limit to the size of a hydrofoil which can be supported by the assumed foil configuration (inverted π forward and aft) beyond which no additional range can be gained. Other factors, such as power limitations per strut, would probably govern the maximum hydrofoil ship size before this area of "no range return" is reached.

The range sensitivity was only examined with regard to a foilborne range required; the hullborne range "dropped out" as a dependent variable. It is frequently desirable, however, to specify a Speed of Advance (SOA) along with a required range at the SOA. This SOA may be achieved by using a mixed-mode operation during which efficient hullborne and foilborne speeds are correctly proportioned. Figure 7 can be used to translate any SOA



CHANGE IN FULL LOAD DISPLACEMENT PER 100 NM RANGE CHANGE @ BASELINE VALUES

PAYLOAD	TONNES	PERCENT
30	8.6	2.89
60	21.8	3.10
120	39.6	2.91
240	104.2	3.11

Fig. 6 Foilborne range sensitivity.

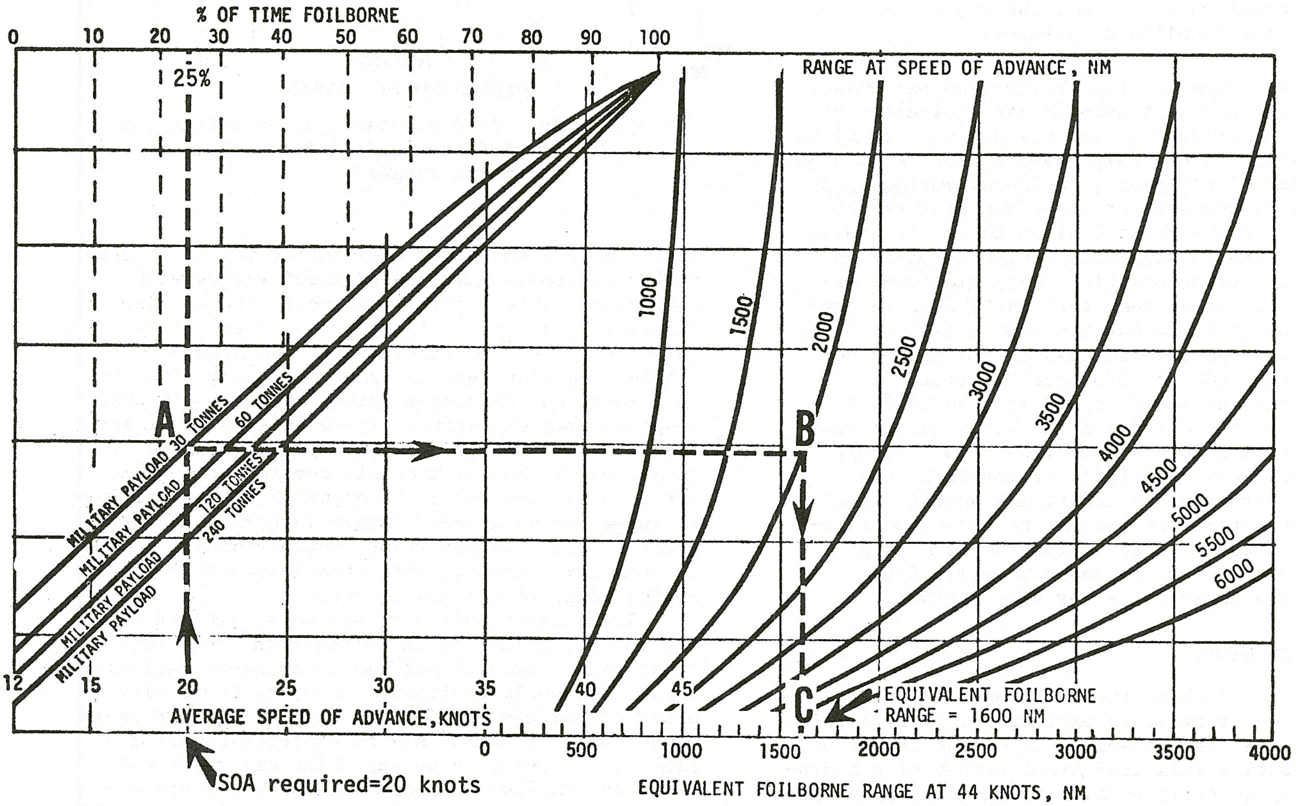


Fig. 7 Equivalent foilborne range required at different speeds of advance for different military payloads.

and associated range requirement into an "equivalent foilborne range requirement". Note that the figure shows the percent of time foilborne necessary to achieve each SOA. An example of this technique for the 30 BL ship is shown on Figure 7. If it is desired to have a range of 2000 nautical miles at a 20 knot SOA, the figure is entered with 20 knots and a line drawn vertically to intersect the 30 tonne military payload curve at point A. A horizontal line is drawn from this point to meet the 20 knot SOA range of 2000 nautical miles at point B. The equivalent foilborne range of 1600 nautical miles can then be picked off the bottom scale at point C. This range could then be used to enter the range column of Figure C-1 to determine the characteristics of the required ship.

As previously mentioned, the hullborne ranges available resulted from the fuel carried to meet the foilborne range requirement. For some missions, longer hullborne ranges may be desired. In such cases the hullborne range would size the fuel load. For the speeds assumed in this study, Figure 8 can be used to determine which range requirement is dominant.

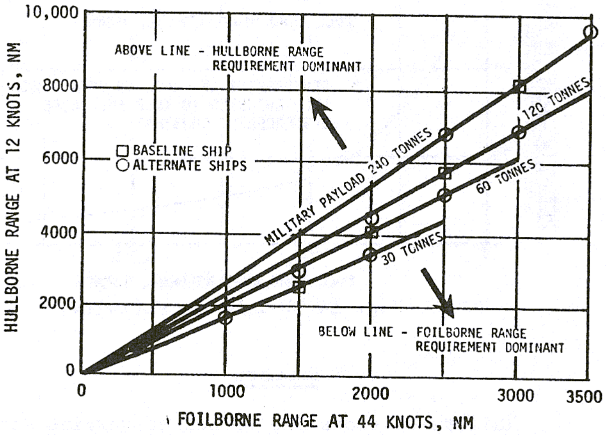


Fig. 8 Relationship between hullborne and foilborne range requirements for different military payloads.

Design Foilborne Speed

One of the key sensitivities to be considered in setting requirements is the effect of speed on ship design. To assess this, the baseline ships' design speeds were lowered to 40 knots and raised to 55 knots. Figures 9 and 10 show the effect of speed on full load displacement, installed power, and specific range. For the same range, reducing the design speed from 50 to 40 knots decreases the full load displacement 10 to 13% and the power 24 to 30%; increasing the design speed from 50 to 55 knots increases the full load displacement 12 to 17% and the power 37 to 41%.

Foilborne Sea State Capability

The sea state requirement primarily affects strut length. This has secondary effects on all ship subsystems; the total effect on full load dispalcement is shown in Figure 11. As one would expect, changes in sea state requirement have more effect on small hydrofoils than on larger ones. For instance, decreasing the foilborne sea state requirement from 4.6 meters (15 feet) to 3.0 meters (10 feet) significant wave height reduces the full load displacement of the 30 BL 11%; the 60 BL 5%; the 120 BL 3% and the 240 BL less than 1%.

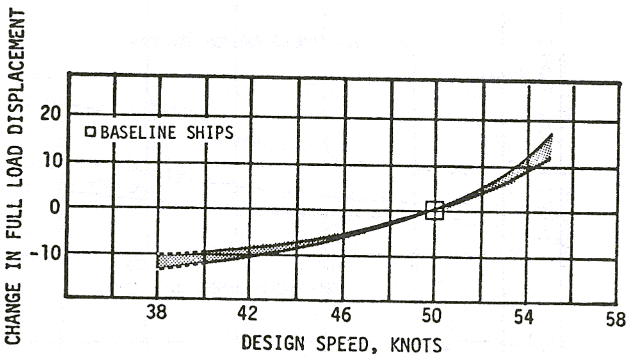


Fig. 9 Sensitivity of speed on full load displacement.

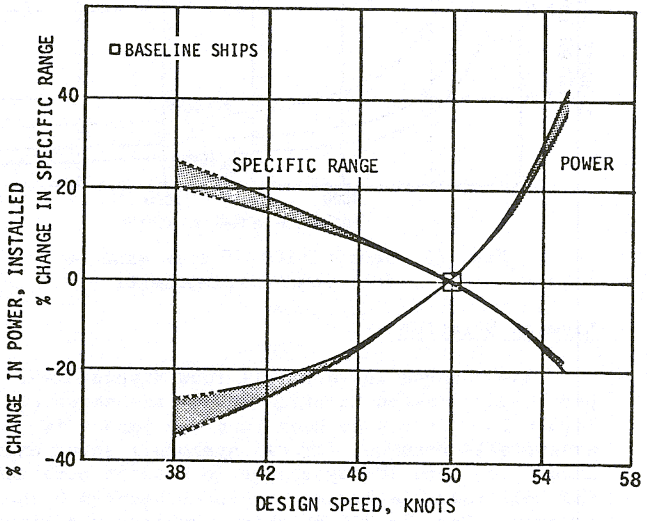


Fig. 10 Sensitivity of power and foilborne specific range to speed.

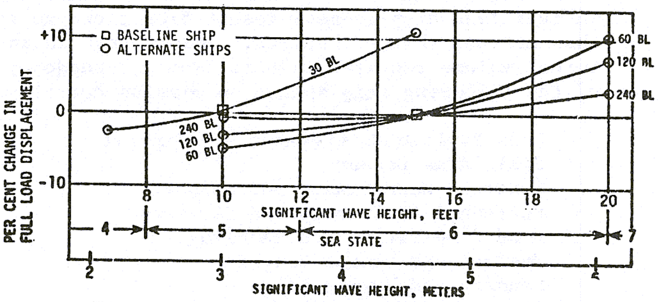


Fig. 11 Effect of design foilborne sea state requirements on full load displacement.

