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AIAA Paper
No. 74-311

DEH, A HIGH ENDURANCE ESCORT HYDROFOIL FOR THE FLEET

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AIAA/SNAME Advanced Marine Vehicles Conference

SAN DIEGO, CALIFORNIA / FEBRUARY 25-27, 1974

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DEH, A HIGH ENDURANCE ESCORT HYDROFOIL FOR THE FLEET

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Abstract

Eventually, an "advanced marine vehicle," having arrived at a point of technical maturity, must relinquish its special classification in order to gain eligibility to assume a major fleet role. In support of the proposition that the 50 knot submerged foil hydrofoil has arrived at that position, this paper describes the results of preliminary design studies which make use of the available technology base to produce a conceptual design for a Destroyer Escort Hydrofoil (DEH).

Starting with a set of mission requirements and choices of weapons suites, the effort proceeds to a definition of vehicle physical and performance parameters, while invoking an absolute minimum of technology advances not now on hand. Full recognition is given to the need for providing routine on-board services, self-maintenance features and internal systems that will generate few demands for new or unusual logistic support.

Of several iterations, the principal results reported are for a 200 foot LBP ship with a vehicle gross weight of 1363 tons. Foilborne endurances typically range from 3700 to 2800 nautical miles dependent on payload selection, with hullborne speeds into the 20 knot range and hullborne endurance of 4000 miles. A range of payloads from 100 to 177 tons is investigated to make visible the arrangement and performance variations that result. Accommodations for crews ranging from 63 to 91 officers and men on a standard habitability basis are incorporated into the alternate mission variants.

It is concluded that a mission-capable, high-endurance, open-ocean hydrofoil escort ship is feasible within the existing framework of developed technology.

Introduction

For more than a decade, developmental hydrofoils have explored many technical alternatives in way of establishing a firm foundation to capture the recognized military advantages offered by the hydrofoil concept. The ongoing PHM program, as the first full "class acquisition" is a direct result of this past development.

However, we can not afford to dwell on accomplishments of the past but must proceed immediately to attack the questions of the future. Specifically, we have not yet publicized a valid basis for a true appreciation of the full potential that has accrued from this excellent buildup of available, demonstrated technology. For this reason, there still exists an all too general opinion that the hydrofoil does not lend itself to extrapolation into the domain of a full-blown open ocean escort ship with all the attendant implications of long endurance, self-maintenance and integration into the existing fleet logistics situation. In addition, the often discussed "size barrier" ascribed to hydrofoils has not been adequately challenged in the context of a real design based on contemporary data.

For over one year, specific preliminary design studies have been underway to define and quantify the properties of a large hydrofoil ship suitable for task force escort deployment, which makes use of the existing technology base and requires only engineering design (6.4 level of RDT&E) to support a fleet prototype procurement.

In this paper, we not only present the principal results of this work, but also elaborate on our conclusion that a 50 knot Escort Hydrofoil (DEH) can be designed and constructed which offers:

(a) A quantum improvement in speed and seaway performance.

(b) Foilborne and hullborne endurance suitable for open ocean escort service.

(c) Size to support an effective payload suite with adequate crew and conventional facilities for high endurance missions.

The Operational Perspective

The incentive for advanced marine platforms stems from a desire for more speed, better seakeeping or a combination of both. Displacement ships with destroyer type hull forms succeeded in making speeds in the 35-40 knot range some 60 years ago but over the years the usual problems of deck wetness, structural limitations and habitability factors have prevented the utilization of this speed regime under adverse sea conditions. Captain J. R. Keyhoe in a recent article (Ref. 1) graphically summarized the existing situation for U.S. and U.S.S.R. destroyers as regards seaway speeds.

Figures 1 and 2 contain data taken from his treatise. We have superimposed a point on Fig. 1 and a curve on Fig. 2 which compares the hydrofoil (DEH) with conventional escort data, as regards the seaway effect for a typical voyage.

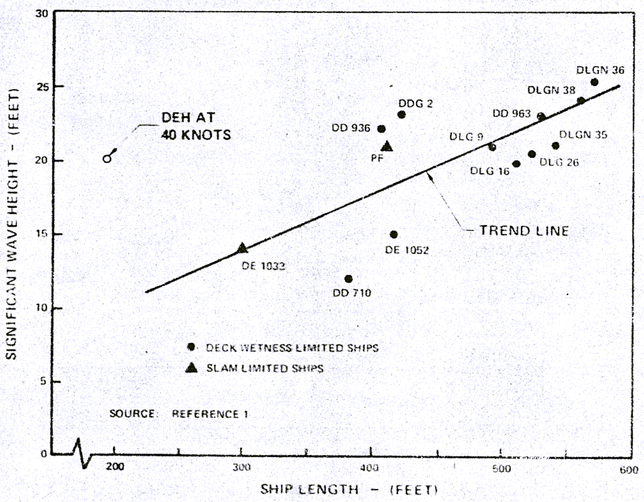

Figure 1: MAXIMUM WAVE HEIGHT CAPABILITY IN HEAD SEAS AT 20 KNOTS

The speed capabilities of several vehicle types as a function of sea state are plotted in Figure 3. It will be noted that the very large conventional ship (CVAN) suffers only slight degradation in usable speed until significant wave heights of 20-25 feet are reached. The performance of the conventional destroyer escort begins to degrade at seas of about 10 feet and for significant

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*This paper represents an independent Boeing Aerospace Co. development.

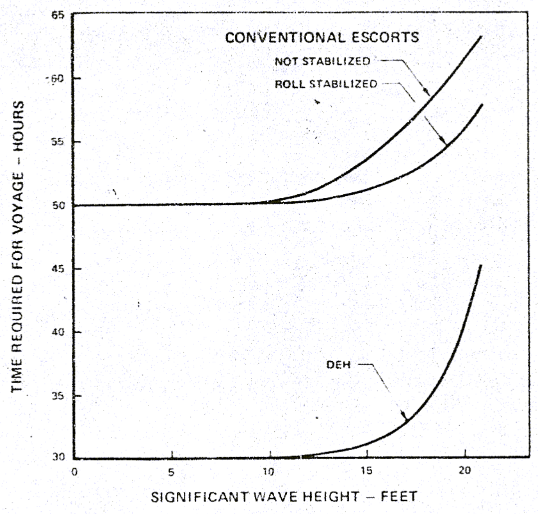


Figure 2: 1500 MILE VOYAGE TIME COMPARISON

wave heights of 20 feet can be optimistically credited with an average speed of about 15 knots. The large SES with calm water capabilities of 80 knots must give up much of this performance in the higher sea conditions for many of the same reasons that apply to the displacement hull. The 50 knot hydrofoil, although not completely immune to sea effects retains its speed properties because the main hull is decoupled from the sea surface and its seaway response is largely governed by the design length of the struts and the specific type of dynamic control system employed. It is the only escort vehicle which can match or exceed the seaway performance of the task force nucleus.

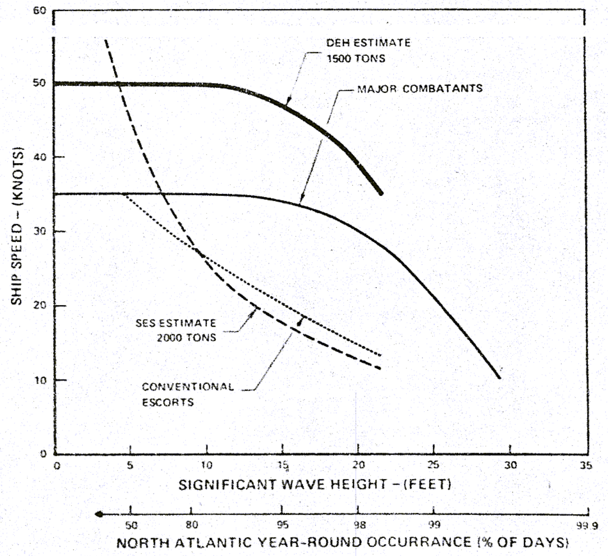


Figure 3: OCEAN ESCORT OPERATIONAL ENVELOPES

The many tactical benefits of hydrofoil high speed capabilities are summarized in Fig. 4. Notably, as speed increases, the number of ships required for most tasks decreases, the investment in force size tends to go down, and the number of escort ships per task force group or element is smaller.

