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ADVANCED NAVAL VEHICLE CONCEPT EVALUATION

PART I
TECHNICAL ASSESSMENT

HYDROFOIL(U)

VOLUME I

DAVID TAYLOR NAVAL SHIP RESEARCH & DEVELOPMENT CENTER

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From: Project Officer, Advanced Naval Vehicles Concepts, Evaluation
To: Distribution List

Subj: Advanced Naval Vehicles Concepts Evaluation (ANVCE) State-of-the-Art Technology Assessment for Hydrofoil Ships

Ref: (a) OPNAV memo ser/59694 of 25 July 1975; subj: Directive for Advanced Naval Vehicle Concepts Evaluation

Encl: (1) State-of-the-Art Technology Assessment for Hydrofoil Ships; forwarding of

1. Enclosure (1), prepared by the David Taylor Naval Ship Research and Development Center (DTNSRDC) under the aegis of the ANVCE project office is forwarded for review and consideration. The assessment was conducted under the direction of ANVCE and does not necessarily represent an opinion of the Chief of Naval Operations or the Chief of Naval Material.

2. Enclosure (1) is an assessment of Hydrofoil Ship state-of-the-art technology compiled in response to the requirements of reference (a). The objective of this assessment is to provide a concise summary of what is known about the theory, design, performance and technical potential of the Hydrofoil Ship concept. During the course of this assessment, the technological effort necessary to support the development of point designs has been defined and initiated. In addition, it has formed the technological basis from which to select appropriate Hydrofoil Ship concepts for development as point designs. Ultimately, the assessment will be utilized in evaluating the military worth and technical feasibility of the Hydrofoil Ship selected for analysis.

3. This document has been prepared solely for use within the context of the ANVCE project.

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Part A

DESCRIPTION OF HYDROFOIL CONCEPT

(U) The fundamental concept of a hydrofoil ship is, through efficient lifting surfaces, to raise the hull of the ship above the water surface and thereby eliminate the hull friction and wavemaking drag which limits the maximum speed of conventional ships which depend on buoyancy for sustention. A second, but very important advantage to raising the hull above the water surface is that seaway induced forces and motions on the hull can be essentially eliminated, allowing the ship to proceed at high speed even in relatively heavy seas. At low speeds, before wave drag becomes dominant, buoyant lift is very efficient, and a hydrofoil operates on its hull much as a conventional ship. As speed is increased, however, the efficiency of the lifting surfaces (foils) increases to a point where they are more efficient lift producers than the hull,, and start to sustain a higher and higher portion of the ship displacement until a speed is reached (designated takeoff speed) where the whole weight of the ship is carried by the dynamic and buoyant lift of the foil system, and the hull is completely free of the water. Since the foils are considerably more efficient lift producers than the hull above takeoff speed, the hydrofoil ship can sustain much higher speeds for the same specific power than conventional ships. This is illustrated in Figure I.A-1.

(U) Hydrofoil ships use essentially two types of foil systems to achieve the basic principle of lifting the hull clear

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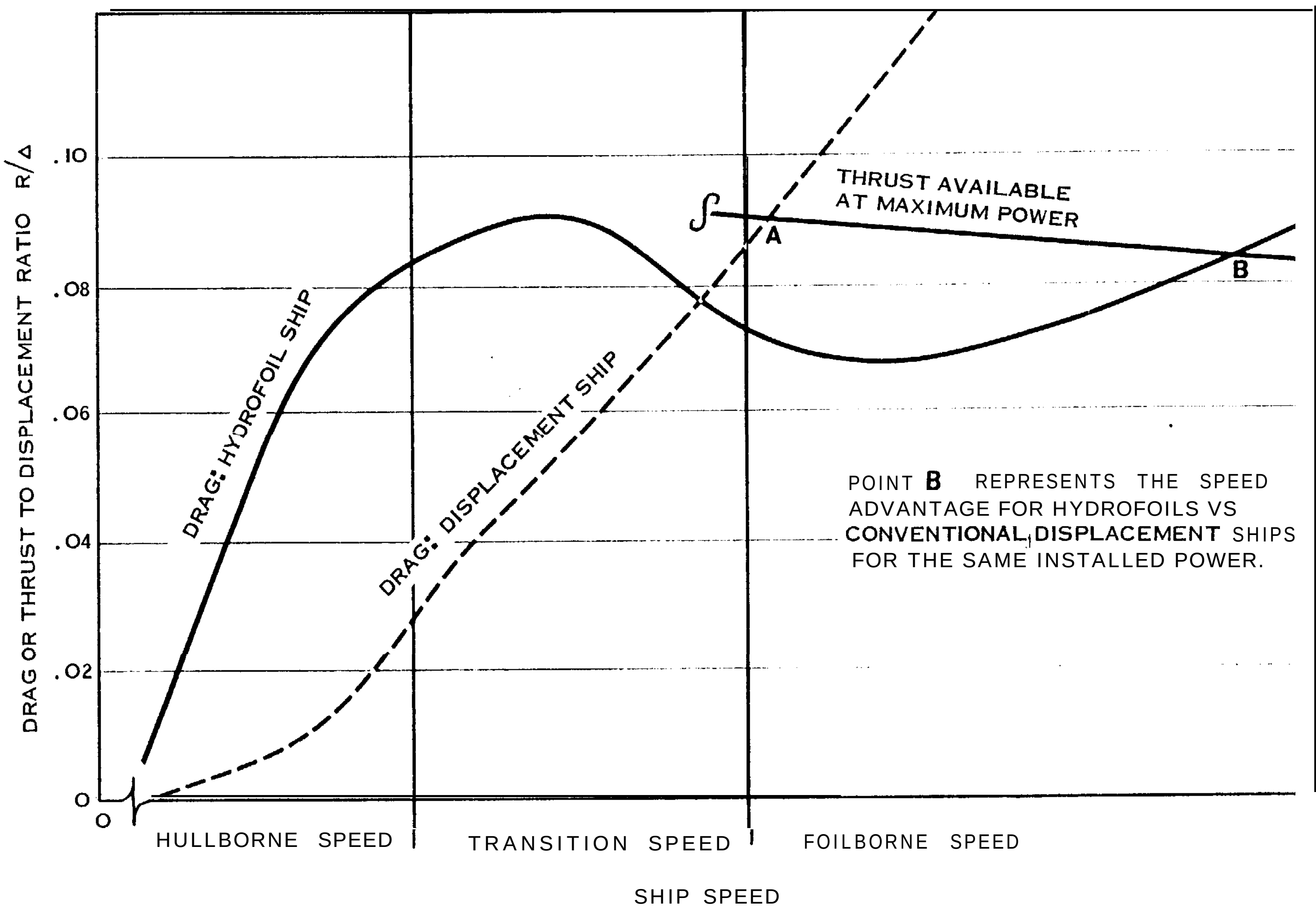

Figure I.A-1 HYDROFOIL SHIP DRAG-THRUST-SPEED CURVES

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of water. They are the surface piercing system and the fully submerged foil system as illustrated in Figure I.A-2. The surface piercing foil system is inherently stable through its variation of foil area with immersion and does not depend upon a sophisticated automatic control system for stability. Of the 650 to 800 commercial and military hydrofoil ships in existence, over 90% use the simplified surface piercing concept. Most are designed to operate in protected or calm water where the cost and sophistication of an automatic control system cannot be justified. In general, these ships have low operating speeds and are incapable of achieving full load speed much over 35 knots in calm water. Although the simplified surface piercing foil concept performs the first function, namely, lifting the hull clear of the water, it suffers many of the same problems inherent in buoyant ships or those ships which are closely coupled to the surface of the sea. This close coupling results in forces and motions on the ship which are directly related to the irregularities of the sea surface.

(U) The submerged foil system derives its stability from the lift control of the hydrofoils which function completely below the surface of the water. This submergence decouples the hydrofoil ship from the water surface. Lift control can be achieved by moving the entire foil surface, which is called incidence control, by having most of the foil surface fixed and using trailing edge flaps to achieve lift variations, called flap control, or by using a combination of incidence, flaps and tabs. A sensing system is

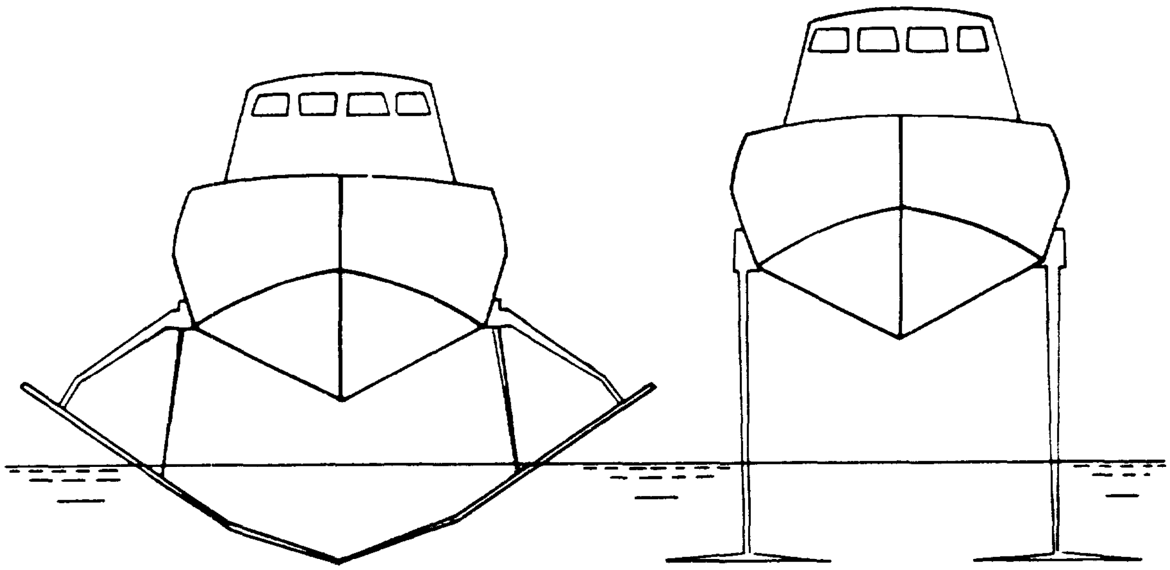


Figure I.A-2. HYDROFOIL SHIPS FOIL SYSTEM TYPES

'required to measure the ships roll, pitch, acceleration, and height above the water surface. This information is supplied to a computer which relays signals to hydraulic actuators which control the lifting surfaces. The entire system is called an automatic control system (ACS).

(U) Over the years, the surface piercing system has increased in sophistication to (1) improve the ride quality and (2) increase the speed. This sophistication has taken the form of added automatic control systems for pitch control augmentation or ride stabilization. Such effort has produced a hybrid which becomes a mixture of submerged foil and surface piercing technology. Increased speeds have resulted; both the BRAS d'OR and the DENISON achieved speeds over 60 knots. However, the motions of these two craft in a seaway are higher by a factor of 2 than motions for comparable size submerged foil vehicles such as PHM.

(U) At the same time, the added sophistication increased the cost of surface piercing foil ships which reduced one of their inherent attractive features. The increased costs are associated with heavier foil systems and stabilization systems. BRAS d'OR foils are 18.7% of full load displacement compared with 13.6% for the PHM. Both of these ships are about the same displacement--BRAS d'OR displacing 223 tons and PHM 235 tons. The result was not only increased costs, but also reduced payload.

(U) During the 1950s, the United States Navy, under the direction of the Office of Naval Research, very carefully evaluated surface piercing concepts, submerged foil systems, and hybrids. In 1958 a small test craft, SEA LEGS, made a remarkable at-sea demonstration of the potential of submerged foils. This test vehicle, built on a standard Chris Craft hull, weighed 5 tons and had a speed of 30 knots. It ran from New York Harbor to Annapolis taking the outside route and with remarkable at-sea comfort, completely outran its escort vessel, a USN PT boat. At the same time, HALOBATES, a LCVP on foils, was also demonstrating the feasibility of a 40-knot automatic control system and utilization of lightweight, gas turbine propulsion plants.

(U) When the Bureau of Ships, now the Naval Sea Systems Command, started the modern U.S. Navy hydrofoil development in 1960, the decision was made to pursue the submerged foil concept based on the information gained as a result of these trials. This decision was further confirmed when, in 1961, the first U.S. open sea hydrofoil, the DENISON, sponsored by the Maritime Commission, began operation. While the DENISON, a hybrid, achieved speeds of 60 knots, its motions in rough water were higher than smaller test craft with submerged foils.

(U) Since 1960, the Naval Sea Systems Command has continued to develop the submerged foil system. So today the U.S. Navy is the worldwide leader in hydrofoil capability. This summary will therefore concentrate on describing the state-of-the-art of the submerged foil system.

Part B

CAPABILITIES AND LIMITATIONS OF THE HYDROFOIL CONCEPT

(U) A hydrofoil ship has the capability to operate in the open sea at a size that is small by conventional ship standards. Its operational capability can be maintained in all but the worst weather on the foil system with good platform stability and at considerably higher speeds than displacement ships. At the same time, the basic hull shape is conventional, so that the concept permits the operator to go hullborne for lower speed operation. Since in the displacement mode the foils are good stabilizers, even hullborne the hydrofoil ship has kindly motions.

(U) In the 30- to 50-knot speed range, hydrofoils are more efficient than other types of sea craft. This fact is shown on Figure I.B-1 taken from Reference I.B-1. They therefore have an attractive ratio of horsepower to displacement. Accordingly, this leads to relatively good fuel consumption.

(U) The hydrofoil ship also has an attractive payload carrying capability. In fact, as will be shown in the following technical section, the useful load fraction improves with size (Reference I.B-3). This useful load can be proportioned between fuel and weapons, depending on range and mission requirements.

(U) The limitations of hydrofoils are, in many respects, matters of design trade-off. The hydrofoil ship has no technical

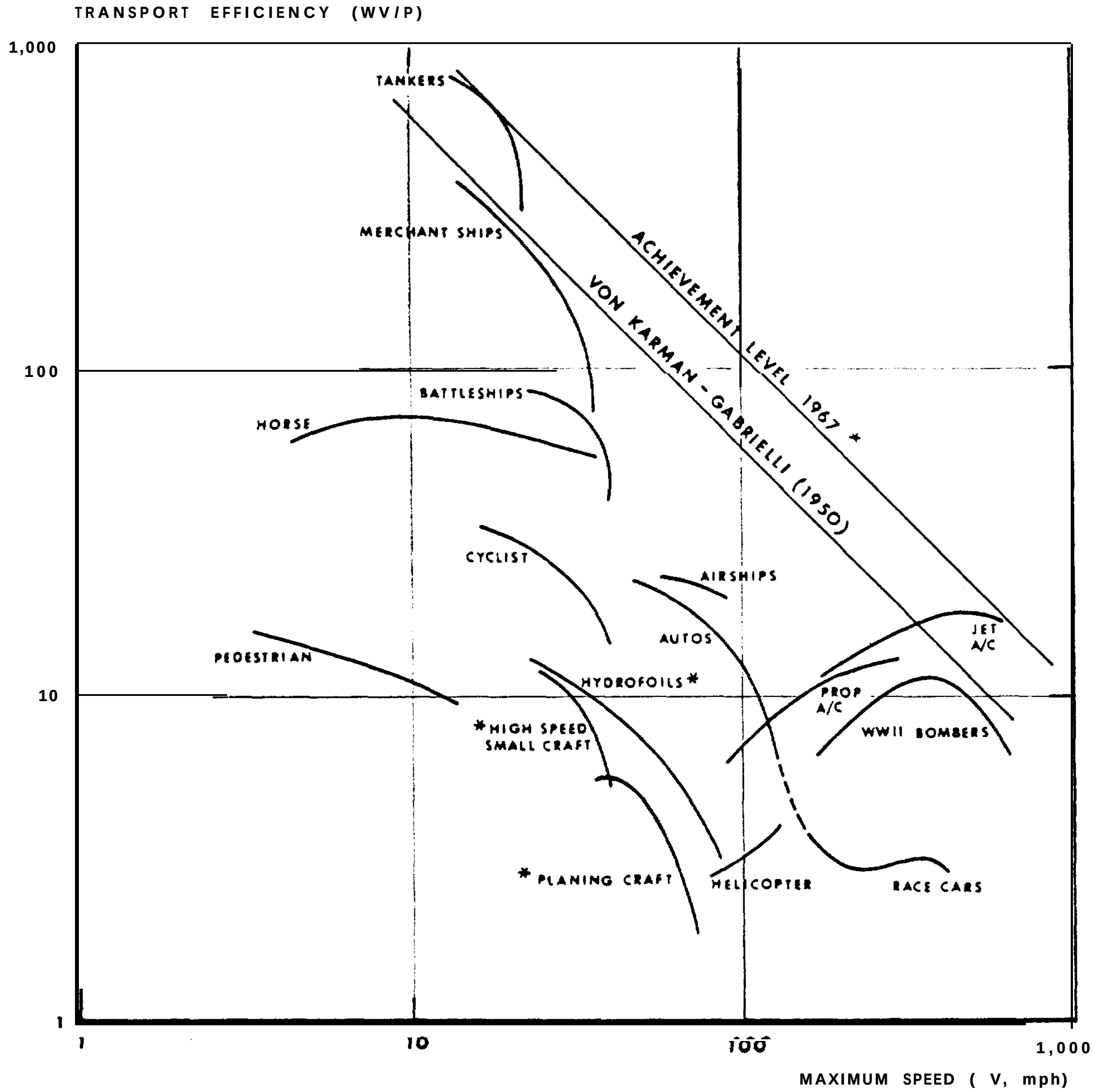


Figure I.B-1. TRANSPORT EFFICIENCY OF SEVERAL CRAFT AS A FUNCTION OF MAXIMUM SPEED

*Reference I.B -2

characteristic which relates to "dropping off a performance cliff." The limitation compromises are related to size, speed, and propulsion selection.

(U) As to size, studies to date have not indicated any particular limitation. Hydrofoil ships have been demonstrated from small runabouts to 330 tons. Studies have been made of craft in the 2,000- to 3,000-ton size. All are considered feasible.

(U) Certain fundamentals need to be considered as ships get larger. The linear dimensions of the foil tend to increase as the square root of displacement ($\Delta^{1/2}$), while the linear dimensions of the hull increase as the cube root of displacement ($\Delta^{1/3}$). Therefore, the foil dimensions vary as the 3/2 powe-r of the hull dimensions. Practical foil spans become a matter of consideration, such as fabrication damage to exposed foil tips, docking, refueling, and transiting the Panama Canal. Solutions to this problem can be addressed by equally distributing the lift load between fore and aft foil systems in tandem arrangements. If draft and retraction are not considerations, additional foils and biplanes can be considered, although these will increase the weight and drag of the system.

(U) One feature that benefits the bigger hydrofoil ship is that the sea does not get bigger; therefore, for the same sea state the length of the struts remains constant, which makes them proportionately shorter with increasing ship size.

(U) In plotting the buoyancy of foil systems with increasing size, the trend shows that buoyancy is increasing slightly, from 4 to 10%, with increasing size. (See Figure I.B-2.) This trend causes larger ships to be somewhat more efficient than smaller ones since the buoyant lift of the larger foil systems is achieved with no increase in drag. This has been substantiated on studies of hydrofoil ships up to 1,600 tons with the results considered valid on hydrofoil ships up to 3,000-ton size. Ships larger than 3,000 tons require more study to draw any significant conclusions.

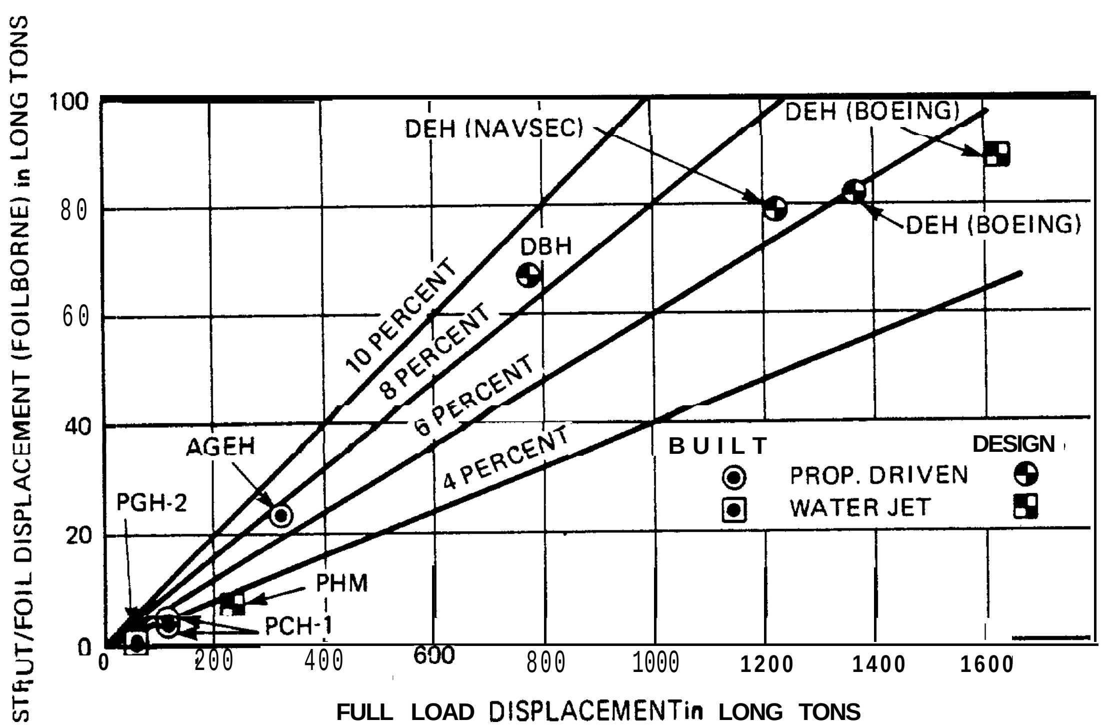


Figure I.B-2. BUOYANCY OF FOIL SYSTEMS VS INCREASING SIZE

(U) The speed of hydrofoils introduces limitations imposed by cavitation. When a foil begins to cavitate, the foil continues to operate. As cavitation develops, drag increases, but lift can be maintained. So again, there is no sharp drop-off in performance. The most serious consideration of cavitation is the deterioration of the foil surfaces. Therefore, long term operations should either be in the subcavitating or supercavitating regime.

(U) As will be developed in this document, the understanding of subcavitating foils is well in hand, and designs can be accurately assessed to ensure cavitation-free operation. A practical limitation for subcavitating foils is about 55 knots as indicated in Figure I.B-3.

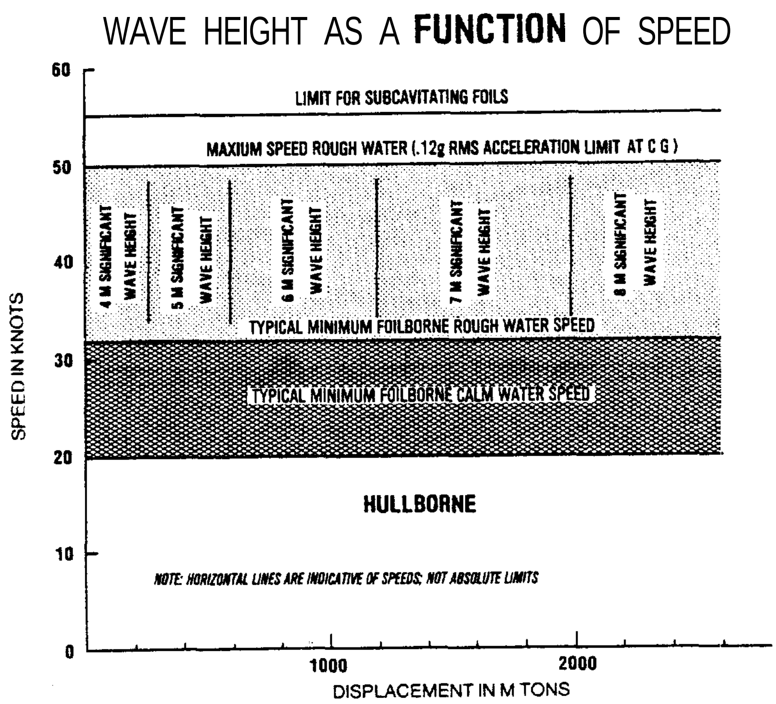


Figure I.B-3. LIMITATIONS FOR SUBCAVITATING FOILS

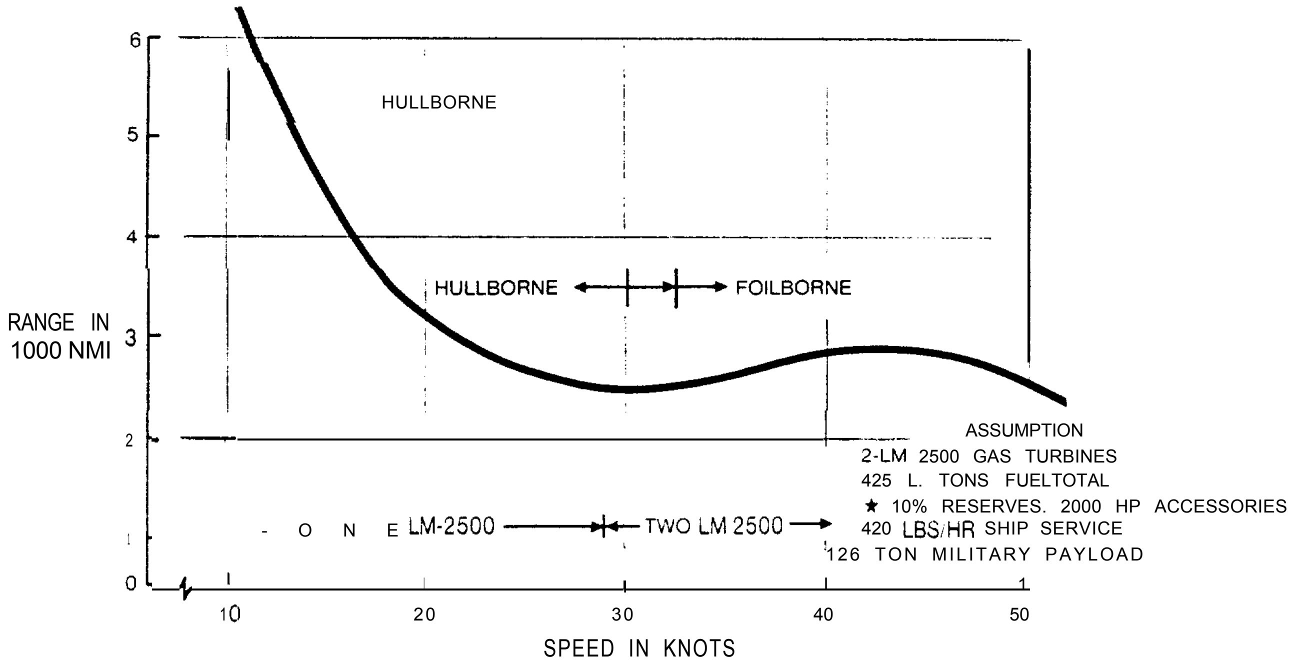
(U) Above 55 knots other approaches such as supercavitating hydrofoils should be used. Supercavitating foils have the characteristic that the cavitation bubble collapses downstream from the foil, and no damage to the foil surface results. Exploratory models have demonstrated the ability to build feasible, supercavitating foils for the 70- to 80-knot operating range. The lift-to-drag ratio of supercavitating hydrofoils is lower than that of subcavitating foils, which reduces range and/or payload. Therefore, the applications of supercavitating hydrofoils are more limited.

(U) Mention should be made here of the exploratory work that has been done on transiting hydrofoils. These are foil section and planform combinations that operate subcavitating at speeds to 55 knots and supercavitating about 65 knots. From 55 to 65 knots smooth transition takes place so that adequate stability and controllability are maintained in this transition region. Good lift-to-drag ratios in the subcavitating range can be achieved while providing the ship with very high speed operational capability.

(U) Figure I.B-3 indicates a rough water maximum speed of about 50 knots while sustaining very comfortable acceleration limits of 0.12g rms. Speed degrades about 5 knots in rough water operations. This Figure I.B-3 also displays the effect of sea state on the size of the hydrofoil ship. Since increasing strut length is the primary means of achieving higher sea state operation, this is a practical plot of strut length for ship size. It should be emphasized that when a hydrofoil ship goes into a higher-than-design sea state, it does not stop operating. The motions will increase, and the acceleration will be higher, but the ship will continue to fly. Maximum sustained speed is a matter of operator decision.

(U) In addressing limitations relative to speed, some consideration must be given to minimum foilborne speeds. Hydrofoil ships can operate at any speed down to minimum foilborne. Again, it is a matter of operator discretion as to where the ship will operate hullborne or foilborne. The lines indicated on Figure I.B-3 for minimum foilborne speeds in rough water and smooth water are only indicative and are not to be taken as absolute. The designer and the operator have some flexibility in establishing these speeds. It can be said that minimum rough water speeds will, in general, be 3 to 5 knots higher than calm minimum water speed for subcavitating foil systems. Particular attention in the design process must be paid to hull shape and hullborne propulsion plant selection to ensure no major range compromises at the minimum foilborne operating speed and maximum hullborne speeds. Figure I.B-4 is an envelope of design ranges determined by recent studies indicating the potential for achieving good range characteristics for a hydrofoil ship at all speeds to maximum foilborne. These ranges would decrease about 5% in sea state 6.

(U) One of the considerations that places a limitation on hydrofoil ships is the horsepower of available gas turbines. Hydrofoil ship arrangements are most satisfactory using port and



(C) Figure I.B-4. DESIGN RANGES INDICATING POTENTIAL AT ALL SPEEDS (U)

starboard plants. For subcavitating hydrofoil ships restricted to two gas turbines, the following is a ship size limitation for the large turbines under development today:

Turbine	Ship Maximum Size
2-LM 2500	1,200 - 1,600 tons
2-FT 9	1,600 - 2,000 tons

It should be noted that AGEH-1 has room to install four LM 1500 gas turbine engines, two port engines, and two starboard engines. If, for the examples above, four engines are considered, the maximum size ship can be doubled.

(U) The propulsion system places one more limitation on the hydrofoil ship designer that must be considered. That limitation is related to the characteristics of the thrust producer and the design speed of the ship. The two thrust producers of interest today are the waterjet and the propeller. The waterjet's efficiency improves with increasing speed. They are therefore poor for lifting large ships off at low speeds, but become competitive above 60 knots.

(U) Propellers can be classified either subcavitating or supercavitating with and without controllable pitch. The selection is therefore based on the operating speed envelope for the ship. For large hydrofoils, the propeller is preferred because of its higher efficiency, particularly at takeoff. The characteristics of several available propeller designs are discussed in Chapter II, Status of Vehicle Technology, in the sections of this document on propulsion.

Part C

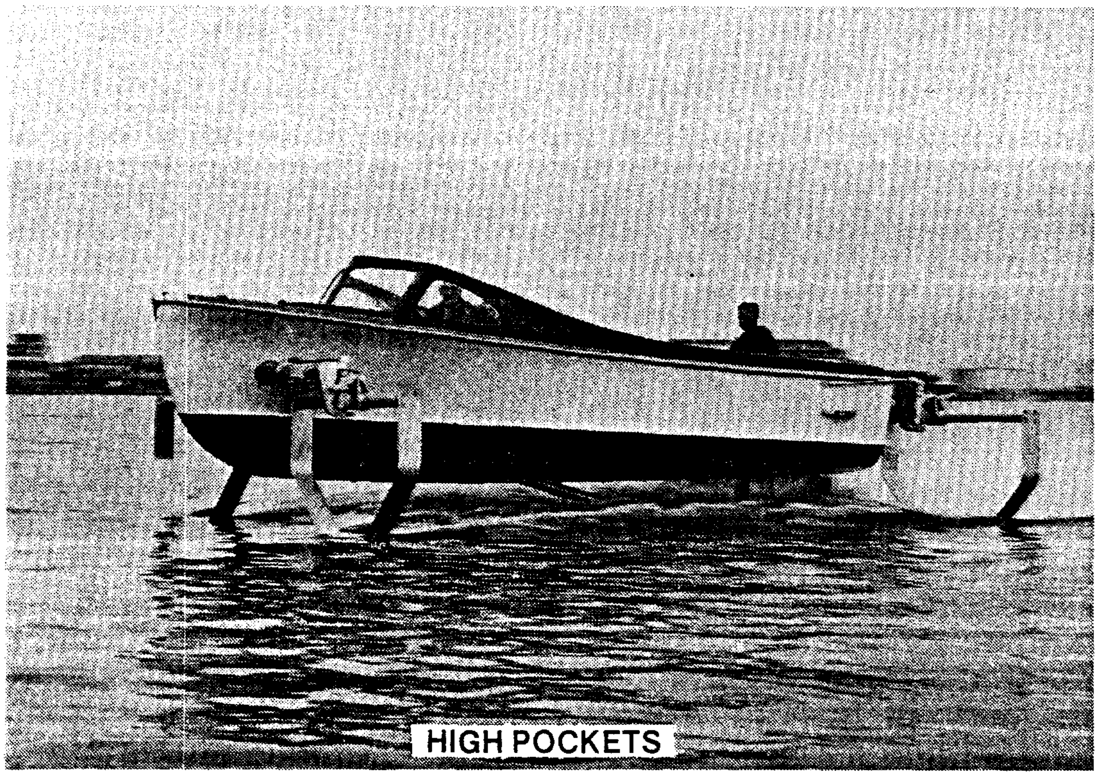
HISTORY OF THE HYDROFOIL EFFORT AND PRESENT STATUS

(U) The early history of hydrofoil development which dates back to the beginning of this century has been well documented. Those who are interested are referred to papers by Oakley (Reference I.C-1), Lacey (Reference I.C-2), Ellsworth and O'Neill (Reference I.C-3), and Johnston and O'Neill (Reference I.C-4). This history will not be repeated in any detail in this document; only the highlights of more recent developments will be discussed.

1. EARLY U.S. NAVY RESEARCH

(U) The U.S. Navy, as well as the Soviet and other navies, took an active interest in the hydrofoil work done by Germany during World War II. Beginning in 1947, the Office of Naval Research (ONR) funded hydrofoil developmental efforts by several industrial organizations with support from universities, research institutes, and government laboratories, principally the David Taylor Model Basin, now the David W. Taylor Naval Ship Research and Development Center. With the support of the Bureau of Ships and the Bureau of Aeronautics (now NAVSEA and NAVAIR), a broad program including mathematical analysis, model experiments, and tests of a variety of hydrofoil craft was conducted.

(U) ONR had built a series of demonstration test craft. Two of these, HIGH POCKETS and XCH-4 (Figure I.C-1), had surface piercing foils utilizing their inherent stability in heave, pitch, and roll. Other hydrofoil craft, notably HALOBATES, FLYING



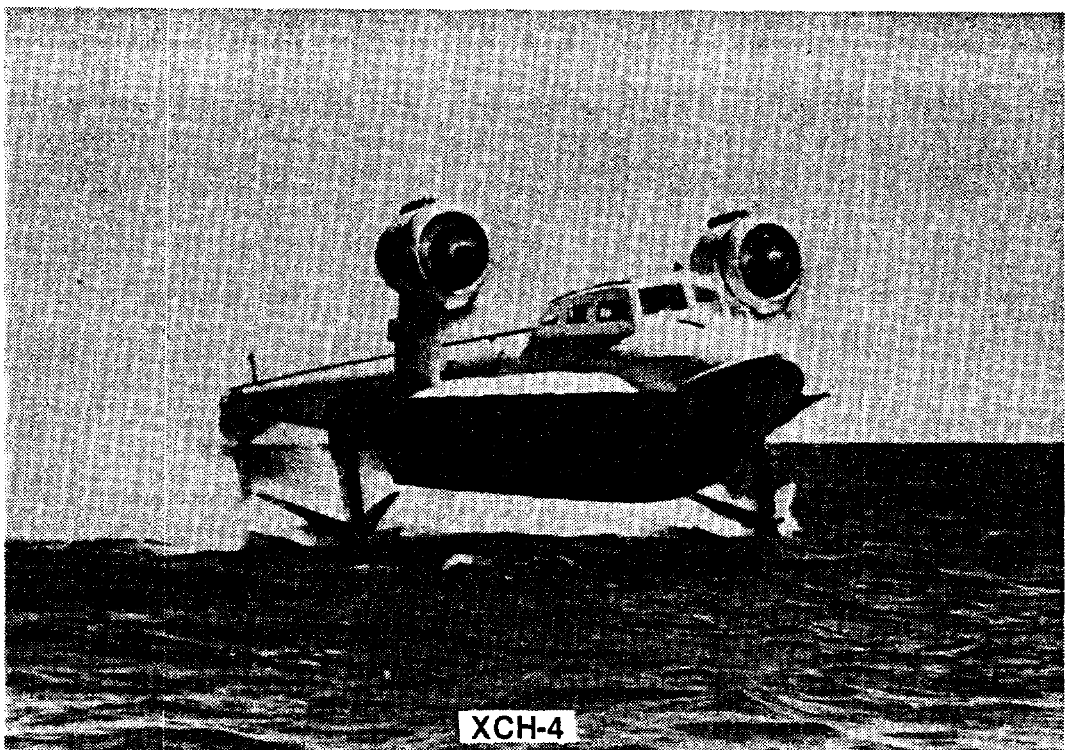
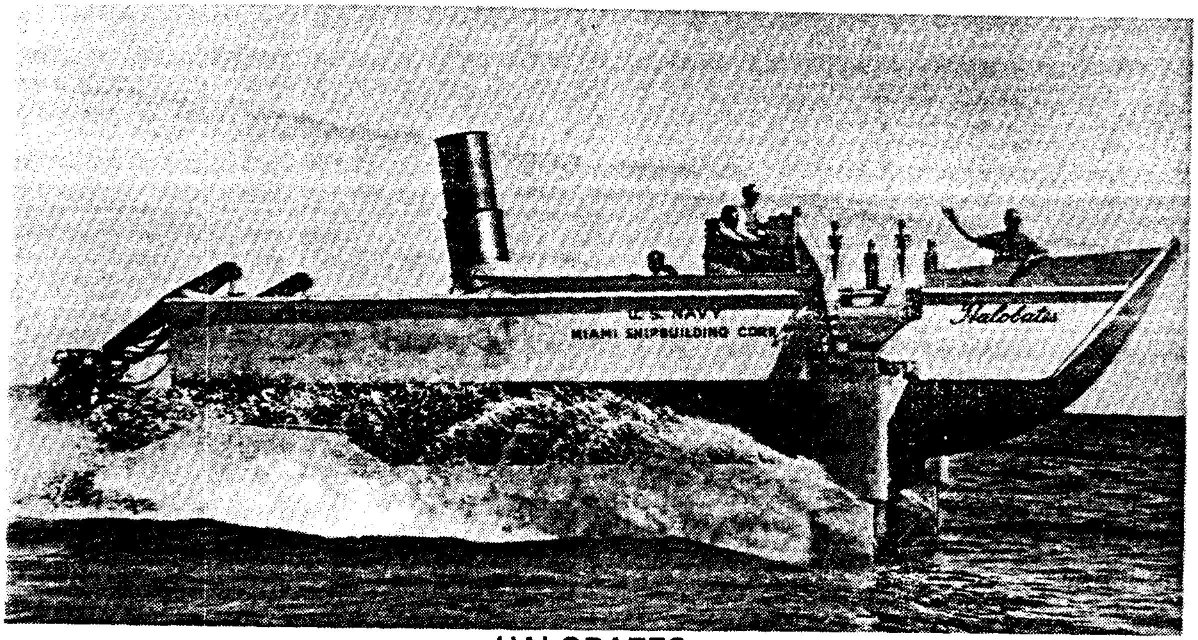


Figure I.C-1. ONR SURFACE PIERCING DEMONSTRATION CRAFT

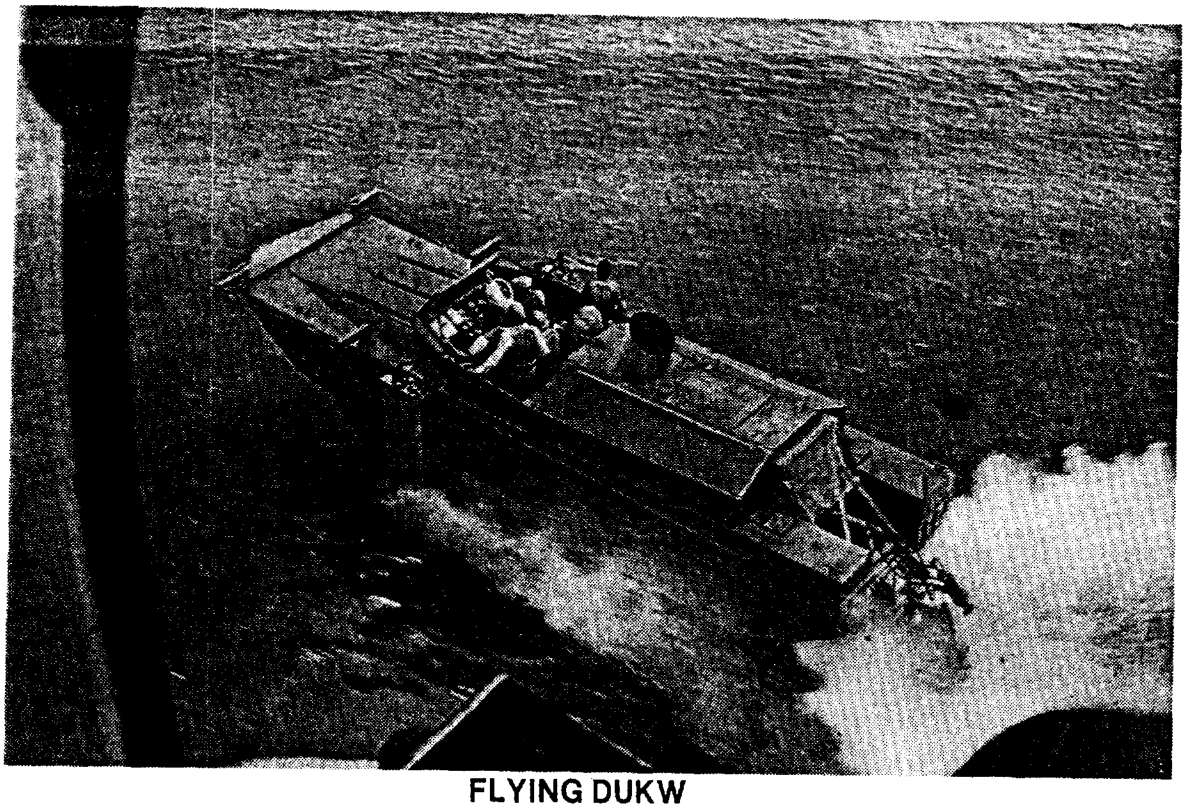
DUKW, HIGHTAIL, and SEA LEGS (Figure I.C-2 and I.C-3) explored fully submerged foil systems. The most significant demonstrations were made by the fully submerged hydrofoil SEA LEGS, which was converted from an ordinary Chris Craft hull, with a gross weight of 5 tons and a speed of 30 knots. This was a joint effort of Gibbs & Cox, Inc. and the Massachusetts Institute of Technology Flight Control Laboratory which installed an automatic control system along with the submerged foils. This craft demonstrated the feasibility and seakeeping advantages of such a combination in rough water in 1958. The 300 hours and 8,000 miles of foilborne operation of SEA LEGS over a 6-year period produced much valuable information which formed the basis for the design of the first U.S. Navy hydrofoil, HIGH POINT, PCH-1 (Figure I.C-4). The use of a marinizedgas turbine engine and ZEE-drive gear transmission, demonstrated on the ONR research craft HALOBATES (Figure I.C-2) and XCH-6, were incorporated into the HIGH POINT. The DENISON (Figure I.C-4), a combination surface piercing and submerged foil ship of 80 tons, sponsored by the Maritime Administration, also utilized a gas turbine driving a supercavitating propeller through a ZEE-drive and was the first U.S. "open-ocean" hydrofoil ship.

2. THE HYDROFOIL ADVANCED DEVELOPMENT PROGRAM

(U) The Navy Hydrofoil Advanced Development Program began in FY 1960 when HIGH POINT was authorized. It was designated the Hydrofoil Accelerated Research Program. Emergency RDT&E funds were allocated to the Bureau of Ships for initial support. The decision to begin the program in 1960 was based on the judgment that

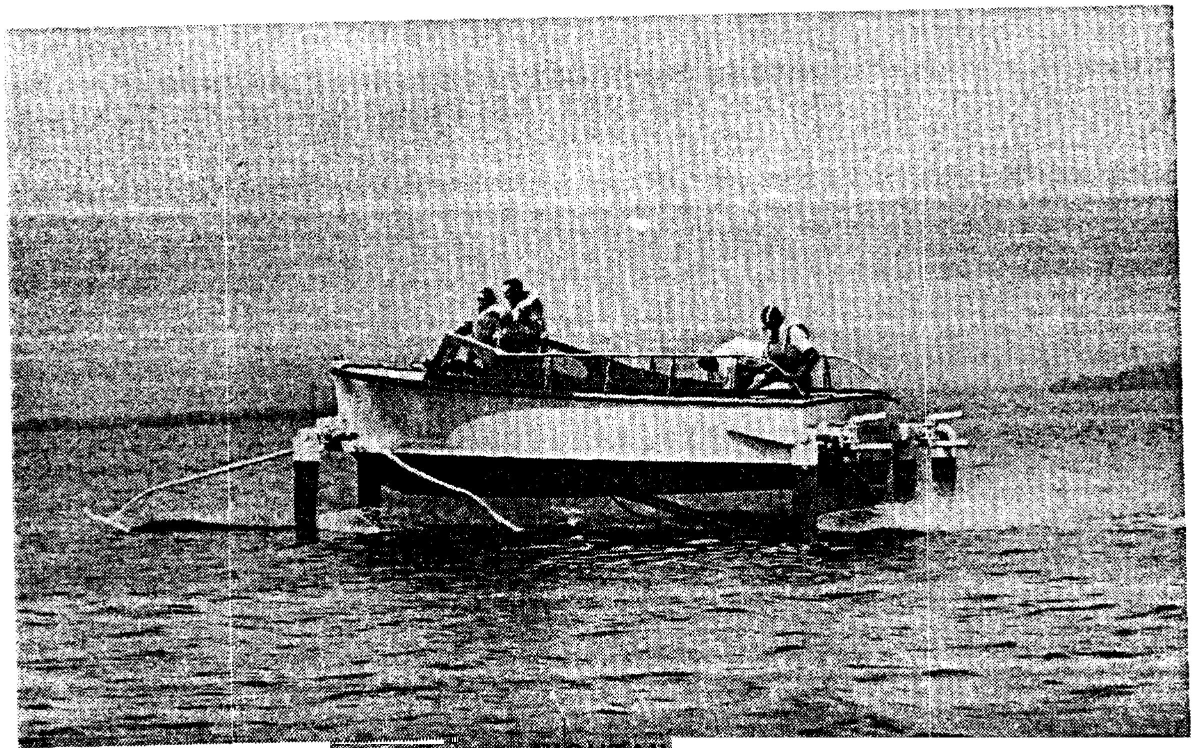


HALOBATES



FLYING DUKW

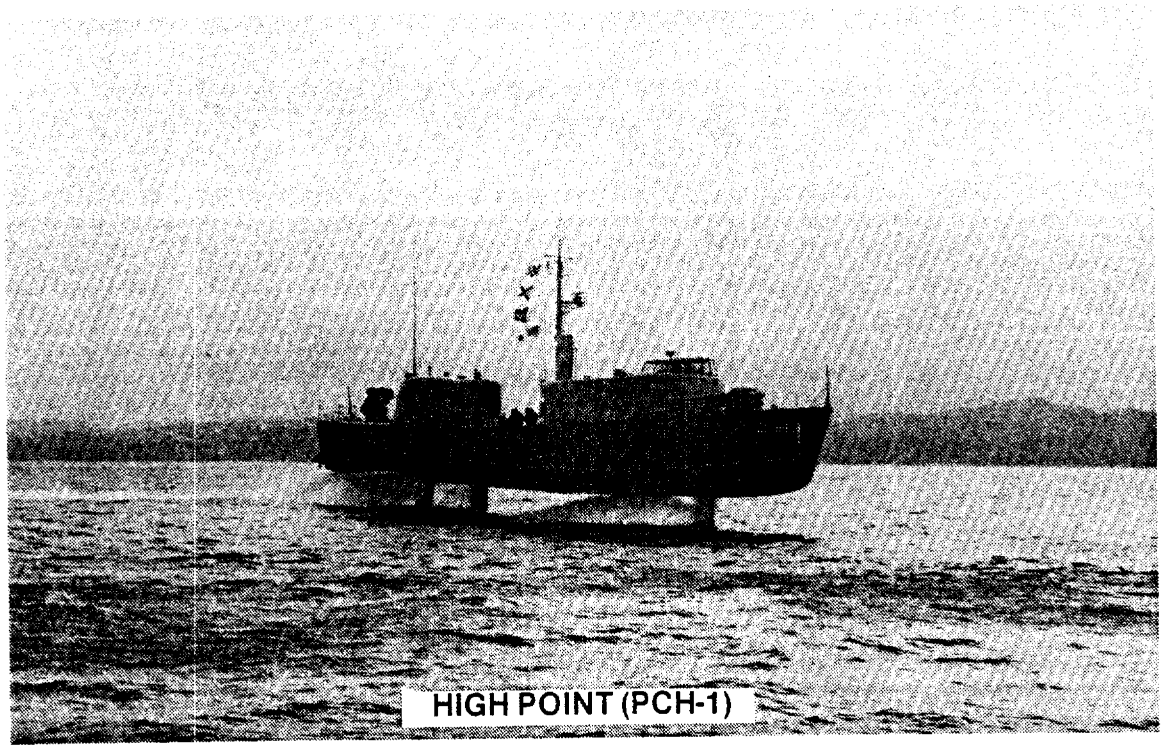
Figure I.C-2. SUBMERGED-FOIL TEST CRAFT



HIGHTAIL

SEA LEGS

Figure I.C-3. U.S. NAVY SUBMERGED-FOIL TEST CRAFT



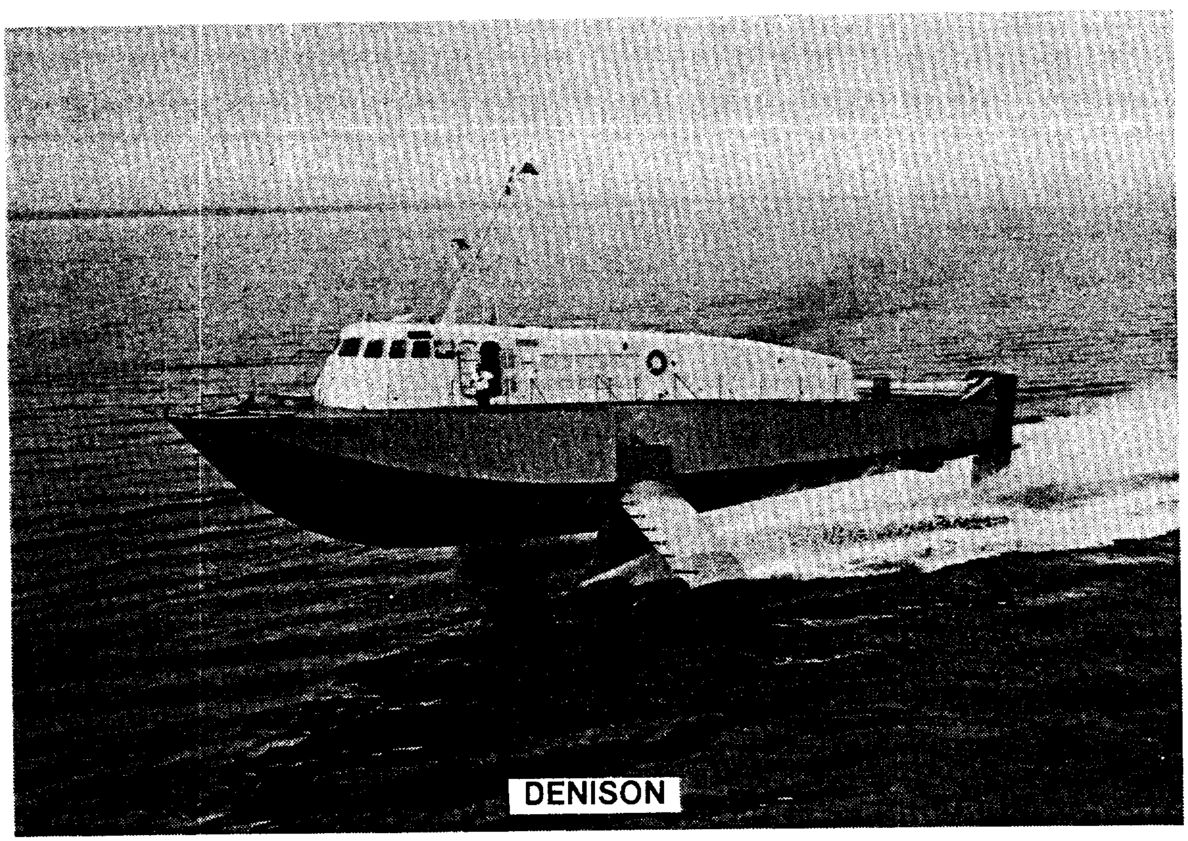


Figure I.C-4. HIGH POINT AND DENISON

sufficient knowledge and experience had been accumulated to demonstrate that submerged foil hydrofoil ships were feasible and could provide the Navy with a significant improvement in high-speed, all-weather mission capability.

(U) Since the inception of the Advanced Development Program, the broad purposes have been:

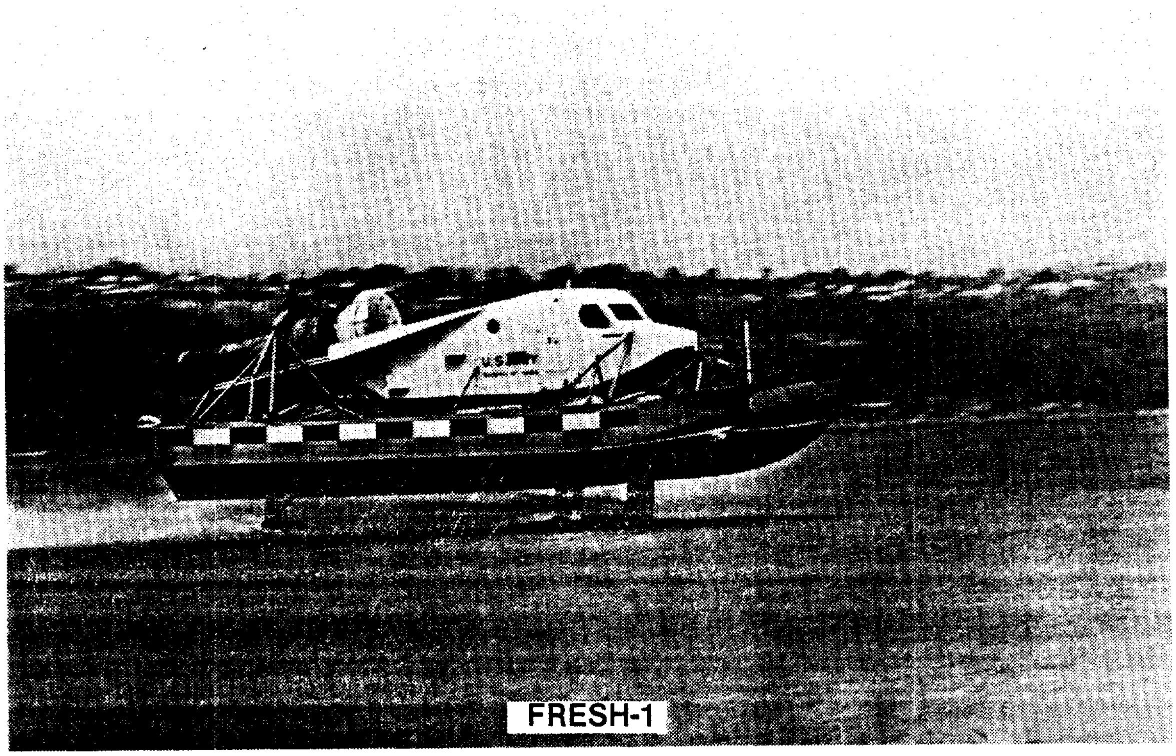
1. To demonstrate feasibility, financial acceptability, and military usefulness of hydrofoils in various naval missions

2. To demonstrate operation reliability

3. To generate design criteria for future operational craft

(U) Initially, there was a strong push towards speeds between 60 and 100 knots. The ONR test craft XCH-4 (Figure I.C-1) demonstrated a speed of 78 knots in 1954. The Maritime Administration's DENISON (Figure I.C-4) achieved an open-sea speed of over 60 knots. A contract was awarded to The Boeing Company in 1961 to build FRESH-l (Figure I.C-5), which currently holds the speed record of 83 knots.

(U) Construction of PLAINVIEW, AGEH-1, (Figure I.C-5) was authorized in FY 1962, and supporting studies were undertaken under the Advanced Development Program. PLAINVIEW was planned to have an ultimate speed of 90 knots, and the hull was designed for that speed. The first Advanced Development Objective (ADO in 1963) reflected the emphasis on speeds up to 90 knots. It: also identified the prime mission of hydrofoils as ASW. Following difficulties with the 48-knot HIGH POINT, the 1965 ADO de-emphasized speed by stating



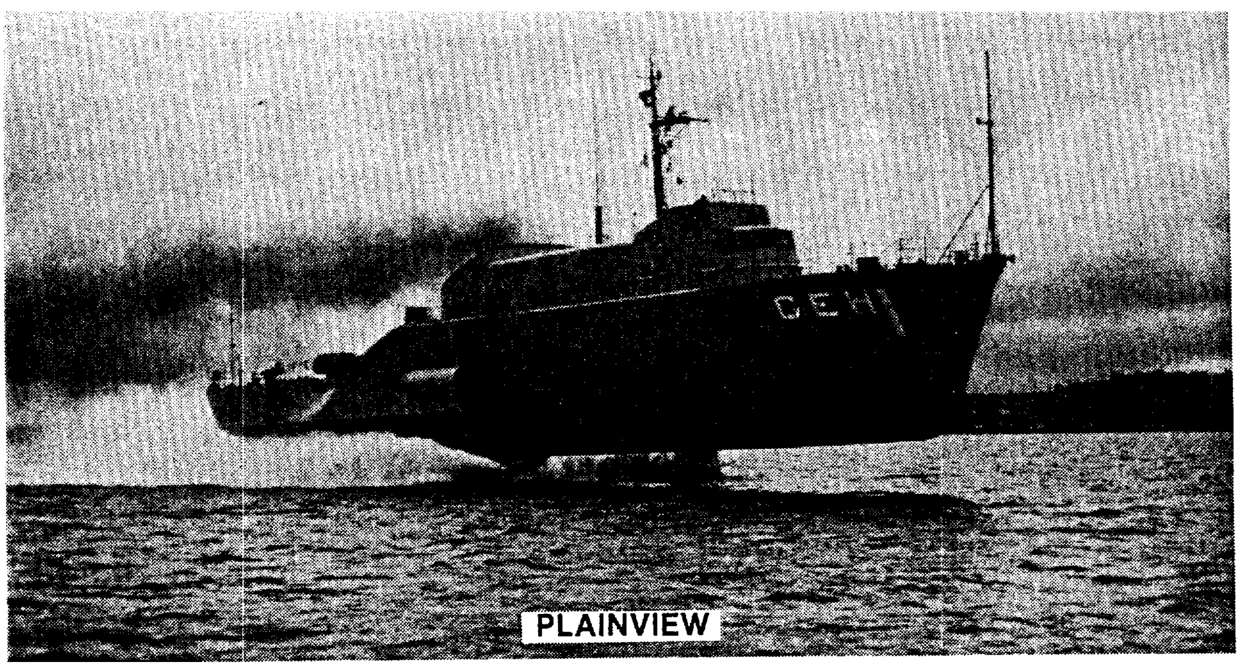


Figure I.C-5. PLAINVIEW AND FRESH-l

a nominal speed range up to 50 knots and emphasized seakeeping by stating sea state 6 as the highest sea state to be pursued. This revision of the ADO also explicitly included the evaluation of AGEH-1 in the program. In 1972, the ADO was again revised* to its present form to explore larger and faster hydrofoils.

3. HYDROFOIL SPECIAL TRIALS UNIT

(U) With the issuing of the ADO dated 2 June 1965, provisions of a precedent-setting nature were made to conduct a broad trials program. The Navy had recognized for some time the need for a unit to be devoted to the conduct of technical trials of advanced surface craft. The first step was to establish a Hydrofoil Special Trials Unit (HYSTU). In November 1966, upon request of the Naval Ship Systems Command, DTNSRDC established HYSTU at Rremerton, Washington, as a tenant activity of the Puget Sound Naval Shipyard with office and shop spaces on the pier. It is staffed with both civilian and military personnel. The Officer-in-Charge is responsible to the Commander of DTNSRDC and to the Technical Manager of the Hydrofoil Development Program Office for the conduct of all special trials of assigned craft. Technical control of HIGH POINT was transferred to DTNSRDC, with operational control provided by the Commandant of the 13th Naval District, effective in December 1966. PLAINVIEW was likewise assigned following her delivery in March 1969.

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*ADO 46-06XR2, Advanced Hydrofoil System (U), Mar 1972

3.1 HIGH POINT (PCH-1)

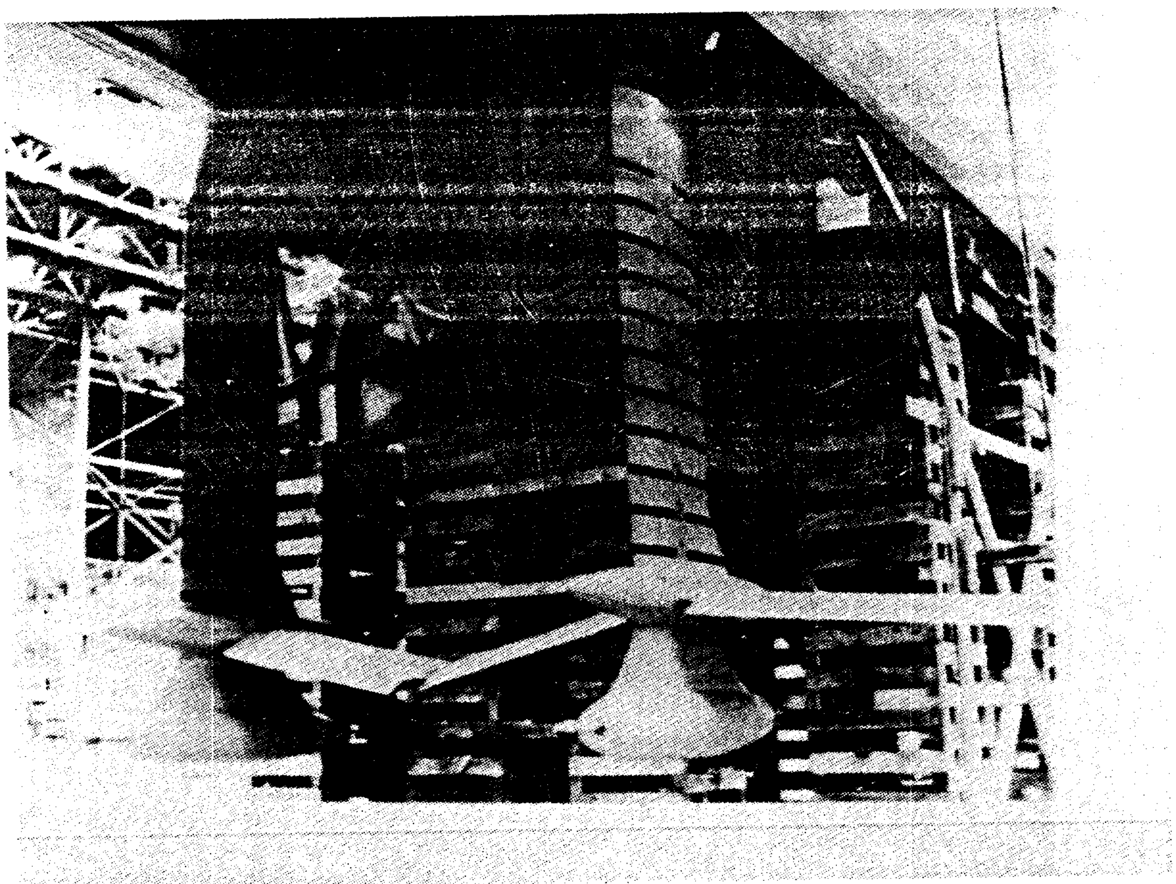
3.1.1 HIGH POINT MOD 0

(U) HIGH POINT was delivered in October 1963, and her first year of trials, consisting of 53 foilborne hours, indicated the need for modifications. Trials of HIGH POINT were resumed in September 1966. During the next year, almost 80 hours of foilborne operation were made in calm water and in seas in excess of sea state 4. These trials began to restore Navy confidence in the capabilities of HIGH POINT, although the operations were restricted to speeds less than 40 knots to alleviate cavitation effects. Foilborne operating hours were rapidly added in 1968. This experience demonstrated the capability to operate the craft and to gather data, and it also demonstrated the basic value of the HYSTU concept for conducting developmental trials.

3.1.2 HIGH POINT (PCH-1 MOD 1)

(U) Operational experience showed that major foil/strut and propulsion problems required a redesign. A 1966 design study led to detailed design changes, denoted MOD 1. These changes incorporated advanced technologies to improve on the MOD 0 design, correct deficiencies, and achieve an acceptable level of performance and reliability.

(C) The complete MOD 1 configuration is shown in Figure I.C-6. Performance improvement is such that HIGH POINT now has a top speed of over 50 knots at a displacement of 130 tons.



HIGH POINT MOD-1

Figure I.C-6. HIGH POINT MOD-1

3.2 PLAINVIEW (AGEH-1)

(C) Final contract trials on PLAINVIEW were conducted in March 1970. During trials, a maximum foilborne speed in excess of 50 knots was achieved. A stable flying speed of 27 knots (8 knots lower than design) was also achieved. During 25 hours of operation at over 40 knots, the struts and foils were shown to be free of cavitation damage. PLAINVIEW was put in a post-shakedown availability in the last half of 1970 to correct deficiencies, primarily in the hydraulic system. Hullborne trials were conducted for the first half of 1971, during which machinery deficiencies were corrected. In July 1971, PLAINVIEW began to fly with regularity and conducted smooth water trials interspersed with a variety of mission trials.

(C) PLAINVIEW conducted its first rough water trials in sea state 4 seas in December 1972. At that time, it was also making the first launchings of a missile from a hydrofoil ship. A control linkage rod in the starboard pod failed while the ship was foilborne. Because of continued hydraulic system component deficiencies, a major overhaul of PLAINVIEW was scheduled. Major repairs and refurbishments were planned to begin in January 1973. A delay of funds prevented this, and the work had to be rescheduled with a resulting extensive delay. The overhaul is now scheduled to be completed in the summer of 1976.

3.3 PATROL GUNBOAT HYDROFOIL

(U) In response to a requirement for a high-speed hydrofoil gunboat, established by the Chief of Naval Operations in

1963, two Patrol Gunboat Hydrofoils (PGH) were authorized in the FY 1966 shipbuilding program. Based on design data generated by the Hydrofoil Advanced Development Program* and feasibility studies conducted by the Bureau of Ships, final characteristics for the craft were approved in early 1965. Two contracts were awarded in April 1966. TUCUMCARI (PGH-2), designed and built by The Boeing Company, was delivered to the Navy in February 1968. FLAGSTAFF (PGH-1), designed and built by Grumman Aerospace Corp., was 'delivered in September 1968. Both craft were assigned to the Pacific Fleet for operational evaluation.

(U) FLAGSTAFF, PGH-1 (Figure I.C-7), built by Grumman Aerospace Corp., has a conventional foil configuration similar to PLAINVIEW with 70% of the lift provided by the forward main foils and 30% by the smaller after foil. Lift control is effected by varying the incidence which changes the angle of attack of the foils. This is called incidence control. Foilborne propulsion is provided by a single, variable-pitch, supercavitating propeller located on the after end of the pod of the after foil/strut system. The prime mover is a 3,200-hp Rolls-Royce Tyne gas turbine which drives through a right-angle bevel gear transmission. Hullborne propulsion consists of two Buehler waterjets, each powered by a 160-hp General Motors diesel engine. The three identical foils are of subcavitating design and are made of solid forged aluminum.

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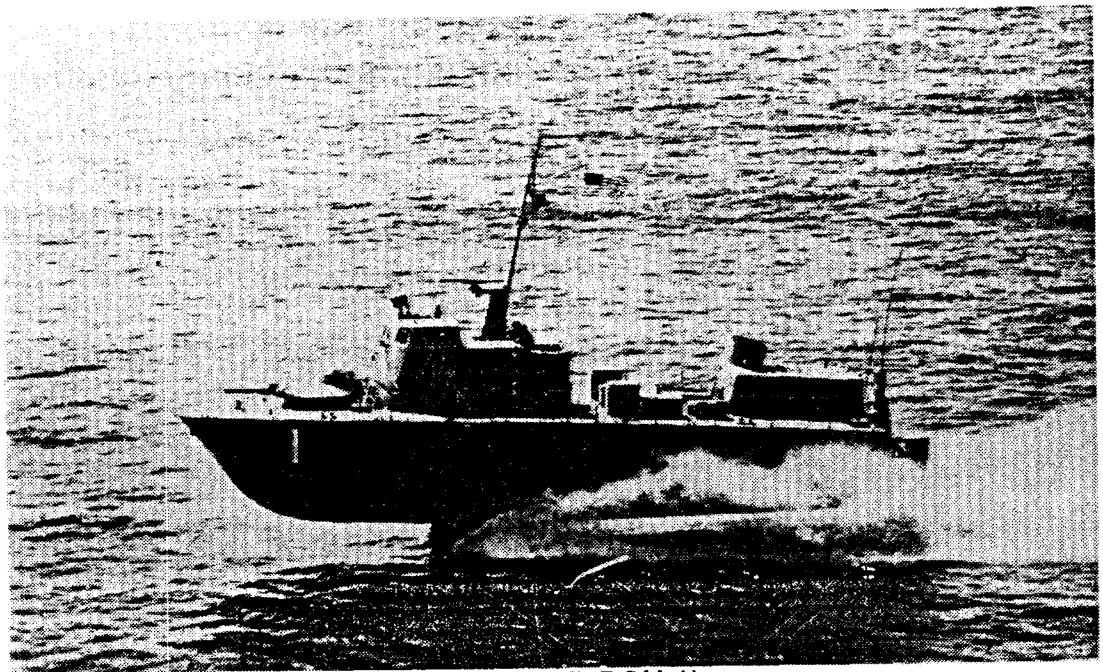
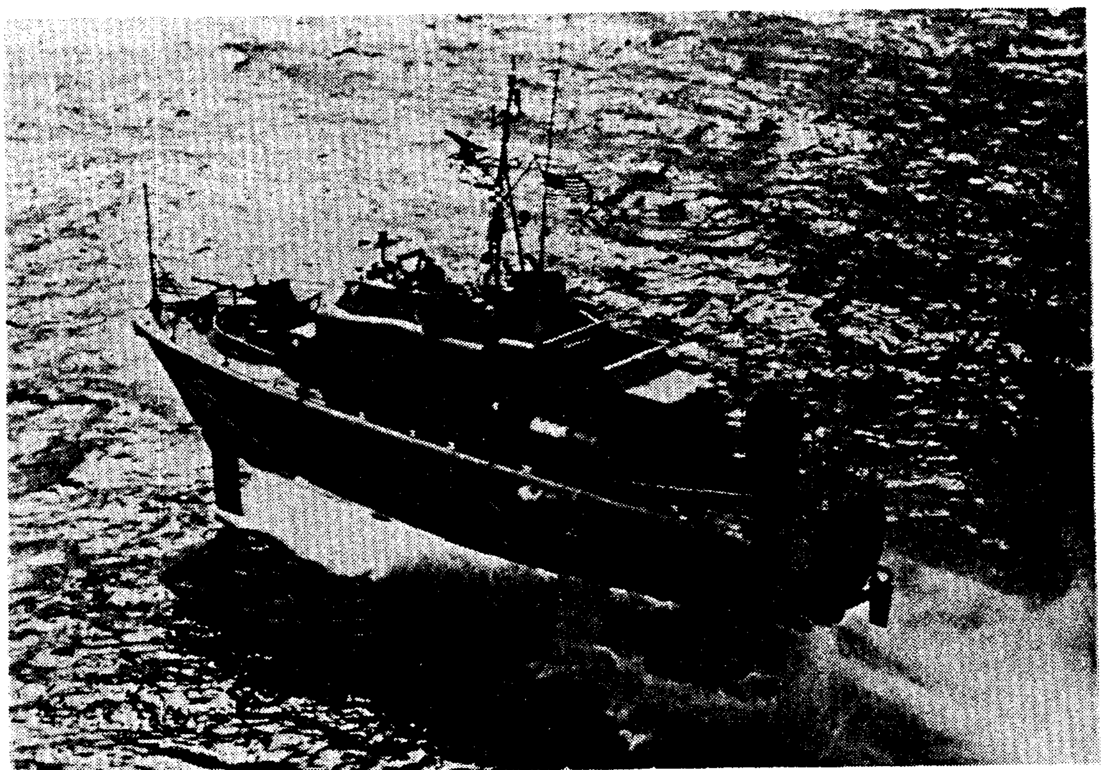
*Supporting AD046-06



FLAGSTAFF (PGH-1)



TUCUMCARI (PGH-2)

Figure I.C-7. FLAGSTAFF AND TUCUMCARI

(U) The Boeing Company built TUCUMCARI, PGH-2 (Figure I.C-7), which is a canard configuration with a 31/69 load distribution and flap control system. The foils are of subcavitating design and the main foils incorporate anhedral to supply more directional stability and to reduce their tendency to ventilate in banked turns. Foilborne propulsion is provided by a waterjet system consisting of a Byron-Jackson pump driven by a 3,200-hp Bristol-Proteus gas turbine. Water inlets are located at the juncture of each main strut and foil. Hullborne propulsion is provided by a single Buehler waterjet driven by a 160-hp General Motors diesel engine.

(U) Operational evaluation tests on the PGHs were conducted by the Operational Test and Evaluation Force (OPTEVFOR) in the San Diego and Long Beach operating areas from 7 October 1968 until 8 April 1969. At the end of the operational evaluation, the two craft went into a restricted availability to prepare them for deployment to Southeast Asia aboard the LSD U.S.S. GUNSTON HALL. The craft were assigned to Market Time Forces with a variety of missions and based in Danang. The deployment was considered militarily successful with the ships showing their ability to remain operational in a remote combat area. Their superior utility compared to displacement craft of similar size was demonstrated.

(U) After return to the states in February 1970, FLAGSTAFF was assigned to operate with Coastal River Squadron One at San Diego as part of the Pacific Amphibious Forces. She currently continues to conduct technical and mission operations in this assignment.

(U) Following the deployment in Vietnam, TUCUMCARI (PGH-2) was sent to Europe for a NATO tour and demonstration. From April 1971 until October 1971, TUCUMCARI operated in European waters. She visited seven different NATO countries performing numerous demonstrations and VIP presentations. The underway refueling experiences under many different situations and sea conditions were most gratifying. A number of combat exercises demonstrated the potential effectiveness of hydrofoil ships. These exercises influenced the decision of NATO to proceed into a program to procure a fast patrol hydrofoil, later designated the PHM. The 390 hours of foilborne time logged during TUCUMCARI's deployment further contributed to the hydrofoil community's confidence in their potential.

(U) After returning from Europe, TUCUMCARI was assigned to Coastal River Squadron Two, Atlantic Amphibious Forces. In November 1972, while conducting night exercises with the 2nd Fleet, TUCUMCARI flew into a coral reef north of Vieques Island. The ship was salvaged and transported to her home base at Norfolk, Virginia, and was removed from service on 7 November 1973 after a decision to forego repair of the damage caused by the grounding. The hull, struts, and foils were transported to DTNSRDC and are being used for structural and material tests.

3.4 PHM PROGRAM

(U) In 1970 NATO indicated a need for a fast, seaworthy missile ship to operate in the Mediterranean, North, and Baltic Seas. Comparisons were made between planing hulls, catamarans, hydrofoil ships, and hovercraft. A hydrofoil ship was identified as best meeting the requirements, based on the proven U.S. Navy technology, and the PHM program was launched in FY 1971. Italy, Germany, and the United States became partners under a Memorandum of Understanding, and a contract was awarded to The Boeing Company for engineering development and construction of two U.S. Navy lead ships, PEGASUS and HERCULES. Figure I.C-8 is a picture of PHM-1. Work on HERCULES has been suspended with the hull about 30% complete. Early PHM design studies in the Navy dealt with ships of 150 to 170 tons displacement based on a scaled-up version of the successful TUCUMCARI. The U.S. Variant of PHM has since evolved into a 235-metric ton ship equipped with a 76mm gun and a HARPOON missile system. Italian and German variants will be equipped with alternate mission suites. The PHM will add a new dimension to the U.S. Navy and NATO forces. PHM-1, PEGASUS, was launched on 9 November 1974, and her first underway operation began in February 1975. For the past year she has undergone an extensive test and evaluation period. A favorable production decision is expected in late summer 1976.

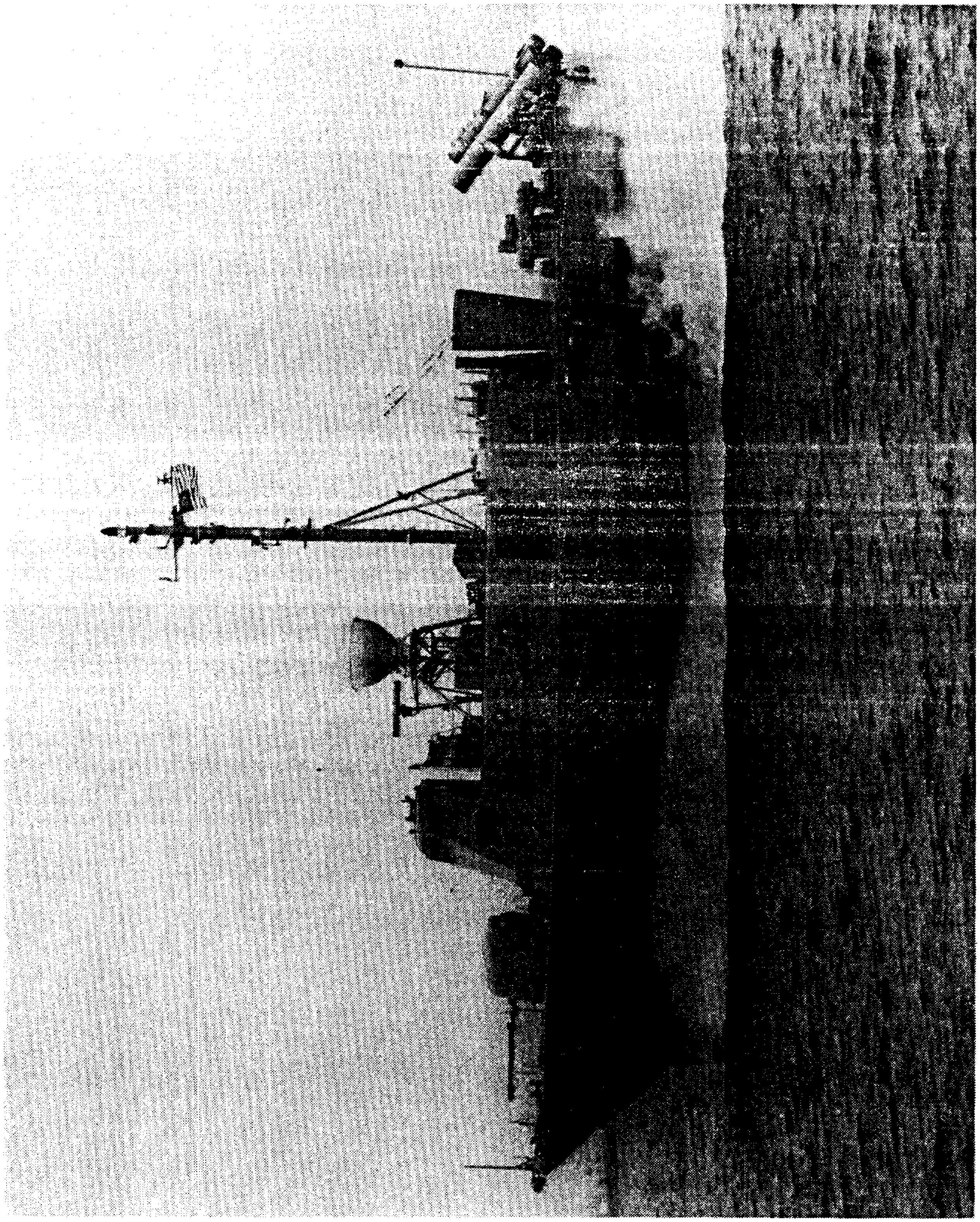


Figure I.C-8. PEGASUS

. Part D

DESCRIPTION OF EXISTING HYDROFOIL HARDWARE

(U) Table I.D-1 is a summary of the characteristics of hydrofoil ships that are active today. Pictures and some of their features were presented in the preceding section.

(C) Table I.D-1. CHARACTERISTICS OF ACTIVE HYDROFOIL SHIPS (U)

CHARACTERISTICS		U.S. NAVY HYDROFOIL SHIPS PCH-1	AGEH-1	PGH-1	PHM
DISPLACEMENT FULL LOAD (L. TONS)		126	320	69	231
DIMENSIONS	LOA (FT)	115	212	74	146
	BEAM (FT) W.L. (MLD'D)	22.16	30.40	18.17	24.42
	MAX	32.0	40	21.5	27.6
	OVER FOILS	36.4	71	37	47.6
	DRAFT (FT) FOILS UP	8.58	6.25	4.25	6.01
	FOILS DOWN	19.83	25	13	22
PERFORMANCE	SPEED (KTS) MAX HULLBORNE	12	13	9	11
	MAX FOILBORNE	51	50(+)	53	51
	RANGE FOILBORNE	620	400	580	718
	HULLBORNE	1200	2500	2000	1280
	DESIGN SEA STATE	5	6	4	5
CONFIGURATION		CANARD	AIRPLANE	AIRPLANE	CANARD
MAX CONT SHP		6200	28000	3200	18000
PROPULSOR		PROPELLER	PROPELLER	PROPELLER	WATERJET
GAS TURBINE		PROTEUS(2)	LM 1500(2)	TYNE	LM 2500
REFERENCE		DTNSRDC DESIGN DATA LOG			

[redacted]

Part E

SUMMARY OF CURRENT PLANNING FOR FUTURE EFFOKT

(U) In March 1972, the currently applicable Advanced Development Objective (ADO) No. 46-06XR2 was issued. This defined the Advanced Hydrofoil Program requirements to demonstrate the feasibility of larger and faster hydrofoil ship systems in terms of performance and mission potential. This development shall provide technical and operational data adequate to support decisions to proceed with Engineering Development and acquisition of such hydrofoil ship systems with confidence that they will perform as predicted.

(C) The program has three major parts. One is to demonstrate the technical feasibility of larger (over 300 tons) systems. The second is to demonstrate technical feasibility of faster (50 to 90 knots) systems. The third is to identify, develop, and demonstrate mission capabilities. All hydrofoil ship systems will be developed to operate with minimal performance degradation in all sea states.

(U) Effort to date on the ADO has concentrated on the larger hydrofoil ship systems and their application to future naval tasks. Based on this effort, in June 1975 the Assistant Secretary of Navy for Research and Development forwarded to the Director of Defense Research and Engineering a plan for developing a Hydrofoil Ocean Combatant (HOC). This plan, Reference I.E-1, was supported by a baseline design, Reference I.E-2, and an analysis of economic desirability, Reference I.E-3. The following outline of future effort is summarized from Reference I.E-1.

(U) The HOC plan is developed under five major headings:

I. Management, documentation, instrumentation, and test and evaluation planning

II. Subsystem Technology Development

III. Test, trial (PCH-1 and AGEH-1 support)

IV. Mission Development

V. HOC Design, construction, and test

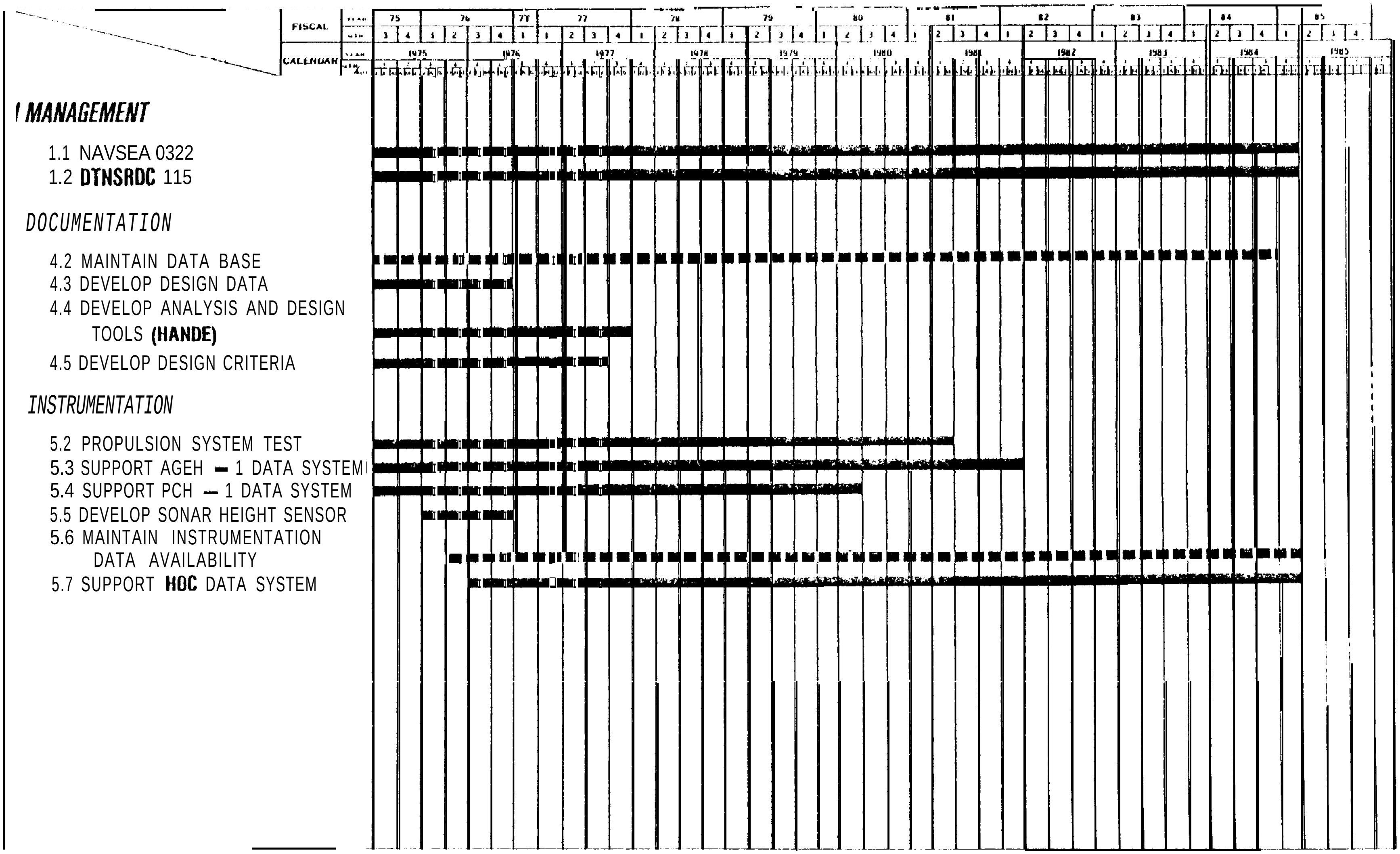
Tasks I through IV are essentially the research and development effort required to support the direct HOC effort task V. These tasks are basically risk reduction efforts. Figures I.E-1, I.E-2, I.E-3, I.E-4, and I.E-5 are schedules and outlines of the above tasks.

(U) The outlines on these figures are considered self-explanatory. If more detail is desired, this can be found in Reference I.E-1.

(U) Figure I.E-6 presents a summary of the cost of the entire development program in FY 1975 dollars and escalated in accordance with DOD standards. The cost of the design, construction, and test of the HOC is $140,800,000 unescalated. Other costs are relative to the supportive R&D Program.

(U) Reference I.E-1 also developed two alternative plans. One was the impact of no change to the then June 1975 FYDP. The impact on schedule is shown on Figure I.E-7. A second plan was prepared which permitted construction to follow estimated hardware deliveries without delaying installation for resolution of risk areas.