Crew Size

Figure 12 shows the effect on full load displacement for each officer, chief petty officer and enlisted man added or removed. When the crew size changes, the primary change is in the internal ship volume. This change impacts on all ship systems and contributes 80 to 85% of the change in full load displacement while provisions and outfit and furnishings account for the remaining 15 to 20%.

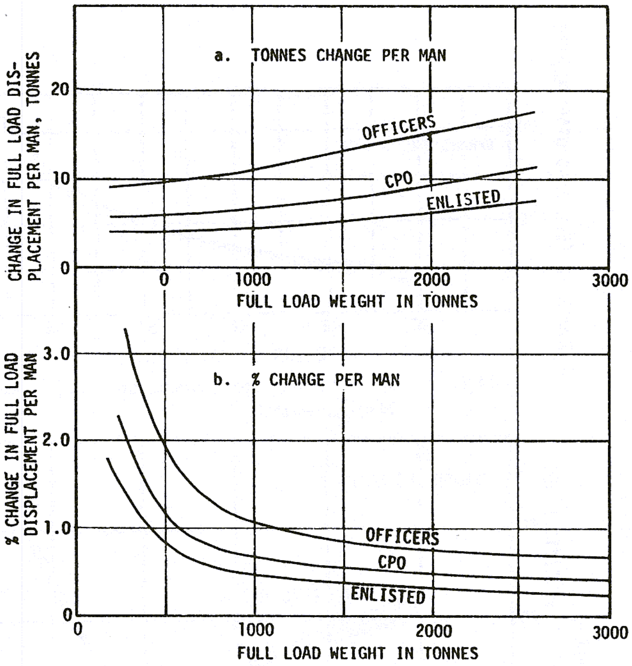


Fig. 12 Sensitivity of crew size on full load displacement.

Mission Duration

The changes in ship full load displacement per 10-day mission duration change are shown on Figure 13. It can be seen that the impact is essentially constant for all hydrofoil ships examined. For each 10-day change in mission duration the full load displacement changes between 5 and 7 percent. For the 240 BL ship, lowering the mission duration from 30 to 10 days reduces the full load displacement from 2600 to 2250 tonnes. The changes in full load displacement result from a change in the internal volume required. This change in internal volume required results from a dependency of the following ship spaces on mission duration:

Ship Payload Maintenance and Support
Small Arms Locker
Aircraft Maintenance and Support
Personnel Administration Services
Food Preparation and Handling
Medical and Rental Stores
Laundry and Drying Rooms
Ship's and Personnel Stores
Ship's Offices
Ship's Maintenance
Stores and Supplies
Crew Messing
Crew Accommodation

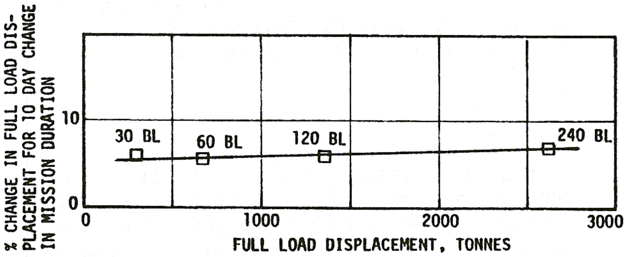


Fig. 13 Sensitivity of full load displacement to mission duration.

Weight Sensitivity

The sensitivity to changes in weights which do not directly have a concomitant volume are shown in Figure 14. Such weight changes would be those required for ballistic protection, passive fire protection, et cetera. These data can also be used to assess the impact of weight savings efforts. The sensitivity to weight changes are shown in terms of full load displacement keeping range constant in Figure 14a, and in terms of range keeping full load displacement constant in Figure 14b.

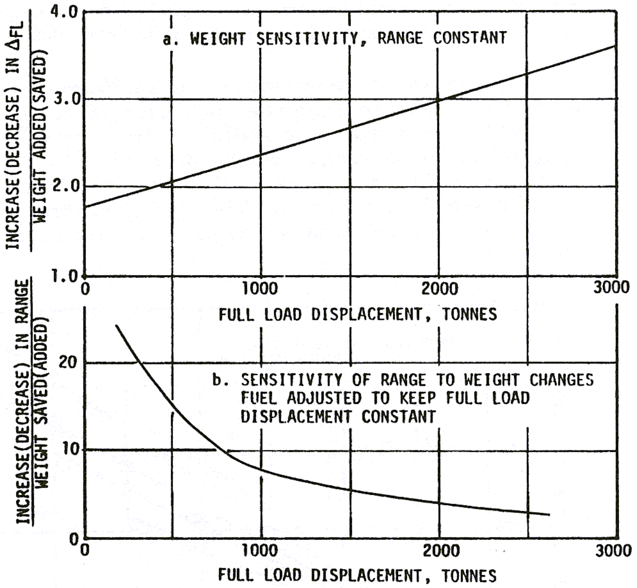


Fig. 14 Weight sensitivity.

Summary

This paper shows the effect of varying six mission requirements on the characteristics of notional hydrofoil ships with military payloads of 30, 60, 120, and 240 tonnes. Data are presented which assess the impact of payload, range, design speed, sea state capability, crew size, and mission duration on hydrofoil ship platform characteristics. The weight sensitivity of hydrofoil ships is also quantified.

This study was performed using the hydrofoil computer aided design tool, HANDE, to reach the level of integrated analysis and design detail necessary to obtain accurate sensitivity and trending data. This design tool improves the Navy's capability to assess the impact of mission requirements on hydrofoil design characteristics and aids in establishing top level requirements.

The capability demonstrated is important for hydrofoil ships which, like all high performance ships, are particularly sensitive to mission requirements and the interdependency of subsystems design and technical disciplines. HANDE can respond to queries in a short time frame (usually less than a day). This quick response can expedite and improve the decision making process by providing the operational community timely and more definitive trade off data than heretofore available.

The capability to trade off operational requirements and platform characteristics is only the first step in providing an improved method to establish mission requirements. A cost model which is sensitive to ship design characteristics is needed to quantify the impact of mission requirements on acquisition and operational costs. A model of this type would help supply answers to such questions as:

1. Is it more cost effective to distribute the military payload on several small ships rather than place it on a single ship? For example, is it cheaper to have 6 ships with 60 tonne military payloads or 3 ships with 120 tonne payloads?

2. If the range requirement is reduced, how many more ships can be built for the same acquisition cost?

3. What is the overall effect, in terms of life cycle cost, of reducing crew size by automating certain payload functions such that the payload weight is increased?

When a cost model is incorporated in HANDE, the above and other cost-effective issues can be addressed.

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APPENDIX A

DESCRIPTION OF *HANDE* PROGRAM

The HANDE program consists of four major sections as illustrated in Figure A-1. These can be called upon by the designer, interactively, to create and analyze a candidate ship configuration. A single ship configuration is available for evaluation within the program at any given time. This ship is referred to as the *CURRENT MODEL*.

A data bank provides a means of temporarily or permanently storing different *CURRENT MODELs* between analyses or between different computer sessions. The data bank also provides a source of data describing existing hydrofoil ships and ship components.

An *INITIALIZATION* section uses parametric methods to perform initial ship size and performance estimates. This module also provides a detailed estimate of ship internal space requirements as guidance for the designer in sizing the hull. The space required estimating technique used in HANDE is based on the surface ship space estimating relationships as defined in the Highly Sensitive Ship Synthesis Model for Surface Combatants developed by The Naval Ship Engineering Center (NAVSEC). These relationships have been modified to introduce mission duration sensitivity and be appropriate for hydrofoil ships up to 3500 tonnes.

The real power of HANDE is contained in the *SYNTHESIS* section of the program. *SYNTHESIS* consists of ten technology modules which use more detailed analytic methods to size major ship components. Figure A-2 illustrates the sequence of design through the *SYNTHESIS* section of HANDE. Two iterative loops are provided to ensure internally consistent designs. To provide a feel for the depth of analysis, a brief description of the technology modules is in order.

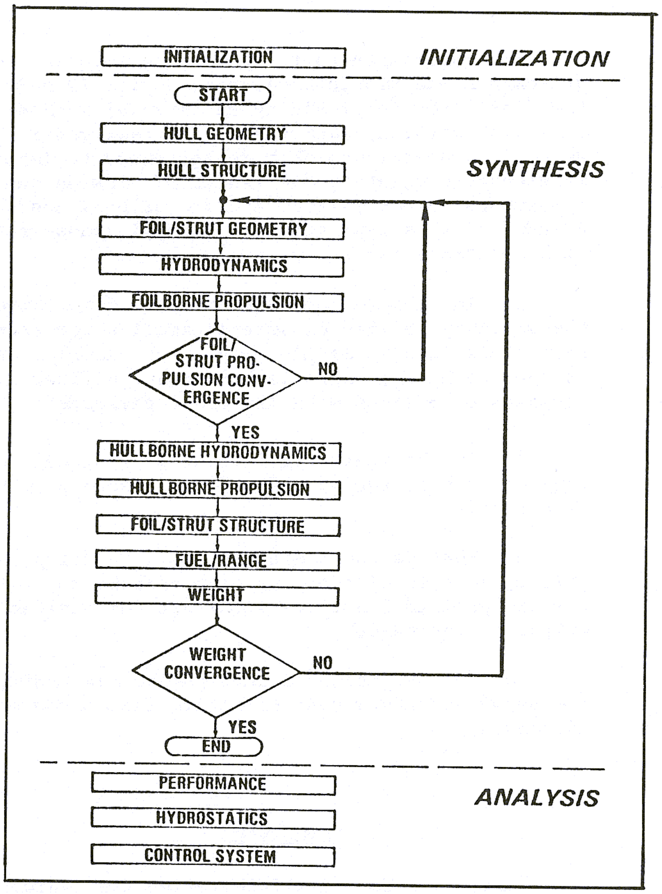


Fig. A-2 HANDE flow diagram.