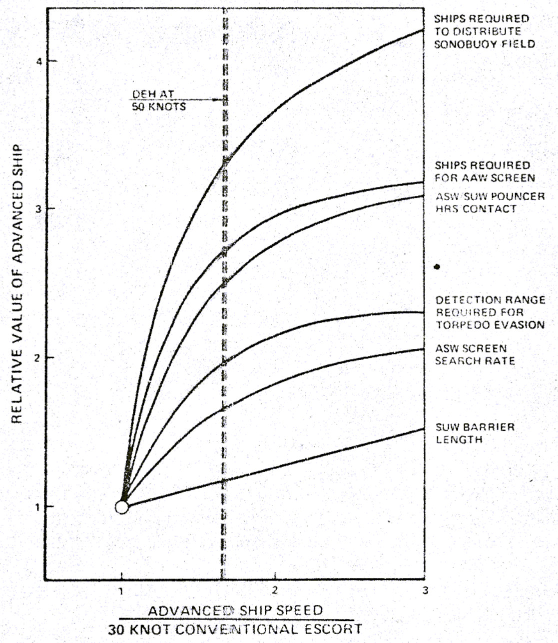


Figure 4: COMPARISON OF EFFECTIVENESS OF HIGH SPEED ADVANCED SHIPS TO 30 KNOT CONVENTIONAL ESCORTS

The hydrofoil payoff can be realized merely by exploiting the body of design practice and operating experience that constitutes the technological base produced by a 15 year investment in the subcavitating submerged-foil hydrofoil. Accordingly, this paper describes an escort ship sized to meet specific performance and mission goals, but predicated on meeting the given requirements while invoking an absolute minimum of technology not on hand.

Characteristics Formulation

Operational experience is the only sure route to provide the guidance needed to derive a firm "best set" of military vehicle design characteristics. Presently, we must make the best visualization or forecast to produce the most flexible set of properties to design into DEH. Certain areas are worthy of explanation insofar as they represent a break in the pattern of development of previous military hydrofoils.

It is postulated that DEH should offer a dual capability. It will provide the high speed, high sea state characteristics of the hydrofoil but also be required to operate for long periods in a hullborne mode at speeds into the 20 knot range, with hullborne endurance comparable to existing escorts (5,000 N.M.). Continuous foilborne endurance should be much greater than previous hydrofoils and provide an "ocean-crossing" capability (at least 2600 N.M.) so that no new or unusual logistic demands will be placed on existing fleet operations.

It will be necessary to make available an adequate complement along with stores, maintenance facilities and range of crew skills so that the level of self maintenance will be comparable to that of conventional escorts. There is no inherent basis to persist in the notion that a hydrofoil can only support a minimum operating crew with a high degree of logistic dependence on base facilities. On the other hand, we endeavor to take advantage of the manning economies inherent in the gas turbine propulsion system and the general degree of automation otherwise characteristic of the newest ships, coupled with the smaller overall size of the platform.

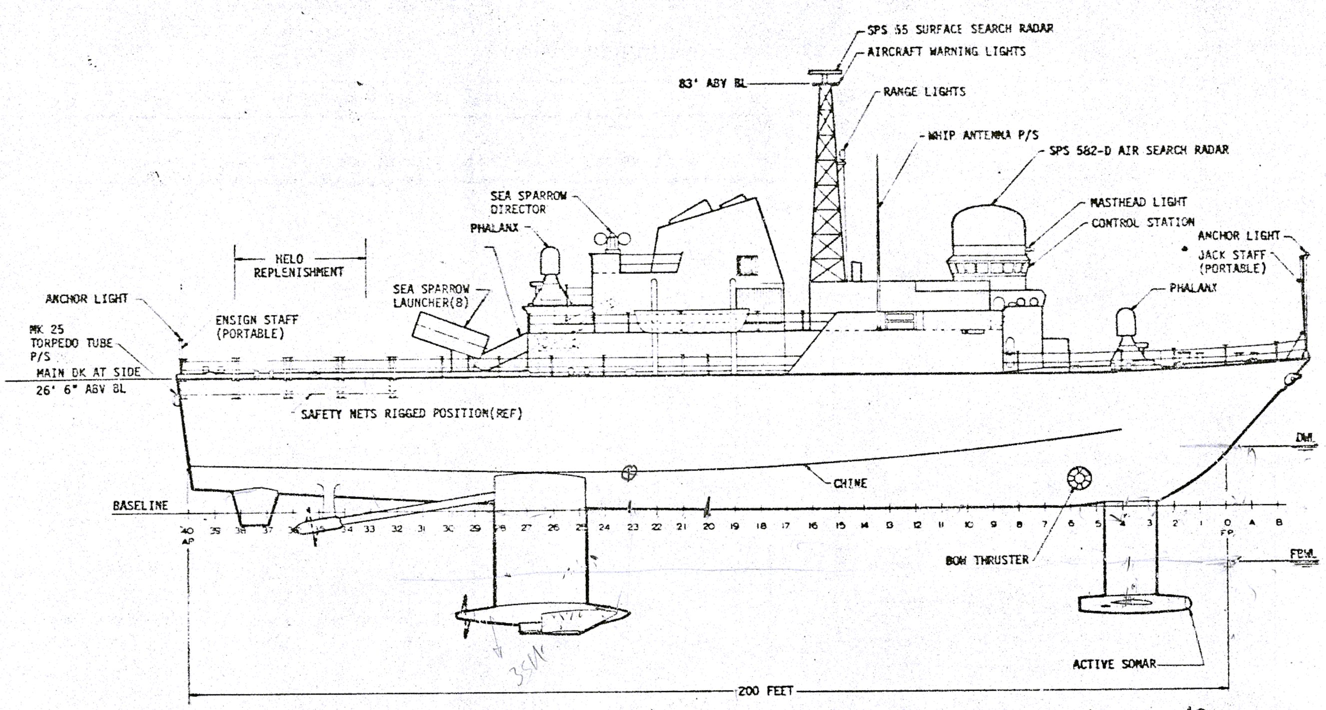
TABLE 1: SHIP CHARACTERISTIC SUMMARY

MODEL	WATERJET SHIP	PROPELLER SHIP VERSIONS		
	001E BASELINE ASW	002B BASELINE ASW	102B HELICOPTER ASW	202A MULTI-MISSION
PHYSICAL PARAMETERS				
LENGTH BP, FT.	200	200	200	200
MAX. HULL BEAM, FT.	48.4	48.4	48.4	48.4
MAX. WL BEAM, FT.	40.5	40.5	40.5	40.5
AFT FOIL SPAN, FT.	120	108	108	108
GROSS WEIGHT, TONS	1625	1363	1363	1363
FOIL DRAFT, FT.	39.5	36.7	36.7	36.7
PERFORMANCE				
MAXIMUM SPEED, KTS.	49	50.7	50.7	50.7
F/B ENDURANCE, N.M.	2300 AT 42 KNOTS	3670 AT 42 KNOTS	3530 AT 42 KNOTS	2900 AT 42 KNOTS
H/B ENDURANCE, N.M.	4000 AT 19 KNOTS	4000 AT 19 KNOTS	3850 AT 19 KNOTS	3060 AT 19 KNOTS
ACCOMMODATIONS				
OFFICERS	10	12	14	14
CPO	2	2	2	5
ENLISTED	51	56	60	72
TOTAL	63	70	76	91
STORES	45 DAYS	45 DAYS	45 DAYS	45 DAYS
ARMAMENT	COMMON TO BOTH MODELS (2) PHALANX (1) SEA SPARROW BOX LAUNCHER (8 RELOADS) (2) MK 25 TORPEDO TUBES (8) MK 48 TORPEDOES (2) HARPOON MISSILES		(1) PHALANX (1) OTO MELARA 76MM (240 RDS) (2) MK 32 TORPEDO TUBES (16) MK 46 TORPEDOES (2) HARPOON MISSILES	(2) PHALANX (16) SM-2 VERTICAL LAUNCHERS (16) HARPOON/TARPON MISSILES (1) OTO MELARA 76MM (240 RDS) ([illegible]) MK 25 TORPEDO TUBES (8) MK 48 TORPEDOES
SONAR	COMMON TO ALL MODELS (1) PASSIVE TOWED ARRAY, (1) VDS, (1) FOIL MOUNTED CTFM			
ELECTRONICS	COMMON TO BOTH MODELS SPS-55 SURFACE SEARCH RADAR SPS-58-2D AIR SEARCH RADAR SEA SPARROW FC NAV & COMM. SUITE STANDARD FOR TYPE ESM SUITE		SPS-55 SURFACE SEARCH RADAR MK 92 FC RADAR NAV & COMM. SUITE STD. FOR TYPE ESM SUITE	SPS-55 SURFACE SEARCH RADAR MK 49 AIR SEARCH RADAR MK 74 TRACKER ILLUMINATOR NAV & COMM. SUITE STD FOR TYPE ESM SUITE
AVIATION FEATURES	HELO REPLENISHMENT		(1) LAMPS (SH2-D HANGERED)	HELO REPLENISHMENT
TOTAL PAYLOAD, TONS*	100	100	94	177

*INCLUDES: PARTIAL GRP. 4, GRP. 7, AMMUNITION, CREW & EFFECTS, PROVISIONS AND POTABLE WATER WEIGHTS.