MANAGEMENT SCHEDULE



I.E-1. MANAGEMENT SCHEDULE

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TECHNOLOGY SCHEDULE

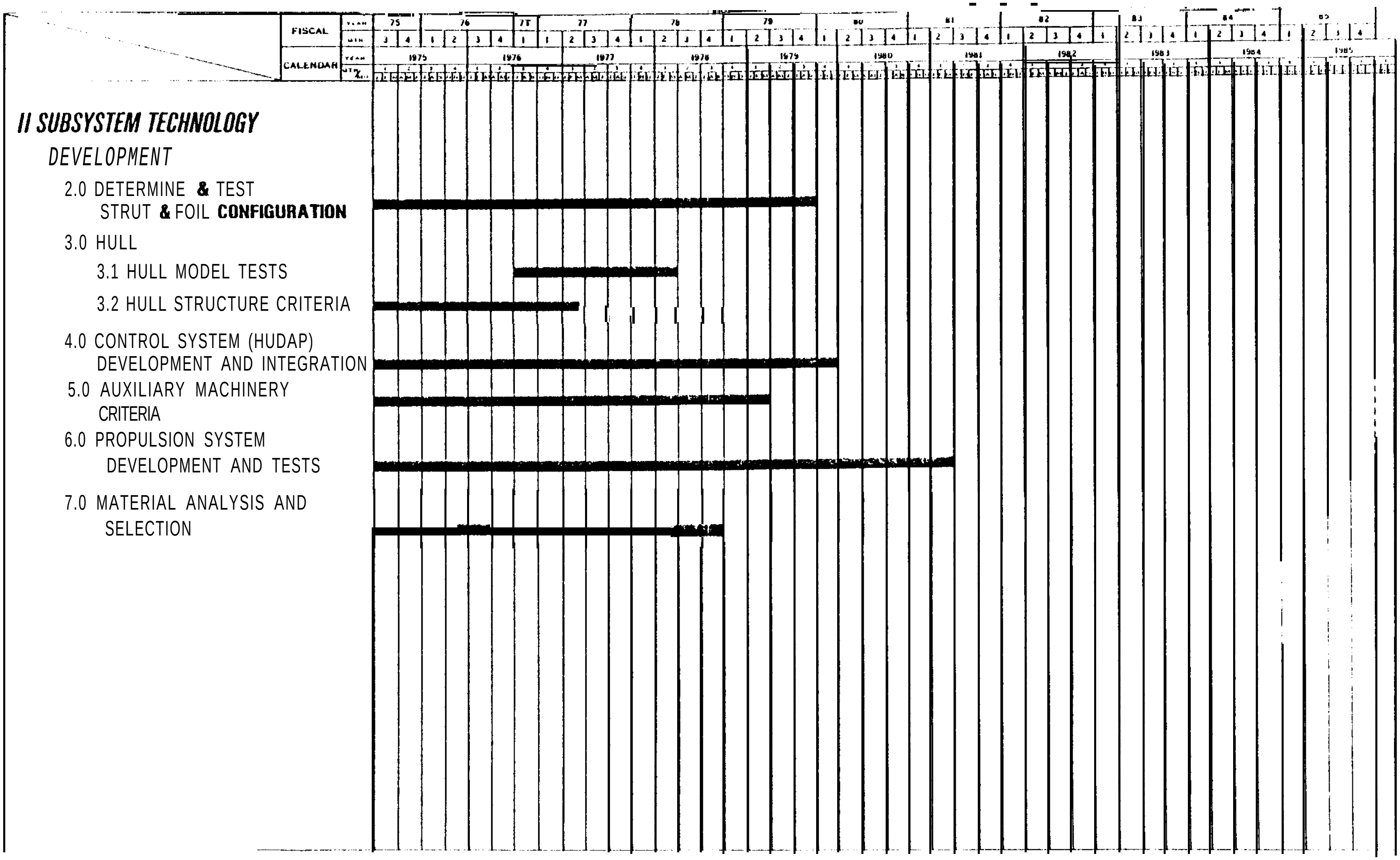

Figure I.E-2. TECHNOLOGY SCHEDULE

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TEST & TRIALS SCHEDULE

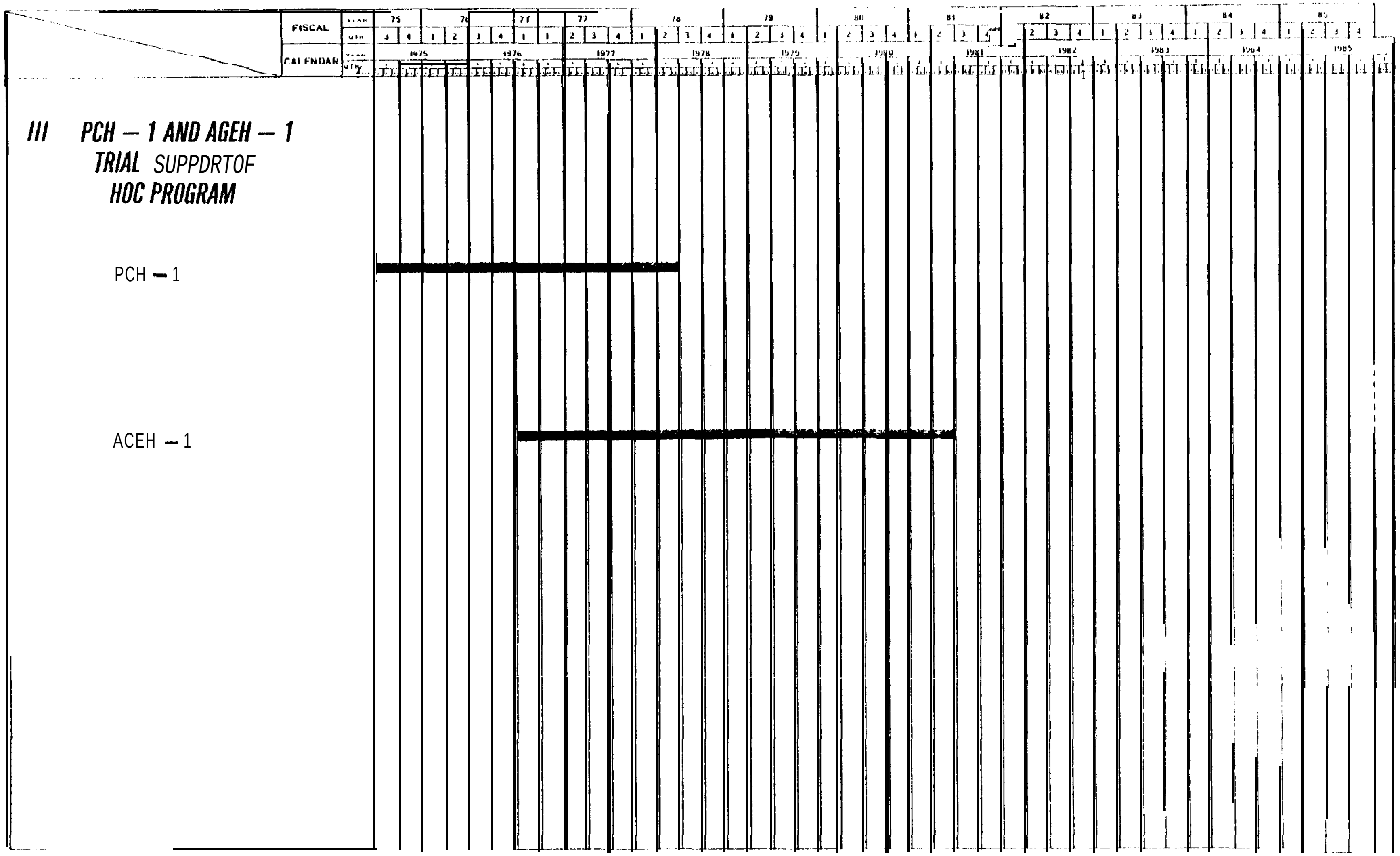

Figure I.E-3. TEST AND TRIALS SCHEDULE

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MISSION SCHEDULE

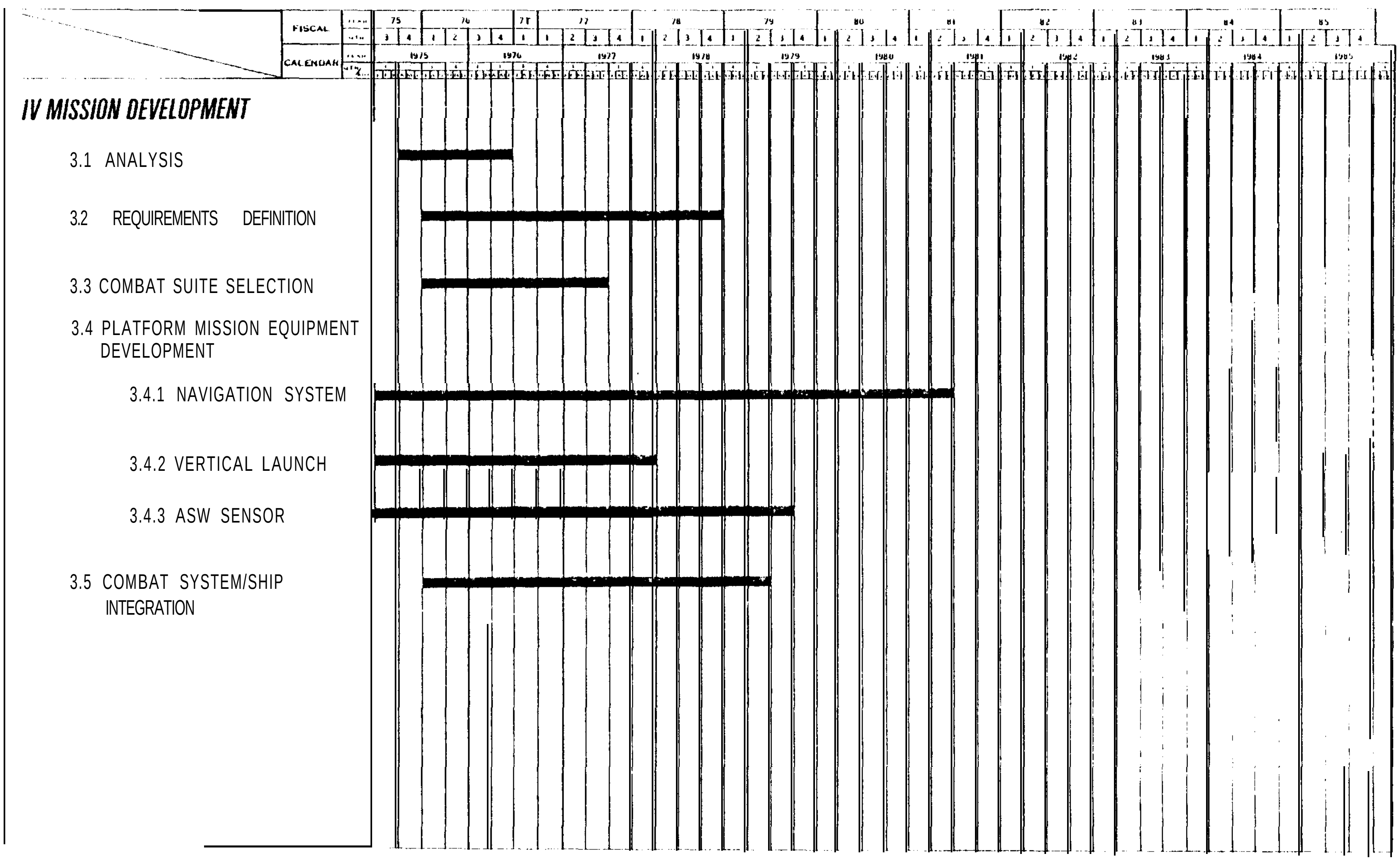

Figure I.E-4. MISSION SCHEDULE

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HOC SCHEDULE

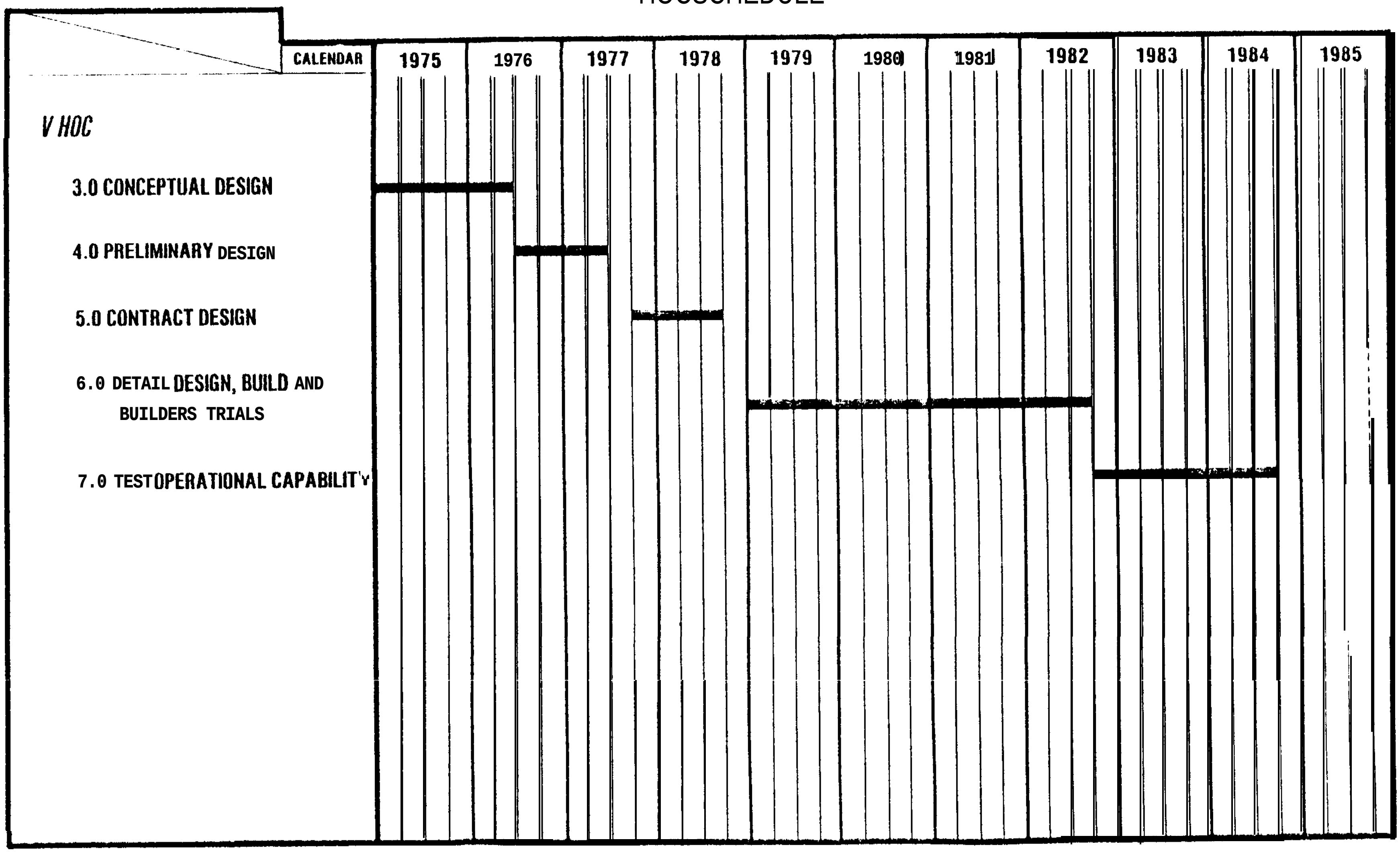

Figure I.E-5. HOC SCHEDULE

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BASELINE PLAN FUNDING SUMMARY
(IN THOUSANDS OF DOLLARS BY FISCAL YEAR)

SECTION 1-MANAGEMENT **10 MARCH 1975**

TASKS	1975	1976	197T	1977	1978	1979	1980	1961	1982	1983	1984	TOTAL
I. MANAGEMENT & DOCUMENTATION	1,400	2,660	640	2,120	1,680	1,290	1,240	1,160	1.190	1,230	1,270	15,900
ILSUBSYSTEM TECHNOLOGY	2,090	2,390	680	3,490	2,660	1.380	1,060	590				14,300
III. TEST, TRIALS OPERATIONS,& SHIPSUPPORT	1,210	2,950	1,630	5,560	4,760	2,040	1,740	940	910	360	360	22,500
IV. MISSIONS DEVELOPMENT	396	1.090	240	950	1,940	2,240	2,450	1,440	450			11,200
V. HOC	900	1,400	630	3,600	7,500	30,500	37,200	34,200	10,900	7.000	7,000	140,800
COSTlNFY1975	6.000	10,490	3,820	15,720	18,540	37,450	43,690	38,330	18,450	8,590	8,630	204,700
ESCALATION ALLOWANCE	--	1,100	620	2,580	4,060	10,190	14,070	13.920	5,530	3,870	4,230	60,200
TOTALS	6,000	11,590	4,440	18.300	22,600	47,640	57,760	52,250	18,980	12,460	12,860	264,900

Figure I.E-6. BASELINE PLAN FUNDING SUMMARY

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ADVANCED HYDROFOIL SYSTEMS

DEVELOPMENT SCHEDULE ALTERNATIVES

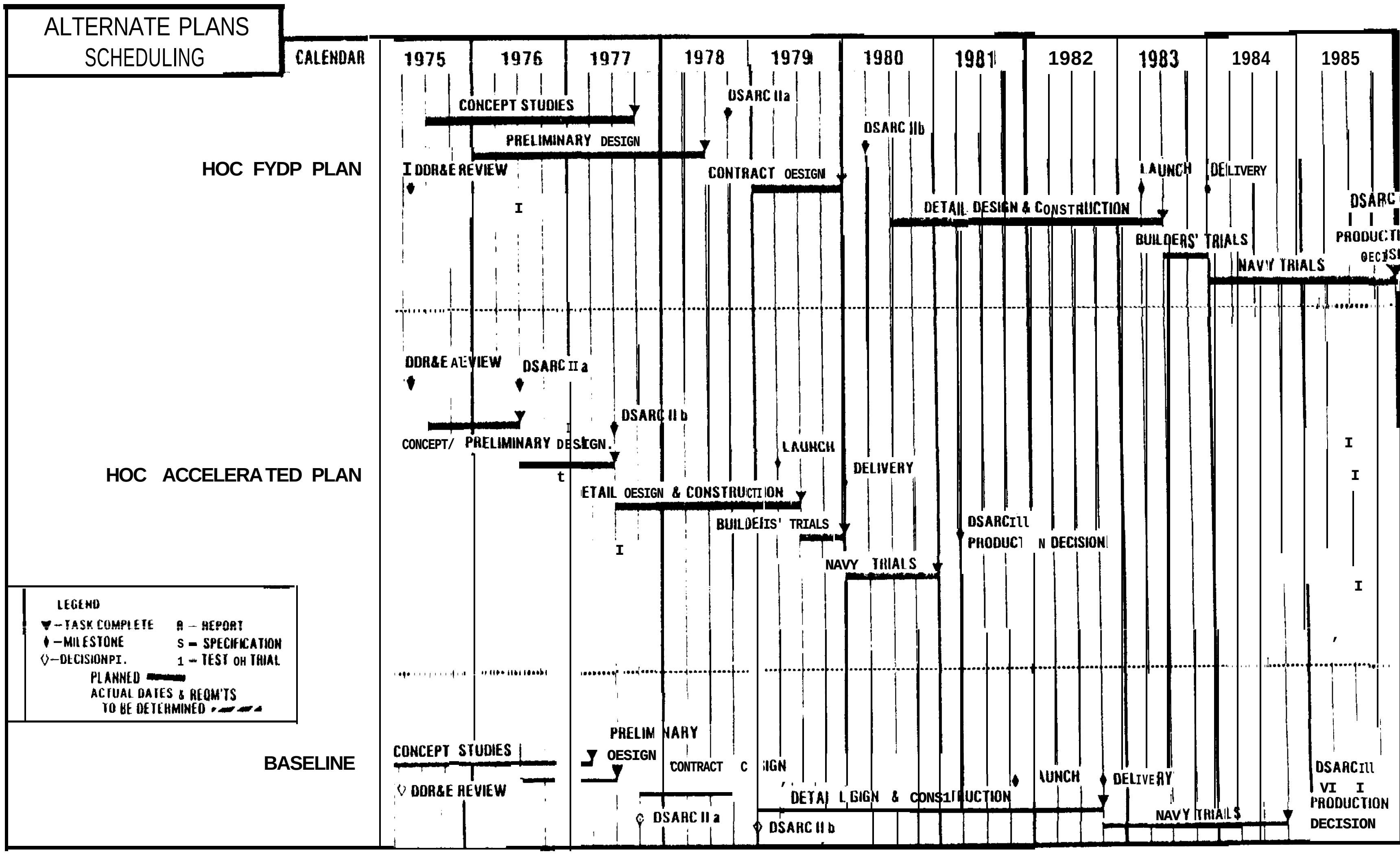

Figure I.E-7. ADVANCED HYDROFOIL SYSTEMS DEVELOPMENT SCHEDULE ALTERNATIVES

In other words, the HOC accelerated plan shown in Figure I.E-7 is a high risk program as compared to the baseline plan which is based on minimizing all risks.

(U) The costs for the three plans are compared in Figure I.E-8 in escalated dollars. It is interesting to note that, while the accelerated or high risk plan saves some 3 years in time, the cost saving over the baseline plan or the minimum risk plan is only about 20 million dollars. Funding has not been provided in accordance with the baseline plan and as of this writing, April 1976, the HOC Program has slipped at least a year. In the meantime, the technology base is being expanded and some of the basis for fundamental trade-off decisions of a large hydrofoil program are being established. These include the development of U.S. Navy design criteria for hydrofoil ships and a computerized hydrofoil ship analysis and design tool (HANDE). These efforts will assist in the design management of any future Navy hydrofoil ship program. Means of steering large hydrofoil ships and of minimizing control power are being determined. Material studies of HY-130, titanium and composites are continuing for future foil and strut application. In addition, the AGEH-1 will soon resume operations which will expand the operational understanding of large hydrofoil ships in the open sea.

(U) The ANVCE program is assisting its study evaluation task and the HOC program by supporting model tests to determine wave drag of large hydrofoil ships (low Froude number) during the

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CUMULATIVE FUNDING SUMMARIES FOR THREE PLANS

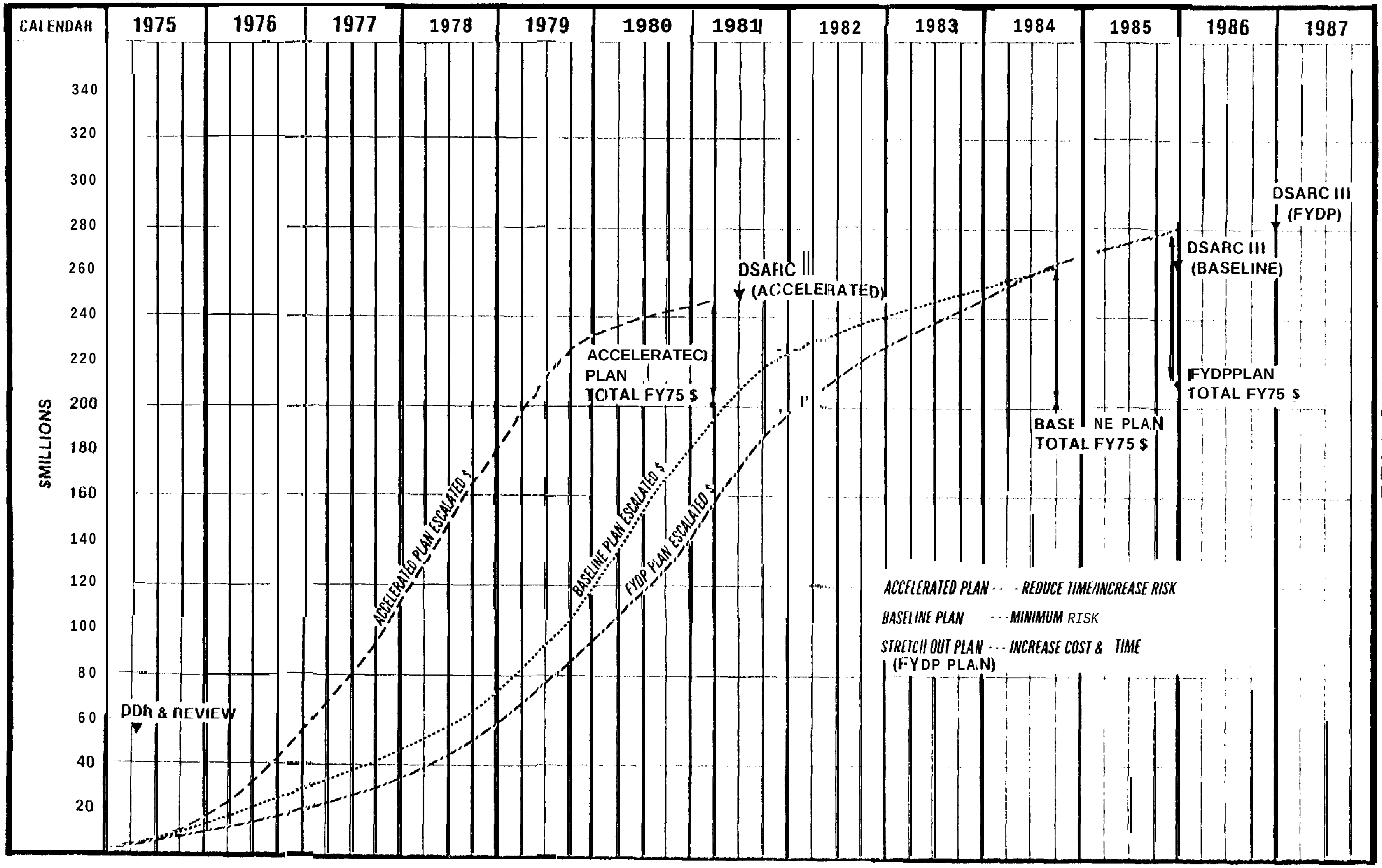

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Figure I.E-8. CUMULATIVE FUNDING SUMMARIES FOR THREE PLANS

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takeoff mode. Recent studies have indicated major discrepancies in various theories that could have the result of a 25% difference in installed horsepower for takeoff. The takeoff wave drag theory for higher Froude numbers, appropriate to smaller hydrofoil ships up to and including AGEH-1, has been confirmed by model tests and the drag can be accurately predicted.

(U) Effort to develop a fast hydrofoil ship system is essentially dormant; this has been the status for the past 10 years. Some exploratory effort has been done on superventilating and supercavitating foil systems to achieve efficient lift-to-drag ratios with smooth control characteristics over the operating foil-borne speed range.

REFERENCES

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II. STATUS OF VEHICLE TECHNOLOGY

A. TECHNOLOGICAL PERFORMANCE FEATURES

1. AERODYNAMICS/HYDRODYNAMICS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

II.A. TECHNOLOGICAL PERFORMANCE FEATURES

1. HYDRODYNAMICS

1.1 INTRODUCTION

(U) Hydrodynamics is the discipline used to predict the drag, lift, and moments on bodies traveling in water. It is closely correlated to aerodynamics, and most of the incompressible aerodynamics theory and data can be directly used to predict hydrodynamic phenomena, provided that the two areas of fluid dynamics, which distinguish the hydrodynamics from the aerodynamics, are not present. One is the effect of the free surface, which is necessarily a constant pressure surface and on which waves are formed because of the action of gravity. The other is the occurrence of cavitation, which arises when the pressure in the flow over any component of the ship is reduced to the vapor pressure of the water. While cavitation is to be avoided on subcavitating hydrofoils, for the most part, it has been found more effective to use propellers operating in the fully cavitated regime for ships with a top speed above 45 knots. The technology of such propellers has no parallel in aerodynamics. Hydrodynamic predictions are based on well established analytical programs and model and full-scale testing. Although analytical programs which have extensive model and full-scale verification can be used with confidence, more credence can be placed on model tests for which scaling effects are well understood. The closer the model is to full-scale size, the more confidence the designer has in the predictions obtained from tests; that is why data from sea trials on real ships are so valuable for predicting the performance of envisioned large hydrofoils.

(U) It is the purpose of this section to give an overview of the hydrodynamic discipline as it is applied to the design of hydrofoil ships.

(U) The study of hydrodynamics, as with most branches of physical science, has developed along both theoretical and experimental paths. Theoretical hydrodynamics provides insight to the dependence of forces and moments on the governing parameters, which are the engineer's concern, such as speed, depth of submergence, and geometric proportions. Until the advent'of modern computers, solutions of the theoretical equations have been generally limited to cases with bodies of simple geometry and have mostly excluded the free surface and friction. With the help of modern computers and computational techniques, more complicated and realistic cases can be solved. Even so, for complicated problems which include the effect of friction and the free surface, model tests and full-scale trial results provide the empirical support for performance predictions. Thus, we shall be discussing the status of both the theoretical and empirical branches of hydrofoil hydrodynamics.

(U) We will consider the application of hydrodynamics in relation to the following areas of hydrofoil design:

- Estimation of drag and its practical minimization.
- The control of lift and the development of forces for the control of ship motions.
- The avoidance of cavitation.
- Supercavitating Struts and Foils.
- The determination of design loads on the structure.

1.2 DRAG ESTIMATION

(U) Since the hydrofoil ship must operate in the hull-borne mode as a displacement or semi-planing vehicle as well as in the foilborne mode and must accomplish the transition from hullborne to foilborne (and vice versa), it is necessary to consider both the drag of the hull over a range of speed and loadings and the drag of the lift system over a range of lift and speed. The buildup of foilborne drag for PCH-1 MOD-1 is shown on Figure II.A.l-1. These various drag components will be discussed in the following sections.

1.2.1 Lift System Drag

(U) The lift system drag includes that drag associated with the lifting surfaces (foils) and the drag of the associated appendages (struts, pods, and fairings) required to connect the lifting surface to the hull. (The power required to overcome the drag of the struts and pods is directly comparable to the lift-fan power of an ACV or SES.)

(U) The drag of the lift system can be divided into two principal components:

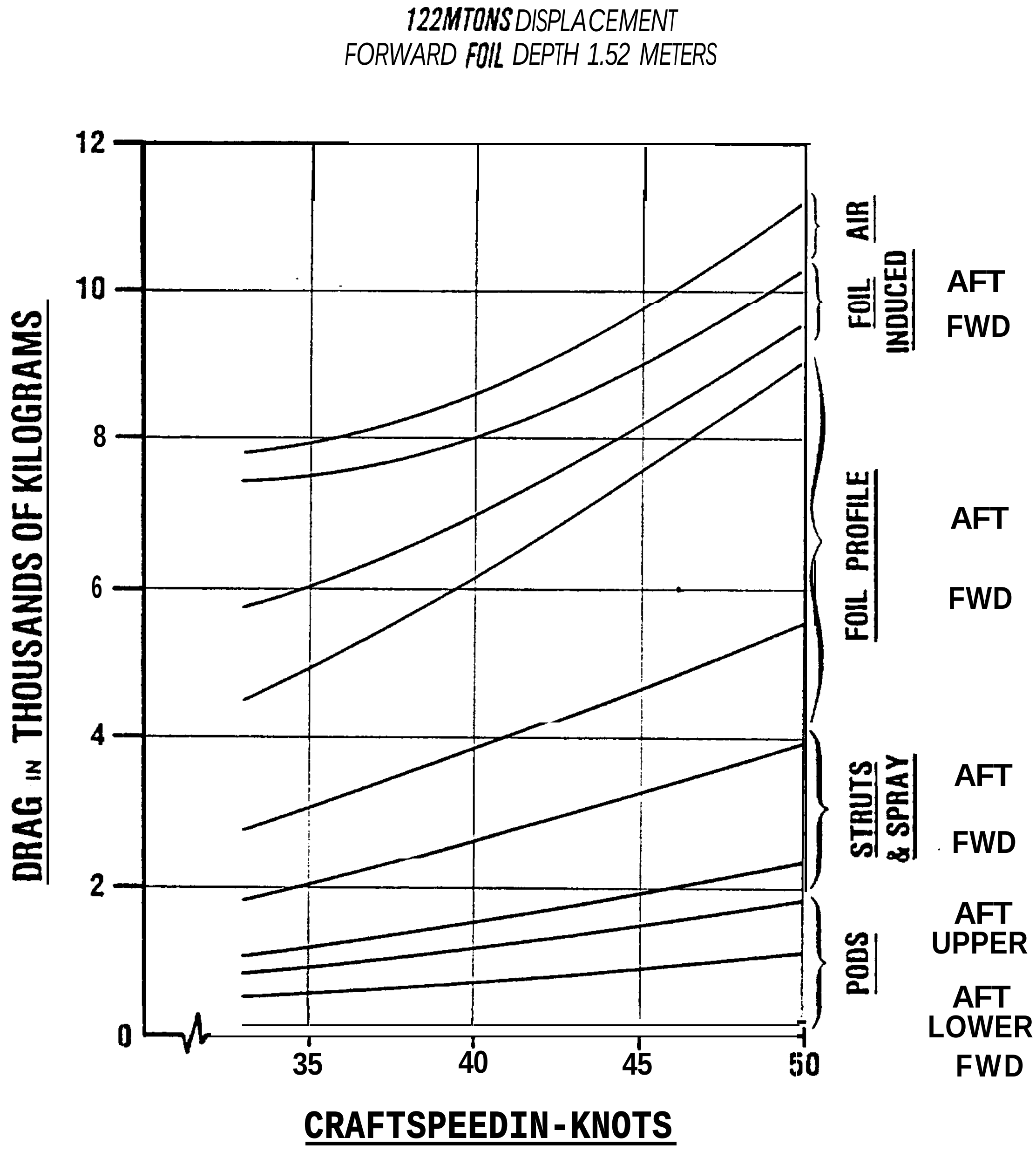

Figure II.A.1-1. PCH-1 MOD 1 FOILBORNE DRAG BUILD-UP

a. Zero lift drag, or parasite drag including the section profile drag, the effects of fluid friction and flow separation associated with the development of the boundary layer, the spray drag, and air drag on the hull.

b. Drag due to lift which includes the induced drag, which is associated with the energy of the down-wash in the wake of a lifting surface, and the wave drag, which is associated with the energy in the wave produced on the free surface.

(U) The zero lift drag varies with V^2, making this the predominant drag at high speed. The drag due to lift, on the other hand, varies as $1/V^2$, making it predominant at low speeds. In fact, when combined, there is a speed at which the drag is a minimum which, for most hydrofoils, occurs from 5 to 10 knots above take-off speed.

(U) Figure II.A.1-2 illustrates the relative magnitude of the components of zero lift drag for a typical lift system designed to carry 1,000 tons on two equal foils at a maximum speed of 50 knots. The drag due to lift for the same foil system is shown in Figure II.A.1-3. Finally, these are combined to give the total drag for normal foilborne cruise submergence and for the takeoff submergence (just as the hull leaves the water), Figure II.A.1-4.

1.2.1.1 Zero Lift or Parasite Drag

(U) Each of the components of drag which make up the total zero lift drag are shown on Figure II.A.1-2. How they are determined will be briefly addressed below.

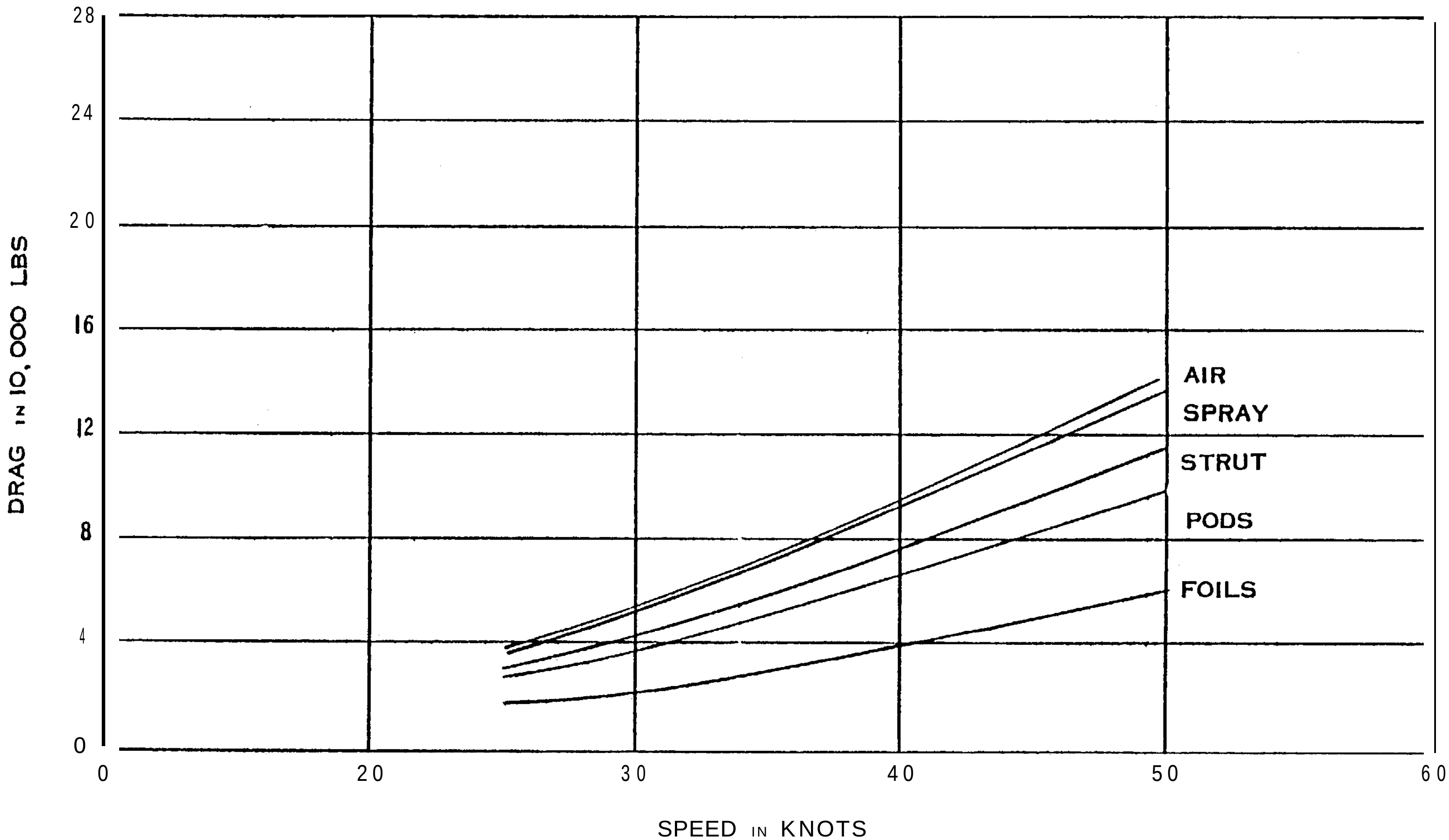

Figure **II.A.1-2.** **1,000-TON** HYDROFOIL, ZERO LIFT DRAG, CRUISE SUBMERGENCE, SMOOTH SEA WATER

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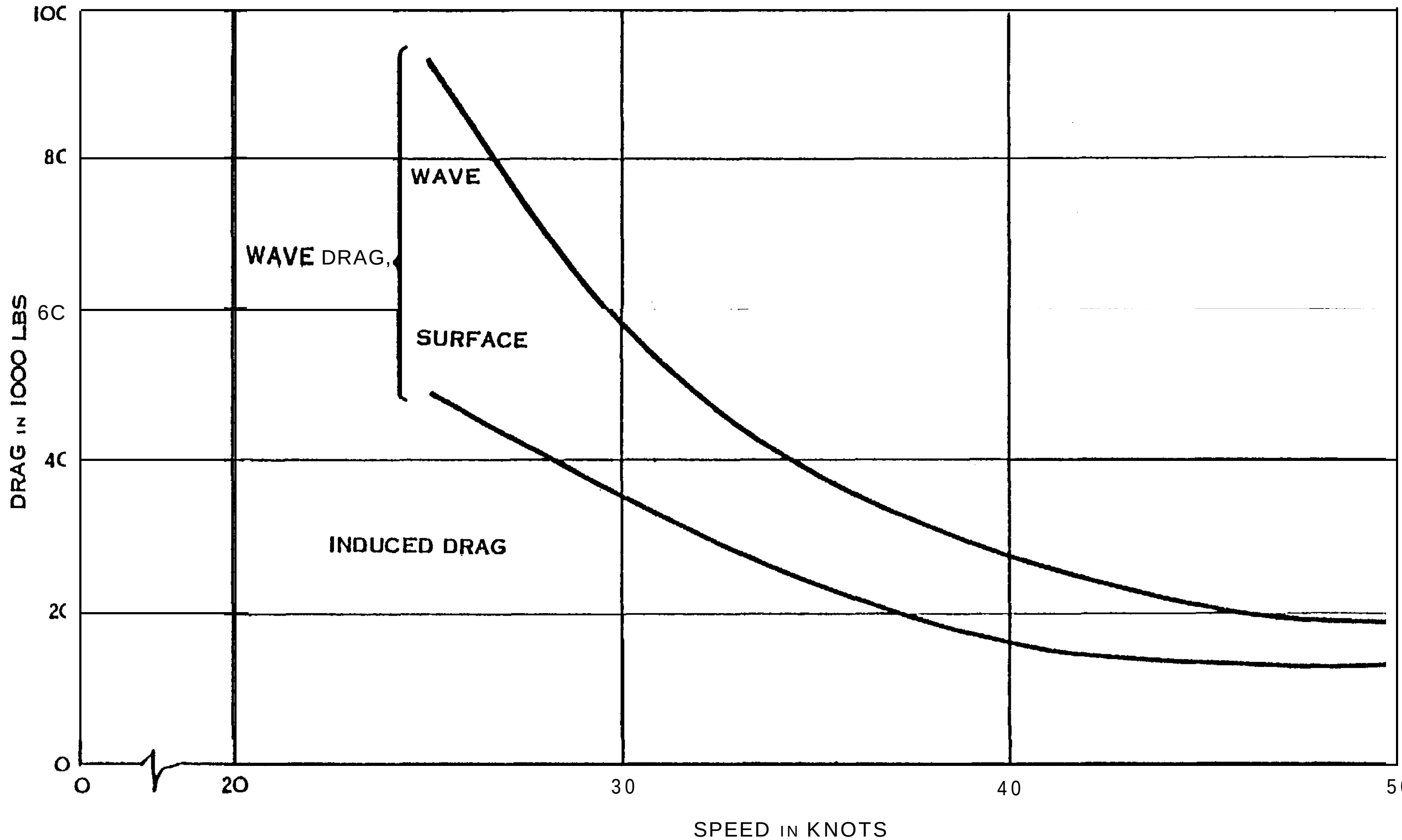

Figure II.A.1-3. 1,000-TON HYDROFOIL, DRAG DUE TO LIFT, CRUISE SUBMERGENCE, SMOOTH SEA WATER

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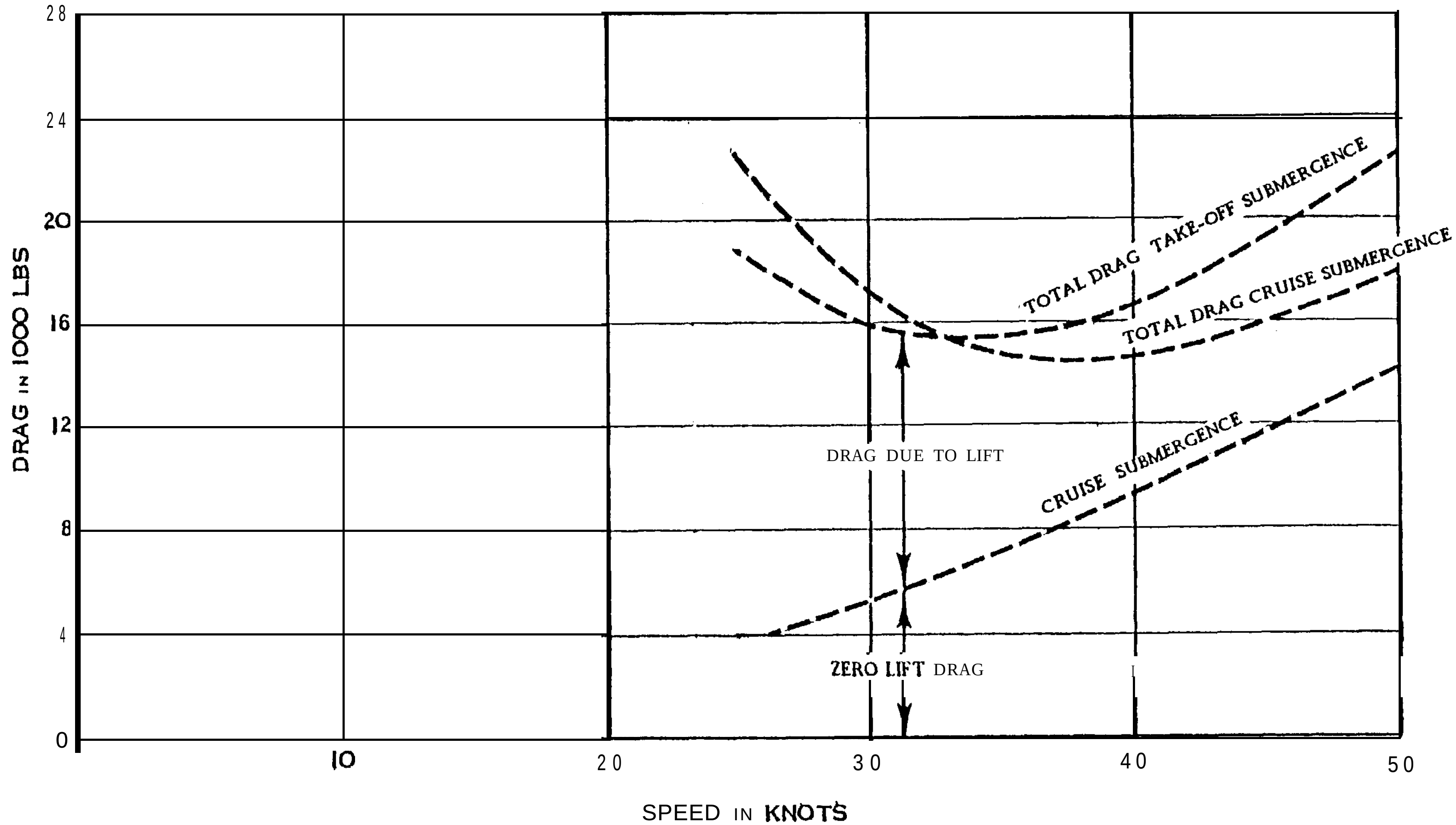


Figure II.A.1-4. 1,000-TON HYDROFOIL, TOTAL DRAG, DRAG DUE TO LIFT, ZERO LIFT DRAG VS. SPEED, SMOOTH SEA WATER

UNCLASSIFIED

a. Foil Zero Lift or Profile Drag including viscous friction drag

The profile drag coefficient of the foil is usually taken directly from two-dimensional section data based on the extensive series work done at NACA and published by Abbott and Von Doenhoff. (Reference II.A.1-11)

b. Strut Drag

The drag of the submerged portions of the strut is analogous to the profile drag on the foils and is readily treated in a similar manner.

c. Spray Drag

At the water surface a considerable flow disturbance is created, as is evidenced by the visible spray plume behind the strut. The energy in the spray is manifestly produced by the work of a drag force, which is called spray drag. Empirical data, derived from model experiments, (Reference II.A.1-1) are used for estimating the spray drag. Briefly, this shows:

$$D_{spray} = 0.24\, t^2 \cdot \rho/2\, V^2 \quad \text{for } t/c < 0.2$$

$$= 0.12\, t^2 \cdot \rho/2\, V^2 \quad \text{for } t/c > 0.2$$

where t = Maximum thickness

c = Strut chord

V = Speed

ρ = Fluid density

That is, the spray drag depends primarily on the square of the thickness: with a proportionality factor which shows a discontinuity at a thickness to chord ratio, t/c, equal to 0.2.

d. Drag of Pods or Nacelles

Nacelles fitted at the junctures of foils and struts to cover bolted structural joints may be quite small. Larger structures are frequently-required to house transmission components for propeller drives or inlets for waterjet propulsion systems. Surface friction and form drag components can be estimated from a wealth of aeronautical and hydrodynamic experimental data.

e. Interference Drag

Two kinds of flow interference not shown in Figure II.A.l-2 contribute to the drag. In the first instance, we note that the after foil is in the downwash from the forward foil. Positive downwash corresponds to a downward inclination of the resultant flow at the after foil so that the lift vector is tilted rearward and produces a drag component.

The downwash velocity calculation follows from the vortex theory of wing action, References II.A.1-2 and II.A.1-3, with suitable modification for the effects of the free surface. One result of the free surface is a system of transverse waves behind the forward foil which cause the downwash to vary with the distance from that foil. At the surface there will even be an upwash on the face of the following wave, and the drag can be negative on a foil not too deeply submerged at that point, or in any event reduced. This favorable location varies with the speed, however, and may not be suitable for a given size of ship. This consideration will probably not be decisive in design.

The second kind of interference arises at the juncture of foil and strut or nacelle and results from the superposition of perturbation velocities associated with the flow over each component by itself. This component of drag is usually lumped with the pod drag. An extensive discussion of the drag due to this kind of interference is given in Reference II.A.1-1.

f. Air Drag

Air drag is the aerodynamic drag of that portion of the hydrofoil that is out of the water during foilborne operation. An accurate drag coefficient can be obtained by testing a model in the wind tunnel. Since aerodynamic drag is usually a small portion of the total drag, it can be estimated with sufficient accuracy for design purposes by using a drag coefficient of 0.5 based on frontal area.

1.2.1.2 Drag Due to Lift

(U) The two components of drag which are functions of lift are shown in Figure II.A.1-3, and how they are determined is addressed below.

a. Induced Drag

Classical incompressible aerodynamics has established that there is a drag associated with a lifting surface which, at a given speed, is proportional to the square of the lift and inversely proportional to the aspect ratio.

The expression for this drag is:

$$D_i = \frac{L^2}{AR\eta} \bullet \frac{1}{1/2\rho V^2 S} = \frac{L^2}{\pi b^2 \eta} \cdot \frac{1}{1/2\rho V^2}$$

Where Di = The induced drag

L = Lift

AR = Foil aspect ratio = b/c

η = The efficiency factor which has been established empirically from experiments to be 0.9 for foils of reasonable aspect ratios (>3).

ρ = Mass density of water

V = Speed

S = Foil plan form area

b = Foil span

c = Mean Foil chord = S/b

Since for any weight hydrofoil the lift is fixed, the induced drag is minimized by maximizing the foil span (for any given foil loading, this increases the aspect ratio). The foil span, however, is limited by practical considerations such as:

a. The distance the foil extends beyond the hull beam

b. Structural limitations

c. Weight

d. Operational limitation (Panama Canal clearance)

The designer must consider the above to achieve the best balanced or "optimum" foil design. Figure II.A.1-5 shows the effect of aspect ratio on the foil lift to drag ratio of a typical hydrofoil with a profile drag coefficient of .006.

b. Wave Drag

When a hydrofoil approaches the surface of the water, the flow over the foil is altered and the lift and drag forces are affected--the more so the closer the proximity to the surface. Coincident with these changes in foil hydrodynamics are disturbances of the water surface and of the flow in the wake of the foil to which the modification of foil forces is attributed. The surface disturbance includes a system of transverse waves, moving with the foil, and a dual system of divergent waves originating from the foil tips. The downwash in the foil wake is altered from that behind a deeply submerged foil.

The lifting foil beneath a free surface presents one of the most difficult problems of theoretical hydrodynamics. An exact solution has not been attempted, but a number of approximate

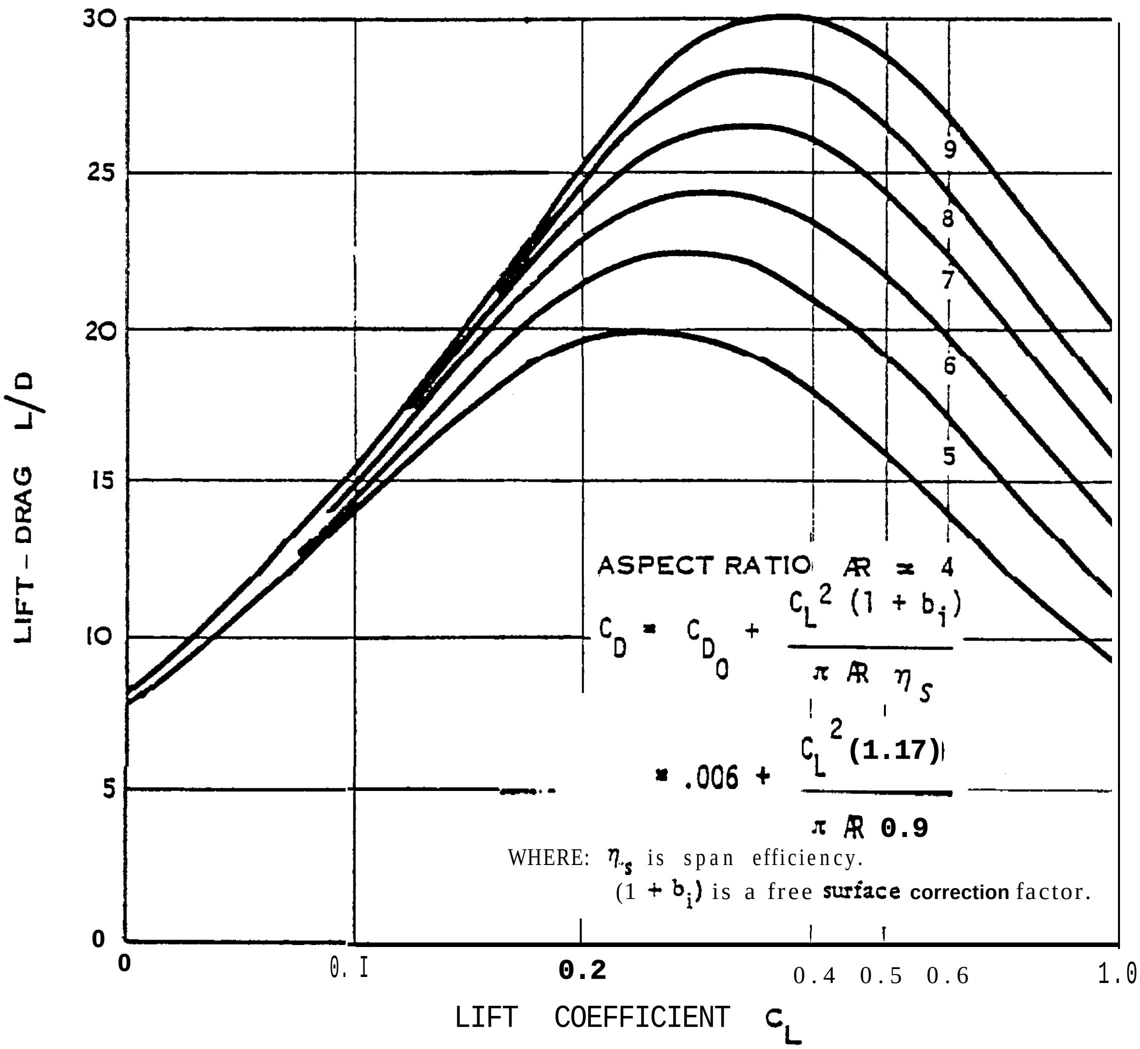


Figure II.A.1-5. VARIATION OF LIFT-DRAG RATIO WITH LIFT COEFFICIENT FOR BARE FOIL AT I CHORD DEPTH analyses have been carried out which serve to define the important parameters and provide a basis for estimating the effect on foil lift and drag.

Considering only circumstances when cavitation does not occur, it can be said that the variation of lift and drag from their values for the deeply submerged foil depend on the depth of submergence--expressed as the ratio to the foil chord, h/c--and on the speed, most meaningfully expressed by the Froude number, $F_c = V/\sqrt{gc}$, where

V = Speed

g = Acceleration of gravity

c = Foil chord

h = Depth of submergence

Nishiyama (Reference II.A.1-4) developed theoretical variations of lift and induced drag with submergence for of foils aspect ratio 6. These are shown in Figures II.A.1-6 and II.A.1-7. Some experimental results are shown for a submergence of one and one-half chords for aspect ratio of 6. Agreement for lift is excellent, but for drag is poor. The agreement of experimental work for an aspect ratio of 10 and a submergence of 0.84 chords shown in Figure II.A.1-8, however, is excellent. This shows that the theoretical formulation is in error for either the effects of aspect ratio, for foil submergence, or, quite possibly, the experimental technique may have had flaws.

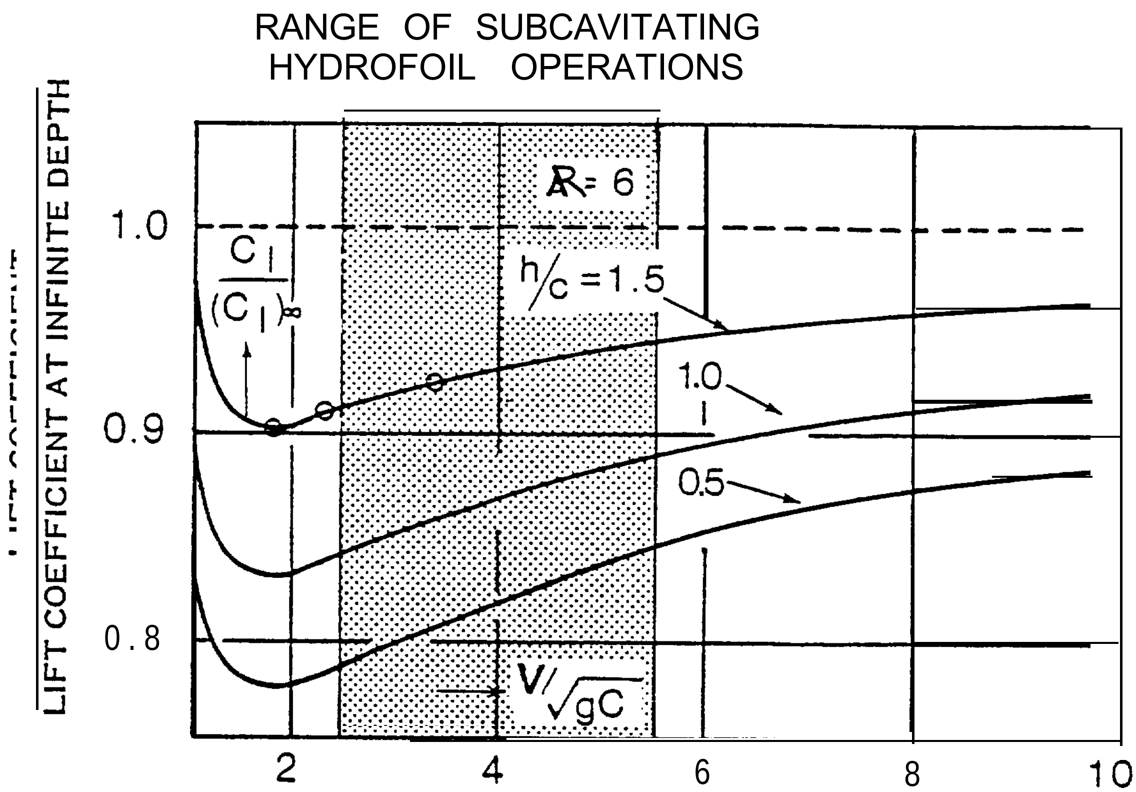


Figure II.A.1-6. EFFECT OF SUBMERGENCE DEPTH ON LIFT OF HORIZONTAL HYDROFOIL AND COMPARISONS WITH EXPERIMENTAL DATA

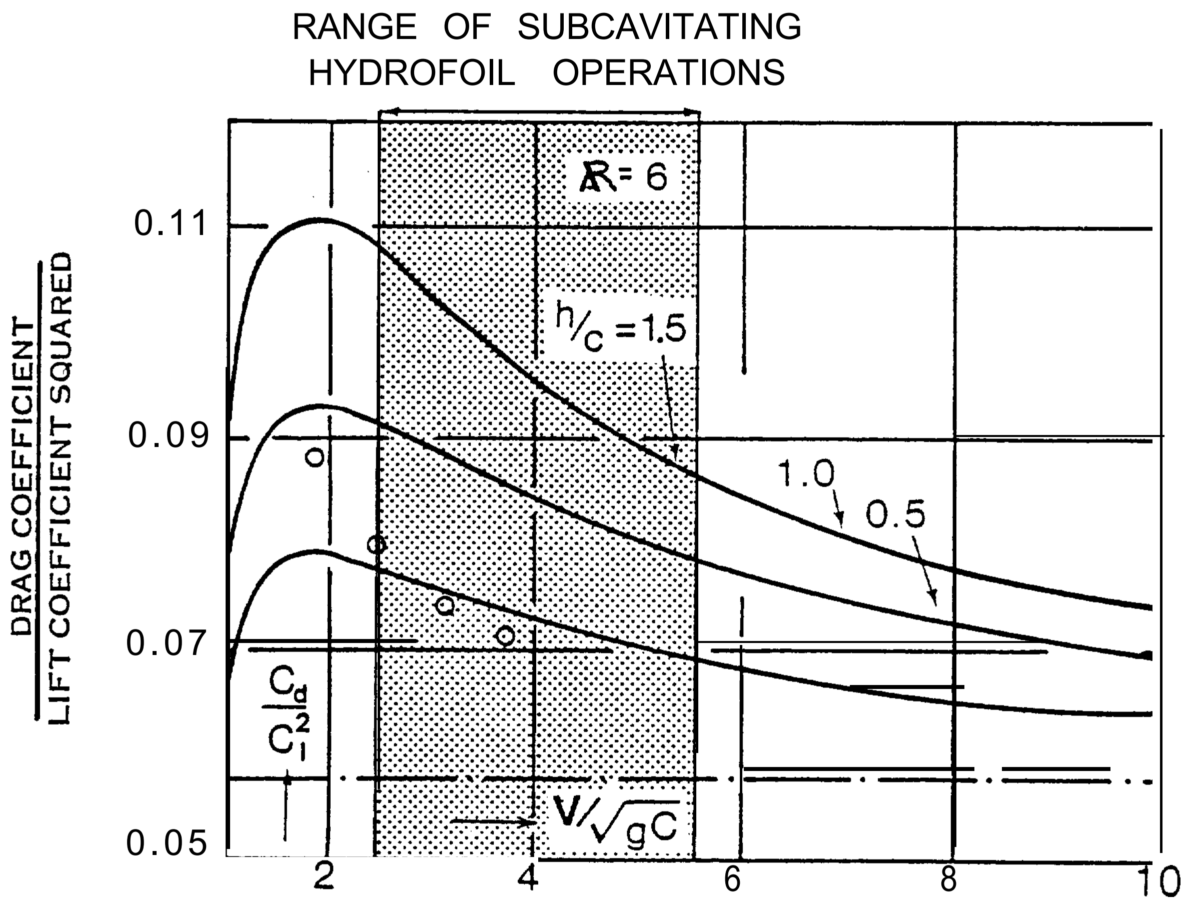


Figure II.A.1-7. EFFECT OF SUBMERGENCE DEPTH ON RESISTANCE AND COMPARISONS WITH EXPERIMENTAL DATA

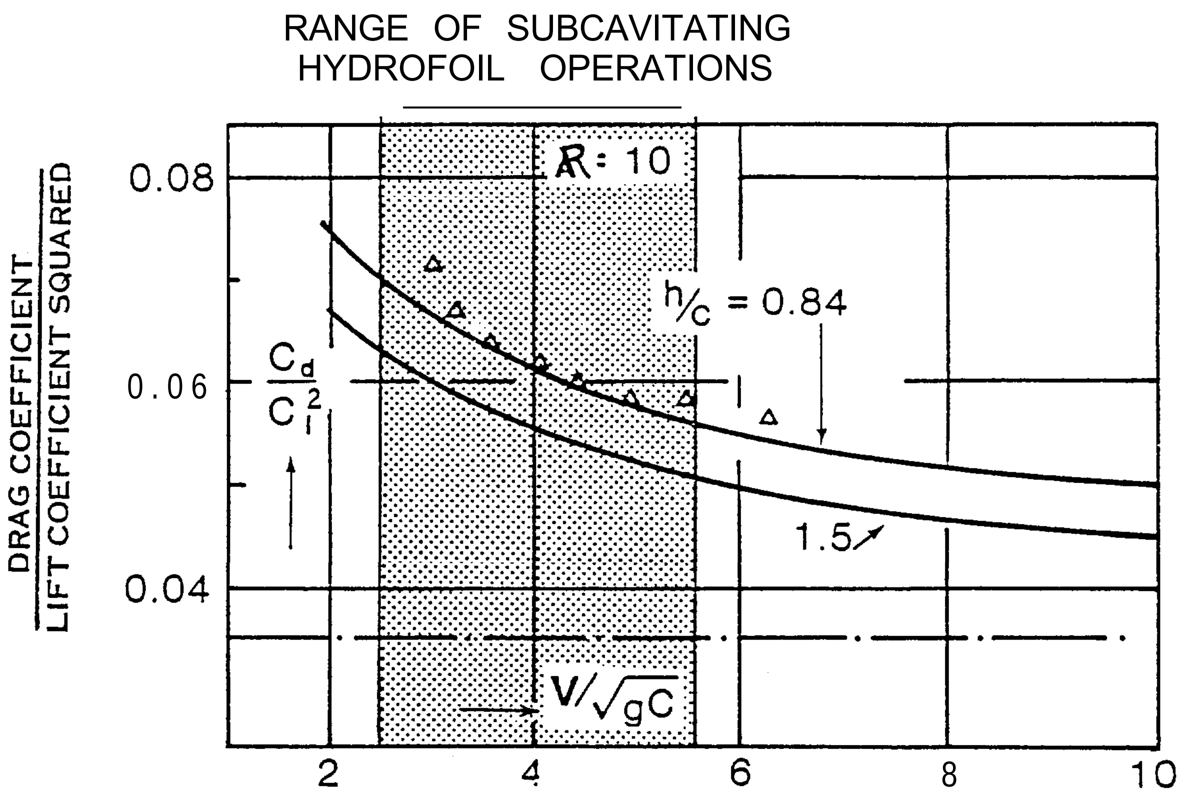


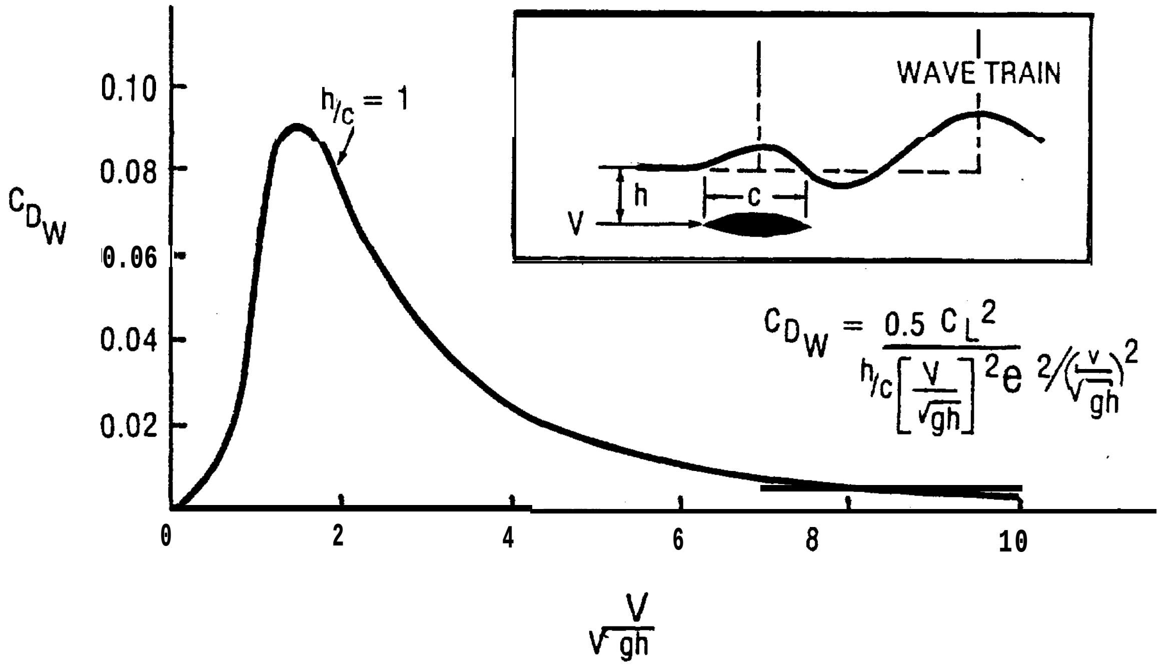
Figure II.A.1-8. EFFECT OF SUBMERGENCE DEPTH ON RESISTANCE AND COMPARISONS WITH EXPERIMENTAL DATA

(U) Kochin gives another formulation of wave drag which is shown in Figure II.A.1-9. This formulation has not been experimentally verified.

(U) Although the above shows there is some basis for estimating the wave drag due to the free surface, the experimental background is meager. Since hydrofoils built to date generally have operated at Froude numbers above 5, where the wave drag is small as can be seen from Figure II.A.1-9, the lack of good wave drag data has not posed problems to the designer. Large hydrofoil ships (1,000 tons) will, however, operate at takeoff at Froude numbers around 3 where the wave drag could become quite significant. To overcome the shortcomings in estimating wave drag at the lower Froude numbers, a model test program is underway at DTNSRDC, supported by the ANVCE study, which is expected to provide benchmarks to assure reliable prediction of foil drag throughout the foilborne speed range. These tests were completed in June 1976, and the results will be published in the fall of 1976. In addition, of course, the design for any new ship will be tested in model scale over the appropriate range of Froude numbers.

1.2.2 Hullborne Drag

(U) A hydrofoil ship, if fitted with a separate hullborne propulsion system and retractable foils, may operate hullborne with foils retracted or extended. When the foils are extended, either the hullborne or the foilborne propulsion systems may be used. Thus several configurations have to be considered when estimating the



WHERE:

- C_L = LIFTCOEFFICIENT
- h = FOILDEPTH
- V = SHIPVELOCITY
- g = ACCELERATION DUE TO GRAVITY
- C_{D_W} = WAVE DRAG COEFFICIENT
- c = FOILCHORD

Figure II.A.1-9. HYDROFOIL WAVE DRAG

drag in hullborne operation for any projected design. In one or another of these configurations, if not in all, each of the following drag components must be evaluated.

- Bare hull drag. The hull displacement will be different with foils retracted or extended.
- Lift system drag.
- Hull/strut interference drag.
- Propulsion system appendage drag.

(U) The hull configuration for hydrofoil ships is generally derived from those used for planing craft. Drag estimation is consequently based on techniques developed in that field of naval architecture. Other pertinent information is available in studies of the hydrodynamics of seaplane hulls.

(U) A recent program of model tests was undertaken expressly to provide lift, drag, and trim data on hull forms suitable for hydrofoil ships. The forms tested (designated Series 65) were derived from the hull of PLAINVIEW (AGEH-1) as a parent by varying the proportions and, for some, using only the forebody. The models were tested with a range of displacements and center of gravity positions to provide the data necessary for drag prediction of the hydrofoil hull throughout the takeoff run. The results of these tests and projections to full scale, along with similar model tests and projections for an earlier Series 62, are presented in References II.A.1-5, II.A.1-6, and II.A.1-7.

(U) In 1964 Savitsky (Reference II.A.1-8) presented formulas for the lift, drag, and trim of planing hulls. Hadler, Hubble, and Holling (Reference II.A.1-6) compared the results of model tests of Series 62 and 65 forms with Savitsky predictions, suggesting the Savitsky formulas needed correction for non-prismatic hull forms. Such a correction has been attempted by Blount and Fox (Reference II.A.1-9) particularly to improve the prediction of drag near the hump speed. Such formulations provide the basis for preliminary drag estimates and also assist interpolation between available model test results. Ultimately, model tests will be made of any proposed design to provide the best possible basis for power estimates.

(U) In order to estimate the minimum drag at the takeoff hump, it is necessary to know the hull drag over a range of displacements down essentially to zero. (There is even some evidence that, perhaps due to wave formation, the water adheres to the bottom and causes some drag even after the keel is raised above the still water level.) For this purpose, model tests at DTNSRDC on hulls suitable for hydrofoil ships have for some time always been tested over a wide range of displacement. Such data are included in References II.A.1-5, II.A.1-6, and II.A.1-7.

(U) With increasing ship size and essentially unchanged takeoff speed, the lift/drag ratio of the hull is improved. At some point it becomes preferable to drive the ship up to flight speed without use of foil lift. The criterion is the speed at which the hull drag/weight ratio becomes greater than the ratio of foil drag-due-to-lift increment to the foil lift increment.

(U) The drag of the struts and foils can be derived from estimates of the foilborne drag with an addition for the increased wetted length of the struts. At higher speeds, thought must be given to carrying some lift on the foils especially if flaps are used for lift control.

(U) Hull/strut interference may be significantly affected by the incorporation of fairings at the juncture. The design of an optimum configuration will require careful model tests.

(U) The importance of propulsion system drag depends on which system is used, if separate hullborne and foilborne propulsion systems are fitted. If extensive hullborne cruising is required, with foils extended, it may be preferable to use the foilborne propellers with separate hullborne engines.

1.2.3 Takeoff Drag

(U) Hydrofoils typically exhibit a maximum of drag at or near takeoff speed, which constitutes one of the critical requirements for the propulsion system. Consequently, careful attention will be given to control of the hump drag.

(U) The dashed curves in Figure II.A.1-10 show the drag in the foilborne mode down to the minimum speed at which sufficient lift can be developed by the foils to support the ship, and

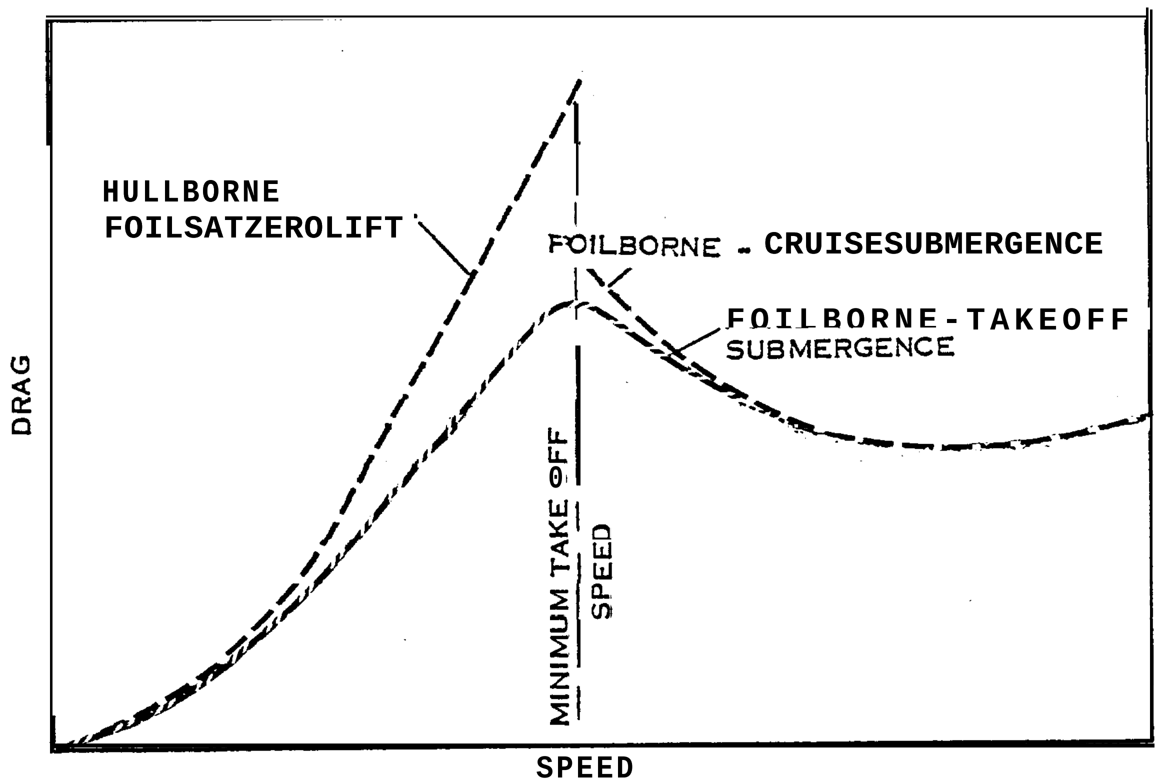


Figure II.A.l-10. TAKEOFF DRAG

below this speed, the drag of the ship in the hullborne mode with no lift generated by the foils. There is also shown, by a dotted curve, the drag in the range of foilborne speeds with the foils at such a depth that the hull is just clear of the water.

(U) It is evident from these curves that the foils are more efficient than the hull at the minimum foilborne speed, which suggests that the drag during takeoff can be reduced by carrying some of the ship weight on the foils. This is indeed the case, and, by a suitable controls program, the drag throughout the takeoff run may be made to follow the solid curve.

1.3 CONTROL HYDRODYNAMICS

(U) The capability to vary and control the foil lift and the side forces on the struts is a primary requirement for a ship with submerged foils. Just to maintain level flight at constant speed, small adjustments of lift must be made. The lift on a foil varies with the square of the speed; therefore a change in angle of attack or flap position must be made to maintain constant lift over the foilborne speed range. With increasing sea severity, disturbing forces are generated by the change of angle of attack produced by the orbital motion of the water in the waves. These must be countered by deliberate control action.

(U) Roll control is achieved by variations of lift on port and starboard foils, on ships with split main foils, or on port and starboard semi-spans when single main foils are used.

(U) Turning maneuvers are best made by banking the ship and using the horizontal component of foil lift to provide the necessary centripetal force. Some small increase in foil lift is required, typically less than 4 percent of steady state lift. More importantly, however, the steady state angle of attack on the foils is altered by the kinematics of the turn so that adjustment of the foils or flaps must be made to maintain the required lift.

(U) Control of the side force on either the forward or after strut(s) is required to turn, as well as to counter wave disturbances.

(U) The ways in which lift and side force may be controlled, and the effectiveness achieved, are discussed below.

1.3.1 Lift Control

(U) Foil lift may be varied most simply by changing the angle of attack or by changing the angle of a flap on the trailing edge of the foil*. One way to do this is by altering the pitch angle of the boat, which is used for takeoff. Pitch angle changes cannot be induced, however, without independent control of lift on the forward and after foils. Therefore, the lift of individual foils is made variable and controllable to provide lift control. Lift control on the FLAGSTAFF (PGH-1) and PLAINVIEW (AGEH-1) is accom-

*Leading edge flaps such as those sometimes used on aircraft have not been seriously considered for underwater surfaces because of their potential for damage.

plished by incidence angle variation, while on the hydrofoil ships PEGASUS (PHM-1), TUCUMCARI (PGH-2), and HIGH POINT (PCH-1), lift control is accomplished by trailing edge flaps.

(U) Figure II.A.1-11 shows the effect of incidence variation on the foil lift coefficient. Model test data are shown for speeds of 20, 30, 40, and 50 knots. Considering the low aspect ratio, the rather large sweep of this foil, and operation at a submergence of about one chord length, the accuracy of the prediction is impressive and certainly adequate for performance predictions.

(U) For this foil section, at low speeds, the maximum lift obtainable by increased angle of attack is limited by the onset of stall at a lift coefficient a little more than 1.0. At higher speeds the lift is limited by cavitation originating at the leading edge of the foil. This is shown in Figure II.A.1-12 which is a plot of the lift coefficient, C_L, versus angle of attack for speeds from 35 knots to 60 knots for a particular foil. The same information is presented in Figure II.A.1-13 which shows the average loading on the foil as a function of the speed for constant angle of attack. This clarifies the existence of an absolute limit on the lift which can be developed by this foil. This absolute limit, which greatly exceeds the lift in nominal operation, is used by the structural engineers in the structural load criteria. Since the nominal foil design loading is 1,100 to 1,500 psi, there is much more lift available than is ever needed for flight control in rough water. Here

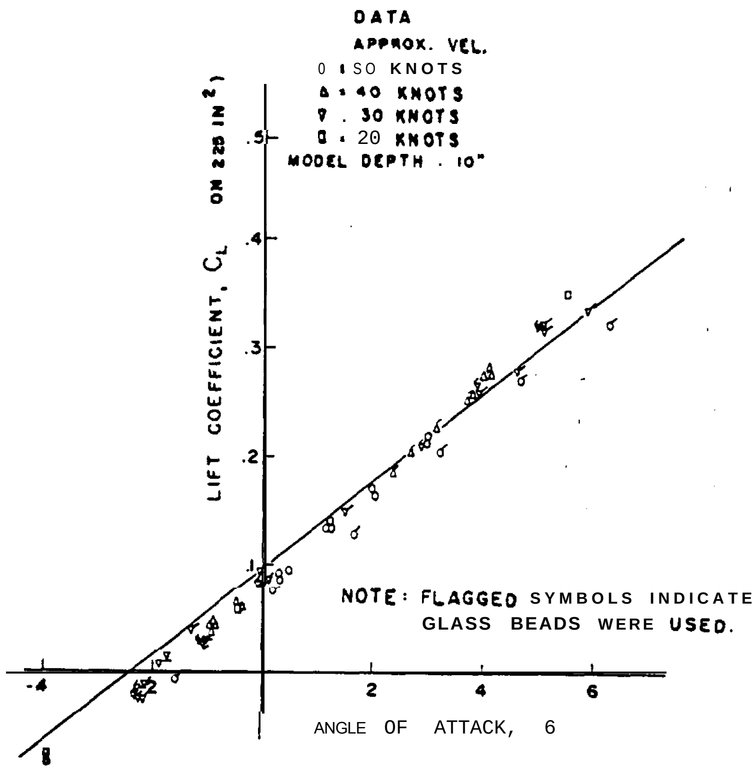


Figure II.A.1-11. LIFT COEFFICIENT VERSUS FOIL INCIDENCE WHEN FOIL MOVES RELATIVE TO NACELLE FOR MODEL B WHEN NACELLE IS AT 0 DEGREE ANGLE OF ATTACK

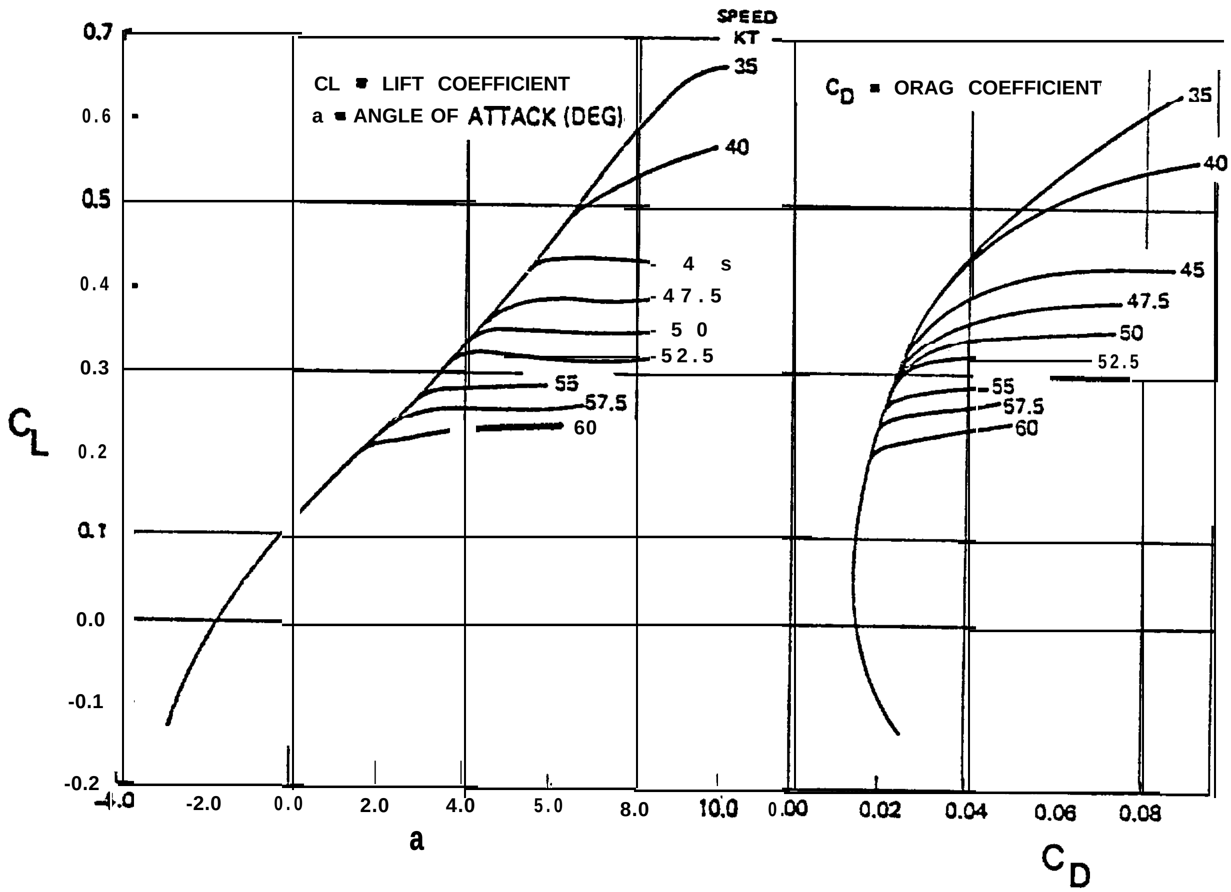


Figure II.A.l-12. WHIRLING TANK STUDY OF HEGA CAVITATION CHARACTERISTICS

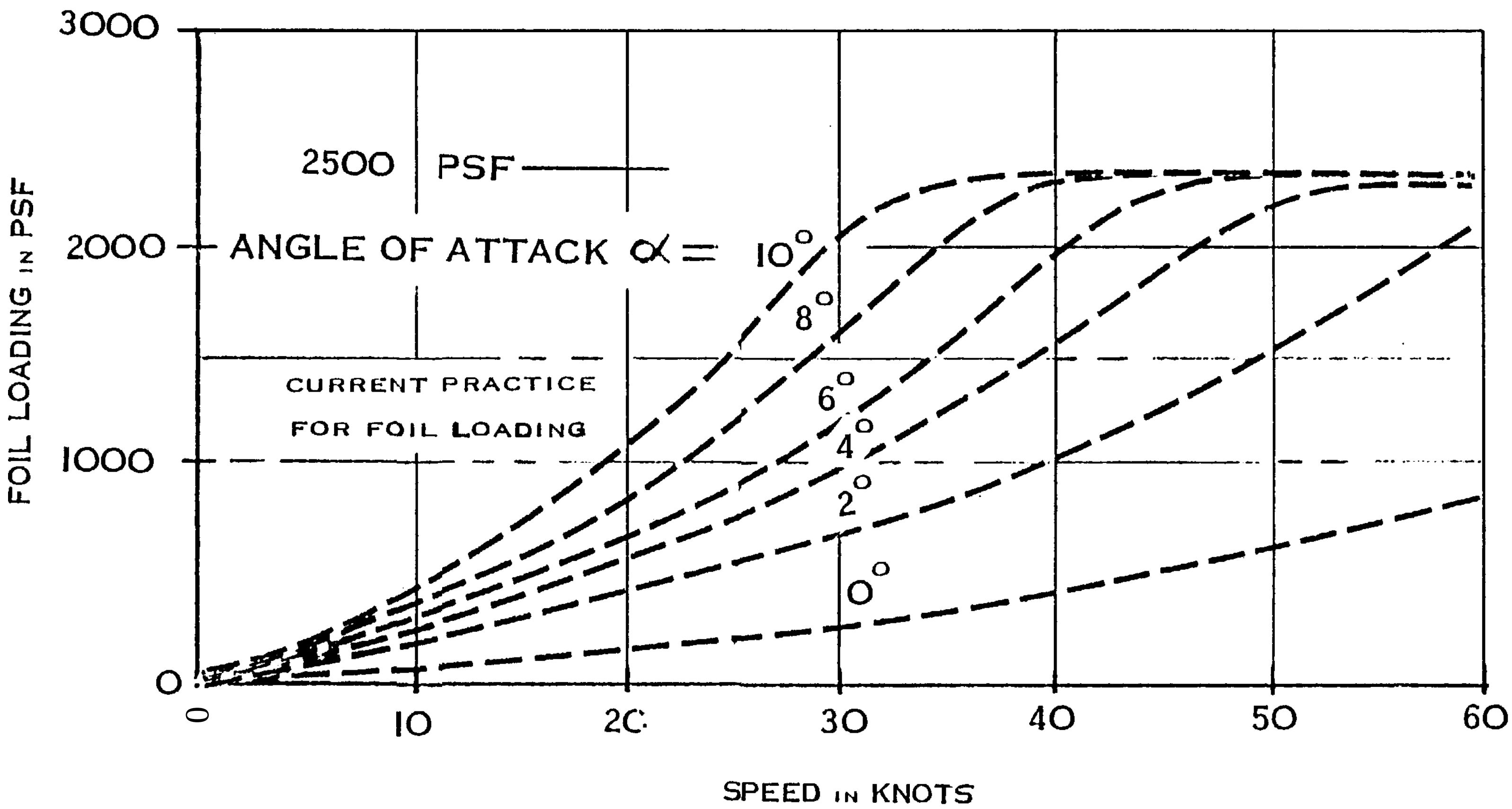


Figure II.A.1-13. EFFECT OF CAVITATION ON FOIL LOADING the aim is to maintain constant loading and decouple from the disturbing forces of a seaway.

(U) One difficulty with the application of variable incidence for control is the power required to move the foil. This is due to the inertia of the foil, and the associated hydrodynamic added inertia, and aggravated by the variation of the center of pressure with changing angle of attack. Largely because of these considerations, and also for structural reasons, use has been made of flaps for lift control on HIGH POINT (PCH-1), PEGASUS (PHM-1), and TUCUMCARI (PGH-2). On each of these ships, plain, hinged, trailing edge flaps have been used on both the forward and after (main) foils.

(U) The effectiveness of flaps depends on the ratio of the flap chord to the total foil chord and is usually expressed as the ratio of incidence change (with fixed flap) to the flap deflection required for equal change of lift. This ratio shown in Figure II.A.1-14 for a two-dimensional foil is considerably higher than measured full scale on 16 series foils. Recent model tests on 64 series foils however, show that the two-dimensional value may be used for full span, constant percent chord flaps on a foil of moderate aspect ratio and at small flap deflections.