Ship Geometry is handled by two *SYNTHESIS* modules. The Hull Geometry Module operates on user provided hull lines and warps these to define a new hull form which meets the physical characteristics requested by the designer. This module also

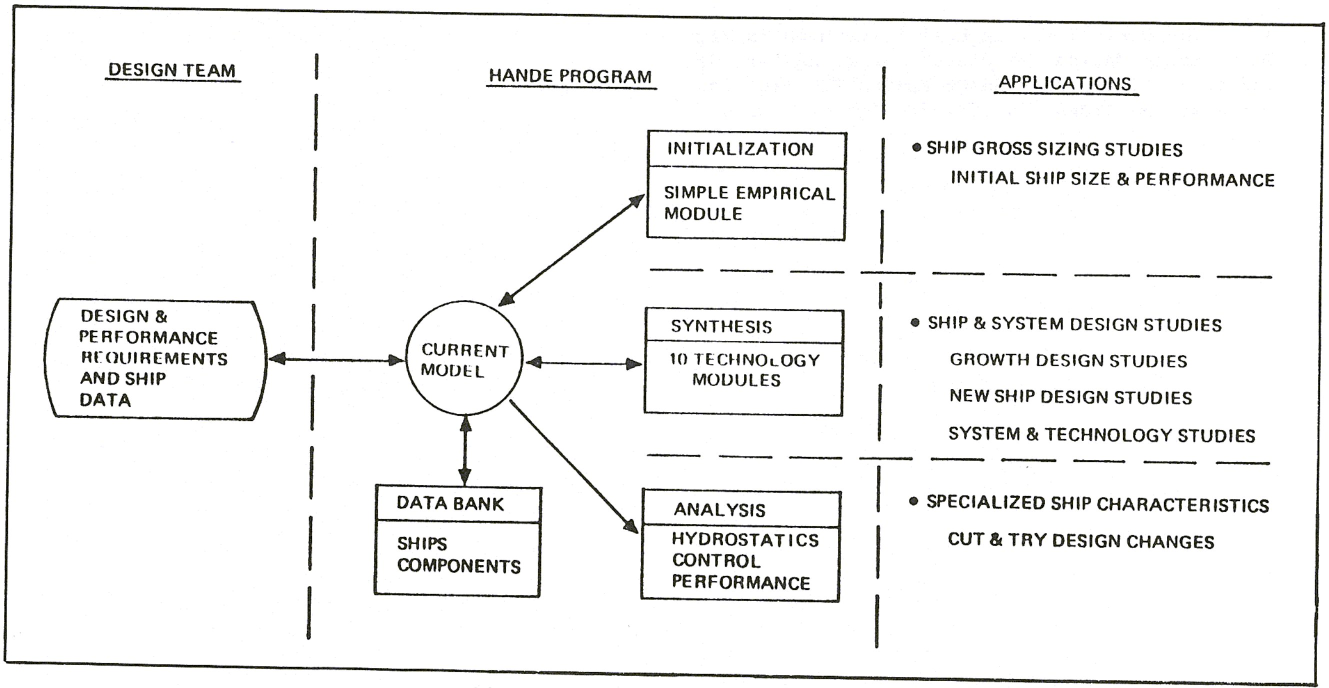


Fig. A-1 HANDE program structure.

defines geometric parameters for bulkheads, deck and girder locations, and superstructure size and location. The Foil/Strut Geometry Module sizes the foils, struts and pods in accordance with defined hull size and foil system configuration. Inverted T, Double inverted T, inverted π, U or three-strut configurations can be used for either forward or after foils.

The Structural Design in the HANDE program is performed by two modules. The Hull Structure Module calculates hull scantling data for hull elements defined in the Hull Geometry Module. These calculations are based on pressure loading data which may be calculated by this module or specified by the designer. Scantlings are calculated at three longitudinal positions for the hull bottom, hull sides and weather deck. Additional scantling information is calculated for lower decks, bulkheads, frames, girders, beams and stiffeners. The Foil/Strut Structure Module calculates the scantlings of the primary load carrying structure of the struts and foils. These calculations are based on the geometry data previously defined and on loading conditions derived from hydrodynamics and inertia forces developed during foilborne operations.

Hydrodynamic Calculations are performed in two modules. The Hydrodynamics Module calculates drag in the hullborne mode based on the hull and strut and foil geometry. Hullborne drags which are passed on to Hullborne Propulsion Module assume the foils to be in down position and their associated drags are included in sizing the hullborne plants.

Propulsion Calculations are handled by three modules within the *SYNTHESIS* section. The Foilborne Propulsion Module performs component sizing calculations for a foilborne waterjet or gear drive propeller propulsion system. The horsepower requirements for takeoff and maximum foilborne speed are based on the drag calculations received from the Hydrodynamics Module. The Hullborne Propulsion Module performs similar sizing calculations for separate or integrated hullborne propulsion plants using waterjets or propellers as propulsors. The Fuel/Range Module calculates fuel requirements for the propulsion plants, and the electrical and auxiliary power requirements in accordance with standard NAVSEC practices.

Weight Estimation is performed within the Weight Module which also calculates dynamic lift, and centers of gravity. Major emphasis is placed on those ship systems and components which are the largest weight contributors. Accordingly, the weight data is calculated to the following Ship Work Breakdown Structure (SWBS) levels:

SWBS 100 - Hull Structure Weight	3rd Level
SWBS 200 - Foilborne Propulsion Plant	4th Level
SWBS 200 - Hullborne Propulsion Plant	4th Level
SWBS 300 - Electric Plant	1st Level
SWBS 400 - Command and Surveillance	input
SWBS 500 - Auxiliary System (- SWBS 567)	1st Level
SWBS 567 - Strut and Foil System	5th Level
SWBS 600 - Outfit and Furnishings	1st Level
SWBS 700 - Armament	input
SWBS F00 - Loads	2nd Level or input

First level estimates for electrical plant, auxiliary system and outfit and furnishing weights are parametrically derived and further described in Appendix B.

The *ANALYSIS* section of HANDE is designed to provide additional information on the ship designs generated in the SYNTHESIS section for the designer's evaluation. These modules rely on the designer's judgement and experience for decisions too complex for the program to make automatically. The Hydrostatic Analysis Module allows the designer to determine the hydrostatic and stability characteristics of the ship. The Control Analysis Module analyzes the dynamic stability and controllability of the ship in a sea state. The Performance Analysis module permits the effects of sea state, fouling, off-design speed and fuel burn-off to be estimated. If the examination of the results of the *ANALYSIS* modules reveals a requirement to modify the ship, the designer usually has numerous alternatives. He then must decide on his course of action, modify the current model and rerun the design through the *SYNTHESIS* modules.

The modular structure and executive program of HANDE simplifies updating the state-of-the-art and expanding its capability. Currently, interactive graphics and the option to provide design data in metric or English units are being added.

APPENDIX B

DESIGN CONSTRAINTS

The main purpose of this appendix is to discuss briefly the assumptions and constraints used in this study and to justify their validity by comparing them to the demonstrated or accepted State-of-the-Art.

Hull

Hull Form

The selection of the hull involves all the traditional displacement ship considerations plus aspects peculiar to hydrofoils. A typical hydrofoil ship hull form was chosen to match foil load distributions. To reduce foilborne bottom impact and to minimize wetted surface at take-off, a midship deadrise angle of 16.5 was chosen for all ships. Also, a fine fore-foot and moderate bow flare were selected to keep spray to a minimum in both the hullborne and foilborne modes of operation.

The principal hull characteristics of length, beam, and depth were altered for each design to provide adequate stability while maintaining good hull performance. Each ship met the NAVSEC criteria of DDS 079-1 (Reference 2) for the following conditions: foils up and foils down at full load and minimum operating weights, 100 knot wind for intact stability, wind speed as determined from figure 30 of Reference 2 for damaged stability, and two compartment flooding.

The internal hull volume of each design matched the volume requirement estimated by the HANDE program (see Appendix A). The resulting densities of the baseline ships are shown on Figure B-1. The

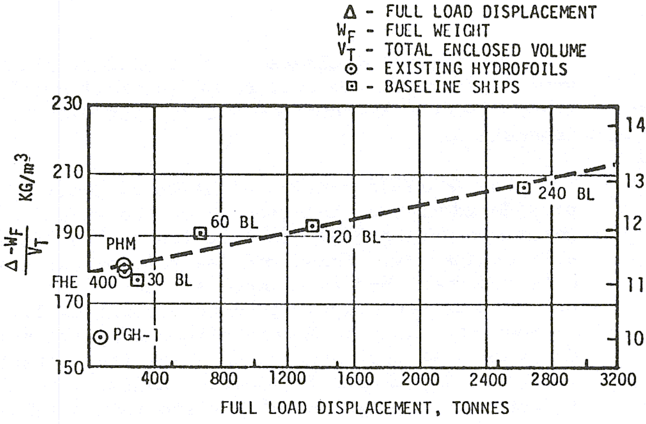


Fig. B-1 Baseline ship densities as a function of full load displacement.

ratio of superstructure to total volume for the 30, 60, and 120 tonne payload ships was essentially held constant while that for the air-capable ship was increased to account for the helicopter hangar. Table B-1 summarizes the principal hull characteristics for the four baseline ships.

Table B-1 Baseline ships principal hull characteristics.