For seakeeping criteria, it is proper that we fully utilize one of the prime features of the craft. This is a design goal for DEH to operate foilborne 98% of the time in seas representative of the North Atlantic on a year round basis. This quantifies to a design significant wave height of 20' (upper sea state 6). This is not a "wish" goal and selection of this criterion is based on extensive seakeeping studies utilizing known hydrofoil response characteristics.

As for allocation of missions, roles and weapons systems, an authoritative determination must be left to the formal military planning procedure. It is our objective to select representative suites that will display the feasible range of possibilities. Consequently, configurations have been developed which include a basic ASW ship utilizing available weapons systems, a variant housing one SH2-D helicopter and a third arrangement cast as a multi-mission platform employing weapons concepts still in the planning stage.



KEEL HEIGHT ABOVE SURFACE 12FT

Figure 5: MODEL 002B (BASELINE ASW) PROFILE

35
40

For propulsion, past hydrofoils have employed either waterjet or angle drive propeller systems. The attractive feature of the waterjet system is its mechanical simplicity combined with a high degree of accessibility of the mechanical components resulting in reliable trouble-free performance as demonstrated fully on TUCUMCARI. Although many factors are involved, it is noted that the one hydrofoil with waterjet propulsion, of the four major developmental ships, has accumulated 43% of the total foilborne time.

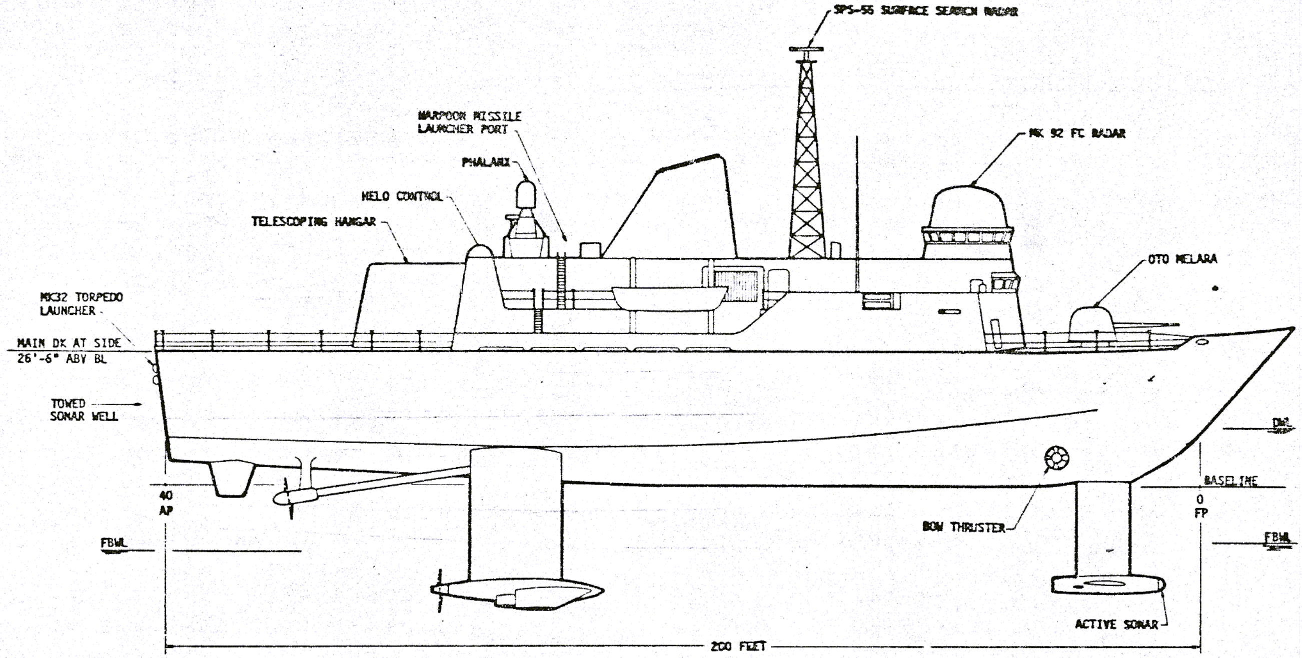
Appreciating that the demands for very long foilborne range represent one of the more significant departures as compared to previous hydrofoil characteristics, competing design teams were set up, each to produce the best overall ship design solution for a waterjet thruster and an angle-drive propeller system respectively. Table I summarizes the characterizing data of the several DEH versions as derived by our studies and selection processes. Configurations are set forth in Figures 5 through 8. It should be noted that some additional operational considerations, including at least maintenance and mission equipment compatability, need to be further studied before a definitive decision can be made.

TABLE 2: PROPULSION SYSTEMS COMPARISON

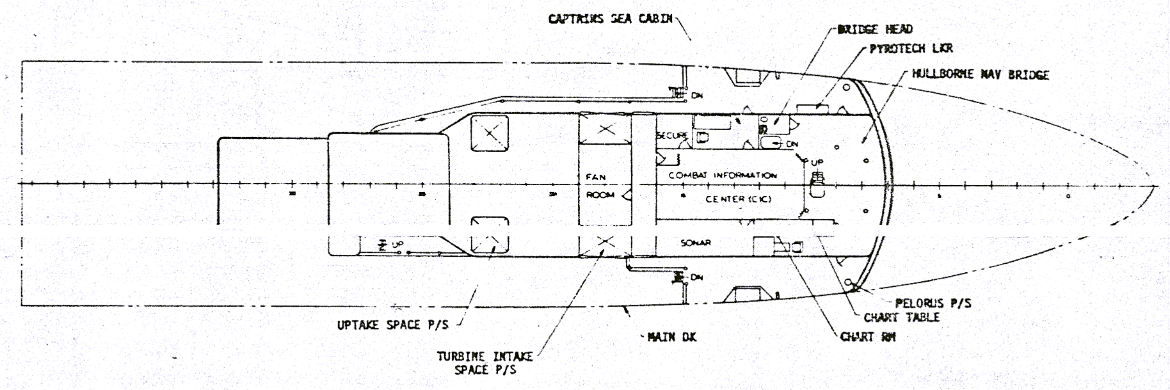
PROPULSION SYSTEM	FOILBORNE WATERJET SYSTEM	FOILBORNE PROPELLER SYSTEM	HULLBORNE SYSTEM
ENGINE TYPE 2-REQUIRED FOR EACH SYSTEM	TURBO-POWER AND MARINE SYSTEMS FT9-D (MARINE VERSION, NOT IN PROD.)	GENERAL ELECTRIC LM-2500 (IN PRODUCTION TO BE USED ON PF, DD963 AND PHM)	AIRESEARCH GTPF 990 (G) (UNDER USN DEVELOPMENT NOT IN PRODUCTION)
TAKEOFF POWER INTERMITTENT RATING AT 100°F, PER ENGINE	45,000 SHP WITH WATER INJECTION	25,000 SHP	--
CRUISE POWER CONTINUOUS RATING AT 80°F, PER ENGINE	39,200 SHP	23,400 SHP	7,560 SHP
CRUISE PROPULSIVE EFFICIENCY, PERCENT**	43.9 AT 49 KNOTS	61.8 AT 50 KNOTS	57.8 AT 19 KNOTS
SHIP GROSS WEIGHT, TONS	1625	1363	--
NOMINAL ENDURANCE, N.M.	2,300 AT 42 KNOTS	3,670 AT 42 KNOTS	4,000 AT 19 KNOTS
CRUISE SHP/TON	48.2	34.3	--
SPECIFIC PROPULSION SYSTEM WEIGHT LBS/SHP	5.34*	2.74*	4.90
AVAILABLE FUEL, TONS	587	546	587/546