(U) Figures II.A.1-15, II.A.1-16, and II.A.1-17 show the lift coefficient achieved in model tests of the PHM after foil design, for a range of angles of attack and of flap deflection at

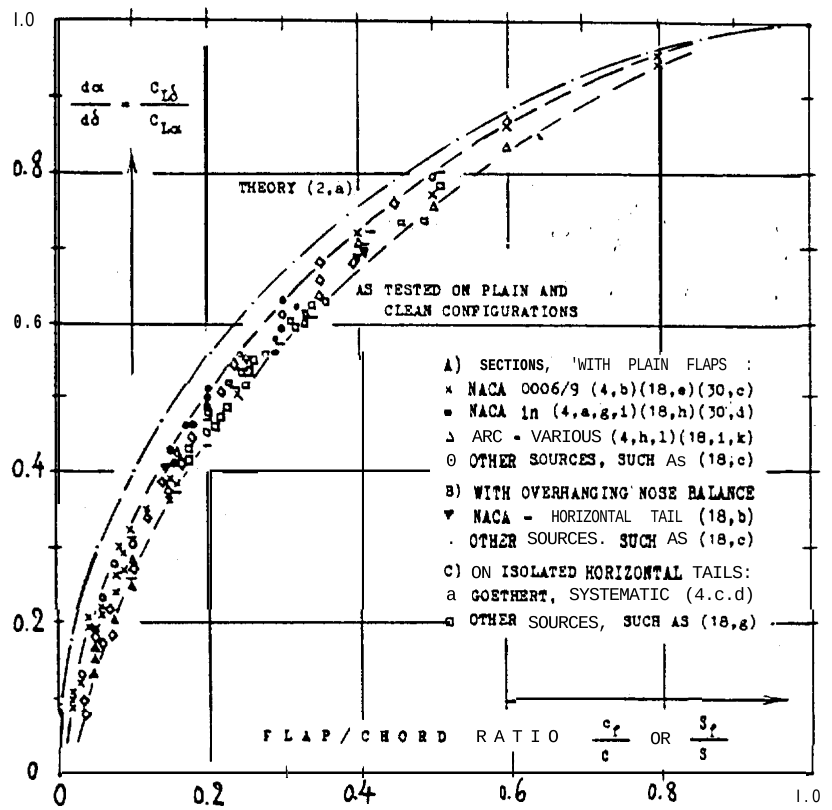


Figure II.A.l-14. EFFECTIVENESS RATIO OF VARIOUS TYPES OF TRAILING EDGE CONTROL FLAPS (ELEVATORS, RUDDERS, AILERONS) AS A FUNCTION OF THEIR CHORD RATIO

DEPTH TO CHORD RAT10 **h/c = 1.338**
SPEED = 25 KNOTS
YAW ANGLE = 0°
FLAP CHORD / FOIL CHORD = 0.25

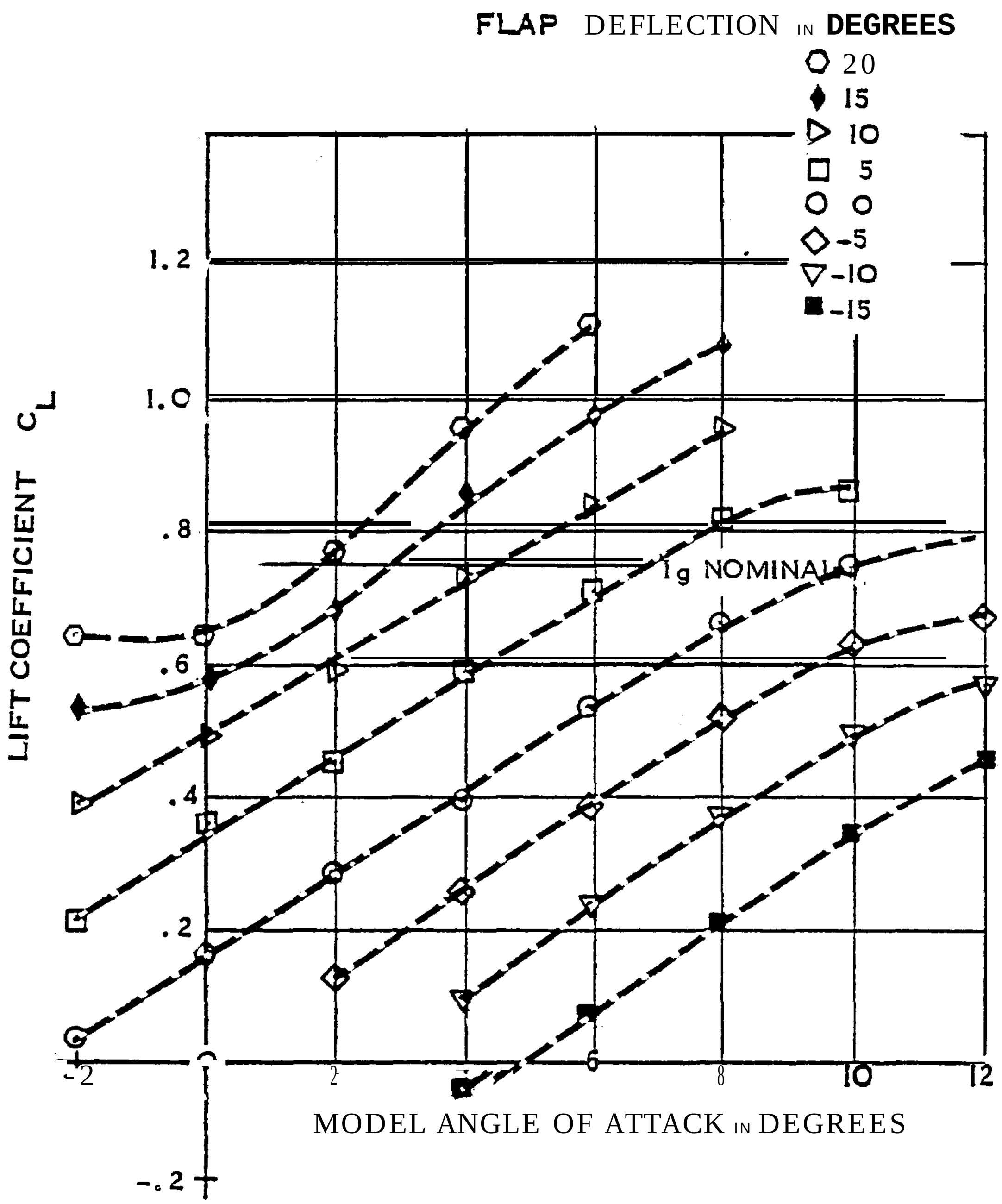


Figure II.A.1-15 PHM-1 MODEL TEST LIFT DATA SPEED = 25 KNOTS

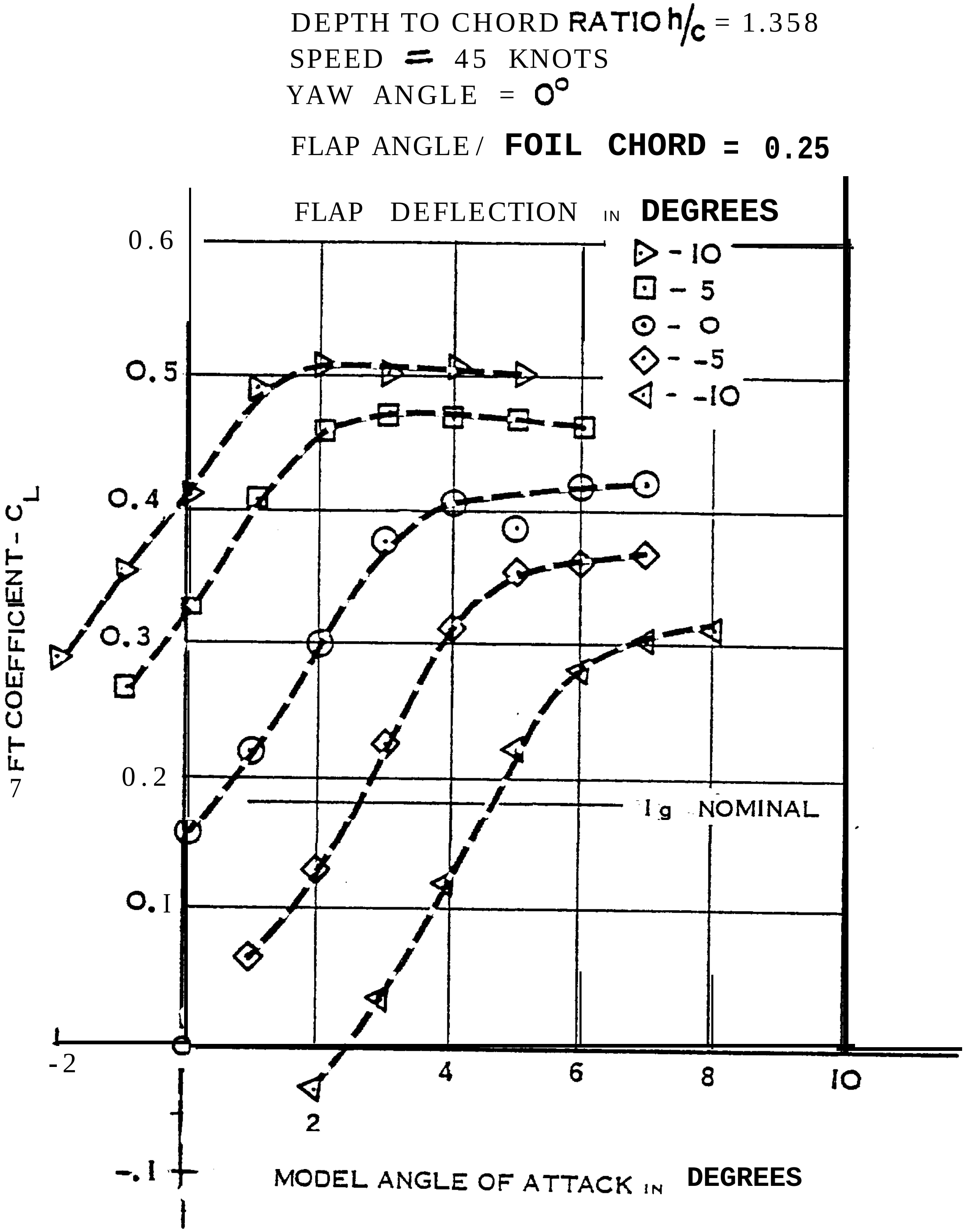


Figure II.A.l-16 PHM-1 MODEL TEST LIFT DATA, SPEED = 45 KNOTS

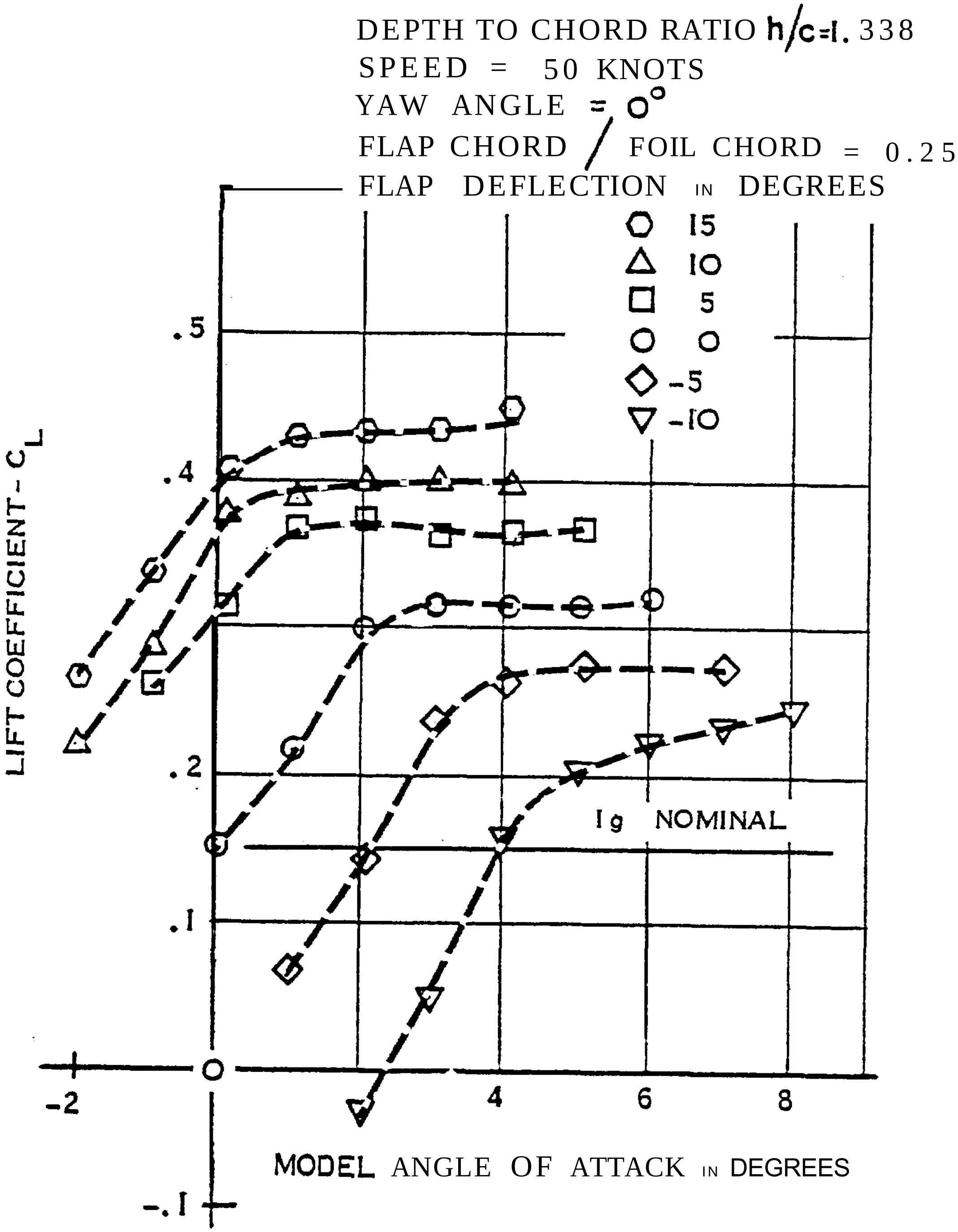


Figure II.A.1-17 PHM-1 MODEL TEST LIFT DATA, SPEED = 50 KNOTS speeds of 25, 45, and 50 knots, respectively. The flap effectiveness in Figure II.A.1-15 for small flap angles (± 5 degrees) is 0.5, which matches what one would obtain from Figure II.A.1-14. The potential for the development of increased lift by flap deflection is clear at all speeds.

(U) At 50 knots (Figure II.A.1-17) a limitation on maximum lift imposed by leading edge cavitation is evidenced by the flattening out of each curve above a certain angle of attack. Likewise, a limit on flap effectiveness is also indicated by the curves coming closer together above 5° flap angles, which is the result of flap hinge line cavitation.* This is not a problem in normal operation, since the 1g lift coefficient at this speed is only about 0.15 for this ship. It can, for larger hydrofoils, become significant on the forward foil where, in a banked turn at maximum turn rate, the angle of attack can be reduced by the kinematics of the maneuver to a point where the available lift is marginal.

(U) It is clear that higher lift coefficient for take-off could be obtained if both the incidence and flap deflection could be controlled. Since only slow variation of incidence would be needed,

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*The 1g lift coefficient is shown on each figure.

the power requirement would not be large. In practice, however, pitching the ship up about 3 degrees negates the need for incidence trim on present flap-controlled ships.

(U) There is evidence (Reference II.A.1-1) that the NACA 16 series sections, much used in recent years for hydrofoils because of a favorable pressure distribution at the design lift coefficient, are not wholly satisfactory when fitted with flaps because of the fullness of the trailing edge. Recent tests compared these sections with the 64 series section. Preliminary results show a considerably higher flap effectiveness with 64 series cections.

(U) Although the control power required for plain flap controls is generally much less than for incidence control, it is still appreciable for larger ships. One way to reduce the power requirement, which is being explored, is the use of a detached flap - or auxiliary foil - below the trailing edge of the main foil which can be hinged near its center of pressure to minimize the hinge moment. This and other methods are being investigated to provide an adequate control range and authority with less required control power.

1.3.2 Strut Side Force and Steering Control

(U) Hydrodynamic lateral forces developed on the struts are crucial for directional stability and steering control of a hydrofoil ship. Lateral forces arise in the same way that lift forces are generated on the foil, that is, (1) by side slip (equivalent to angle of attack on a foil) resulting from ship motions or wave action or by deliberate rotation of the strut about a vertical steering axis, or (2) by the use of flapped type rudders hinged to the trailing edge.

(U) In normal operation, that is, for small side slip angles, the side force on a plain strut varies nearly linearly with the side slip angle and is proportional to the square of the speed, as shown in Figure II.A.1-18. The side force coefficient also varies with the extent of submergence as measured by the aspect ratio (ratio of submergence to strut chord). A knowledge of the slope of the curve of side force versus side slip angle is essential for analysis of directional stability and the design of the steering control system.

(U) When the side slip angle reaches a certain value, depending on speed and submergence, there is a sudden loss of side force (see Figure II.A.1-19). This is due to what is termed "ventilation" and involves separation of the flow from the low pressure side of the strut and the penetration of atmospheric air down the strut. The pressure on the "suction" side is thus increased from near zero* to atmospheric; that on the high pressure side is reduced by changes in the flow accompanying the formation of the

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*In model tests, a vapor-filled cavity is observed over most of the strut just before ventilation occurs.

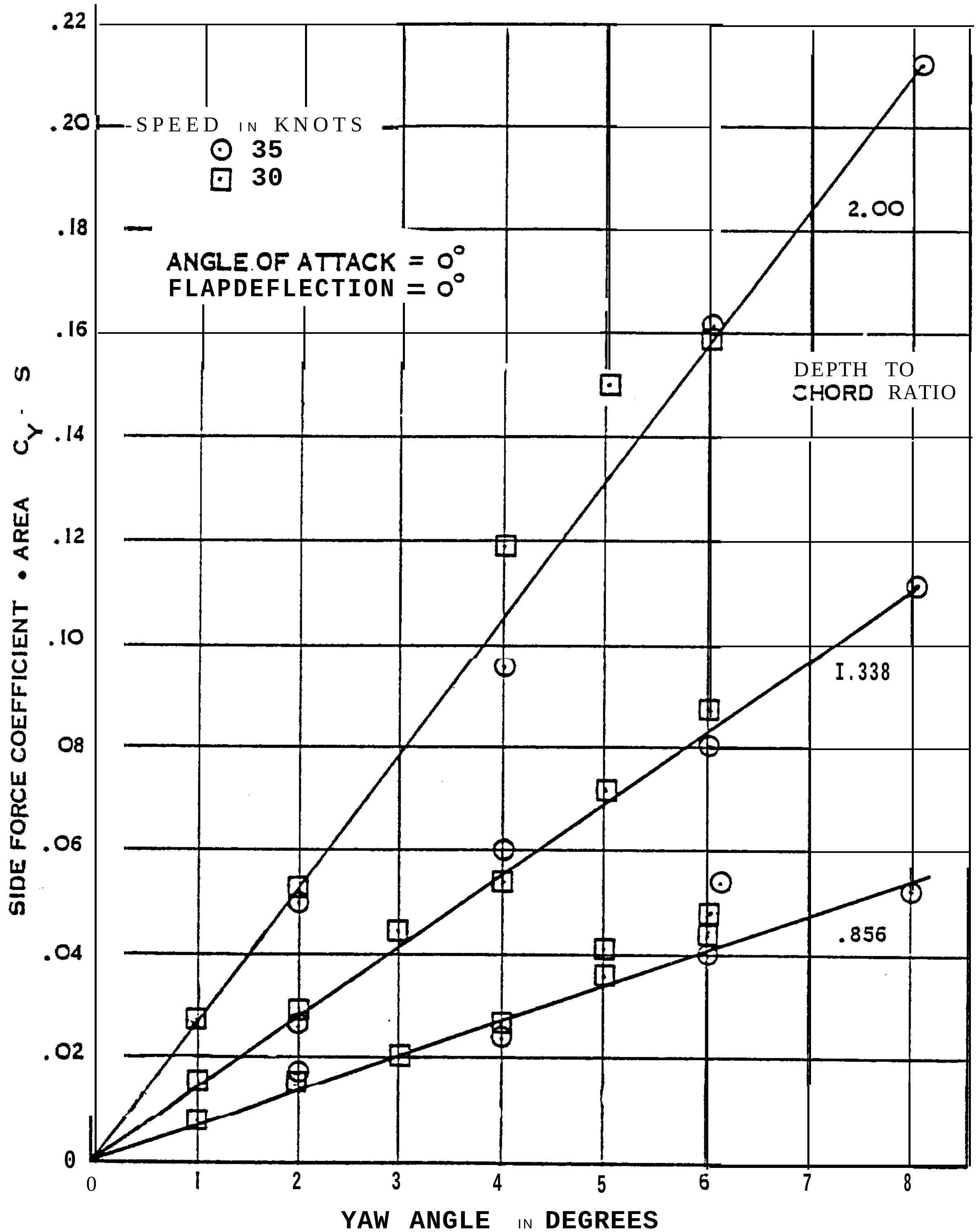

Figure II.A.1-18. TYPICAL STRUT SIDE FORCE DATA

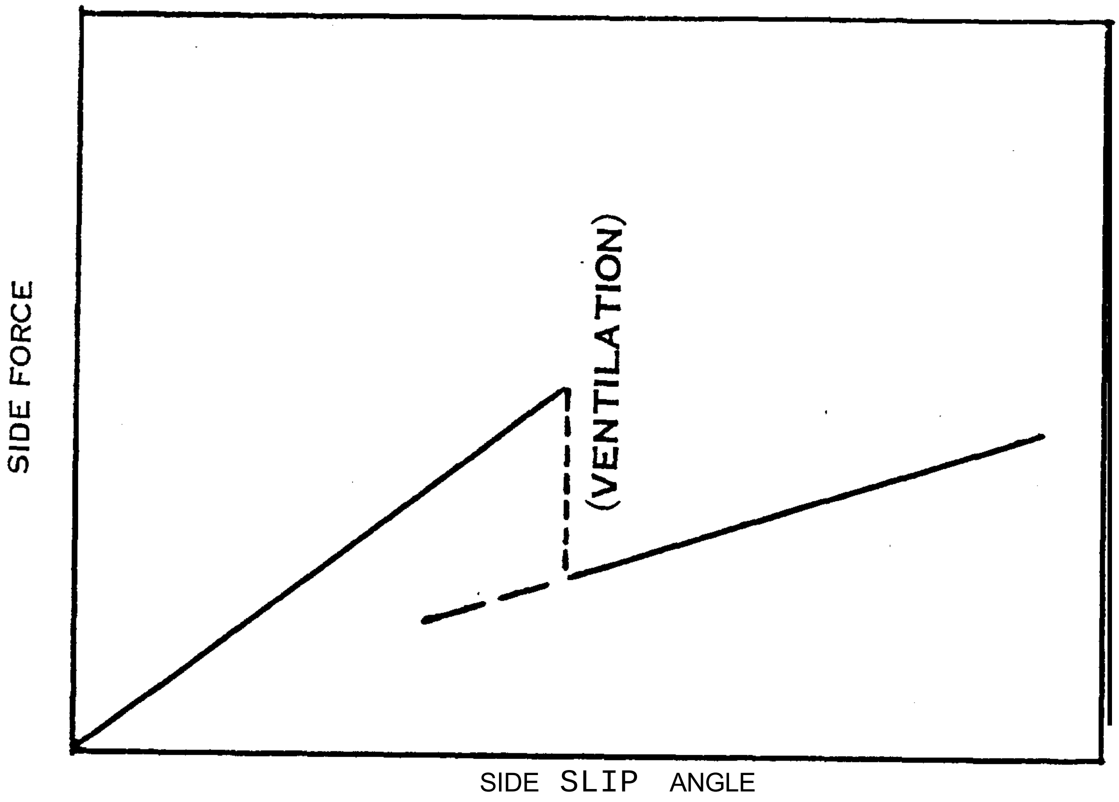

Figure II.A.1-19. TYPICAL STRUT SIDE FORCE VARIATION WITH ANGLE OF ATTACK FOR A BLUNT-BASED STRUT ventilated cavity. The result may be an actual reversal of the side force, which must be considered in the ship control and foil strut design. Additionally, the slope of the side force versus side slip angle is considerably less when the strut is ventilated, which has significant ramifications on directional stability. (The ship tends towards instability if the after strut(s) is ventilated.)

(U) Model tests have shown that ventilation can be precipitated at small side slip angles by the effects of contour errors on the strut surfaces, coupled with misalignment or flow disturbances due to waves. Unexpected and erratic ventilation of the main (after) struts of HIGH POINT (PCH-1), Mod 0, resulted in many problems including loss of directional control and sometimes divergent skidding which had to be arrested by landing the ship. These problems were eliminated after reworking of the struts to improve the contours and alignment.

(U) Model tests of the after (main) struts for the PHM indicate that ventilation does not occur at side slip angles less than 8 degrees for speeds up to 35 knots, and less than 6 degrees for speeds up to 50 knots (Figure II.A.1-18). During full-scale evaluation trials of PEGASUS (PHM-1) no serious strut ventilation has been observed. (Early PHM-1 trials showed some ventilation associated with strut stiffeners but after these were faired into the strut, ventilation had not been noted.)

(U) In order to steer a hydrofoil ship, it is necessary!,. to provide for control of the side force on either the forward or after strut(s). On existing ships this has involved the single forward struts on the canard ships and the single after struts on those with an airplane foil configuration. On SEA LEGS, an early developmental craft of 4.9 tons with canard foils, a flap on the forward strut was used for steering. HIGH POINT, also with a canard configuration, had a flap rudder on the forward strut which proved inadequate and was augmented by a spade rudder fitted below the forward foil. With this background of experience, The Boeing Co., in the design of TUCUMCARI (PGH-2), incorporated a fully steerable forward strut with the forward foil turning with the strut. This concept maintained the side slip angle on both forward and after struts nominally at zero degrees in the banked turn. This was so successful that a similar installation was made on HIGH POINT, Mod 1, and on PEGASUS (PHM-1). Similarly, DENISON, the first ocean-going U.S. hydrofoil ship, was fitted with a flap rudder on the after strut while later airplane configuration ships, such as PLAINVIEW and FLAGSTAFF, have had all-moveable after struts for steering.

(U) Hydrodynamically, the all-moveable strut is much more effective than a trailing edge flap since it will always be at a zero side slip angle in a turn as well as when running straight. A fixed strut, on the other hand, always has an adverse side slip angle in a turn so that the flap rudder has to first overcome a force tending to resist the turn and must be deflected to large angles in a tight turn. Such a configuration is very prone to separation, stall and early ventilation due to large strut side slip angles and large contrary rudder deflections. Nevertheless, the weight penalty inherent in the all-moveable strut, and the limits imposed on the size and aspect ratio of the associated foil have motivated a re-examination of alternative steering configurations for larger ships. One concept under study is a steerable envelope surrounding a fixed structural strut while, at the same time, continuing studies are aiming at better forms and control methods to extend the utility and capabilities of trailing edge rudders.

1.4 CAVITATION

(U) Cavitation occurs where the local pressure is reduced to the vapor pressure of the water and vapor filled cavities are formed. These cavities, if they collapse on the surface of the lift system, can cause erosion of the material; and if these cavities are extensive, they can greatly increase the drag and affect the lifting capability of the foil. It therefore becomes important to avoid, or at least to limit, the extent of the cavitation.

1.4.1 Foil Cavitation

(U) Since cavitation occurs where the pressure is reduced to (approximately) the vapor pressure of water, the successful control of cavitation depends on the capability to predict the pressure distribution on the foil. The procedures used consist of the application of aerodynamic wing theory, with appropriate correction for the effect of the free surface, to determine the spanwise load distribution and then to examine the most heavily loaded section by means of two-dimensional aerofoil theory. Since the sections most used for hydrofoil ships are well-known NACA sections, a preliminary estimate of the minimum pressure can be made with the use of published velocity distribution for the basic thickness distribution, for the chosen mean line, and for any angle of attack (Reference II.A.1-11). Greater precision can be obtained by the use of computer programs, such as the Brockett program (Reference II.A.1-12) developed at DTNSRDC, which carry out the calculation of the distribution of the pressure coefficient over almost any specified foil shape. Nonstandard or modified standard foils can be examined in this way over a range of operating conditions: The Brockett program has been applied recently to determine the conditions of loading and speed for incipient cavitation on the foils of PCH-1, Mod 1, with the control flaps deflected (Reference II.A.1-13). Model test results shown in Figure II.A.1-20 show good correlation with Brockett's predictions. Recent full-scale cavitation trials on the PCH-1 show that DTNSRDC cavitation prediction techniques are conservative. The DTNSRDC method predicts cavitation at 10 percent less foil loading than was observed in these trials.

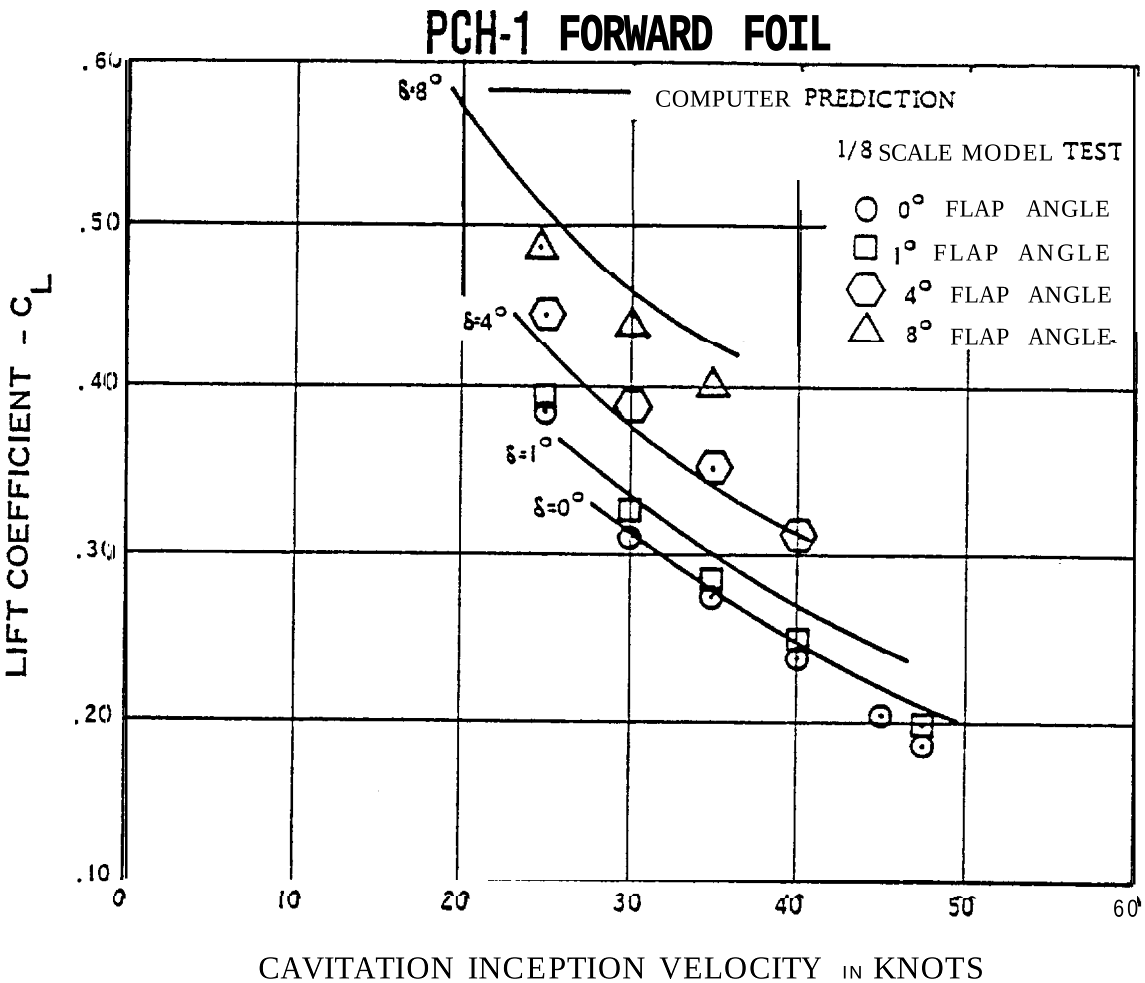

Figure II.A.1-20. COMPARISON OF COMPUTER-PREDICTED AND EXPERIMENTAL LEADING EDGE CAVITATION INCEPTION RESULTS

(U) The design of the foil will usually be made to avoid any cavitation in calm water over the foilborne speed range and in waves up to the design sea state. Intermittent cavitation, which may occur in heavier seas, appears not to be damaging to the foil.

(U) A more serious concern is the loss of lift--and the concomitant increase in drag--which occurs under conditions of heavy loading. At takeoff, for example, since the speed is low, the lift coefficient is high and the takeoff speed is governed by the maximum lift capability of the foil. Extensive sheet cavitation may originate at the leading edge with much the same effect as the stalling of an airplane wing. A comparable effect is observed when the control flaps are deflected to large angles at high speed; the desired increase of lift fails to materialize because of cavitation originating at the flap hinge line. See Figures II.A.1-15, II.A.1-16, and II.A.1-17. This effect, compounded with the adverse influence of out-of-tolerance foil contours, has produced cavitation on PHM-1 and made the ship sensitive to pitch angle. A careful balance of foil section design and foil incidence and flap trim angles is expected to alleviate this problem.

1.4.2 Strut Cavitation

(U) Cavitation on the struts is observed in model tests to occur first some distance below the surface, even though the ambient pressure is, of course, a minimum at the surface. Water near the surface can rise as it flows around the strut and is not accelerated as much as that lower down, which is constrained to a nearly plane horizontal path. It is appropriate, therefore, to design the struts for freedom from cavitation at a depth of one foil chord. The critical area then becomes the surface of the pod or nacelle at the strut/foil juncture. Consideration must be given to the superposition of velocity increments due to each of the three components. Cavitation on the struts of existing hydrofoil ships has been avoided by careful adherence to manufacturing tolerances and avoiding high angles of attack on the strut by using banked turns and fully pivoting the steering strut.

1.5 SUPERCAVITATING STRUTS AND FOILS

(U) The successful operation of existing subcavitating hydrofoil ships (40-50 knots) has been well demonstrated and discussed in Reference II.A.1-14. Thus far, most foil and strut section shapes used in U.S. Naval craft have been those selected from the NACA design literature such as the 16 series (Reference II.A.1-15). Experiences indicate that it is difficult to avoid cavitation on a subcavitating foil at speeds much above 50 knots at practical depths of submergence. At speeds greater than this, small bubbles or cavities tend to form on the low pressure side of the foil. They are detrimental to performance and, as they collapse, are destructive to the foil structure itself. New strut and foil configurations have to be developed if future hydrofoil ships are to be operated at speeds 55 knots. It is the purpose of this section to review the state-of-the-art of hydrofoil strut-foil design for those higher speeds.

1.5.1 Past High-Speed Strut-Foil Design Efforts

(U) Thus far, most foil section shapes used in the U.S. naval hydrofoil ships have been selected from NACA 16. As noted in Reference II.A.1-15, it appears that speeds much above 50 to 55 knots will always be associated with some cavitation unless extreme care is taken in the design and fabrication of the foil system.

(U) Extensive activities have been pursued in industries, laboratories, and institutes to develop means of delaying the incep- a small spoiler above the foil can be utilized effectively to suppress or delay the inception of cavitation (Reference II.A.1-16). A sketch of the foil and spoiler is shown in Figure II.A.l-21. So far no information is available to estimate quantitatively the effectiveness of this scheme.

(U) Air-stabilization of hydrofoil ships has been successfully developed by Supramar in their commercial craft (Reference II.A.l-17). It is noted by von Schertel that during the transition from the partial to the full cavitating range, the air-fed foil remains controllable. Cavitation can be delayed by the admission of a very small quantity of air. Also the cavitation bubbles will be filled with air so that the high transient pressures from cavity collapse and thus erosion are greatly reduced.

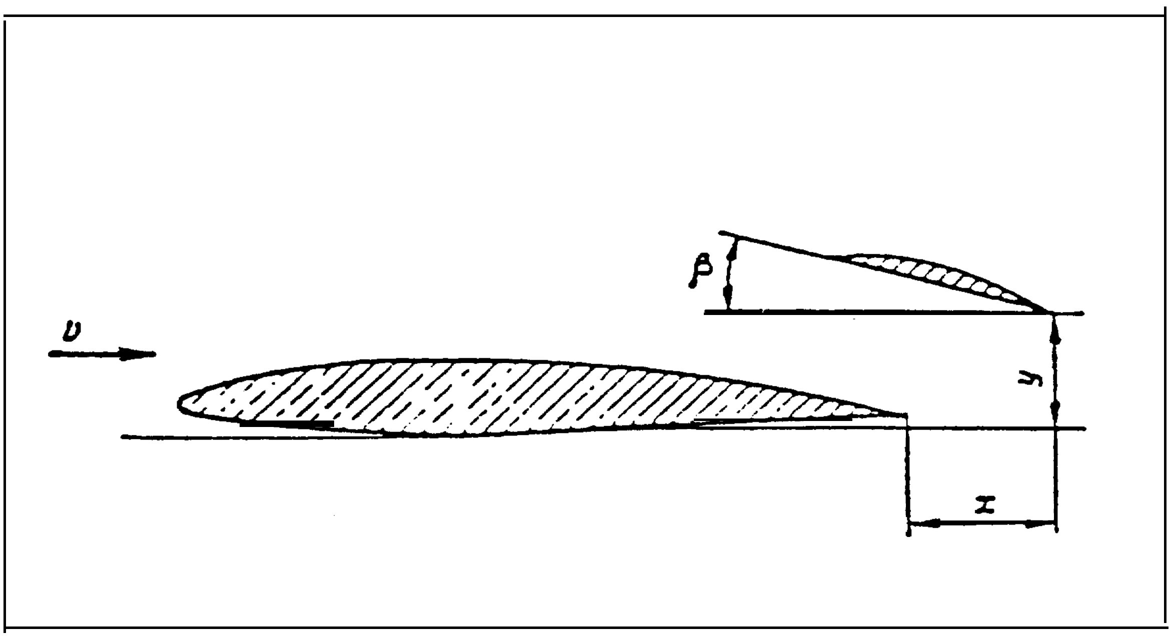

Figure II.A.1-21. CROSS SECTION OF FOIL WITH SPOILER

(U) Recently, an experimental investigation of 60 knot air-fed hydrofoil ships with an intention to go to much higher speeds, was carried out by von Schertel (Reference II.A.1-18). Three notable features stand out. First, the foil was designed to operate at a depth of two-chords submergence in order to minimize the surface effect; second, a very thin strut was used to avoid cavitation at 60 knots; and third, the maneuverability of a hydrofoil ship fitted with such a thin strut has not been investigated. Due to these considerations, a relatively large strut wetted area is obtained. This results in weight penalty and high friction drag.

(U) Another innovative approach to this problem was developed in the Canadian hydrofoil program. Cavitation can be delayed to higher speeds by careful section design, following the principle of uniform pressure distribution. A suitable section was designed by Richardson (Reference II.A.1-19) for cavitation-free operation up to 60 knots in calm water, with angle-of-attack tolerance for rough water operation at 50 knots. The section is termed a "delayed cavitation section" by Eames and Jones (Reference II.A.1-20). Figure II.A.1-22 is a sketch of this delayed cavitation/section compared with a subcavitating and supercavitating section. Three notable features of the delayed cavitation section stand out. First, the foil is similar to a planoconvex section (ogival foil section). Second, the leading edge of the foil is sharp and wedged shape.

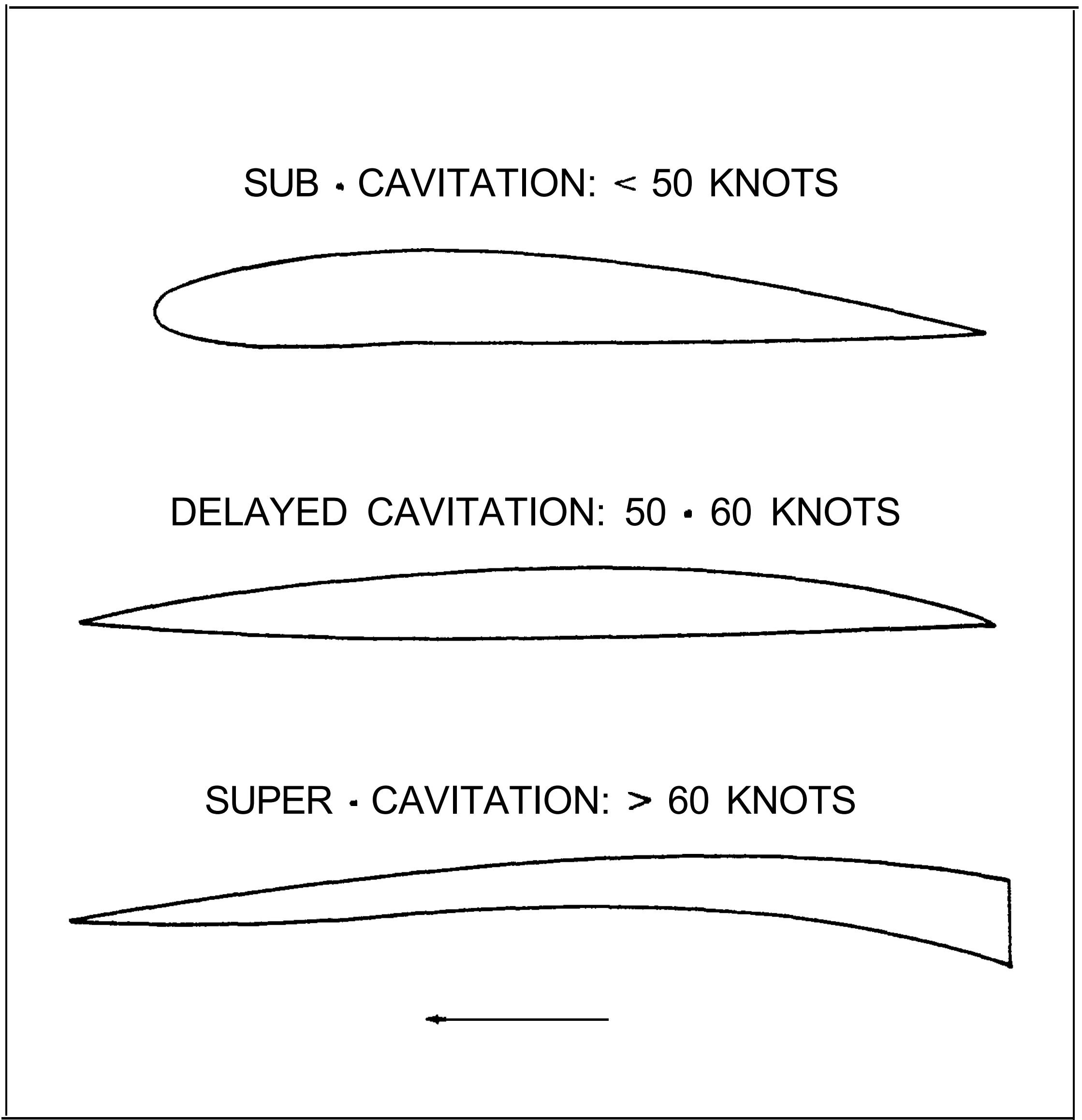

Figure II.A.1-22. SPEED REGIMES AND TYPICAL SECTIONS

It is to be noted that this foil was designed to operate in a sub-cavitating mode. Third, the thickness-to-chord ratio is quite thin to avoid possible cavitation at high speeds.

(U) This delayed cavitation section was fitted on the main aft foil of the Canadian surface-piercing hydrofoil ship BRAS D'OR. The bow foil was a supercavitating section. Extensive sea trials of this 200-ton hydrofoil ship were carried out both in calm water and rough seas. The technical feasibility of operating this foil section at 60 knots in calm water and 50 knots in rough seas was demonstrated. However, it is pointed out by Eames and Jones that this is probably the practical limit of the delayed cavitation regime. At higher speeds, lift coefficients are restricted to un-realistically low values and even at 60 knots the limit on section thickness causes very severe structural problems.

(U) The lift-to-drag characteristics of a subcavitating hydrofoil ship operated at high-speeds was studied by Johnson and Tulin (Reference II.A.1-21) and are shown in Figure II.A.1-23. The L/D ratio of a subcavitating strut/foil system degrades significantly and is shown to be lower than that of a supercavitating foil at high speeds. The same conclusion was obtained in a recent study by Wang (Reference II.A.1-22).

1.5.2 Base-Vented Foil

(U) Early work on base-vented foils was conducted by Johnson and Rasnich, Lang and Daybell, and Fabula (References

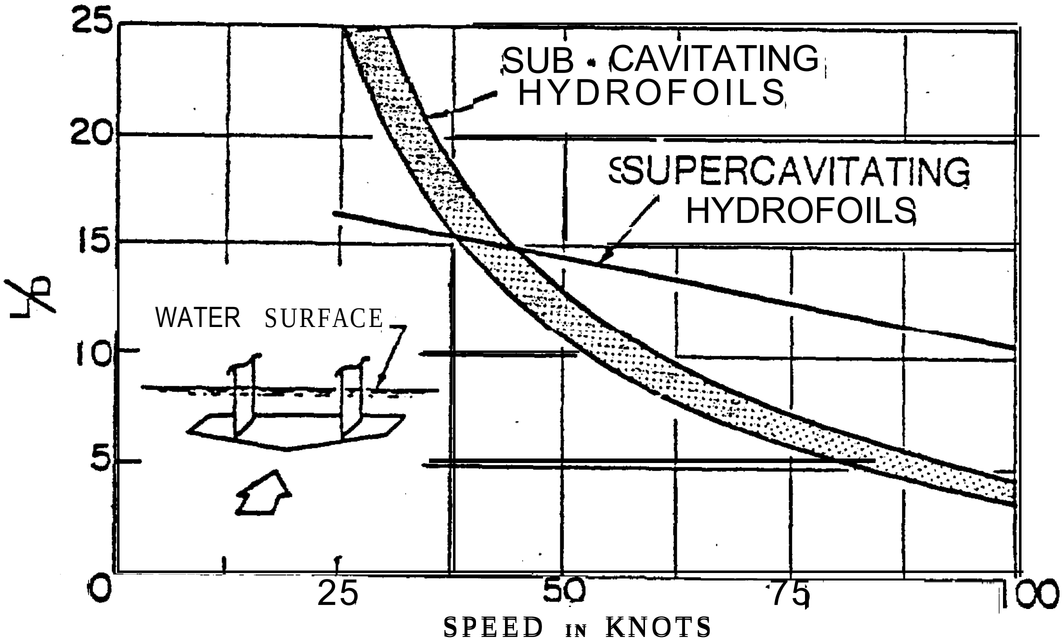

Figure II.A.1-23. THE INFLUENCE OF SPEED ON THE MAXIMUM LIFT-DRAG RATIO OF SOLID NONCAVITATING AND SUPERCAVITATING HYDROFOIL SHIPS SUPPORTED BY TWO STRUTS AND OPERATING AT A DEPTH CHORD RATIO OF 1 IN CALM WATER

II.A.1-23, II.A 1 24 and II.A.1-25). They also provided supporting experimental evidence of good lift-to-drag ratio. A foil system based on the base-vented principle *was* tested on the FRESH-1 testing craft at speeds up to 83 knots. As noted in References II.A.1-26 and II.A.1-27, the tolerance in angle-of-attack variation for cavitation-free operation on this type of foil is relatively limited.

(U) Due to the proximity of the free-surface, a base-vented foil operated at high-speeds may be subject to a phenomenon called "surface ventilation." The whole upper surface of the foil is then enclosed in a fully ventilated cavity. This will result in a significant reduction in lift and will create a very difficult control problem, especially at high speeds.

(U) A linearized theory to improve the leading edge cavitation problem on a base-vented foil was studied by Huang (Reference II.A.1-28). However, the predicted result was not realized in the model tests. Lang's theory shows that the upper surface cavitation can be delayed by increasing the leading edge radius and bluntness of the foil. This will result in an increase in the cavity drag. A tradeoff study on this subject must be conducted so that the applicability of a base-vented foil can be assessed.

(U) Thus far, the available information from theories and experiments seem to suggest that further research and development are greatly needed if a base-vented foil is to be used successfully in naval high-speed hydrofoil ships.

1.5.3 Supercavitating Foil (Fully Cavitated)

(U) The undesirable phenomena of upper surface cavitation and ventilation on the subcavitating and base-vented foils can be circumvented by designing a foil to operate in a fully cavitated (ventilated) condition. A major advance in this concept was made by Tulin and Burkart (Reference II.A.1-29) who pointed out that the wetted, pressure surface of the foil could be designed in such a way as to optimize the lift-to-drag ratio. Since then, a great amount of research activity, both theoretical and experimental, has been carried out in many institutes and laboratories.

(U) A summary review of the major high-speed hydrofoil development program from 1955 to 1972 was given in Reference II.A.1-30. The major programs carried out in this period were:

a. NASA high-speed hydrofoil program

b. Grumman whirling tank test series

c. Accelerated hydrofoil development program

d. BUSHIPS parent foil program

e. Demonstration foil program

f. Boeing annex foil development program

g. Grumman transit foil program

(U) The activities performed in the first four of these were research-oriented to get a fundamental understanding of supercavitating sections. The program was carried out in (a) to explore the characteristics of supercavitating foils; in (b) to explore the effects of camber, taper, sweep, and aspect ratio on the foil performance; and in (c) to explore the effectiveness of forced-ventilation on the foil performance. Because of the difficulties encountered in correlating data between facilities, a correlation model, the BUSHIPS parent fully cavitating hydrofoil was designed and tested in a number of facilities, both fully-cavitating and ventilated. The Last three programs above were developments as opposed to research-oriented, designed with specific tasks for high speed operation. Program (e) developed the foils for the FRESH-l demonstration.

(U) Program (f) developed the design of The Boeing Company annex foil (Reference II.A.1-31). This foil had an innovative concept of variable geometry first introduced by Hydronautics, Inc. The foil wetted area at the takeoff (annex wetted) is double the wetted area at cruise (annex not wetted). The annex also provided additional structural strength with no penalty in drag at cruise as it lies within the vapor cavity. The foil was designed to operate at speeds above 60 knots in the supercavitating mode with full ventilation provided from a blunt-based strut. No design consideration was given on this foil to operate at speeds less than 60 knots. This model was tested on The Boeing Company High-Speed Test Craft. Because of the complicated flap geometry, six different flow regimes over the foil were observed. The most pertinent problem during the tests was getting the annex to unwet (Reference II.A.1-32).

(U) Program (g) developed the Grumman Aerospace Corp. transit foil based on an innovative concept of smooth transition from the subcavitating to the supercavitating regime (Reference II.A.1-33). The foil has a very thin air-foil section of NACA 16 series with the thickness to chord of 4 percent. The strut is a base-vented profile. This program was carried out by Grumman Aero space Corp. with the intention to replace the demonstration foil on the FRESH-1 test craft. The system was designed to operate in a transcavitating or partially cavitating flow. As designed, the cavity would first form at the wing tips and migrate inward toward the pod as speed was increased. The objective of this program was then to achieve a smooth transition, as the speeds increased. However, due to the existence of hysteresis effect, it is unclear whether the smooth transition can still be achieved as the craft speeds decreased. Experiences show that if the cavity length is greater than approximately the half chord, the partial cavity flow is very unstable. This makes the operation of partially cavitating flows in waves uncertain. No mention is made of possible cavitation damage in the Grumman Aerospace Corp. report. Aside from the disadvantage of its thick leading edge, the transit foil section is much different from a conventional low-drag supercavitating profile. This will result in inefficient operation at high speed in full cavity flows. During the operation in a partial cavity flow condition, the chance to develop surface ventilation is likely to be increased due to the presence of base cavity behind the blunt-based strut. Sudden foil surface ventilation would present some difficulties for the foil control.

1.5.4 Base-Vented Struts

(U) For a strut of practical size, experiences indicate that it is extremely difficult to avoid cavitation on a subcavitating strut at speeds above 50 knots. To overcome this cavitation barrier, struts of blunt-based section have been extensively studied. The basic concept in the design of strut shape for high-speed application is that shape which initially has no negative pressure along its chord at zero side slip angle. Based on a linearized theory by Tulin the minimum drag shape which meets the above criteria is a parabola with a ventilated cavity (Reference II.A.1-34). Later, this theory was extended by Johnson and Starley (Reference II.A.1-35) to develop the modified parabolic struts.

(U) A base-vented strut is still subjected to the danger of strut side ventilation. The possibility of using super-cavitating struts for high-speed application has been proposed. Extensive model studies of base-vented parabolic struts, modified parabolic struts, and supercavitating struts were carried out at the Aerojet General Corp. ring channel (Reference II.A.1-36). The supercavitating sections hold promise of providing struts of high structural strength-to-drag ratios. However, this type of strut is inadequate to provide sufficient side forces and moments required for craft control. Thus far, struts of base-vented sections had been used extensively in the past high-speed programs.

1.5.5 Recent High-Speed Hydrofoil Program (TAP)

(U) Until 1972 there had not been a concentrated R&D effort in high-speed foil systems since the termination of the Navy's accelerated hydrofoil program some ten years earlier. In September 1972, the Naval Material Command requested the David W. Taylor Naval Ship Research and Development Center to undertake a three-year program designed to determine the feasibility of a system of high-speed (above 50 knot) struts and foils (Reference II.A.1-37). The selection of strut and foil section profiles was one of the most intricate problems in this study. After a brief period of review of past literature, foils of supercavitating sections and struts of base-vented sections were selected for this study.

1.5.6 TAP-1 Foil

(U) In the past, design efforts have concentrated on the development of low drag supercavitating sections. Although a foil with a thinner section generally produces less cavity drag and higher hydrodynamic efficiency than does a thicker section, this improved hydrodynamic efficiency is achieved at the expense of lower structural strength. In a recent paper by Wang and Shen (Reference II.A.1-38) the effect of the thickness of a subcavitating foil on its hydrodynamic efficiency was found to be small. On the contrary, a significant reduction in the hydrodynamic efficiency of a supercavitating foil was observed as the foil thickness was increased for a given lift coefficient and cavitation number. This salient feature, which emphasizes the need for a careful tradeoff study between structural requirements and the foil L/D ratio, is discussed in References II.A.l-39 and II.A.1-40.

(U) As a result of the above considerations a foil was designed for 80 knot operation and designated TAP-l (Reference II.A.l 39). An aspect ratio of 2.4 and a thickness to chord ratio of 0.086, with a taper ratio of 0.5, were selected on the basis of a conservative choice of allowable stress for the solid model. The section is a typical, cambered supercavitating section with a 30 percent annex. A base-vented, parabolic strut was chosen for use with this foil.

(U) The TAP-l strut/foil system was first tested in the Aircraft Landing Dynamic Facility at NASA to determine its high-speed performance (Reference II.A.1-41). The maximum L/D measured in full cavity flow at one chord submergence was 6.6. No vortex shedding or leading edge vibration was observed.

(U) In order to assess the structural feasibility of the TAP-l foil geometry, a conceptual design of the structure was carried out for a full scale foil to carry a load of 60 tons. Estimates were made of the limit loads to which the foil might be subjected in service (Reference II.A.1-42) and stress analysis was carried out, by conventional beam-bending techniques, which indicated that a simple shell, spar and rib structure of reasonable proportions would be adequate. A more sophisticated stress analysis, using modern finite-element methods applied to a solid structure, confirmed the conservativeness of the results of the beam-bending analysis.

(U) As a result of these studies it was concluded that, by using a solid structure of HY 130 or 17-4PH stainless steel, the aspect ratio could be doubled. The required minimum angle-of-attack of the foil to achieve full cavitation is reduced (Reference II.A.1-42a) and the L/D significantly improved.

1.5.7 Practical Problems with Supercavitating Foils

(U) The studies so far indicate that reasonable L/D can be achieved, using a supercavitating foil such as the TAP-1, if the foil is operated in the design condition. However, the capability to operate efficiently at moderate speeds (40-50 knots) may be equally important in the design of a high-speed hydrofoil craft as the actual operational capability at high speeds. Unfortunately, most supercavitating foils that enable hydrofoil ships to operate at high speeds make operation at moderate speeds very inefficient. The difficulty stems from the different requirements on the lift coefficient (C_L) at moderate and high speeds. The increase in the drag coefficient (C_D) of a supercavitating foil is generally much higher than that of the C_L and will result in poor hydrodynamic efficiency at off-design operation. The consequence is a great reduction in the available range of foilborne operation.

(U) A successful takeoff must be achieved before a hydrofoil ship can begin to operate in the foilborne condition. When a supercavitating foil is employed, the takeoff drag penalty is very severe. If the drag is too large, there may be inadequate thrust to accelerate the craft.

(U) A takeoff test of the TAP-l strut/foil system was conducted at DTNSRDC towing tank (Reference II.A.1-43). Experiments show that takeoff with this system will be difficult. The Boeing Company annex foil was designed to operate in a fully-wetted base-vented mode from takeoff to the transition speed of 60 knots. No design consideration was given on this foil to operate at speeds less than 60 knots. Consequently, a difficulty to control this foil in waves was indicated in that study. The Boeing Company demonstration foil was a fully-wetted base-vented foil fitted with a parabolic strut. Due to the problem of surface ventilation, the takeoff of FRESH-1 test craft was accomplished at 45 knots. Such a high takeoff speed may not be practical for an operational naval hydrofoil ship. It was to preclude these problems that the mixed foil or TAR-2 concept discussed in the next section was developed.

1.5.8 TAR-2 Foil System

(U) As already indicated, both fully-wetted base-vented sections and supercavitating sections are operated with cavity flows. The maximum hydrodynamic efficiency obtainable with these strut/foil systems are inherently lower than conventional subcavitating strut/foil systems at speeds less than 50 knots. The performance of subcavitating foils on *naval* hydrofoil ships equipped with streamlined foils and struts has already been demonstrated at speeds up to 50 knots. It has also been observed that takeoff speeds in the neighborhood of 30 knots are not a problem for present-day, moderate-speed hydrofoil ships. The L/D ratios of such a moderate-speed hydrofoil ship are generally 10 to 12 at takeoff and greater than 15 in the foilborne condition. To circumvent the takeoff problem as observed in the TAP-l foil and to increase the range of foilborne operating speeds, it becomes desirable for a high-speed hydrofoil ship to have the capability to cruise at moderate speeds and to takeoff in an efficient subcavitating mode.

(U) To achieve that goal, a new design concept was introduced--the mixed foil and pseudoblunt-based strut (Reference II.A.1-37 and II.A.1-38). A mixed foil is a streamlined hydrofoil equipped with a flap or other device which can be activated above a certain speed to change the flow around the foil into a supercavitating flow. At takeoff and at moderate speeds, a mixed foil is operated as a subcavitating foil; at high speeds, it is operated as a supercavitating foil. A pseudoblunt-based strut is a streamlined strut equipped with a flap or other device which can be activated above a certain speed to become a base-vented strut. Sketches of this mixed foil and pseudoblunt-based strut are given in Figures II.A.1-24 and II.A.1-25.

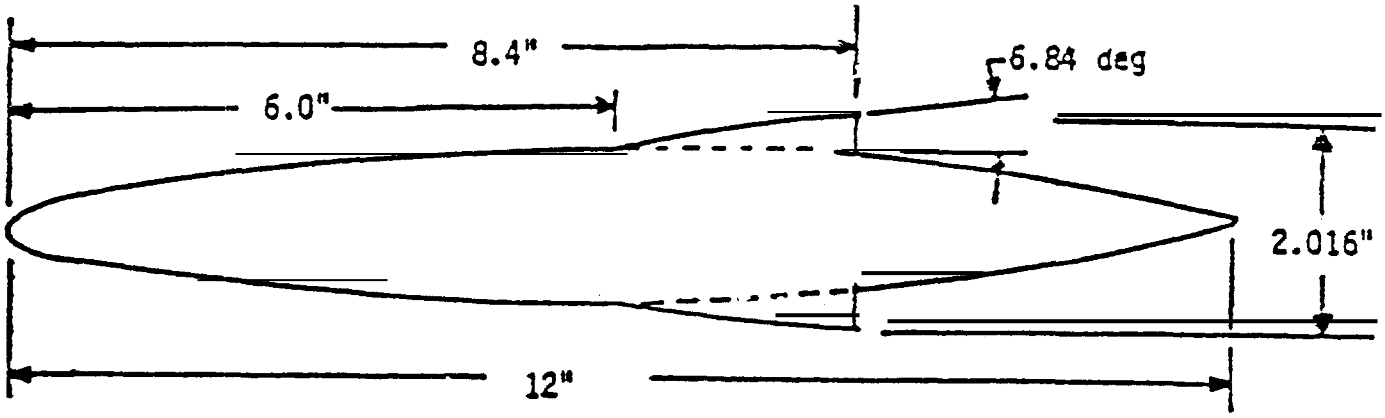

Figure II.A.1-24. PSEUDOBLUNT-BASED STRUT

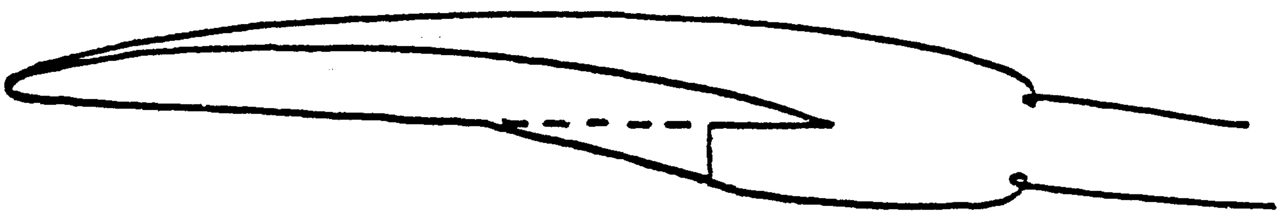

Figure II.A.1-25. MIXED FOIL

(U) Based on a series of two-dimensional tests, a hydrodynamic validation study of the concept of the mixed foil was carried out theoretically on two hydrofoils of planoconvex sections and a pseudoblunt-based strut (Reference II.A.1-38). The L/D ratio of this strut/foil system was found to be around 13 to 14 at takeoff and about 18 at moderate cruising speeds. At high-speed cruising (80 knots), the foil was operated in a supercavitating condition with an L/D ratio of 7.6.

(U) These results suggest that a reasonably good L/D ratio can be achieved at high-speed cruising and that the hydrodynamic efficiency of a mixed foil at moderate-speed cruising is similar to that of existing hydrofoil ships.

(U) This new concept and the knowledge gained from the TAP-1 foil studies were utilized in the design of the strut/foil system designated as TAP-Z. The TAP-2 foil was designed with a small leading edge radius and the strut section was the NACA 16-012 profile fitted with two types of midchord flaps.

(U) A series of simulated high-speed experiments was conducted at Lockheed Underwater Missile Facility, a controlled atmosphere towing tank (Reference II.A.1-44). The model was tested under simultaneous cavitation and Froude scale conditions. At high-speeds, the foil was designed to operate in a supercavitating condition. Results of these tests are shown in Figures II.A.1-26 and II.A.1-27. The maximum L/D ratio for the TAR-2 foil measured in full cavity if the foil is operated at the half-chord submergence, the L/D in

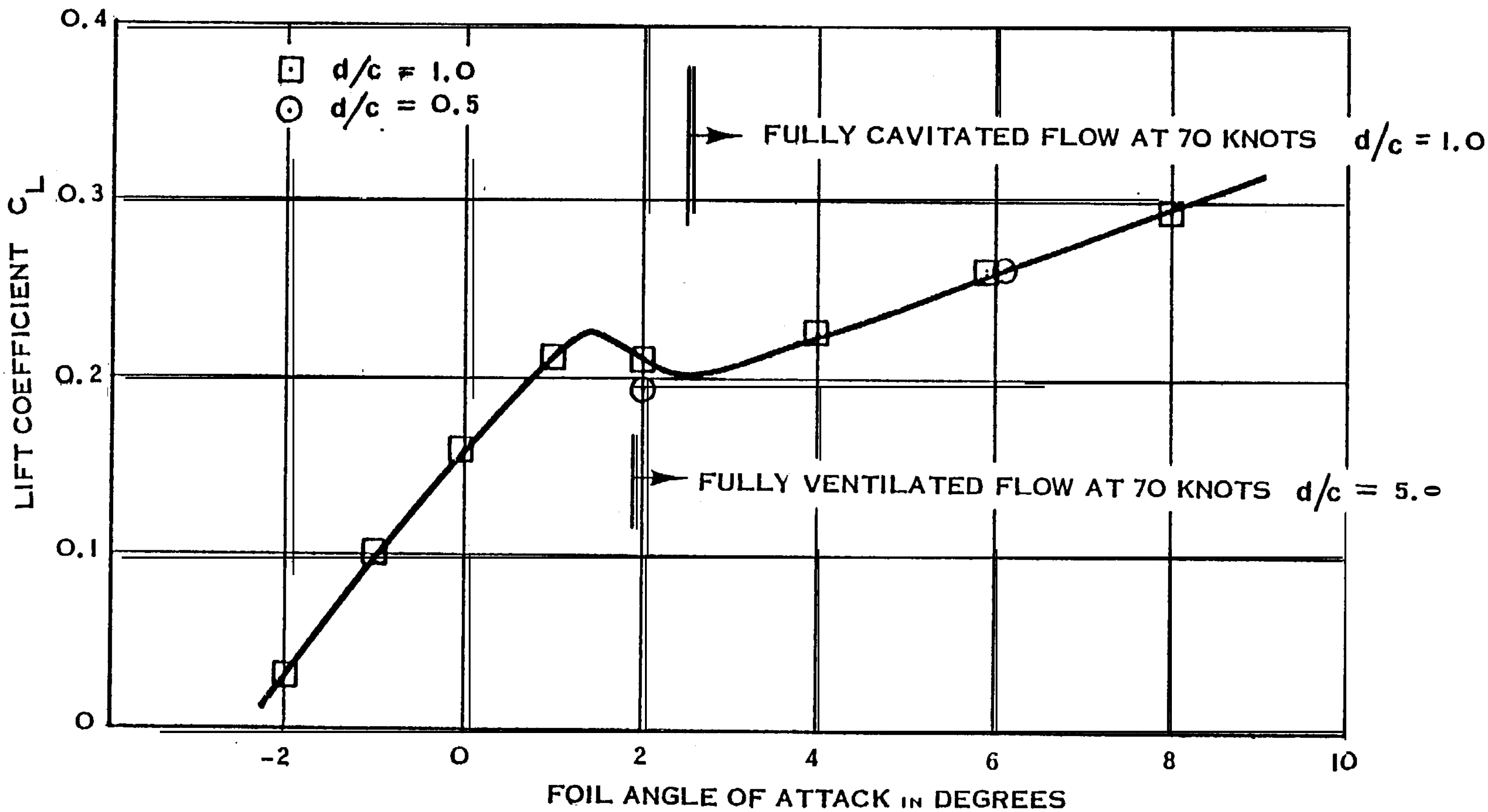

Figure II.A.1-26. MODEL SCALE RATIO =1/10

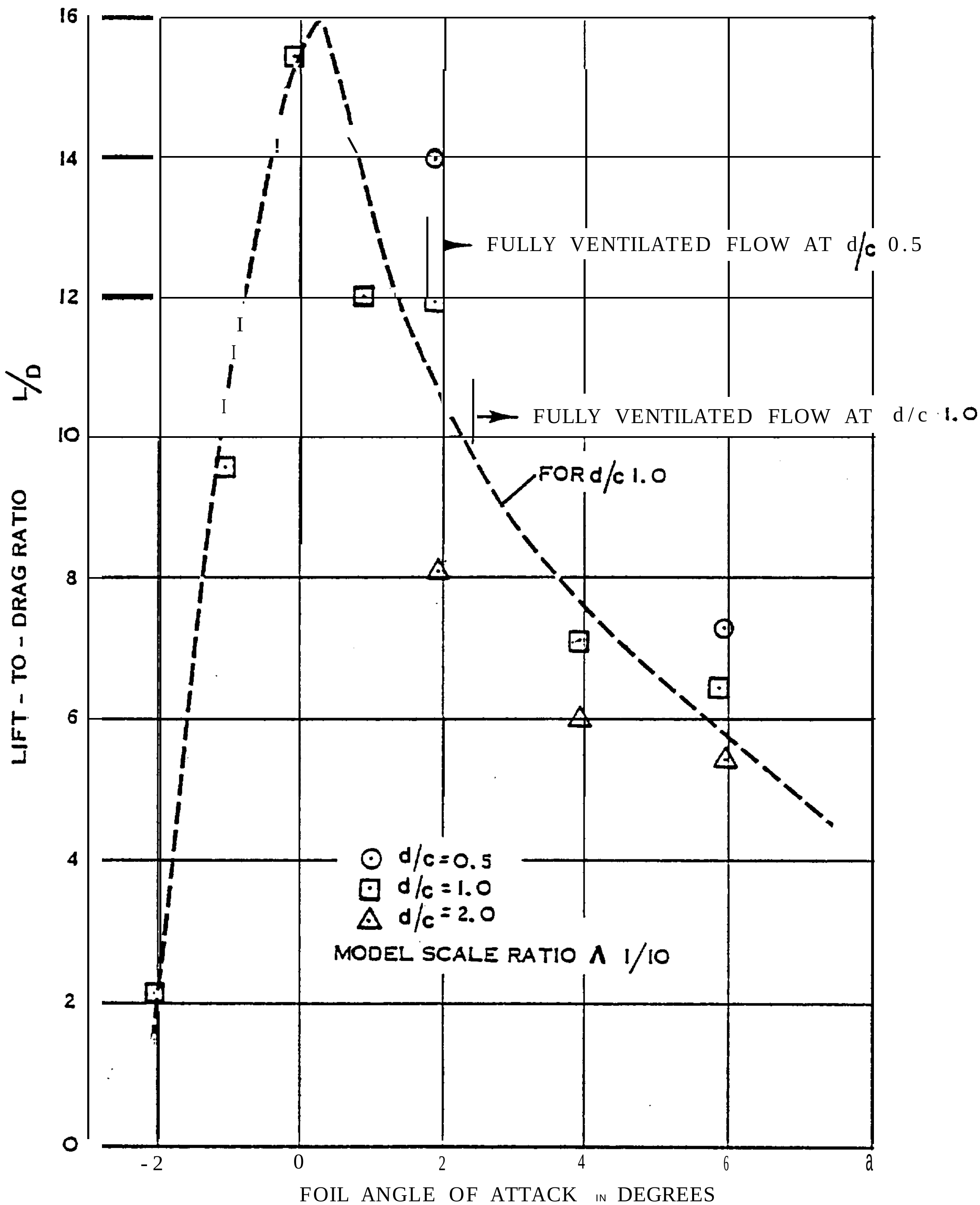

Figure II.A.1-27. TAP-2, G_V = 70 KNOTS full cavity flow is greatly improved to approximately 13 to 14. This improvement in the foil efficiency at shallow submergence is partly due to the reduction in strut drag and partly due to the reduction in cavity cavitation number on the foil. The same trend is also observed in the test results of the annex foil and the TAP-1 foil. On the other hand, if a supercavitating foil is designed to operate in deeper submergence, a degradation in L/D will result.

(U) On a conventional subcavitating hydrofoil ship, the foil is generally operated at around one-chord depth of submergence to minimize the free-surface effect. However, the free-surface effect on the lift coefficient of a supercavitating foil is relatively mild. In addition, the upper surface of a supercavitating foil is already fully ventilated. The undesirable phenomena of upper surface cavitation and ventilation on subcavitating and fully-wetted base-vented foils are not problems for supercavitating foils. It is thus of great importance to explore the possibility of operating a supercavitating foil at shallow submergence so that the high L/D can be achieved. Of course, the possible effects of orbital velocity due to waves and the loss of directional stability due to the reduction in the strut wetted area must be carefully examined.

(U) A series of takeoff studies on TAR-2 was carried out at DTNSRDC (Reference II.A.1-45). At the takeoff speed of 35 knots and foil submergences of d/c = 2.0 and 3.0, the maximum measured

L/D of the strut/foil system was 14.25, as shown in Figure II.A.1-28. This value is the same as that obtained in the mixed-foil validation study. Consequently, successful takeoff with the TAR-2 strut/foil system can be anticipated.

1.5.9 Summarv

(U) If the propulsive efficiency and the aerodynamic drag of a vehicle are known, the payload and foilborne range of a hydrofoil ship can be determined from the L/D ratio of the strut/foil system. Theoretical studies on mixed foils and experimental investigations on TAR-2 suggest that a high-speed hydrofoil ship equipped with mixed foils and pseudoblunt-based struts can be designed to operate efficiently at moderate speeds and have a moderately efficient high-speed dash capability.

1.6 HYDRODYNAMIC LOADS

(U) The loads applied to the structure of a hydrofoil ship are predominantly of hydrodynamic origin. They are applied to the foils and struts, and transmitted through the struts to the hull, during normal foilborne operation.

1.6.1 Foil Loads

(U) Maximum hydrodynamic lift may occur in calm water or in waves and results from combinations of ship speed, angle of attack and flap deflection. Normal ACS responses in sea states, possibly coupled with maneuver inputs, could lead to maximum lifts; on the other hand sharp maneuvers in calm water might exceed hydrodynamic

Figure II.A.1-28 LIFT-TO-DRAG AS A FUNCTION OF FOIL INCIDENCE ANGLE FOR SPEED OF 35 KNOTS AT d/c = 3.0

limits, or a system malfunction could lead to full flap deflections and maximum lift on a semi-span. Maximum foil loads have occurred in calm water on both the HIGH POINT and the TUCUMCARI. It has been observed in sea trials, however, that upon forward foil reentry after a broach, ventilation of the foil prevents the development of the expected lift. The flaps are therefore driven to maximum deflection. On closure of the ventilated cavity, then, the foil is subjected to the maximum lift it is capable of developing. Whether maximum attainable lift can be reached on the after foil(s) is a matter of conjecture at this point but, for purposes of design, it must be assumed that this *can* occur after a tip broach.

(U) The maximum attainable lift on a foil panel, as observed in model tests, is limited by vapor cavitation. For foils with incidence control this amounts to about 2500 PSF at 50 knots, as shown in Figure II.A.1-13. With control flaps *a* maximum loading of about 3200 PSF at 50 knots is indicated in Figure II.A.1-17, assuming that the flap deflection does not exceed 20 degrees. If the design loading is 1250 PSF, the maximum attainable load represents a 2 factor load for the incidence controlled foil and about 2 1/2 factors with control flaps.

(U) It is to be noted that these loads have been measured under steady flow conditions, whereas the anticipated circumstances for maximum loading at sea are distinctly dynamic and unsteady. Strain measurements on HIGH POINT (PCH-1) have, nevertheless, confirmed the appropriateness of these load levels. Monitoring of full scale foil loads is continuing.

(U) While the foil drag is not a significant burden on the foil structure, it does constitute an important part of the strut bending and torsion loading. This is especially important for a steerable forward strut/foil assembly. Critical circumstances arise when foil lift is lost due to cavitation or ventilation and increased incidence or flap deflection is imposed by the control system. It is clear from Figure II.A.1-29 that the drag increases almost linearly with the increase of either incidence or flap deflection. If one semi-span of an inverted T-foil is vented, the development of maximum attainable lift on the unvented side produces the limit transverse bending load at the strut/foil juncture and the associated asymmetric drag causes a simultaneous limit torsional load at the juncture and perhaps at the upper end of the strut as well.

(U) Foil structural fatigue lift may be an overriding factor in the design. Fatigue loading tends to be severe with many cycles of loading approaching limit load and with possibility of load reversals due to hull wave impacts. Foil fatigue life is further hampered by reduction in material fatigue properties when immersed in sea water. A design to accommodate fatigue life must be based on realistic evaluation of the foil loading environment considering, distribution of sea states, headings, automatic control system characteristics and foil system geometry. Reversal of foil loads due to hull upward acceleration during wave impacts has been observed during trials of HIGH POINT and Boeing commercial hydrofoils. The combined effects of foil loading, material fatigue characteristics,

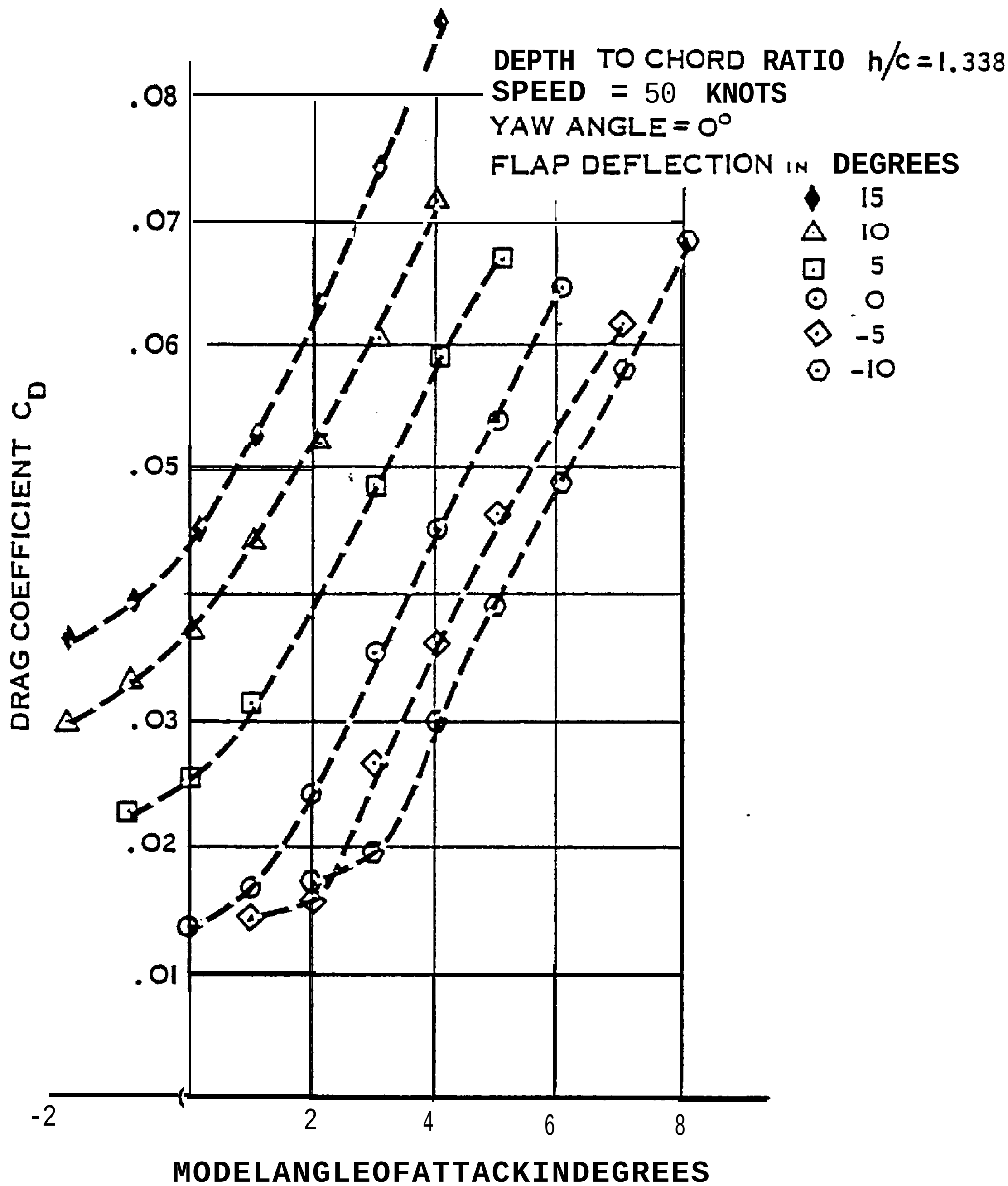

Figure II.A.1-29. DRAG DATA

complex structural configurations and welded structure make constructi- and testing of a full scale model in sea water advisable.

1.6.2 Strut Side Loads

(U) A criterion for strut side loading, used in the design of PCH-1 and PGH-2, was based on an assumed flat turn maneuver with a centripetal acceleration of 1/2 g. With the present trend to the use of banked turns, the deliberate, intentional turn maneuver imposes only minor loads on the struts. However, when a helm reversal must be made during a turn, to avoid debris for example, much larger strut side loads are developed during the resulting transient maneuver. Large strut side loads have also been observed in heavy, beam seas expecially when breaking waves are encountered.

(U) The largest side loads on the forward struts of TUCUMCARI (PGH-2) and HIGH POINT (PCH-1) have occurred when log impacts caused fracture of the steering actuators, permitting the steerable struts to turn until they hit hard stops. The resulting loads were at least comparable to the maximum steady load which can be developed on a strut. A knowledge of these loads is therefore pertinent.

(U) The maximum side load which can be developed on a strut is limited by the advent of cavitation and ventilation, as is illustrated in Figure II.A.1-19 and discussed in Section 1.3.2. The maximum, ventilation limited side loading is shown in Figure II.A.1-30 as a function of speed for three aspect ratios. These data, derived from model tests of bare struts for the most part,

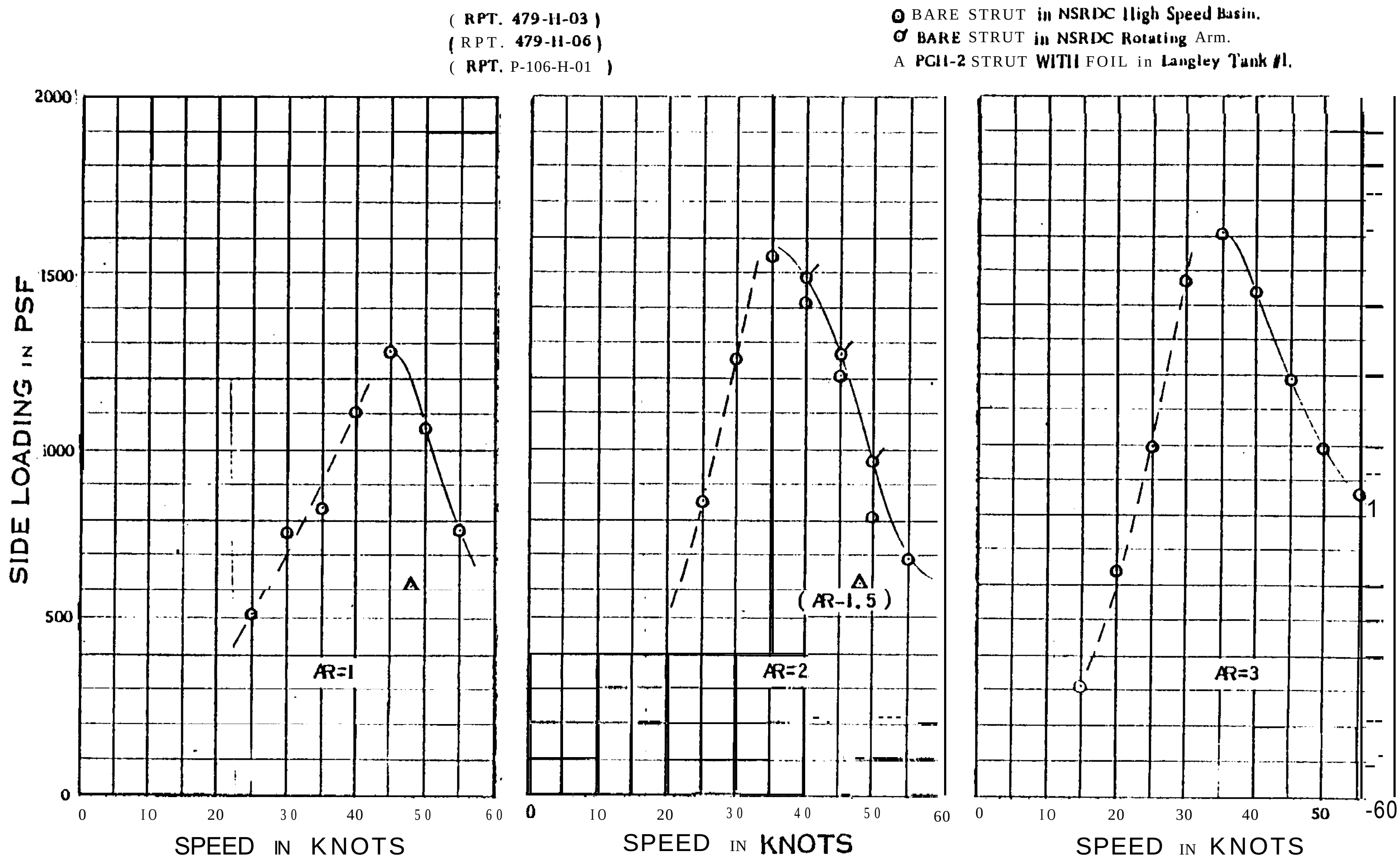

Figure II.A.1-30. VENTILATION LIMITED SIDE FORCE

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show some increase of the average loading with increased tip submergence but suggest a practical limit of about 1,600 pounds per square foot. Two tests of the PGH-2 strut foil assembly produced maximum, preventilation side loads of only 600 pounds per square foot at about 48 knots. Apparently superposition of strut and foil pressure fields leads to earlier cavitation and ventilation even though the angle of attack is zero and the lift small. Strut fatigue loading can be as significant as foil fatigue loading and consideration should be given to fatigue testing of the entire foil-strut system.

1.6.3 Hull Loads

(U) Design loads on the shell, decks and superstructure and on the hull gider are either directly or indirectly of hydrodynamic origin. The hull girder loads, both bending and torsion, include forces originating on the struts and foils which have been discussed previously and inertial loads, which must be derived from analysis of vehicle rigid body dynamics, as well as integrated loads on the hull envelope. Only the last will be considered here.

(U) When operating hullborne at low speeds the hull loads are primarily a result of buoyant forces in waves which are calculated on a quasisteady basis by procedures usually applied to surface ships and described in Section 4, Chapter IX of Reference II.A.1-46. With increasing speed, hullborne, bow flare slamming is encountered which can be treated by digital computer programs available inhouse at DTNSRDC. The influence of control system activity on the motion of the ship must be included.

(U) Maximum loads on the bottom result during foilborne operation from impact with wave crests, from rapid landing or dropping due to control system malfunction, or from a combination of these. Maximum topside loads occur, especially forward, following a foil broach and resultant bow slam. Critical deck and superstructure loads probably occur when hullborne in storm seas when a breaking wave may come right aboard.

1.6.3.1 Bottom Loads

(U) Limit loads on the bottom structure depend on the relative velocity between the bottom and the surface water and on the angle between planes tangent to the bottom and to the wave surface. In order to calculate impact pressure loads it is, therefore, necessary to estimate the kinematics of the ship in a potential impact situation including the dropping velocity, the angular velocities in roll and pitch and the attitude (roll and pitch) at the beginning of the impact. It is also necessary to postulate the wave length, height, and direction and the position of the wave at impact. Computer simulation of foilborne ship motions is used at DTNSRDC and at The Boeing Company to estimate the ship motion in deliberate ditching maneuvers and also followng control system malfunctions.

(U) Model tests were employed to explore the possible motions of PLAINVIEW (Reference II.A.1-47) in crash landings and following control malfunctions. These tests disclosed a fault in the control system logic which was fortunately corrected before the AGEH experienced a severe slam following a control rod failure, during which a bottom pressure of 80 psi was measured.

(U) Such studies, whether analytical or experimental, serve to establish an envelope of extreme ship motions which are unlikely to be exceeded. The position of the ship relative to the wave at impact is also important and a range of phase relations must be explored to find the critical loading for different parts of the ship's bottom.

(U) A number of procedures have been devised, by various investigators, to calculate the pressure on the bottom during hull/water impact. Several of these have been computerized and combined with aforementioned ship dynamics simulation programs. Thus means are available for a comprehensive analysis of ship bottom loading.

(U) Most of the pressure calculation methods intended for hydrofoil applications anticipate a hard chine, V-bottom hull form and are derived from pioneering work by Theodore Von Karman (Reference II.A.1-48) and Herbert Wagner (Reference II.A.1-49) aimed at the seaplane landing problem. The general similarity of seaplane hulls, planing craft, and most hydrofoil hulls accounts for a large dependence on the extensive work done in the aeronautical field.* What is peculiar to hydrofoils is the serious possibility of substantial roll at the moment of impact. It should be realized, also

*An extensive bibliography on hydrodynamic impact may be found in Reference II.A.1-50.

that the large hydrofoil may be required to operate extensively at moderately high hullborne speeds. Such a requirement could lead to the adoption of a round bilge hull form, in the interest of reduced drag and slamming loads. Recourse may then have to be taken to the extensive work on ship slamming loads summarized by K. Ochi and Motter in Reference II.A.1-51.

(U) Hydrodynamic theory by itself is inadequate for calculation of the pressure over the whole bottom of a hydrofoil in impact with the sea. Available theories have been combined and modified with the aid of empirical data to develop procedures for estimating bottom pressures. One such procedure, developed by Smiley and described in Reference II.A.l-52, has been further modified and applied by Jones and Allen (Reference II.A.1-53) and at The Boeing Company (Reference II.A.1-54)..

(U) A serious shortcoming of classical hydrodynamic theory is the prediction of infinite pressure when the hull and water surfaces meet in a mutually tangent aspect. An important factor tending to mitigate the peak pressure, and ignored by the classical theory, is the cushioning effect of the air which must be forced out from between the hull and the water before actual bottom/water contact can occur. Experiments by Chuang (Reference II.A.-55) disclosed that the effect of air cushioning, of bottom elasticity and of body deceleration combined to limit the peak pressure for small impact angles to finite values. A comparison of the model test results with predictions from formulas derived by Chuang is shown in Figure II.A.1-31, taken from Reference II.A.l-55. Chuang's formulas have also been applied to estimate the impact pressure on the 'tween-hull cross structure of the catamaran oceanographic research ship USNS HAYES. A comparison with pressures measured during full-scale sea trials, shown in Figure II.A.1-32 taken from Reference II.A.1-56, indicates that peak pressures are reliably predicted.