PAYLOAD, TONNES	30	60	120	240
LBP, m [FT]	39[129]	52[170]	69[225]	82[270]
Δ,2/3 FUEL, TONNES	274	612	1221	2327
$\Delta/(.01L)^3$, TONNES/m³ [TONS/FT³]	4520 [126]	4379 [122]	3779 [106]	4175 [116]
BEAM AT WATERLINE, m [FT]	8.0[26.3]	9.9[32.8]	12.4[40.9]	14.0[46.1]
DRAFT AT FULL LOAD, m [FT]	2.0[6.7]	2.7[8.8]	3.4[11.0]	4.2[13.9]
FULL LOAD FREEBOARD AT FP, m [FT]	3.7[12.2]	4.7[15.6]	5.9[19.5]	6.0[19.8]
LBP/B_{WL}	4.91	5.18	5.50	5.86
LBP/D	8.9	9.0	9.8	10.5
LCB/LBP	.576	.576	.576	.576
C_B	.418	.425	.427	.438
C_P	.623	.623	.623	.623
TOTAL INTERNAL VOLUME, m³	1305	2591	5069	8637
[FT³]	[46,100]	[91,500]	[179,000]	[305,000]
SUPERSTRUCTURE VOLUME, %	23	21	20	33*
DEADRISE MIDSHIPS, DEGREES	16.5	16.5	16.5	16.5

* INCLUDES HELO HANGAR

Adequate freeboard was provided for all designs. Freeboard to length between perpendiculars (LBP) ratios are plotted against LBP on Figure B-2. This figure was developed by NAVSEC to consolidate freeboard criteria.

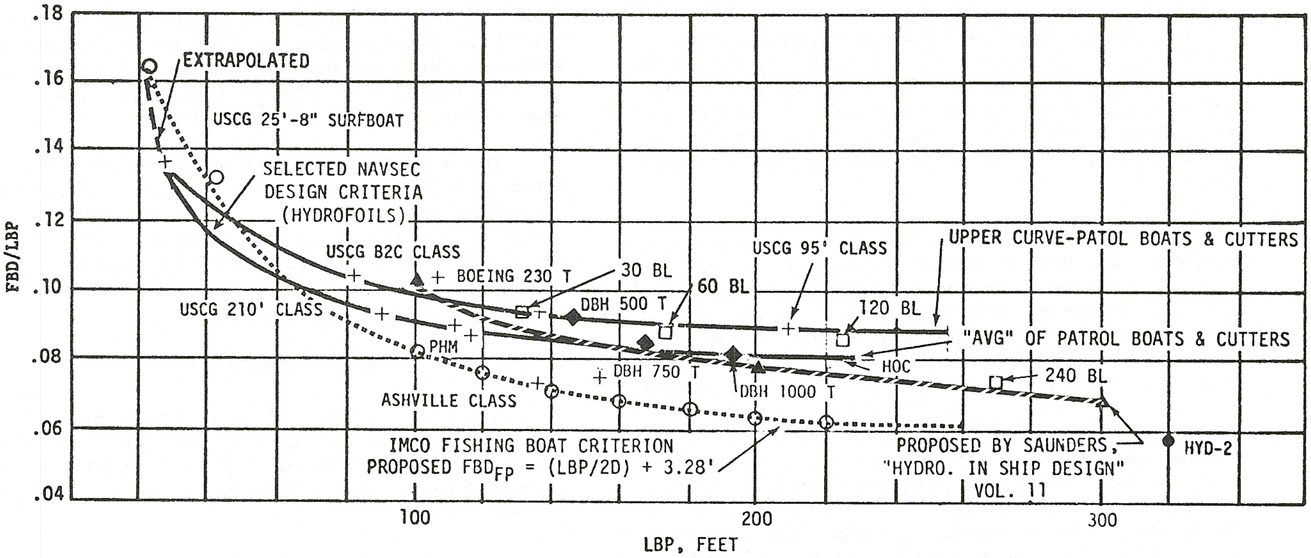
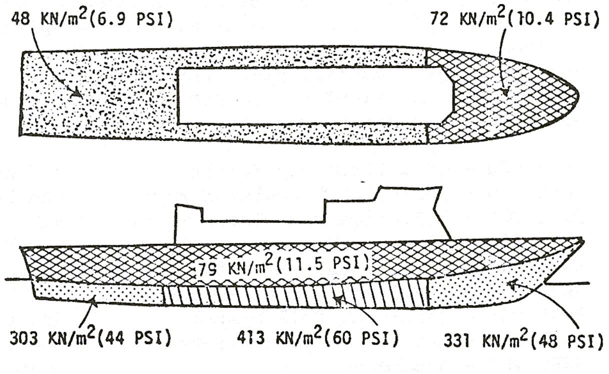


Fig. B-2 Freeboard/LBP as a function of LBP.

Hull Structure

All hulls are constructed of aluminum having a welded yield strength of 179 MN/m² (26,000 psi) and a safety factor 1.15 based on yield. The local loads imposed on the hull are shown in Figure B-3. The structural sizing and analysis done by HANDE does not take into account longitudinal bending because hull structure of hydrofoil ships designed to date have been governed by local loading. Recent studies have shown that for a hydrofoil ship of approximately 90 meters (295 feet) in length the hull structural arrangement which HANDE synthesizes to meet only local loads can be reconfigured to satisfy the bending moment applied with no increase in hull weight. It is thus felt that the hull structural weights derived by HANDE represent a reasonable estimate of hull weight for all ships studied. Figure B-4, taken from Reference 3, shows the variation of vehicle density with structural weight fraction for a variety of marine vehicles.



NOTE: SUPERSTRUCTURE WEIGHT DETERMINED BY ANALYSIS OF EXISTING DATA

Fig. B-3 Local hull exterior loads.

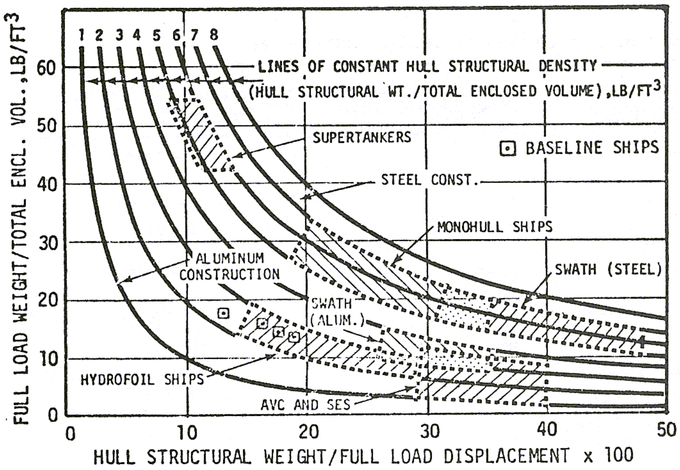


Fig. B-4 Relationship of vehicle density and hull structural weight fraction.

The reference explains that for similar types of vehicles where the structure is predominately governed by local loading requirements, lines of constant hull structural density (the ratio of total hull weight to enclosed volume) are indicative of structural integrity. From the figure it can be seen that all four baseline ships have a structural density between 2.3 and 2.6 pounds per cubic foot which is comparable to existing hydrofoils. The air capable 240 BL ship has the lowest hull structural density of 37.48 kg/m^3 (2.34 lb/ft^3) because it includes a higher percentage of relatively light superstructure.

From previous hydrofoil ship studies a longitudinal stiffener spacing of 38 cm (15 in.) and a frame spacing of 1.5 meters (4.9 feet) were found to produce an efficient hull structure. These values were used on all ships throughout the study.

Propulsion

The propulsion system includes the primemovers (engines), the transmission system and the propulsor. For hydrofoil ships, the two modes of operation- hullborne (low-speed) and foilborne (high-speed)-impose such conflicting requirements on the propulsion system that for this study a separate propulsion system for each mode was assumed. This follows the current practice on all Navy hydrofoils built to date.

Prime Movers

Marinized gas turbines were used for both the hullborne and foilborne systems because of their low weight and competitive and constantly improving fuel economy. Installed power matched required power in all cases.

The engines were sized to meet the following two power conditions:

1. At maximum continuous power the engine must have sufficient power to drive the ship at design speed.

2. At maximum intermittent power the propulsion system must supply 125% of the calm water takeoff thrust.

The former sized the engines for all ships in this study except for the 40 knot design speed ships, which were sized by the latter. In addition to the propulsive power required, all power to operate the control surfaces is assumed to be supplied by the main engines.

The specific fuel consumption at maximum continuous power and the correction for partial power used in this study are shown in Figures B-5 and B-6 which were derived from existing engine data.

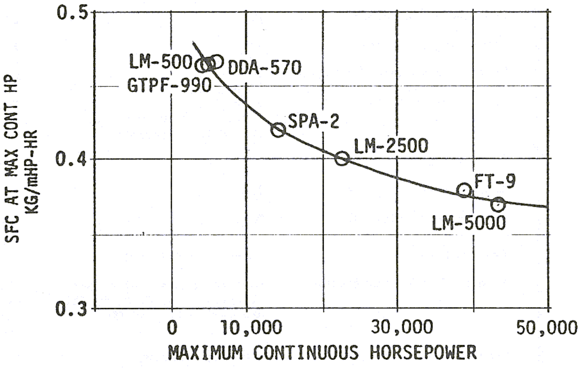


Fig. B-5 SFC as a function of maximum continuous horsepower.