**PROPULSIVE EFFICIENCY = NET THRUST HP/ENGINE SHP.

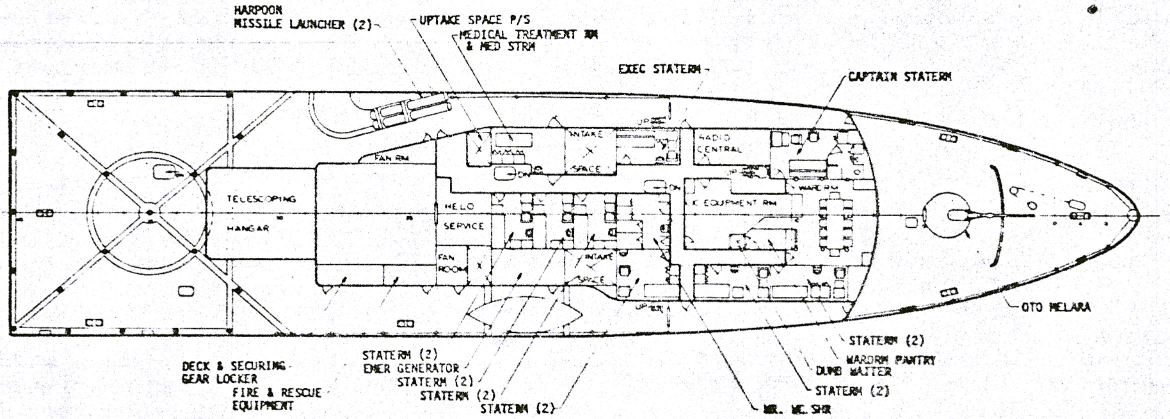
*INCLUDES ALL PROPULSION SYSTEM FLUIDS EXCEPT USABLE FUEL



OUTBOARD PROFILE

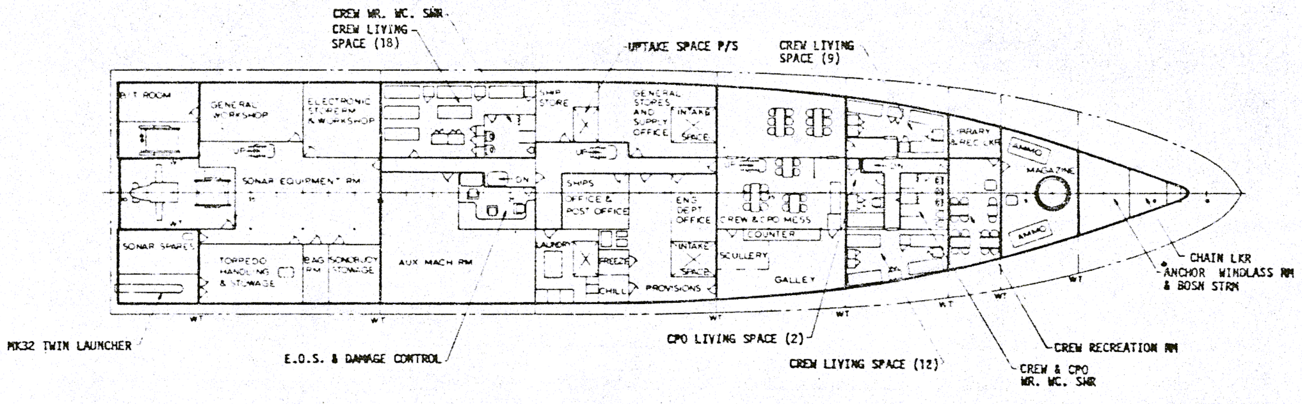


01 LEVEL

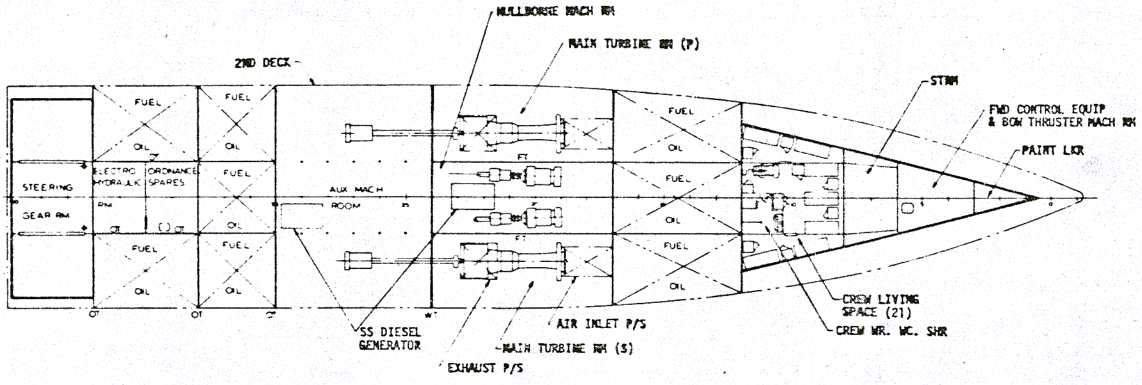


MAIN DECK

Figure 6: MODEL 102B (HELIOCOPTER ASW) PROFILE AND ARRANGEMENT



2ND DECK



1ST PLATFORM

Figure 7: MODEL 102B (HELIOCOPTER ASW) ARRANGEMENT

Performance

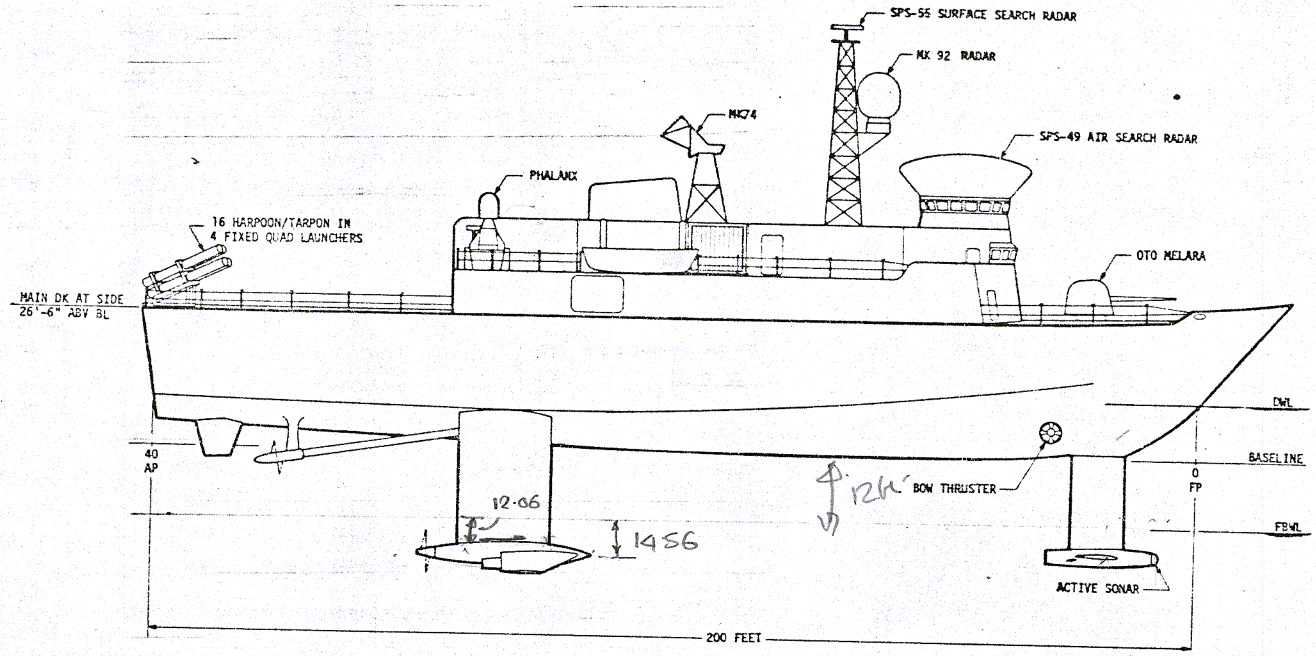
Thrust-drag relationships and smooth water foilborne endurance vs. speed are plotted in Figure 9. Take-off conditions are adjusted to provide a minimum thrust margin of 25% assuming an outside air temperature of 100°F. The apparent "excess" foilborne range indicated for the propeller ship over a nominal goal of 2600 miles is subject to some degradation when service factors and rough water cruise power increments are applied. Beyond this, the difference may be considered as a performance margin convertible to payload optimization, and growth margins. The waterjet ship is initially more limited and does not offer this flexibility.