(U) The pressure distribution on the hull bottom at any instant during an impact will, characteristically, show a maximum over a very limited region with high pressures extending along a line leading diagonally from keel to chine. The pressure decreases fairly rapidly with increasing distance away from such a peak or ridge. As a result, the average pressure within constant pressure contours decreases as the area within the contour is increased and the pressure at the boundary is decreased. This aspect of the bottom pressure distribution is emphasized by Jones and Allen (Reference II.A.l-53) in a study presenting a computerized procedure for bottom loads calculation. From the structural point of view this means that no structural panel of appreciable size will have the peak pressure applied over its whole area. By application of Jones and Allen's procedure a suitable average load can be calculated as well as a typical pressure distribution for panel design.

(U) A comparison of loads, estimated by Jones and Allen's method, with measurements made during rough water trials

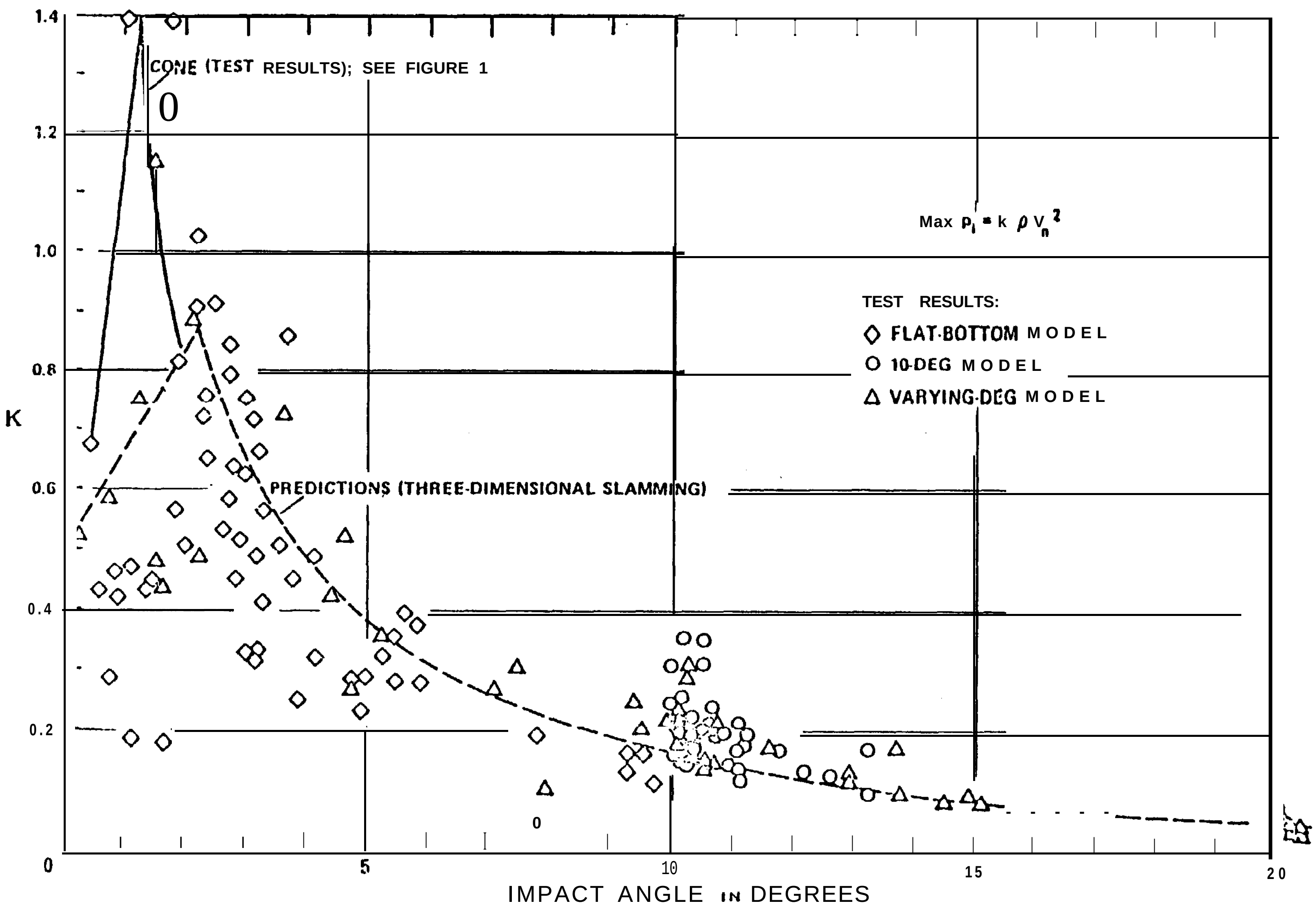

Figure II A.1-31 COMPARISON OF PREDICTED AND EXPERIMENTAL RESULTS FOR VARIOUS MODELS IN WAVES

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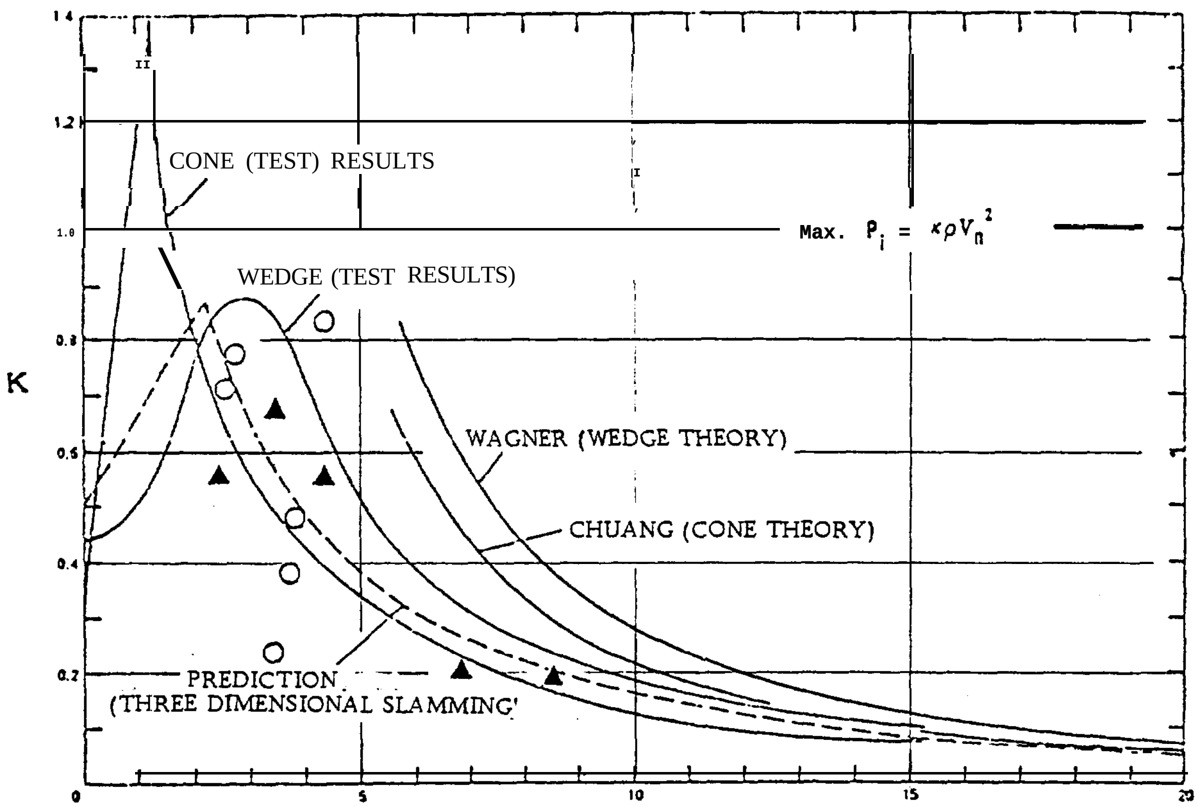

Figure II.A-1-32. PREDICTED AND MEASURED PEAK PRESSURE COEFFICIENT VERSUS IMPACT ANGLE FOR HAYES AS BUILT of the OSPREY class PTF is shown in Figure II.A.l-33 from Reference II.A.1-57. The "reference area" is a rectangle on the bottom near the bow with six pressure gauges installed in a 2x3 array. Signals from these gauges were summed in six combinations of 1, 2, 3, 4 and 6 gauges to obtain an average pressure over increasingly larger areas.* A similar comparison for the CPIC is shown in Figure II.A.1-34 (Reference II.A.1-58) with the total bottom area between chines as the reference area. Both comparisons indicated a conservative prediction of plate and panel pressures and a realistic prediction of the attenuation of average pressure with increasing area. Variations of attitude and wave phase and direction must be explored to determine a limit loading for each part of the bottom. Procedures to accomplish this have been computerized at The Boeing Company and have been applied to derive design loads for the hull of the PHM, as described in Reference II.A.1-54.

*Since the active area of a single gauge is very small compared with the reference area, maximum single gauge pressure is plotted at zero area. The maximum average pressure from the sum of n gauges is plotted at an area ratio of n-l.

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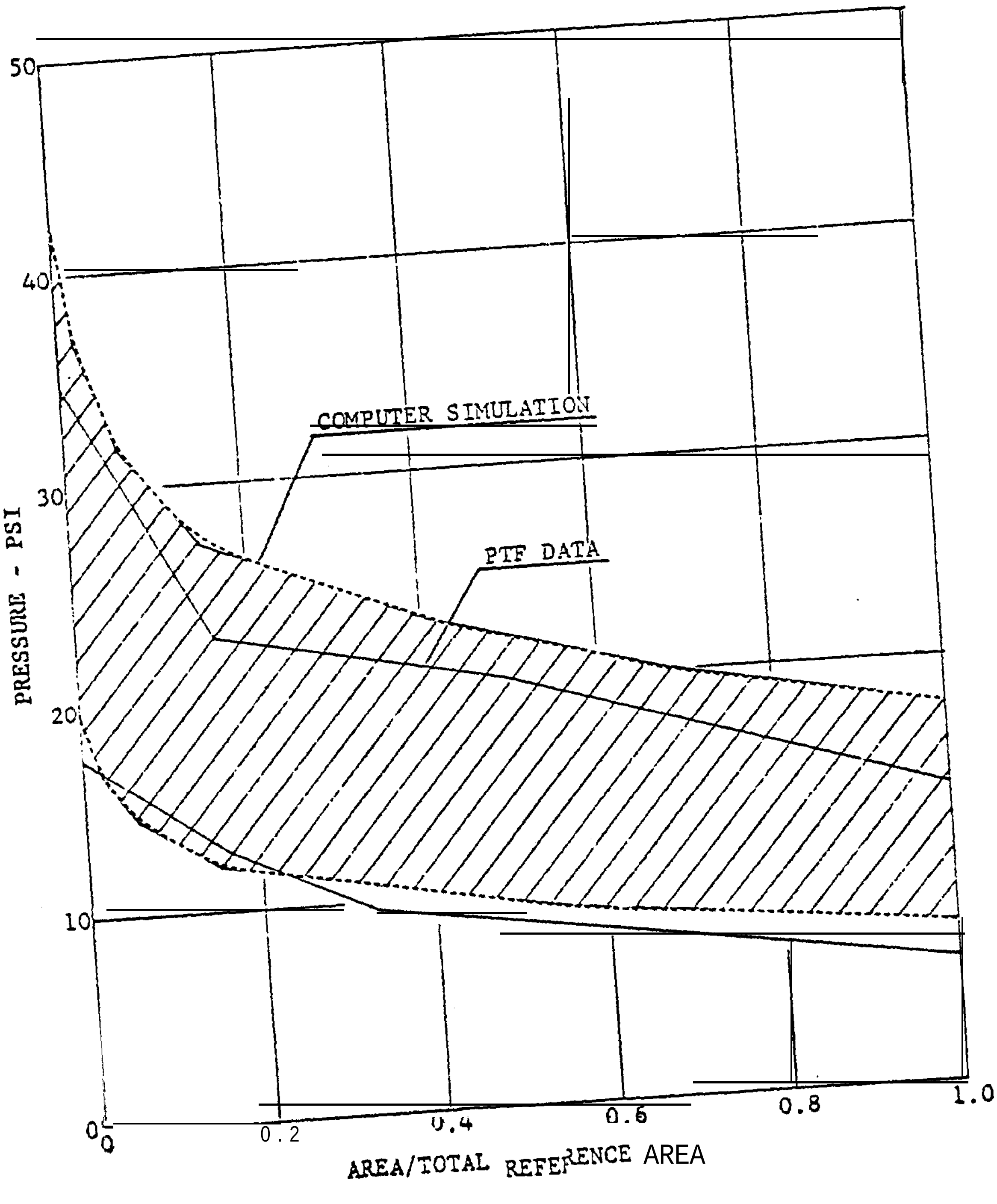

Figure II.A.1-33. COMPARISON OF PRESSURE VERSUS REFERENCE AREA RATIO FOR PTF HEAD SEA TRIALS RUN WITH 1.0 DEGREE ROLL ANGLE

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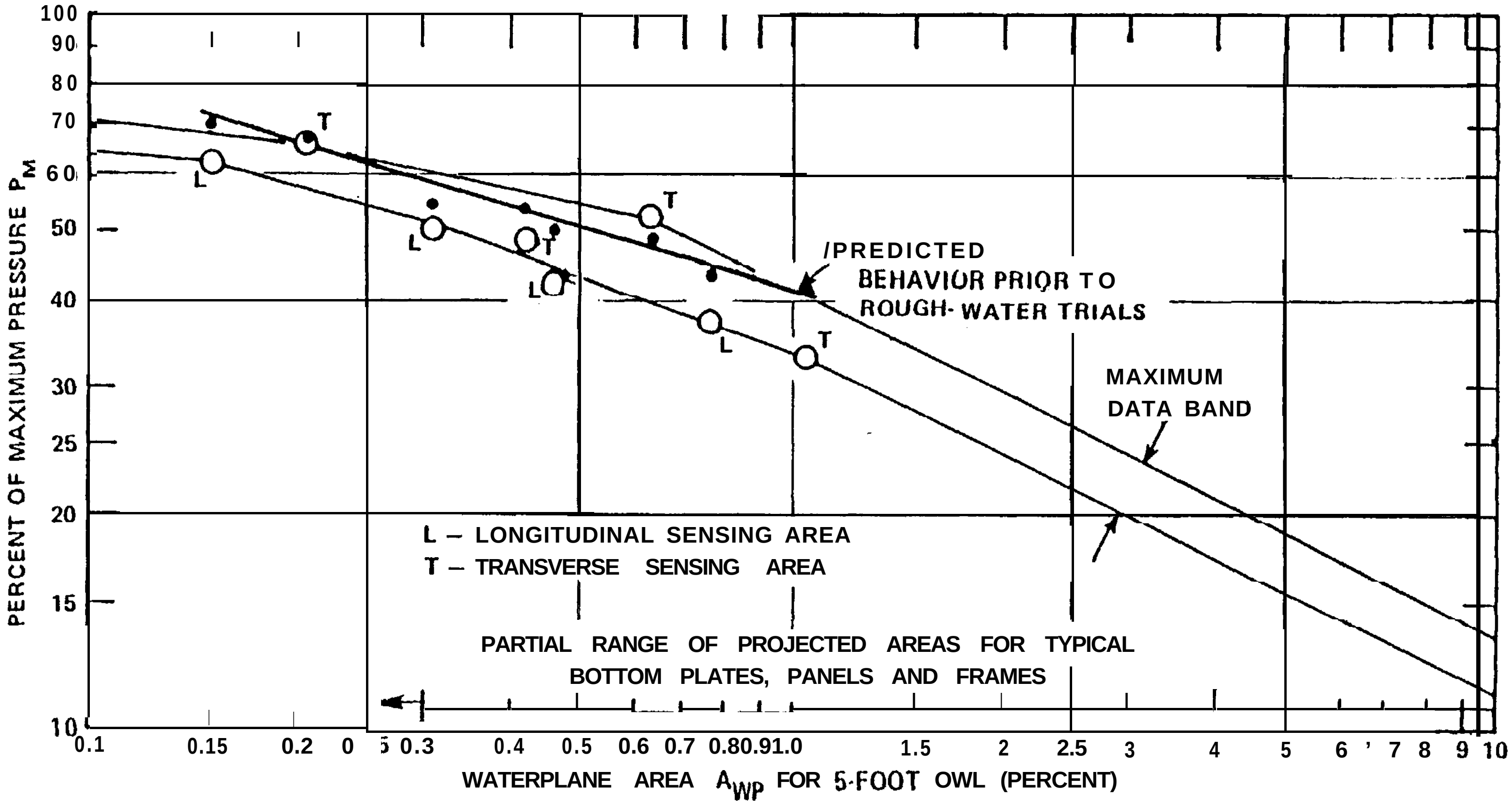

Figure II.A.1-34. COMPARISON OF PREDICTED VERSUS RECORDED PRESSURE REDUCTION BEHAVIOR FOR CPIC (U)

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II. STATUS OF VEHICLE TECHNOLOGY

A. TECHNOLOGICAL PERFORMANCE FEATURES

2. DIRECTIONAL STABILITY/MANEUVERABILITY/CONTROL

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II.A. TECHNOLOGICAL PERFORMANCE FEATURES (U)

2. HYDROFOIL DIRECTIONAL STABILITY/MANEUVERABILITY/CONTROL (U)

2.1 INTRODUCTION

(U) Any state-of-the-art review of hydrofoil stability, maneuverability, and control must in fact be a state-of-the-art review of the controlled ship behavior, since the control system is inseparable from the ship. In the following paragraphs, the state-of-the-art is reviewed first in terms of demonstrated capabilities and characteristics of existing or past hydrofoil ships. This forms a solid base of demonstrated capabilities as well as some basic trends which indicate the type of technology advances achieved. A second section then assesses the analytical methods and tools used in design. Comparisons of analytical predictions with actual ship trials data demonstrate the high degree of accuracy attained with the analytical tools. Lastly, the study assesses the state-of-the-design technology as applied to the ship configuration and the control system.

(U) It can reasonably be concluded from the data which follow that the controlled hydrofoil ship maneuverability, controllability, stability, and rough water responses are impressive in that seaway motions and accelerations are low. Maneuverability is essentially unrestricted, and control is solid and positive even under extreme environmental conditions. The analytical design tools (basically the ship motion simulations) can and do accurately model ship responses to the various disturbances.

(U) Finally, the design technology is sufficiently advanced that new or proposed ships can be thoroughly analyzed for both the extrinsic ship operational characteristics and capabilities and for the intrinsic characteristics such as stability, control authority, strut/foil configuration effects, and detail control system feedback characteristics.

(U) Before proceeding further, the reader's attention is directed toward two technical papers (References II.A.2-1 and II.A.2-2) which, when combined, form a significant baseline for the understanding of ship configuration and ship foilborne control.

2.1.1 Definitions

(U) Hydrofoil controls technology is a marriage of ship technology and aircraft/missile technology, and as such, frequent misunderstandings occur due to differences in meaning. The following set of definitions are established. (See Figures II.A.2-1 and II.A.2-2 for pictorial representation.)

Canard Configuration. Hydrofoil configuration where the major portion of the ship weight is borne on large after foils, and a smaller single foil is placed forward.

Conventional Configuration. Hydrofoil configuration where the major portion of the ship weight is borne by large foils forward, and a smaller single foil is placed aft.

Tandem Configuration. Hydrofoil configuration where the load is borne approximately equally between the forward and after foils.

Center Foil. The single foil located amidships; for the canard it is the forward foil, and for the conventional system it is the after foil.

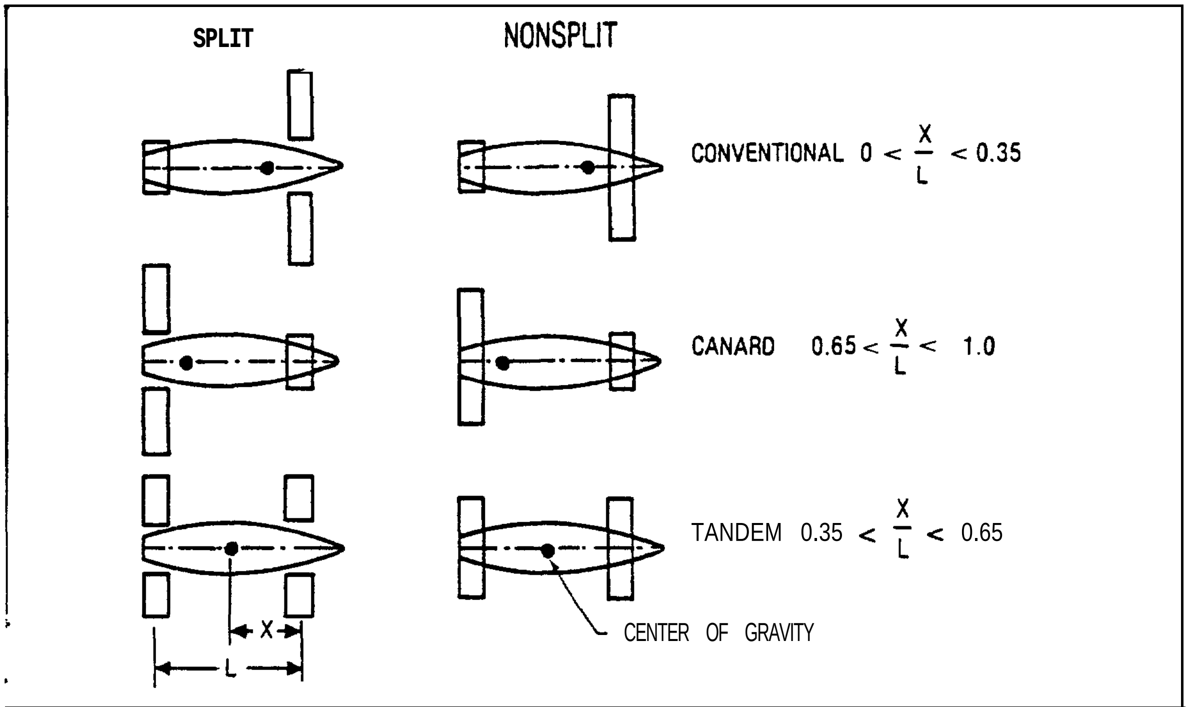

Figure II.A.2-1. DEFINITIONS - CRAFT FOIL SYSTEMS CONFIGURATIONS

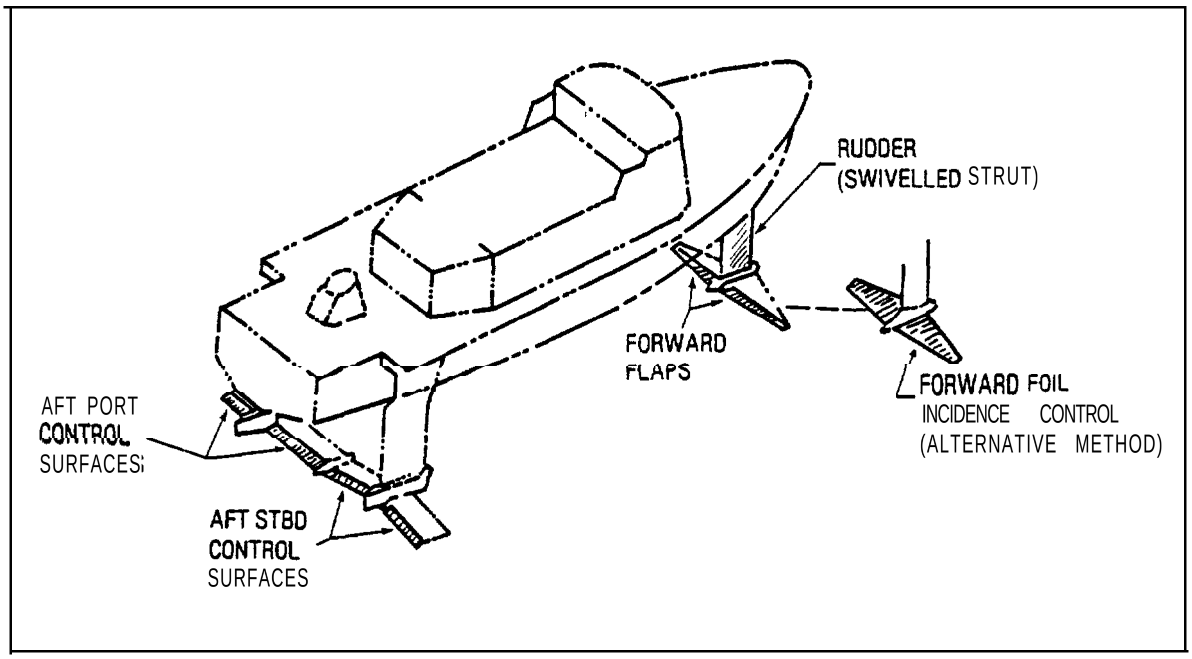

Figure II.A.2-2. CONTROL SURFACE DEFINITIONS AND TYPICAL CONFIGURATION (FOR CANARD)

Outboard Foil. The portion of the main foil outboard of the ships centerline.

Flaps. Trailing edge flaps on the foils used for lift control (not trim).

2.1.2 Data

(U) The data developed in the following sections address first the overall behavioral characteristics and capabilities of the foilborne hydrofoil ship and, secondly, the technology capabilities as related to ship/control system design. In each of these areas, we will be working with three levels of data as follows:

- Measured data from underway ship operations.
- Detailed comparison of measured ship performance and behavior with predictions developed by analytical tools such as dynamic ship simulations.
- Analytical data.

(U) Measured data for underway trials are the "hardest" data available to any evaluation; however, in many instances, significant design parameters cannot be, or are not, measured routinely during ship underway trials. Furthermore, measured data from underway trials are very limited in that data can be obtained only for specific ship configurations and for specific conditions under which the ship(s) was operated.

(U) In order to evaluate "what would be if?," it is necessary to rely on predictions generated by analytical tools, which is the third level of data listed above. Confidence in analytical predictions is developed by comparing measured ship responses with analytical predictions. (The second level of data listed above) The credibility of the analytical data is enhanced by correlation data which verify the analytical methods.

(U) The measured data presented herein come primarily from the published hydrofoil ship evaluations, References II.A.2-3, II.A.2-4, II.A.2-5, II.A.2-8, II.A.2-9, II.A.2-10, II.A.2-11, and II.A.2-12. The theoretical data shown were for the most part generated on six-degree of freedom hydrofoil simulations for the various ships discussed. Reference II.A.2-6 contains the detailed equations embodied in the PHM simulation; while Reference II.A.2-7 is an extensive evaluation of the PHM foilborne motions, maneuverability, and rough water behavior of the PHM conducted on the PHM simulation. These two documents (References II.A.2-6 and II.A.2-7) represent the latest, most thorough, and most extensive expositions on the simulation and analytical studies conducted on simulations.

2.2 HYDROFOIL SHIP CAPABILITIES AND CHARACTERISTICS

(U) The control and stability characteristics of the hydrofoil craft are manifested outwardly by: (1) maneuverability characteristics, (2) rough water motions and accelerations, and (3) foilborne operating envelope.

(U) Data gathered from underway trials of several military hydrofoil ships are presented in the following discussion. From these data, both the current capabilities and the degree of improvement obtained over successive ships are made visible.

2.2.1 Maneuverability

(U) The smooth water turning capabilities of a ship are defined by three characteristics:

- Turn rate
- Turn diameter
- Advance and transfer distances

(U) Figure II.A.2-3 shows turn rate data versus rudder angle for HIGH POINT Mod 1. The significance of this curve is the maximum turn rate capability demonstrated, not the slope, since rudder effectiveness and location of the rudder would change the slope.

(U) Figure II.A.2-4 summarizes the demonstrated turn rate capabilities of the five hydrofoil ships in smooth water and in their respective design seas. The data shown for PCH-1 Mod 1 and PHM (PEGASUS) are perhaps most representative of the state-of-the-art, although the rough water turning capabilities of both will probably be very close to their smooth water turning capabilities. The problem at this time is that sufficient rough water turning tests have not been conducted to determine ultimate rough water turning capability.

(U) Turn diameters are also shown on Figure II.A.2-3. Basically, the turn rate capability of the hydrofoil ships remains almost constant over the operating speed regime and, therefore, the lesser turn diameters at the lower speeds are simply the results of the lower forward velocity of the ship.

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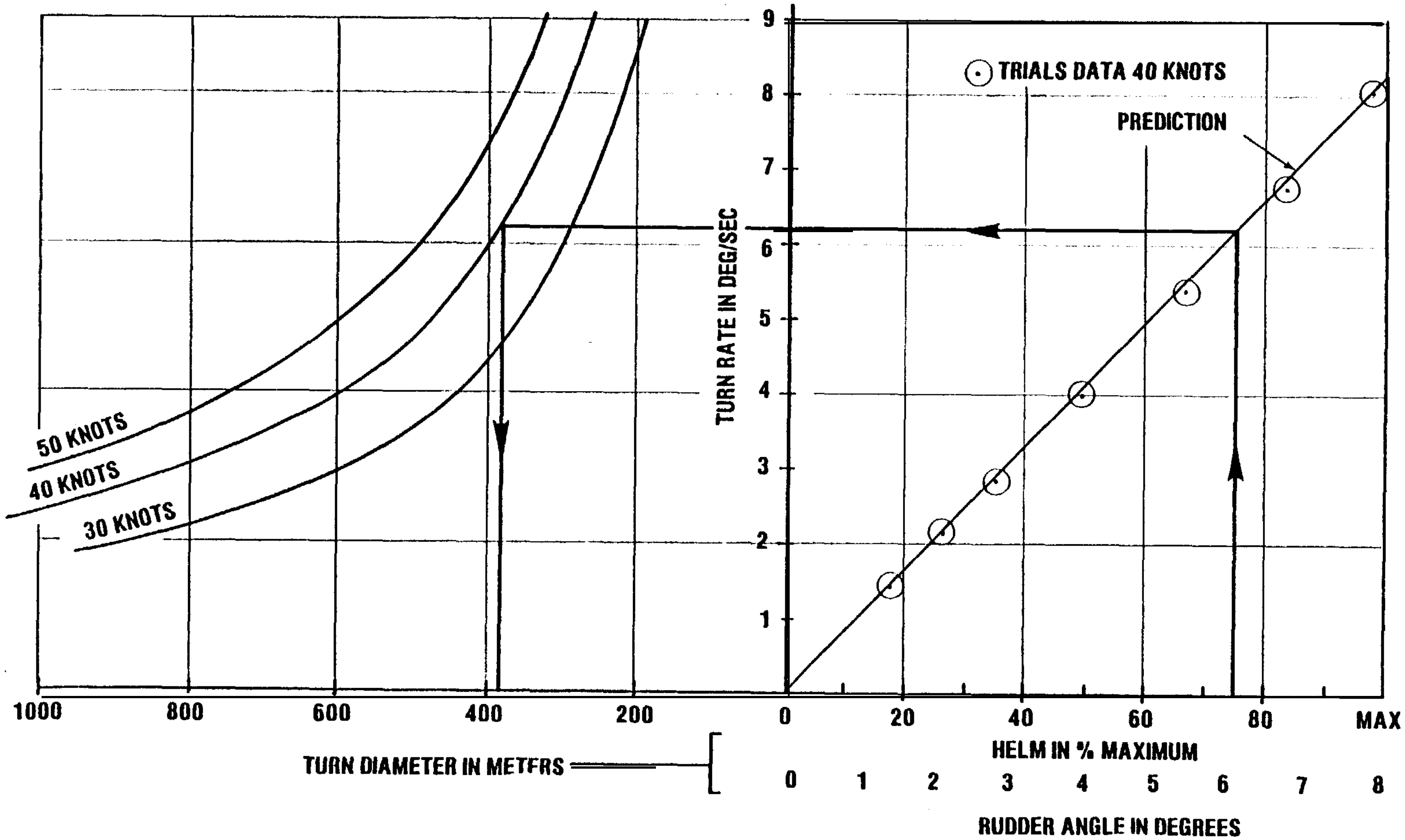

Figure II.A.2-3. PCH-1 MOD 1 TURNING PERFORMANCE TRIALS 4-4-75

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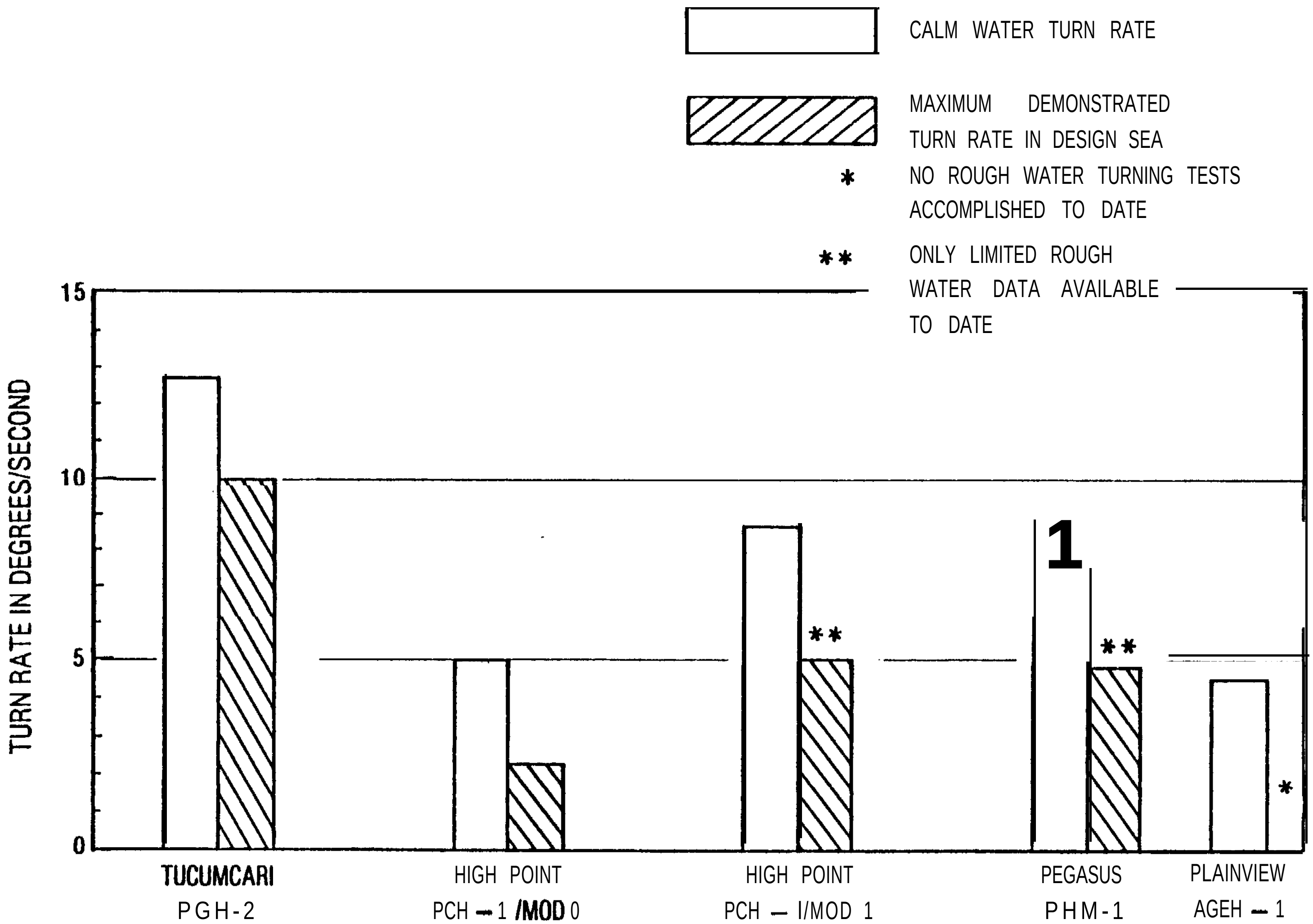


Figure II.A.2-4. SUMMARY OF DEMONSTRATED TURNING CAPABILITIES (U)

(U) Transfer and advance distances as well as actual measured ground track for maximum turn rate maneuvers to left and right are shown in Figure II.A.2-5. This curve illustrates that the ship (PEGASUS) quickly and positively takes up the commanded turn rates, which results in the advance and transfer distances being considerably less than the final diameter.

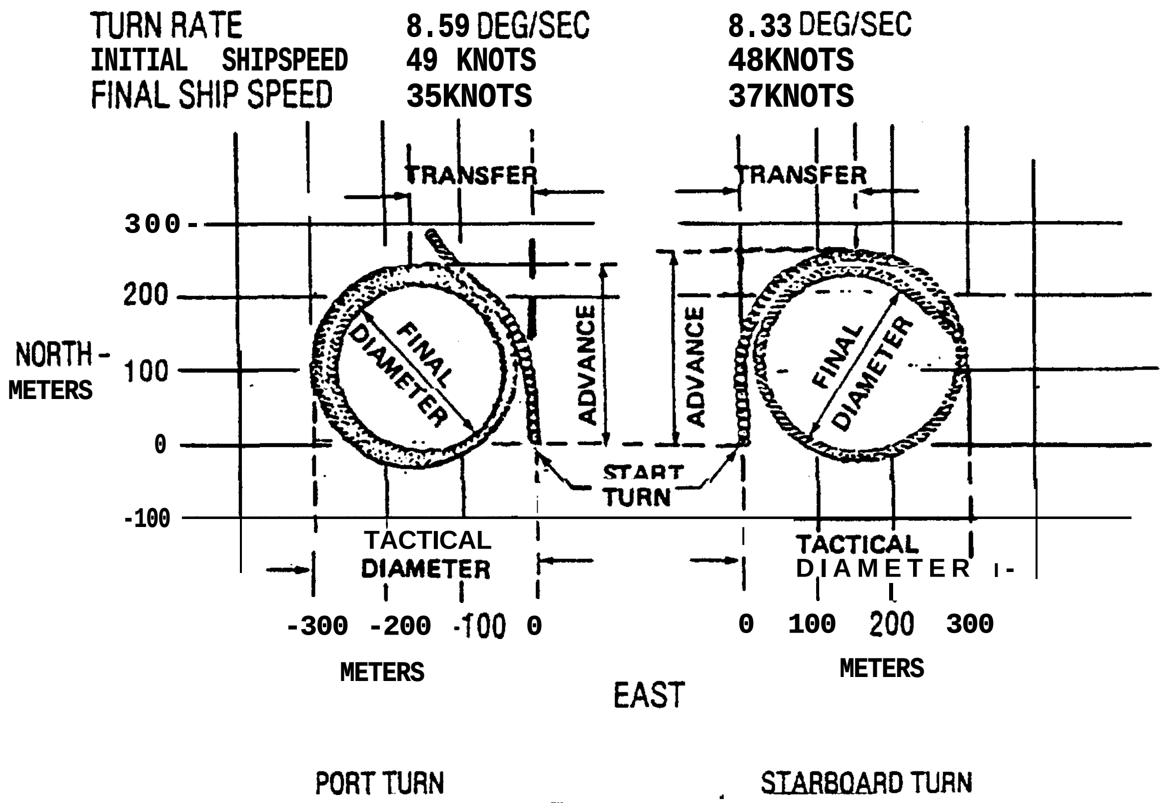
2.2.2 Rough Water Characteristics

(U) The dominant characterization parameters of the ship in rough water are:

- RMS accelerations, which relate to ride quality as it affects both man and machine.
- RMS motions which relate to the weapons and tracking systems and machinery.
- The ability to turn and maintain given headings in the presence of seas and wind.
- The ability to maintain speed and remain foilborne in a seaway.

(U) Figure II.A.2-6 shows measured RMS vertical and lateral accelerations versus significant wave height for HIGH POINT Mod 0 (PCH-1), TUCUMCARI (PGH-2), and PEGASUS (PHM-1) for worst case headings - head sea for vertical accelerations and bow sea heading for lateral accelerations. Figure II.A.2-7 shows the same TUCUMCARI and PHM vertical acceleration data plotted against current International Organization for Standards (ISO) human tolerance boundaries. Figure II.A.2-8 lists measured lateral accelerations against similar ISO human tolerance boundaries. As can be seen, the measured accelerations all fall to the left of established fatigue decreased proficiency

TURN RATE REQUIREMENT ≥ 8.0 DEGREES/SECOND



VOYAGE 75·PHM I – 59

TEST 645

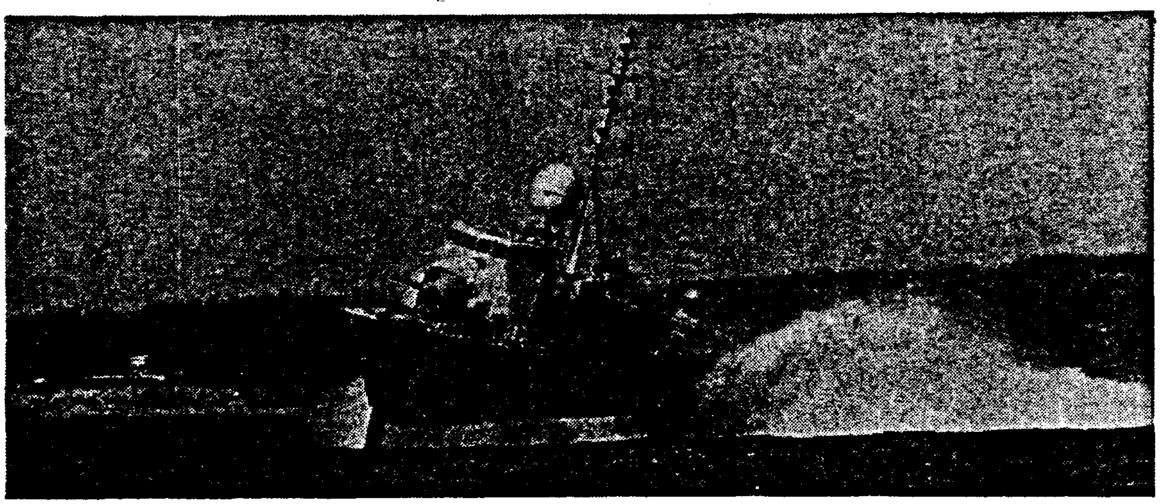


Figure II.A.2-5. FOILBORNE TACTICAL CAPABILITY (U)

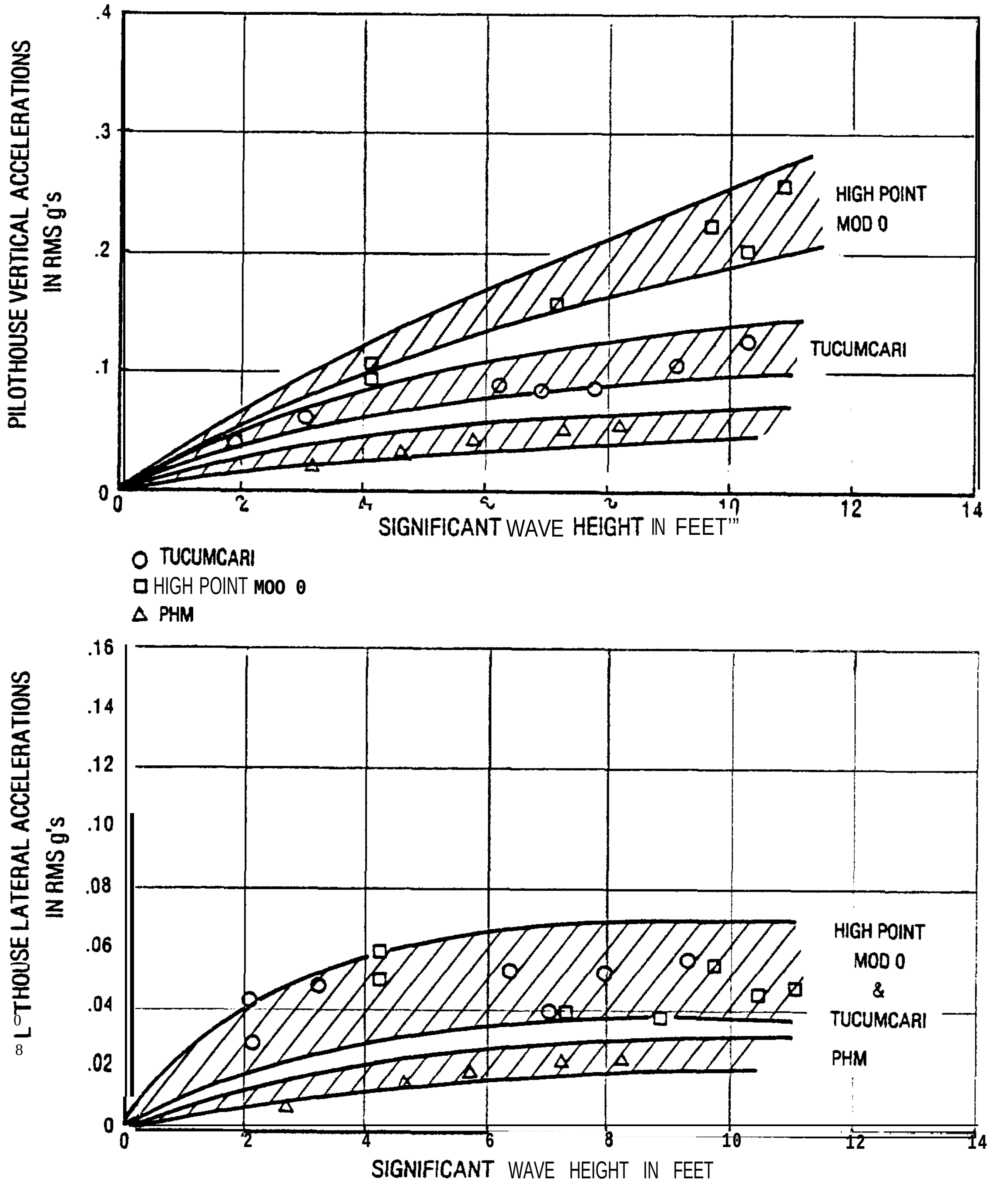


Figure II.A.2-6. MEASURED ACCELERATIONS FOR VARIOUS HYDROFOIL SHIPS

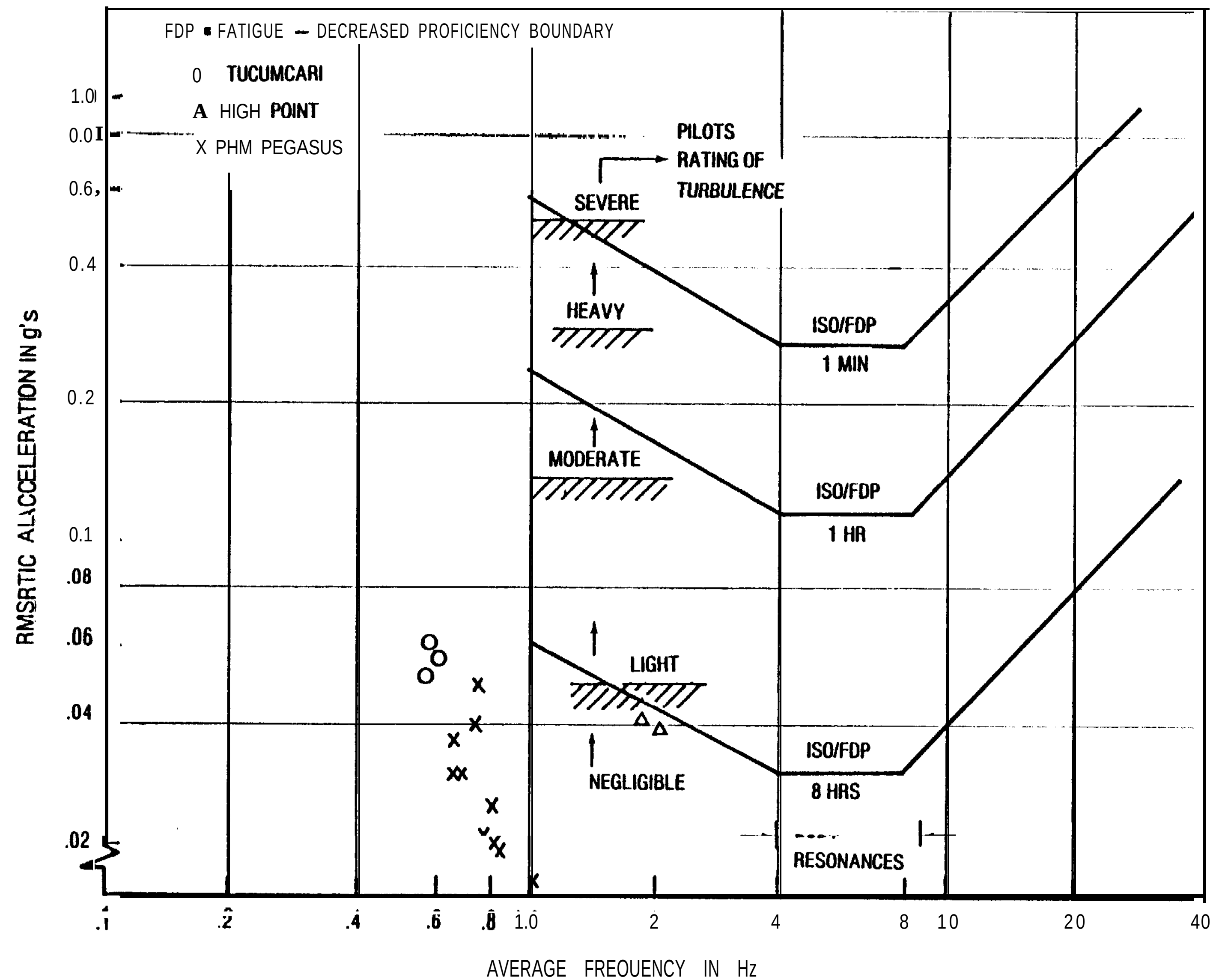


Figure II.A.2-7. HUMAN TOLERANCE DARIES
INTERNATIONAL ORG. ZATION FOR STANDARDIZATION (ISO)

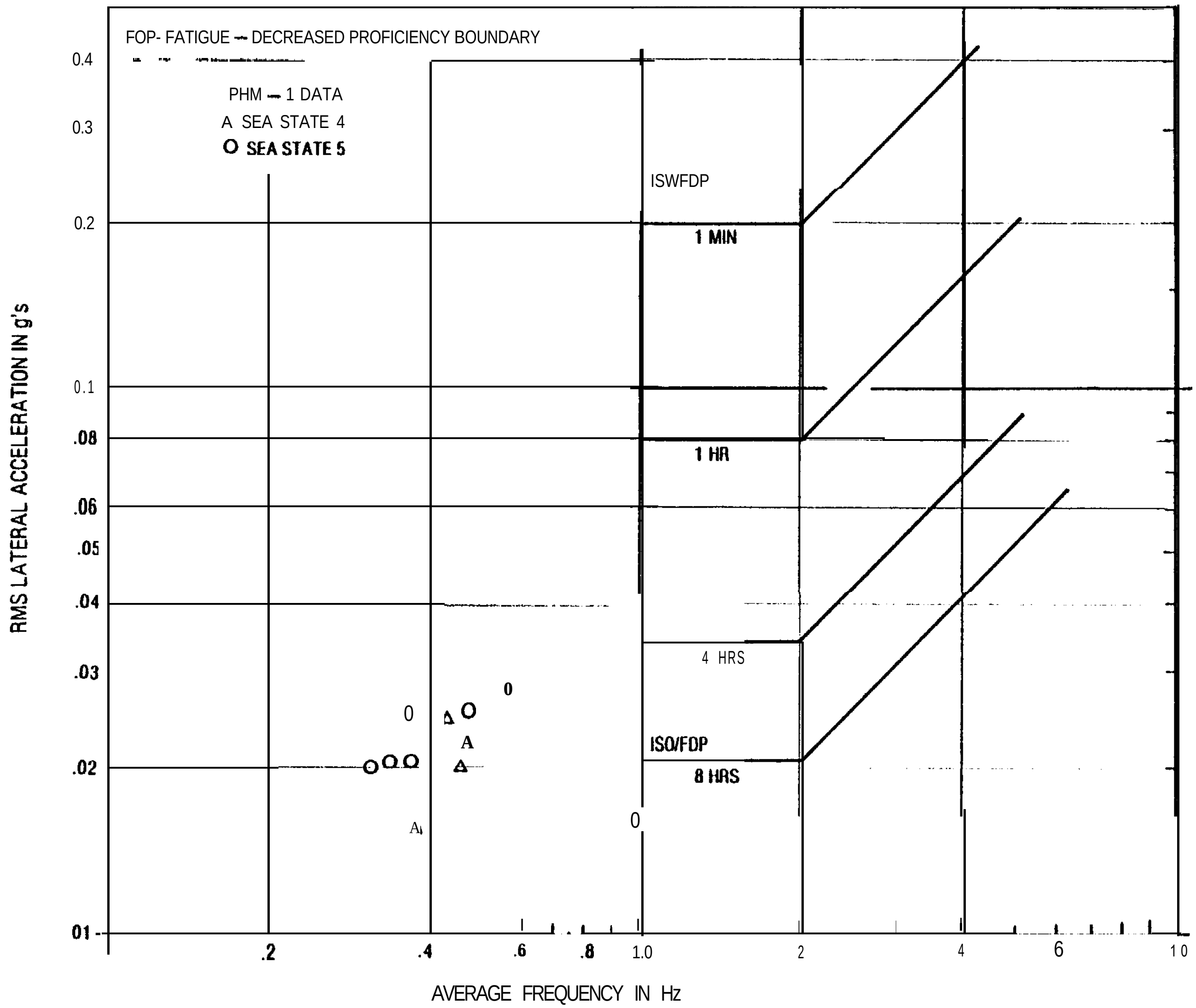


Figure II.A.2-8. HUMAN TOLERANCE BOUNDARIES INTEKNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

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curves. Hence, from a human factors standpoint, the acceleration levels appear to be quite good, but the criteria or standards do not extend sufficiently low in frequency to make absolute comparisons.

(U) Figure II.A.2-9 shows measured motion variations (standard deviations) at the worst case headings versus significant wave heights for HIGH POINT Mod 0, TUCUMCARI, and PEGASUS.

(C) The ability to turn in a seaway is illustrated by Figure II.A.2-10 which shows TUCUMCARI and HIGH POINT Mod 0 turning characteristics in Sea State 5. (HIGH POINT Mod 0 was equipped with a very inadequate rudder system* which resulted in seriously limited turning capabilities.) Mod 1 to HIGH POINT replaced the rudder system with a swiveled forward strut for steering, and those limitations have been eliminated. Figure II.A.2-4 shows the demonstrated turning capabilities in smooth water and in the respective design sea conditions for TUCUMCARI,** HIGH POINT Mod 0, and HIGH POINT Mod 1. Rough water turning data are not available for PLAINVIEW, and only limited turning tests have been conducted with HIGH POINT Mod 1. Turning trials were conducted in early 1976 for PEGASUS and demonstrated that she is capable of $8^{\circ}/s$ turn rate in the design seas as required by the Ship System Requirements (SSR).

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* See References II.A.2-8 and II.A.2-11 for further details on PCH-1 and Mod 0 turning difficulties.

**See Reference II.A.2-5 for detailed data on TUCUMCARI turning.

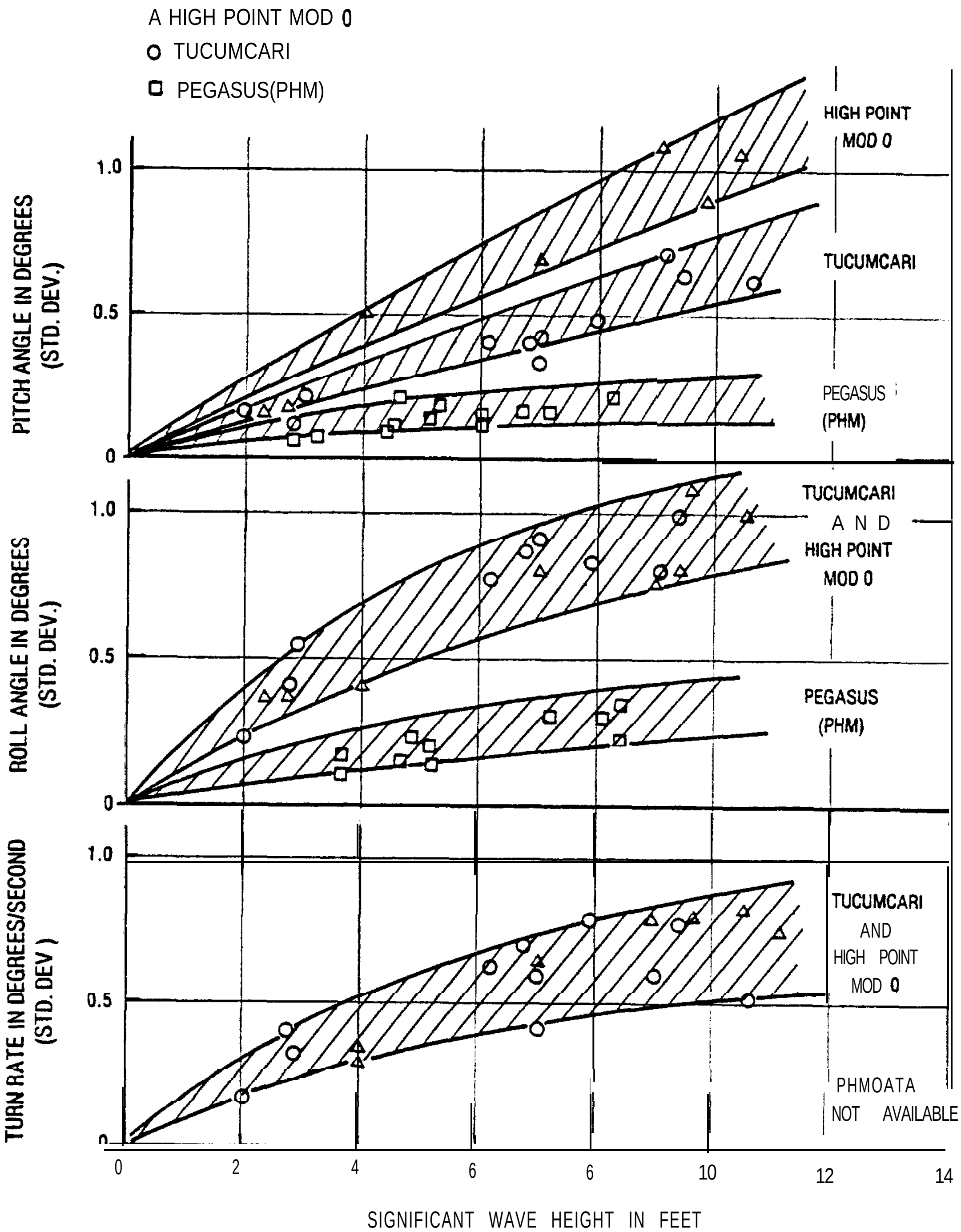

Figure II.A.2-9. MEASURED ROUGH WATER MOTIONS FOR VARIOUS HYDROFOIL CRAFT

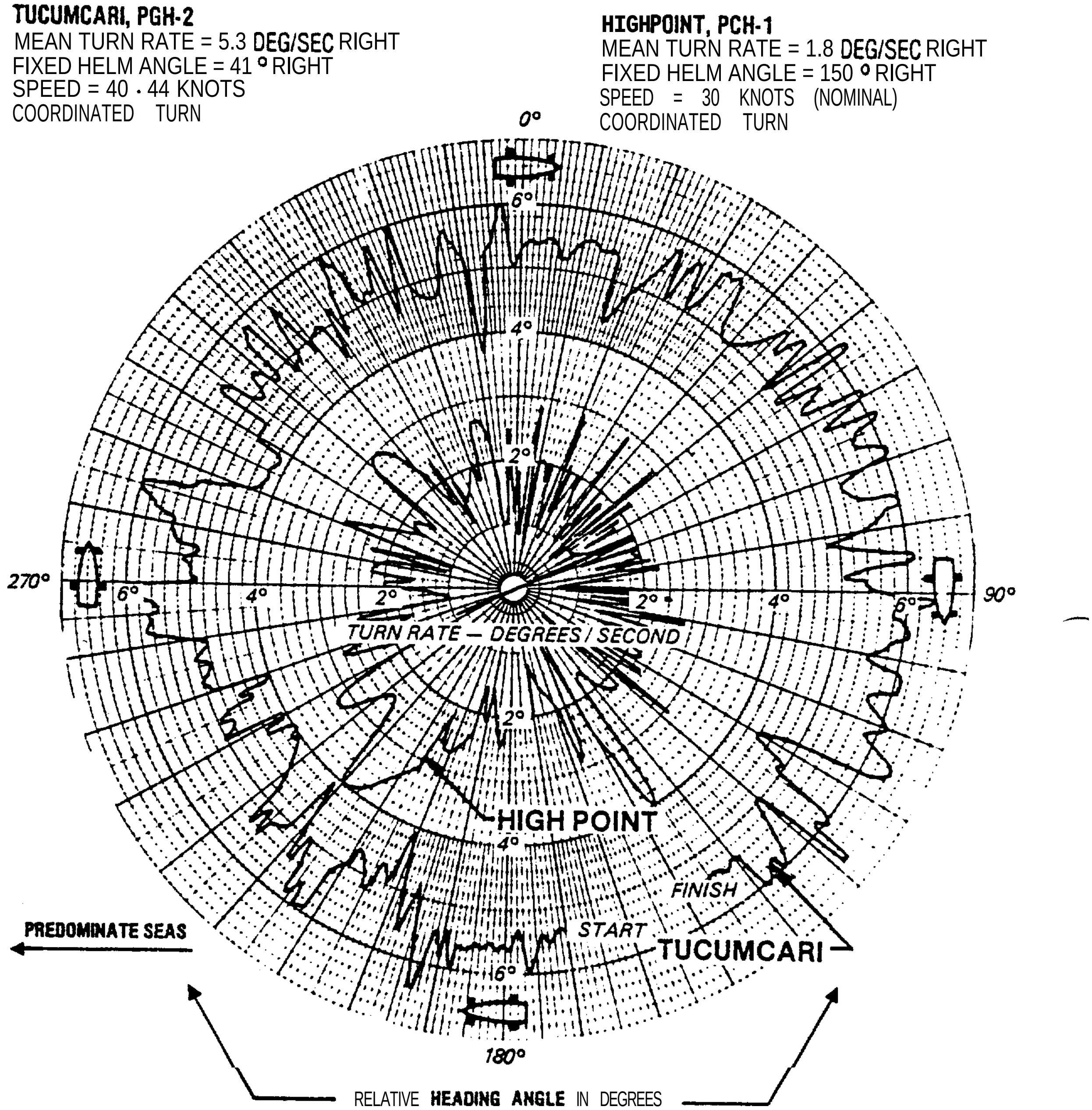

Figure II.A.2-10. COMPARISON OF FIXED HELM TURN RATE - SEA STATE 5

(U) PEGASUS is equipped with a heading hold system which is designed to hold the ship's heading within given bounds. Table II.A.2-1 shows measured steady state heading errors and standard deviations of heading angle, taken in lower Sea State 5. These data illustrate the current capabilities of a hydrofoil ship to maintain an ordered heading in the presence of sea and wind.

(C) A basic characteristic of the hydrofoil ship is its ability to maintain high speed foilborne operation in large seas. Figure II.A.2-11 shows actual hydrofoil ship operation (speed) measured as a function of significant wave height for the hydrofoils TUCUMCARI, HIGH POINT Mod 0 and Mod 1, and PEGASUS. Note that every point on the figure represents an extensive set of sea trials including operation at five *or* more headings relative to the direction of the sea plus foilborne turning. TUCUMCARI, during its 5-year operational life, actually conducted similar operations in many different seas, which by visual estimate included all of Sea State 5 and some of low Sea State 6. However, she was not instrumented after delivery, so detailed data are not available for inclusion on Figure II.A.2-11. The important thing to remember in this regard is that Figure II.A.2-11 presents only data measured from underway trials. This represents only a small percentage of actual rough water operations.

2.3 ANALYTICAL DESIGN TOOLS AND METHODS

(U) In the design of hydrofoil ships, analytical methods and tools are used to conduct the necessary trade-off studies and dynamic analyses which lead to the design decisions.

Table II.A.2-1. FOILBORNE HEADING HOLD IN SEA STATE 5

Voyage 75PHM1-14 TIME PERIOD 11:40 THROUGH 12:17

Significant Wave Height ≈ 2.5 to 2.7 meters

Significant Wave Period ≈ 6 to 8 seconds

CONFIGURATION 2

HEADING RELATIVE TO THE WAVES	ORDERED HEADING ANGLE -DEGREES	MEAN HEADING, ANGLE -DEGREES	MEAN HEADING ANGLE ERROR - DEGREES	HEADING ANGLE STANDARD DEVIATION - DEGREES
HEAD	293	293.2	0.8	0.59
BOW	248	248.1	0.1	0.36
BEAM	23	22.6	- 0.4	0.68
QUARTERING	159	158.2	- 0.8	0.69
FOLLOWING	113	113.4	0.4	0.64
SHIP SYSTEM REQUIREMENT	—		within ± 3.0	< 2.0

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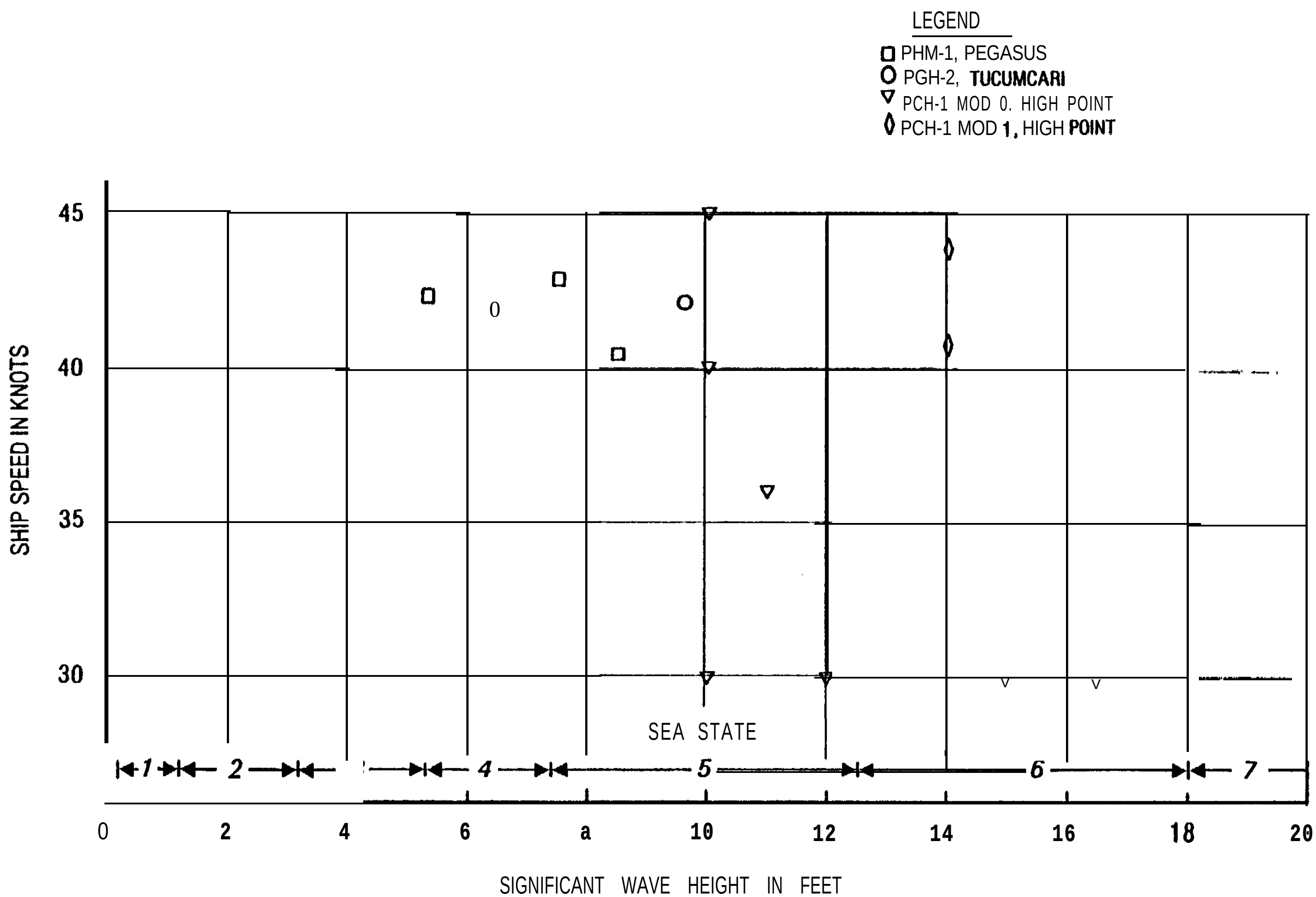

Figure II.A.2-11. DEMONSTRATED ROUGH WATER FOILBORNE OPERATIONAL CAPABILITIES (U)

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(U) Perhaps the most significant engineering achievement produced by the Navy Advanced Hydrofoil Systems Program has been the analytic and predictive technology developed for dynamic control of a hydrofoil platform with submerged foil systems. Sophisticated simulations have been documented which accurately model ship behavior in the total environment and foilborne operating envelope. (For example, see References II.A.2-6 and II.A.2-7.)

(U) From such simulations, foil system configuration, automatic control system functional configuration, and related subsystem design and performance requirements can be developed. Figure II.A.2-12 is an overview of the PHM motion simulation.

(U) Prediction from analytical tools are only as good as the tools themselves; therefore, an important link in the state-of-the-art in hydrofoil control and stability is the state-of-the-art of the basic analytical tools. In the following paragraphs, the correlation between analytical predictions and actual ship measurements are reviewed to show the degree of accuracy obtained from the tools.

(U) In general, the correlation data have indicated the accuracies of the simulation to be very good, and in fact for most of the data shown, the differences between craft measurements and predictions approach the accuracy of the shipboard measurement systems.

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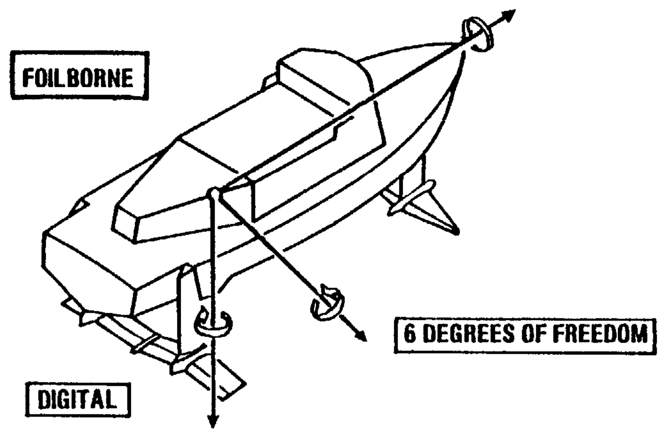

INPUT	CONTENT	OUTPUT

• SPEED
• FOIL DEPTH
• HELM COMMAND
• HEADING
• SEA CONDITION
  • WAVE HEIGHT
  • WAVE PERIOD
• WIND VELOCITY AND DIRECTION
	• **EQUATIONS** OF MOTION
	• **HYDRODYNAMIC** DATA
	• MASS AND **INERTIA** DATA
	• SHIP DIMENSIONS
	• AUTOMATIC CONTROL SYSTEM CHARACTERISTICS
	• SEA DESCRIPTION
		• MANEUVERABILITY
		• RIDE QUALITY
		• FAILURE RESPONSE
		. CONTROL SYSTEM DESIGN EVALUATION
		• STABILITY CHARACTERISTICS

Figure II.A.2-12. PHM MOTION SIMULATION

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2.3.1 Turning - Correlation of Predictions with Actual Ship Predictions

(U) Figure II.A.2-13 shows steady state turning data from PCH-Mod 1 trials and predictions from the simulation. As can be seen, turn rates, roll angles, rudder angles, and speed for any given helm input are within measurement tolerances of the predictions for steady state turns.

2.3.2 Ship Trims - Correlation of Actuals with Predictions

(U) Figure II.A.2-14 shows steady state pitch angle and flap deflections versus ship speed from PCH-1 trials and predictions from the simulation. It can be seen that the trends of the various elements versus speed are in agreement.

2.3.3 Dynamic Responses

(U) One of the most important aspects of the simulation correlation with the craft is the correlation of the responses to rapidly varying inputs. Figures II.A.2-15 through II.A.2-18 compare ship dynamic. responses and control surface deflections to step commands induced in the control system. The agreement between the simulation and actual craft responses is indicative of the high degree of accuracy in prediction available with the simulation. The correlation data were taken from HIGH POINT Mod 0 trials, as reported in Reference II.A.2-9.

2.3.4 Rough Water Correlation

(U) Figures II.A.2-19 and II.A.2-20 show measured ship acceleration against predictions. In the case of the random rough water environment, it has been found that the accelerations

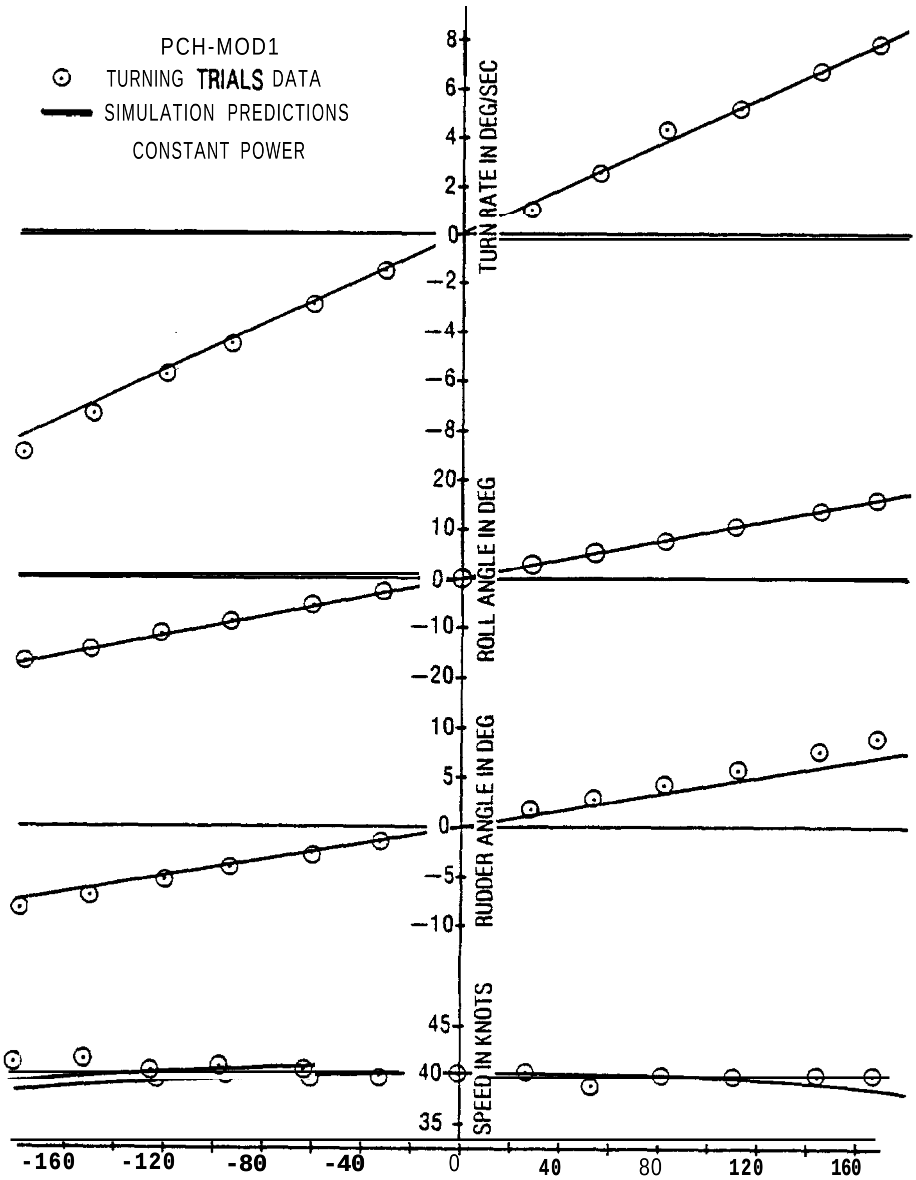

Figure II.A.2-13. PCH-MOD 1 STEADY STATE TURNING CHARACTERISTICS

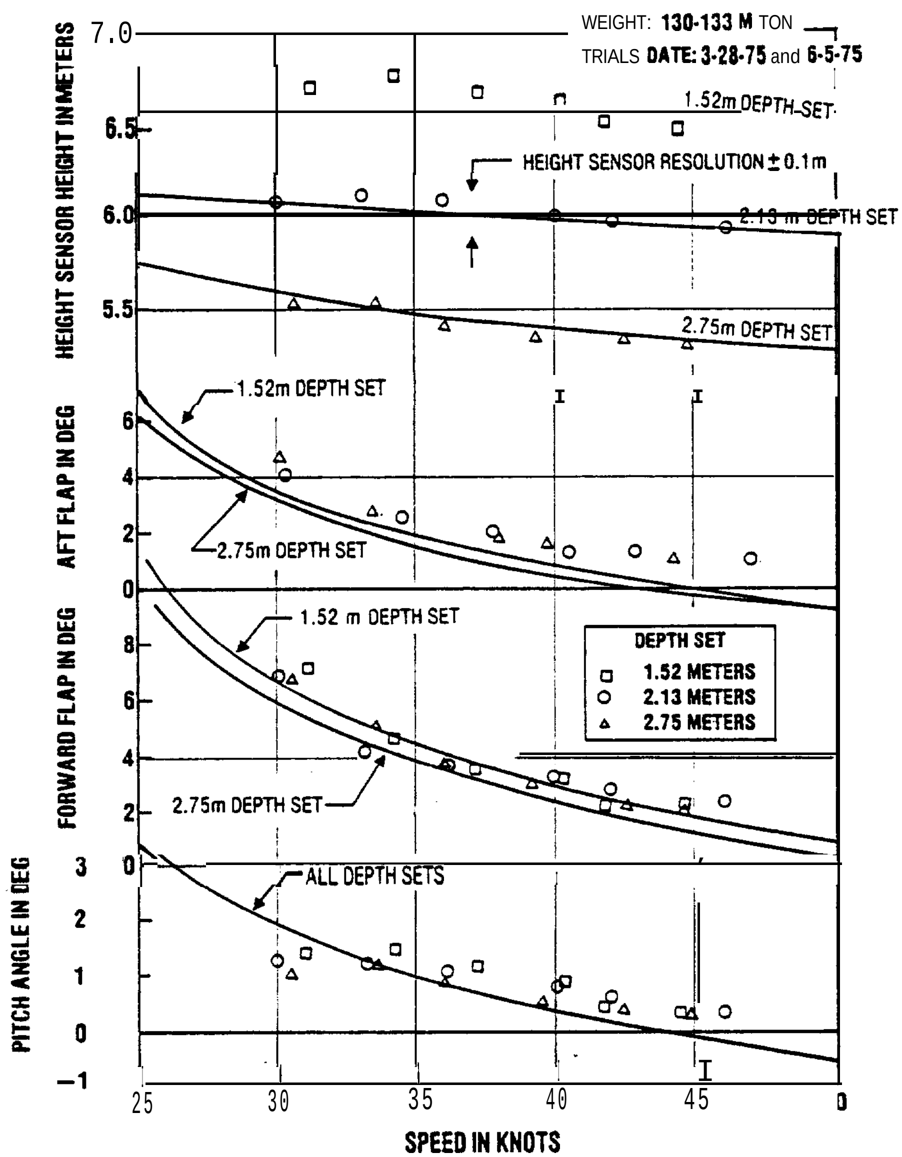

Figure II.A.2-14. PCH-1 MOD-l STEADY STATE FOILBORNE TRIM CONDITIONS AS A FUNCTION OF SPEED

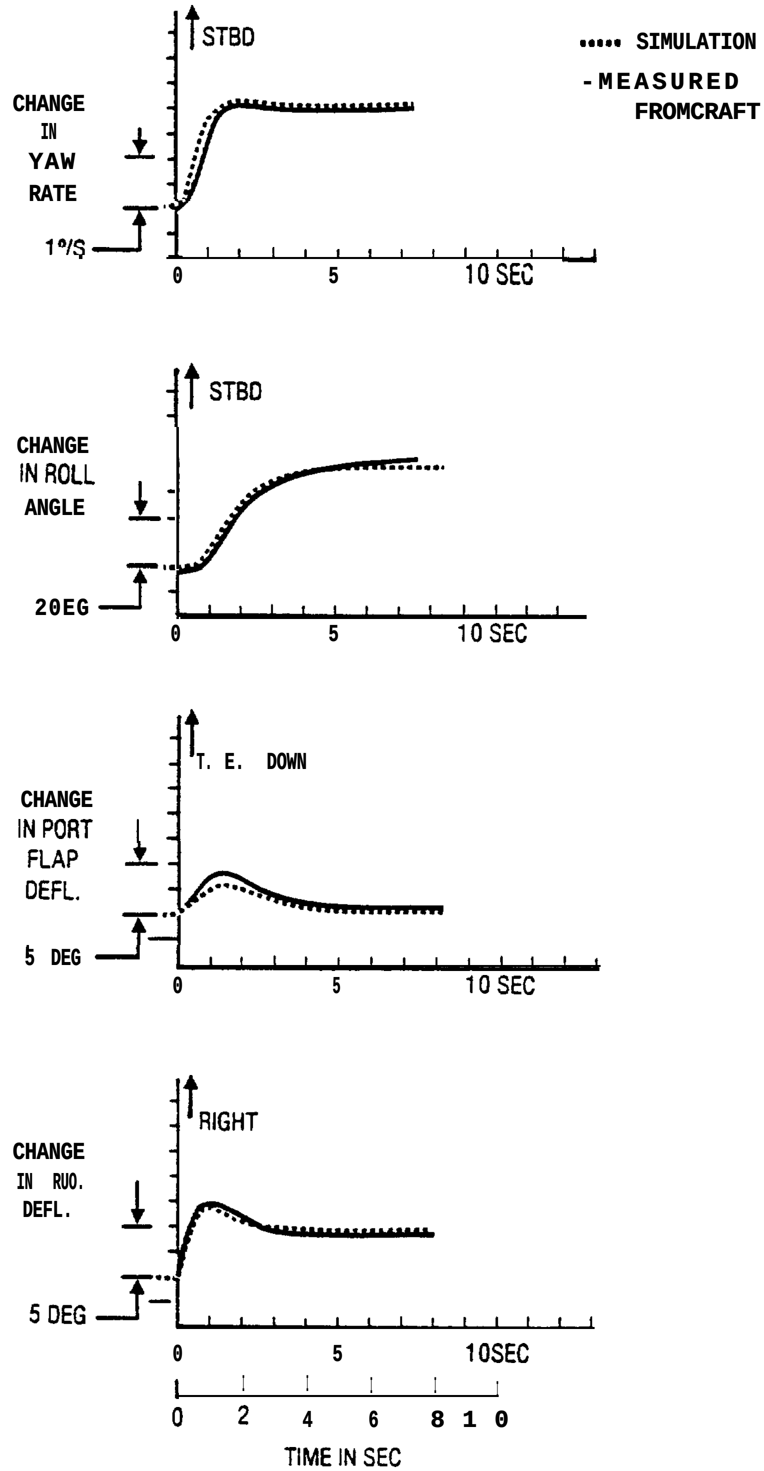

Figure II.A.2-15. TURNING RESPONSES TO STEP HELM COMMAND HIGH POINT MOD 0

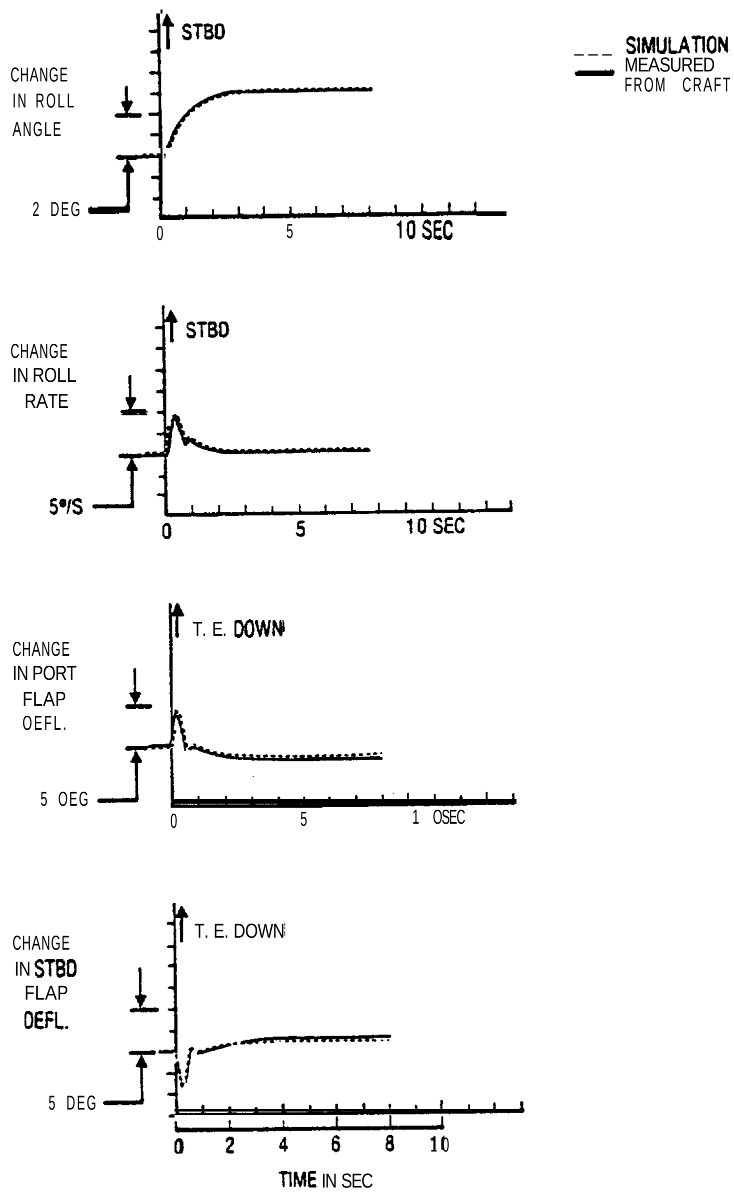

Figure II.A.2-16. ROLL RESPONSES TO STEP ROLL COMMANDS HIGH POINT MOD 0

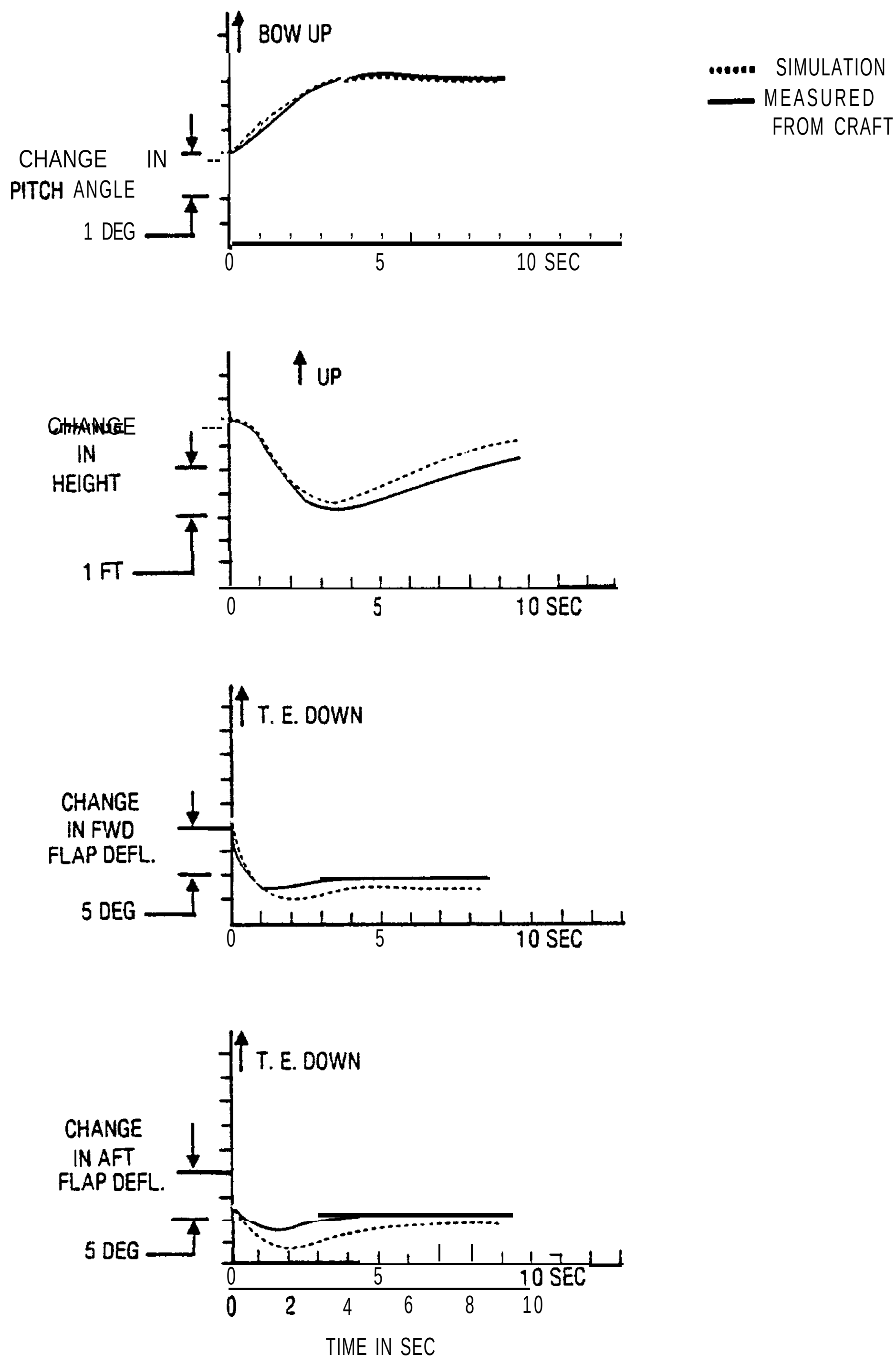

Figure II.A.2-17. PITCH/HEAVE RESPONSES TO STEP PITCH COMMAND HIGH POINT MOD 0

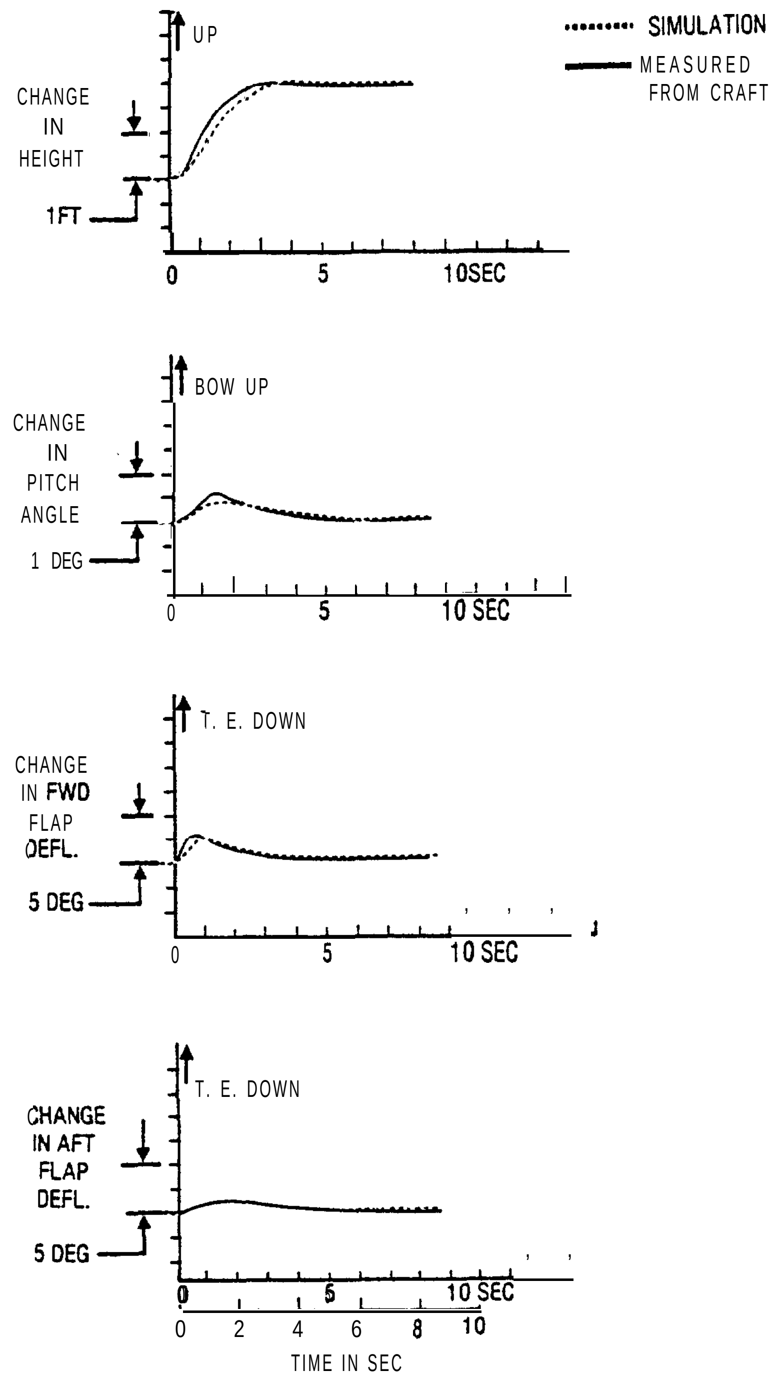

Figure II.A.2-18. PITCH/HEAVE RESPONSES TO STEP HEIGHT COMMAND HIGHPOINT MOD 0

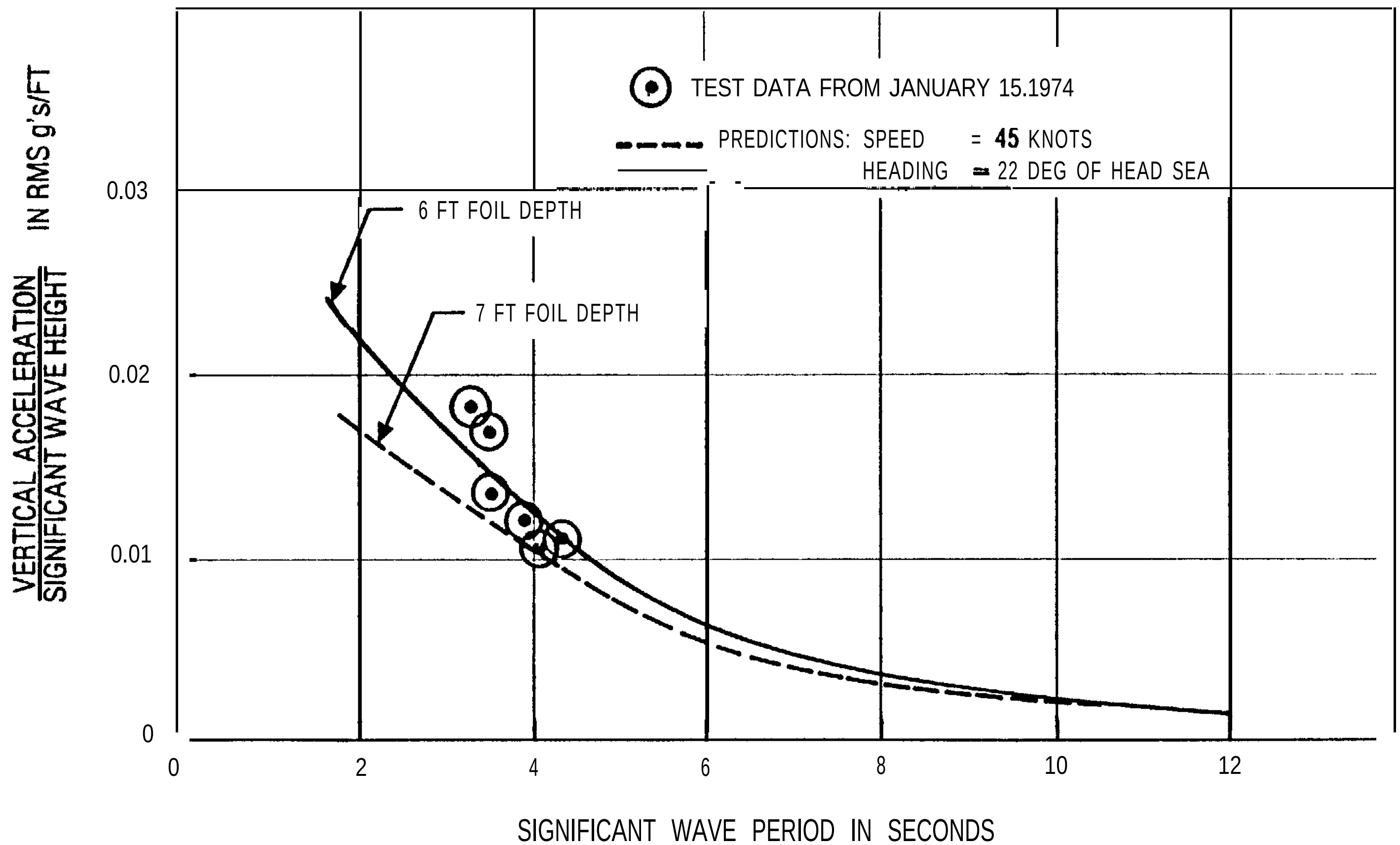

Figure II.A.2-19. PCH-1 MOD-l - VERTICAL ACCELERATIONS

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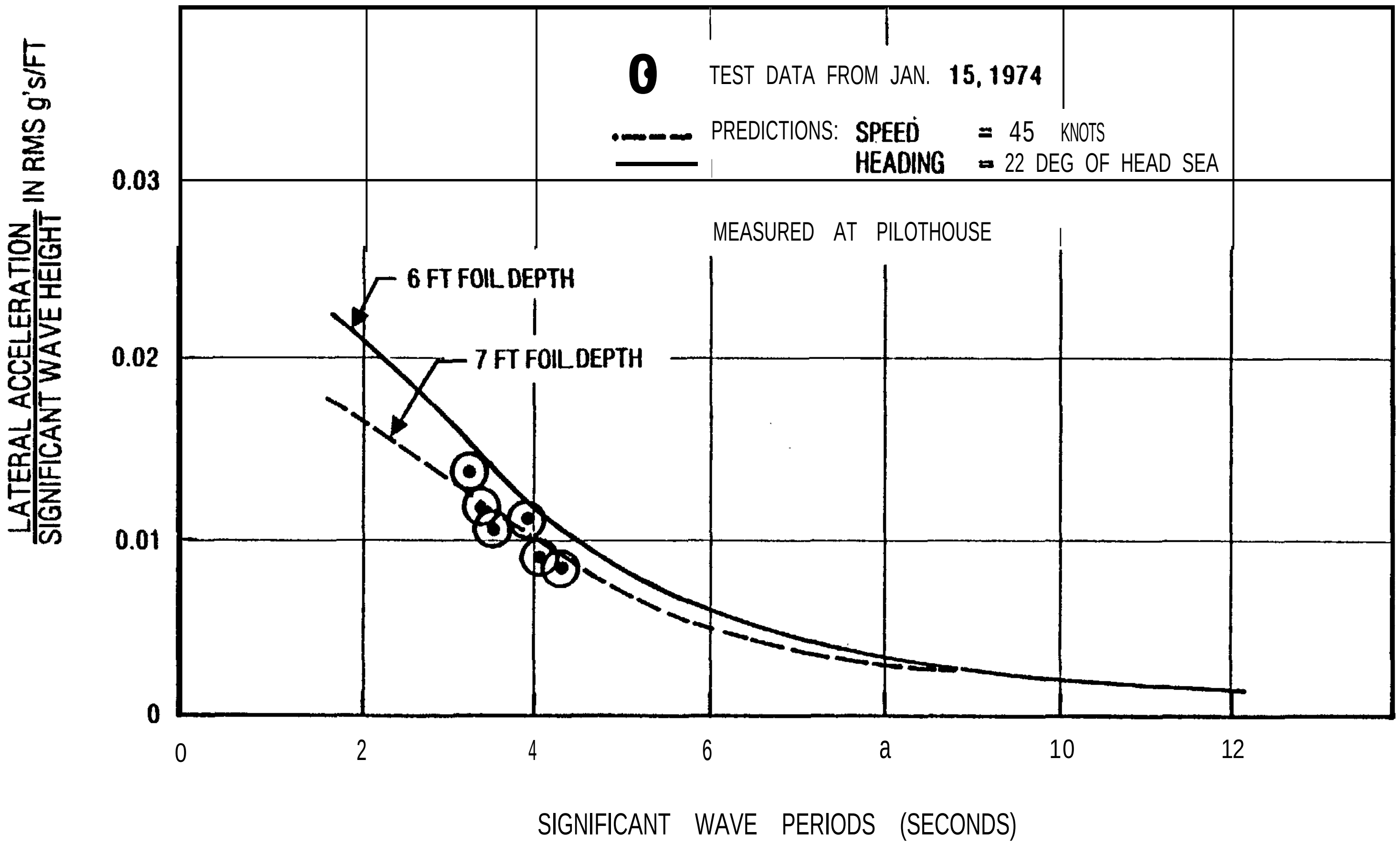

Figure **II.A.2-20.** **PCH-1** MOD-1 - LATERAL ACCELERATIONS

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are dependent upon significant wave height, significant wave period (the two dominant characterizations of the seaway), craft heading relative to the sea, and ship speed. When these factors are all taken into account as is shown in these figures, the agreement between measured results and predictions is phenomenal.