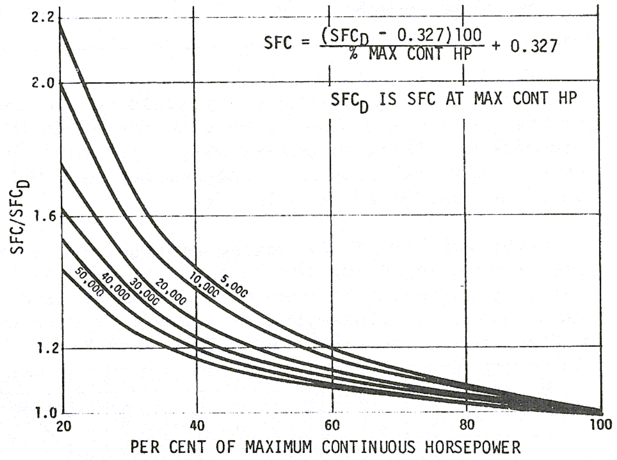


Fig. B-6 Specific fuel consumption ratios gas turbines at partial power (1980).

Gas turbines were assumed to have an installed weight of 0.227 kg per metric horsepower (0.50 lb per SHP) for all sizes, which is in line with the PHM value of 0.236 kg per metric HP. This may seem to be an oversimplification but is justified for trending data as the engines make up less than 2% of the full load weight making the ship size relatively insensitive to the accuracy of this assumption.

Transmission System

Right angle dual mesh Z-drives with final speed reducing planetary gear boxes in the propulsion pods were used to transmit the power from the engine to the propeller. Gear parameters were kept within the current state-of-the-art of gear design (see Table B-2) for all ships except those carrying 240 tonnes of military payload. For these ships

Table B-2 Recommended foilborne transmission design parameters.

PARAMETER	GE STUDY FOR HYDRONAUTICS/ NAVSEC-DDH REPORT APPENDICES G&H-DEH RECOMMENDATIONS	DIEHL AND LUNDGAARD, INC. REPORT NO. 7418-1-LHF RECOMMENDED CRITERIA	NAVSHIPS 0943-002-3010 and D&L REPORT No. 7418-T AGEH-1 AS BUILT	RECOMMENDED CHARACTERISTICS FOR A LARGE HYDROFOIL FOILBORNE PROPULSION TRANSMISSION
Tooth bending stress, psi	25,000 max. (28-30,000 with develop.)	25,000 max.	30,720	25,000 max.
Tooth compressive stress	150,000 max.	150,000 max.	150,700	150,000 max.
Tooth scoring index	---	25,000 max. (`25,875 required)	21,730	26,000 max.
Pitch line velocity, ft/min.	30,000 @ 26 in. dia. (34,000 possible)	25,000 max.	10,685	25,000 max.
Diametral pitch	---	2.0 min, 2.25 preferred	2.0	2.0 min.,2.25 preferred
Pressure angle, degrees	20	20	20	20
Spiral angle, degrees	30	25, wherever possible	30	25 where possible, 30 elsewhere
Maximum bevel gear diameter, inches @ ratio (manufacturing limitation on size).	26 @ 1.0:1 30 @ 2.0:1 33 @ 10.0:1 (Grinding 33 @ 1.0:1 and 36 @ 2.0:1 - expensive)	Currently, 26 @ 1.0:1 28 @ 1.5:1 Projected, (1976) 28 @ 1.0:1 30 @ 1.5:1	26.0	---
Face width, in.	---	---	5.0	---
Bevel Box Reduction, ratio	1.02	1.0	1.02	---
Bevel Gear Arrangement	Dual Mesh, Back-to-back	Dual Mesh, Back-to-back	Dual Mesh, Back-to-back	Dual Mesh, Back-to-back
Gear material	Carburized AISI 9310	---	AISI 9310/AMS 6260	Carburized AISI 9310/AMS6260
Method of gear manufacture	Gleason method (Cut,double carburized, HT to RC 58-60, and ground to ≤ 20 RMS)	Gleason method (Cut by model 26 generator, Case carburize to 0.110-.120 depth after grinding)	Gleason method (Cut, case carburized to 58-63 RC and depth of 0.100-.120 after grinding) Tip ends chamfered.	Gleason method (Cut, case carburize to 58-63 RC and depth of 0.110-.120 after grinding to 20 RMS) Tip ends Chamfered.
Bevel bearing arrangement	Straddle mounting	Straddle mounting	Straddle mounting	Straddle mounting
Antifriction bearing B_{10} life, Design Hours	4000	5000 minimum with CEVM 52100 material	800	5000 hours minimum with CEVM 52100 material
Lubricant	MIL-L-2190TEP/RL-285C	---	Mobil RL-285C	MIL-2190 TEP/RL-285C or equiv.
Strut downshaft arrangement	Dual	Dual, MIL-S-890	Dual, MIL-S-890, Alloy I	Dual

improvements in gear technology would be required, or the power would have to be distributed on three propellers. Three propeller ships with three power struts, although within the capability of HANDE, were not considered in this study.

The weights of the foilborne transmission systems (including propellers) are calculated and built-up component by component in HANDE. The net results fall in line with the results of more detailed studies as can be seen in Figure B-7.

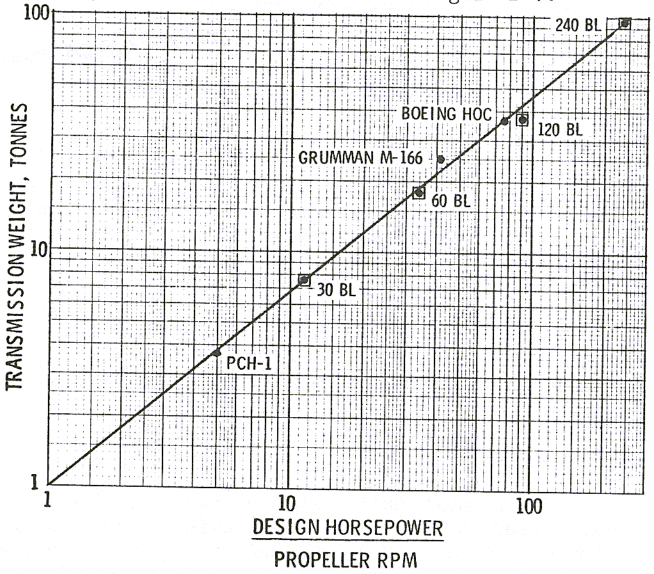


Fig. B-7 Foilborne transmission system weight trends.

Propellers

Fixed-pitch, transcavitating propellers of the Newton-Rader series were used for foilborne propulsors and controllable pitch propellers of the Wageningen B-Series were selected for hullborne operation. The foilborne propulsive coefficient, including thrust and wake reduction and gear box losses, calculated by HANDE from propeller-maps average around 0.63 at 44 knots which is consistent with experience on operating hydrofoil ships.

Electric Plant

The capacity in kilowatts and the electric plant weights are based on empirical data derived from hydrofoil and conventional ship data. Figure B-8 shows the relationship of plant capacity to the combined weight of the major consumers of ship's electrical power, i.e. command and surveillance equipment (SWBS* 400), auxiliary systems (SWBS 500 less the Strut and Foil System) and armament (SWBS 700). The electric plant weight trend used by HANDE for this study is illustrated in Figure B-9. Either gas turbines or diesels can be used for the ship service power units; gas turbines were selected for the ships in this study.

Command and Surveillance

Except for the navigation system (SWBS 420) and exterior communications (SWBS 430), the command and surveillance group was provided as part of the

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*Ship Weight Breakdown Structure

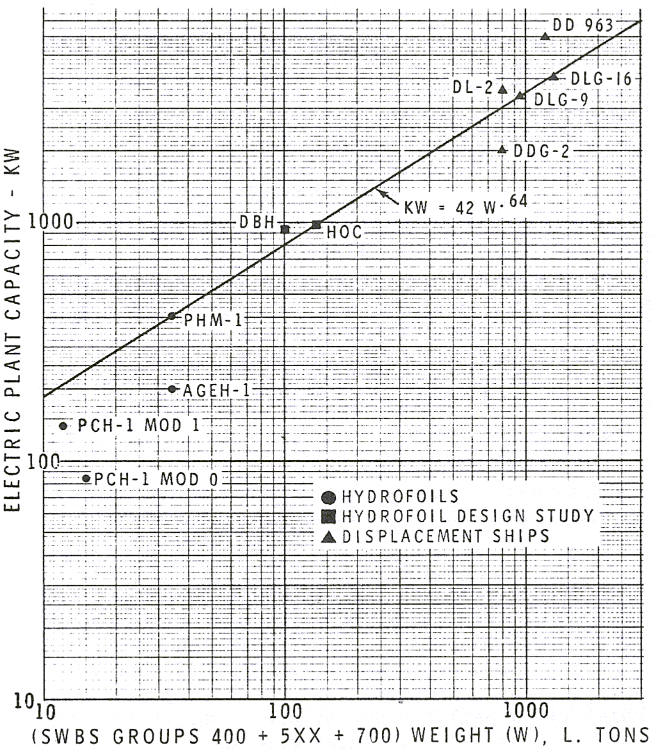


Fig. B-8 Electric plant capacity.