Hullborne performance is summarized in Figure 10. In the higher hullborne speed range overall craft L/D is improved by utilizing foil lift, assuming the constant hydrofoil lift coefficient that would be appropriate for a 32 knot takeoff. This helps to overcome the relatively high hull resistivity as indicated by the comparative drag curves applicable to the propeller ship.

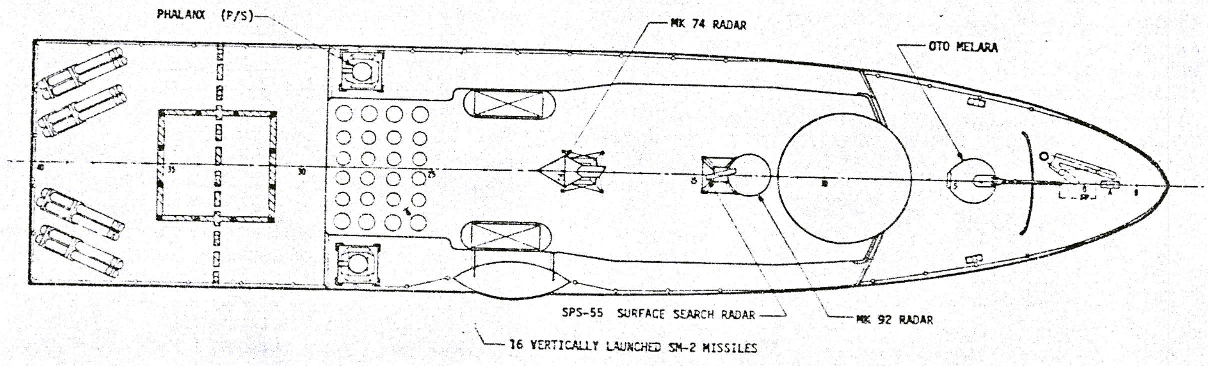
Propulsion

As noted previously, our work has encompassed waterjet and propeller foilborne propulsion systems on the basis of common hulls and payloads. The selection of gas turbines was unrestricted and performance was optimized where possible by designing up to the full capability of available engines. A common hullborne propeller system was used in all cases. Overall comparative data of these systems is summarized in Table 2.

There are a number of contingent effects inherent in the above tabulation. The lower efficiency and higher weight of the waterjet system drives one towards higher fuel loads and heavier takeoff weights which in turn provides incentive to go to higher rating prime movers. The increased weight drives the foil area up resulting in both larger main foil and forward steerable T-foil. The process of optimization of the waterjet plant itself brings in variations in inlet duct influencing strut size and drag. The large pumps make greater demands on available space so that total volume allocated to machinery is increased. In this ship, we must weigh the above effects against the waterjet system's demonstrated mechanical simplicity and high reliability that has resulted in the choice of waterjets on TUCUMCARI, PHM and the Boeing JETFOIL.



OUTBOARD PROFILE



PLAN VIEW

Figure 8: MODEL 202A (MULTI–MISSION) PROFILE AND PLAN

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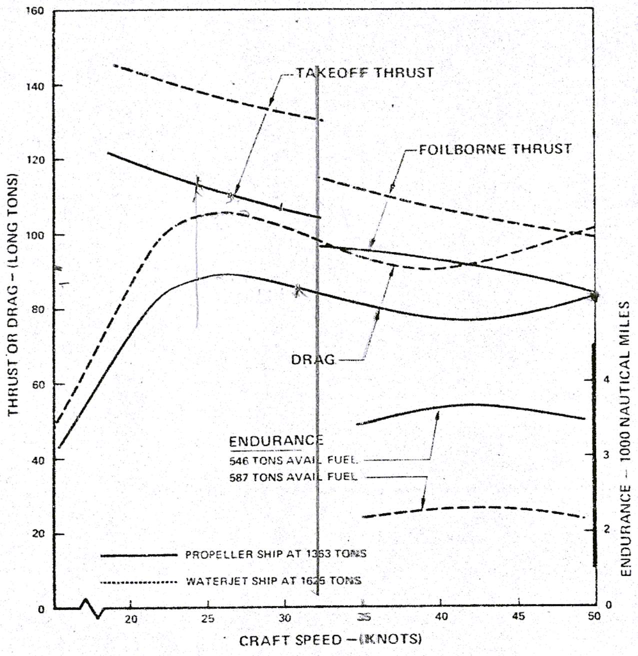


Figure 9: CRAFT PERFORMANCE AND FOILBORNE ENDURANCE

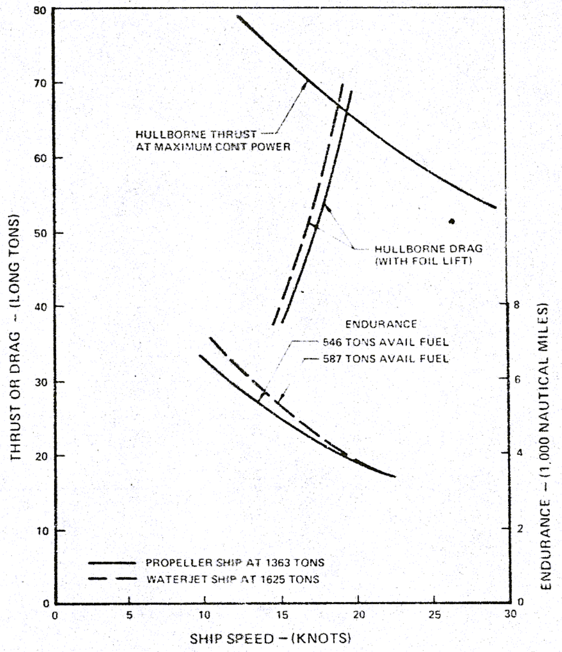


Figure 10: HULLBORNE PERFORMANCE AND ENDURANCE

Earlier experience with high power-density angle drive propeller systems on hydrofoils resulted in significant hardware problems and lack of operational reliability. Today we can take advantage of much of this experience and of an improved manufacturing technology to design reliable drive trains for the hydrofoil environment. In this regard, the Navy developed AGEH gear system is the highest rated train to date and has turned in a generally excellent performance in approximately 200 hours of sea trials. Originally designed to handle the output of two LM 1500 engines/shaft (30,000 H.P.) it has been deployed with half the designed input power. Table 3 sets forth the key angle drive train parameters needed for DEH and their relationship to acceptable gear design factors. Our assessment indicates that bearing life would be the limiting factor. With available bearing technology it is confidently anticipated that a system exhibiting a MTBO in excess of 4,000 hours can be produced. Figure 11 is a schematic of the foilborne and hullborne propulsion trains.

Employment of a pod mounted 4:1 ratio planetary reducer is a key factor in keeping system weights down, and operating the right angle train at low torques. A fortuitous investment by the Navy Department in the early period of the hydrofoil technology buildup has resulted in the development, construction and shop testing of a very lightweight high performance planetary gear box. This unit produced by Curtiss-Wright was designed as a 40,000 SHP reducer and has been shop tested up to 50,000 SHP. Its physical dimensions, light weight, and overall ratio precisely fit the needs of our proposed ship and it provides necessary visibility to one of the key components of the concept.

Supercavitating propeller estimates are derived from an existing successful supercavitating blade series. The selected characteristics are shown in Table 4. Figure 12 offers comparative data which indicate that although the diameter is somewhat larger than previous propellers, disc loading as an overall comparator falls well within the body of previous practice. Figure 13 illustrates a rationale for characteristics selection. Some compromise in peak efficiency has been taken to improve take-off thrust performance and to ensure suitable transmission system reduction ratios.