2.4 SHIP STABILITY AND CONTROL DESIGN TECHNOLOGY

(U) In the context of the overall controlled ship design, there are five primary areas of concern to the designers:

- Stability
- Maneuverability
- Rough Water Motions and Accelerations
- Controllability
- Safety

(U) These five areas of concern must be satisfied over a wide range of environmental and foilborne operational considerations as depicted in Figure II.A.2-21.

2.4.1 Stability

(U) The foilborne stability of the hydrofoil ship pivots around directional stability and roll stability. Pitch-heave stability is of concern, but poses significantly lesser problems. In these instances, the stability or instability characteristic of concern is typified by an ever-increasing motion. Mathematically, it is represented by an e^{+at} function.

AREAS OF PRIMARY CONCERN

- **STABILITY**
- MANEUVERABILITY
- RIDE QUALITY
- CONTROLLABILITY
- SAFETY

CONSIDERATIONS

- SEA CONDITIONS
- WIND
- SPEED RANGE
- TURNING ENVELOPE
- OPERATING DEPTHS
- TAKEOFF AND LANDING

Figure II.A.2-21. FOILBORNE CONTROL - DESIGN

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Roll Stabilitv

(U) All hydrofoil ships with fully-submerged foil systems have a basic roll instability brought about primarily by the overturning roll moment produced by the struts. In some instances where the foils are operated very near to the surface, the near surface hydrodynamic effects on the foil system can be sufficiently strong as to provide roll stability. Even under such a condition, however, the craft is marginally stable; hence, the control system is required to provide absolute roll stability.

(U) Roll angle feedback via the automatic control system to the outboard control surfaces has been found to be the fundamental method of stabilizing the hydrofoil ship in roll.

(U) Roll angle feedback to a properly placed rudder can provide roll stability augmentation and in some limited circumstances it could provide absolute roll stability. In practice on hydrofoils TUCUMCARI, HIGH POINT, PHM, PLAINVIEW, and JETFOIL, roll angle feedback to the after flaps (outboard control surfaces) suitably compensated, has been the primary control element to provide absolute roll stability and roll damping, and to limit seaway induced roll motions. The lateral separation of the outboard foils, and hence the control surfaces, strongly affects the roll control surface (aileron) effectiveness. (See References II.A.2-1 and II.A.2-2.)

Directional Stability

(U) Directional stability is basically a **two-degree-of-freedom**, yaw-sway characteristic and is commonly referred to as "weathercock" stability. The directional stability characteristics of the hydrofoil ship are dominated by the foil/strut configuration.

(U) To achieve desirable directional stability characteristics, it is necessary to maximize side force generation abaft the ships center of gravity (CG) and minimize the side force generation forward of the CG. As would be expected, directional stability is degraded as the after struts approach the surface while the forward strut is deeply immersed (ship is pitched bow down). Stability is similarly degraded by waves, where due to the wave profile, the forward strut becomes deeply immersed and the after struts are mostly unwetted.

(U) It is desirable and possibly mandatory that the hydrofoil ship have positive directional stability over most of its foilborne operating regime; but on the other hand, the realities of operating in a seaway dictate that the ship will go through momentary periods of instability as the wave profile can momentarily create relatively large forward strut submergences and small to zero after strut submergences. Momentary loss of directional stability, while being undesirable, is acceptable for short periods of time and will have negligible effect on total directional control. However, the greater the directional stability margin the ship has, the less likely will be the effects of momentary loss of directional control in rough water.

(U) Since directional stability is so strongly related to strut depths, the stability boundaries are presented as functions of the forward and after strut depths. The stability boundaries presented in this section are applicable for both calm and rough water and are generally true of any foilborne speed.

(U) Figure II.A.2-22 shows a typical directional stability study which was conducted for PCH-1 in the process of developing the Mod 1 foil/strut system design. Note that the areas above and to the left of any given curve are stable regions, whereas regions below and to the right of the curve are unstable regions. Each curve on Figure II.A.2-22 represents a different foil/strut configuration being considered. It can be seen that the final design selection for HIGH POINT Mod 1 (lower curve) provided the most stable design. That is, for any given forward foil depth, considerably less after foil depth can occur before the ship becomes unstable.

(U) Figure II.A.%-23 shows two of those same stability boundary curves with a typical foil depth trajectory for quartering sea. The foil depth trajectory is really the sequence of forward and after foil depths that are experienced as the ship passes through a wave. This illustrates the benefits of, and the necessity for, directional stability. As can be seen for this particular wave, the craft with lengthened after struts would be operating in an unstable regime for some period of time as it passed through the wave.

(U) A worst case directional stability condition occurs when both after struts ventilate and the forward strut remains wetted.

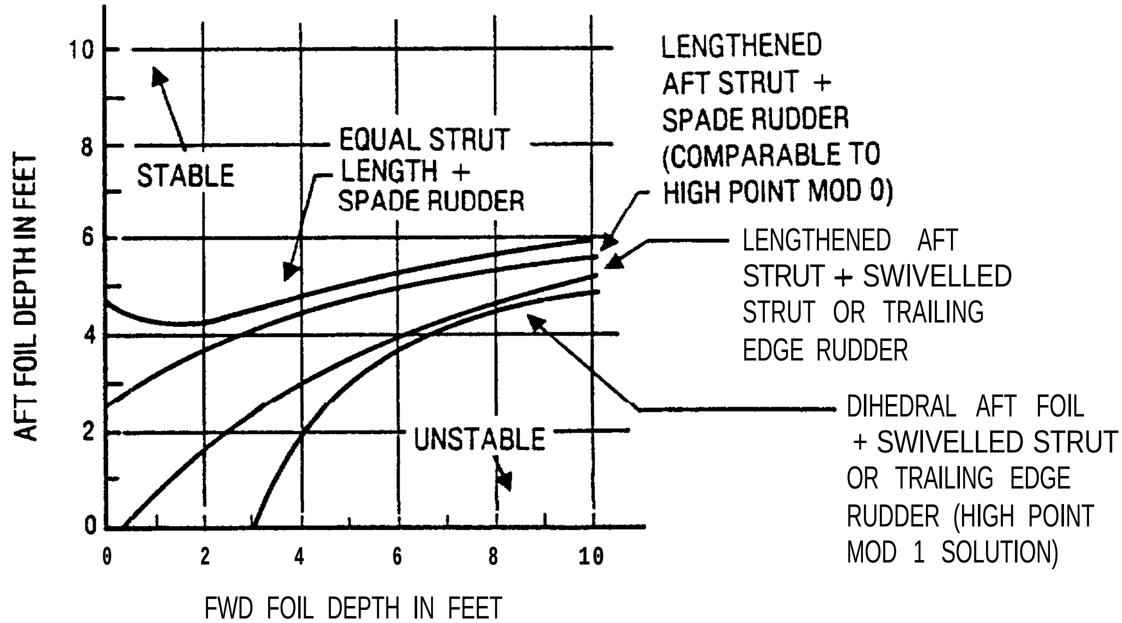

Figure II.A.2-22. DIRECTIONAL STABILITY BOUNDARY LOCATION HIGH POINT DESIGN TRADE STUDY

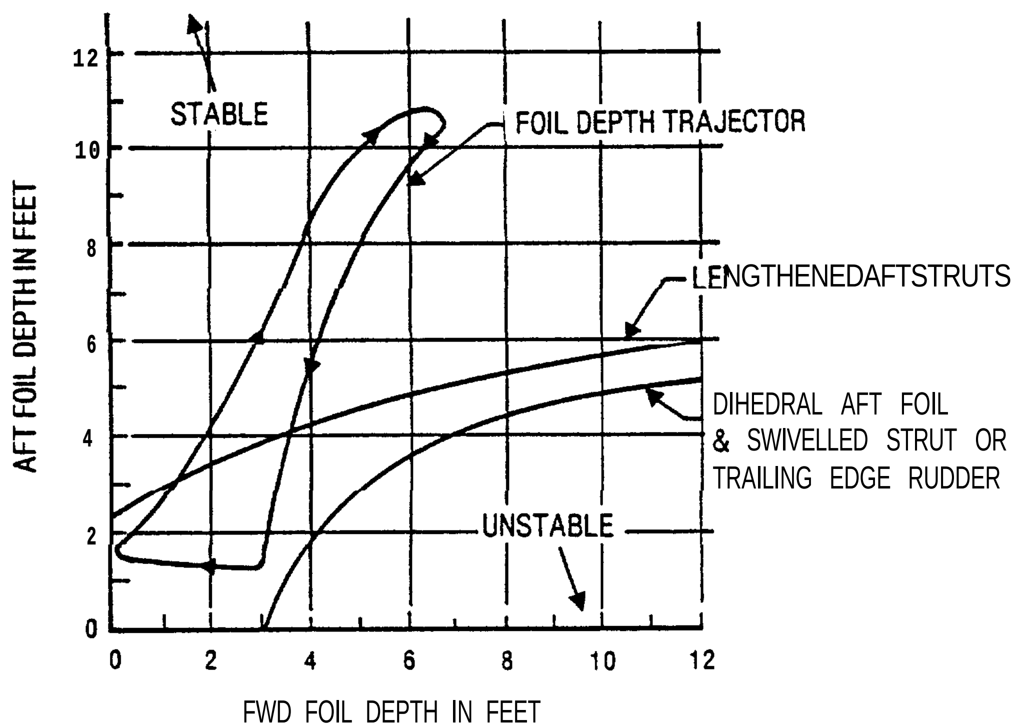

Figure II.A.2-23. ROUGH WATER EFFECTS QUARTERING SEA STABILITY

Figure II.A.2-24 compares the PHM (PEGASUS) directional stability characteristics for unwetted after struts with those for fully wetted struts.

(U) In general, the following observations can be made with regard to directional stability:

- Directional stability margin is in general degraded at the lesser foil submergences.

- Dihedral in the after foil system is quite effective in providing positive directional stability for conditions where the after foils are near the surface (Figure II.A.2-22 is typical). At greater foil depths, dihedral is relatively ineffective. It is significant to note that the dihedral foil inboard of the aft struts has been found to be the dominant source of added stability, and the outboard foil does not significantly contribute to stability. A keen observer might conclude that added after strut length can provide essentially the same improvement in stability as the after foil dihedral which is true for fully wetted conditions; but the point must be made that the foil is a much more reliable source of side force than the strut and does not tend to ventilate when the strut ventilates.

- Directional stability is significantly degraded when the after struts are ventilated and forward struts are fully wetted. This is considered to be the fundamental condition for which the design must assure adequate stability.

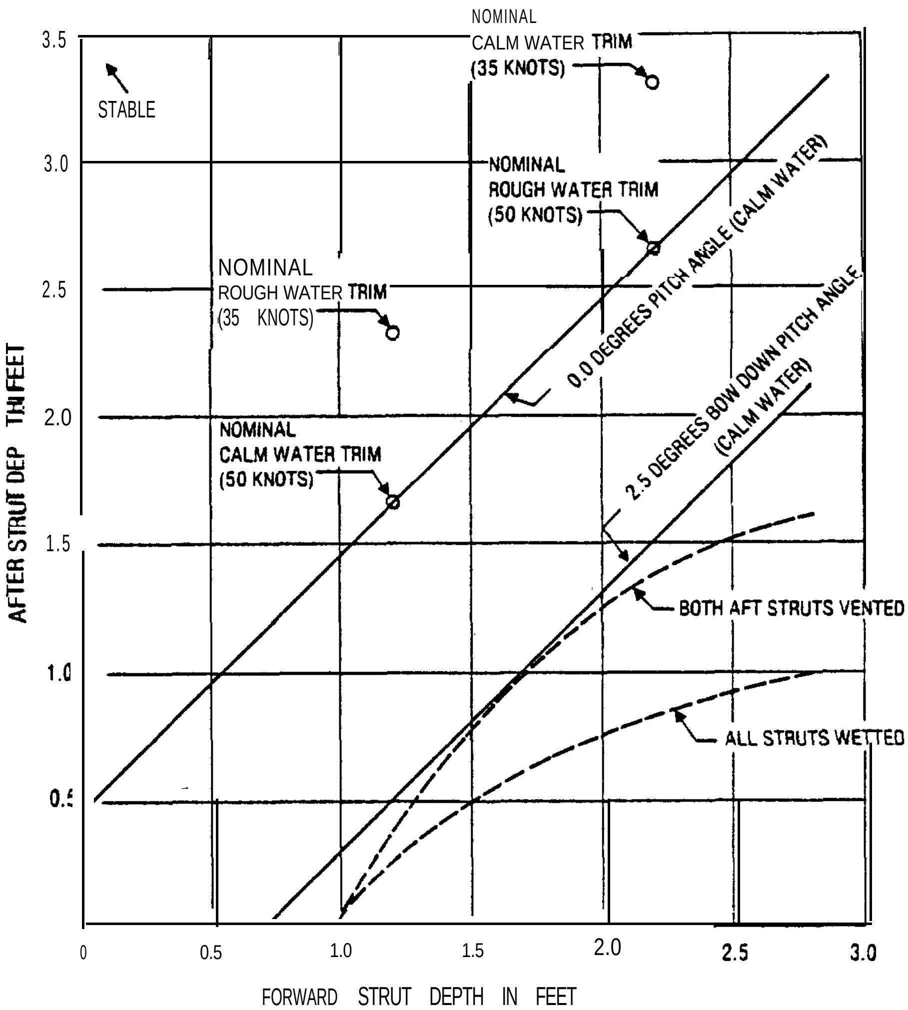

Figure II.A.2-24. PHM DIRECTIONAL STABILITY BOUNDARIES - UNCONTROLLED SHIP

- Current design philosophy as implemented on TUCUMCARI, SPARVIERO,* HIGH POINT Mod 1, and PHM (PEGASUS) employs dihedral in the after foil system to provide that extra bit of stability at shallow foil depths. Further, the foil system configuration is selected to provide for a significant directional stability margin in the presence of after strut unwetting.

(U) Verification of the effectiveness of this design philosophy can best be summed up by observing that HIGH POINT Mod 0 (see stability boundary on Figure II.A.2-22) became directionally unstable on numerous occasions in both smooth and rough water. During the more than 3,000 hours foilborne time accumulated on TUCUMCARI, PEGASUS, HIGH POINT Mod 1, and the Italian ship SPARVIERO, there has been only one recorded instance of forced landing due to directional instability.

2.4.2 Maneuverability

(U) The modern hydrofoil ship has proved to be a highly maneuverable vehicle, but not without some major difficulties and some specific design solutions. Some specific aspects of turning and some detail characteristics which have been found to enhance turning are listed below.

Turning Characteristics

- Banked turns (coordinated) where the ship is banked such that the lateral forces necessary to turn the ship are developed by the foils is preferred method of turning.

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*SPARVIERO is the Italiam military hydrofoil lead ship.

- In a banked turn (100% coordinated) the ship tends to pivot about the after struts for a forward rudder and about the forward strut(s) for an after rudder.
- Flat turns (roll angle approximately 0°) require large side forces be developed by struts, both fore and aft. Turn rate is very limited in this mode due to tendency of the struts to ventilate, which in turn tends to produce directional instability.

(U) In banked turns, the angle of attack on a fixed strut containing the rudder or steering device is proportional to turn rate and the longitudinal spacing of the struts. Mathematically, the angle of attack on the strut with the rudder is given by the relationship:

$$\beta_{STRUT} = \frac{\left(X_F - X_A\right) R}{U_o} \cos \phi$$

where:

X_F = longitudinal distance from CG to fwd strut

X_A = longitudinal distance from CG to aft strut (Note: X_A is negative.)

R = ship turn rate in earth axis

U_o = craft forward speed

ϕ = craft roll angle

(U) Thus for any given turn rate and speed, the angle of attack due to turning kinematics on the strut containing the steering device is proportional to strut longitudinal spacing.

(U) Figure II.A.2-25 shows the effects of turn rate on angle of attack on a fixed strut. Thus as ships get larger, longitudinal spacing between the struts increases and the angle of attack on a fixed strut containing the rudder will increase for any given turn rate.

(U) Now keeping in mind that the total side force on that strut has to be zero in the banked turn, it follows that a rudder has to generate a side force equal and opposite to that produced by the angle of attack on the strut. Thus, in a turn the rudder will be generating a force in one direction and the strut as it is swept around will be generating a force in the opposite direction. This relationship is true whatever type rudder is applied to a fixed strut.

(U) It was precisely for this reason that the steerable strut was implemented as the rudder. With the strut rotating into the turn, the total angle of attack on the strut is effectively maintained at zero degrees. With zero degrees angle of attack on the steering strut at all turn rates, the tendency for the strut to ventilate or cavitate has been eliminated, and positive directional control even at high turn rates has been a hallmark of the ships equipped with swiveled steering struts. (TUCUMCARI, HIGH POINT Mod 1, PEGASUS.) Turning capabilities of ships employing fixed struts with rudder had generally been limited to $4^{\circ}/s$ or less; whereas the turning capability of ships with swiveled steering struts has been in the realm of 8 to $12^{\circ}/s$.

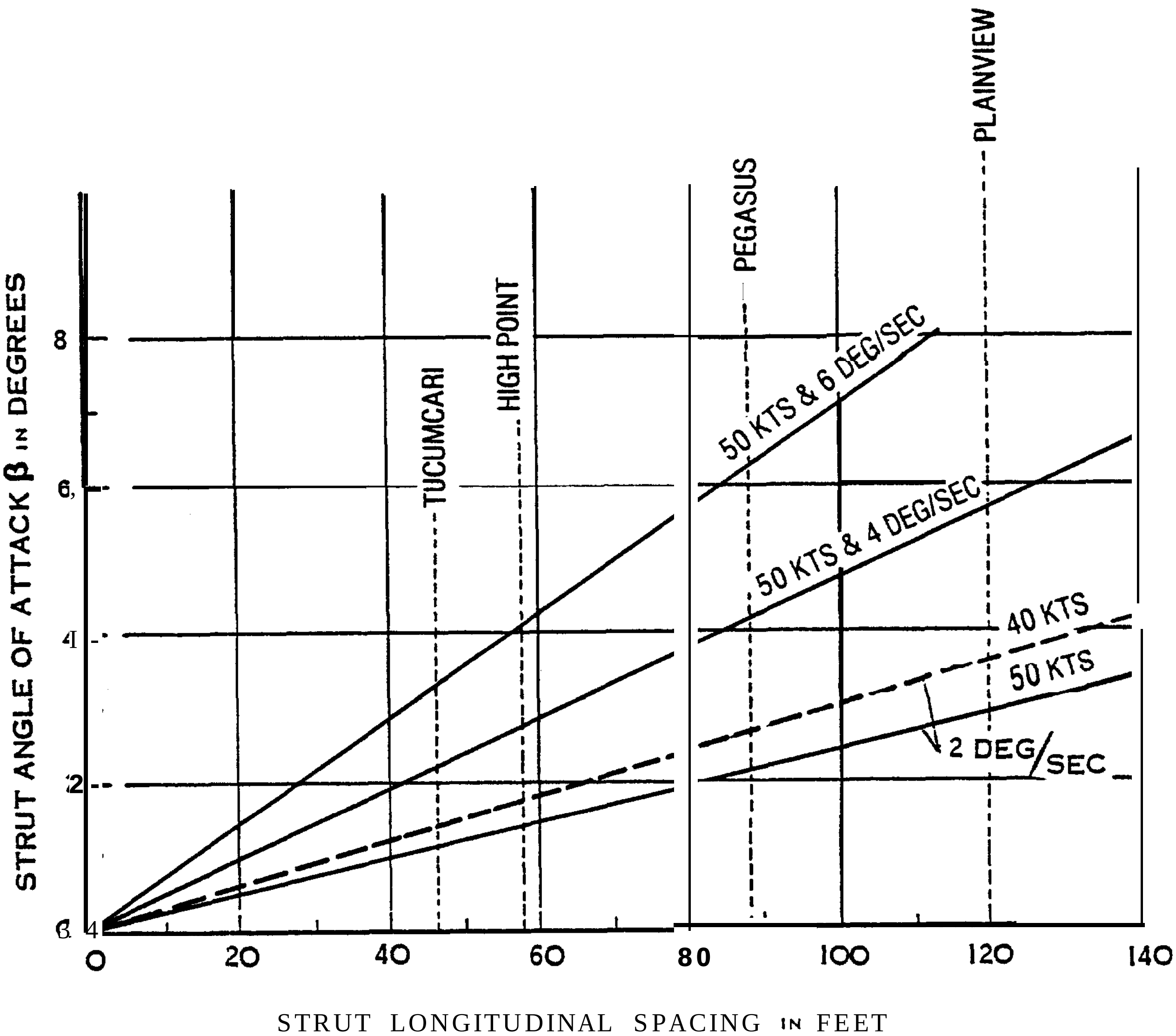

Figure II.A.2-25. STRUT ANGLE OF ATTACK DUE TO TURNING (FIXED STRUT WITH RUDDER)

(U) Another configuration related effect of turning is the problem of keeping the outboard foil tip wetted when banking. Dihedral on the outboard foil system has been used effectively to reduce the problem of the outboard foil piercing the surface.

(U) Figure II.A.2-26 depicts a desirable craft configuration for directional stability and maneuverability, the advantage of such a configuration being:

- Canard configuration places steering function at forward strut. Angles of attack generated by steering actions and control system feedbacks tend to maximize expected angle of attack on the steering strut; hence, forward strut is most probable to ventilate, which is best from directional stability considerations.
- Dihedral after foils provide additional directional stabilty (primarily at shallow foil depths) plus foils provide a more reliable source of side force than do the surface piercing struts.
- Outboard dihedral angle on after foils reduces tendency of foil tips to broach surface in banked turns.
- Steerable forward strut minimizes angle of attack variations in turns and, hence, maximizes turn rate capability and turning reliability.
- Widely spaced after foils maximize roll control authority.

2.4.3 Turning Dynamics

(U) In the dynamics of turning, the Automatic Control System via its electronics and sensors also plays an important part. The most desirable steering control configuration for a canard craft has been found to be what is termed the "roll-to-steer" method wherein the helm commands are fed differentially to the after flaps,

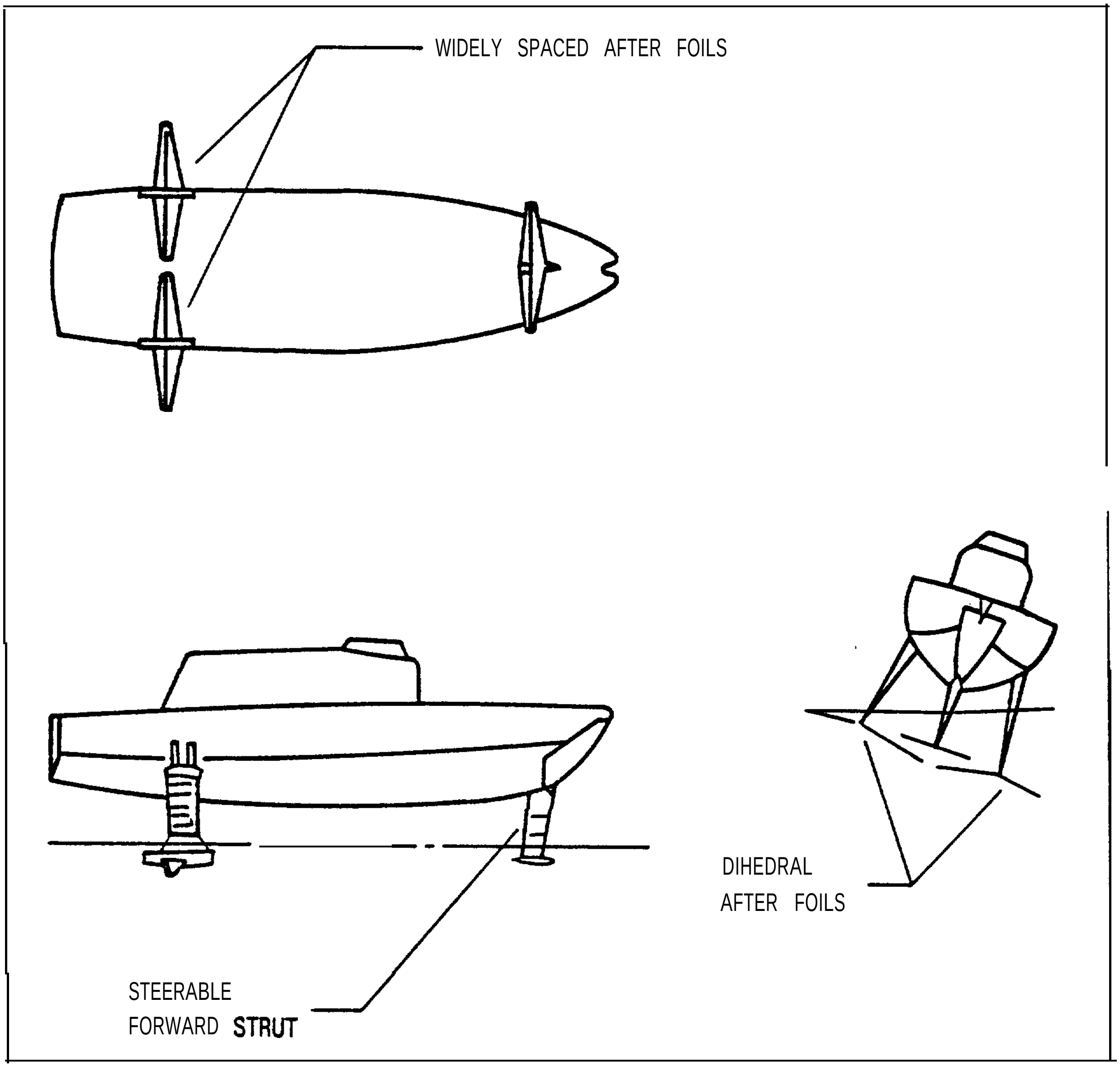

Figure II.A.2-26. A DESIRABLE CRAFT CONFIGURATION FOR STABILIZATION AND MANEUVERING causing the ship to roll. Ship roll angle information is then fed to the forward strut or rudder which causes the ship to take up a turn rate nearly proportional to the ship roll angle.

(U) This configuration maximizes the ship roll control authority and directional stability characteristics, and in detailed failure studies it has repeatedly been demonstrated to be the most tolerant system to hardover or dead failures in the control system. (See Reference II.A.2-7 for examples of failure studies.)

2.4.4 Ship Trims

(U) Ship trimming is primarily a pitch-heave function as roll trim is a negligible problem. Roll forces and moments do not appreciably change with speed. High roll feedback gains tend to minimize effects of hydrodynamic uncertainties and structural offsets, and the helm to aileron steering path allows the helmsman to automatically trim out the remaining roll unbalances with the helm.

(U) In the pitch heave plane, however, the ship trims, (pitch attitude and foils depths) tend to vary with ship speed and ship weights. The Automatic Control System has been used very effectively to control the pitch-heave trims.

(U) For hydrofoil ships employing fixed foils and trailing edge flap control, the trim of the foils must be accomplished by trimming the pitch attitude of the craft. Figure II.A.2-27 shows typical trim as a function of speed for such a craft, and as can be seen, the pitch trim is quite easily modified to provide the

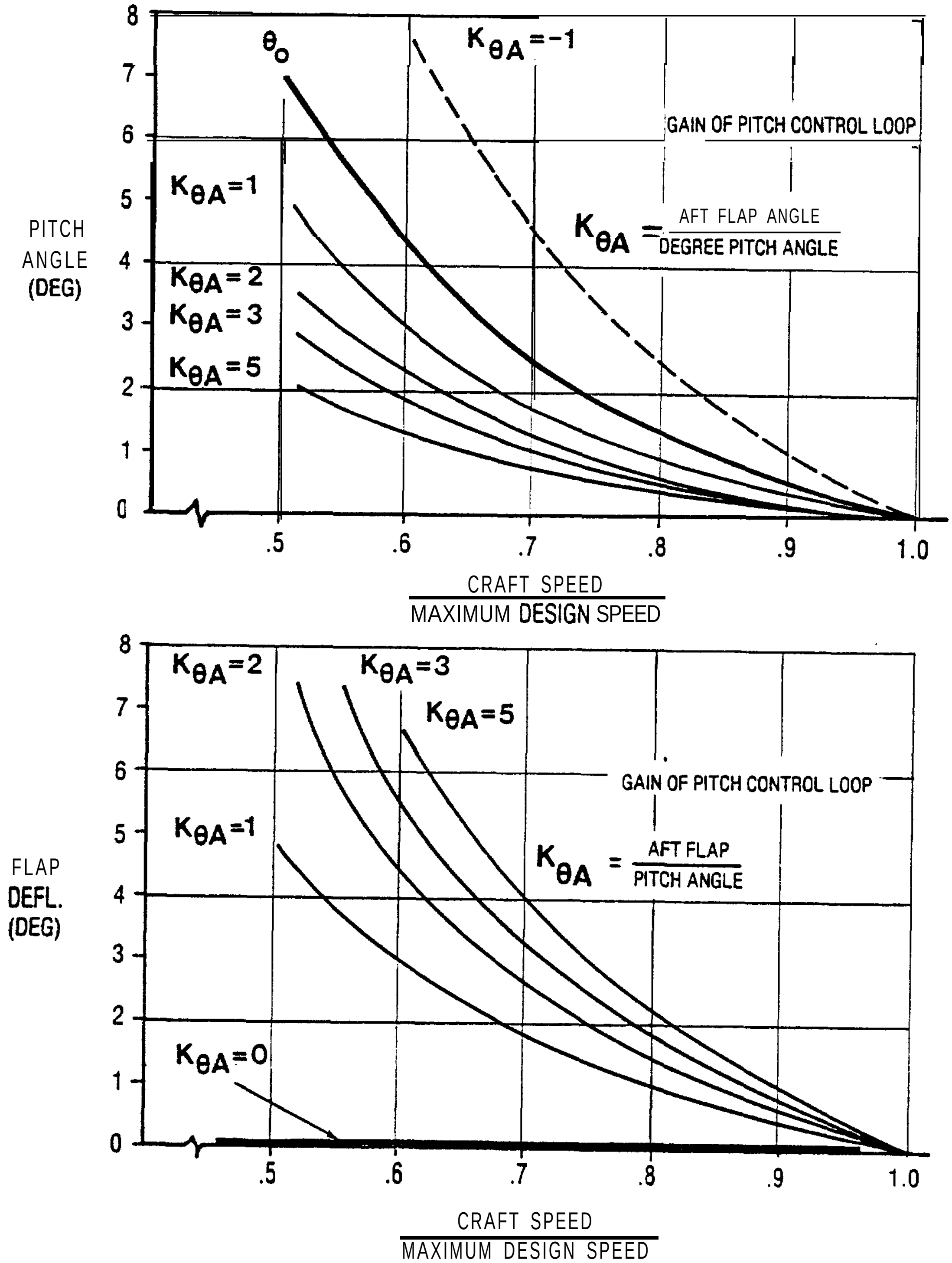

Figure II.A.2-27. PITCH TRIM AS A FUNCTION OF SPEED FOR VARIOUS CONTROL GAINS desired trim by proper selection of the pitch angle feedback to the after foils. While other more complex schemes can and are used to provide the desired trim schedule, this figure illustrates the relative simplicity of developing the desired steady state pitch trim without having to sense speed.

(U) For a ship employing incidence control or incidence control plus trailing edge flap control, the incidence angles can be controlled without pitching the craft which could be of significant advantage in longer ships, because the usable rough water strut length is lessened as the craft is pitched up or down.

(U) Pitch trim requirements or criteria are not yet clearly defined, but the following considerations influence the selection of pitch trim:

- It is a generally accepted goal that the craft would be trimmed so that the pitch angle and flap deflections at design speed be at or near 0° to minimize drag at this condition. The built-in foil angle of attack relative to the craft baseline and foil causes are generally selected with this objective in mind. The desired pitch angle and flap angles at lower speeds are determined so as to give as near minimum drag as practical.

- One school of thought holds that the pitch trim should be scheduled so that the trailing edge flaps are operating near the midpoint of the dynamic lift range. This provides maximum control authority for coping with sea state and failures, thus providing nearly equal control force capability (range) for positive or negative going control surface deflections. The PCH-1 and PHM designs employ such a pitch schedule, with pitch angle and flap deflections being nominally 0° at design speed. The pitch angle increases to approximately 2° bow-up and the trailing edge flaps position to approximately 4° trailing edge down at 30 knots.

- Another pitch trim schedule, which could be of importance from a range point of view, would trim the foils for minimum drag. Height trim could also be adjusted for minimum drag.

(U) With today's sophisticated computer systems it would be possible to provide multiple pitch-height trim characteristics to optimize the trims for sea state performance, or for minimum drag (maximum fuel economy), and the operator would select the configuration depending upon sea condition.

2.4.5 Ride Quality and Rough Water Behavior

(U) The ride quality and overall rough water behavior of the hydrofoil ship are a major plus in its overall characteristics. Figure II.A.2-9, which shows pilothouse vertical accelerations versus significant wave heights, demonstrates the type of improvement that has been attained in ride quality in progressive ships.

(U) The major factors which have resulted in the reduced accelerations are:

- Higher acceleration feedback gains in the Automatic Control System.
- Location of sensors to optimize their utility for control.
- Refinements in control feedback loops through filtering and shaping.

- The configuration of the ship, and foil and strut system, the uncontrolled directional stability, and pitch heave stability characteristics have been important adjuncts in allowing the increased acceleration gains.

(U) A potential problem to be considered in closing acceleration feedback loops is structural dynamic coupling. For large hydrofoils, as with large aircraft and missiles, the designer must include the effects of structural dynamic characteristics in the design of the control system. In the relatively small ships built to date, including PHM-1 (PEGASUS), the design has carefully concentrated on keeping the structural elements of the foil/strut and the control actuation system very stiff and the size of these systems minimum, consistent with their basic design requirements. In this manner, the fundamental structural frequencies of the various elements have been kept fairly high. Most fundamental structural frequencies on the PHM foil system for instance were greater than 6 Hz; whereas feedback control is needed in a seaway primarily below 2 Hz. By maintaining a sizeable gap between the frequencies where high feedback gains are required for control and the structural frequencies where low feedback gains are desired to prevent structural interaction, the designer has some latitude to add filters and operate on the system to prevent instability.

2.4.6 Controllability

(U) The last feature of the controlled ship to be discussed herein is "controllability" by which is meant the ability or authority of the control surfaces to generate the necessary forces and moments on the ship so as to cause the ship to behave in the manner intended. To best illustrate the importance of controllability, the following discussion will point out some of the good and bad results attained on operating hydrofoils which are related to controllability.

- HIGH POINT Mod 0 had a small trailing edge rudder on the forward strut plus a skeg rudder under the forward foil. This system proved inadequate for directional control and on numerous occasions the ship was blown off course by high winds, or was unable to come about into a wind. Also, minor hydrodynamic perturbations on the forward and after struts were able to cause sufficient side force offsets that the ship would barely be able to turn in one direction. There were numerous occasions where $2^{\circ}/s$ to the right was the maximum turn rate attainable even in smooth water. With the change to a fully swiveled forward strut (on Mod 1) the directional authority of the rudder is dominant, and the ship simply turns or proceeds ahead at will even in severe winds. Concomitant with the change to a fully swiveled forward strut, most of the hydrodynamic irregularities were eliminated which also helped the directional stability. Most of the improvement in directional controllability, however, can be attributed to the swiveled forward strut.

- Roll control on HIGH POINT Mod 0 was also found to be marginal and on several occasions the control surfaces were overpowered by other wave forces and moments, and, during takeoff and at low foilborne speeds, the ship slowly rolled to the hull in beam seas (see 1966 and 1968 Rough Water Trials Reports, References II.A.2-10 and II.A.2-11).

Mod 1 design studies explored these and other incidences of loss of roll control and increased the length of the aft outboard foils from 7.75 ft to 10.25 ft. Additionally, the Mod 1 control system incorporated roll angle feedback to the swiveled forward strut which further enhanced its roll control authority. Subsequently, Mod 1 has lost roll control and landed on at least two occasions in very large seas, but subsequent data anlayses showed that the ship had been allowed to slow down by the operator and become hull-borne and when roll control authority was lost, the speed was approximately 18 knots. The overall improvement in roll control has been obvious to the operators.

- In large sea states, the dynamic changes in flow and in angle of attack on the foils and struts can be quite large, and the bigger the seas, the larger will be the angle of attack variations. Thus, if positive control of the ship and the improvement in ride quality shown are to be realized via the Automatic Control System, then it is axiomatic that the control surfaces must be able to generate the desired control forces and moments to accomplish the control function. Figure II.A.2-28 shows the la orbital particle velocity variation (year round distribution) for the North Atlantic Ocean. Also superimposed are two points, the design sea for TUCUMCARI and for PHM. It can be seen that the variations in orbital particle

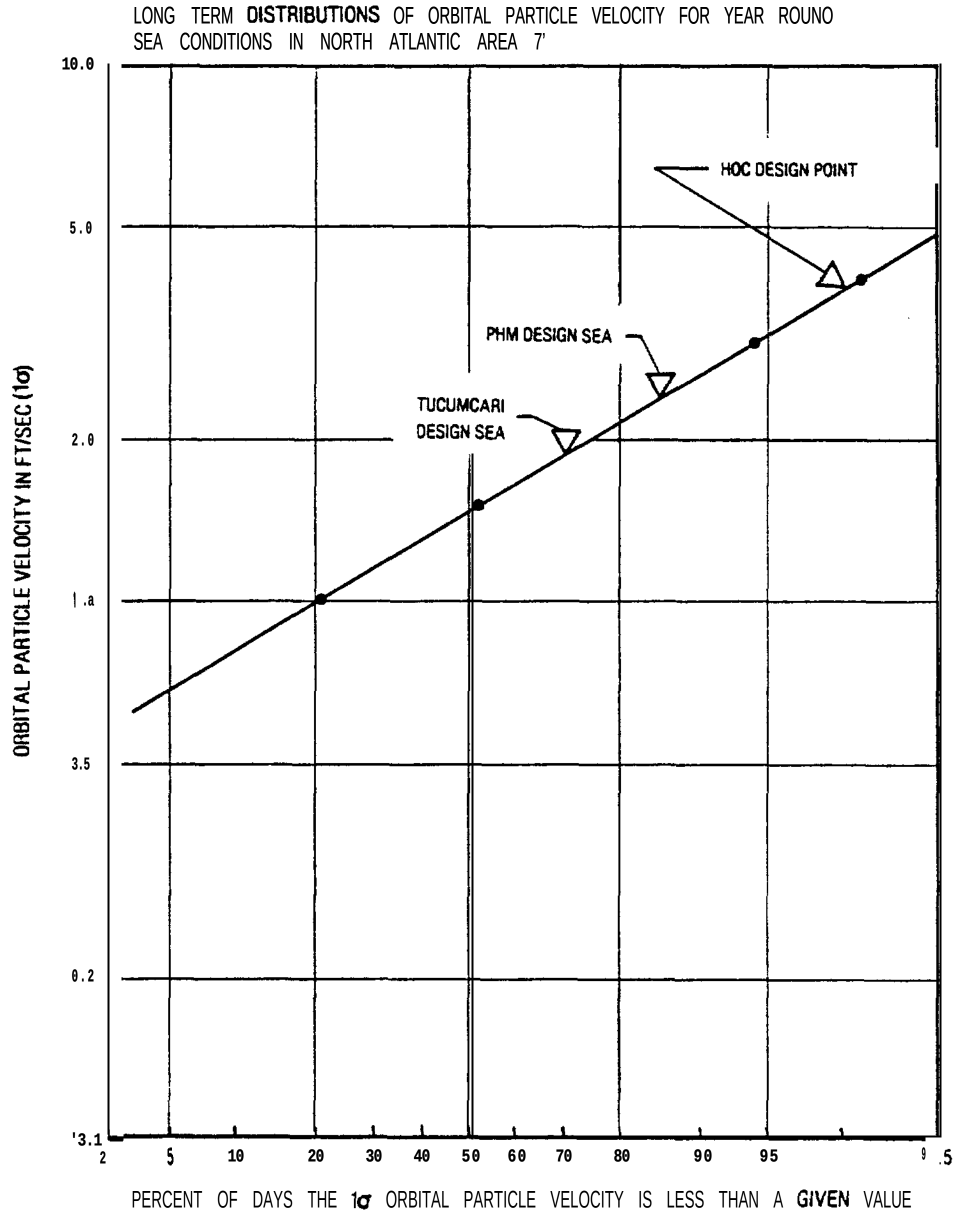

Figure II.A.2-28. LONG TERM DISTRIBUTIONS OF ORBITAL PARTICLE VELOCITY FOR YEAR-ROUND SEA CONDITIONS IN NORTH ATLANTIC AREA 7*

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*See Hogben & Lumb, "Ocean Wave Statistics " (Reference II.A.2-14.)

velocity for a North Atlantic hydrofoil will be considerably greater for the upper 15% of the days. Since angle of attack on the foils and struts is directly proportional to orbital particle velocity, it can be readily seen that larger seas will require large dynamic range for the control surfaces. This does not mean larger mechanical travel; rather, it means larger hydrodynamic range over which control forces can be developed.

Larger ships will obviously be designed for higher seas, and in spite of the fact that the foils will be operating deeper, the trend shown will hold, as the orbital decay with depth will be minimized in the larger waves. Additionally, the angle of attack variations on the struts at the surface are absolute, so that as ships are designed for higher seas, the dynamic operating range of the struts and foils as well as the control surfaces will have to be wider.

2.4.7 Safety

(U) In the design of high speed vehicles operating in a seaway, safety of the ship and of the crew has to be paramount in the ship design. In the hydrofoil ship where the full time automatic control system is married with the high speed ship and with rough water operation, ship safety has an even greater importance. Safety has to be considered from at least two important views:

- The control system provides a capability for operating the ship in very large seas, at very high speeds which would not otherwise be attainable. Thus, an important consideration *must* be to assure that in the design of the ship and the control system there are no sudden cliffs in the operating envelope which, if the ship could inadvertently pass over, would be an unsafe condition.

- The control system by its very nature must be capable of producing sizeable forces and moments on the ship. Therefore, in terms of safety, the effects of control system malfunctions must be carefully considered and the design so configured such that the ship and personnel will be safe in the presence of any and all control system failures.

(U) In terms of ship safety in the presence of automatic control system failure, the PHM system represents the latest 'and most thoroughly engineered safety design in existence. Reference II.A.2-11 reports the failure modes and effects and analyses conducted on the PHM foilborne simulation. These failure analyses represent the most extensive and thorough failure analyses ever conducted for a hydrofoil ship, and possibly for any kind of ship. The failure studies conducted encompassed the control system electronics and sensors, the hydraulic actuation system, and the control system electrical power system and all their interfaces. In all, over 200 detailed failures were simulated and analyzed in these studies. Tables II.A.2-2 and II.A.2-3 give summary results of selected failures in the hydraulic actuation servos and in the control system electronics.

Table II.A.2-2. SUMMARY OF HYDRAULIC ACTUATION SERVO FAILURES

Failure Mode	High-speed Straightaway	Low-speed Straightaway	High-speed Turning
Fwd flap servo, passive	S (AL)	S (AL)	S (AL)
Frd flap servo hardover, • 20 deg	S (LO)	S (LO)	S (LO)
Fwd flap servo hardover, - I 5 deg	S (AL)	S (AL)	S (AL)
Port flap servo, passive	s (O)	S (O)	S (O)
Port flap servo hardover, + 20 deg*	u **	S (AL)	U
Port flap servo hardover, -IS deg*	S (AL)	S (AL)	S (AL)
Stbd flap servo, passive	S (O)	S (O)	S (O)
Stbd flap servo hardover, + 20 deg*	• •	S (AL)	U
Stbd flap servo hardover, - I 5 deg*	S (AL)	S (AL)	S (AL)
Rudder servo, passive	S (O)	S (O)	S (O)
Rudder servo hardover, + 12 deg	S (LO)	S (LO)	5 (LO)
Rudder servo hardover, - 12 deg	S (LO)	s (LO)	S (LO)

U = Unsafe; S = Safe; (O) = Operational; (LO) = Limited operation possible; (AL) = Ship will automatically land.

*With a dual tandem actuator configuration this failure mode is eliminated.

● *If the ship is landed within 10 s after failure, and no helm action raker place during this time, this failure is safe.

Table II.A.2-3. SUMMARY OF ELECTRONIC FAILURES

Failure Mode	High-speed Straightaway Hard Over (+)	High-speed Straightaway Hard Over (-)	High-speed Straightaway Dead	Low-speed Straightaway Hard Over (+)	Low-speed Straightaway Hard Over (-)	Low-speed Straightaway Dead	High-speed Turning Hard Over (+)	High-speed Turning Hard Over (-)	High-speed Turning Dead
Forward acceleration loop	S (LO)	S (AL)	S (O)	S (LO)	S (AL)	S (O)	S (LO)	S (AL)	S (O)
Pon acceleration loop	S (O)	s (O)	S (O)	S (O)	S (O)	s (O)	S (O)	S (O)	S (O)
Stbd acceleration loop	s (O)	s (O)	S (O)	S (O)	S (O)	S (O)	S (O)	S (O)	S (O)
Height loop	S (LO)	S (AL)	S (LO)	S (LO)	S (AL)	S (LO)	S (LO)	S (AL)	S (LO)
Fitch gyro	S (LO)	S (AL)	S (O)	S (LO)	S (AL)	S (O)	S (LO)	S (AL)	S (O)
Pitch compensation, fwd	S (AL)	S (LO)	S (O)	S (AL)	S (LO)	S (O)	S (AL)	S (LO)	s (O)
Pitch compensation, aft	s (LO)	S (AL)	S (O)	S (LO)	S (AL)	S (O)	S (LO)	S (AL)	S (O)
Roll loop	S (AU	S (AL)	S (O)	S (AL)	S (AL)	S (O)	S (AL)	S (AL)	S (O)
Heading hold loop	S (O)	S (O)	s (O)	S (O)	S (O)	S (O)	S (O)	S (O)	S (O)
Helm loop	S (M)	S (M)	S (M)	S (M)	S (M)	S (M)	S (M)	S (M)	S (M)
Yaw rate loop	S (LO)	S (LO)	S (O)	S (LO)	S (LO)	S (O)	S (LO)	S (LO)	S (O)

S = Safe; (O) = Operational; (LO) = Limited operational possible; (AL) = Ship will automatically land; (M) = Must manually land.

(U) These failure modes and effects studies resulted in several significant changes to the PHM control system* as follows:

- A second vertical gyro was added to eliminate unsafe ship responses associated with a hardover roll gyro failure or with a dead roll failure while in a banked turn.

- Dual-roll electronics channels were added for the same reason.

- A failure detection and automatic landing circuit was added to cause ship to land when the difference in the two roll channel outputs exceeds 10^{o} for more than 100 ms. This circuit was added to assure safety in the event of dead or hardover failures in the roll gyros or electronics while in a sharp turn.

- Dual tandem actuators were chosen for the after flaps to eliminate (for practical purposes) hardover failures of either after control surface servo. A hard-down failure of either aft control surface was shown by simulation studies to be potentially unsafe; however, the total probability of a hard-down failure of the dual tandem actuator was shown by analyses to be less than $2/10^{11}$ operating hours; hence, the dual tandem practically eliminates the hardover failure of an aft control surface servo.

- Scaling limits are selectively applied to the output of each control electronics channel such that a balance in authority exists between the various signals feeding into each servo.

*See Reference II.A.2-1 for detailed discussion of the PHM control system development.

By maintaining a careful balance of the limits, most single failures can be effectively counterbalanced by the other inputs to the servo, resulting in fail-safe, and often fail-operational capability.

(U) With the incorporation of the features identified in Section 2.3 above, the ship has either complete operational capability, or limited operational capability, for approximately 70% of all single-level failures analyzed, and the ship was shown to be fail-safe for all single-level failures induced.

(U) With regard to the safety of the ship in large seas, there have been several specific craft configuration and control system characteristics developed which have led to the capability of the hydrofoil ship to operate in extreme sea conditions with safety.

(U) Foremost among the craft configuration characteristics which provide the capability is the canard configuration. It is a demonstrated fact that hydrofoils operating in rough water can and do encounter waves so large that the forward foil(s) will come out of the water (foil broach). When that occurs, the lift is lost and the ship rapidly becomes hullborne. For the canard configured craft, the bow simply drops until it hits the water and then the hydrodynamic forces on the hull terminate the drop and the ship quickly resumes foilborne operation. PCH-1 and TUCUMCARI, for instance, have operated beyond their design sea states on many occasions where the forward foil broaching and subsequent hull slamming were occurring many times, per minute.

(U) With a conventionally configured ship, in large waves one forward foil often becomes unwetted while the other foil remains immersed. Under these conditions, roll moments are induced into the ship. Countering this roll moment with the immersed foil causes the ship to land momentarily under such circumstances. Such action may be attenuated if reasonable degree of roll control can be placed on the after foil.

(U) Other large sea safety considerations are associated with the directional stability characteristics and with the roll control authority which have been discussed in previous sections.

2.4.8 Summary of Design Capabilities

(U) The design knowledge and tools necessary to develop hydrofoil ships with desirable and required operational capabilities have been demonstrated and well documented. This capability is shown to be on very solid grounds for current hydrofoil ships, as is well demonstrated by the TUCUMCAHI, HIGH POINT Mod 1, and PEGASUS operational trials.

(U) In a look forward to future ships, it would appear that in most respects the tools and technology are well honed to develop systems to meet most, if not all, system requirements. In that regard, definitive requirements are currently lagging behind capabilities. Completion of Volume 3 of the Hydrofoil Design Criteria and Specifications - "Ship Controls and Dynamics" - later this year will close that gap and put the requirements back on a par with design capabilities.

(U) In looking forward to larger ships such as the proposed HOC, the capabilities documented herein should be more than adequate for extrapolation and problem identification, which is the first major step in such a development.

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II. STATUS OF VEHICLE TECHNOLOGY

A. TECHNOLOGICAL PERFORMANCE FEATURES

3. INTACT AND DAMAGED STABILITY

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II.A TECHNOLOGICAL PERFORMANCE FEATURES

3. INTACT AND DAMAGED STABILITY PERFORMANCE FEATURES

3.1 INTRODUCTION

(U) This section will discuss the stability and buoyancy criteria for hydrofoil ships, including the topics of intact stability, floodability, and damaged stability. The application of the criteria to existing hydrofoil craft will be documented, and the implementation on future ships of this type discussed.

(U) Implicit to the treatment of these topics is the recognition that hydrofoil craft are, in essence, conventional naval craft with large topside weights and a sail area conditioned by the retraction of the lift systems. With foils extended, hydrofoil craft have more than adequate stability to withstand high wind and wave conditions; in most instances far greater stability than in ships of similar size and mission. Stability in the foils-extended condition is most often in excess of that required in the design sea environment for the craft. Retraction of the lift system for whatever purpose, for a military mission such as higher hullborne speed or while at anchorage, raises the vehicle center of gravity and increases the lateral wind area. This condition governs the ability of the craft to satisfy the stability and buoyancy criteria.

3.2 CRITERIA

(U) The stability and buoyancy criteria generally applied to hydrofoil craft can be found in References II.A.3-1 and

II.A.3-2. Of note is that while Reference II.A.3-2 specifically addresses "Advanced Marine Vehicles," the criteria contained therein for hydrofoil craft types is unchanged from the criteria of Reference II.A.3-1, which has been successfully applied to hydrofoil ships for more than a decade. All other craft types treated in Reference II.A.3-2 required a redefinition of criteria for their non-conventional hull forms.

(U) In summary, the governing stability and buoyancy criterion for hydrofoil and conventional ships is as follows:

> Intact Stability. Be able to sustain a wind velocity of 60 to 100 knots, depending on craft size and mission, without adverse roll (no greater than 15° max.> and with sufficient reserve restoring energy to withstand wind-accompanied waves.

(U) A general application to hydrofoil ships to date has been to specify an 80-knot wind.

(U) A second intact stability criterion addresses roll moments caused by lifting of large weights and side crowding of passengers. These have not had application to hydrofoil craft.

> High Speed Turning. Be able to turn at high speed (hullborne) with a heel angle of no more than 10° for new designs with adequate reserve restoring energy to prevent capsizing under the action of wind and waves.

(U) Previously not applied to hydrofoil ships due to relatively low hullborne speeds, this may have application to future designs with higher hullborne speeds.

Top Side Icing. Be able to sustain an ice accumulation of 3 to 6 inches (thickness specified by design requirements) on all exposed horizontal and vertical surfaces in a specified beam wind without adverse roll and with sufficient reserve restoring energy *to* withstand wind-accompanied waves.

(U) Previously not applied to hydrofoil ships due to anticipated areas of operation, this may be applied to "blue (white) water" designs, with potential application of unsymmetric icing conditions.

Damaged Flooding

- For craft less than 100 ft in length, be able to withstand the flooding of any single main compartment.
- For craft between 100 and 300 ft in length, be able to withstand the flooding of any two adjacent compartments.

Damaged Stability. Be able to have adequate stability under flooded conditions as in the preceding with no more than 15° of heel with adequate reserve restoring energy to sustain rolling from moderate seas.

3.3 PERFORMANCE OF EXISTING DESIGNS

(U) All existing hydrofoil craft have met the stability and buoyancy criteria as summarized in Table II.A.3-1.

(U) In general, the criteria have been applied and evaluated at two operating conditions, full load and minimum operating. The latter condition assumes one-third fuel load and reduced amounts of other disposal loads. For hydrofoil craft, as in most other naval ships, the minimum operating condition establishes the governing situation. Studies now being conducted at Grumman Aerospace Corporation

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Table II.A.3-1. INTACT AND DAMAGED STABILITY CRITERIA OF EXISTING HYDROFOIL CRAFT

CRAFT	COMPARTMENTS	MINIMUM COMPARTMENT LENGTH (in feet)	NUMBER FLOODABLE	STABILITY CRITERIA
PCH-1	6	10	1	Criteria not specified. (Vertical Foil Retraction)
AGEH-1	11	12	2	80 Knot Beam Wind Intact
PGB-1	6	7	2	80 Knot Beam Wind Intact
PGH-2	5	8	1	80 Knot Beam Wind Intact
PHM-1	8	10	2	80 Knot Beam Wind Foils Extended 50 Knot Beam Wind Foils Retracted Both Intact

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in assessment of criteria for future hydrofoil ships are addressing the reality of a minimum operating condition with near zero fuel.

(U) In application of the criteria to existing hydrofoil ships, the most difficult solutions have been those designs with main machinery aft. As a rule, in the minimum operating condition these craft trim bow up, tending to decrease the ability of the craft to sustain flooding aft. Prudent design practice has dictated that floodability analysis should be conducted over the craft's operating range of expected trims. Figure II.A.3-1 illustrates this analysis for PGH-1 FLAGSTAFF.

(U) The criteria for Damaged Flooding do not specify a minimum damage length for U.S. Navy ships under 300 ft in length. Recognizing that the criteria could be impractically satisfied by numerous closely spaced watertight bulkheads, a minimum effective bulkhead spacing of 5 ft and 3 percent LBP (in feet) has been recommended as a design standard. For FLAGSTAFF, Figure II.A.3-1, this results in a minimum bulkhead spacing of 7 ft.

(U) An additional recommended practice has been to assume that both adjacent foil foundation support bulkheads will be rendered non-watertight in the event of a hard grounding foilborne. General practice has been to assume that integral fuel tanks are flooded in measuring subdivision while remaining undamaged in assessment of damage stability.

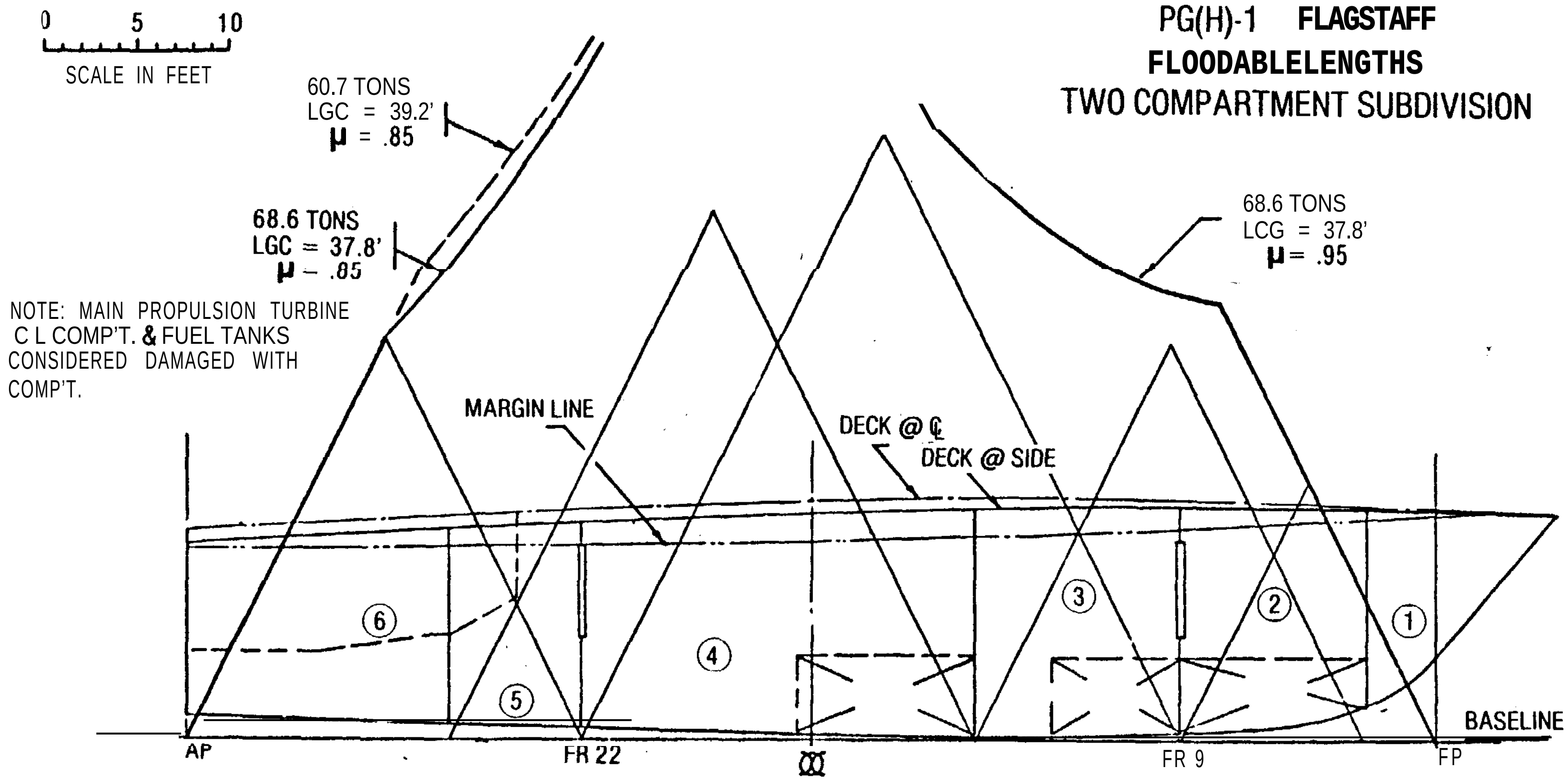

Figure II.A.3-1. PGH-1 FLAGSTAFF FLOODABLE LENGTHS, TWO COMPARTMENTS SUBDIVISION

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3.4 PERFORMANCE OF FUTURE DESIGNS

(U) Future hydrofoil craft, particularly larger ships, in view of past experience, should have little difficulty in providing adequate intact and damaged stability, principally because future craft will tend to have 90^o foil retraction arcs as opposed to near 180^o arcs on several of the existing hydrofoil vehicles. In addition, while lift system weight percentages (of full load) will tend to increase with displacement, strut lengths will tend to decrease in proportion to size, Reference II.A.3-3. Vehicle vertical centers of gravity will tend to a constant value (without fuel) as a function of the number of decks contained within the hull, illustrated in Figure II.A.3-2. Thus, while the overall effect will be a proportional rise in vehicle center of gravity with retraction (essentially a function of foil system weight percentage), sufficient stability can be maintained with 90^o retraction arcs.

(U) In addition, the effect of greater disposable loads, principally fuel, on future designs tending to cause a wider range in vertical center-of-gravity shift from full load to minimum operating conditions must be considered.

(U) Future hydrofoil ships will also tend to have greater length-to-beam ratios reducing the initial stability at low angles of heel. Initial stability up to approximately 15^o of heel can be stated in the form of:

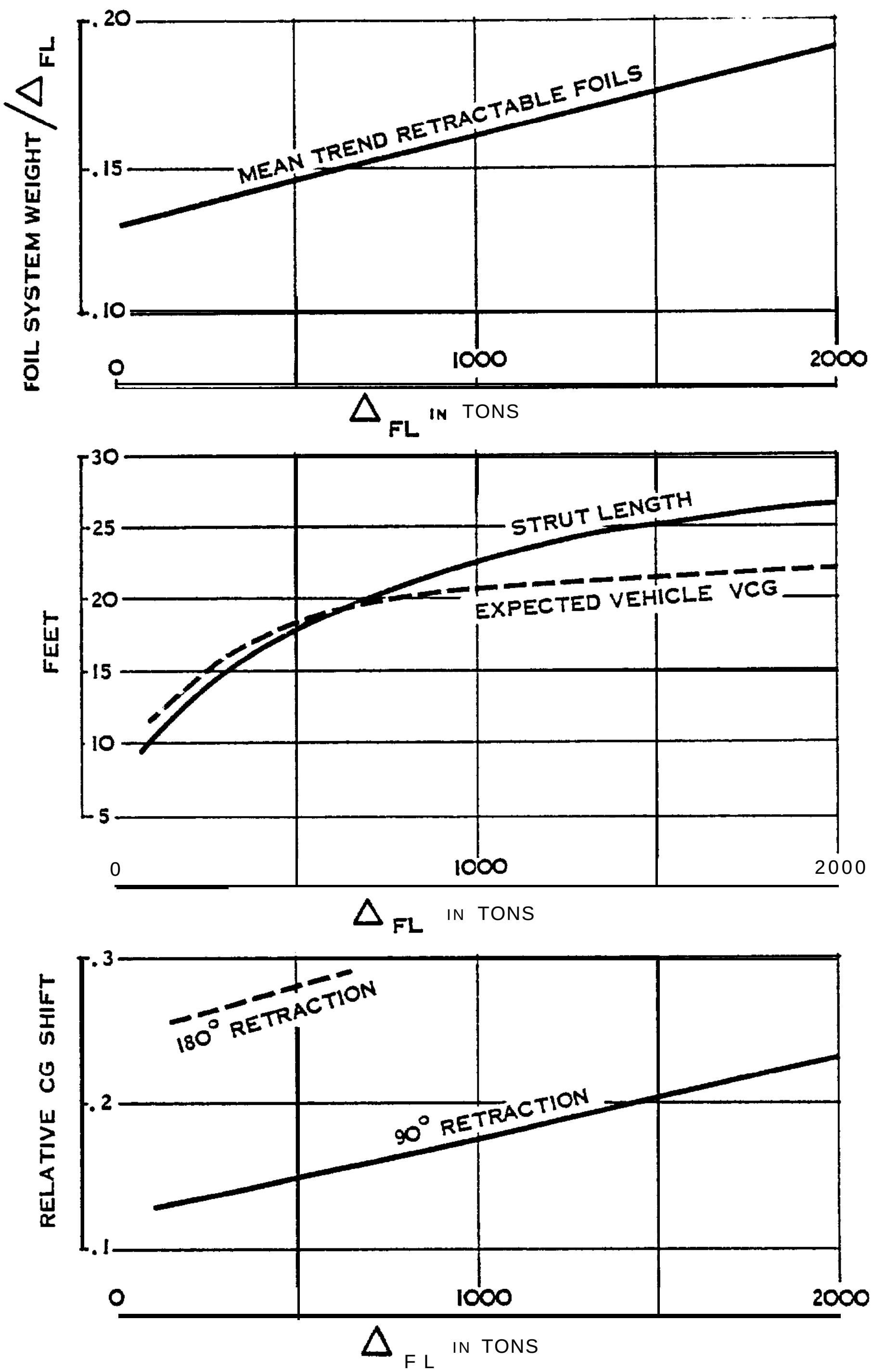

Figure II.A.3-2. CG, STRUT LENGTH, AND STRUT FOIL SYSTEM TRENDS WITH RETRACTION VS SHIP DISPLACEMENT

$$\overline{KB} + \frac{C_I \, LB^3}{\nabla} - \overline{KG}$$

Where: $\overline{KB}$ is the vertical center of buoyancy in ft

$\overline{KG}$ is the vertical center of gravity in ft

L is the ship waterline length in ft

B is the maximum beam at the waterline in ft

∇ is the volumetric displacement in ft^3

and C_I is a coefficient based on water plane form.

(U) If we assume a 100-ton displacement craft has a length of 100 ft and a beam of 20 ft, initial stability will be:

$$\overline{KB}_{100} + C_I \, (395) \, \overline{KG}_{100}$$

(U) If this hull is expanded to 1000-ton displacement without change in form and while retaining the L/B ratio of 5, initial stability can be shown to be:

$$2.15 \, \overline{KB}_{100} + 2.15 \, C_I \, (395) - \overline{KG}_{1000}$$

(U) However, expanding the 100-ton hull to 1000 tons, retaining the same form but increasing the L/B ratio to 6, initial stability will be:

$$2.02 \, \overline{KB}_{100} + 1.17 \, C_I \, (395) \, \overline{KG}_{1000}$$

(U) Thus, initial stability is potentially lowered by increasing L/B. However, vehicle vertical centers of gravity as shown in Figure II.A.3-2 are expected to tend to a constant value. Figure II.A.3-3 illustrates the overall expected trend.

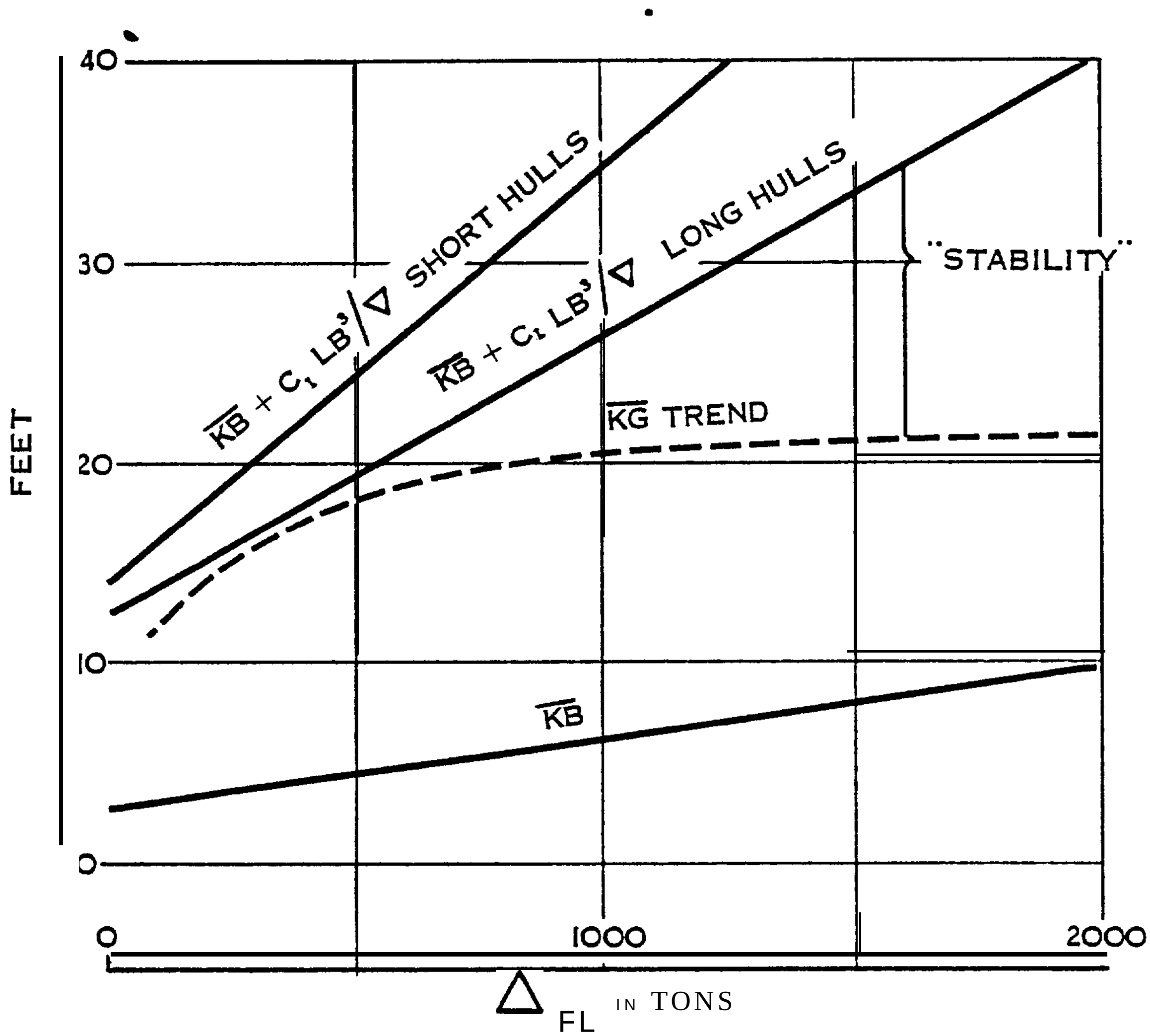

Figure II.A.3-3. $\overline{KB}$, $\overline{KG}$, STABILITY TRENDS

(U) Design studies conducted at Grumman Aerospace Corporation on hydrofoil ships up to 1600 tons have verified the ability to provide adequate stability to that displacement, as shown in Figure II.A.3-4.

3.5 HAZARDS UNIQUE TO THE CONCEPT

(U) Historical hazards unique to the hydrofoil concept have fallen into three types: log strikes, whale encounters, and hard grounding foilborne.

(U) The frequency of occurrence of the first two have been primarily a function of the operational areas chosen for hydrofoil ships on the West Coast of the United States in the Puget Sound and Southern California regions. Both are basically by reason of high vehicle speeds and have not endangered the watertight integrity of the hull.

(U) Hard grounding hazardsare a function of both high vehicle speed and navigational ability. Damage to the PGH-2 would in all probability have been less severe than would be incurred by a planing or displacement craft striking the same reef at similar speed. Continued attention should, however, be maintained in future designs to account for this potential hazard.

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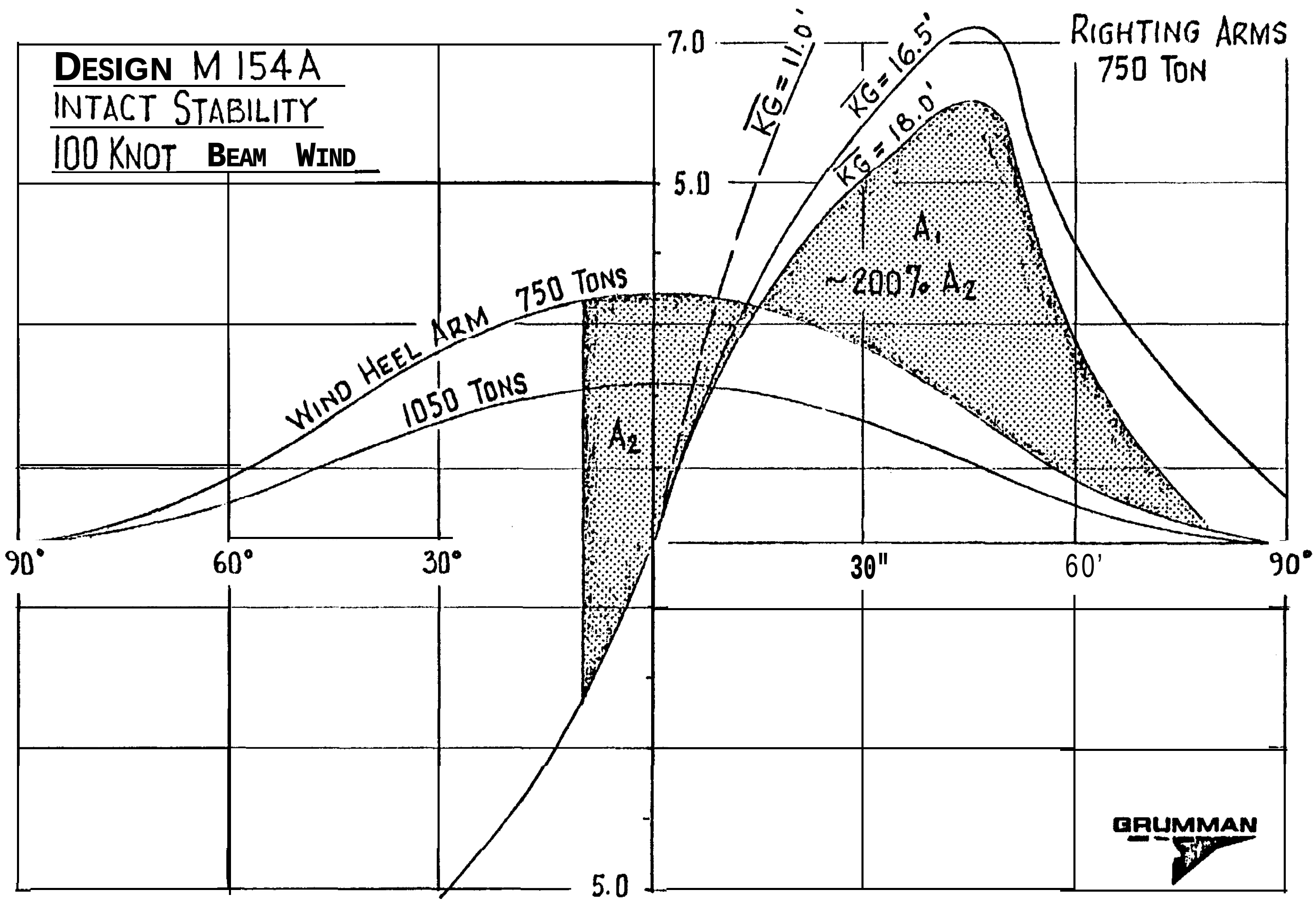

Figure II.A.3-4. DESIGN M154A. INTACT STABILITY, 100-KNOT BEAM WIND

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REFERENCES

II.A.3-1 "Stability and Buoyancy Criteria for U.S. Navy Surface Ships" - Sarchin and Goldberg, SNAME, November 1962.

II.A.3-2 "Current Status of U.S. Navy Stability and Buoyancy Criteria for Advanced Marine Vehicles" - Goldberg and Tucker, AIAA/SNAME, February 1974."

II.A.3-3 "The Large Hydrofoil Advanced Development Program" - Johnston and O'Neill, NSRDC Report SDD-11-C-16, October 1974.

II. STATUS OF VEHICLE TECHNOLOGY

A. TECHNOLOGICAL PERFORMANCE FEATURES

4. MATERIALS

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II.A. TECHNOLOGICAL PERFORMANCE FEATURES

4. MATERIALS

4.1 INTRODUCTION

(U) The U.S. Navy has designed, built, and operated hydrofoil ships for some 15 years. This has resulted in a steady accumulation of experience regarding the selection, fabrication, and maintenance of materials for hydrofoil ship systems:

- Lightweight aluminum hulls
- Struts and foils
- High speed propellers and impellers
- Control surfaces and associated components
- Coatings in high velocity flow

(U) In addition, a strong Navy/Industry demonstrated capability exists to perform material trade-offs and build practical operational hardware. It is important to recognize that in addition to the hydrofoil experience in The Boeing Company and Grumman Aerospace Corporation, an extensive group of subcontractors exists in the United States. For each item listed below, two to four contractors have experience in hydrofoil ship systems materials and component requirements and have produced hardware for service trials:

- Plates and extrusions
- Castings (propellers, impellers)
- Bearings and fittings
- Fairings and sealants

- Subassembly welding and fabrication
- Composite materials and construction

4.2 SUMMARY

(U) Since hydrofoil ships are weight critical (must be lifted dynamically) and operate in the marine environment, the overall material technical problems are severe. Important considerations in the selection of materials include:

- Strength to density ratio
- Modulus to density ratio
- Corrosion fatigue strength
- Corrosion (general and local)
- Fracture resistance (impact and sustained loads)
- Ease of fabrication

During the material selection process, all of these factors are optimized to the extent that the lowest cost material is utilized.

4.2.1 Hulls

(U) Experience with hydrofoil ships weighing 60 to 320 tons indicates that the 5,000 series aluminum alloys are the most practical hull materials (see Tables II.A.4-1 and II.A 4-2). Other potential candidates are listed below but at present they do not appear to offer sufficient improvement to displace aluminum.

Steel - too heavy since minimum available gages would not be much less than those of aluminum at present.

Table II.A.4-1. HULL AND SUPERSTRUCTURE MATERIALS

Craft	Aluminum Alloy	Form
PCH-1	5456-H321 5456-H311 6061-T6	Plate Extrusion Plate, Shapes
AGEH-1	5456-H321, H323, H343 5456-H311	Sheet, Plate Extrusion
DENISON	5456-H321 5456-H311	Plate Extrusion
PGH-1	Honeycomb Deck Panels 5456-H321, H343 5456-H311 Fiberglass	Bonded Sheet, Plate Extruded Plate Laminate
PGH-2	5456-H321 5456-H311 6061-T6	Sheet, Plate Extrusion Sheet, Forms
FHE-400	Alcan D54-S 6061-T6 7075	Sheet, Plate, Extrusions Plate Forging, Thick Plate
PHM-1	5456-H116/117, H112	Sheet, Plate, Extrusions

Table II.A.4-2. TYPICAL MECHANICAL PROPERTIES OF HULL ALLOYS

Alloy	Nominal psi Yield Strength[1] Base/Weld	Ultimate Tensile Strength,[1] .2% offset, in psi Base	% Elongation in 2 inches	Sheer Stress, oin psi Base	Modulus of Elasticity,! E, psi
5456-H321 and 5456-H116/H117	33,000/26,000	46,000	12	30,000	10.3x106
5086-H321 and 5086-H116/H117	28,000/22,000	40,000	8	25,000	10.3x106

[1] Specification properties from Reference II.A.4-1.

Fiberglass - (conventional) considered feasible but accounting for stiffness and deflections in design would be a problem. Construction experience is'very limited in this scale. Final weight comparison is not known, but probably would be higher than aluminum (used in PGH-1 pilothouse overhead).

Composites - (high strength fibers) could effect weight savings over aluminum (10-20 percent) but development cost and fiber costs are too high. For this application it currently has a low priority in NAVSEA Exploratory Development

Titanium - too expensive.