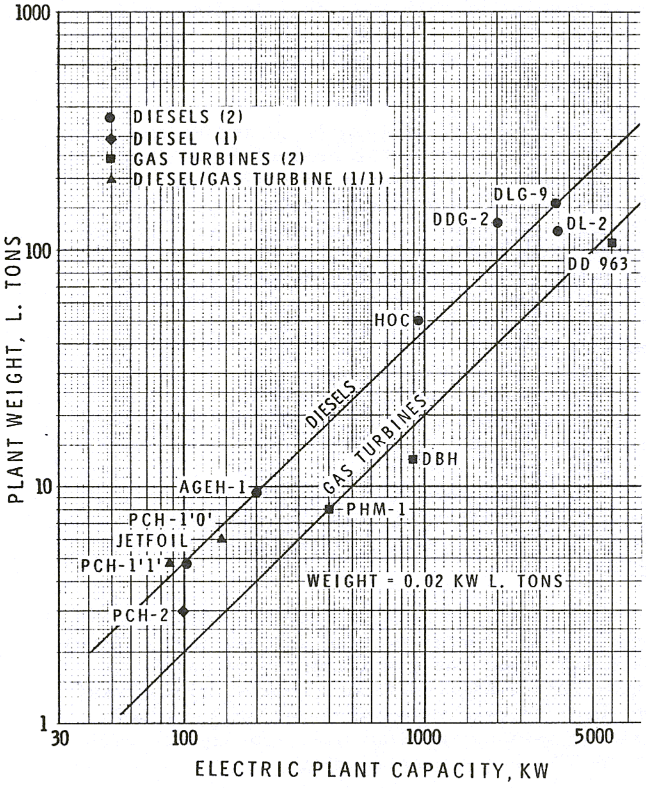


Fig. B-9 SWBS 300 electric plant weight.

military payload described in the Methodology section. Examination of these two weight subgroups showed the navigation system averaged about two tons for current ships and the interior communication weight could be expressed as a function of total internal volume (V_T) as follows:

$$W_{430} = 1.1 \times 10^{-6} \; V_T \quad \frac{\text{Tonnes}}{\text{m}^3}$$

$$W_{430} = 38 \times 10^{-6} \; V_T \quad \frac{\text{Tons}}{\text{ft}^3}$$

Auxiliary System Excluding Strut and Foil System

HANDE uses algorithms sensitive to crew size and internal volume to estimate the auxiliary systems weight as shown in Figures B-10 and B-11.

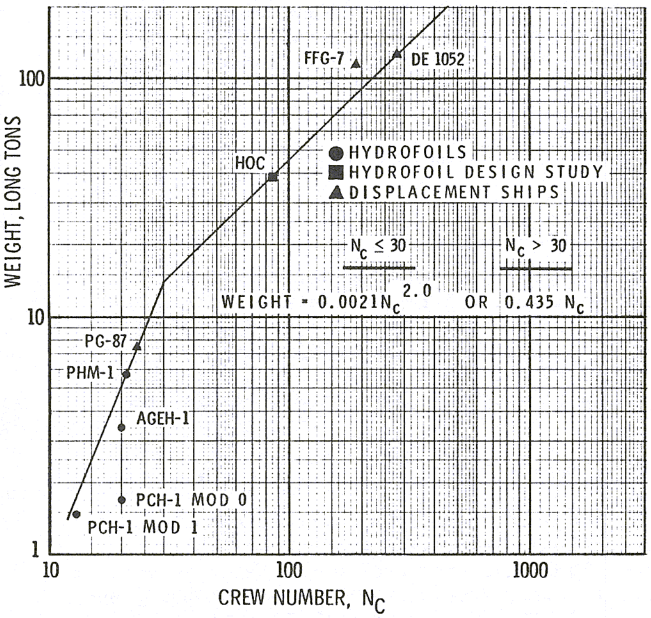


Fig. B-10 Auxiliary Systems (SWBS 500 except strut and foil system) crew dependent weight.

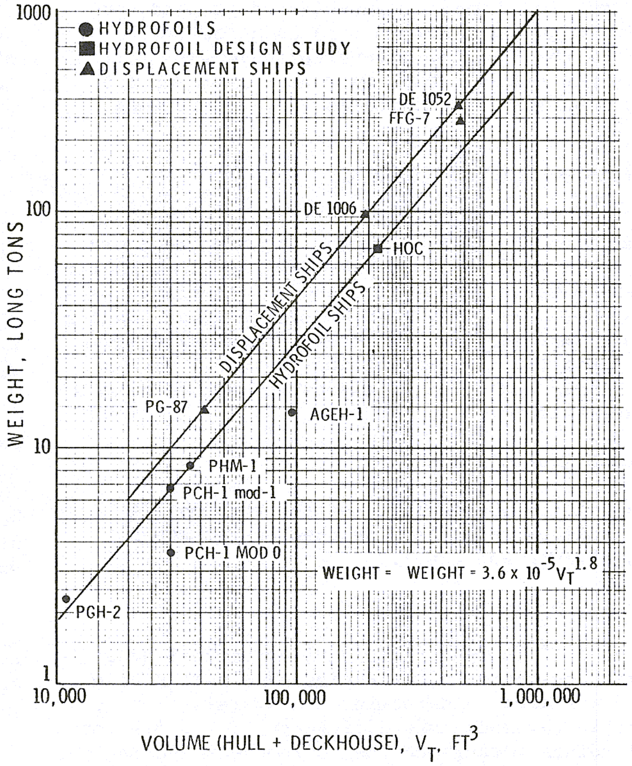


Fig. B-11 Auxiliary Systems (SWBS 500 except strut and foil system) volume dependent weight.

Strut and Foil System

With the exception of the forward foil of the smallest ships, all the lift systems have identical characteristics as follows:

Configuration

Inverted π strut and foil system configurations were used for both except for ships below 360 tonnes which used an inverted T configuration forward. The inverted π configuration is used on the aft foil system of the PCH and PHM and has been selected in all design studies of larger hydrofoils as being structurally and hydrodynamically the most efficient. For smaller ships the inverted T configuration used on PCH and PHM was selected. All strut and foil systems are dry retractable.

Weight Distribution

The forward foil carries 40% of the lift. The selected 40%, 60% distribution is felt to be a good compromise between foil span and ship arrangements. For the smaller ships with an inverted T configuration forward, a 33%, 67% distribution was chosen to keep the forward foil within practical size.

Foil Aspect Ratio

Hydrodynamic efficiency increases but structural efficiency decreases with higher aspect ratios. Span also increases with higher aspect ratio. Detailed studies made on several point designs for ANVCE showed that with inverted π configurations, for a given range and payload, an aspect ratio of 6.5 required the smallest ship or conversely for a given size ship and payload, the longest range was achieved with an aspect ratio of 6.5. For the inverted T configured forward foil used on the smaller ships an aspect ratio of 5.5 (as used on PHM) is considered close to optimum.

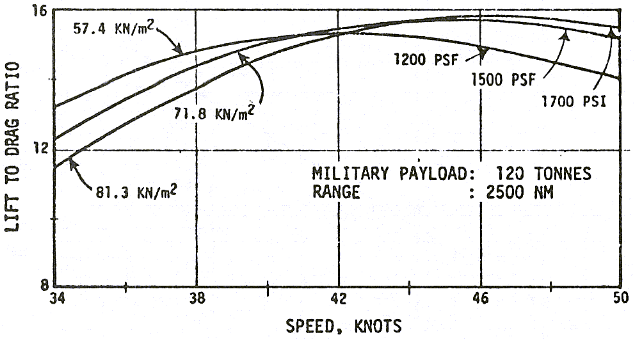
Thickness to Chord Ratio

Relatively thick foils are structurally more efficient and lighter. Higher thickness to chord ratio foils, however, have more drag and have poorer cavitation characteristics. The thickness to chord ratios used were 10% for 40 kt design speed, 8% for 50 knots, and 6.5% for 55 knots. These have adequate cavitation margins at 40, 50, and 55 knots respectively, and offer a reasonable balance between drag and weight.

Lift Control

All foils obtain lift control through 25% chord trailing edge flaps as used on the PGH-2, PCH-1, JETFOIL and PHM-1.

Foil Loading



FOIL LOADING	FULL LOAD WEIGHT FOR 2500 MILE RANGE	MAXIMUM FOIL SPAN	AVERAGE L/D 34 THRU 50 KTS
$57.4\frac{KN}{m^2}$ (1200 PSF)	1471 TONNES	30.1m(98.7 FT)	14.7
$71.8\frac{KN}{m^2}$ (1500 PSF)	1350 TONNES	26.1m(85.6 FT)	14.9
$81.3\frac{KN}{m^2}$ (1700 PSF)	1363 TONNES	24.5m(80.4 FT)	14.6

Fig. B-12 Comparison of lift-to-drag ratios for different foil loadings.

The foil loading (lift divided by foil area) is a key parameter in the design of a foil system. A study was made to determine the overall lift to drag ratio (hydrodynamic efficiency) for different foil loadings throughout the foilborne speed regime. The results are shown in Figure B-12. Higher foil loading results in higher efficiency at high speeds and lower efficiency at low speeds. Higher foil loading also reduces the size of the foil, but increases the takeoff speed. A foil loading of 72 kN/m^2 (1500 psf) had the highest average lift to drag ratio from 34 to 50 knots and resulted in the lightest ship for a constant range. Therefore all ships were designed with this foil loading at full load weight.

Strut Length

The length of the struts is dependent on the sea state requirements. The criteria used in this study and stated below assure that all ships meet the following motion characteristics: vertical acceleration of less than 0.1g rms, lateral acceleration less than 0.07g rms, roll angle and pitch angles less than 1.0° rms while foilborne in the design sea state. The struts length, keel to foil chord plane, shall be such that the following conditions are met:

1. Foils shall not broach the surface more than once every 1000 wave encounters while foilborne in the design sea state.

2. Hull emergence during cresting waves shall not exceed 30% of its hullborne displacement for more than 1 wave in 1000 while foilborne in the design sea state.

Condition (1) translates into a nominal foil submergence (mean water surface to foil chord plane) equal to 0.9 times the significant wave height. Condition (2) translates into a nominal flying keel height (keel to mean water surface) of 0.9 times significant wave height less hull submergence equivalent to 30% ship's displacement.

Applying the above criteria for seas with a significant wave height of 4.6 m (15 feet) results in strut lengths of 7.13 m (23.4 ft), 6.71 m (22.0 ft), 6.55 m (21.5 ft), and 6.40 m (21.0 ft) for the 30, 60, 120 and 240 BL ships respectively.