TABLE 3: RIGHT ANGLE BEVEL GEAR PARAMETERS APPLICABLE TO DEH FOILBORNE DRIVE PINION

PARAMETER	VALUE	COMMENT
NO. OF TEETH	50	SAME AS AGEH
DIAMETRAL PITCH	2.228	SMALLER THAN AGEH
PITCH DIAMETER	22.442 IN.	26 IN. MANUFACTURING LIMIT
PRESSURE ANGLE	20 DEGREES	SAME AS AGEH
SPIRAL ANGLE	30 DEGREES	SAME AS AGEH
TORQUE	241,000 LB-IN.	300,000 LB-IN (AGEH DESIGN)
RPM	3,600	3,130 (AGEH DESIGN)
BENDING STRESS	24,400 PSI	30,000 PSI IS GLEASON STANDARD
CONTACT STRESS	141,500 PSI	LOWER THAN GLEASON FOR 10^9 CYCLES
PITCH LINE VELOCITY	21,600 RPM	30,000 FPM SHOULD BE POSSIBLE

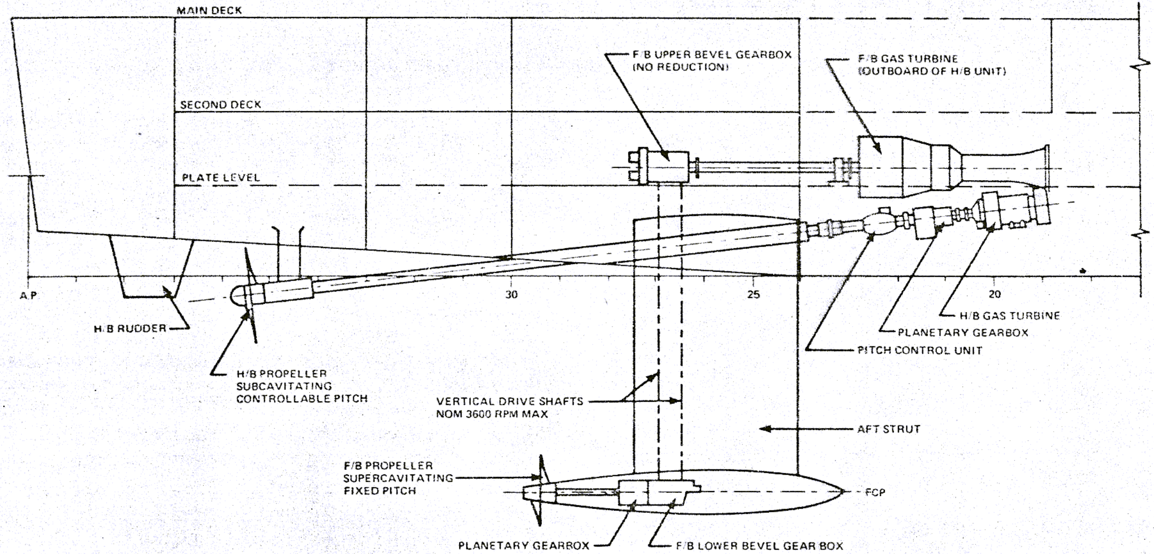


Figure 11: PROPULSION SYSTEMS SCHEMATIC

TABLE 4: FOILBORNE PROPELLERS

TYPE	SUPERCAVITATING-FIXED-PITCH
DIAMETER, FEET	7.0
PITCH-DIAMETER RATIO	1.10
BLADE AREA RATIO	0.60
NUMBER OF BLADES	3
PERFORMANCE:	
DESIGN CONDITION	
SPEED, KNOTS	50
POWER, PROPELLER HP	22,230
RPM, MAXIMUM	850
NET THRUST, LBS PER PROPELLER	96,300
TAKEOFF OPERATION	
SPEED, KNOTS	25
POWER, PROPELLER HP	23,180
RPM,	750
NET THRUST, LBS PER PROPELLER	125,600

η = .66511

SHP=23,400

SHP=25000

η =0.41595

570 hydraulic HP

Hullborne driving equipment is identified in Table 2 and utilizes 10' diameter controllable pitch subcavitating propellers. Because of the conventional drive arrangement, specific weights are high and it would appear desirable to delete the entire hullborne system in favor of exclusive utilization of the foilborne thruster. Figure 14 gives estimated hullborne endurance/speed comparisons assuming all hullborne operation on a foilborne controllable pitch supercavitating propeller. Further development of this idea is reserved for downstream consideration which must take into account the viability of supercavitating blade operation in this speed regime, the possible implementation of forced ventilation, the physical aspects of pitch control and a more astute definition of desired underwater acoustic properties for the ship.

Overviewing the entire propulsion situation, the utilization of an angle drive propeller system emerges as substantially superior from the performance and weight point of view. The basic power system elements are either developed components or have undergone engineering development and shop level testing. What is needed for a propeller drive DEH is a detailed design, development and qualification program of all the components of the propulsion system This requires careful considerations to avoid past problems as regards preventing lube system contamination, subsequent bearing deterioration, over-emphasis on weight economy, seal integrity and reliability of attached auxiliaries, all factors that have contributed to "down-time" on the existing developmental propeller ships.

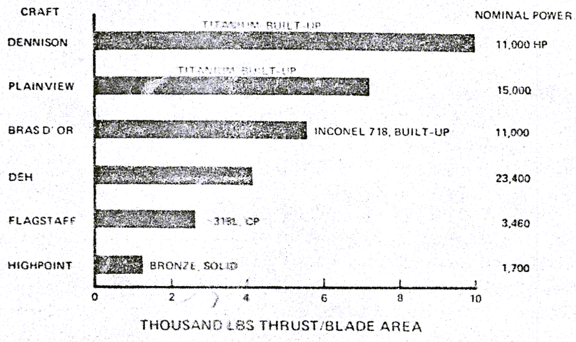


Figure 12: COMPARISON OF PROPELLER THRUST LOADING

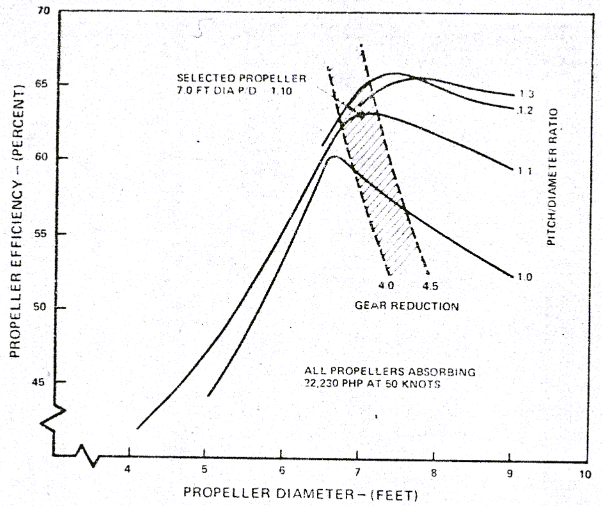


Figure 13: PITCH-DIAMETER EFFECTS ON PROPELLER EFFICIENCY

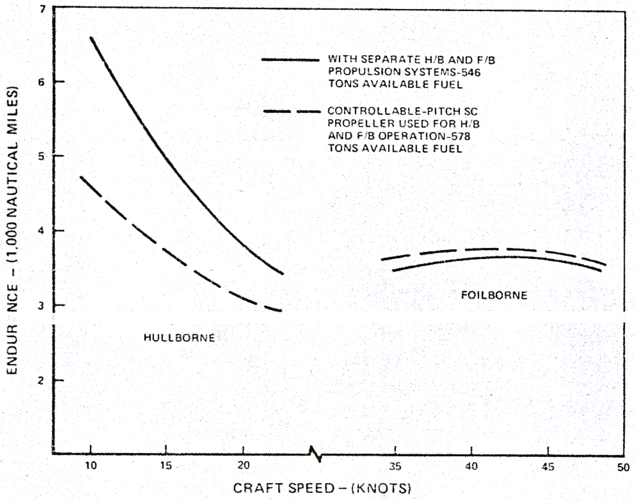


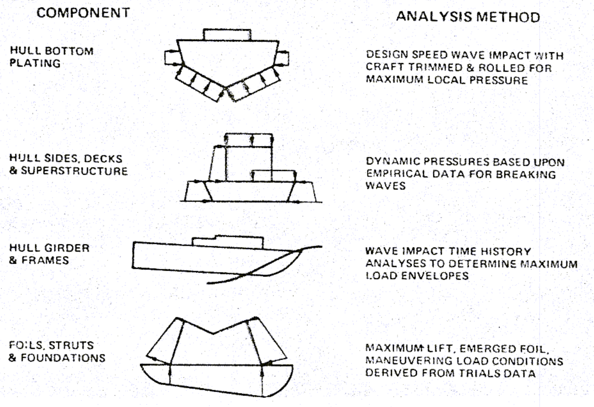
Figure 14: ENDURANCE WITH ALTERNATE PROPULSION SCHEME

Structure

Generation of loads data for structural design purposes is an area where the hydrofoil designer, motivated by the necessity to fully appreciate the dynamic loads imposed on the vehicle, has built up a body of practice that departs from the conventional approach to ship hull design. The loads criteria directly relate significant wave height for the design sea state to a "limit load" represented as the highest single load that can be imposed by the environment for the condition investigated. The governing limit load is compared to material yield properties, or when increased by an arbitrary factor of 1.5 is designated as an "ultimate load" which may be compared to the ultimate properties of the material. Stresses must be adjusted so that neither criterion exceeds the nominal material properties. Dependent on the condition under investigation, additional dynamic factors are inserted to account for "springing" effects or freebody vehicle response dynamics. Figure 15 graphically summarizes the various loads conditions investigated. Dynamic sea loading on decks and superstructure is related via the significant wave heights to dynamic pressures encountered in breaking waves.