(U) Current hull weight fractions are reasonable at 15-20 percent. The emphasis must now be placed on hull fabrication cost reduction. This is directly related to the training and skill level of welders, improvements in welding and other joining processes and design innovation. The driving criteria for shell plating is pressure requirements of 6 to 75 psi (depending on location), thus stiffened aluminum plating (0.125-0.250 inches thick) is utilized. Wherever possible, these are extruded panels, although extrusion sizes are limited to that which can be produced through a 30-36 inch diameter die. Welding of the resultant complex shapes has been successfully accomplished by at least 5 aerospace/shipbuilding companies (The Boeing Company, Todd Shipyards, Grumman Aerospace Corp., Tacoma Boatbuilding Company, Peterson Shipbuilding Company and Lockhead Shipbuilding and Construction Company) and is well within the state of the art.

(U) With regard to large hydrofoil ships (2,500 tons), the material of choice is still likely to be aluminum. In-house Industrial Research and Development (IRAD) and government contract work are presently underway at Bell Aerospace Company, Rohr Industries, and Aluminum Company of America to develop and optimize the most efficient method of welding these materials.

4.2.2 Struts and Foils

(U) A progression of increasingly complex and higher strength materials has been used in hydrofoil ship struts and foils since 1960 (see Table II.A.4-3). These are:

- 1960-1965: HY80, HY100 Steels
- 1965-1970: AL 6061 + 4340 Steel, 17-4PH Steel
- 1970-1976: HY130, 15-5PH, 17-4PH Steels

(U) Promising candidates have been in development since the mid-60s and will be available for construction of larger hydrofoil ships.

- 1978-1984: Ti 6-2-l-l and Ti-6-4
- 1985-1990: High Strength Composites

(U) Confidence has been gained in the use of HY80, HYlOO, and 17-4PH steels. Preliminary design of HY130 struts and foils for the PHM has been completed and the detailed design and construction of a HY130 tail strut for the AGEH-1 is complete and should supplement the experience gained from KY-130 PCH Mod 1 after struts.

Table II.A.4-3. STRUT AND FOIL MATERIALS

CRAFT	ALLOY	FORM	APPLICATION
PCH-1	HY-130 HY-80 Steel	Sheet, Plate Sheet, Plate	Aft Struts Struts, Foils
AGEH-1	HY-80 Steel I-E-100 Steel HY-130 Steel	Sheet, Plate Sheet, Plate Sheet, Plate Forging	Strut, Foil Foil, Skin Aft Strut
DENISON	AISI 4130 Steel AL5456-H321 AL7079-T611 HY-80 Steel AISI 4130 Steel	Sheet, Plate Plate Forging Sheet, Plate Plate	Forward Struts and Foils Aft Pod Skin Aft Foil Struts Struts
PGH-1	4330 Modified Steel *Fiberglass AL 6061 T 653	Casting Laminate Forging	Support Fittings Main Foil Pods Strut Leading Edges Foils
PGH-2	17-4PH-H950 17-4PH-H950	Sheet, Plate Wrought	Struts Foils
FHE-400	18Ni Maraging Steel 250 CVM 18Ni Maraging Steel 250 CVM Inconel 718	Sheet, Plate Forging Forging	Struts, Foils Internal Fittings Strut and Foil Leading Edges
PHM-1	17-4PH (H1100)	Plate	Struts and Foils

*Initial pods were welded and riveted AL 5456-H321 plate

(U) Experience indicates that the following quantified properties are considered necessary for a viable material for the strut-foil system:

- Yield Strength 100 ksi*
- Corrosion Fatigue Strength - 30 to 40 ksi 10^8 cycles
- KISCC - 80 ksi $\sqrt{in}$
- ♍□⬩♦ ~ $60-75 per fabricated pound
- Heat Treatment - None required to develop weld properties

In addition the following general attributes are important overall material considerations:

- Ease of Fabricability - amenable to shipyard practice
- Ease of Repair - amenable to shipyard/field repair
- Distortion - minimum during fabrication
- Availability - routinely produced to military/ commercial specifications
- Corrosion Resistance - for both continual and intermittent exposure

(U) Obviously the design process allows some give and take with these properties, especially as a function of ship size. For example, in ships of less than 100 tons, solid machined foils have been very successful and welding is not a primary factor. In large ships sizes (> 500 tons) strength to weight ratio is more critical; and with hydrofoil ships involving nonretractable foil systems, the corrosion behavior is paramount.

* 1 ksi = 1000 lbs/sq. in.

4.2.3 Coatines

(U) Interior and exterior hull Military Specifications coatings exist and have been used on many aluminum Navy ships. These coatings are generally acceptable for hydrofoil ships but extra care must be taken during application because of the more severe impact and erosion requirements.

(U) Struts and foils made of low alloy steels and aluminum require protective coatings primarily to prevent corrosion fatigue and secondarily to prevent cavitation damage. A series of coatings has been evaluated in laboratory tests and service trials since the early 1960s and the capability now exists for coating life of 500 foilborne hours without major repairs. Recently evaluated polyurethane and epoxy coatings require minor touchup (taking about 2 hours) applied monthly. Resistance to impact damage and retention of coating adhesion strength in the marine environment appear to be the most desirable attributes for acceptable strut/foil coatings.

4.3 HULL

4.3.1 Materials and Construction

(U) Either 5086 or 5456 aluminum alloys are used for hydrofoil ship hulls. These alloys containing 4 to 5 percent Mg and minor amounts of Mn, Cr, and Fe are good for general marine use, are weldable and do not require heat treatment. The aluminum alloy temper commonly used in the 1960s was high strength H321. However, the discovery of the exfoliation sensitivity of this temper in the

"Swift" boats in Vietnam, led to development of new H116/H117 tempers. Unfortunately, the H321 temper *was* used in the hulls of many of the existing hydrofoil ships and a number of cases of exfoliation attack occurred on both the inside and outside of hydrofoil ship hull plating. In addition, on the TUCUMCARI (PGH-2) a number of minor deck cracks appeared due to (a) excessive loading on the thin deck plating which resulted in considerable local waviness, (b) stress concentrations at stiffened frame intersections and prior deck repair welds, and (c) possible stress corrosion of thin H321 temper. In many cases the affected plate was removed in large patches and the exfoliation resistant temper H116/H117 inserted. There has been no occurrence of exfoliation of H116/H117 tempers in either service or extensive laboratory evaluation of heat sensitized material.

(U) The mechanical properties of the aluminum alloys used are listed in Tables II.A.4-2, II.A.4-4, II.A.4-5, and II.A.4-6. There is no difference in mechanical properties between the old H321 and new H116/H117 tempers. As can be seen, aluminum alloys have low corrosion fatigue strength and require coatings for long-term protection against both fatigue and general corrosion attack.

(U) The fabrication characteristics of aluminum are deceptively simple. The alloys are soft, easy to machine and form. However, they are deceptive in that they are very easy to weld poorly. The weld properties are most sensitive to weld start-stop crater cracks, cleanliness, gas moisture content, and welder skill. Macro and micro-porosity are easy to entrap and distortions tend to be

Table II.A.4-4. TYPICAL MECHANICAL PROPERTIES OF ALLOYS

Grade	Yield Strength (ksi)*	Tensile Strength (ksi)*	% Elongation in 2 in.	% Reduction in Area	Charpy Vee Notch (ft-lbs @ R.T.)+
Steels					
HY 80	88	103	27	70	100
HY 100	100	120	22	65	
HY 130	140	150	21	65	50
Maraging					
18 Ni	184	191	15	65	60
17-4 PH	150-170	155-175	14-20	58-64	13-50
15-5 PH	150-170	155-175	14-20	58-64	13-50
Titanium					
Ti-6211	110	125	12	30	40
Ti-6-4	120	135	12	25	20
Nickel					
Inconel 718	147-175	150-200	12-24	15-30	50-25
Inconel 625	60	120	50	48	

* 1 ksi = 1,000 psi
\+ R.T. = room, or ambient, temperature

Table II.A.4-5. FATIGUE PROPERTIES OF METALS

Grade	Fatigue Strength[1] @ 10^8 cycle Smooth (ksi)* Air	SRW[2]	Notch (ksi)* Air	SRW
Steels				
HY 80	42	9	20	4
HY 100	66	12	16	4
HY 130	67	9	43	4
Maraging				
18 Ni	65	7	35	4
17-4 PH[3]	60	20	30	10
—	—	—	—	—
Aluminum				
5 456	20	< 5	16	< 5
Titanium				
Ti-6211	38	40	20	20
Ti-6-4	55	55	38	35
Nickel				
Inconel 718	84	25	25	20

1 Rotating Cantilever Specimens, 1,450 cpm

2 SRW - Severn River Water. Past experience has shown this usually has the same effect as seawater. (See text)

3 Base metal only ST + Aged at 1,135°F, weld results inconclusive.

Table II.A.4-6. TYPICAL CORROSION CHARACTERISTICS, COST, AND MODULUS OF ALLOYS

Grade	Cost	Modulus, E, in psi	Corrosion Resistance: General	Stress Corr.Cr.	Pitting and Crev.	Erosion & Cavit.
Steels						
HY 80	55 ¢/lb.	29x106	Fair (Uniform)	Good	Fair to Poor	Poor
HY 100	60 ¢/lb.	29x106	Fair (Uniform)	Good	Fair to Poor	Poor
HY 130	75 +/lb.	29x106	Fair (Uniform)	Good	Fair to Poor	Poor
Maraging						
18 Ni	$3.50/lb.	28 $x10^6$	Fair to Good	Bad	Good	(Fair?)
17-4 PH	$2.50/lb.	28 $x10^6$	Good	Good	Very Bad	Good
Aluminum						
5,456	60 +/lb.	$10.3x10^6$	Good	Good	Fair	Bad
Titanium						
Ti-6211	$8-10/lb.	$16x10^6$	Excellent	Excellent	Excellent	Excellent
Nickel						
Inconel 625, 718	$5-6/lb.	$30x10^6$	Good	Good	Fair	Good

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high in the thicknesses employed due to the low melting temperatures and large heat sink. Experience has shown that it is possible to achieve excellent weld quality in shipyard environments but extreme conscientiousness and care are required on the part of the welders. Specifications exist, but are based to a large extent on steel fabrication criteria. Aluminum fabrication specifications for thin gages employed in hydrofoil ships are under review and modification at present.

(U) In short the lessons learned and which are being applied in the PHM program consist of:

- Design Simplification
- Rigorous training of welders
- Care and attention to detail while welding

4.3.2 Hull Coatings and Interior Materials

(U) Interior and bilge coatings use standard Navy paints (MIL-P-24441) on aluminum ships. There are no unique hydrofoil ship requirements.

(U) For exterior hull coatings, with antifouling capability standard Navy paints (MIL-P-24441) with MIL-P-16189 or MIL-P-15931 antifoulant coating are acceptable. The Glidden No-COP Antifoulant coating system is also acceptable and may provide a longer effective coating life (24 months versus 18 months). Experience indicates that no special problems exist with the hull/water interface at either hydrofoil ship take-off or landing. For exterior decks standard Navy nonskid paints (MIL-D-23003 Type II) are acceptable.

4.3.3 Fire Protection

(U) This topic is discussed in the Auxiliary Systems section II.B.3.

4.4 STRUTS AND FOILS

(U) The mechanical properties and other characteristics of the materials discussed are listed in Tables II.A.4-4, II.A.4-5, II.A.4-6.

4.4.1 Materials in Use

4.4.1.1 Aluminum 6061 (Foils on PGH-1)

- Solid machined foils
- Requires coatings
- Excellent choice for small (< 100 ton) ship
- Inexpensive ($10,000 each)
- 900 hours foilborne service to date

4.4.1.2 High Strength Steels (4330, struts on PGH-1)
(18 Ni Maraging, struts and foils on FHE-400)

- Requires coating
- Susceptible to stress corrosion cracking in the welds
- Low toughness
- Not being pursued as strut/foil candidate

4.4.1.3 HY 80 (3 percent NI-1 1/2 percent Cr) (Struts and foils on PGH-1 Mod 0, Strut-foil frames on AGEH-1)

- Welding and fabrication procedure well in hand
- No major structural cracking or other material/ fabrication problems after 1,207 hours of service

- Demonstrated repairability in the field and compatible with shipyard practice
- Requires a coating
- Limited yield strength, therefore as ship weight increases it becomes a less viable candidate

4.4.1.4 HY 100 Similar composition to HY 80, but plates are heat-treated at the mill (strut/foil plates on AGEH-1)

- Same comments as HY 80
- Due to adequate yield strength, this alloy remains an attractive high strength steel candidate

4.4.1.5 HY 130 (5 percent Ni)

4.4.1.5.1 PCH-1 MOD 1 used in combination with HY 80

(U) The major strut/foil modifications to PCH-1 in 1970-1972 involved significant changes to the strut/foil system. Portions of the new struts and foils were designed for HY 130 material by The Boeing Company (see Figure II.A.4-1) and fabricated by a local subcontractor. No major problems have been encountered in the 522 foilborne hours since the modifications were completed.

4.4.1.5.2 Preliminary Design for PHM Struts and Foils

(U) In 1973, the Grumman Aerospace Corp. was contracted to complete preliminary design of a ship-set of PHM struts and foils made of HY 130 material. The overall guidelines required that the weight and configuration of the new structure be identical to the existing 17-4 PH structure. The important output of this work consisted of:

- Consideration of the unique problems associated with the "water box" up the struts (PHM is water-jet-driven)

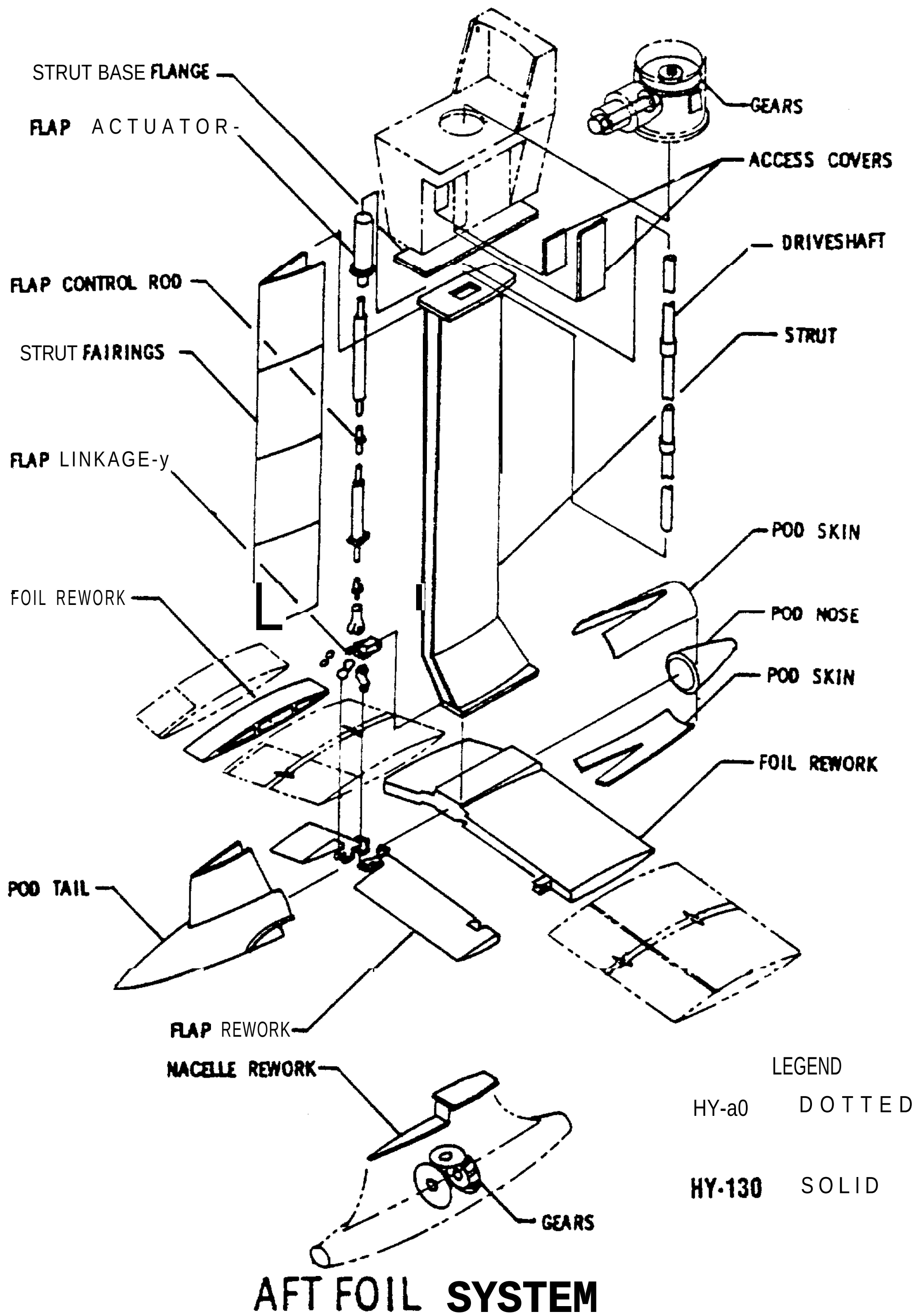

Figure II.A.4-1a. PCH-MOD 1 HY 130 MODIFICATIONS TO STRUT/FOIL SYSTEM

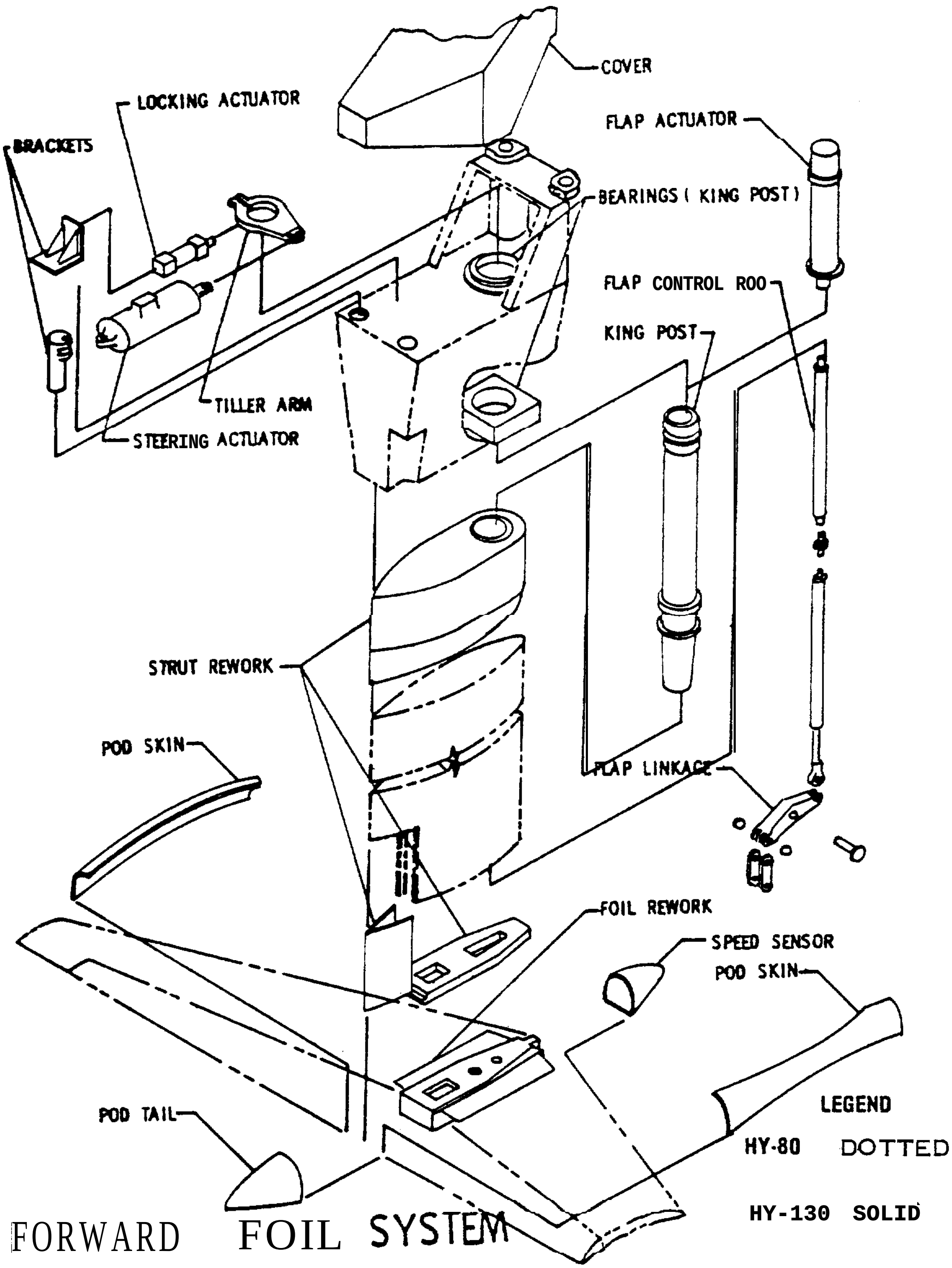

Figure II.A.4-1b. PCH-MOD 1 HY 130 MODIFICATIONS TO STRUT/FOIL SYSTEM

- Internal and external corrosion protection
- Development of a Fabrication Document, consistent with existing Navy documents
- Procedures to maximize internal weld inspectability
- Weld sequencing and other techniques to minimize distortions
- Development of procedures to maximize structural integrity

4.4.1.5.3 Design and Fabrication of an HY 130 Tail Strut for AGEH-1

(U) The design and fabrication of this structure, recently completed, has incorporated all prior HY 130 experience and particularly has validated the preliminary design work accomplished in 4.4.1.5.2 above. The significant points from this work include:

- Validation of the fabrication procedures (see Figures II.A.4-2, II.A.4-3, II.A.4-4)
- Realistic appraisal of the contour tolerances achievable
- Confidence and experience of the manufacturer in the use of HY 130. This will be reflected in cost reduction in future HY 130 construction due to the elimination of risk. Due to the uniqueness of this one-of-a-kind strut, extensive hand welding was used. For multiple unit manufacturing, additional tooling and automated welding would be utilized. This saving is estimated to be 15 to 20 percent and does not include the cost reductions due to being lower down on the learning curve.

In summary of HY 130 for struts and foils, the material exhibits these characteristics:

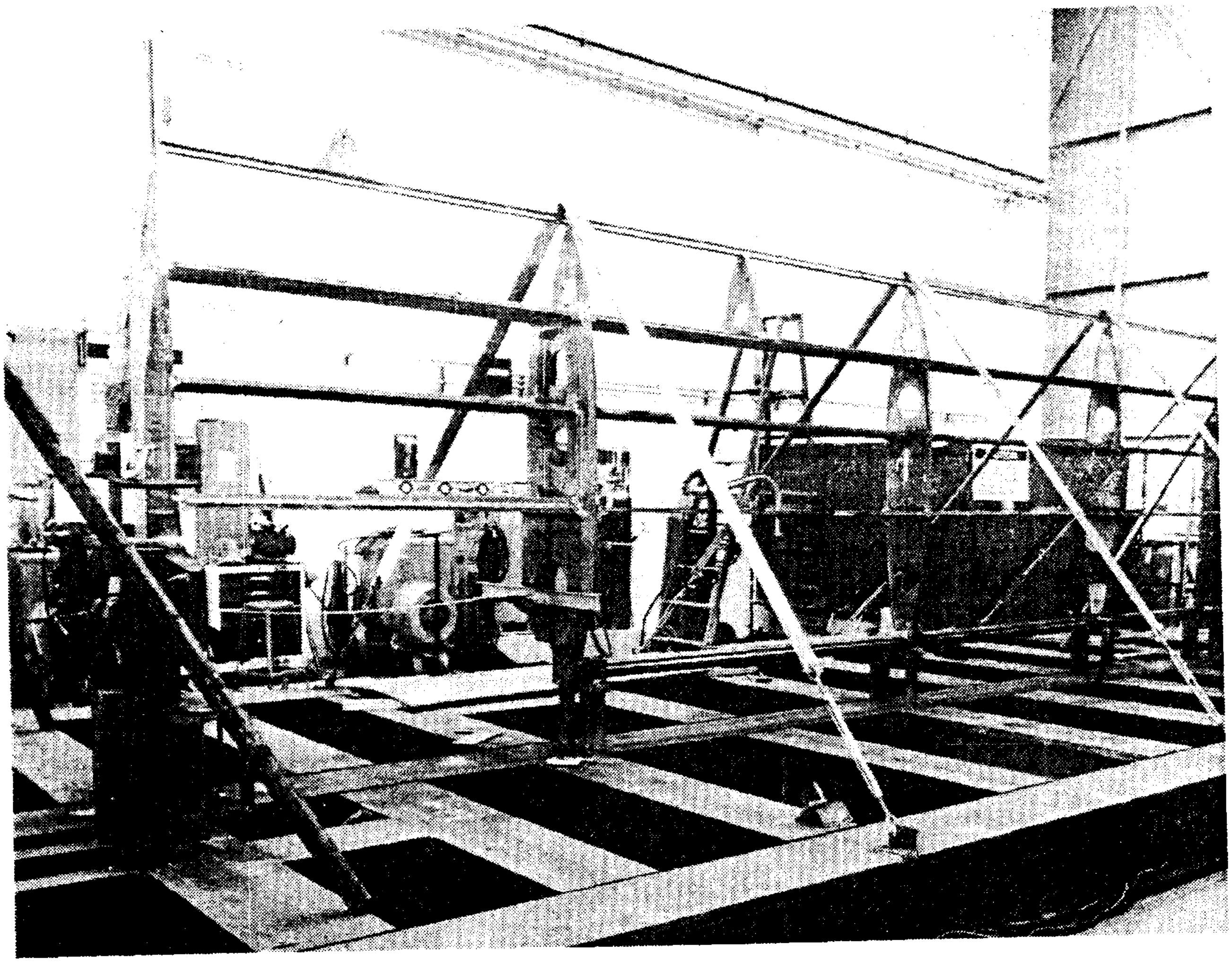

Figure II.A.4-2. AGEH-1 HY130 FOIL STRUT
(STRUT-RIB-SPAR ASSEMBLY PORT SIDE)

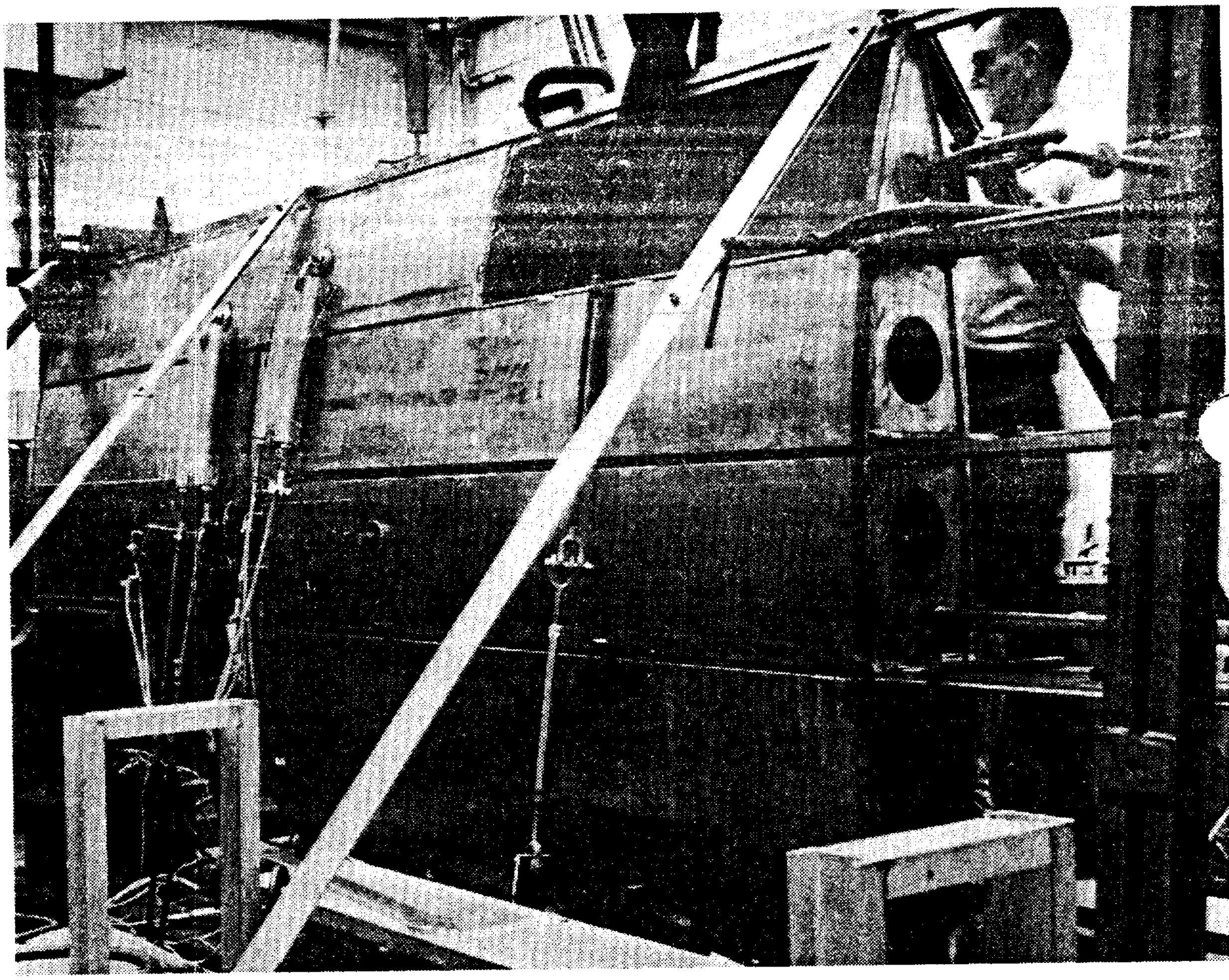

Figure II.A.4-3. AGEH-1 HY130 FOIL STRUT (UPPER STRUT SKIN INSTALLATION PORT SIDE LOOKING DOWN)

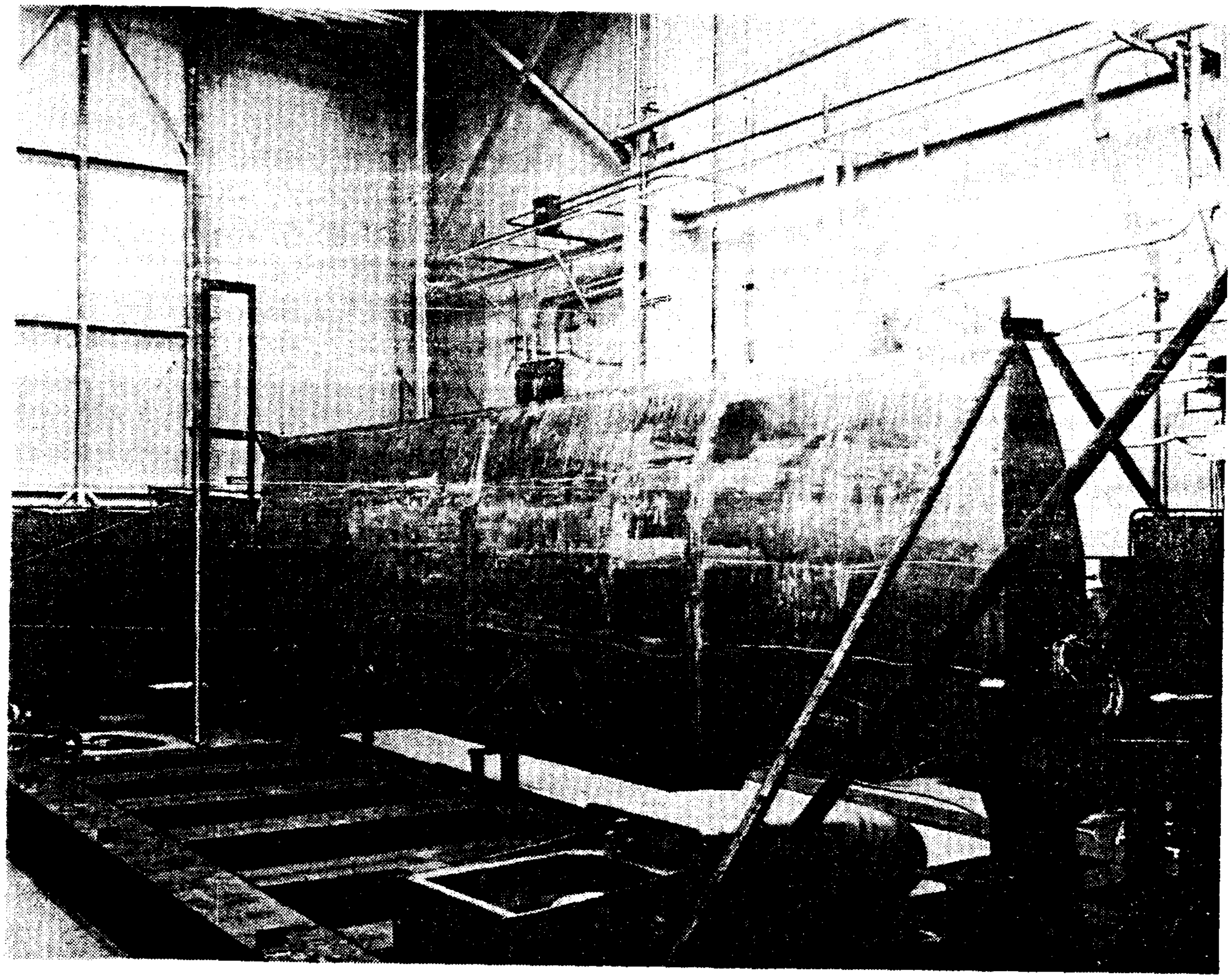

Figure II.A.4-4. AGEH-1 HY130 FOIL STRUT
(TAIL STRUT WELDMENT STARBOARD SIDE)

Favorable

- Desirable mechanical properties (particularly strength)

- No heat treatment required with resultant:

  Relatively low amount of rework, cost and distortion, compared to PH steels and titanium

  Field Repairability

Unfavorable

- Weak industrial base (Navy submarine use is other primary use>

- Requires protective coating

4.4.1.6 17-4 PH Stainless Steel

4.4.1.6.1 H 950 Condition - Struts and Foils on PGH-2

(U) TUCUMCARI foils were solid machined 17-4 PH steel and the struts were a combination of 17-4 PH and 304 stainless steel (inadvertently used in manufacture and has a low yield strength of 30 ksi). This craft had a service life of 1,200 foilborne hours before her grounding and subsequent decommissioning. The strut/foil system was examined in detail and the flaws categorized to service-related and grounding-related. Significant findings from PGH-2 include:

- The grounding on a submerged reef at 40 kn caused surprisingly little personnel injury (several crew members hospitalized for about one week). The forward strut took the majority of the impact and collapsed all of aluminum structure in its path. It did, however, remain intact and connected to the hull at its yoke.

- There were numerous pre-existing fatigue cracks. In many cases these were associated with the low strength 304 stainless steel/17-4 PH welds. In some instances cracks were associated with section discontinuities (e.g., thick to thin plate welds) or weld defects. The few major cracks found have been attributed to both of these causes. (See Figure II.A.4-5.)

- Stress corrosion of this sensitive alloy (H 950) condition was not a major problem although one SCC crack was found at the strut/foil connecting lug roots.

- There was some localized corrosion of the 304 stainless steel weld and adjacent plate, but no severe pitting or crevice attack at the many numerous potential sites.

- 303 stainless steel and high strength steel bolts corroded but A286 steel bolts were intact.

(U) The significant lessons learned and applied in the PHM program are:

- Control of material during fabrication

- Attention to design and fabrication detail is mandatory

- Localized corrosion of 17-4 PH steel is not a problem due to foil retraction and natural repassivation

- Use A286 fasteners in 17-4 PH steel plates

4.4.1.6.2 17-4 PH Steel (H 1100 and Direct Age, PHM-1)

(U) This alloy was selected for PHM based on its strength, corrosion, and fatigue resistance and its successful application on PGH-2.

(U) It was quickly recognized that the heat treatment of this highly complex alloy would create difficulties in distortion and possible quench cracks at uninspectable locations. A major effort was conducted to analyze and simplify welded joints, particularly "blind" ones. This was pursued so that the level of detail now in

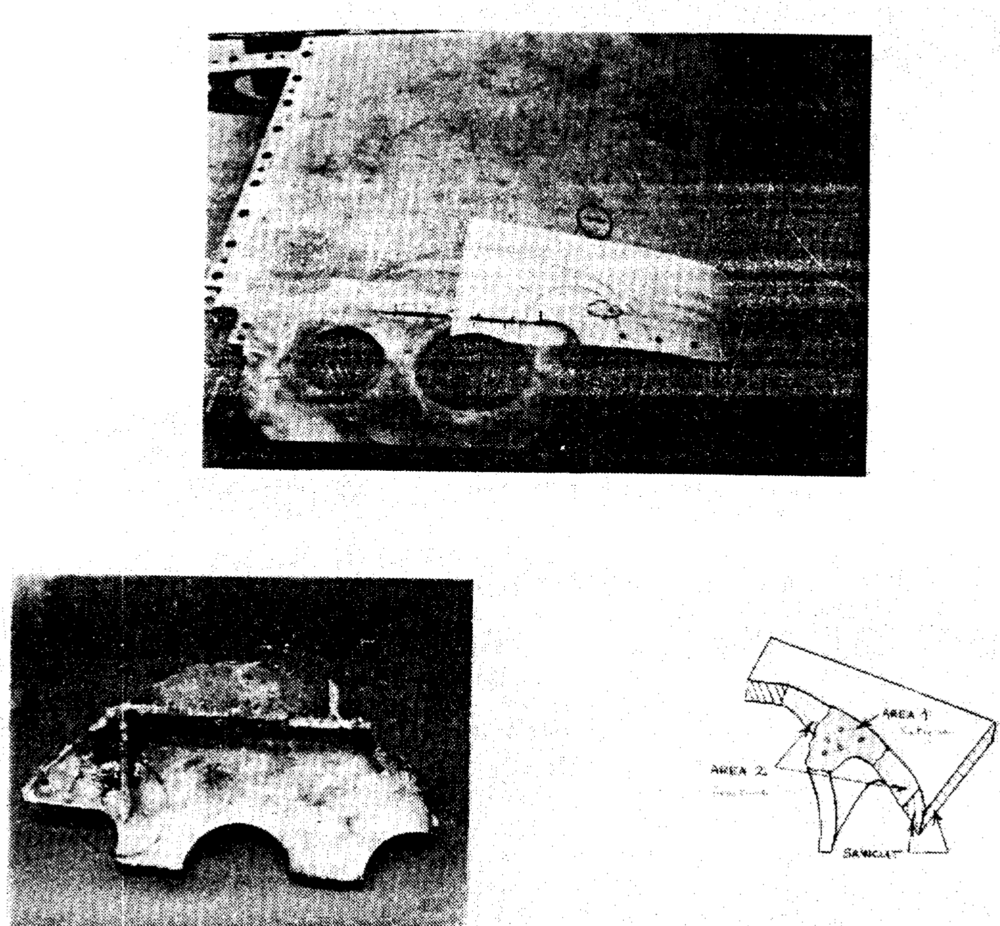

Figure II.A.4-5. TYPICAL FAILURE ON TUCUMCARI (PGH-2) FORWARD STRUT the PUN-1 strut/foils is higher than in any previous system. In order to achieve adequate toughness and overcome heat treatment difficulties, the strength allowable was reduced from 130 ksi to 100-110 ksi yield. The heat treatment required poses these difficulties:

- Lack of available furnaces (for the PHM strut, only one large enough in U.S.>
- Distortion, quench cracks, and associated rework
- Handling difficulties in and out of furnace
- Limitation on piece size has impact on applicability to larger ships
- Weld repair in the field limited to minor low strength work

(U) The complexity of this alloy results in unpredictability. Minor heat treatment variables, alloy chemistry variations, and plate surface treatment cause, for example, variations in laboratory corrosion behavior. Recent experience in the Boeing Commercial Jetfoil (which uses 15-5 PH steel, an alloy with a chemistry specification overlapping 17-4 PH) indicate that continuous immersion can indeed cause corrosion attack. This leads to the possibility that 17-4 PH steel may require a protective coating, which obviates one of its prime advantages.

(U) In summary these factors would indicate that 17-4 PH (at 130 ksi yield) is a less viable strut/foil candidate than HY 130:

- Possible need for coating on 17-4 PH
- Heat Treatment
- Field Repair

4.4.1.7 (U) 15-5 PH is an alloy that has a chemistry specification which overlaps that of 17-4 PH steel; however, it is only produced in the vacuum melt condition, which is an advantage. It has been used in the Boeing commercial hydrofoil, JETFOIL, and performance to date has been the same as would be expected of 17-4 PH (severe pitting in locations continually immersed in seawater). In general this alloy has similar characteristics to 17-4 PH steel. One of the reputed advantages is the elimination of ferrite with increased ductility in the weld. However, this does not always occur, which is characteristic of the variability of 15-5 and 17-4 PH stainless steels. The cracking occurring so far in JETFOIL foils is due to overstress conditions rather than an inherent metallurgical problem. The difficulties with repair welding 15-5 PH are the same as 17-4 PH.

4.5 OTHER CANDIDATE MATERIALS

4.5.1 Titanium

(U) This attractive material has been considered for strut/foil applications for over 10 years. Funding limitations have prevented the development of detail structural analysis and fabrication.

(U) Advantages include:

- High strength to weight ratio
- Corrosion fatigue characteristics
- Corrosion resistance

(U) The areas of concern include:

- Low modulus
- Oxygen protection at the backside of inaccessible welds

(U) Present activities in research include:

- Significant spin-off in titanium technology from the hull plate program
- Initial design analysis regarding the low modulus
- Preparation of a box beam specimen (see Section 4.6.1)

4.5.2 Advanced Composites

(U) These materials utilizing graphite or boron fibers are also attractive candidates and have been studied extensively for hydrofoil application. Current research and development involve:

- Material properties in the marine environment
- Load transfer techniques
- Definitions of cost/benefit payoffs for hydrofoil applications
- Detail design and construction of two box beams, see Section 4.6.1 below
- Detail design and construction of two flaps for PCH-Mod 1 service and laboratory evaluation.

4.5.3 Clad HY 130

(U) An interesting possibility under study to improve the corrosion resistance of HY 130 steel involves roll cladding the steel plates with a nickel base alloy (Inconel 625) prior to fabrication.

- The materials are weld compatible
- Production feasibility of composite plate has been demonstrated
- Mechanical properties of HY 130 base plate (with cladding) and welds are satisfactory

- HY 130 steel plate heat treatment does not affect Inconel 625 corrosion properties
- Corrosion and corrosion fatigue of Inconel 625 are excellent

(U) This approach would use the HY 130 plate as the structural member and the Inconel 625 cladding for corrosion protection. There is further work required with regard to forming and detailing of the composite weld joint.

4.5.4 Castable Polyurethane on a Steel Substrate

(U) A novel approach to strut/foils concerns fabricating a steel shape without regard to contour and distortion and then casting the hydrodynamic surface on it. The substrate can be a crude shape designed for strength and ease of fabrication with attendant performance and cost-saving benefits. Over this fabricated structure is cast, to required hydrodynamic contour, a polyurethane compound ranging in thickness from 1/8 to greater than 2 inches, which will provide corrosion and impact resistance.

4.6 LABORATORY EVALUATION

4.6.1 Hydrofoil Tapered Box Beam Program

(U) Although small laboratory coupon testing is useful as a screening process, a more meaningful material evaluation can be achieved from test on fabricated sections. For this reason a specially designed test segment of a strut/foil system called a tapered box beam was designed and is shown in Figures II.A.4-6 and II.A.4-7. This (5'x2'x4") section simulates (four cells created by an intersecting rib and spar) a typical foil section. The plate thickness

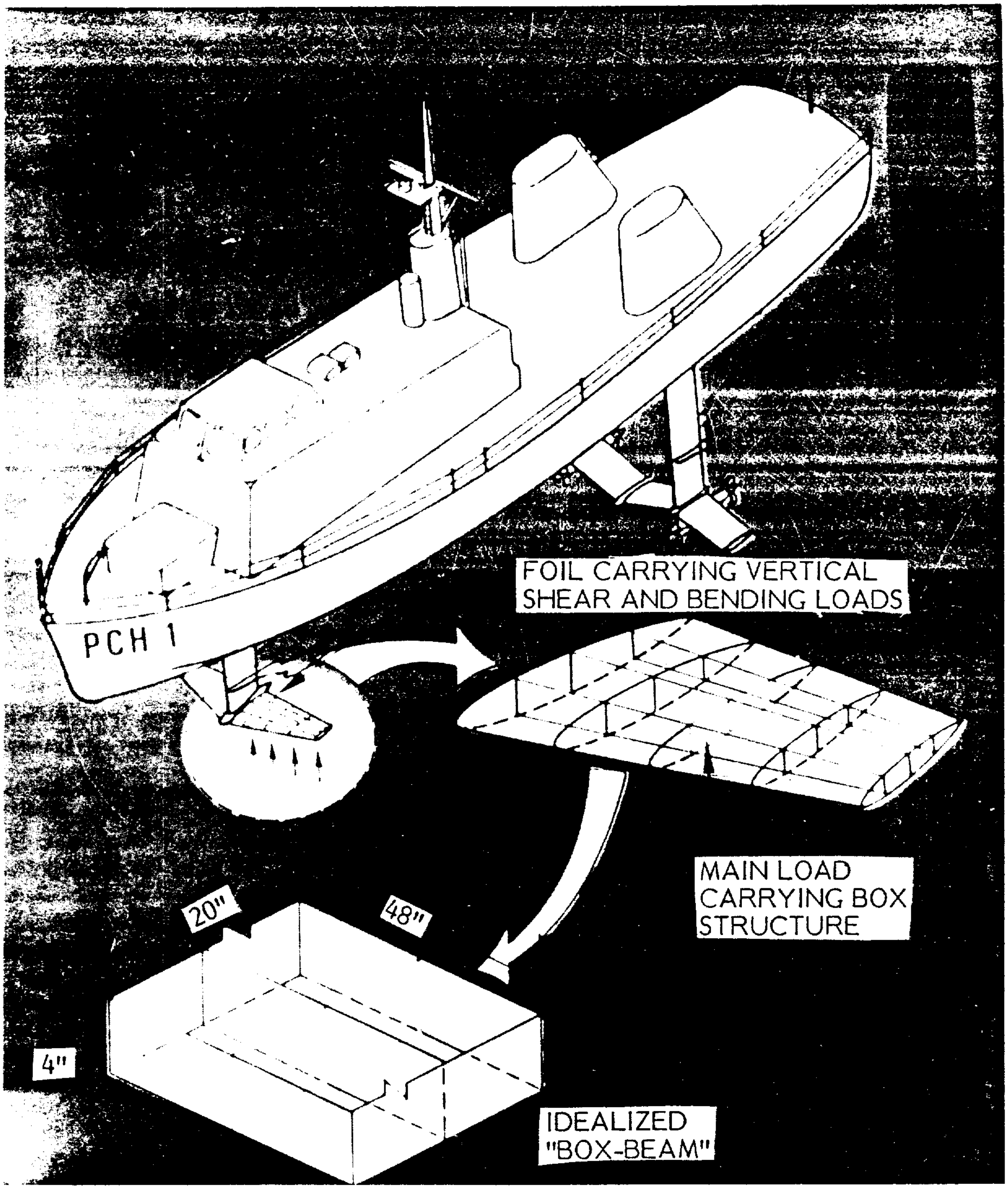

Figure II.A.4-6. EVOLUTION OF HYDROFOIL FATIGUE ELEMENT

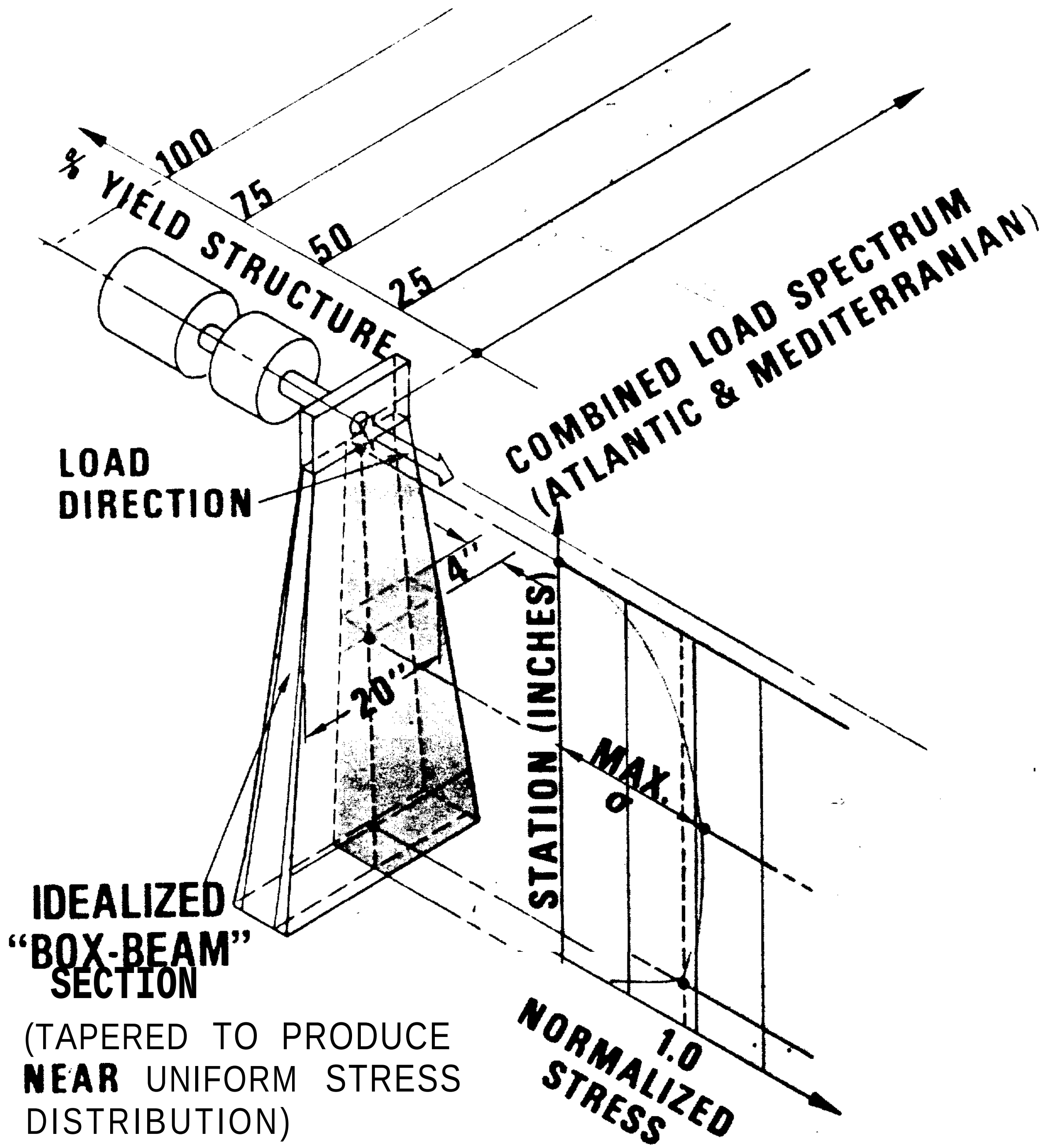

Figure II.A.4-7. HYDROFOIL FATIGUE ELEMENT and structural details are representative of a typical hydrofoil ship. The fatigue loading spectrum has been derived from actual trial data tapes and the environmental conditions have been chosen to simulate the sea conditions profile that would be encountered in 10 different locations in the world. Assuming an operational requirement for 1,000 foilborne hours per year, then a 15-year life would represent approximately $7.5x10^6$ cycles.

(U) This program, which was initiated in FY 1972, originally consisted of 8 different box beams using different materials and methods of box closure as described in Table II.A.4-7. Since then, a titanium box beam has been fabricated using electron beam welding, and an advanced composite box beam is planned. The status as indicated by the cycles to date is also shown. As can be seen, the program is still in testing, but information on fabrication cost, fabrication distortions, weld repair techniques, and fatigue life have been obtained. The relative cost of each of the eight box beams is shown in Table II.A.4-8. The relative fabrication cost in order of increasing cost would be HY 80 slot weld, HY 130 slot weld, 17-4 PH either configuration and HY 130 patch configuration.

(U) Even though the Hydrofoil Tapered Box Beam Program is not complete, certain conclusions can be made at this time. All experimental results and conclusions drawn from them are dependent upon the assumptions used in designing the box beams and in developing the load spectrum. Comparison of materials and fabrication

Table II.A.4-7. SUMMARY OF BOX BEAM STATUS
(Box beams tested to the same percentage of material yield)

Box Beam #	Material	Method of Weld Design Closure	Test Environment	Status Cycles to Date
1	HY 80	Slot Weld	Air	Static Failure*
2	HY 80	Slot	Salt Water	7.631x106
3	HY 80	Closure Patches	Salt Water	9 106x10^6
4	HY 80	Slot	Air	10.404x106
5	HY 130	Closure Patches	Salt Water	4.00x10^6 **
6	HY 130	Slot	Air	2.146x10^6 **
7	17-4 PH	Tee	Salt Water	In Testing
8	17-4 PH	Closure Patches	Salt Water	In Testing
9	Titanium		Salt Water	In Testing
10	Advanced Composite		Salt Water	In Design

* @ 190,000 cycles.

** In testing.

Table II.A.4-8. APPROXIMATE RELATIVE COSTS BOX BEAMS

Box Beam	Material	Configuration	Facility	Approximate cost
1	HY 80	Slot	A	N
2	HY 80	Slot	A	.6N
3	HY 80	Patch	B	1.4N
4	HY 80	Slot	A	.4N
5	HY 130	Patch	B	1.7N
6	HY 130	Slot	A	N
7	17-4 PH	Tee	C	1.3N
8	17-4 PH	Patch	C	1.2N

details is based on testing of the box beams to the same percentage of material yield strength. Those conclusions offered at this time are:

- Box beams with slot weld configurations have the best adherence to tolerances.
- HY 80 is the least expensive material to fabricate, followed by HY 130 and then 17-4 PH.
- There is a significant decrease in fabrication cost once manufacturing experience has been gained.
- Based on the results to date for uncoated foils, minor fatigue cracks are inevitable in the operating life of the foil. A program of periodical inspections will be required. Coatings to protect the foils from corrosion should improve the fatigue life and extend the period between inspection.
- Slot weld configurations last appreciably longer than closure patch configurations.
- HY 80 appears to last approximately four times as long as HY 130 in corrosion fatigue.
- GTAW in the horizontal position is the best process for repairing box beam type structures.
- Single-sided butt weld repairs (or initial fabrication) made with a backing strap left in place are preferable to unbacked single-sided butt welds from a fatigue standpoint.
- Repair of HY 130 after cycling is more difficult than repair of HY 80.
- "Ultimate" strength for box beam type structures in the as-fatigued condition can be conservatively predicted based on net section yielding.
- Cumulative damage theory can predict fatigue failure reasonably well for box beam type structures if the as-fabricated condition is well defined.
- Fracture mechanics techniques predict through crack growth very well for box beam type structures but as yet have not predicted first failure.

4.7 ASSESSMENT OF TECHNOLOGY

(U) The materials selection and fabrication of struts and foils has been an evolutionary process involving:

Existing Materials

- Use of existing common materials in simple structures (solid foils, bolted skins)
- Use of all welded construction of robust low strength alloys (HY 80)
- Use of all welded construction of high strength available material (17-4 PH stainless steel)
- Use of all welded construction of newly developed alloy (HY-130)

From this point advances in material strut/foil technology will be aimed at:

Cheaper, low maintenance materials

- Use of integral cladding materials
- Use of robust skeletons with nonmetallic overlays

Higher Performance Materials

- Use of titanium
- Use of high strength composite materials

Experience to date has identified additional needs which *are* being addressed.

- Fatigue and fracture control
- Attention to design, fabrication, and inspection detail
- "Engineer" the systems to make them more reliable in fleet operations

4.8 STRUT AND FOIL COATINGS

4.8.1 Requirements

- Provide protection from corrosion fatigue, thereby permitting the use of air fatigue allowables
- Provide general corrosion protection and anti-foulant protection (for nonretractable systems)
- Provide smooth surface to minimize onset of cavitation
- Must be field repairable
- Impact and erosion resistance

4.8.2 Past Experience

- Moderate success with Laminar X-500, which exhibits some brittleness with resultant undercutting corrosion. This may be reduced by a recently modified teflon-filled Laminar X-500 (see Figure II.A.4-8).
- Repair and touch-up are required. This has not been a major problem and procedures have been developed for 2-hour and 12-hour field repairs.
- Laboratory programs have been developed and testing criteria are available with a moderate degree of confidence established in the service life correlation.

4.8.3 Current Status

- The best candidates are now in an extensive service trial evaluation on PCH-1
- Results to date indicate that PR-1654 and Plasite 713317155 systems have performed effectively over 150 hours and will achieve projected 500 hours life with minimum maintenance.
- The use of "cosmaline" for interior protection has been demonstrated. Methods of field repair welding with a "dirty" inside plate surface have been initiated and will be completed in FY 77.

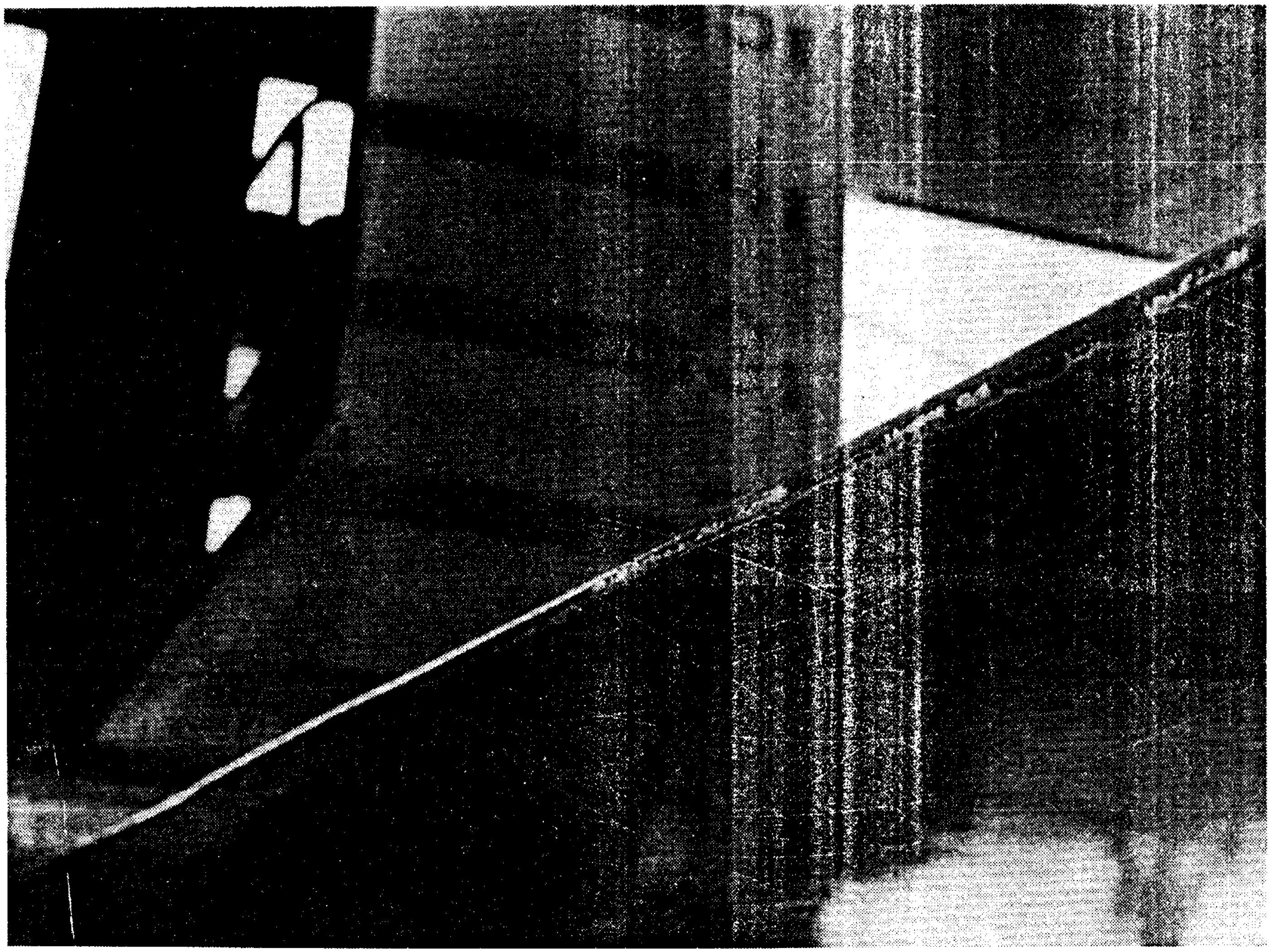

Figure II.A.4-8. PCH-1 MAIN STRUTS AND FOILS LAMINAR X-500 (CERMET) COATING WITH LEADING EDGE IMPACT/EROSION DAMAGE

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4.8.4 Antifoulant Coatings

(U) With fully retractable strut/foil systems there is no need for antifoulant strut/foil coatings. In addition, one of the more promising coating (PR-1654) contains small amounts of tin compounds which provide antifouling protection to a limited degree.

(U) For nonretractable or wet retractable systems on ships operating in warm waters, an antifouling coating is required. At present, The Boeing Company, in an in-house IRAD program, is investigating incorporation of existing antifoulants in PR-1654 and the results will be evaluated. Laboratory efforts in the development of a new, inherently antifouling coating utilizing the OMP (Organo-Metallic-Polymer) antifoulant concepts are underway. This will provide a longer life antifouling capability (5 years versus 18 months). Application for hydrofoil ship strut/foil may be available in the FY 79 timeframe.

4.8.5 Sealants and Fairings Compounds

(U) A number of sealants and fairing compounds (for hydrodynamic smoothing and cavitation prevention) have been evaluated on existing hydrofoils and in the laboratory. For fairing large surface areas, the HYSOL Aerospace Adhesive EA960F appears most effective and is compatible with the PR-1654 coating system. For structural intersections which experience more movement, the 3M XA-3517 fairing system is a more suitable material.

4.9 OTHER COMPONENTS IN STRUTS AND FOILS

4.9.1 Bearings

- Both rolling element and slide types of bearings are successfully used in current hydrofoil ships. AISI 52100 steels are used extensively for auxiliary equipment and gearbox ball and roller bearings. Bearings used in high performance gear boxes are generally class ABEC-5 or ABEC-7 precision bearings. Corrosion protection is provided by oil or grease lubrication depending upon operating speeds and loads.

- Control surface linkage bearings are generally self-aligning spherical self-lubricating slider bearings, made with 17-4 PH stainless steel. Outer race liners are either a teflon-fabric or an injection molded plastic. Balls are either 17-4 PH or a chrome-oxide coated 6Al-4V titanium alloy. Control surface hinge bearings are either sleeve or spherical slider bearings with either teflon fabric or injection molded plastic liners. Shafts for slider bearings are generally 17-4 PH stainless steel with surface finished polished to 8 to 16 RHR.

- Kingpost bearings are required to carry thrust loads and provide a self-aligning capability resulting from Kingpost deflections. Three different bearing designs are currently used in Kingpost applications. One design is a self-aligning AISI 52100 steel spherical roller bearing with an oil lubrication system. The two remaining designs are self-lubricating slider bearings. Bonded teflon fabric provides the lubrication in the ball bore and on the thrust washer surface. The metal components of slider bearings are fabricated from 17-4 PH stainless steel.

- A carburizing grade of electric furnace steel is specified for tapered roller bearings used in propeller thrust bearing applications. Oil lubrication is required for these high-load, high-speed applications.

4.9.2 Linkage Systems

(U) The present mechanical flap control linkage systems are subjected to repetitive (1 cps) high loads (25 ksi) in a seawater environment (see Figure II.A.4-9). Some corrosion fatigue failures have occurred in 4,340 steel parts and improperly treated 17-4 PH steel parts. It is now clearly recognized that titanium, nickel, or 17-4 PH are the only materials suited to this application and are being used in PHM and the current modification to AGEH-1.

4.9.3 Flaps

(U) These components are normally made of the same material as the foil, and are built-up structures employing ribs, end closures, and coverplates. No problems have been experienced to date. These items, however, offer a good location for the testing of new concepts and material choices in a realistic service environment (e.g., composite flap program).

4.10 PROPULSION COMPONENTS

4.10.1 Propellers

(U) Sixteen different propellers have been used on a variety of hydrofoil and other craft in the last 15 years. (See Table II.A.4-9.) Conclusions to date are:

- The high speed, highly stressed propeller technology requires vigorous load prediction and analysis research.
- The approaches to data are mainly empirical.
- The most successful applications have used high corrosion fatigue resistant alloys (titanium and nickel alloys) although the stainless steels and bronzes have occasionally been adequate.

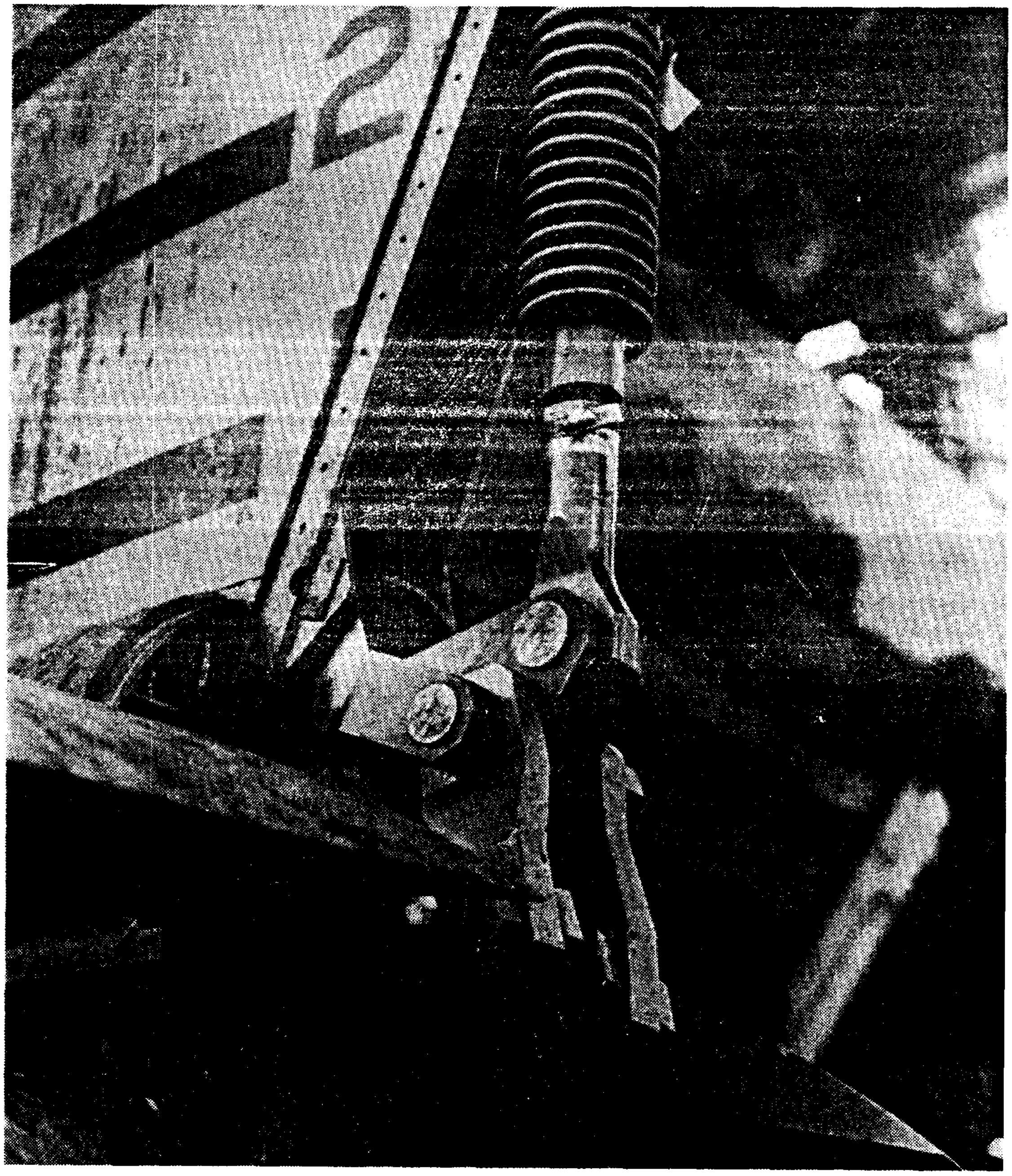

Figure II.A.4-9. PCH-1 FLAP CONTROL LINKAGE, LOWER END

Table II.A.4-9. CRAFT/PROPELLER MATERIAL MATRIX

Craft	Propeller Material
*HF PCH-1, Mod 0	Ni-Al Bronze Manganese Bronze Mn-Ni-Al Bronze Ti 6Al-4V CF3M Cast Stainless Steel CF3 Cast Stainless Steel 17-4 PH Cast Stainless Steel Inconel 718
HF Sea Legs	Ni-Al Bronze
HF MH30	"Aluminum Bronze"
HF PAT20	"Aluminum Bronze"
HFs PT20/59	"Aluminum Bronze"
HF PTS75 Mk III	"Bronze"
HF P46	"Bronze"
HFs Comet (or Kometa)	"Brass"
HF Denison	Ti-6Al-4V CA40 Mod. Stainless Steel
PGs 84 to 101	Ti-6Al-4V CF8 Mod. Stainless Steel Inconel 625
Eagle and Double Eagle	Ti-6Al-4V
HF AGEH-1	Ti-6Al-4V
Bell SEV	Ti-6Al-4V
HF PGH-1	Type 414 Mod. Cast Stainless Steel
HF Dolphin	Type 414 Mod. Cast Stainless Steel
HF Proteus	17-4 PH Cast Stainless Steel
HF XCH6 Sea Wings	"Stainless Steel"
HF FHE400 Bras d'Or	Inconel 718

* HF: hydrofoil ship

- Cost considerations are forcing the use of castings, where high quality control is essential.

4.10.2 Waterjet Pumps

- Cast aluminum was used for the waterjet pump housings on TUCUMCARI. The housing was adequate although several weld repairs were performed. The impeller (17-4 PH steel) performed satisfactorily (1,200 foilborne hours).

- Cast aluminum was used on the PHM pump housing and 17-4 PH stainless steel for the impeller. Several problems have developed in the operation so far, related to:

  - Galvanic corrosion (aluminum housing and steel components)

  - Inadequate fatigue strength, ductility, and quality of the cast aluminum housing

  - Cavitation damage on the impeller

It is evident that short-term fixes can be achieved on the present pump design such as:

- Higher quality casting specifications

- Substitution of titanium and wrought aluminum for some housing components

- Epoxy coating of the impeller

The long-term solutions will require a redesign of the pump to achieve better galvanic isolation and the substitution of more corrosion resistant materials.

REFERENCES

II.A.4-1 "A Guide for Selection and Use of Aluminum Alloy for Structure of Ships," U.S. Navy, NAVSHIPS 0900-029-9010, July 1971.

II. STATUS OF VEHICLE TECHNOLOGY

A. TECHNOLOGICAL PERFORMANCE FEATURES

5. STRUCTURES

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II.A. TECHNOLOGICAL PERFORMANCE FEATURES

5. STRUCTURES

5.1 INTRODUCTION

(U) The subject of vehicle technology assessment in relation to structures is addressed here on the basis of the following question: What is our current ability to design and build hydrofoil ship structures to required weight limits and estimated costs, and to have them free of corrosion, cracks, and gross failures in service? The question is answered with respect to the following major areas of interest: Design and Construction, Tests and Trials, and Service Experience. Brief consideration is also given to development trends in order to assess technology problems which are expected to be more significant in the future than they are at the present time. No attempt is made to discuss structural technology in depth; instead, emphasis is placed only upon those aspects of the technology which have a significant bearing on the answers to the above question.

5.2 DESIGN

(U) Design technology is examined here relative to the state of the development of Load Criteria, for which Stress Analysis, Weight Predictions, and Structural Design and Material Applications are concomitant factors.

5.2.1 Loads

(U) The basis of structural (i.e., strength) design of hydrofoil ships is usually quite different from that of conventional displacement ships inasmuch as the aircraft limit load approach to structural design is employed. In this case, limit loads which represent the highest load levels anticipated in service, are first established. From these, Yield and Ultimate loads are derived for individual structural components by applying specified yield and ultimate factors of safety to the limit loads. The structure is then required to be free of excessive deformation under Yield loads and to sustain Ultimate loads without collapse. It is implicit in this approach that the limit loads employed as a basis of structural design be close to realistic maximum values, since the associated factors of safety are generally small (1.20 for yield and 1.50 for ultimate strength) and since the weight critical nature of the structure generally precludes overly conservative estimates of the limit loads. As a result, considerable emphasis tends to be placed on *accurate* limit load *assessments* and upon subsequent comparisons of measured and predicted maximum service loads. (Additional discussion of the limit load approach is given in Reference II.A.5-1.)

(U) With regard to fatigue strength, detailed assessments of the cyclic nature of service loadings are required and here again comparisons of predicted and actual loadings are important if adequate fatigue strength in critical structural areas is to be assured.

5.2.2 Foilborne Operating Limits

(U) If the limit load approach to structural design is used, it is necessary to postulate from the measured loads on existing hydrofoils those conditions which impose the highest loadings. To determine the maximum foilborne loads it is not enough just to analyze the loads in the design sea state. The maximum load must be determined from the highest sea state in which the ship can remain foilborne. Experience has shown that hydrofoils can and will be operated in sea states higher than design. Hydrofoil operation will continue as long as it is capable of remaining foilborne. This is particularly true for a hydrofoil since, as it is driven into rougher and rougher seas, its motions and accelerations are well within the limit of the crew to operate.

(U) From the extensive rough water trials on the PCH, three conditions set the sea state limit in which it can operate. The first, which is a rather benign limit as far as structural loading is concerned, occurs when climbing a long swell and the ship slows down until it can no longer remain foilborne.* Such a condition is illustrated in Figure II.A.5-1 which shows trials data measured on the PCH while climbing a 45 foot peak to tough swell.

(U) The second condition occurs when the frequency and magnitude of hull cresting of waves slows the ship down until it cannot remain foilborne. Figure II.A.5-2 shows an example of speed reduction where the primary cause of speed loss is drag due to wave impacts, although not enough to cause suspension of foilborne

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*Climbing a 2 degree wave slope increases the drag by about 50% for the PCH.

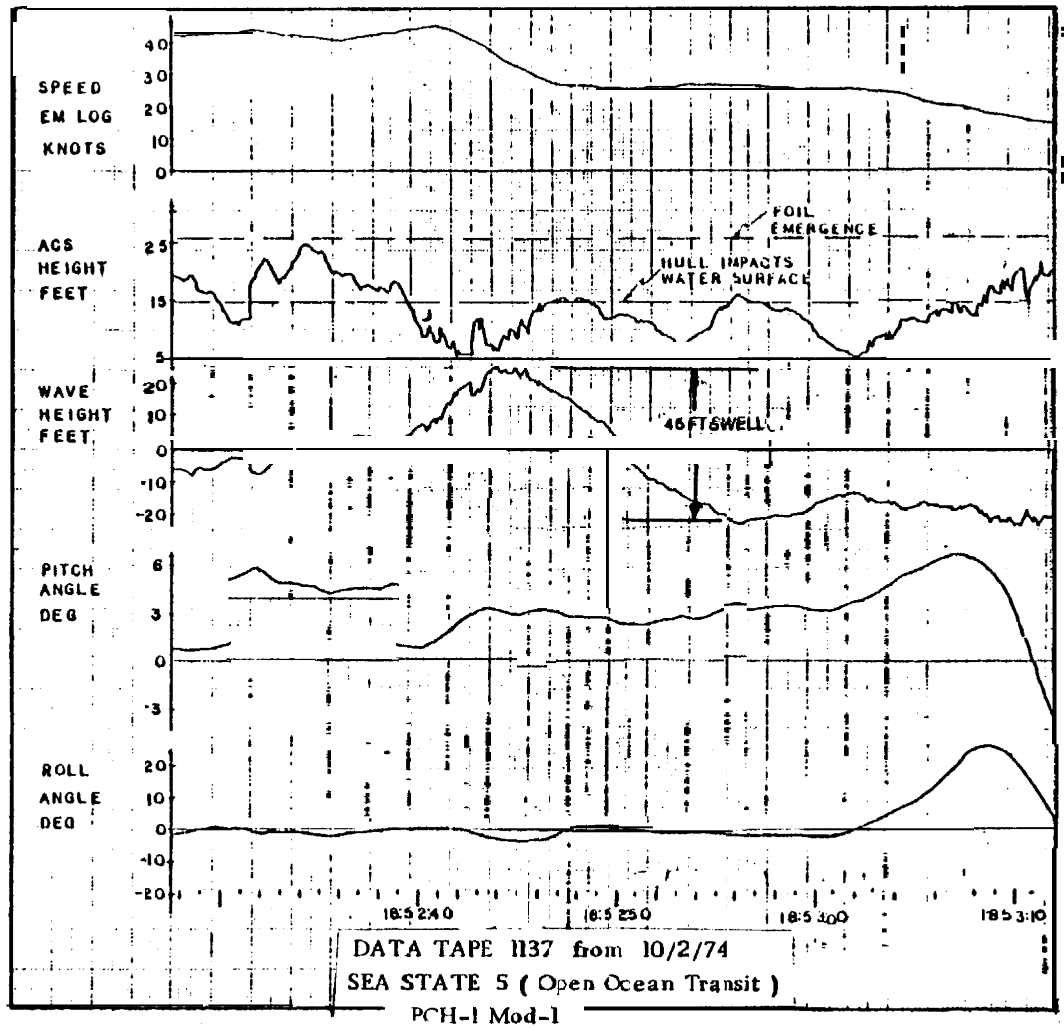

Figure II.A.5-1. PCH-1 MOD 1 DATA TAPE 1137 FROM 10/2/74
SEA STATE 5 OPEN OCEAN TRANSIT IN QUARTERING SEA

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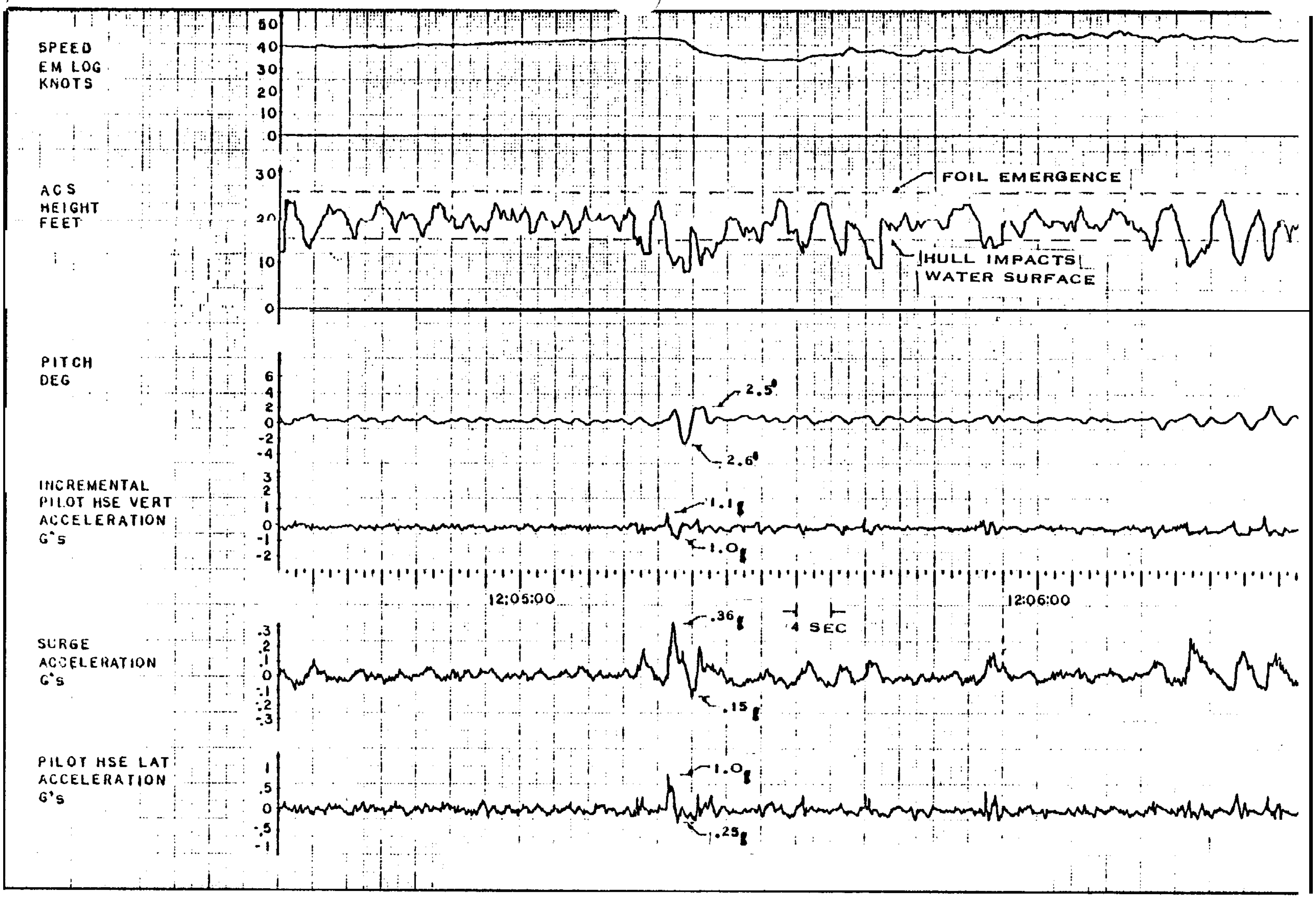

Figure II.A.5-2. PCH-1 MOD 1, ROUGH WATER TRIALS 11/4/75 PORT BOW SEAS SEA STATE 5

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operation. It is of interest to note that wave conditions during the incident illustrated by Figure II.A.5-1 caused suspension of foilborne operation, while the trials operations of Figure II.A.5-2, also in Sea State 5, did not. The seaway associated with Figure II.A.5-2, however, produced structural loads on the PCH-1 Mod 1 foil system up to 100 percent greater than those of Figure II.A.5-1 in which swells as high as 45 feet were encountered.

(U) The third condition which limits foilborne operation occurs when the forward foil broaches repeatedly, which is generally followed by the hull slamming. (When a foil emerges from the water it is said, in the hydrofoil community, to broach.) With an airplane-type foil configuration with main, split foils forward, many times only one of the forward foils broaches and loses lift and results in appreciable rolling. The canard configuration features roll control aft and when the forward foil broaches, the ship tends to pitch down rather than roll as a result of loss of forward foil lift. Since the hull characteristically has high deadrise forward, the impact loads and accelerations produced by forward foil broaching are relatively low, as shown in Figure II.A.5-3. As far as hull bottom loads are concerned, this characteristic permits relatively light scantlings. The 130-ton PCH-1, for example, which has operated extensively in high sea states, features 0.250" thick 5456 aluminum plating on the hull bottom. (Most hydrofoil ship bottom plating is in the thickness range of 3/16 to 1/4 of an inch.)

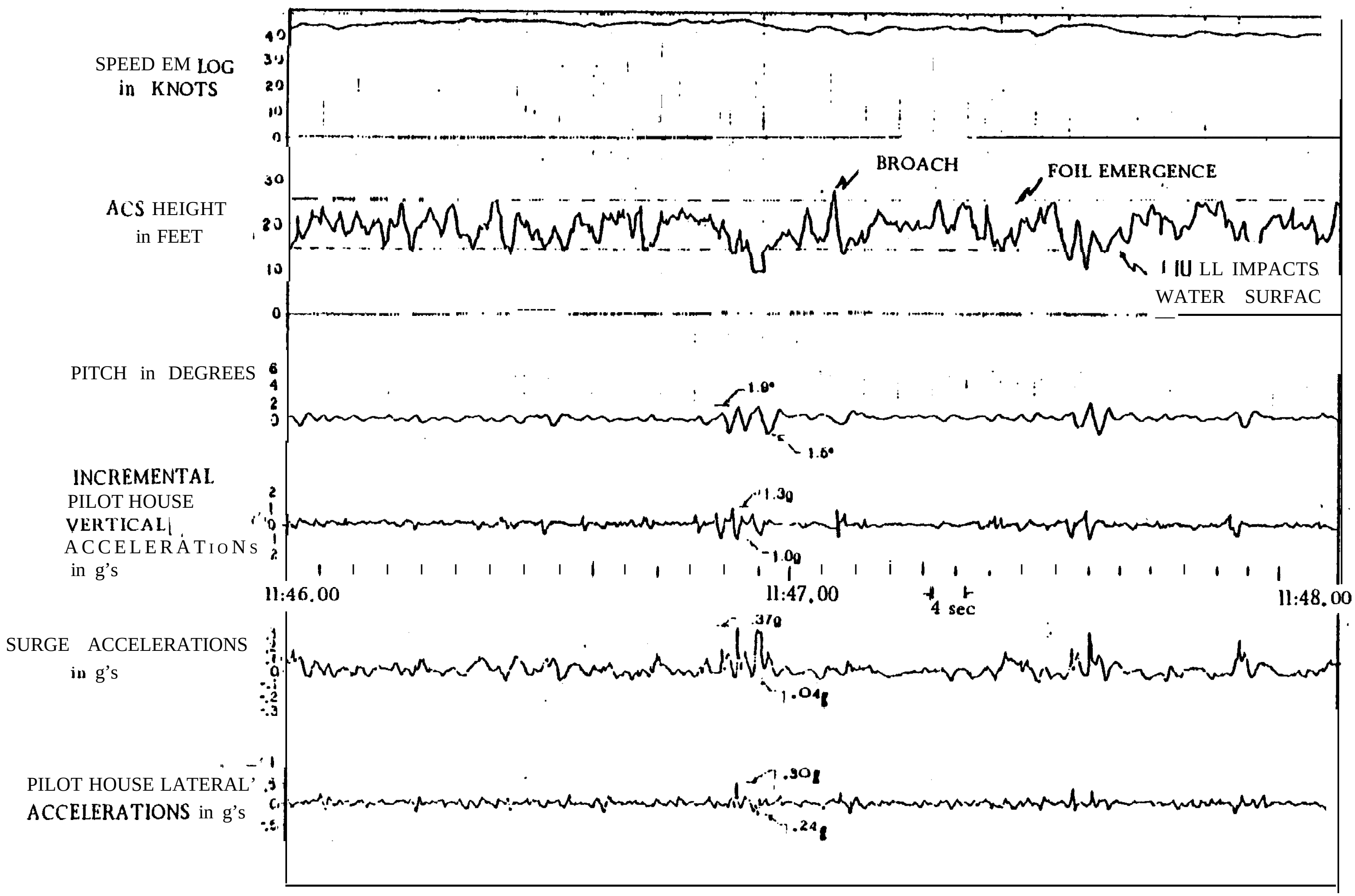

Figure II.A.5-3. PCH-1 MOD 1, ROUGH WATER TRIALS 11/4/75
HEAD SEAS SEA STATE 5

(U) Loads on the foil system under broaching conditions are generally not large when expressed as a percentage of the design foil load. Since cavitation limits the lift forces which the foil system can generate to about 2 to 2.5 times the nominal level flight or lg lift load on the one hand, and since ventilation of the struts on the other hand limits side forces to about 0.5g total side force, the gross loads which can be developed are not unusually high. In terms of basic foil loading (lift per unit foil area), however, foil systems generate relatively high loadings compared to aircraft wings, for example. Modern aircraft lifting surfaces are typically loaded in the 100-150 psf loading range in level flight, whereas submerged hydrofoils are typically loaded to about 1000 to 1500 psf. As a result of such loadings, skin thickness in current foil systems (e.g., PCH-1, PHM-1) is on the order of 0.5 inches in steel having a yield strength of 130,000 psi.

(U) The fact that an automatic control system (ACS) typically "flys" the hydrofoil ship has little influence on alleviating the maximum loadings for which the foil system should be designed. This is true, since the ACS is generally not constrained in any way relative to the loads generated by control surface deflections. Load criteria currently being developed by the Navy therefore require design of the lifting surfaces and steerable struts for maximum attainable loadings. With respect to fatigue loads, the ACS tends to alleviate fluctuating foil lift loads which would otherwise be generated by the seaway. On the other hand, it tends to introduce significant fatigue loads at the control surfaces as a result of the continuous stabilizing action of the ACS. It is only recently that cyclic or fatigue load alleviation has been considered in the ACS design. The new PLAINVIEW ACS considered this from its inception.

5.2.3 Limit Load Criterion

(U) Relative to the ability of existing load criteria to provide adequate static strength levels in canard configuration foil systems, a research program is currently nearing completion within the Navy to develop a hydrofoil structural load criterion. This criterion development has a rationale which correlates between observed rough water loading conditions and the presumptions of the load criteria. Further aspects of concern for limit strength levels have been identified in Reference II.A.5-2.

(U) As the result of recent full-scale trials of PCH-1 Mod 1 with a fairly extensive installation of strain gages on the foil system, as shown in Figure II.A.5-4, new criteria are being developed which more adequately reflect rough water foil system loadings. Table II.A.5-1 presents a summary of the foilborne load criteria being developed by DTNSRDC for canard configuration hydrofoil ships based upon the circumstances of loading found to be critical for PCH-1 Mod 1. This criteria development work will be completed for use as a contractual requirements document in the next major hydrofoil ship procurement.