Structures

The strut and foil structure is designed for the following load conditions: maximum lift, foil emergence, beam wave, and side maneuvering conditions, which are shown schematically and defined in Figure B-13. The maximum stress level under all of these conditions is kept below 2/3 of material yield stress which results in a safety factor of 1.5 based on yield.

Material

The material yield stress used in this study was 896 MN/m^2 (130,000 psi) which is representative of the yield stress of HY-130, 17-4 PH and 15-5 PH steels used on current hydrofoils.

Weight

The resulting strut and foil weight fractions, based on full load displacement are shown for the four base line ships and compared to existing ships and designs on Figure B-14. The weight fractions vary from slightly under 12% for the 30 BL to slightly over 13% for the 240 BL. These are in variance with early strut and foil weight trends projected in the 1950's and 60's which were based on a direct application of the square-cube law*, which showed that strut and foil weight fraction grew rapidly with ship size. Recently, more detailed studies, including complete finite element analyses, take into account the effect of minimum gage plate thickness and the fact that the length of the struts, which makes up the major portion of the weight, does not increase directly with ship size. These confirm the strut and foil weight trends shown in Figure B-14.

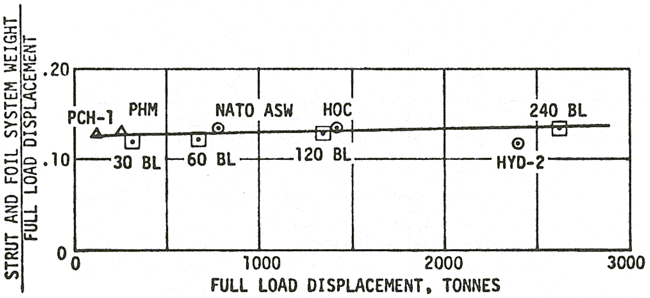


Fig. B-14 Strut and foil system weight trend.

Outfit and Furnishings

The approach to the outfit and furnishing group (SWBS 600) is similar to that used for auxiliary system weight estimation. The HANDE weight algorithms use emperical data based on crew size and total internal volume. Figures B-15 and B-16 illustrate these relationships.

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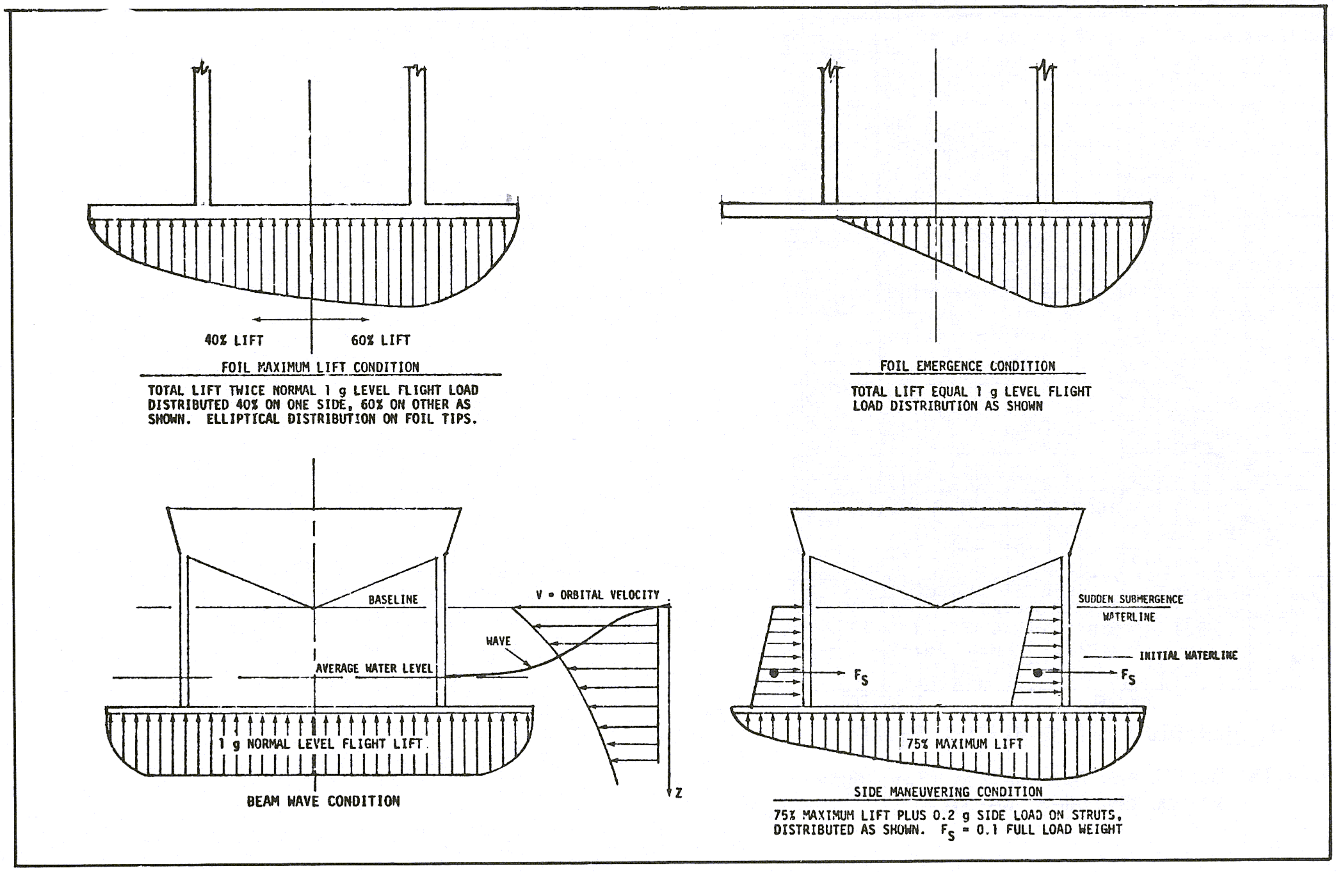
*For geometric scaling, area varies as the square of the length and weight varies as the cube of the length.



FOIL MAXIMUM LIFT CONDITION

TOTAL LIFT TWICE NORMAL 1 g LEVEL FLIGHT LOAD DISTRIBUTED 40% ON ONE SIDE, 60% ON OTHER AS SHOWN. ELLIPTICAL DISTRIBUTION ON FOIL TIPS.

FOIL EMERGENCE CONDITION

TOTAL LIFT EQUAL 1 g LEVEL FLIGHT LOAD DISTRIBUTION AS SHOWN

BEAM WAVE CONDITION

SIDE MANEUVERING CONDITION

75% MAXIMUM LIFT PLUS 0.2 g SIDE LOAD ON STRUTS, DISTRIBUTED AS SHOWN. F_S = 0.1 FULL LOAD WEIGHT

Fig. B-13 Strut and foil structural load conditions.

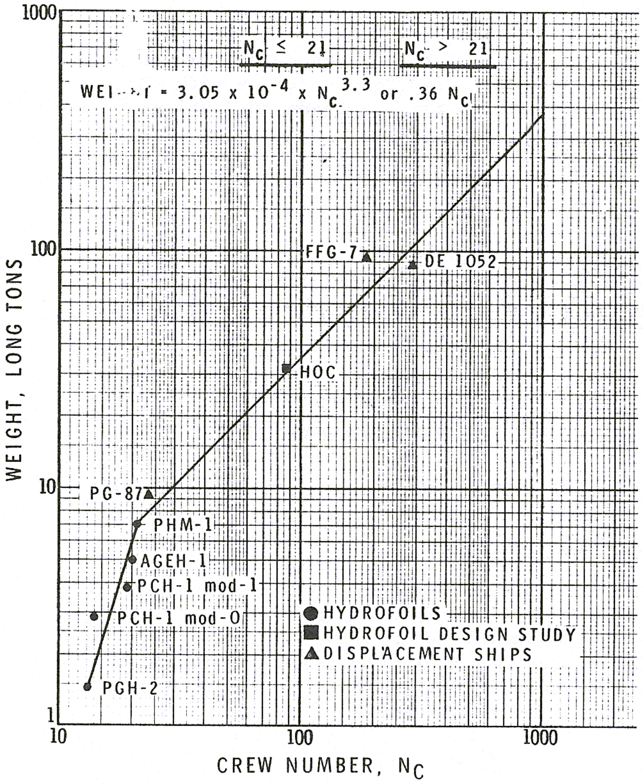


FIG. B-15 Outfit and Furnishings (SWBS 600) crew dependent weight.