At-sea experience has demonstrated the serviceability of hydrofoil hulls and it can be noted that no primary structural failures have occurred, even during operations in sea states substantially higher than design conditions.

Figure 16 is a typical structural section of the DEH hull. Despite the 200' length, main hull scantlings are controlled by bottom impact and local loads on sides and decks, except for distributing strut/hull intersection loads into the main girder. Based on a web spacing of five feet, the structure is conventional except that efforts to minimize weight lead to a rather dense spacing of longitudinals. Further optimization studies will be conducted involving hull weight – manufacturing cost trades. The use of ordinary T-stiffener to shell assembly techniques are assumed. Extruded plate-stiffener sections have been used in the past for additional weight economy. Because of the narrow extrusion panels and the attendant increase in welded plate seams required, it was judged that our larger ship would be better served with conventional assembly practices.



THE DESIGN LOADS ARE BASED UPON BOEING DERIVED CRITERIA USED ON CURRENT HYDROFOIL CRAFT. ANALYSIS METHODS HAVE INCORPORATED EMPIRICAL DATA FROM TECHNICAL TRIALS.

Figure 15: HULL DESIGN LOADS

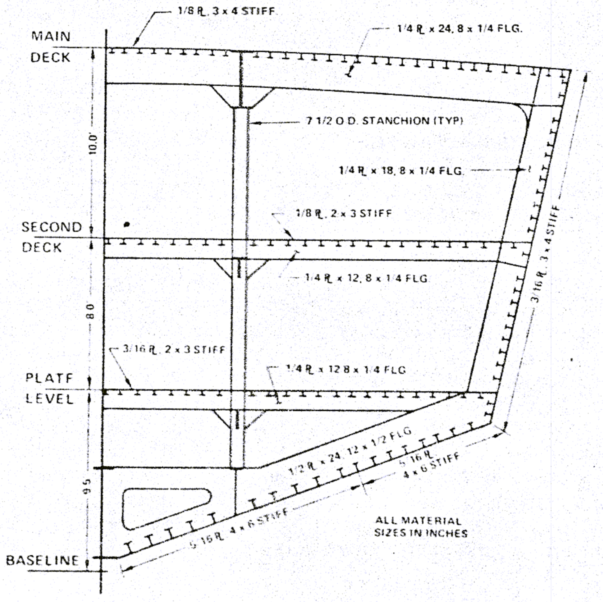


Figure 16: TYPICAL STRUCTURAL SECTION

Hull materials are the conventional 5456 aluminum. The use of HY-80 as an alternate has and is being considered but with the probable need for a corrosion allowance and a redistribution of elements to avoid impracticably thin materials, it is not likely that the latter material will be weight competitive.

Structural design criteria for struts and foils take a more conservative approach in deference to the influence of corrosion fatigue. In this case the governing ultimate load conditions which include appropriate dynamic magnification factors are compared to yield stresses. This reduces the design working stress by a factor of one third. In addition, in the detail design stage, statistical load profiles resulting from computer foilborne simulations for a given environmental situation can be applied to specific joint designs for analysis of fatigue life including crack propagation propensity.

17-4PH stainless steel of 120,000 psi yield or HY-130 are candidate materials for struts and foils. The former has excellent corrosion and cavitation erosion resistant properties but requires a high temperature post-fabrication heat treatment although recent technology investigations indicate a high probability of eliminating heat treatment above aging temperatures. HY-130 requires reliable coatings for corrosion/erosion protection. This matter is being actively pursued and it is anticipated that the present Navy program of HY-130 development will include designing and building an alternate set of strut-foils for PHM, which now utilizes a 17-4PH stainless alloy. The 6A1-4V type of titanium would have excellent general properties and save considerable weight. However relative costs, mill availability and fabrication variables have not been adequately investigated to elevate this material to an equal level of interest.

Hull Form Selection

Selection of the hydrofoil hull encompasses some of the usual considerations encountered in conventional hull design, introduces a few interesting novelties, and also "liberates" the designer in other respects. The novelty occurs in the need to have hull resistance data for many waterlines in order to suitably evaluate overall vehicle drag during the takeoff phase. In the interests of reducing foilborne bottom impact and minimizing wetted surface at takeoff, deadrise angles of about 22° are employed. A relatively fine fore-foot and bow flare are needed to reduce spray when cresting at high speed. Freed from the customary speed/length limitations, the hull is characterized by a high displacement length ratio as compared to destroyer forms. This allows for generous internal deck area, volume for arrangement purposes and freedom from stability limitations often encountered in destroyer forms. An additional important factor in beam selection is the arrangement of main struts to provide effective foil span equalization without excessive strut splay angle. The hull lines utilized are fully supported by an extensive series of towing basin tests. Table 5 lists the characterizing hull data. Analysis of resistance indicated that performance of this hull would be quite satisfactory under takeoff conditions. (75% of total drag at the takeoff hump is vested in the strut/foil system.) Hull resistance is rather high at the 20 knot hullborne cruise condition. However, investigation indicated that the investment in hullborne propulsion equipment was reasonable and acceptable.

Strut/Foil Configuration

Selection of Strut/Foil Configuration is influenced not only by operational criteria, but by external physical limitations which become operative in this large vehicle. Specifically these are:

TABLE 5: HULL CHARACTERISTICS

DISPLACEMENT, L. TONS	1363
TAKEOFF DYNAMIC LIFT, L. TONS	1255
DESIGN LCG, AFT OF MIDSHIP, FT.	15.37
DESIGN DRAFT, FT.	11.61
LENGTH OVERALL, FT.	216.66
LENGTH BETWEEN PERPENDICULARS, FT.	200
MAXIMUM BEAM, FT.	48
MAXIMUM BEAM AT CHINE, FT.	38.5
WATERLINE MIDSHIP BEAM, FT.	40.5
DEADRISE ANGLE, MIDSHIP, DEG.	22.5
WETTED SURFACE, SQ. FT.	8350
WATERPLANE AREA, SQ. FT.	6696
BLOCK COEFFICIENT (C_B)	0.494
MIDSHIP COEFFICIENT (C_M)	0.65
WATERPLANE COEFFICIENT (C_{NP})	0.81

Foil span (Drydocking and canal limitations)
Navigational draft hullborne
Nominal foilborne keel height (sea state related)
Design sea state
Foil loading and foil distribution
Control dynamics and ride quality
Structural feasibility
Ship arrangement
Fabrication and material considerations
Contiguous use of strut (i.e., waterjet ducts or angle drive transmission components)

Obviously these are interrelated factors and command much attention in prosecuting our design.

The selected foil arrangement is a fully submerged canard, with a relatively high ratio of main to forward foil area distribution. Experience has shown that, holding the proportion of total lift supported by the forward foil to a low value gives the best overall ride and minimizes perturbations caused by forward foil broaching and "flyout." Also, in the large hydrofoil the smallest possible forward steerable "T"-foil is of benefit from the point of mechanical actuation and hydraulic power demands. The high distribution ratio also brings the main foil forward for better interfacing with the main machinery in a fore and aft location which facilitates locating inlet ducts and stacks free of interference with afterdeck ordnance or helicopter installations. Rapid automatic course corrections are available from the faster responding small "T"-foil. The balancing effect of this general approach is that the larger resulting main foil reaches an imposed span limit sooner, or that compromises in foil aspect ratio are required, impacting take-off L/D. To allow maximum design latitude, a main foil span limit of 120' (dry docking limit) was established along with a limiting hullborne draft of 40' with expectation of reducing these dimensions as the ship definition developed.

Figure 17 shows the key planform and sectional dimensional properties of the foils selected for the propeller ship. The use of taper and variable t/c promotes optimum structural utilization of material and is a very important consideration in holding foil weights down.