(U) In the case of hull loading criteria for rough water operation very little full-scale data gathering has been done

Ⓓ RETIRED 12NOV75

2▷ 1 SHEAR & 1 BENDING GAGE REMAIN ACTIVE ON STBD SEMISPAN - PORT SIDE HAS NO ACTIVE GAGES

Ⓐ-AXIAL STRAIN GAGE

Ⓑ-BENDING STRAIN GAGES

Ⓢ-SHEAR STRAIN GAGES

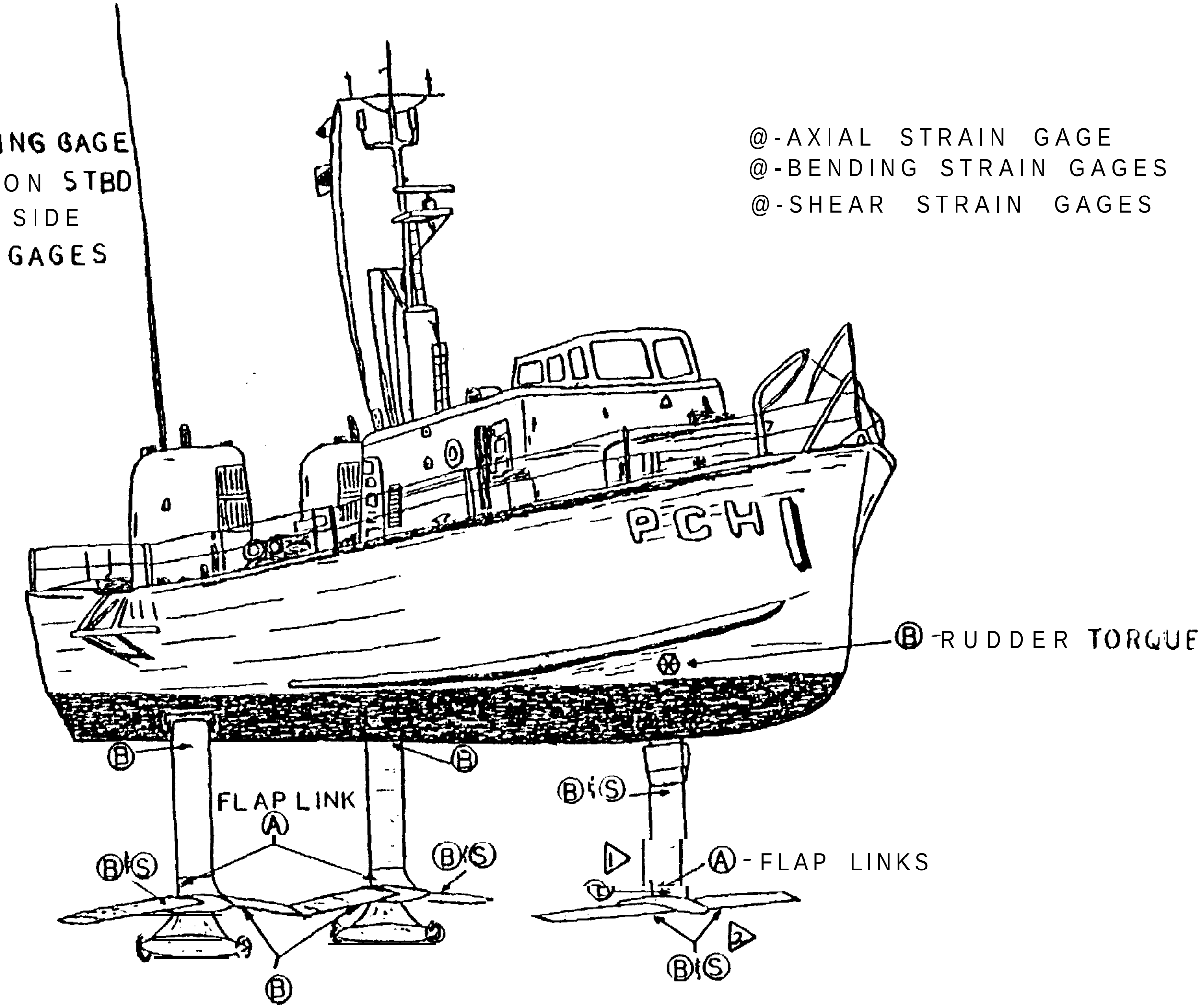

Figure II.A.5-4. PCH-1 MOD 1 STRUCTURAL INSTRUMENTATION

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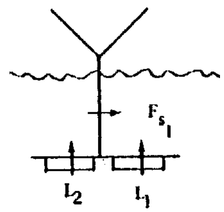
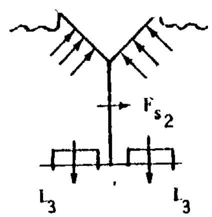
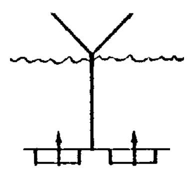
Table II.A.5-1. DEVELOPMENT OF FOIL SYSTEM LOAD CRITERIA

CONDITION	DESCRIPTION	RATIONALE	STATUS OF CRITERIA DEVELOPMENT
		Maximum forward strut lateral bending moments have been found to result from forward foil broaching in rough water when one foil semispan is vented while the other is not. Large strut side forces can also act concurrently.	A design condition has been established from trials data analysis in which: F_{S_1} = Maximum attainable strut side force L_1 = Maximum attainable foil lift at full flap deflection (with corresponding drag). L_2 = Maximum vented foil lift at full flap deflection (with corresponding drag).
BROACH RECOVERY		Large forward foil down loads are experienced during broach recovery conditions when the ACS attempts to compensate for hull impact lift loads.	A design condition has been established from trials data in which: F_{S_1} = Maximum attainable strut side force L3 = Maximum attainable negative lift at full flap upward deflection.
		This symmetrical lift situation is seldom observed, but must be considered as a possibility during broach recoveries.	A design condition has been established in which: FS = 0 Ll = Maximum attainable foil lift at full flap deflection (with corresponding drag).

NOTE: This condition results from the forward foil flying out of a wave with a subsequent loss of foil lift. The bow of the ship then drops so that the automatic control system (ACS) calls for full flep deflection ho arrest the downard motion of the bow. The foil typically remains vented until some time after the hull hits. Calm water broaches have been artificially induced in straight ahead flight and in turns to study strut and foil flow conditions with cameras mounted on booms. Similar camera studies have been performed during debris avoidance maneuvers.

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Table II.A.51. DEVELOPMENT OF FOIL SYSTEM LOAD CRITERIA (Continued)

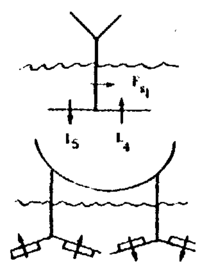
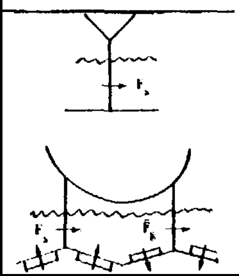
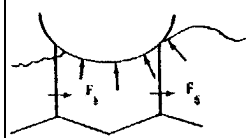
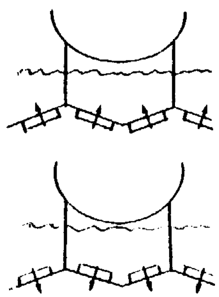
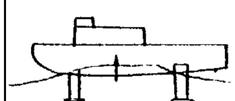
CONDITION	DESCRIPTION	RATIONALE	STATUS OF CRITERIA DEVELOPMENT
DEBRIS AVOIDANCE MANEUVER		Relatively large forward strut lateral bending moments have been measured in calm water trials due to strut loads resulting from rudder control inputs acting in combination with roll damping loads on the foil. The bending moments in calm water have not been as large as those measured to date in rough water.	Loadings associated with this maximum helm induced maneuver have not been found to be critical in calm water. Establishment of a discrete loading condition will depend upon the results of debris avoidance maneuvers in rough water.
	NOTE: This condition corresponds to entering a maximum helm displacement turn and abruptly reversing the helm in less than one half second to a full opposite displacement. Maneuvers of this type have been performed in calm water with video cameras monitoring forward strut and foil flow conditions.		
FLAT TURN		This condition is intended to establish that adequate strut strength exists to deal with hard over rudder actuator failures and for inadvertent skids due to strut ventilation.	Trials associated with this loading condition have not vet been conducted, but are in the planning stage. Strut forces approaching maximum attainable side force are anticipated.

Table II.A.5-1. DEVELOPMENT OF FOIL SYSTEM LOAD CRITERIA (Continued)

CONDITION	DESCRIPTION	RATIONALE	STATUS OF CRITERIA DEVELOPMENT
WAVE PENETRATION		The highest aft strut lateral bending loads measured to date have occurred during a cresting wave impact at a bow sea heading in which large lateral loads were apparently applied to the hull. (This condition may also result in large hull bottom loads amidships.)	This loading condition was identified as potentially critical during PCH-1 Mod 1 rough water trials of 11/4/7 Considerable difficulty is anticipated in rationally estimating maximum hull forces during wave penetrations. Strut lateral loads corresponding to maximum attainable side force may have to be presumed.
MAXIMUM ATTAINABLE LIFT		The condition is arbitrarily imposed to provide for the fact that the ACS is not constrained from generating maximum attainable loading as a result of control surface deflection. Maximum attainable loadings on the forward strut and foil are already covered by other loading caaea.	Arbitrarily imposed loading conditions -- no criteria development required.
DITCHING		This loading condition will result from a sudden decrease in height control lever setting during rough water operation.	This condition has not been investigated in full scale trials due to the absence of hull pressure transducers on PCH-1 Mod 1. Calm water ditching tests of AGEH-1 have been performed, but impact pressures were low.

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to improve the state-of-the-art because of favorable service experience to date with respect to hull bottom structure, and because the resources presently available are being directed almost entirely to foil system loads research. While concern for the design of hull bottom structure is not very great at this time, the state-of-the-art for bottom pressure estimation and particularly bottom pressure distribution requires better definition and correlation. Figure II.A.5-5 shows the limit plating pressures employed in design by two different contractors for ships of essentially identical size and mission (PGH-1 and PGH-2). Alghough hull lines of these ships are not identical, they are similar. In the case of PGH-2, the maximum bottom pressure (away from the keel) was estimated to be 73 psi, while in the case of the PGH-1, 26 psi was'the estimated maximum. In spite of these differences, neither of these ships has experienced hull bottom strength deficiencies in service which has included many hours in sea states beyond their design. Clearly, differences have existed in procedures or presumptions for estimating maximum design pressures, and/or applying these pressures to determining plate thickness and scantling.

(U) Significant advances have been made recently in the analysis of hull bottom pressure data from rough water trials operations as reported in Reference II.A.5-3. Moreover, a computer program for predicting hull impact forces in waves has been found to give reasonably accurate results, as exemplified in Figure II.A.5-6 which is taken from Reference II.A.5-4. The DTNSRDC research has

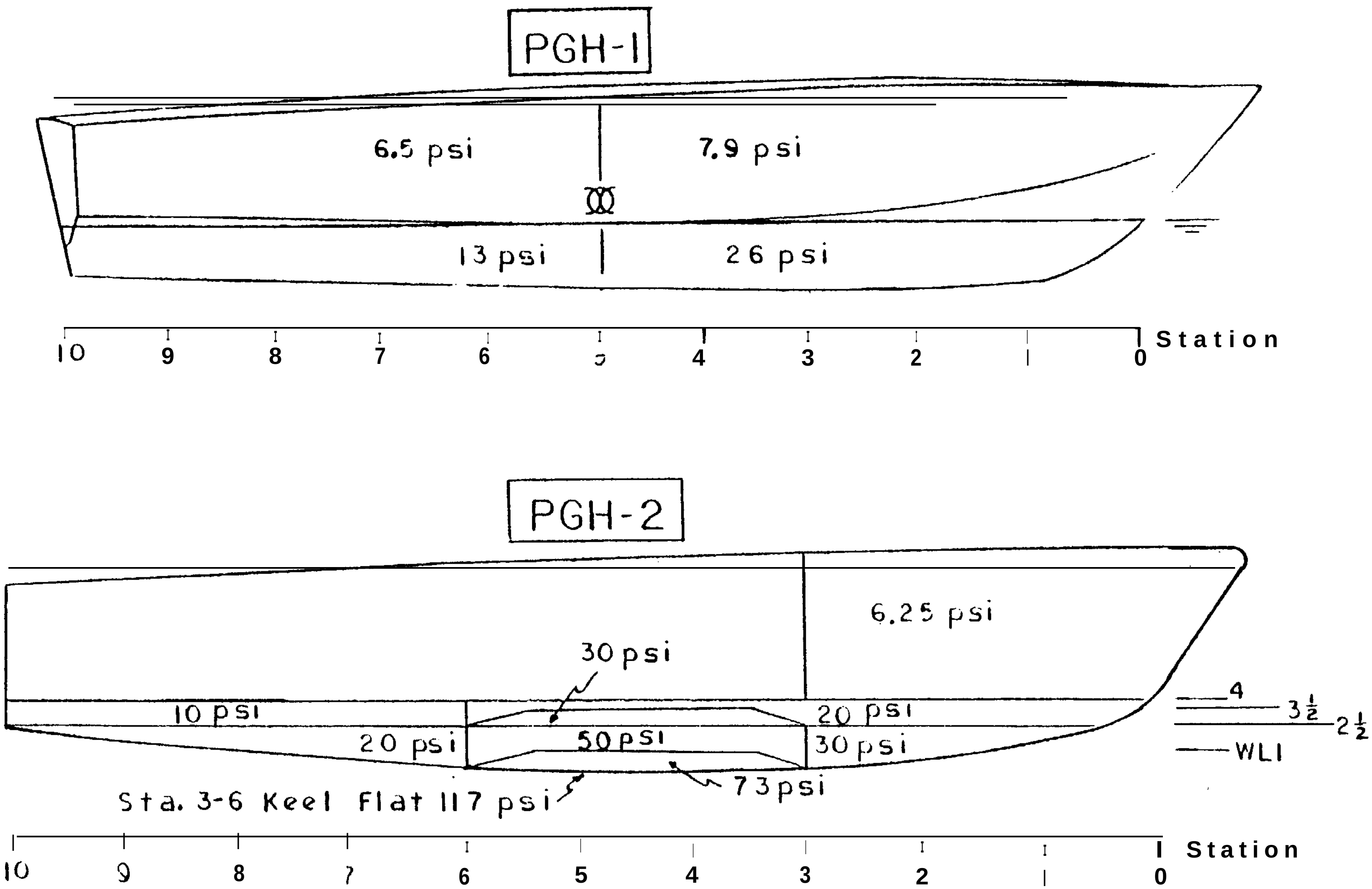

Figure II.A.5-5. COMPARISON OF PGH-1 AND PGH-2 HULL PLATING (LIMIT) PRESSURES

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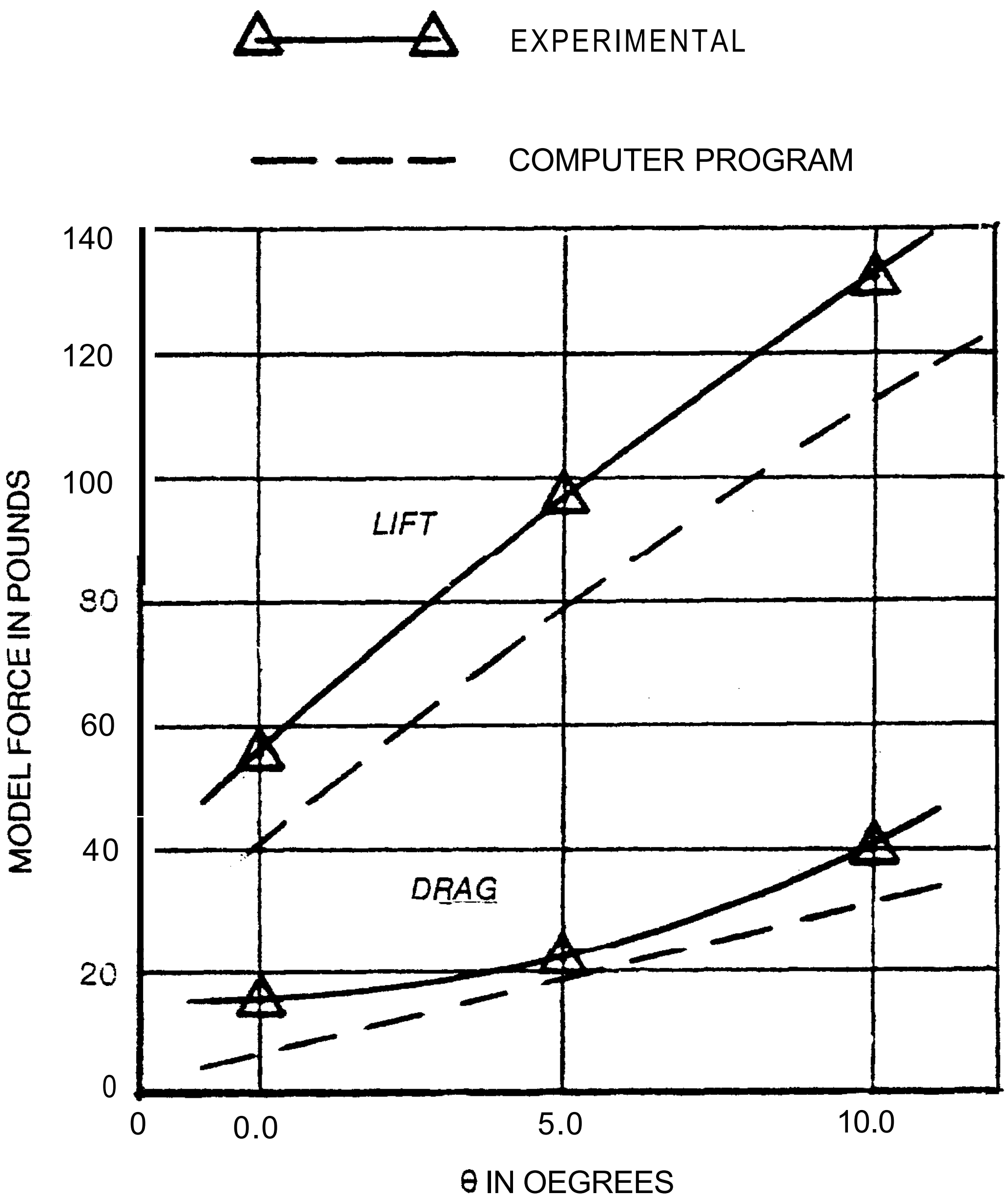

Figure II.A.5-6. MAXIMUM IMPACT LIFT AND DRAG FORCES ON A NONUNIFORM DEADRISE MODEL AT VARIOUS TRIM ANGLES clearly shown that design pressures for hull bottoms must be specified as a function of the size of the hull bottom area over which they act, and that a single unique value of pressure is generally not a realistic design criterion. In the case of hydrofoil ship hulls, however, no data are available at this time comparable to that for the planning craft of Reference II.A.5-3.

5.2.4 Fatigue Load Criteria

(U) Until recently, very little has been done to establish a viable state-of-the-art for fatigue load prediction for foil systems. (No work is anticipated in the immediate future for hull bottom plating fatigue loads in any case, because the hull is generally clear of the water at high speed.) This is due primarily to the generally poor state-of-the-art for predicting typical (as opposed to maximum) foil system loads. Recent increases in the extent of foil system strain gaging on PCH-1 Mod 1, as well as a recently developed procedure for extracting fatigue load information from rough water trials data, have begun to shed light on the more significant sources of foil system fatigue loads. Comparisons have been made recently between the results of fatigue load estimates for a canard configuration forward strut, based upon computer simulation studies, and those derived from normalized strut loads (i.e., expressed as percent of limit load) obtained during rough water transits of PCH-1 Mod 1 along the U.S. West Coast. For example, for a given percentage of limit bending moment, at the upper end of the forward strut, the operational data such as that of Figure II.A.5-7

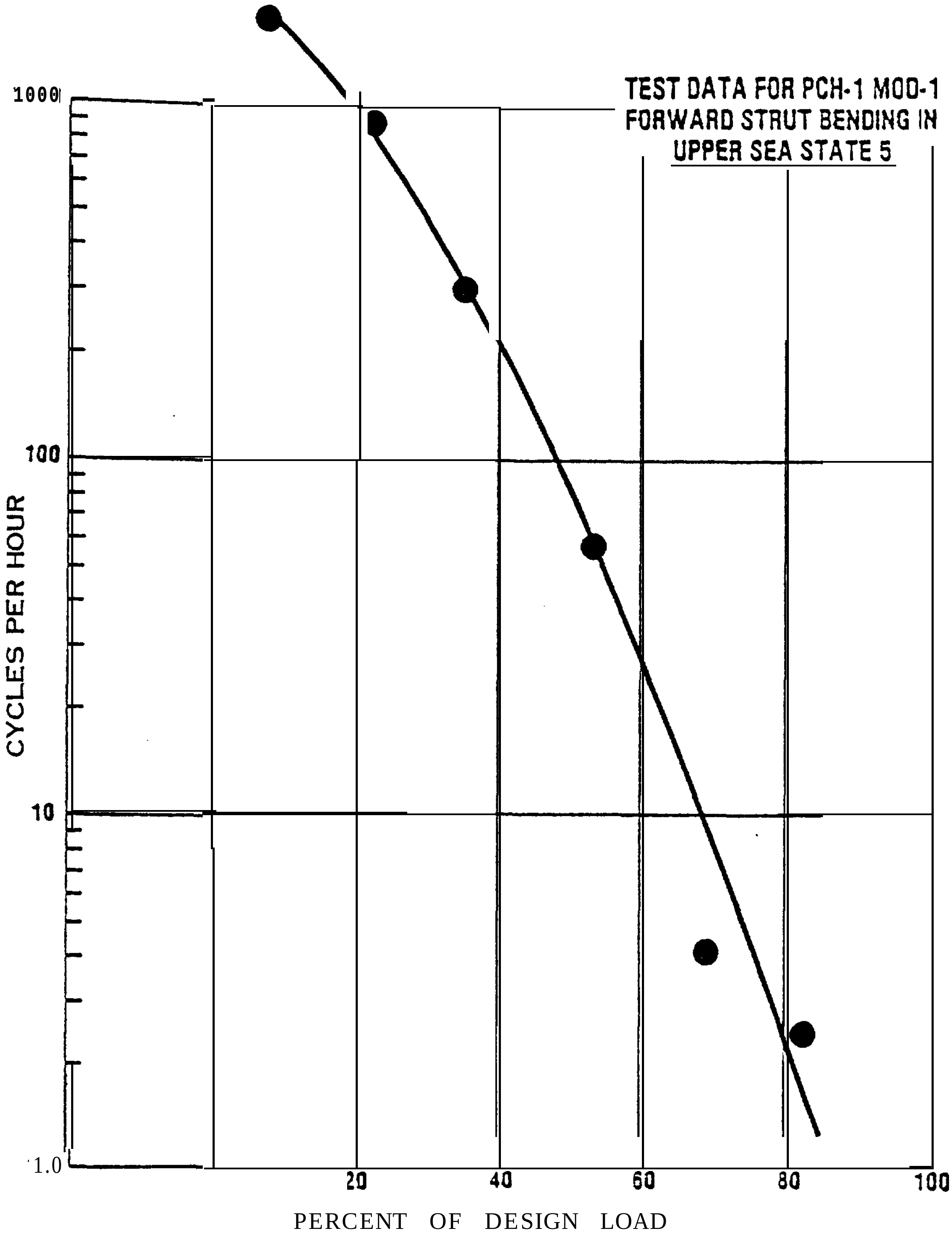

Figure II.A.5-7. PEAK OF CYCLIC LOAD

indicated considerably more load cycles than the predicted loads. The discrepancy in the high load level regime is not related to the simulation accuracy, since the simulation did not attempt to model forward foil broach loads; these were accounted for by other means. In the high cycle, low load regime, however, several tentative conclusions have been drawn relative to apparent deficiencies in the computer simulation. These are:

- The effects of forward foil system vapor cavity shedding, vented flow, and varying downwash from the forward flap must be adequately represented to account for all aft strut and aft foil center section fatigue loads.

- Modal response of the foil system and its foundations as a flexible body should be considered in estimating aft foil system fatigue loads.

- The turbulence, near the water surface, through which the foil system flies and the higher frequency components at orbital velocity may not be modeled correctly in the motion simulators. The state-of-the-art relative to foil system fatigue load predictions by computer simulation will be significantly improved when the above are properly modeled.

(U) For this reason, the fatigue load spectra derived from rough water trials on the PCH-1 in Sea States 3 through upper 5 will be used as a basis for the Navy Hydrofoil Structural Load Criteria. These fatigue load spectra will be continually updated as more trials data become available.

(U) The fact that some fatigue cracks have developed in service is considered to have limited significance as far as the state-of-the-art for stress analysis is concerned, since fatigue analyses for hydrofoil ships have not been required in the past. The incorporation of a fatigue loading spectrum in the Navy Hydrofoil Structural Load Criteria for future procurements will eliminate this deficiency.

5.3 TEST AND TRIALS

(U) This subject is reviewed here primarily with regard to validating the structural integrity under laboratory and full-scale trials conditions. The state-of-the-art for conducting static and fatigue tests under laboratory conditions is considered adequate. Some development work is likely to be required, however, if impact loads are to be simulated. As far as full-scale trials are concerned, no major state-of-the-art developments are believed required as evidenced by the extensive trials experience which have been accumulated with PCH-1 as Mod 0 and later as Mod 1. The major concern at this time is associated with the need for conducting laboratory tests and full-scale trials to assure that adequate structural criteria are used in design and that the ship will have integrity in service.

(U) With respect to this concern, the following points are offered:

- No rational examination of this matter has been performed to date to provide that guidelines are available for single ship and multiple ship procurements. The major issues are believed to be

(1) the percent of total program procurement funds which must reasonably be allocated to such testing in general, (2) the proven need for conducting validation tests in areas where the limit and fatigue loads cannot be accurately predicted, and the consequence of failure is critical, and (3) what alternatives should be considered if the need for the tests has been established, but the cost is beyond the funds available for a meaningful test program.

- Service experience with five Navy hydrofoil ships has totaled approximately 3,600 foilborne hours, whereas the design foilborne life of PHM-1 is 12,000 hours. Moreover, the largest number of foilborne hours seen by any single Navy hydrofoil ship to date is approximately 1,200 hours, which is only l/lOth of the design life of the PHM. The experience base from which to judge the necessity of laboratory and full-scale structural trials is therefore limited.

- Structural experience reviewed to date suggests that full-scale static limit load tests may not be vital, particularly in view of the fact that fatigue criteria appear to be the governing factor in design. Presently the limit and fatigue load criteria employed in structural design are being re-examined and updated, based on data from full-scale trials. (See discussion of Service Experience, Section 5.4, below.)

- Structural experience to date suggests that a program of fatigue testing may prove to be cost-effective, depending on the number of ships to be procured. The state-of-the-art for fatigue load prediction from the simulator, it should be noted, is such that it would not be wise to conduct laboratory fatigue tests at this time with anything less than component load or stress data obtained from full-scale trials.

(U) The above indicates the need for structural validation testing. These areas should be re-examined on a continuing basis to form guidelines for allocating program funds in future procurements of hydrofoil ships.

5.4 SERVICE EXPERIENCE

(U) The structural service experience of Navy hydrofoil ships has come largely from the PGH-1, PGH-2, PCH-1, and AGEH-1 (68, 58, 130, and 320 tons displacement, respectively). Among these ships the PGH-2 is unique since, as the result of decommissioning following a major accident, its structure became available for detailed examination. At the time, it had the highest total number of foilborne hours (approximately 1,200) of any Navy hydrofoil ship. As far as the general flow of service information is concerned, until the recent development of the Advanced Ships Information System-Technical (ASSIST), it has not been an organized activity, but has depended primarily upon individual inquiries or follow-up to ad hoc service problems for information.

5.4.1 Structural Failures

(U) The first category of structural service experience which will be reviewed is structural failures which have required repair of the ship before it could continue in service. Table II.A.5-2 summarizes service experience with the above ships. AGEH-1, which has the fewest foilborne hours of operation (197) and essentially no rough water experience, has encountered one operating and one nonoperating failure. In the former, a main foil incidence control link failed in tension while the ship was operating foilborne at 43 kn in Sea State 2 (see Reference II.A.5-1). As a result of the link failure, the ship rolled and settled abruptly from a foil-borne height of 7 ft; however, no structural damage occurred as a

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Table II.A.5-2. SUMMARY OF SERVICE FAILURES REQUIRING IMMEDIATE REPAIR

FAILURE	PROBABLE CAUSE	EFFECT ON SHIP	REFERENCES
AGEH-1: Starboard Foil Incidence Control Link Failed While Foilborne at 43 Knots in Sea State 2. (11 December 1972)	Corrosion and Corrosion Fatigue in 4340 Steel Control Link at Location of 17-4 PH Bearing, Presence of Fatigue Crack Resulted in Static Failure..	Ship Rolled and Yawed to Starboard Due to Loss of Lift at Starboard Foil. Ship Entered Extensive Overhaul Period Which Had Been Previously Scheduled.	DTNSRDC Memorandum 1731:PY:ams, 73-173-M98, 7 March 73, Failure of PLAINVIEW (AGEH-1) Starboard Foil Incidence Link 11 December 1972.
AGEH-1: Starboard Foil Retraction System Hinge Pin Failed During Retraction. (22 January 1970)	Load Criteria for Retraction System Did Not Provide for Overload Due to Improper Operation of Hydraulic System. Hinge Pin Had Been Designed to be Weakest Element of System.	Foil Fell Back into Water. No Other Significant Damage Occurred Beyond Hinge Pin Failure. Ship Returned to Service in Approximately Two Weeks.	PLAINVIEW (AGEH-1) Structural Log, Problem 131.
PGH-2: Bow Doors Which Accommodate Strut Retraction Failed at Latch Points During Failborne Operation in Sea State 4. (14 July 1971)	Previous Entry of Ram Water During Failborne Operation in Rough Water Believed to Have Caused Initial Damage. Doors Contained Openings at Top and Bottom When in Closed Position.	Operation Suspended Until Temporary Repairs Were Made. Ship Returned to Service in 5 Days. Bow Doors Failures Were a Recurring Problem for PGH-2'.	Boeing Letter Report Dated 13 August 1971, Re: TUCUMCARI Bow Door Casualty.

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Table II.A.5-2. SUMMARY OF SERVICE FAILURES: PCH-1, AGEH-1, PGH-1, PGH-2 (Continued)

FAILURE	PROBABLE CAUSE	EFFECT ON SHTP	REFERENCES
PGH-2: Impact on Forward Strut Occurred While Foil-borne in Strait of Juan de Fuca. Strut Down Lock and Supporting Bulkhead Were Damaged. (12 December 1967)	Log Strike	Ship Landed Immediately With no Further Damage. Repairs Completed in Approximately Three Weeks.	Navy Letter Report Re: TUCUMCARI (PGH-2) Debris Impact Accident of 1 May 1968.
PGH-2: Impact on Forward Foil Caused Failure of Steering Actuator Assem-bly and Rapid Rotation of Strut. Ship was Operating Foilborne in Puget Sound. (1 May 1968)	Deadhead Log Strike on Starboard-Semi-Span of Forward Foil.	Ship Turned to Starboard and Rolled to Port in an Abrupt Manner. Four Crew-men Sustained Cuts and Bruises; One Received a Concussion. Local Damage Also Occurred at Starboard Aft Strut. Ship Returned to Service in Approxi-mately Three Weeks.	Navy Letter Report Re: TUCLJMCARI (PGH-2) Debris Impact Accident of 1 May 1968.
PCH-1 Mod 0: Log Impact on Forward Strut Caused Damage to Forward Strut Foundation Structure. Hull Dented Near Aft Strut Foundation Struc-ture. Ship Was Foilborne in Strait of Juan de Fuca, (30 April 1968)	Large Floating Log Impacted Forward Strut and Starboard Aft Strut.	Ship Landed Normally With No Further Damage. Ship Returned to Service in Ten Days.	Boeing Report D2-133703-34, 8/1/68. DTNSRDC Letter Re: Hydrofoil Debris Impact History, 3/5/75.

Table II.A.5-2. SUMMARY OF SERVICE FAILURES: PCH-1, AGEH-1, PGH-1, PGH-2 (Continued)

FAILURE	PROBABLE CAUSE	EFFECT ON SHIP	REFERENCES
PCH-1 Mod 1: Impact on Port Semi-Span of Forward Foil Caused Steering Actuator to Rupture. Strut Turned Abruptly to Port. Ship was Foilborne in Puget Sound. (25 June 1974)	Deadhead Log Strike on Forward Foil Near Tip.	Ship Turned to Port and Rolled to Starboard. Two Crew Members Experienced Minor Injuries. Ship Returned to Service in Approximately One Month.	DTNSRDC Letter Re: Hydrofoil Debris Impact History, 3/5/75.
PCH-1: Impact on Aft Strut Caused Down Lock Fitting to Fail While Ship Was Foilborne. (21 January 1975)	Whale Strike	Ship Become Hullborne Abruptly. No Significant Crew Injuries Occurred. Ship Was Returned to Service in Approximately Four Weeks (Repaired by Crew).	DTNSRDC Letter Re: Hydrofoil Debris Impact History, 3/5/75.
PGH-1: Impact on Aft Strut Pod Pairing Caused Loss of Nose Cap While Operating Foilborne. (1972)	Fish Strike	Water Gradually Entered Propeller Gearbox After Loss of Fairing; Ship Returned to Hullborne Mode. Three Weeks Required to Obtain New Nose Cone.	(Telephone Conversation)

result of the incident. A complete analysis of the origin of the fatigue crack which ultimately resulted in failure has not been possible, but the primary cause of failure is believed to be corrosive attack of the heat-treated 4340 steel link at an interface with a 17-4 PH spherical bearing. The corrosion is believed to have reduced the component fatigue life as well as producing a large residual tensile stress in the link due to the expanding products of corrosion. Because of this failure, the AGEH-1 foil incidence control system has subsequently been redesigned completely in 17-4 PH stainless steel.

(U) A nonoperating failure occurred in the main foil retraction system when unsteady hydraulic system loads caused a static strength failure in a hinge pin which was designed to be the weakest member of the retraction system. In this instance, the load criteria employed in the design of the retraction system did not consider unsteady and dynamic loads due to an improperly operating hydraulic system.

(U) The PGH-2 experienced failures of the bow doors (which accommodate forward strut retraction) while operating foilborne in rough water. Since the doors contained open slots at both their upper and lower ends, two points of entry existed for ram water during hull impacts. The resulting internal pressure, not included in the structural design, was the cause of failure.

(U) While operating foilborne in the Puget Sound area, the PGH-2 forward strut struck a log which resulted in damage to the strut foundation structure. The damage was repaired, and the ship returned to operation in approximately 3 weeks. On a second occasion the forward foil encountered a deadhead (vertically floating) log which resulted in a torsional load sufficient to rupture the steering actuator. This produced an uncoordinated turn by the ship which led to slight injury of several crew members as a result of the large outward roll angle which accompanied the abrupt turn.

(U) PCH-1 Mod 0 while operating foilborne in the Strait of Juan de Fuca encountered a large floating log which damaged the forward strut foundation structure and then impacted the hull and starboard aft strut. The 30 to 36 inch diameter log was found to have been broken in two by the impact. The ship was returned to service in approximately 10 days. Several years later while operating foilborne in the Mod 1 configuration, the forward foil encountered a deadhead log which led to rupture of the steering actuator in a fashion similar to PGH-2. (The ship in the Mod 1 configuration now features a steerable forward strut.) In this case, no crew injuries of significance were encountered, and the ship was returned to service in approximately 1 month.

(U) While operating in the Pacific Ocean off San Diego, PGH-1 struck a gray whale which resulted in failure of the tail strut down-lock foundation structure. The ship was repaired by the Coast Guard crew operating it at the time, and was returned to service in approximately four weeks. There were no injuries.

(U) The results of service experience to date with operational failures requiring immediate repair suggest that the most significant (limit) strength problem is that associated with log or whale strikes while operating foilborne. In this regard, it has been noted that the most serious consequences of failure **were** associated with steering actuator failures because of the abrupt motion of the ship after the strut is turned. It has also been noted, based upon strain gage measurements obtained on PCH-1 Mod 1 during the log strike of June 1974, that the side loads on a strut which result from such rapid strut rotation may define the ultimate (design) load of the strut.

(U) In order to deal with this problem in the case of PKM-1, an energy absorbing tiller arm has been designed and installed, as shown in Figure II.A.5-8, based upon a conceptual design developed for PCH-1 Mod 1. This device employs a bolt shearing mechanism which protects the steering actuator from excessive loads while at the same time absorbing sufficient torsional energy to prevent excessive rotation of the strut and hence the development of critical hydrodynamic lateral bending loads on the strut.

(U) The criteria for minimum energy absorption capability employed in the design of this device was derived from the AGEH-1 log impact shown in Figure II.A.5-9. The loading was of an

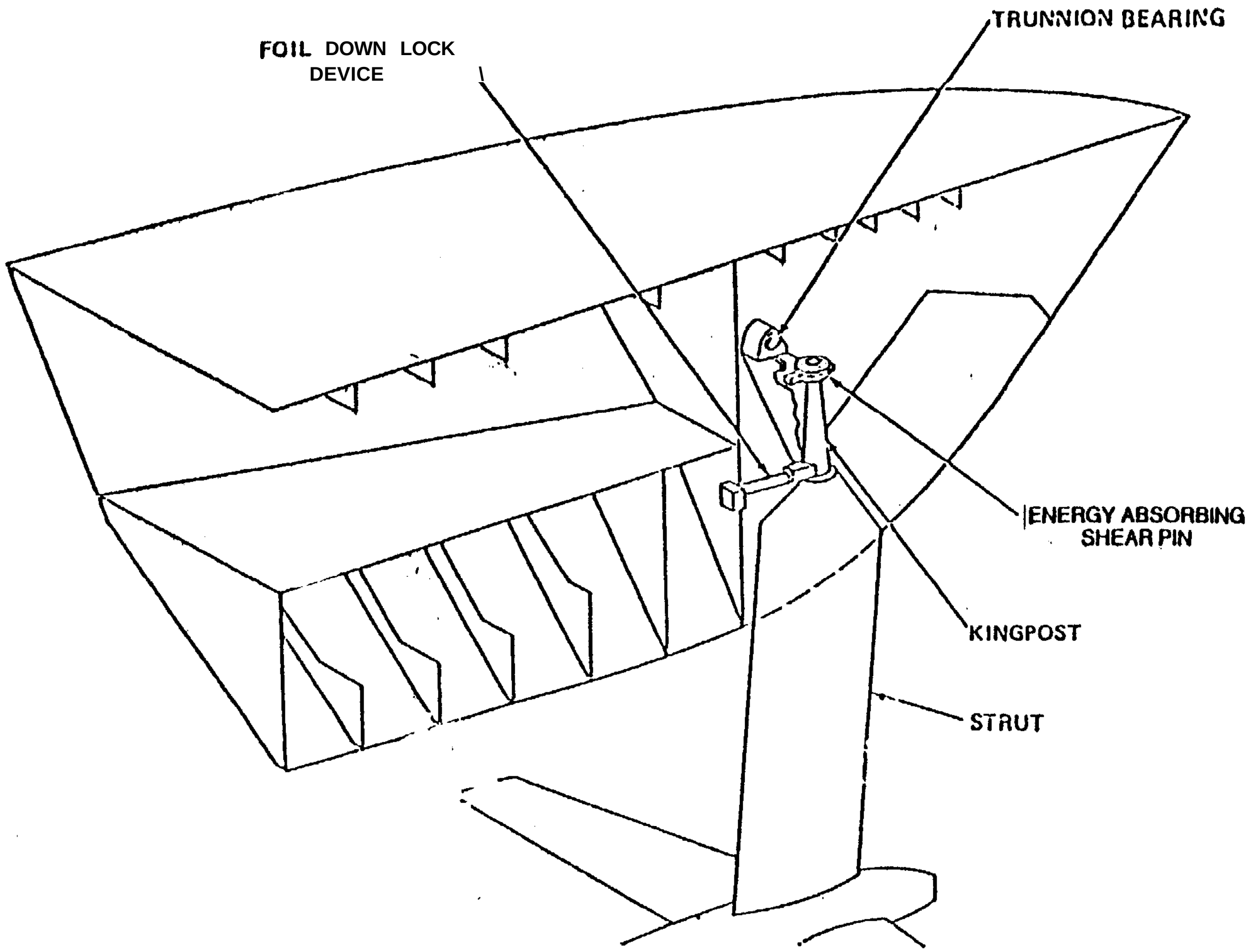

Figure II.A.5-8. LOCATION OF ENERGY ABSORBING TILLER ARM ON PHM-1

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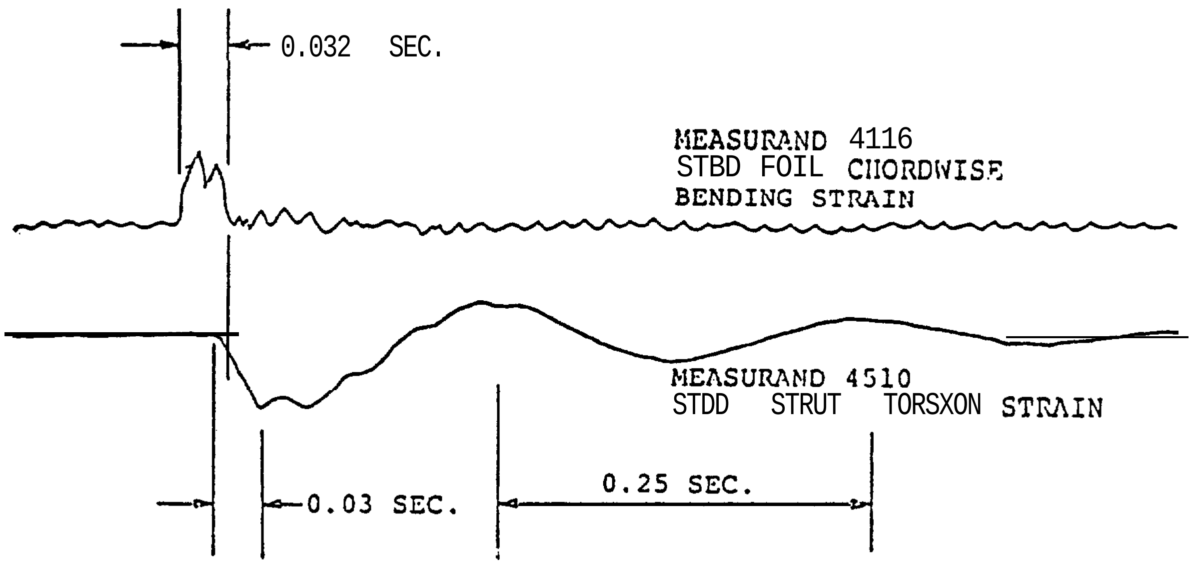

NOTE : MEASURAND **4116** SHOWS DURATION OF LOG IMPACT TO BE ABOUT **0.032** SEC. PEAK LOAD IS ESTIMATED FROM STRAIN DATA TO BE APPROXIMATELY **75,000** LBS.

MEASTJRAND 4510 SHOWS LOG HAS LEFT FOIL BEFORE TORSION AT UPPER END OF STRUT HAS BUILT UP APPRECIABLY. NO STRUCTURAL FAILURE OCCURRED AS THE RESULT OF THIS IMPACT.

AUGUST 24, 1971, T/C 16:22:17, DATA TAPE 66B, STRIKE ON OUTBOARD PANEL AT LEADING EDGE.

Pigure II.A.5-9. FOIL-STRIKE DATA FOR AGEH, 8/24/71 impulsive nature as shown by the response of the foil chordwise bending strain, Measurand* 4116. The strut torsional response as measured by Measurand 4510, located at the upper end of the strut lags the impulsive load since the period of oscillation of the basic torsional mode is about 0.25 seconds while the pulse duration is only about 0.032 seconds. The log had, in fact, ceased to load the foil before the strut torsion had increased appreciably. In this instance, no serious damage occurred because of the high inherent mass and strength of the AGEH-1 strut/foil assembly involved, as well as the fact that a steerable strut was not involved. The impact loading of approximately 75,000 lbs (estimated from the responses of Measurands 4116 and 4510) was used to calculate the influence of a similar tip strike on the forward foil of PCH-1 Mod 1 and also PHM-1. In each case, failure of the steering actuator was predicted. Subsequently, in June 1974, as noted in Table II.A.5-2, such a failure occurred on PCH-1 Mod 1 while operating in Puget Sound.

(U) The Boeing Company JETFOIL commercial hydrofoil ship features energy absorbers on the forward strut to deal with the more common, but somewhat less hazardous, strut debris impact problem. In general, foil systems have been found to be quite resistant to debris strikes, particularly in the case of larger ships such as the AGEH-1 which has withstood one major deadhead log strike on a main foil with only a dent in the leading edge (see above) structure.

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*Data systems Measurand lists exist for each of the three currently instrumented USN hydrofoil ships PCH-1, AGEH-1, and PHM-1.

(U) The state-of-the-art with respect to what might be termed hardening of strut/foil systems for log-type debris impacts has advanced significantly in the past several years. An impact loading is now incorporated in the Navy Hydrofoil Structural Load Criteria.

(U) With regard to service failures associated with hydrodynamic loadings in rough water, experience to date has been favorable. Loads research conducted with PCH-1 Mod 1, however, has shown that several potential deficiencies did exist in its original load criteria. However, these deficiencies have been eliminated by the Navy Hydrofoil Structural Load Criteria.

5.4.2 Fatigue Cracking

(U) Experience with respect to structural cracking under service loads presents a somewhat different picture than is true of static strength failures. Table II.A.5-3 summarizes some of the more significant service cracks found in the PGH-2 when it was subjected to a complete crack survey following decommissioning of the ship. The overwhelming majority of cracks were found in the strut/foil system as opposed to the hull which appears to reflect the fact that the more significant fatigue loads occur during foilborne operation and that they originate in the foil system.

(U) After approximately 600 hours of PGH-2 operation, the king post of the steerable forward strut, near the lower bearing, was found to have developed a fatigue crack, apparently due to drag bending loads. Subsequent reviews of PCH-1 Mod 1 rough water trials

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Table II.A.5-3. SUMMARY OF MAJOR PGH-2 FATIGUE FAILURES

FATIGUE CRACK	BASIS FOR DETECTION	PROBABLE CAUSE	REFERENCES
Crack in Forward Strut King Post at Intersection With Top Closure Plate of Strut.	Free Fall of Strut While Retracted Broke King Post Which Revealed Presence of Fatigue Crack. (20 December 1970)	Apparently Due to Drag Bending Moments Acting on King Post.	Boeing Letter No. 2-1503-0000-03k, 16 April 1971.
Cracks at Juncture of Forward Strut and Foil Attachment Lugs. (Both Lugs)	Inspection ok bcrut Following Strut Drop Accident of 20 December 1970.	Believed Due to Cyclic Flap Loads as Well as Large Asymmetric Foil Lift and Drag Loads During Rough Water Operation.	Boeing Letter No. 2-1503-000-031, 16 April 1971.
Cracks in Forward Strut Retraction Yoke Adjacent to Trunion Structure.	Detailed Inspection of Strut Following Withdrawal of Ship From Service.	Cyclic Strut Lateral Bending Loads in Rough Water.	(DTNSRDC Report in Preparation)

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data have suggested that a significant number of cycles of foil system drag bending moments occur in rough water operating due to the combined effects of drag due to large flap deflections and the associated rearward shift of the center of pressure of foil lift. Following local design modifications of the critical king post area, no further evidence of cracking occurred during the remaining 600 hours of foilborne operation of the ship.

(U) A second area of the forward strut which experienced fatigue cracking was the lower end of the strut near the foil attachment pins. Cracks in this area were discovered at the same time as the king post fatigue crack. In this case, the strut was weld repaired and the local stress concentration reduced by increased fillet radii. At the end of an additional 600 hours of foilborne operation, however, the cracks were found to have reappeared. No analysis has been made of the structural loading aspects of these fatigue cracks because of the relatively complex nature of the loadings involved and the fact that the ship is no longer in commission. Based upon measurement of some of the pertinent forces involved on PCH-1 Mod 1, it is believed that the primary contributors to the failures were cyclic flap loads in rough water, and asymmetric lift and drag loads acting on the forward foil, particularly during broach recovery conditions.

(U) A third area of cracking was found in the 17-4 PH forward strut support structure (i.e., yoke) at the end of 1,200 hours of foilborne operation. The cracks in this case were adjacent to the trunion support lugs which absorbed all forward strut loads except drag link loads which were reacted near the king post lower bearing. Again, no analysis of the fatigue load aspects of these failures was made. Lateral bending moment, lateral shear, and steering torque load measurements on PCH-1 Mod 1, however, have revealed considerable cyclic load activity in rough water, especially under forward foil broaching conditions.

(U) The above type of fatigue failures on PGH-2 occurred because of deficiencies in the load criteria to which the structure was designed. Since the foil system drag bending and fatigue spectrum based on full-scale trials data have now been incorporated into the Navy Hydrofoil Structural Load Criteria, these types of failures should not occur in future designs based on these criteria.

5.4.3 Corrosion

(U) The general status of corrosion problems is reviewed elsewhere in this report. From a structural integrity point of view, the most significant aspect of corrosion is believed to be its effect on material fatigue strength, particularly in strut/foil systems. In the case of noncorrosion-resistant steels, the effect of sea water on high cycle fatigue strength is sufficiently harmful that in a cyclic load environment it is not a question of whether a failure will occur but only of how long it will take. In the case of corrosion-resistant steels, the situation is considerably improved, but is still a matter of concern for several reasons. First is the fact that the 17-4 PH and 15-5 PH stainless steel now in service in foil systems are subject to crevice corrosion in areas where mechanical fasteners are employed. This is expected to have a particularly harmful effect on high cycle fatigue life. A second reason for concern is that the high cycle fatigue life of these stainless steels in sea water is considerably less than in air. The apparent endurance limit stress (fully reversed cycles) is on the order of one half the corresponding "in-air" value. The designer must use this reduced endurance or require that coatings be applied for these materials employed in fatigue critical components of the strut/foil system. Even if coatings are used, the lower endurance limit is advisable to guard against local failure of the coatings.

5.4.4 Erosion

(U) The effects of erosion due to cavitation on strut/foil materials are covered elsewhere in this report. Since the Mod 1 modification of PCH-1 which removed the aft strut/foil intersection from behind the forward propellers, cavitation erosion has not been found to be a significant problem. This is despite the fact that at normal foilborne speeds, areas of continuous local cavitation at the strut-foil pod intersection have been noted in film and video camera studies of the PCH-1 Mod 1 foil system. These areas and their associated coatings have been found to require only minor maintenance and to be of no significance with regard to structural degradation.

5.4.5 Maintenance

(U) Maintenance is considered here only in regard to inspections to detect service cracking of structure of components.

Service experience to date has revealed several items of interest. The first is that critical joints in foil system and strut foundation structure are frequently uninspectable. Further, the required major disassembly is seldom undertaken for structural inspection purposes because of the time and expense involved. Inspectibility and establishment of mandatory structural inspection intervals must be made a design requirement for future hydrofoils.

(U) Of a more encouraging nature is the recent application of eddy current surface crack detection equipment to assist in strut/foil and hull inspections. (See Reference II.A.5-5.) This equipment is inexpensive, entirely portable, and features a variety of pencil-sized probes for use in limited access areas. Most important of all the equipment is that which detects surface cracks without removal of paint systems or other preparation of the surface for inspection. This equipment normally requires the services of an experienced inspector, since it will indicate surface anomalies which are not related to structural cracks and which can therefore be misinterpreted. When used by qualified personnel, however, it has been found to be of considerable value in the inspection of both hulls and strut/foil systems.

(U) Where inspection for cracks below the surface is required, x-ray equipment is commonly used, and where crack depth or material thickness is to be determined, sonic inspection equipment is very useful. While no single type of inspection equipment offers universal capability, the composite capability is relatively good. This tends finally to put the burden of the inspection problem on the structural accessibility side of the ledger, which is more a state-of-affairs problem than a state-of-the-art problem. Firm design requirements for inspectability have been imposed on the HY-130 PHM strut/foil design reference and in the recently completed new AGEH-1 after strut. Inspectability requirements for all critical areas subject to fatigue are recommended for future hydrofoil ships.

5.4.6 Future Hydrofoil Ships

(U) The foregoing comments on hydrofoil ship structure are primarily concerned with the current state of the art as judged from existing hydrofoil ships. The following comments are offered as an indication of problems which are likely to be associated with future hydrofoil ships based upon current mission trends. The Hydrofoil Ocean Combatant (HOC) concept design is assumed in this regard to reflect the most probable development trend for future Navy hydrofoil ships. Since this design is much larger than the present ships and should be expected to withstand open ocean storm environments, and since it could come under attack along with other Fleet ships, the following trends are anticipated with regard to hull and foil system structure.

- The load criteria employed in sizing structural members will have to properly reflect maximum operating loads without excessive conservatism. The current emphasis on fatigue and limit load criteria is therefore likely to continue until it is considered both realistic and validated for a large ocean-going hydrofoil ship. The application of costly weight-saving materials will be unlikely to offer a viable solution to the foil system weight problem because of the inevitable concern for ship cost. The more probable initiatives in this case are apt to be associated with materials offering improved weight/cost trade-offs as opposed to materials which can simply offer a reduction in weight.

- The likelihood of open ocean operation will require careful review of load criteria for those portions of the hull structure which are subject to impact by breaking waves under storm conditions such as the deckhouse, weather deck, and topsides. A recent hydrofoil ship deck house design features 0.080" thick 5456 aluminum on the forward structure and 0.060" on the sides. By comparison, a recent destroyer design features 1.375" to 0.375" 5456 at the front of the deck house and 0.250" 5456 at the sides. There is no reason to believe that an ocean-going hydrofoil ship should have the same deckhouse scantlings as a destroyer. Nevertheless where the existing hydrofoil ship scantlings reflect acceptable structural weights, they may not reflect entirely adequate scantlings for breaking waves. Ice and ice removal loadings, as well as weapon blast loadings must also be considered in these areas.

- A third category of concerns which is also likely to influence structural design to a greater extent than in the past are combat-related requirements such as resistance to underwater explosions, fire containment, and hardening to withstand missile and projectile attacks.

In summary, however, no significant state-of-the-art improvements in existing technology are required to assure a structurally adequate hydrofoil; only proper application of existing knowledge and experience is required.

REFERENCES

II.A.5-1 Proceedings of the Second Structures Workshop - Structures for High Performance Ships at NSRDC, Feb 13-14, 1973, Volume II - Structural Technology; Development of Structural Load Criteria for High Performance Ships.

II.A.5-2 NSRDC Memorandum 173:WHB:dlg, 74-173-M76, 10 April 1974, Adequacy of PCH-1 Mod 1 Forward Strut Design Loads.

II.A.5-3 Proceedings of the Second Ship Structures Workshop - Structures for High Performance Ships at NSRDC, Feb. 13-14, 1973, Volume III - Contributed Papers, Hull Loading and Response, Structural Analysis and Design; The Prediction of Hull-Wave Impact Loads on High Performance Marine Vehicles - A Computerized Tool.

II.A.5-4 DTNSRDC Report 4005, "A Semiempirical Computerized Method for Predicting Three-Dimensional Hull-Water Impact Pressure Distributions and Forces on High-Performance Hulls," Robert R. Jones and Raymond G. Allen, December 1972.

II.A.5-5 NSRDC TN-Z, Structures Department Nondestructive Evaluation Capability, February 1974.

II. STATUS OF VEHICLE TECHNOLOGY

A. TECHNOLOGICAL PERFORMANCE FEATURES

6. PROPULSION

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II.A. TECHNOLOGICAL PERFORMANCE FEATURES

6. PROPULSION

6.1 (U) SUMMARY AND CONCLUSIONS

1. Considerable data exist on propulsors covering subcavitating, transcavitating, and supercavitating propellers and waterjet systems. These data are adequate to predict performance and estimate propulsor system weight with sufficient accuracy to make the necessary trade-off studies to achieve an optimum design for a given set of requirements.

2. Several types of screw propellers are available for hydrofoil propulsion. The primary classification is as follows:

- Subcavitating propellers in twin nacelle, tandem arrangement have been used successfully on HIGH POINT (PCH-1) for speeds up to 48 knots. Design studies suggest that subcavitating propellers can be used for speeds up to 50 knots in a tractor arrangement if the revolutions can be kept low and the diameter large. However, a single pusher arrangement is preferred for lower system drag and less vulnerability and will also be satisfactory for 50-knot speeds.

- Supercavitating propellers have been used successfully on DENISON, FLAGSTAFF (PGH-1), and PLAINVIEW (AGEH-1) for speeds over 50 knots. Because it did not have a free turbine engine controllable pitch propeller was used on FLAGSTAFF to permit higher rpm at takeoff, which increases takeoff thrust.

Although improved design procedures for super-cavitating propellers are being sought, it is the consensus of the most experienced designers in this area that such propellers can be designed to meet the requirements for any hydrofoil ship. No maximum speed limitations are imposed. In general, propulsive efficiency is improved by an increase in diameter.

• Transcavitating propellers (Newton-Rader) have been used for'the Coastal Patrol and Interdiction Craft (CPIC) for speeds up to 50 knots. These propellers were developed by Vosper, Limited, and have been applied by them for a number of high speed patrol craft.

These propellers operate in a fully cavitated condition at high speed. They provide better efficiency at takeoff than supercavitating propellers and appear to be free of erosion damage in partial cavitation operation at lower speeds.

3. Waterjet propulsion systems have been used for TUCUMCARI (PGH-2) and PEGASUS (PHM-1). Design studies were carried out for a waterjet system for DBH and other hydrofoil ships.

A number of analyses of waterjet performance and design have been carried out. Such systems involve complex hydro-dynamic and mechanical interactions and although they present difficult optimization problems, adequate system design procedures are available.

As they have been applied to the PGH-2 and PHM, waterjet systems are not as efficient as screw propellers. To achieve comparable propulsive efficiency, if indeed that is possible, would require increases in system size and weight and result in increased drag. The choice of a waterjet system in preference to screw propellers must be based on other considerations than propulsive efficiency, such as mechanical simplicity and reliability.

6.2 HYDRODYNAMICS OF PROPULSION

(U) Like all fluidborne vehicles (excepting rockets), hydrofoil ships derive the required propulsive thrust by rearward acceleration of a stream of the ambient fluid. Both air and water have been used, water being presently preferred for reasons which will be pointed out later. The device which is in contact with the water and reacts with it to produce thrust and transmit it to the ship, termed the propulsor, is the subject of the present discussion.

(U) The propulsor is only one component of the propulsion system. It receives power from the engines through the transmission and converts it to useful work to overcome the resistance of the ship. Propulsor design must ensure compatibility with the engine and transmission characteristics. In other words, the propulsor must be capable of absorbing available engine power and producing the needed thrust over the whole range of ship operating speeds.

(U) As a power conversion device, it is proper to consider the efficiency of the propulsor, and this is done. It is important to note, however, that the interaction of the propulsor with the characteristics of the other parts of the ship is pervasive and subtle. Thus, an improvement in propulsor efficiency may involve such a weight increase and consequent loss of fuel capacity, as to reduce the range. On the other hand, it may be possible to increase the ship displacement, as a result of improved propulsive efficiency, more than enough to compensate for the increased weight with a resultant increase of fuel and range. Such higher level tradeoffs cannot be treated further here, but are mentioned to emphasize that the relationship between propulsive efficiency and weight is a major consideration in hydrofoil ship design.

(U) Another aspect of propulsion hydrodynamics for high speed ships is the ever present concern with cavitation, to avoid erosion damage, and to minimize the adverse effects on efficiency and performance.

(U) For many decades, the screw propeller has been the favored propulsor for ships and small craft as well. The choice was made only partly on the basis of efficiency, but also in consideration of mechanical simplicity for conventional ships and compatibility with the propulsion machinery torque-speed characteristics. The principal competitor of the screw propeller for hydrofoil propulsion has been the waterjet, a concept which dates from at least as early as 1661 (See Reference II.A.6-1). The principle advantage of the waterjet system for hydrofoil ships is the comparative mechanical simplicity of the power transmission.

(U) The following discussion will, then, be limited to:

- Screw Propellers
- Waterjets

and will address primarily:

- Efficiency
- Performance
- Cavitation

6.3 PROPULSION SYSTEM REQUIREMENTS

(U) It has been customary to fit separate and distinct propulsion systems for hullborne and foilborne operations. This has been dictated by the provision of foil retraction and the consequent unavailability of the foilborne propulsors when hullborne. The much lower thrust and power requirements when hullborne and the need for maneuvering capability not easily provided by the foilborne system are additional considerations.

(U) Hullborne propulsors have included screw propellers, some with 360° steerable mounting, and waterjet systems. Because of the large sail area of retracted struts and foils, and to provide enhanced low speed maneuverability and control, several recent hydrofoil ships have been fitted with transverse bow thrusters in addition to hullborne propulsors. The design of hullborne propulsors and thrusters for hydrofoil ships is entirely within the present state of the art.

(U) The foilborne propulsor, on the other hand, presents a challenging design problem because of the high maximum speed required in conjunction with a demand for equal or greater thrust at takeoff speeds (about one half the top speed). The impact of these requirements constitutes the principal subject of the following discussion of propulsor hydrodynamics.

6.4 ELEMENTS OF PROPULSION ANALYSIS

(U) It is axiomatic that the propulsor must provide a thrust to overcome the drag or resistance of the ship. Power must be supplied to the propulsor by the engine and transmission to accomplish this. The efficiency of the propulsor is expressed by the propulsive coefficient:*

$$pc = \frac{RV}{P_D}$$

where R is the resistance or drag
V is the speed of the ship
PD is the power delivered to the propulsor

(U) Other definitions of propulsive efficiency are used, based on measurements of the power at other points in the power train. The one given here is most appropriate to a discussion of propulsion hydrodynamics. In the following, a more detailed examina-

*This is sometimes called the "quasi-propulsive coefficient."

tion will be made of the factors contributing to the propulsive coefficient.

(U) In general, the thrust delivered by the propeller to the thrust bearing and thus into the ship is not equal to the drag which might be measured by towing the ship. This is because the action of the propeller alters the flow over nearby parts of the ship and increases the resistance. The result is, however, usually expressed by the thrust deduction fraction, t, defined by:

$$t = \frac{T-R_T}{T}$$

so that

$$T = \frac{R_T}{1-t}$$

where T is the propeller thrust
R_T is the (towed) resistance

(U) The thrust deduction is most easily recognized in screw propeller installations and is customarily evaluated by model tests by measuring the propeller thrust in self propelled tests and the resistance by towing the model without a propeller. Techniques for waterjet propulsion of models have not been developed, and the concept of a thrust deduction for such systems is nebulous. One point to be noted is the comparatively higher thrust deduction for tractor propellers than for pushers.

(U) It has been noted (Reference II.A.6-2) that the size of nacelles to house propulsion gearing or waterjet inlets and of struts carrying shafting or water ducting is often larger than would be required for structural or dynamic stability purposes, or merely as fairings, if other propulsion means were employed. Barr has proposed (loc. cit.) that the consequent increase of drag should be charged against the propulsion system in the calculation of propulsive efficiency. He has defined a mounting efficiency, η_m, by the expression:

$$\eta_m = \frac{D_t - D_m}{D_t}$$

where D_m is the increase of drag due to requirements of the propulsion system
D_t is the total drag

(U) It has not been accepted practice to attempt to measure the drag increase, D_m, which would require the preparation of alternative designs and the testing of a stripped down model, as well as a complete model. Estimates can and should be made, however, and included in a comparative evaluation of competing propulsion systems.

(U) It should be remarked that weight differences between competing propulsion systems also lead to differences in drag which are not usually reflected in comparisons of propulsive efficiency. This is simply to acknowledge that ultimate tradeoff judgments must be made on the basis of fuel consumption and other costs to provide a specific military capability. The hydrodynamic considerations addressed here are only a part of the total input to such tradeoffs.

(U) Along with an effect of the propulsor on the drag, there is an influence of other parts of the ship on the environment and the performance of the propulsor, particularly the screw propeller. Thus, the (relative) velocity of flow at the position of the propeller would, in the absence of the propeller, generally be less than the speed of the ship. This is described as, and attributed to, the wake which is by definition the track of and behind a ship. A similar influence is, however, exerted on a tractor propeller mounted ahead of the strut/foil/nacelle assembly.

Analytically, the wake is expressed as a fraction:

$$w = \frac{V-V_A}{V}$$

where V is the ship speed
V_A is the relative flow velocity at the propeller location, called the speed of advance

This leads to:

$$\frac{V_A}{V} = 1-w$$

(U) The flow velocity, V_A, and the wake are not uniform over the propeller disc, but vary both radially out from the propeller axis and circumferentially around the disc at any radius, especially for aft mounted, pusher propellers. These variations have a significant influence on the performance of the propeller and must be considered in propeller design. On the other hand, use is made, in the calculation of propulsive efficiency, of an average or effective wake which is determined by comparing the performance of the propeller in its working position with that in "open water." The open water characteristics of a propeller are determined by a test with the (model) propeller sufficiently far ahead of the mounting equipment to be unaffected thereby. The effective speed of advance is then determined as the speed at which the propeller, in open water, develops the same thrust at the same rpm as it does when operating in its working position on the ship.

The propeller efficiency in open water, η_o, is given by:

$$\eta_o = \frac{TV_A}{2\pi Q_o n}$$

where Q_o is the open water torque
n is the rate of revolution

(U) For the working propeller, however, the torque will (usually) be larger and the propeller efficiency becomes:

$$\eta_p = \frac{TV_A}{2\pi Q n} = \eta_o \cdot \eta_r$$

where $\eta_r = \frac{Q_o}{Q}$ is called the relative rotative efficiency
and Q is the working torque
$2\pi Qn = P_D$, the delivered power

(U) In terms of the component efficiencies defined above, the propulsive coefficient becomes:

$$pc = \frac{RV}{P_D} = \frac{T(1-t)}{PD} \cdot \frac{V_A}{1-t} = \eta_p \cdot \frac{1-t}{1-w} = \eta_o \cdot \eta_r \cdot \eta_h$$

where $\eta_h = \frac{1-t}{1-w}$ is conventionally called the hull efficiency, but for hydrofoil ships is perhaps more appropriately termed the interaction efficiency, Reference II.A.6-2.

(U) Other expressions for propulsive efficiency have been used by different analysts. For example, Barr (Reference II.A.6-2) defines an overall propulsive coefficient:

$$opc = \frac{(D_t - D_m)V}{P_B} \approx \eta_p \cdot \eta_h \cdot \eta_t \cdot \eta_m$$

where, P_B is the engine brake horsepower
η_t is the transmission efficiency
and the other symbols have been defined previously. Brandau (Reference II.A.6-3) omits η_m from this formula, writing:

$$opc = \frac{RV}{P_B} = \eta_p \cdot \eta_h \cdot \eta_t$$

(U) Barr's formula includes all of the factors of concern to the hydrodynamicist except the impact of increased weight on the drag and, hence, on the thrust required.

(U) The same analysis can be applied to waterjet propulsive systems if a suitable definition of the term propulsor is adopted. Thus, for a waterjet system we consider the propulsor to comprise the stream of water which flows through the pump, and all the boundaries of the flow including the pump and its impeller. The propulsor efficiency is then, just as for the screw propeller:

$$\eta_p = \frac{TV_A}{P_D}$$

(U) The hull efficiency may be some less than unity for a hullborne system with a flush inlet submerged in the boundary layer. For a foilborne waterjet, both the wake and thrust deduction factors can be ignored, but not the mounting efficiency, η_m.

(U) In subsequent paragraphs, the emphasis is on propulsor efficiency with appropriate comments on the interaction efficiency factor.

6.5 SCREW PROPELLERS

(U) The efficiency of a propulsor may usefully be compared to the "ideal efficiency" which is that achieved by an hypothetical device with the same swept area which produces a uniform axial acceleration of the affected fluid stream and no lateral velocity. The ideal efficiency of a screw propeller is given (Reference II.A.6-4) by the formula

$$\eta_I = \frac{2}{1 + \sqrt{1 + C_{Th}}}$$

where the thrust loading coefficient, C_{Th}, is

$$C_{Th} = \frac{T}{1/2\, \rho\, A_O V_A^2} = \frac{8}{\pi} \cdot \frac{K_T}{J^2}$$

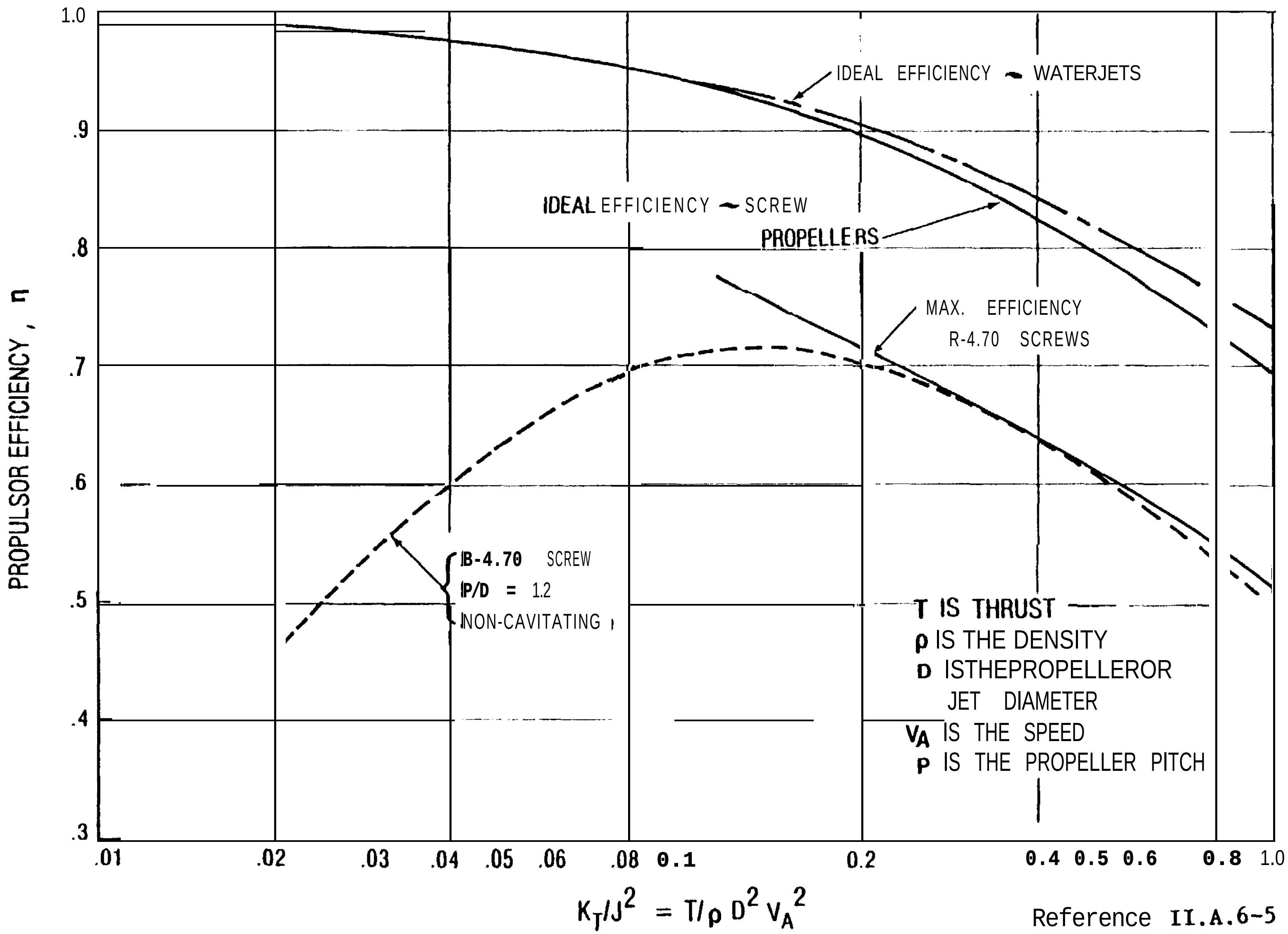
add: T is the thrust
ρ is the density
A_O is the area of the propeller disc
V_A is the speed of advance
$K_T = \frac{T}{\rho^2 D^4}$ is the thrust coefficient
$J = \frac{V_A}{nD}$ is the advance coefficient
n is the propeller rate of revolution per second

D is the propeller diameter.

The ideal efficiency is shown in Figure II.A.6-1 as a function of $\frac{K_T}{J^2}$. There is also shown the efficiency of a typical, conventional propeller of pitch ratio P/D = 1.2, and an envelope which gives the maximum efficiency obtainable at low speed with propellers of this design with the optimum pitch ratio for each value of $\frac{K_T}{J^2}$.

(U) Assuming inviscid flow, failure of the real propeller to reach the ideal efficiency can be attributed to the generation of rotational velocity components in the propeller race and the impossibility of achieving a uniform axial velocity over the whole of the race column. Both of these deviations from ideal propulsor action represent excess kinetic energy which must be supplied by the engine.

(U) This figure makes clear the dominant influence of the diameter on the efficiency of a propeller required to produce a specified thrust at a given speed. Evidently, the efficiency is greater the larger the diameter, up to a point where blade friction becomes dominant. On the other hand, the torque will be greater for the propeller of larger diameter, and the rpm must be reduced with a resultant increase in the weights of propeller and transmission. Thus, a careful tradeoff is required to establish the optimum diameter. There may, in addition, be limitations on the allowable propeller diameter due to submergence requirements, for example, which preclude the use of the hydrodynamically optimum propeller.



Reference II.A.6-5

Figure II.A.6-1. TYPICAL PROPELLER EFFICIENCY

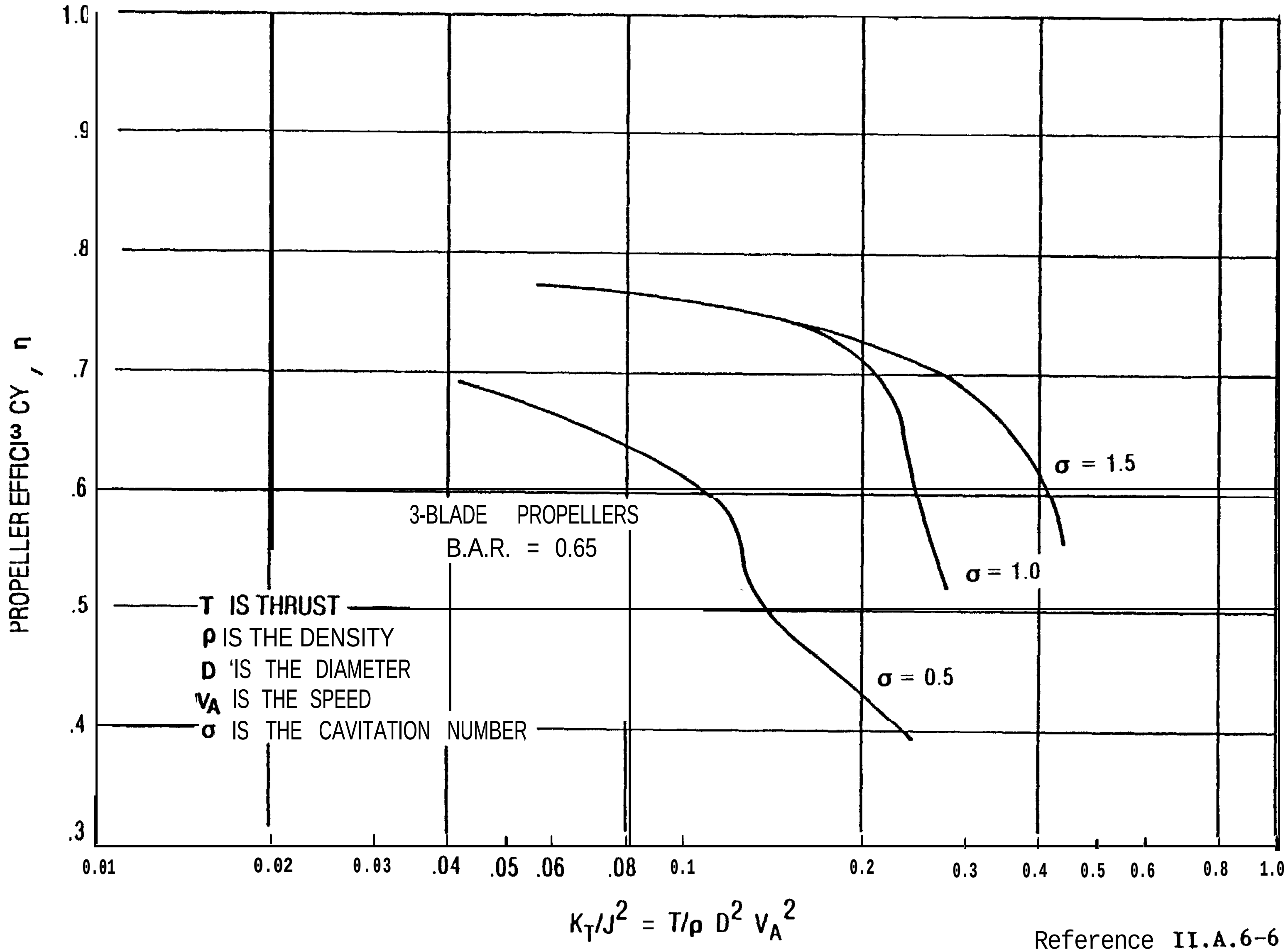
6.5.1 Air Propeller Propulsion

(U) Air propellers mounted on the deck of the ship (such as used on air cushion vehicles) could be used on hydrofoils. In order to reach practical efficiencies, these propellers would become impractically large, as can be seen by looking at the expression for thrust loading coefficient. The denominator in this expression, $1/2\ \rho A_O V_A^2$, is half the flux of momentum in a stream of area equal to the propeller disc area and velocity corresponding to the ship speed. For an air screw, since the density is about 1/800 that of sea water, the propeller disc area would have to be 800 times that of the water propeller to achieve equal loading and, hence, equal ideal efficiency. The cumbersomeness of so large an airscrew, and the consequent interference with useable deck areas, are the reasons for the unattractiveness of air propulsion for hydrofoil ships.

6.5.2 Subcavitating Propellers

(U) With increasing ship speed, it becomes increasingly difficult to avoid the occurrence of cavitation on the propeller blades. This can cause erosion damage to the blade material and, if sufficiently severe, will degrade the performance. The inception of cavitation can be delayed by an increase of blade area, for a given diameter, or by an increase in diameter - up to a point.

(U) The curves in Figure II.A.6-2 show how the performance of a series of conventional, ogival section propellers with



Reference II.A.6-6

Figure II.A.6-2. EFFECT OF CAVITATION

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a Blade Area Ratio of 0.65 is influenced by cavitation as the speed is increased. The speed is represented by the cavitation number defined by:

$$= \frac{p - P_v}{1/2\ \rho V_A{}^2}$$

where p is the pressure in undisturbed water at the depth of the propeller
Pv is the vapor pressure of the water
ρ and V_A have been defined above

(U) The relation between speed and cavitation number is given in the table below at a depth of 10 feet.

V knots	σ
25	1.54
30	1.06
35	.78
40	.60
45	.47
50	.383

(U) The effect of increased blade area is shown in Figure II.A.6-3 for propellers of the same series of ogival section propellers at a cavitation number σ = 0.50 (V = 44 knots). This approach to cavitation control, that is by incorporation of sufficient blade area to avoid cavitation, has been successfully used on the forward, and aft propellers on HIGH POINT (PCH-1) for speeds up to 47 knots.

(U) With a tractor propeller the performance of the propeller itself will approach closely that obtained in the usual tests of series propellers in the model basin or cavitation tunnel.

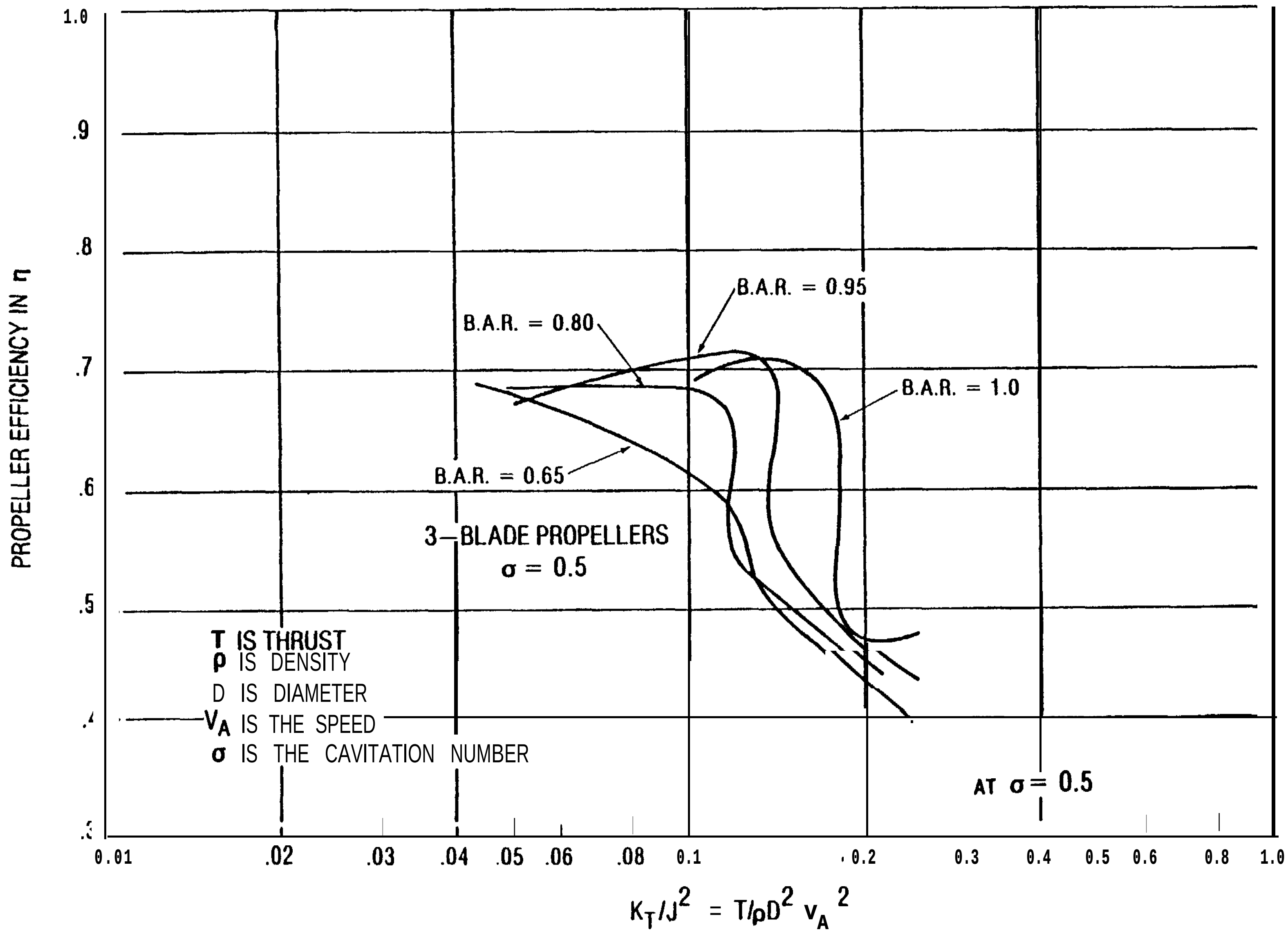

Figure **II.A.6-3.** EFFECT OF BLADE AREA

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There is, however, a reluctance to use tractor propellers on hydrofoil ships. For one thing, cavitation in the tip vortices, which can be very persistent, causes erosion where it impinges on the struts and foils. Also, the high velocity flow in the propeller discharge causes an increase of drag considerably greater than that of a pusher propeller.* The pusher propeller is, however, constrained to operate in the disturbed flow or wake behind the strut and foil. For the individual blades on the propeller, it is as though the ship speed varied during each revolution. Consequently, cavitation can occur during a part of the revolution under loading conditions which would not cause cavitation if the inflow to the propeller were uniform. Such cavitation caused serious erosion damage on the pusher propellers on HIGH POINT which was only finally alleviated by relocating the propellers below the foil. This serious erosion was aggravated by the flow influence of the tractor propeller.

(U) The effects of such non-uniformities in the propeller inflow can be offset only to a limited extent by increase of the blade area, perhaps necessitating an increase in diameter as well. Refinements in the design of the blades, to control the radial distribution of the loading and to assure that cavitation which does occur is not damaging to the blades, are also used. (Reference II.A.6-7).

*Generally termed the thrust deduction

(U) Design procedures are available for subcavitating propellers, that is, for propellers designed to operate without erosion or performance degradation, and include provision for adapting the propeller to the irregularities in the wake. These are set forth in (References II.A.6-8, and II.A.6-9) and have been extensively evaluated by comparison with full-scale ship performance.

(U) Propellers designed for cavitation-free operation at design speed have proved satisfactory at the takeoff drag hump, even though the thrust loading coefficient is approximately four times higher, because the cavitation number is also four times greater or more. Thrust capability is the important criterion. The total duration of such a condition is generally not long enough to produce significant erosion.

(U) Subcavitating propeller designs have been used exclusively for both the forward (tractor) and after (pusher) propellers on HIGH POINT (PCH-1). The original after propellers had insufficient blade area and suffered severe erosion damage. After several iterations, a design was achieved which provided sufficient life to eliminate propeller degradation as a limitation on ship operations. The conversion to Mod 1 has further improved propeller performance by greatly reducing inflow irregularities to the after propellers.

(U) Design studies (Reference II.A.6-10) have indicated that a pair of pusher propellers of subcavitating design could satisfactorily drive HIGH POINT to 50 knots without the help of the forward propellers and within the capability of the existing transmission.

(U) A recent parametric analysis of propulsion systems for a l,OOO-ton hydrofoil has been undertaken (See Reference II.A.6-11). This study also examined the maximum ship displacement within the limits of a pair of LM 2500 engines. Results indicate that subcavitating propellers can provide the largest ship range of all competing propellers for either 40- or 50-knot design speeds.

6.5.3 Supercavitating Propellers

(U) An alternative to cavitation-free propellers is the use of supercavitating propellers. These designs operate with a cavity forming at the leading edge and extending beyond the trailing edge so as to cover all of the back of the blade. The performance of such a propeller depends on the shape of the face (pressure side), the sections of which are typically hollowed or cambered to produce the desired pressure distribution. Figure II.A.6-4 shows a typical blade section for a supercavitating propeller.

(U) Successful operation of a supercavitating propeller requires a careful balance of loading, blade area, blade face camber, and rotational speed. In order to avoid erosion damage due to face cavitation and to assure full cavity formation under design conditions, it is necessary, if the circumferential wake variations are appreciable, to employ a larger mean angle of attack than is conducive to maximum efficiency.

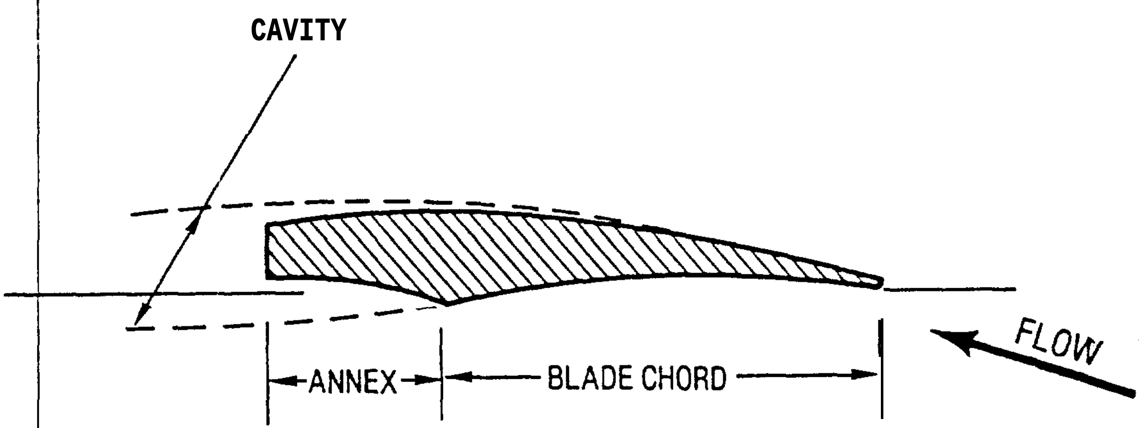


Figure II.A.6-4 TYPICAL SUPERCAVITATING PROPELLER BLADE SECTION

(U) Degradation of thrust capability at low speeds, compared with subcavitating propellers, is characteristic of super-cavitating propellers. It is due to growth of cavity thickness and consequent interference with the inflow. As a result, takeoff performance may be improved by a reduction in blade area ratio below the optimum for design speed. Even so, it may be difficult to develop the required takeoff thrust without exceeding the rated rpm. For hydrofoil ships and other ships with a marked drag hump at low speed, the performance at the hump, as well as design speed efficiency, must be carefully considered in the design process. The us2 of a controllable pitch propeller can be advantageous.

(U) Because of the sensitivity of supercavitating propeller efficiency to blade thickness, the maximum stress is a critical factor, and the material with the highest allowable stress is sought consistent with fatigue life consideration. The effect of loading on maximum efficiency is similar to that for subcavitating propellers. It is, of course, important that appropriate rpm be used. Figure II.A.6-5 (from Reference II.A.6-2) shows the estimated performance, at 80 knots, of propellers of optimum blade area ratio and rpm as a function of thrust and diameter. It may be noted that curves of constant efficiency correspond to constant values of $\frac{K_T}{J^2}$.

(U) Design procedures for supercavitating propellers have been adapted from those developed for subcavitating propellers. This has proved to be difficult because of the effects of extensive cavities on the flow into and through the propeller. The complexities of the mathematical theories of cavity flows, as applied to propellers, have thus far prevented the development of wholly adequate theoretical design and analysis methods. Nevertheless, semi-empirical procedures have been developed, and work is going forward to further this development. With the aid of cavitation tunnel tests and iterations, effective supercavitating propellers have been designed for DENISON, BRAS D'OR, PLAINVIEW, and FLAGSTAFF, the latter incorporating a controllable pitch capability.