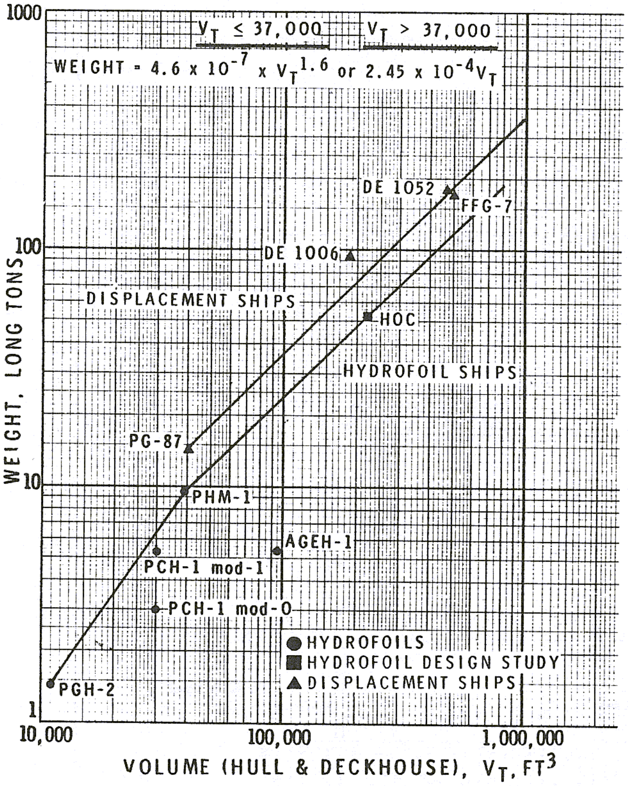


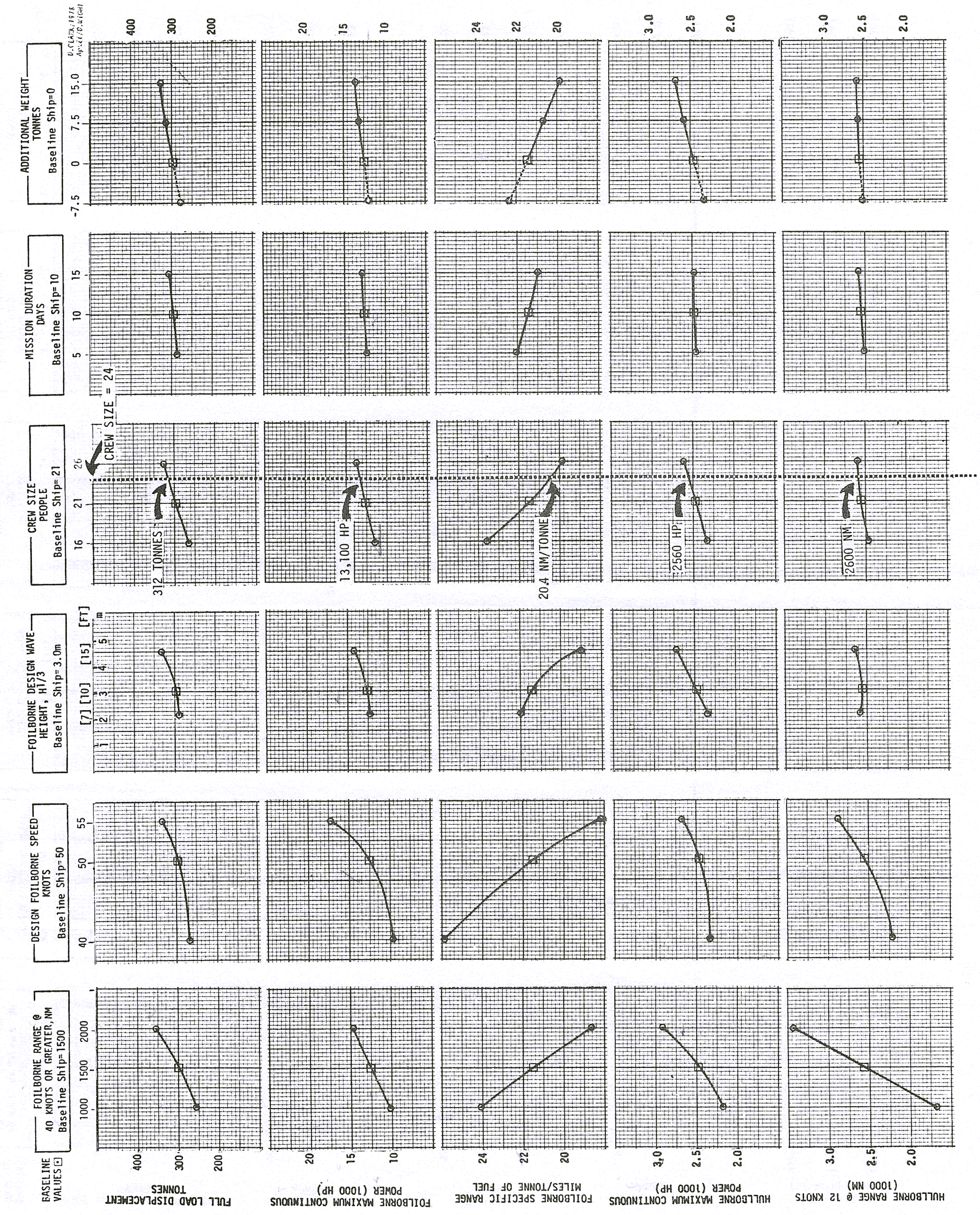
FIG. B-16 Outfit and Furnishings (SWBS 600) volume dependent weight.

Armament

The armament group (SWBS 700) is considered military payload and is summarized in the Methodology section.

APPENDIX C

Appendix C contains Figure C-1 which shows the effects of changing the six operational requirements on the 30 tonne military payload baseline ship (30 BL). This figure is used in the examples presented in the Results section. Similar plots were made for the 60, 120, and 240 tonne military payload ships but these are not contained in the paper.


ADDITIONAL WEIGHT TONNES Baseline Ship=0
-7.5
0
7.5
15.0
MISSION DURATION DAYS Baseline Ship=10
5
10
15
CREW SIZE PEOPLE Baseline Ship= 21
16
21
26
CREW SIZE = 24
312 TONNES
13,100 HP
20.4 NM/TONNE
2560 HP
2600 NM
FOILBORNE DESIGN WAVE HEIGHT, H1/3 Baseline Ship=3.0m
[7] [10] [15] [FT]
1 2 3 4 5 m
DESIGN FOILBORNE SPEED KNOTS Baseline Ship=50
40
50
55
FOILBORNE RANGE @ 40 KNOTS OR GREATER, NM Baseline Ship=1500
1000
1500
2000
BASELINE VALUES ⊡
FULL LOAD DISPLACEMENT TONNES
400
300
200
FOILBORNE MAXIMUM CONTINUOUS POWER (1000 HP)
20
15
10
FOILBORNE SPECIFIC RANGE MILES/TONNE OF FUEL
24
22
20
HULLBORNE MAXIMUM CONTINUOUS POWER (1000 HP)
3.0
2.5
2.0
HULLBORNE RANGE @ 12 KNOTS (1000 NM)
3.0
2.5
2.0
D. CLARK, 1978 Ayres/D. Wright

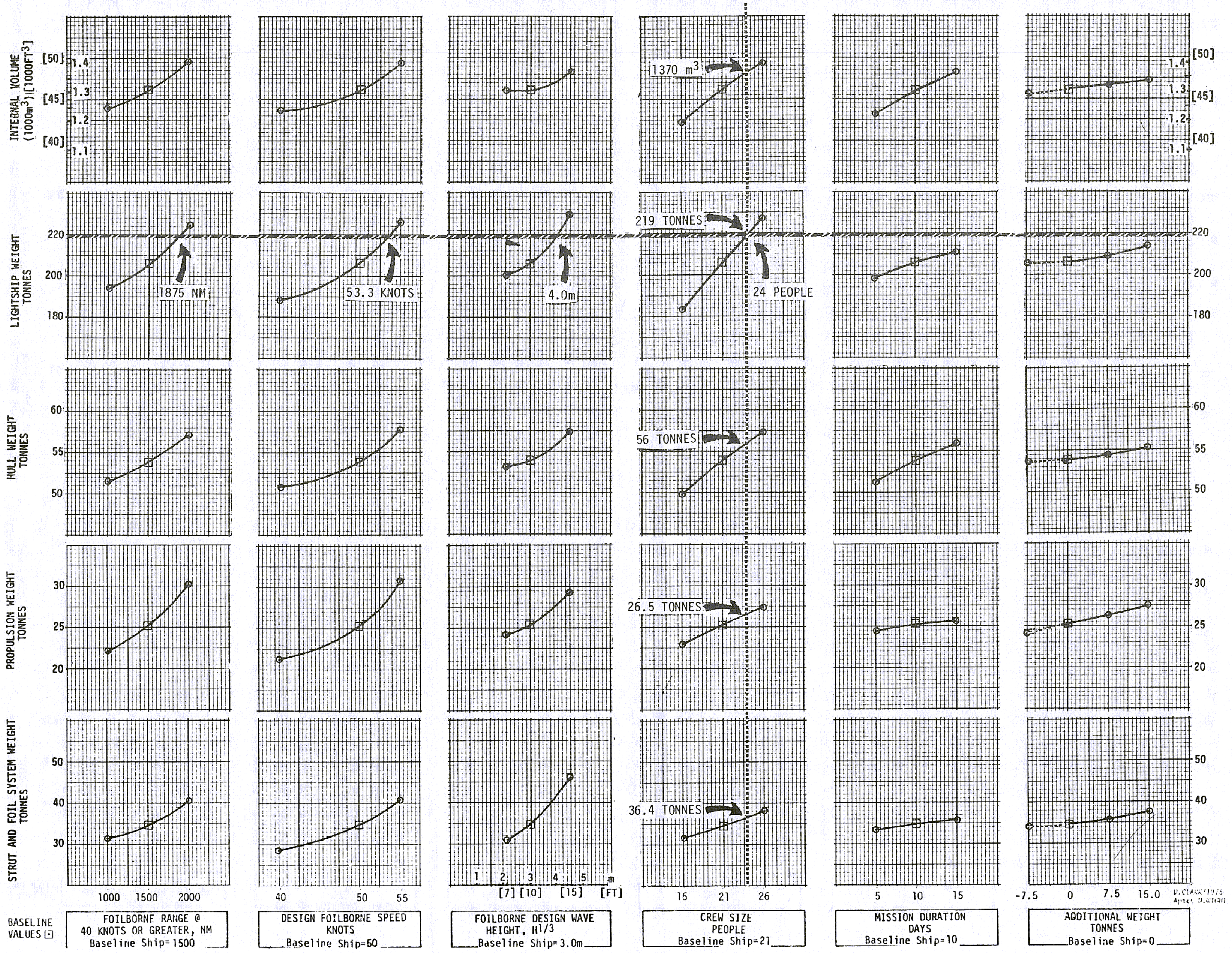


Fig. C-1 Ship characteristics for 30 tonne military payload