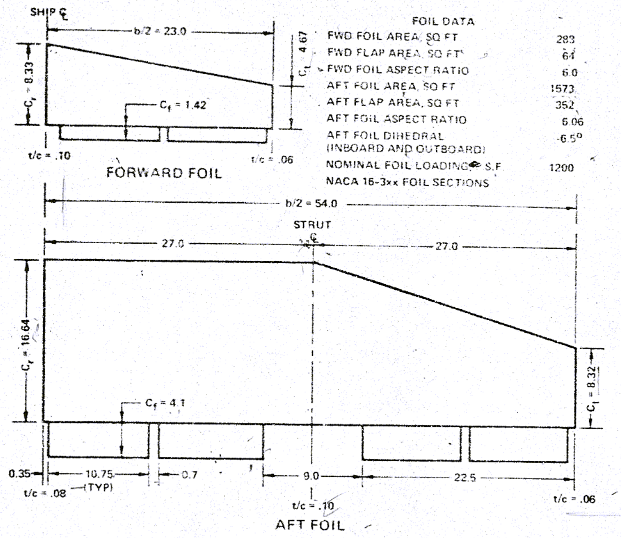


Figure 17: FOIL GEOMETRY

The two conventional control systems in use are (a) incidence control and (b) trailing edge (plain flap) control. The former is not structurally feasible for a ship of DEH size and general arrangement. The latter is feasible but because of inherent hinge point unbalance entails very large hydraulic power commitments. The detached control foil concept indicated in Figure 18 has been adopted for use on DEH. This permits placing the flap hinge point near the quarter chord reducing hinge moments by at least a factor of four as compared to the trailing edge flap. This promises to offer an excellent solution to the "hydraulic power limit" conventionally associated with large hydrofoils. The Boeing Company is presently conducting wind tunnel and flow channel tests of this concept to provide engineering design data.

Placing very strong emphasis on reliability and effectiveness of the entire flap control system, our design provides sufficient flap area and enough redundant flap segments to provide adequate, albeit somewhat degraded, control if one half of the flap elements on either or both sides of the foil system become inoperative. Two feasible concepts for flap actuation power trains are under study, one involving a dual redundant mechanical system from the main hull, through the struts and into the foils. The other employs redundant, independent flap segment power/servo loops which have the advantage of much reduced weight and mechanical complexity.

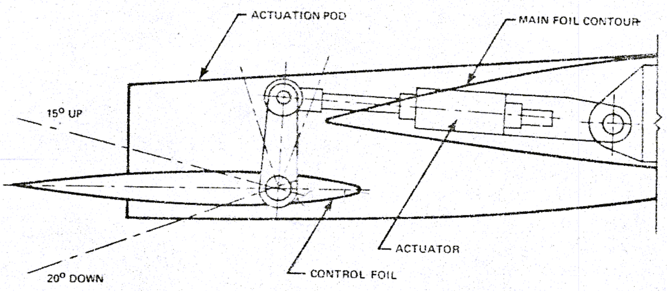


Figure 18: CONTROL FOIL ARRANGEMENT

Weights

Table 6 summarizes weight statements for the various versions of the propeller driven ship. At the present state of development 68% are calculated weights and the remainder estimated or ratiocinations. The Group I (hull) includes 40 tons for foundations and strut/hull interfacing allowances. Group 2 (propulsion) are discrete component weights and system estimates. Group (3) (electrical) is based on employment of an

TABLE 6: PROPELLER SHIP WEIGHT COMPARISONS

	002B BASELINE ASW	102B HELICOPTER ASW	202B MULTI-MISSION
FULL LOAD WEIGHT	1363 TONS	1363 TONS	1363 TONS
USABLE FUEL	546 (40.1)*	525 (38.6)*	433 (31.7)*
OTHER LOADS	55 (4.0)	58 (4.3)	86 (6.3)
ARMAMENT + MIL. P/L OF C&S	48 (3.5)	40 (2.9)	95 (7.0)
USEFUL LOAD	649(47.6)	624(45.8)	614(45.0)
MARGINS	75 (5.5)	77 (5.7)	84 (6.2)
ELECTRICAL + BASIC C&S	55 (4.0)	57 (4.2)	60 (4.4)
OUTFIT & FURNISHINGS	63 (4.6)	63 (4.6)	69 (5.1)
AUX. SYSTEMS LESS FOIL AND STRUT SYSTEMS	80 (5.9)	89 (6.5)	80 (5.9)
FOIL AND STRUT SYSTEMS	134 (9.8)	134 (9.8)	134 (9.8)
PROPULSION PLANTS	90 (6.6)	90 (6.6)	90 (6.6)
HULL AND SUPERSTRUCTURE	217 (15.9)	229 (16.8)	232 (17.0)
LIGHT SHIP	762(55.9)	779(57.1)	844(61.9)

*WEIGHT, TONS (PERCENT OF FULL LOAD WEIGHT) optimized 60 cycle system using diesel prime movers. Although 400 cycle power has been utilized on previous hydrofoils, it was felt that cost, logistic and acoustic problems would outweigh the possible lower weight of the 400 cycle electric plant. Group 4 (communications and control) combines both component and system estimates. The sonar equipment weights which form a large part of this system are estimated from developmental models and would require verification. Group 5 (auxiliary systems) is generally the most difficult group to support with estimates in the preliminary design phase, particularly when there is no parent form precedent. Each three digit group was addressed and direct system estimates were made in the light of the most probable available system development. Heating, ventilating and air conditioning weights in example were based on utilization of standard Navy type system arrangements and components with a view towards logistic continuity and available standard maintenance skills. On the other hand, the anchoring system reflect weights appropriate to a lightweight anchor and nylon-line mooring system as a means of reducing weight over the conventional chain/wildcat arrangement.

Foilborne Control and Motion Dynamics

Of the several sectors of developed hydrofoil technology, the present state of the art as regards the foilborne control system emerges as one of the more notable achievements, with significant contributions creditable to Navy planners, technical personnel and their supporting contractors.

Introduction of the acoustic height sensor, reliable accelerometers, Boeing manufactured solid state analog electronics, and selective system redundancy have combined to produce very reliable highly effective controls. Tucumcari, representative of 1967 control system technology, has never experienced an operational foilborne incident attributed to the control loop. Automation features relieve the helmsman of all coordination activity except for ordered course, turn rate and set foil depth. Ref. 2 offers a comprehensive description of the modern foilborne control system.

Utilizing stability and control derivatives for our propeller DEH, a linear behavior analysis based on typical controller parameters is set forth in Figure 19 with a superimposed comparison of vertical accelerations typical of destroyers.

Conclusions

A 15 year investment in technological development of the 50 knot hydrofoil has reached maturity. Without the inauguration of any new significant research and development effort, a mission effective high endurance hydrofoil escort ship in the 1200-1600 ton size range is feasible, viable and available to the fleet. Of the several "advanced marine vehicle" concepts of the 1960's, the 50 knot hydrofoil can become the advanced performance escort ship of the 1980's.

Dang very optimistic.

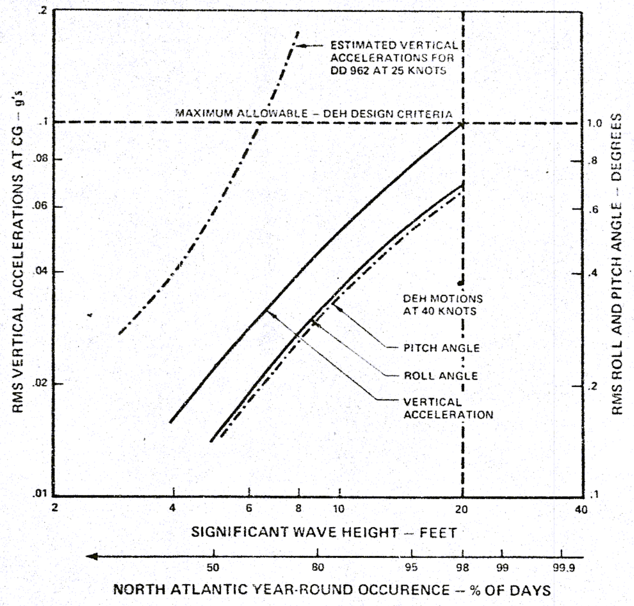


Figure 19: FOILBORNE MOTIONS

Acknowledgements

The authors are indebted to the members of the Boeing DEH preliminary design team who have largely produced the material for this paper.

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