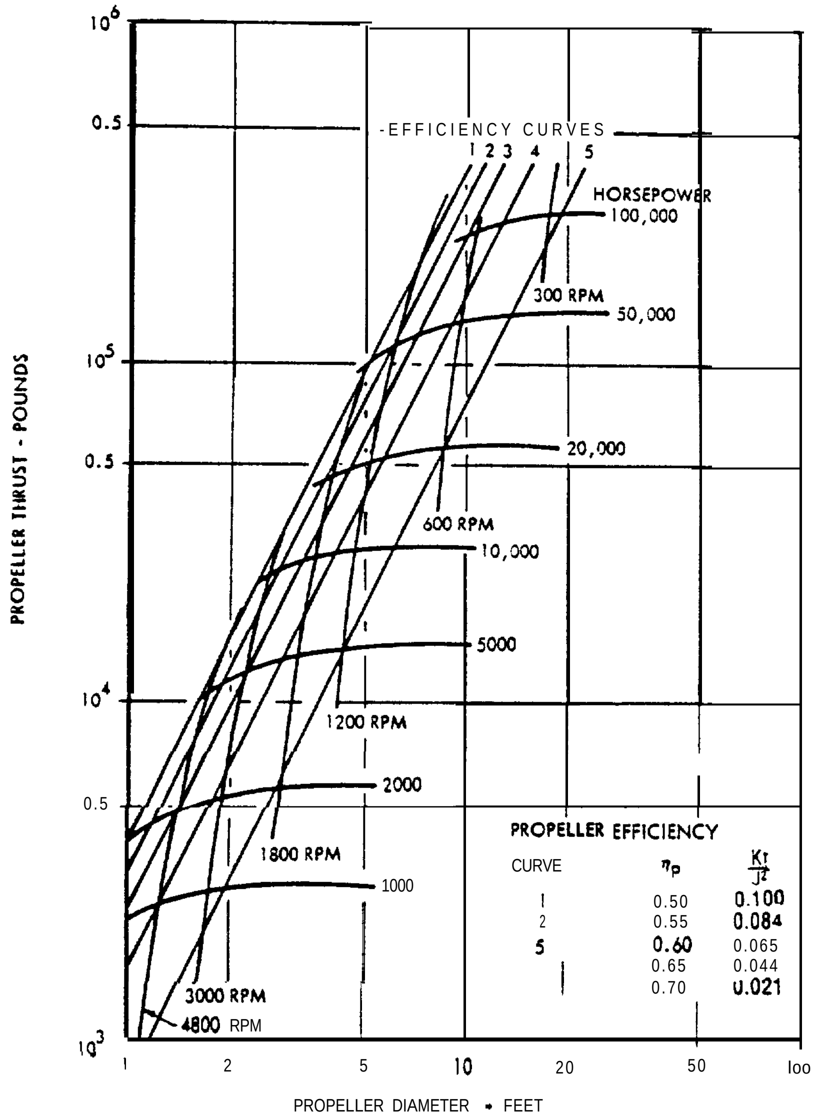


Figure II.A.6-5. PERFORMANCE CURVES FOR OPTIMUM, FOUR-BLADED SUPERCAVITATING PROPELLERS AT 80 KNOTS, WITH 25,000-PSI DESIGN STRESS

(U) Design studies for the 750-ton DBH have shown that supercavitating propellers can provide effective propulsion for this ship. They have the advantage of higher rpm than competing propeller designs, hence, lower reduction ratio and a smaller and lighter transmission. Nevertheless, the tradeoff studies in Reference II.A.611 show that an increase in the diameter of supercavitating propellers permits an increase of ship displacement, and a resulting increase in range for fixed engine power, despite the increase in transmission weight.

6.5.4 Ventiliated Propellers

(U) It is difficult to maintain a full cavity on super-cavitating propellers at lower foilborne speeds without the use of an undesirably large blade angle of attack. Tests of supercavitating foils have shown that cavity size can be increased and performance improved by introducing air into the cavity. Similar benefits have been demonstrated for supercavitating propellers. A reduction of the radiated noise is also anticipated.

(U) Air can be introduced through passages in the blades, but the associated structural and mechanical complexities are a serious deterrent. It has been found that the desired effects can be achieved much more simply by emitting air from a ring in front of the propeller. Tests of such a vented propeller have been carried out on HIGH POINT, and the results are presently being evaluated.

6.5.5 Newton-Rader Propellers

(U) A notably different section profile from that shown in Figure II.A.6-4 was used for supercavitating propellers by the designers at Vosper Limited for the BRAVE class patrol boats. Subsequently, with the support of the British Admiralty Experiment Works, Haslar, this development led to tests of a series of propellers in the cavitation tunnel at Vosper. The results were presented to the Royal Institution of Naval Architects in 1960 by R.N. Newton of the AEW and H.P. Rader of Vosper.

(U) The configuration of these propellers, of which an example is shown in Figure II.A.6-6, is characterized by hollow faced sections for which the NACA a=1.0 mean line was used as the face contour. A "quasi-elliptic" thickness distribution was superimposed on the face contour. This basic shape was subsequently modified by cutting back the leading edge by 5 percent of the blade chord at each radius and lifting the face to provide a new, sharp edge at the undisturbed back contour. The effect of the modification is evident in Figure II.A.6-6, especially at the inner radii.

(U) While intended for operation with a fully developed back cavity, and offering excellent efficiency at suitable loadings (See Figure II.A.6-7), a principal feature of these propellers is the maintenance of good efficiency under more heavily loaded conditions as shown in Figure II.A.6-8. They have proved to be free of cavitation

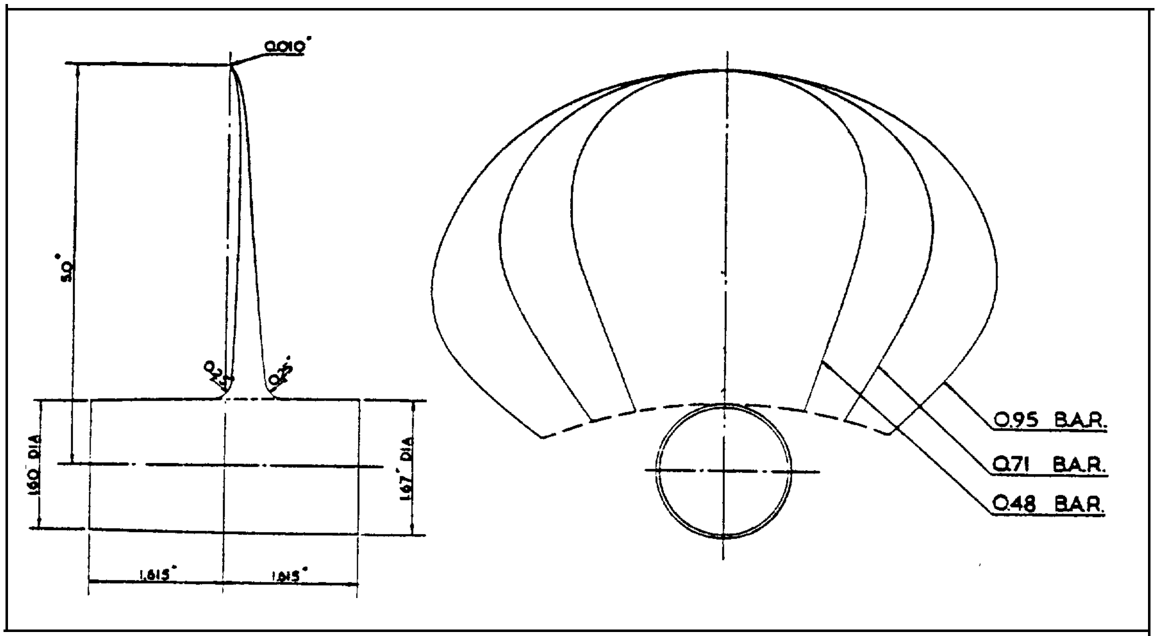
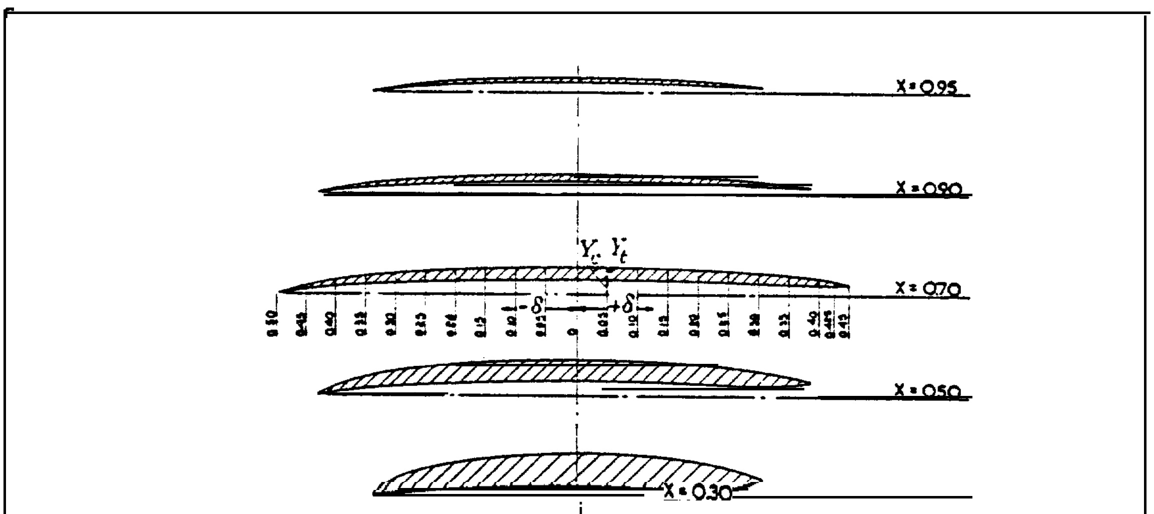


Figure II.A.6-6a. OUTLINE OF MODEL PROPELLERS



BLADE SECTIONS OF MODEL PROPELLERS WITH B.A.R. 0·71

Figure II.A.6-6b. BLADE SECTIONS OF MODEL PROPELLERS WITH B.A.R. 0.71

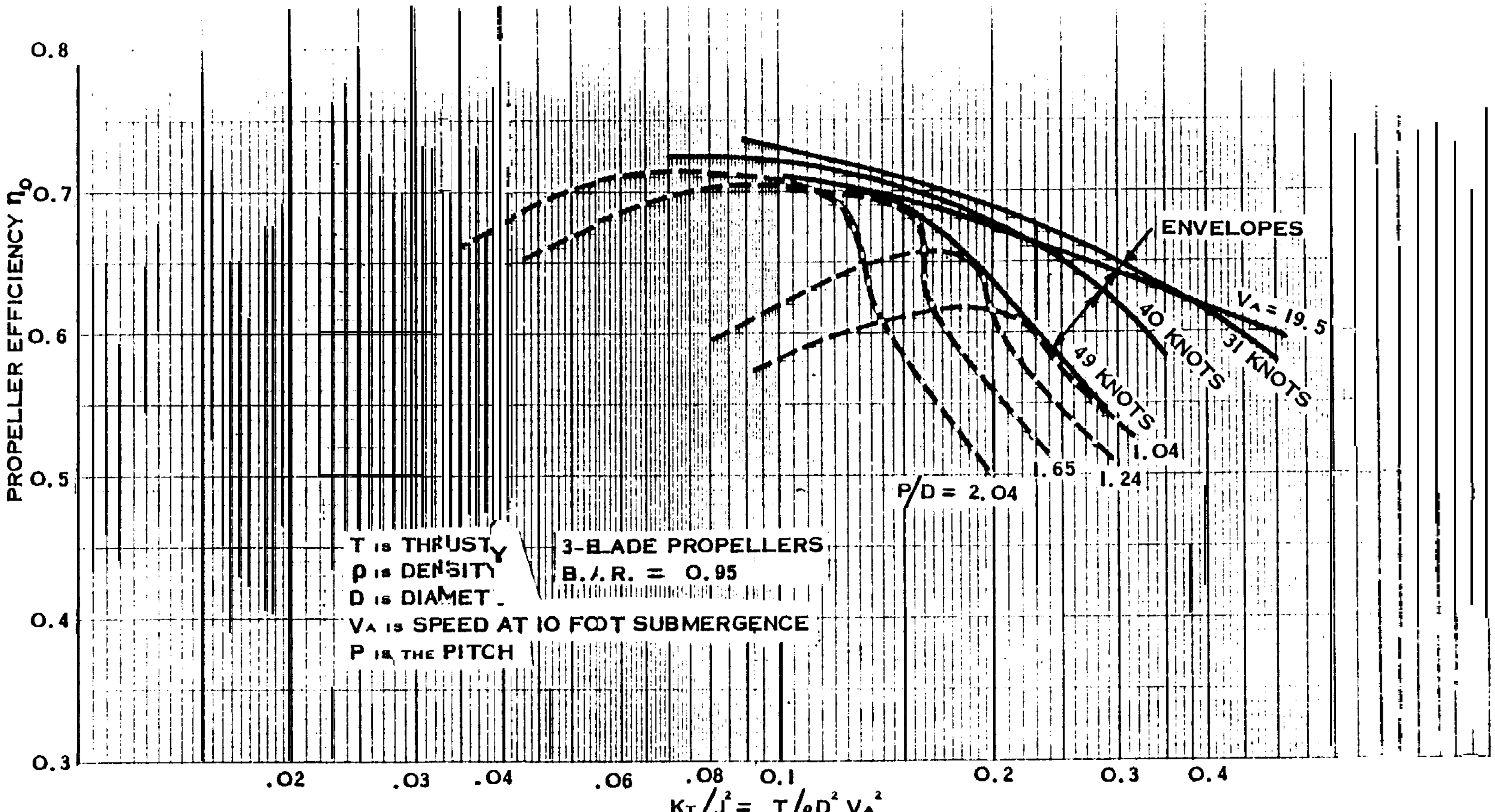


Figure II.A.6-7. NEWTON-RADER PROPELLERS AT A SPEED OF 49 KNOTS

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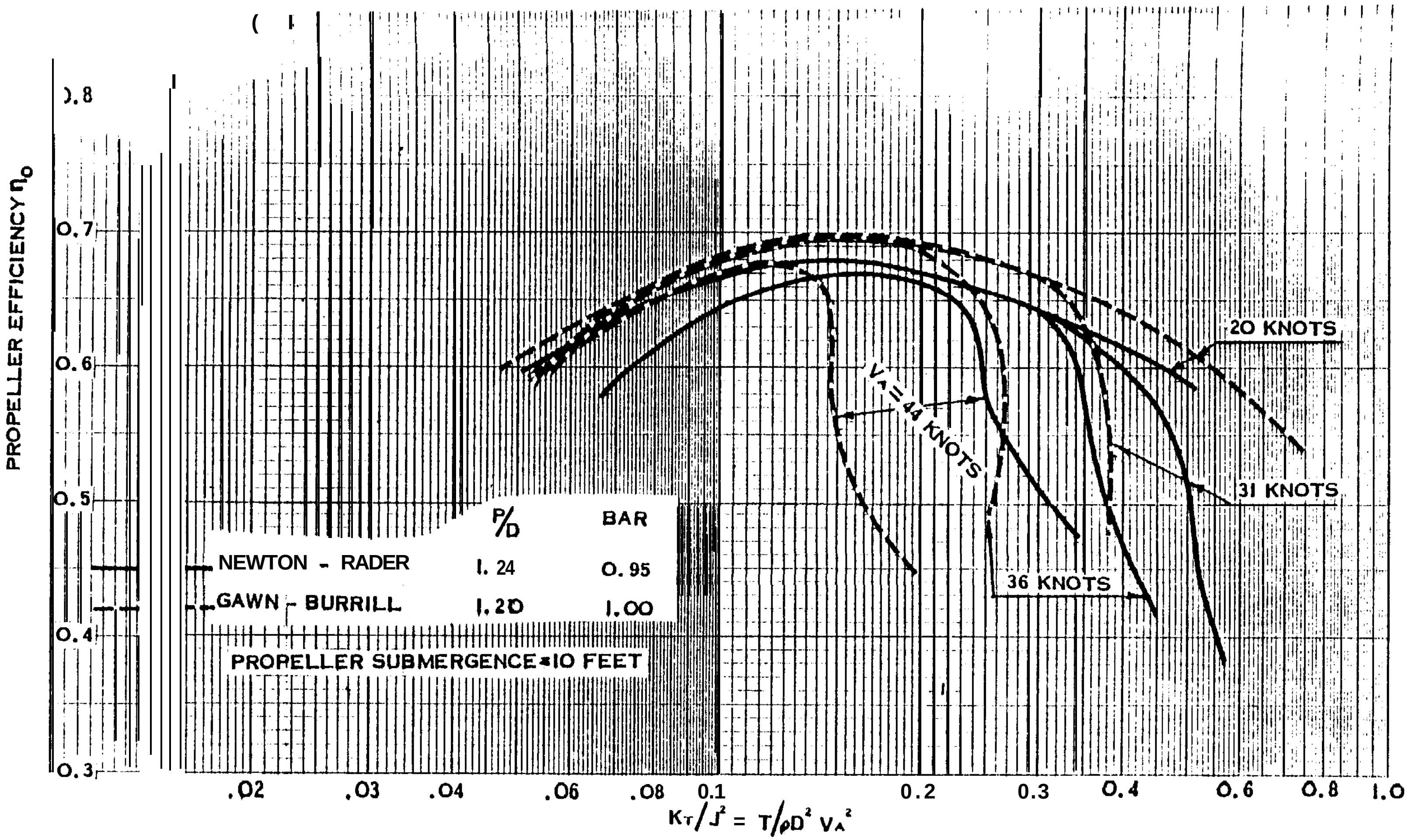

Figure II.A.6-8 COMPARISON OF GAWN-BURRILL AND NEWTON-RADER PROPELLERS erosion even when operating with partial cavitation on the back which is normally damaging to propellers of subcavitating design. For these reasons, they have come to be referred to as transcavitating propellers.

(U) Design information for these propellers, comprising the results of extensive cavitation tunnel tests, has been used for the design of propellers for the CPIC and a proposed candidate tractor propeller for HIGH POINT. The authors of Reference II.A.6-12 have suggested that the propeller loading should be above that for maximum efficiency for the pitch ratio chosen in order to assure freedom from face cavitation, which leads to erosion.

(U) Newton and Rader have suggested that hydrodynamic characteristics of the blade sections can be obtained by a method derived by Prof. H.W. LERBS (Reference II.A.6-13), and have carried out limited analyses of this sort. They propose that the resulting data could be used for design based on accepted vortex theory which would permit adaptation to an irregular wake.

6.6 WATERJET PROPULSION

(U) In the waterjet propulsion system the stream of water, which is accelerated to produce thrust, flows into the ship where work is done on it by a pump and is then discharged aft at higher velocity. A typical installation in a hydrofoil ship is shown in Figure II.A.6-9.

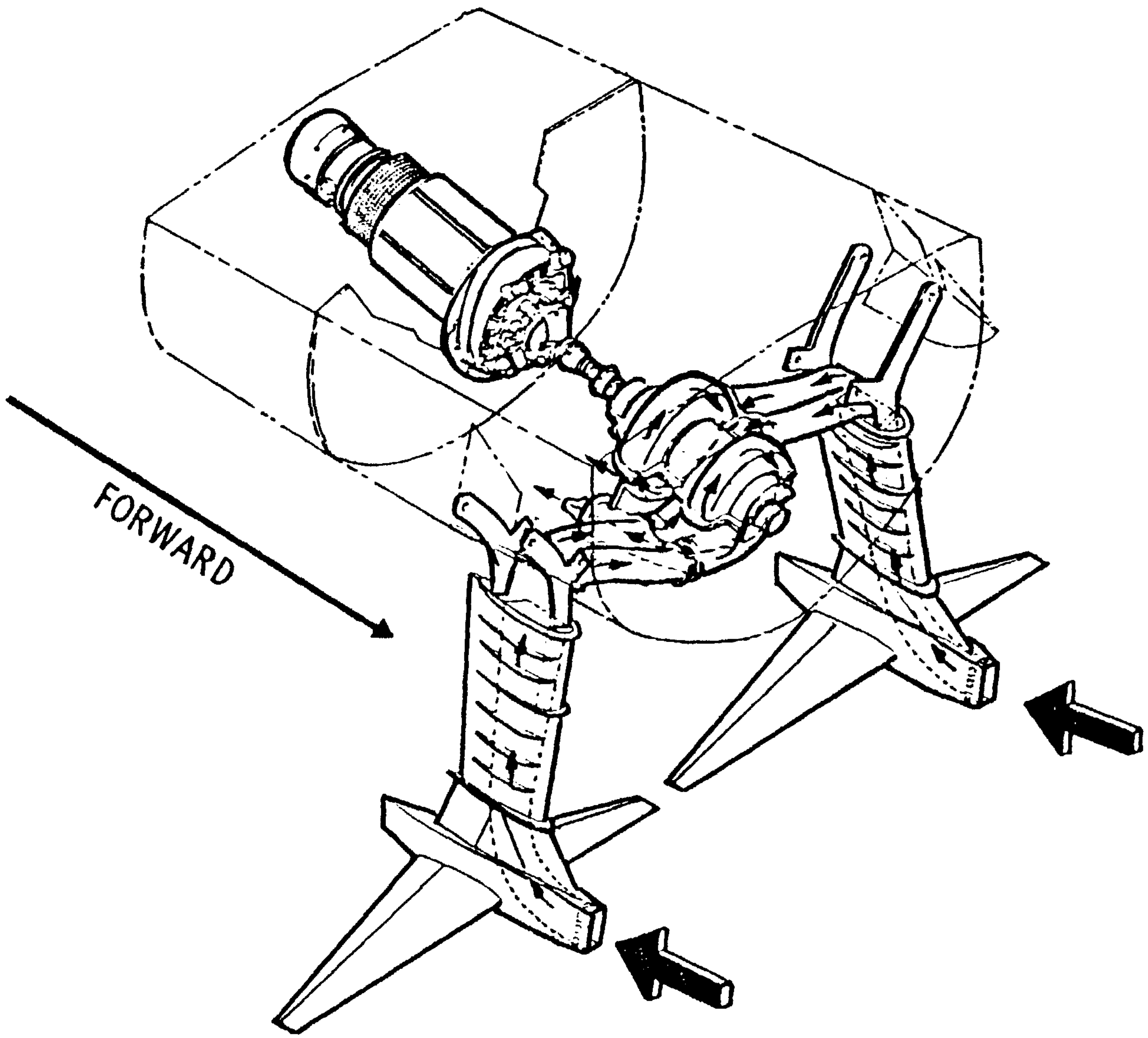

Figure II.A.6-9. PGH-2 PROPULSION SYSTEM

(U) Waterjet performance is subject to the same hydrodynamic constraint as the screw propeller. Thus, the ideal efficiency of the waterjet is given by:

$$\eta_I = \frac{4}{3 + \sqrt{1+2C_{Th}}}$$

where the thrust loading coefficient, C'_{Th}, is

$$C'_{Th} = \frac{T}{1/2 \, \rho \, A_j V^2}$$

and: T is the thrust
ρ is the density
A_j is the cross-sectional area of the discharge nozzle
V is the ship speed

(U) This formulation assumes that the jet issues from the discharge nozzle as a parallel stream at atmospheric pressure. In contrast, the race column behind a screw propeller is converging as it leaves the propeller and only reaches its final, steady diameter some distance downstream. Thus, the propeller disc area, used for definition of the loading coefficient for screw propellers, C_{Th}, is larger than the corresponding jet area, and the two loading coefficients are slightly different. If the same scale is used for plotting C_{Th} and C'_{Th}, the waterjet will appear somewhat more efficient, as is shown in Figure II.A.6-1.

(U) A principal hydrodynamic handicap of the waterjet is the practical impossibility of incorporating a jet area as large as that of the competing screw propeller. Thus, a waterjet propulsion study for DBH* envisioned a jet area of 2.36 ft^2 for each of twin jets. Competitive supercavitating propellers of 7 ft diameter were contemplated which, at cruise loading, give a net race column area of 36.34 ft^2. As a consequence, the ideal efficiency of the waterjet for the DBH is 0.655, while that of the screw propeller is 0.941.

(U) An attempt to increase efficiency by increasing the jet area necessarily involves an increase in the size of the inlet, the pump, and the connecting ducts. As a result, the drag is increased, because a larger pod is required, and the weight of water in the system is increased in direct proportion to the jet area. The result, while not a hydrodynamic effect, is a reduction in payload or in fuel capacity, which generally far outweighs the effect of the increased efficiency.

(U) A further burden is placed on the waterjet, in the usual configuration with the jet discharge at or just below the hull bottom, by the necessity to lift the water to this elevation above the water surface.

(U) The degree to which the actual efficiency of a waterjet installation approaches the ideal efficiency depends on the extent of a number of losses and on the efficiency of the water-jet pump. Figure II.A.6-10 shows the overall propulsive coefficient of a typical waterjet driven hydrofoil compared to a propeller driven hydrofoil. Of particular significance is the large drop in efficiency

* Reference II.A.6-14

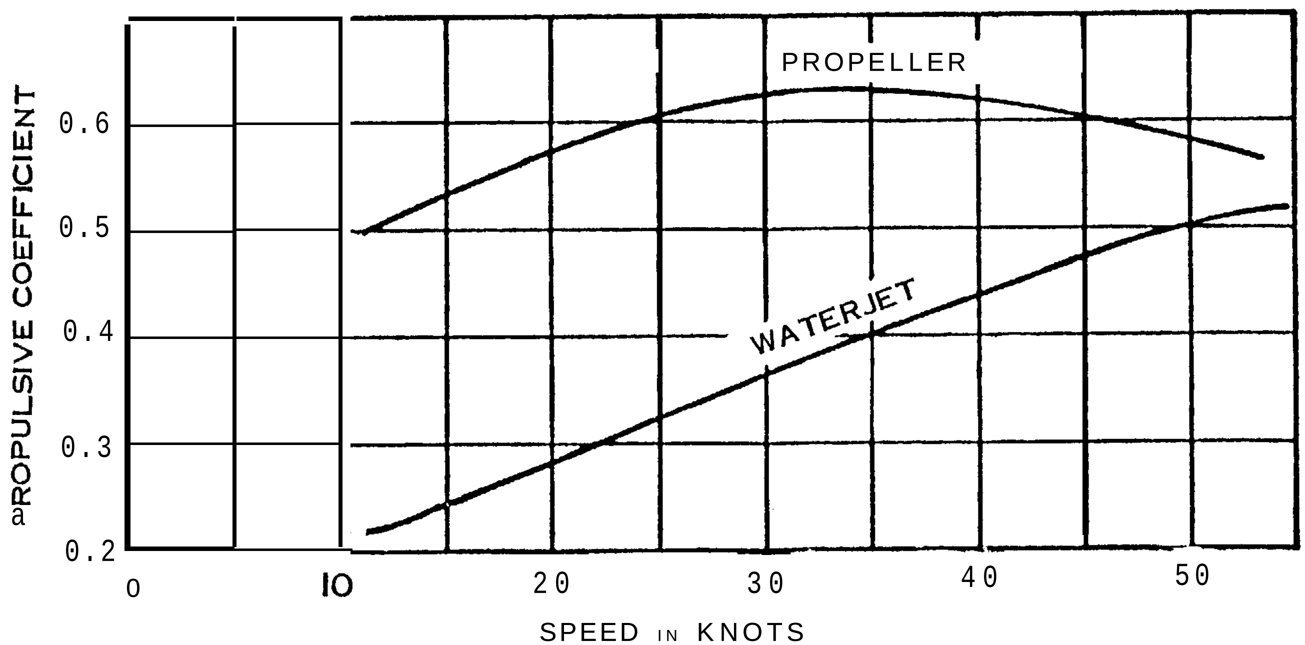

Figure II.A.6-10. TYPICAL HYDROFOIL PERFORMANCE

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of the waterjet as speed drops off. This generally results in a lower full load displacement ship for the same installed horsepower. An extensive treatment of the loss factors in waterjets is beyond the scope of this study. Analyses of waterjet performance, pump efficiency, and system losses are available in References II.A.6-3, II.A.6-15, II.A.6-16 and II.A.6-17.

(U) The following comments are intended only to illustrate some of the considerations involved in system design.

1. The efficiency of waterjet propulsion systems is frequently expressed by:

$$\eta_T = \frac{TV}{P_s}$$

where T is the thrust
V is the ship velocity
P_s is the shaft power

(U) As noted earlier (Section II.A.6-4) account should be taken of the drag of propulsion system components, in particular, the inlet pod drag and any increment in drag if the strut size has to be increased to encompass the water ducting. A preferable expression for efficiency is:

$$D = \frac{RV}{P_s}$$

where R is the basic ship drag. The DBH study (Reference II.A.6-14) indicates that, for the baseline system considered there, the pod drag for a waterjet will be less than that for the proposed propeller system. These differences must be accounted for in order to make a true comparison between a waterjet and a propeller system.

2. For a selected jet area, with the corresponding jet velocity and flow volume, the design of the inlet and ducting to the pump is governed by the requirement to avoid cavitation.

(U) The danger of cavitation is greatest during takeoff when the flow requirement is highest. The critical region, generally, is the elbow at the bottom of the strut, but the pump inlet is also of concern. A critical analysis of duct design and the pressure profiles are contained in Reference II.A.6-15 (Levy & Meggitt).

3. Pumps for waterjet propulsion are not beyond the state of the art. In fact, TUCUMCARI (PGH-2) utilized a standard centrifugal pump design. For PEGASUS (PHM-1) a design was selected which had been prepared especially for waterjet propulsion by Aerojet and is described in Reference II.A.6-15 (Levy & Meggitt). Reference II.A.6-16 - Part 3 (MIT study) contains a discussion of pump design. As with propellers, a suitable compromise is necessary between the optimum pumps for cruise and takeoff conditions.

4. Selection and design of a waterjet propulsion system cannot be made primarily on the basis of hydrodynamic efficiency or even of overall system efficiency. The governing criteria must

include the impact on payload and range or endurance. The Boeing Company has developed a computer program to carry out the relevant analyses, Reference II.A.6-17 (Hatte & Davis).

5. The subject of radiated noise is a pertinent hydrodynamic topic. Good comparisons of radiated noise between waterjet and screw propeller ships have not been made.

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MIT RPT NO		
72-13	Part 1	An Overview
72-14	Part 2	Ram Intake Considerations
72-15	Part 3	Pumps, Gear Boxes, and Main Power Plant Considerations
72-16	Part 4	Computer Program Description and Users Manual

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II. STATUS OF VEHICLE TECHNOLOGY

A. TECHNOLOGICAL PERFORMANCE FEATURES

7. HUMAN FACTORS

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II.A. TECHNICAL PERFORMANCE FEATURES

7. HUMAN FACTORS

7.1 INTRODUCTION

(U) The hydrofoil ships, employing fully submerged foils and a full-time Automatic Control System, have provided a quantum jump in ride quality for a high speed ship operating in a seaway. With today's hydrofoil ships, the concept of slowing down in a seaway for crew functional or comfort consideration is not an operational factor. However, the requirements for those kinds of tasks requiring mental alertness, psychomotor effectiveness, and visual or aural acuity have tended to rise sharply in recent years, and they are expected to continue apace. Therefore, in order to maximize the effectiveness of this type of human function, emphasis must continuously be placed on improving the environmental conditions in both working and living spaces.

(U) Ironically, those environmental factors primarily responsible for degradation of command and operating efficiency (accelerations and motions) have not yet found a leading position in our specifications. Thus, while the hydrofoil ship has provided major reductions in ship accelerations and motions, realistic standards as to their adequacy and criteria to guide new designs are lagging considerably behind demonstrated capabilities. New ride quality criteria are currently being developed, specifically for hydrofoil ships, as a part of the NAVSEA Hydrofoil Criteria Development Program. These should provide a reasonable basis for new design as well as a standard of comparison against which measured data from any ship can be evaluated.

(U) In the following sections, the data base of demonstrated hydrofoil ship qualities is reviewed, both in terms of quantitative acceleration and motion data; and in qualitative terms, relating to the actions and reactions of personnel involved in hydrofoil ship operations and testing. Finally, the status of basic human response data are reviewed in terms of their suitability and applicability to the hydrofoil ship operational situation.

7.2 HYDROFOIL SHIP RIDE QUALITY ASSESSMENT

(U) Over the past decade much data have been developed from operational and research-oriented hydrofoil ships. Measured ship accelerations and motions from underway trials of these ships provide a clear demonstration of the ride quality that can be expected for hydrofoil ships. In this regard, it is important to understand both the nature of the hydrofoil environment, and the extent of the data base from which the conclusions are drawn.

7.2.1 The Hydrofoil Ship Environment

(U) The concomitant accelerations and motions experienced by hydrofoil ships are random in nature, being induced by the random seaway in which the ship operates. Vibrations due to machinery or high Q structural resonances have not been a measurable factor in hydrofoil ship ride quality, nor are they expected to be.

(U) The frequency range of the seaway-induced accelerations and motions is essentially bounded on the lower end by zero frequency and on the upper end at 4 Hz for ships operating in the SO-knot regime; with the vast majority of the energy occurring below 2 Hz.

(U) Acceleration and motion spectra measured from underway ship trials tend to be fairly narrow band, but not necessarily as narrow as the 1/3 octave band pass spectra being used extensively in basic human factors research (See Reference II.A.7-1).

(U) The sea in which the ship operates is constantly changing, and in addition, the ship motions and accelerations vary with ship heading in any given sea. Therefore, no single condition can adequately describe the ship ride quality. In reality there is an infinite family of sea conditions and headings in which the ship operates. Thus, in the final analysis, ride quality should logically be assessed for such an infinite family of conditions.

(U) On the opposite side of the coin, however, quantitative data from sea trials are obviously going to be available for only a small portion of actual ship operation, so an infinite family of ship response data is never going to be available. Therefore, for purposes of this assessment, the measured ride quality data are presented as rms acceleration versus significant wave height of the seas for a relatively small number of sea conditions.

7.2.2 The Hydrofoil Ship Data Base

(U) Rough water motions and accelerations have been continuously measured and recorded, along with continuous wave height measurements taken from the moving ship for several military hydrofoil ships. The data from rough water trials conducted by these ships have been reduced and extensively reported in References II.7-2 through II.A.7-7. These ships, from which the enclosed rough water data were taken, are:

- HIGH POINT Mod 0 (PCH-1)
- TUCUMCARI (PGH-2)
- PEGASUS (PHM-1)

(U) In the conduct of tests, wave height was continuously recorded from an onboard wave height measuring system*. The wave height recordings were then reduced to determine the significant wave height and significant wave period of the seas in which the ship operated. Accelerations and motions were measured from precision accelerometers and gyros, with accelerometers being positioned at various points about the ship (primarily the operating areas>.

(U) The quantitative data presented are for worst case headings relative to the sea as measured in the pilothouse, which is generally representative of worst case operating area acceleration levels.

*Reference II.A.7-8 describes the wave height measurement instrument employed.

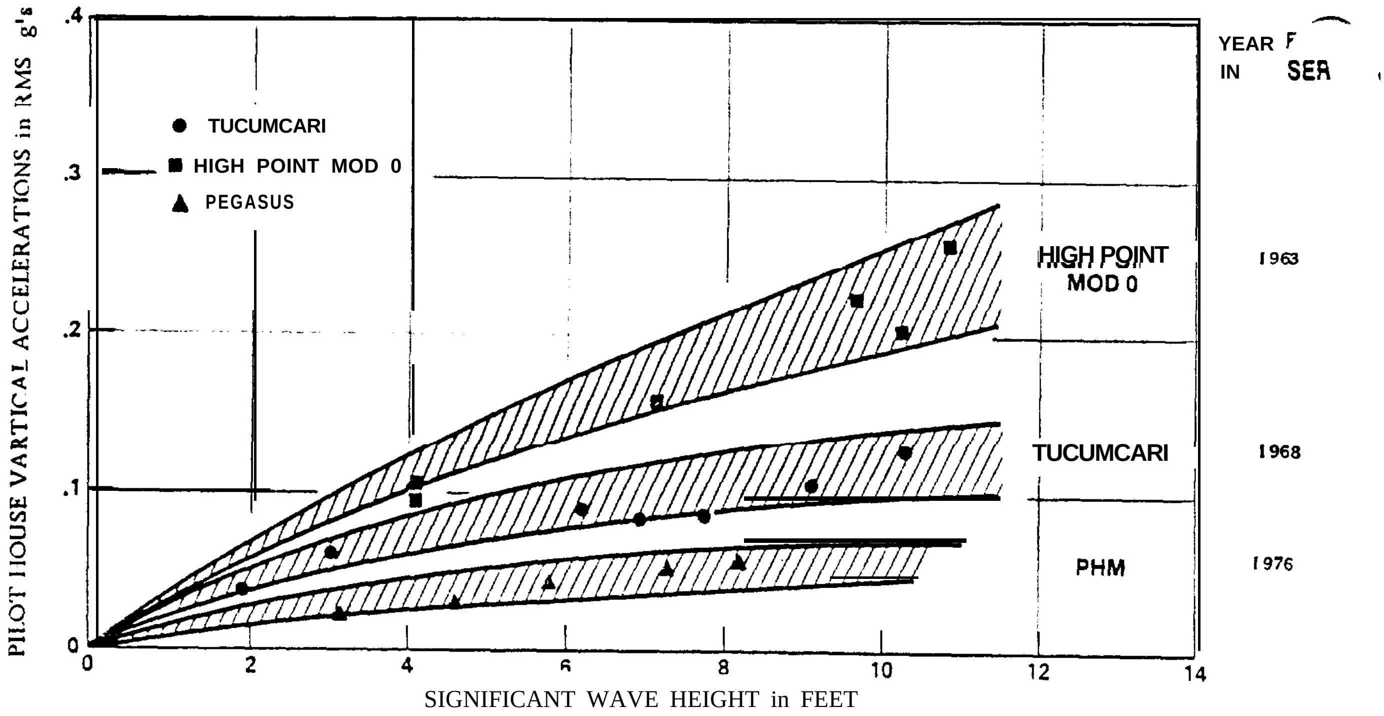
(U) The qualitative data come from observations made by operators and engineering test crews who were typically in one of three locations:

- Pilothouse
- Engineer's Operating Station
- CIC or Data Station

7.2.3 Quantitative Data - Ride Quality

(U) Figure II.A.7-1 shows measured rms acceleration levels (vertical and lateral) versus significant wave height. Figure II.A.7-2 shows pitch angle, roll angle, and turn rate standard deviations versus significant wave height. Figure II.A.7-3 shows some of PHM and TUCUMCARI ride data (vertical accelerations plotted against the IS0 criteria). As can be seen, the ride quality demonstrated in seas from Sea State 3 through Sea State 5 shows in a most favorable light against those curves. Figure II.A.7-4 shows similar lateral acceleration data taken from PHM-1 trials. Here the problem of inadequate criteria is made obvious as the lower frequency data are far removed from the lower end of the criteria curve.

(U) To better understand the capabilities and quality of the ride demonstrated, it is useful to investigate what the long term riding qualities of a ship would be if it were deployed in a given ocean area. Figure II.A.7-5 shows predicted long-term acceleration distributions for PHM-1 (PEGASUS) for year-round operation in the North Sea, which is well known as a rather severe sea environment.



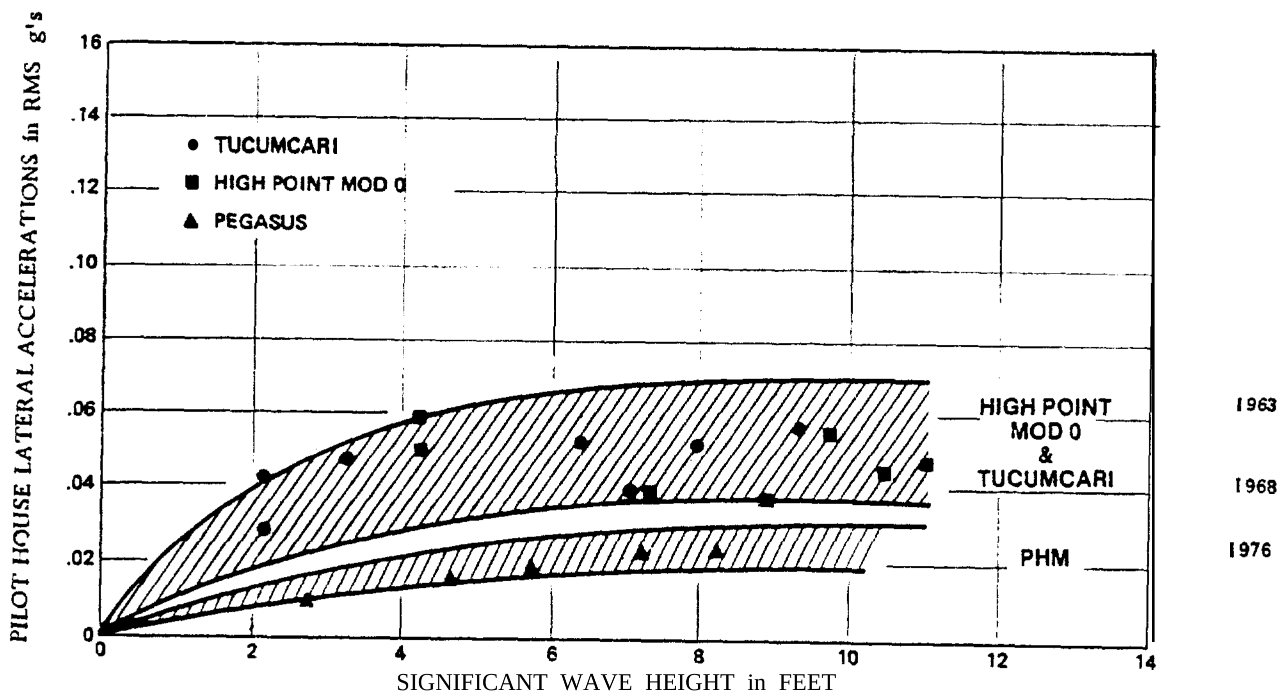


Figure II.A.7-1. MEASURED ACCELERATIONS FOR VARIOUS HYDROFOIL SHIPS

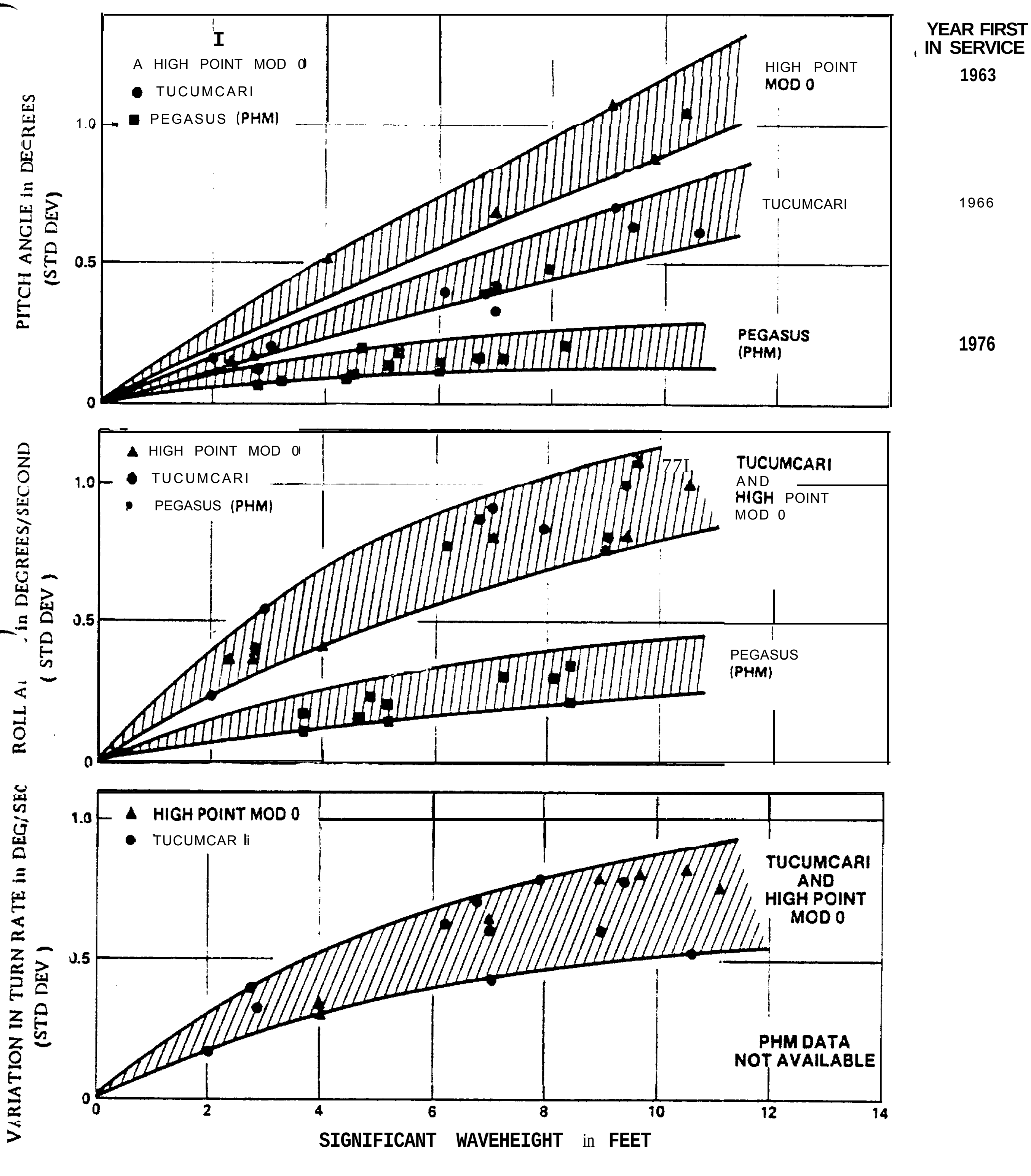


Figure II.A.7-2. MEASURED ROUGH WATER MOTIONS FOR VARIOUS HYDROFOIL CRAFT

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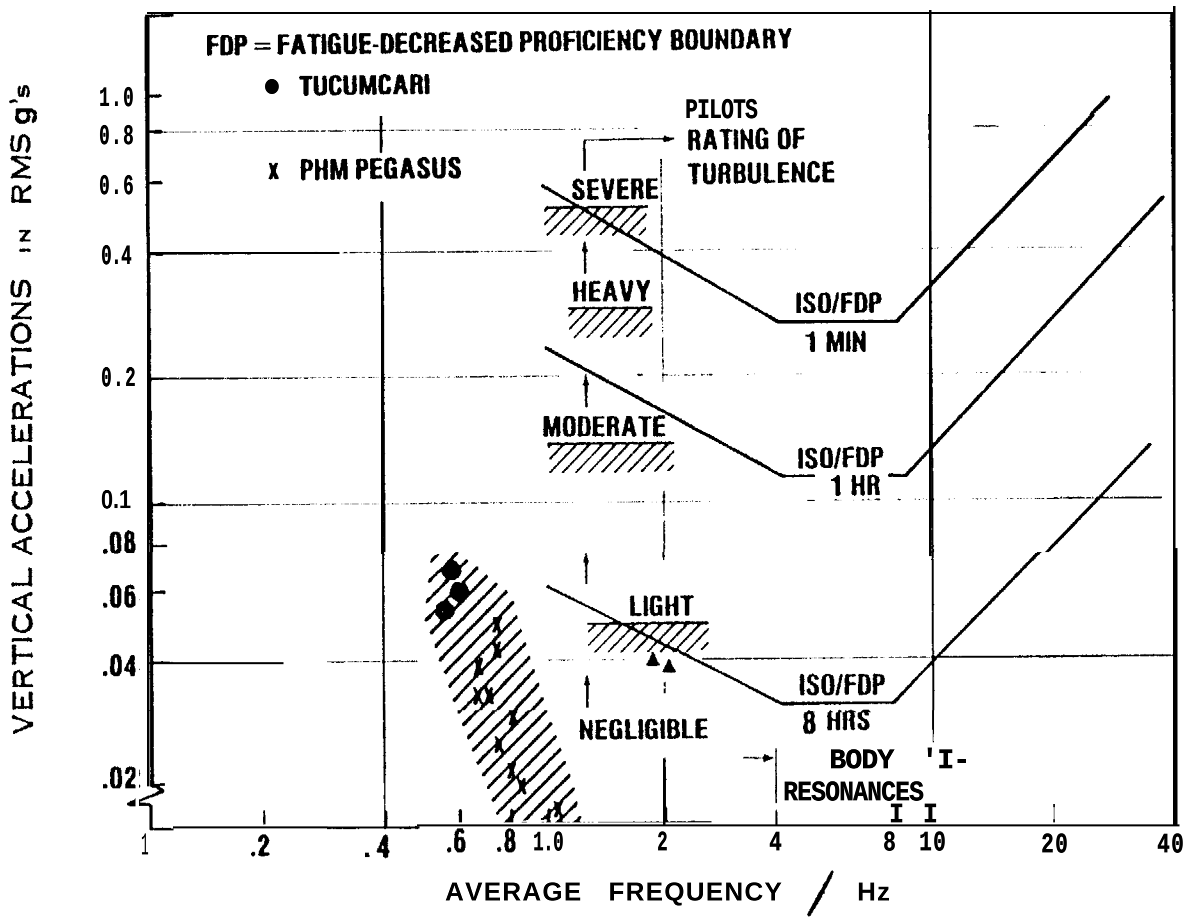

Figure II.A.7-3. HUMAN TOLERANCE BOUNDARIES, INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

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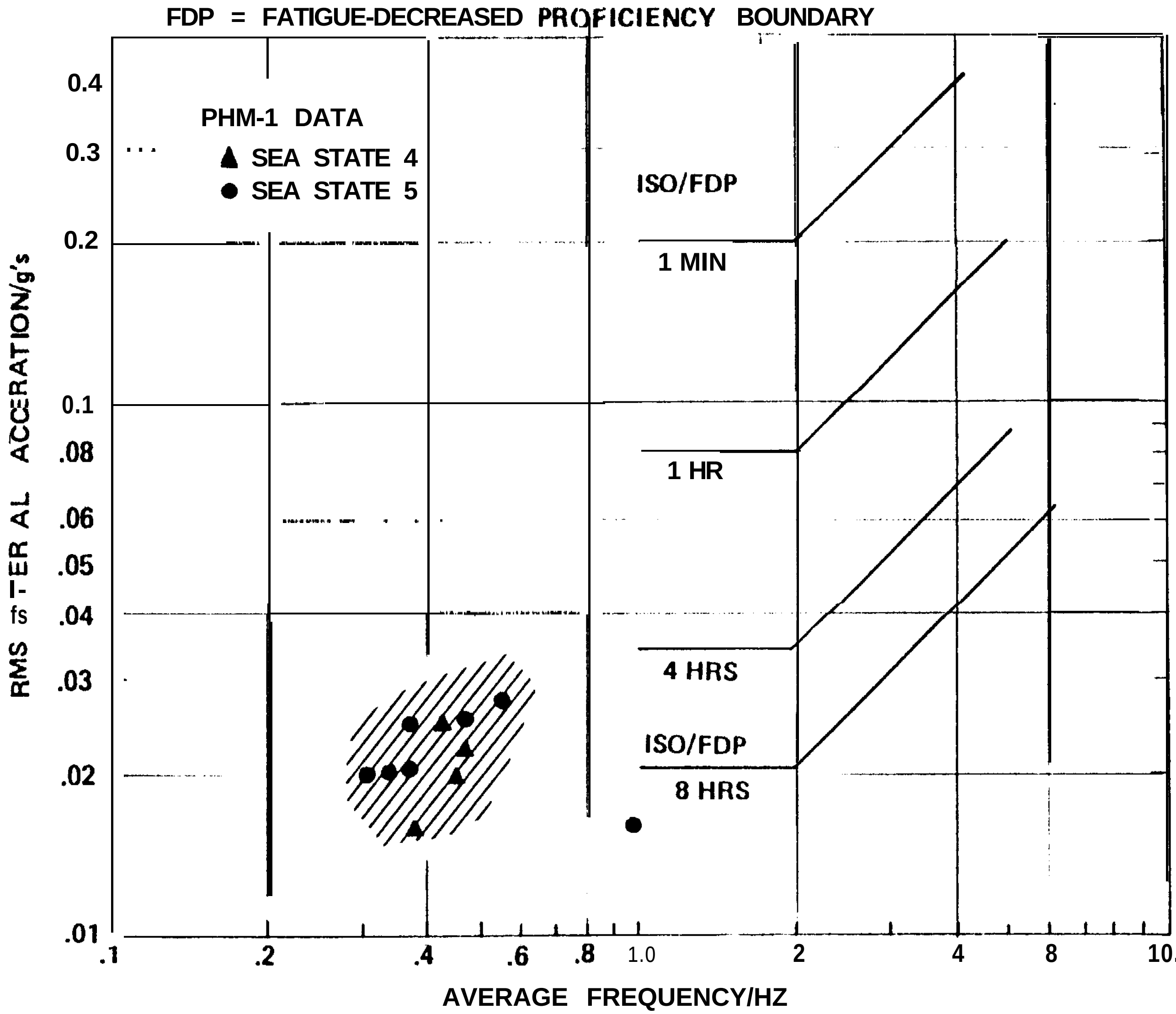

Figure II.A.7-4. HUMAN TOLERANCE BOUNDARIES, INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

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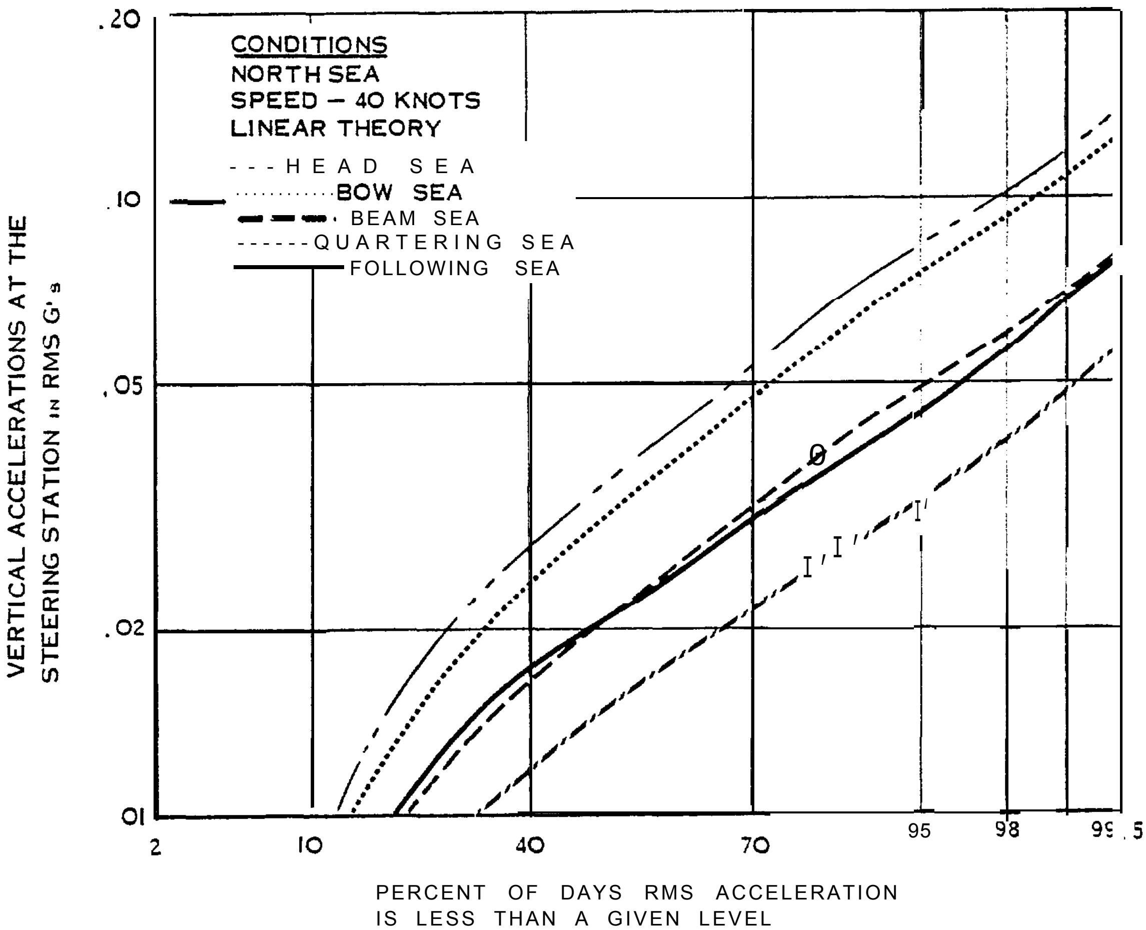


Figure II.A.7-5. LONG-TERM VERTICAL ACCELERATION DISTRIBUTIONS IN THE NORTH SEA FOR PHM-1 (PEGASUS)

The Figure 11.7-5 curves are based on extensive statistical data for year-round sea conditions in the North Sea as reported by Hogben and Lumb (Reference II.A.7-9) and on proven acceleration response characteristics of the PHM. From these data it is seen that at the worst case heading (head sea) vertical accelerations in the pilot-house would be expected to exceed 0.1g rms only 2 percent of the days of the year.

(U) From these data it can be seen that the hydrofoil ship has demonstrated unique qualities in providing a smooth ride even at high speeds in large seaways. Further, the Automatic Control System provides the means for significantly altering the riding qualities of a hydrofoil ship. Through the refinement of the Automatic Control System, significant improvements in ride quality have been attained in hydrofoil ships over the past decade as is demonstrated by Figures II.A.7-1 and II.A.7-2.

7.2.4 Qualitative Data

(U) The hydrofoil ship HIGH POINT, TUCUMCARI, PEGASUS, and FLAGSTAFF have conducted extensive rough water operations over many years and in many oceans. In particular, TUCUMCARI operated in U.S. Pacific and Atlantic coastal waters, the South China Sea, the North Sea, the Baltic Sea, and the Mediteranean Sea. HIGH POINT has conducted extensive rough water trials off the North Pacific Coast (Cape Flattery) and off the Coast of California. PEGASUS has likewise conducted detailed rough water tests off the North Pacific Coast and in California waters. FLAGSTAFF has operated the South

China Sea, California coastal waters, and off the Florida Coast. In all, this represents approximately 3,000 hours foilborne operation with approximately 20 percent or 600 hours of this operation being conducted in Sea State 4 or above.

(U) To illustrate the ride qualities achieved, a few examples of the type of work being accomplished and the accelerations levels are offered.

(U) The most extensive human factors evaluation of a high-speed hydrofoil ship was made during an extended ocean foilborne transit and exercise operation on PCH Mod 0. This study (Reference II.A.7-10) was conducted aboard the HIGH POINT from 5 January to 16 March 1971 when she made a foilborne transit from Bremerton, Washington, to San Diego, California. While in San Diego she participated in two multiship exercises, composite training/unit exercise (COMPTU EX) l-71 trials and exercise ADMIXTURE trials, and several equipment and measurement trials. Data were collected from the 16-man crew aboard during the lo-week operation. A personnel questionnaire was used to ascertain crew experience factors and a technical questionnaire was used to examine the effect of hydrofoil ship operations on various job and environmental factors.

(U) The results of the personnel questionnaire are summarized in Table II.A.7-1. Tabulation reveals that the crew of HIGH POINT has a normal Navy educational background, more than a majority having a high school education. The length of service is

Table II.A.7-1. TABULATED RESULTS OF PERSONAL QUESTIONNAIRE

Education	Nonhigh school graduate High school graduate Some college experience College graduate	1 man 12 men 2 men 1 man
Length of Service	Total, Average	158 years 9 years
No. of Sea Tours	Total, Average	34 tours 2 tours
Types of Vessels	IFS, DD, C, Tng, AR, AE, MSO, APA, AVR, APD, PCF, AF, DE, LST, AO, MSC, SVB	
Preference for Hydrofoils	Yes NO	11 men 5 men
Time on HIGH POINT	Total, Average	20½ year: 1 year
Rough Water Experience	Frequent Occasional Never	8 men 8 men 0 men
Motion Sickness	Frequent Occasional Never	3 men 7 men 6 men
Rest Needed	1-3 hours 4-6 hours 7-9 hours	3 men 9 men 1 man
Average Sleep	5-6 hours 7-8 hours	7 men 6 men
Time on Watch	Smooth seas Moderate seas Heavy seas	8 hours 6 hours 4 hours

high with the average crew member having 9 years in service. The crew as a whole was very experienced and exposed to a wide variety of ships (17 different types) and when asked if they preferred hydrofoil ship duty, 11 out of 16 responded affirmatively.

(U) The results of the technical questionnaire are illustrated in Figures II.A.7-6 through II.A.7-10. Figure II.A.7-6 shows a comparison between those task-oriented items (alertness, outside vision, etc.) that the crew rated as very important to their job and the crew rating of those same items as being much trouble during foilborne operations. Figure II.A.7-7, II.A.7-8, and II.A.7-9 show the same information but as rated by the command and control personnel, engineering personnel, and deck force. Figure II.A.7-10 illustrates the response of the whole crew during the four operational periods. As shown in Figure II.A.7-10, the problems increase slightly during the ADMIX exercise as compared to the other periods of data collection. The ADMIX exercise exceeded the design limits of PCH Mod 0 in terms of length of continuous at-sea time. PCH-1 was designed for a 24-hour mission cycle and the ADMIX exercise required her to be underway for a continuous 4-day period in both hullborne and foilborne modes. Considering the environmental hardships of poor lavatory conditions and short water supplies, the results of the data collection show that the crew members did not perceive any remarkable difficulties in performing their jobs.

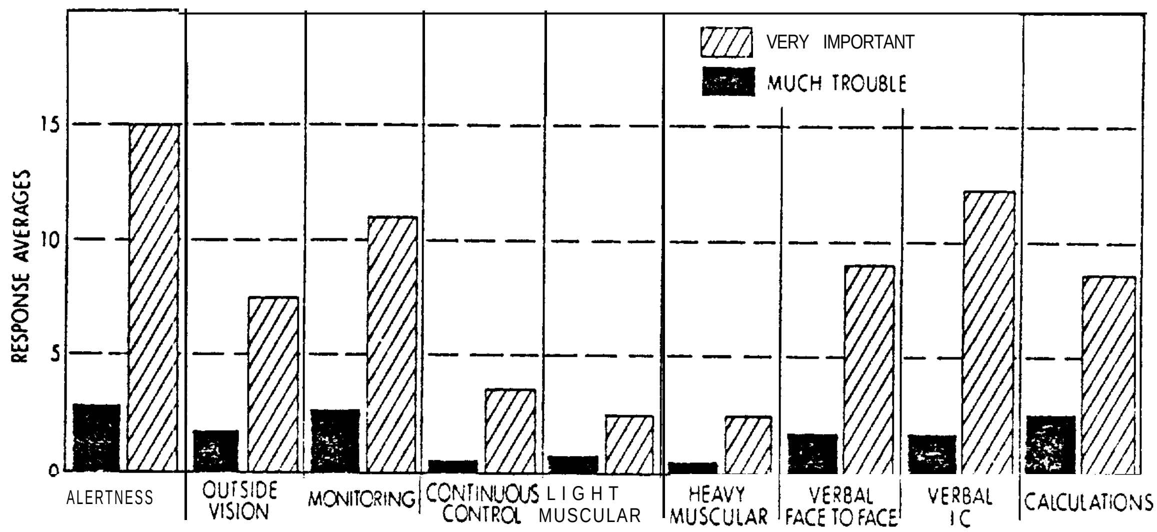


Figure II.A.7-6. ITEMS CONSIDERED VERY IMPORTANT TO JOB, COMPARED TO THE EFFECT OF HYDROFOIL OPERATIONS ON THESE SAME ITEMS

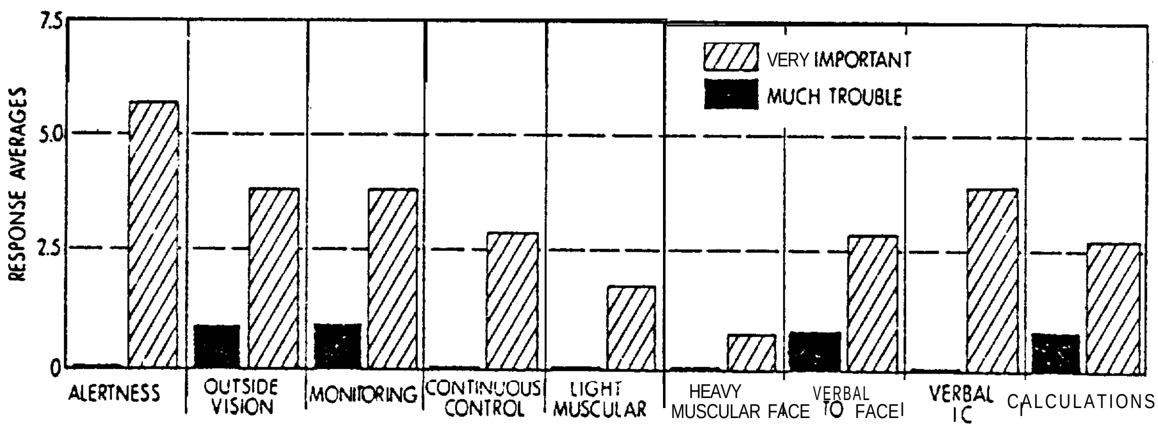


Figure II.A.7-7. ITEMS CONSIDERED VERY IMPORTANT BY COMMAND AND CONTROL PERSONNEL, COMPARED TO THE EFFECT OF HYDROFOIL OPERATIONS ON THESE SAME ITEMS FOR COMMAND AND CONTROL PERSONNEL

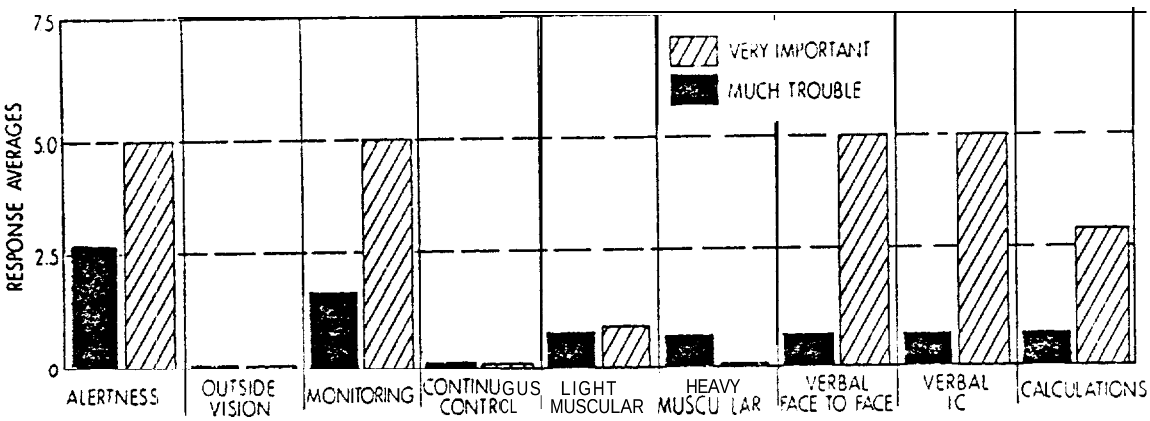


Figure II.A.7-8. ITEMS CONSIDERED VERY IMPORTANT BY ENGINEERING PERSONNEL, COMPARED TO THE EFFECT OF HYDROFOIL OPERATIONS ON THESE SAME ITEMS FOR DECK PERSONNEL

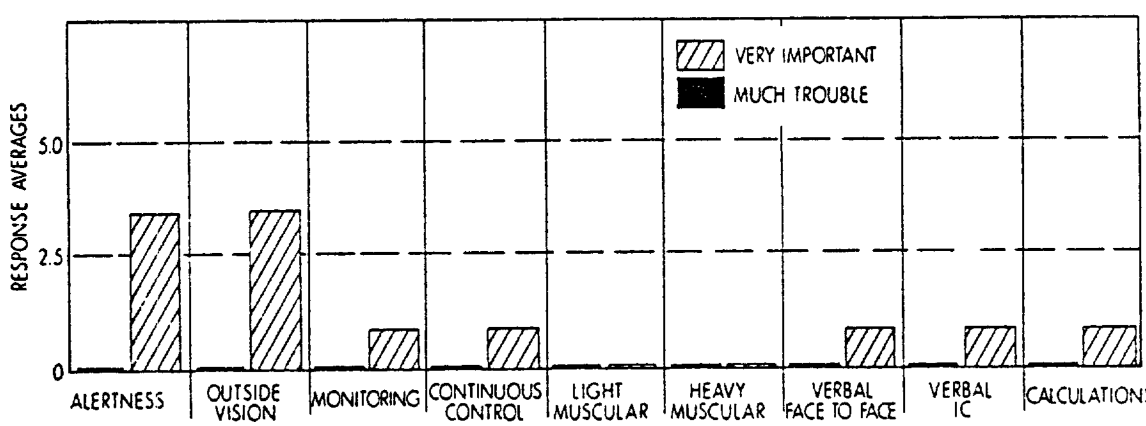
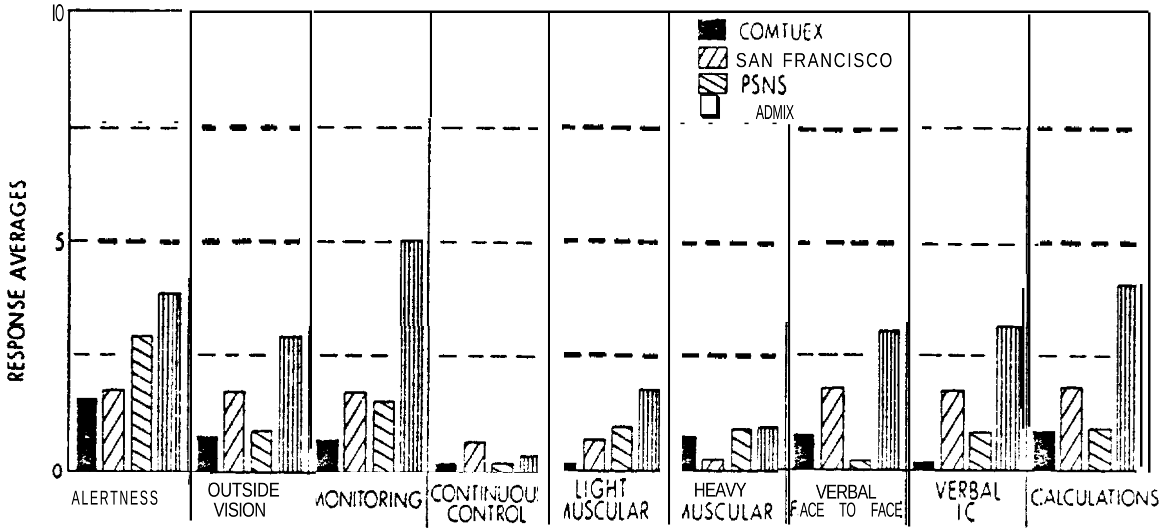


Figure II.A.7-9. ITEMS CONSIDERED VERY IMPORTANT BY DECK PERSONNEL COMPARED TO THE EFFECT OF HYDROFOIL OPERATIONS ON THESE SAME ITEMS FOR DECK PERSONNEL



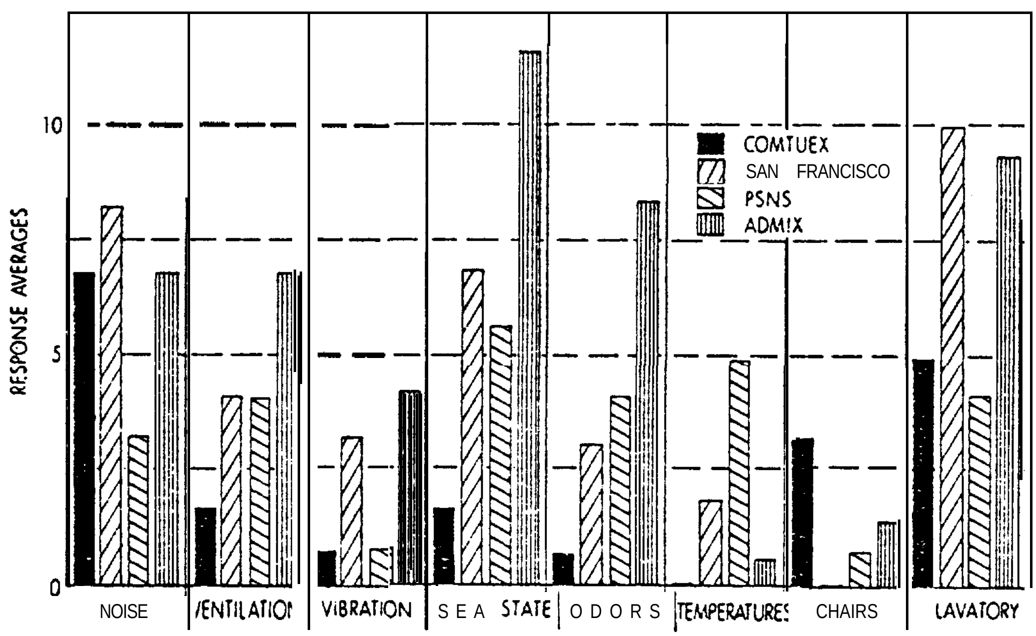


Figure II.A.7-10. ITEMS RATED MUCH TROUBLE BY HYDROFOIL PERSONNEL FOR EACH OF THE FOUR DATA COLLECTION PERIODS DURING THE TRANSIT AND EXERCISE OPERATIONS

(U) Typical rough water testing for HIGH POINT Mod 0 involved 10 to 12 hours underway foilborne including up to 4 hours transit in relatively smooth water. Under the circumstances, it was typical that the engineers supporting the test as well as most of the crew would work one continuous shift. Often testing under such circumstances would continue for 2 or 3 days in succession. The types of tasks being accomplished included navigation, command, and control associated with conduct of relatively complex rough water testing, data collection, and on-board data reduction.

(U) One of the more complex tasks involved the determination of sea condition by manually reading off peaks from a continuous recording of wave height for 5 to 10 minutes, then averaging the peak amplitudes to determine significant wave height. These onboard "quickie" analyses consistently fell within 5 percent to 8 percent of subsequent wave height calculations for the same time periods made by complex data reduction processes at the home base. The acceleration levels during which such onboard calculations were made typically ranged from 0.1 to 0.2 g's rms.

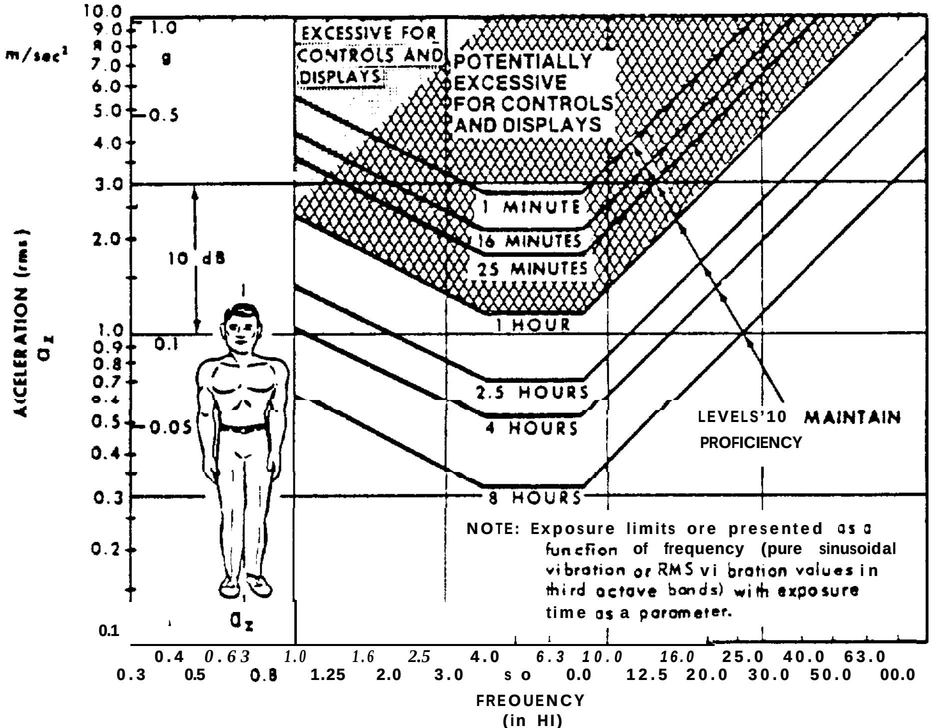
(U) TUCUMCARI conducted similar rough water tests plus operational deployment to Viet Nam where all manner of military missions were accomplished.

(U) When one considers the improvements attained for PHM and Mod 1 of the PCH coupled these with the fact that at no time were the acceleration and motions on TUCUMCARI or HIGH POINT found to be deleterious to the conduct of the required ship board tasks (in seas up to 10 ft significant wave height), one can logically conclude that current capabilities in ride quality are outstanding.

7.3 RIDE QUALITY STANDARDS AND CRITERIA

(U) At this time there are no ride quality standards or specifications that are truly suitable to the hydrofoil ship. This is basically because hydrofoil ship accelerations occur chiefly below 1 hz and are random in nature. Figure II.A.7-11 shows MIL-STD-1472B. These curves are coincident with the current IS0 guide for exposure to whole body vibrations. The Figure II.A.7-11 curves are based primarily on basic human research using sinusoidal vibrations, but a reasonable agreement between 1/3 octave random accelerations and sinusoidal vibrations has led to a somewhat tenuous acceptance of the format for both sinusoidal and random accelerations. But since the hydrofoil ship environment is dominated by random motions below 2 Hz, these curves have limited value.

(U) New hydrofoil ship criteria are currently being developed as part of the NAVSEA Hydrofoil Design Criteria Development. The new criteria will attempt to realistically assess the hydrofoil ship environment and the human responses to that environment and to develop specific means for evaluating measured and analytical data against the criteria. A basic problem in such development is the lack of basic human response data (as will be discussed) upon which quantitative levels can be based.



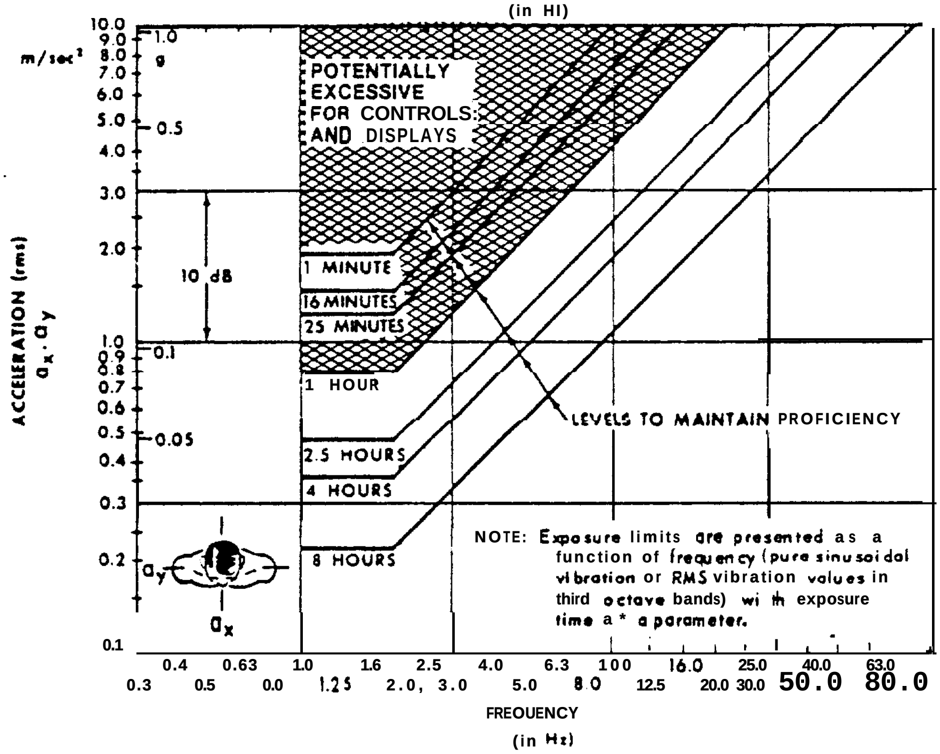


Figure II.A.7-11. VIBRATION EXPOSURE CRITERIA FOR LONGITUDINAL (UPPER CURVE) AND TRANSVERSE (LOWER CURVE) DIRECTIONS WITH RESPECT TO BODY AXIS

7.4 HUMAN RESPONSE DATA BASE

(U) Basic research must provide the fundamental response data upon which hydrofoil ship ride quality criteria and standards of comparison can be established. In the following paragraphs, this data base is discussed in the vein of its applicability to hydrofoil ship operations. It quickly becomes apparent to the reader that the fundamental deficiency in this whole area of ride quality is the lack of significant human response data upon which to base firm conclusions or criteria.

7.4.1 Vibrations

(U) The ISO and MIL-STD-1472B curves of Figure II.A.7-11 are based primarily on basic human research using sinusoidal vibrations, but a reasonable agreement between 1/3 octave random acceleration and sinusoidal vibrations has led to a general acceptance of the format for both. Since the marine environment is dominated by random motions below 2 Hz, these curves have limited value as guides or criteria.

7.4.2 Sea Sickness Causes and Incidences

(U) Only recently has any substantive data on the causes and incidence of sea sickness (motion sickness) been available. Perhaps the most meaningful data on this subject are coming out of studies sponsored by the Office of Naval Research and reported in Reference II.A.7-11. Figure II.A.7-12 shows a 3-dimensional relationship between acceleration levels, frequency of acceleration, and motion sickness incidence within 2 hours exposure.

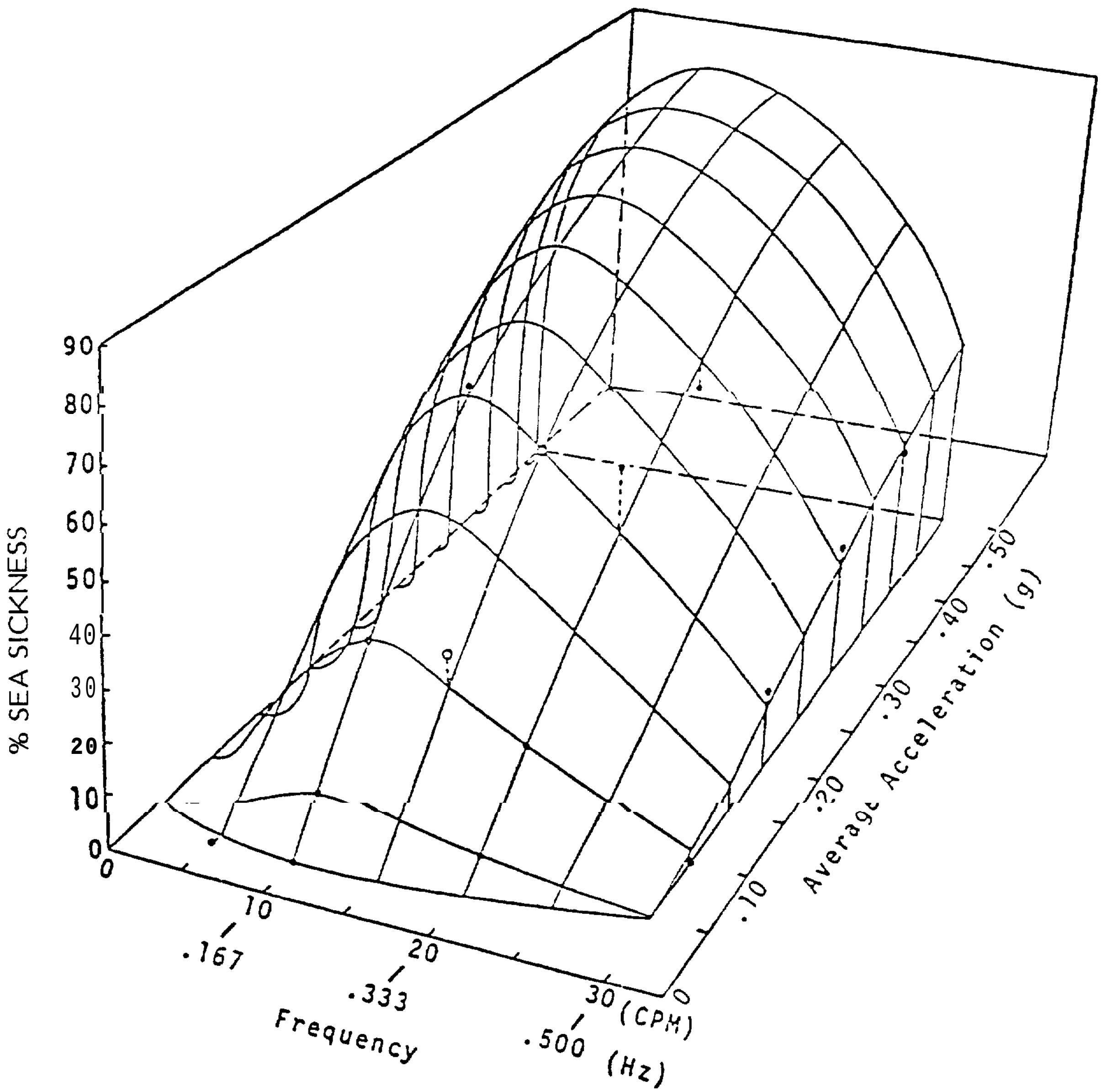


Figure II.A.7-12. RELATIONSHIP OF MOTION SICKNESS TO WAVE FREQUENCY AND EFFECTIVE ACCELERATION IMPARTED DURING EACH HALF-WAVE CYCLE FOR VERTICAL PERIODIC MOTION (HEAVE)

(U) Absolute levels of acceptability have not yet been established, and several significant questions have not been answered with respect to applicability. For instance:

- How do random accelerations relate to the results obtained for sinusoidal vibrations?
- What are the effects of longer exposure times?
- To what degree does "adaptability" modify the results?
- Are vertical accelerations the dominant cause of motion sickness or are there other major motion parameters which are involved?

(U) In spite of the above questions, the empirically derived relationships of Figure II.A.7-3 are considered invaluable in the development of criteria, in that they provide what is believed to be the basic shape of the motion sickness profile.

(U) From these data, reasonable first estimates of acceptable acceleration levels below 1 Hz can be developed. As more basic data are obtained, corrections can be made; but the significant fact is that we have the basis for a format for vertical accelerations that is compatible with the MIL-STD-1472B and IS0 fatigue decreased proficiency boundaries.

7.4.3 Slamming

(U) Slamming in all forms of marine vehicles is a fact of life. It occurs in destroyers causing them to slow down. It occurs to a large extent in smaller surface ships. It occurs in air cushion vehicles. It occurs on hydrofoil ships. In most, if not all, instances, the acceleration in the forward part of the ship due to slamming tends to stand out in terms of its magnitude far above the acceleration induced from the normal seaway-induced acceleration.

(U) While these types of accelerations are present in all forms of operating ships today, almost no scientific data are available upon which to place judgment as to acceptable bounds or the effects of such factors on fatigue and on operator proficiency,

7.4.4 Internal Noise

(U) Since large amounts of power are contained in lightweight structures and this generated power is usually in close proximity to people, noise specifications for hydrofoil ships are very difficult to meet. This is primarily true for the foilborne mode of operation. This condition is worse for the smaller hydrofoil ships because of the closer quarters,

(U) Proper design features have to be compromised because of weight restrictions and restrictions on acceptable materials. New double wall type noise insulation construction can be utilized weighing over 1.5 lb/ft^1. Airborne noise specifications being used on the production version of the PHM-1 class are shown in Table II.A.7-2. These incorporate new specifications that were estimated for unmanned machinery spaces, where none existed before in the Navy. Figure II.A.7-13 shows results of a refined acoustic treatment installed on AGEH-1.

Table II.A.7-2. PHM NOISE LEVEL REQUIREMENT

ALLOWABLE AIRBORNE NOISE LEVELS - db RELATIVE TO 0.0002 dyn/cm^2

	OCTAVE BAND CENTER FREQUENCIES, HERTZ 32	63	125	250	500	1000	2000	4000	8000
CIC Pilot House Communications Room	90	84	79	76	(SIL REQUIREMENT)			69	68
EOS D 1 Staterooms Wardrooms Crew Berthing Crew/CPO Mess Galley WR	90 to 94 D	a4 to 91	79 to 89	76	73	71	70	69	68
WC & SH	90 to 100	84 to 97 4	79 to 94	84	82	79	78	75	74
Machinery Spaces Except fpr Foilborne	119	120	121	111	108	110	117	115	115

1 D Teletypewriter not operating.

4 D The exact value for the noise requirement, within this spectrum, will be the highest values measured in the listed spaces on the first production configuration PHM.

NOTES:

(1) Speech Interference Level (SIL) is the measure of the effect of airborne background noise on intelligible speech. Numerically, it is the arithmetical average of sound pressure level, in decibels, in the octave bands with center frequencies of 500, 1000, 2000 Hz. The SIL requirement is 64 db maximum.

(2) Noise requirements apply at head level of seated positions at operating stations in the Pilot House and engineering operating station. Noise requirements apply at head levels of each sleeping crew member in the berthing areas. Noise requirements apply at head level of seated positions in the CREW/CPO Mess, Wardroom, Staterooms, and WR, WC, and SH.

(3) Noise requirements apply at head level of standing positions in the Galley. In other areas the requirements apply at the geometric center of the space.

(4) Main engine room and auxiliary engine room allowable noise levels permit a maximum exposure time of 2 hours within 24-hour period provided that ear muff protection is worn. Without protection these levels are hazardous to hearing. Suitable warning plates shall be posted at entrances to and throughout compartments where other than unlimited exposure with no ear protection is allowed.

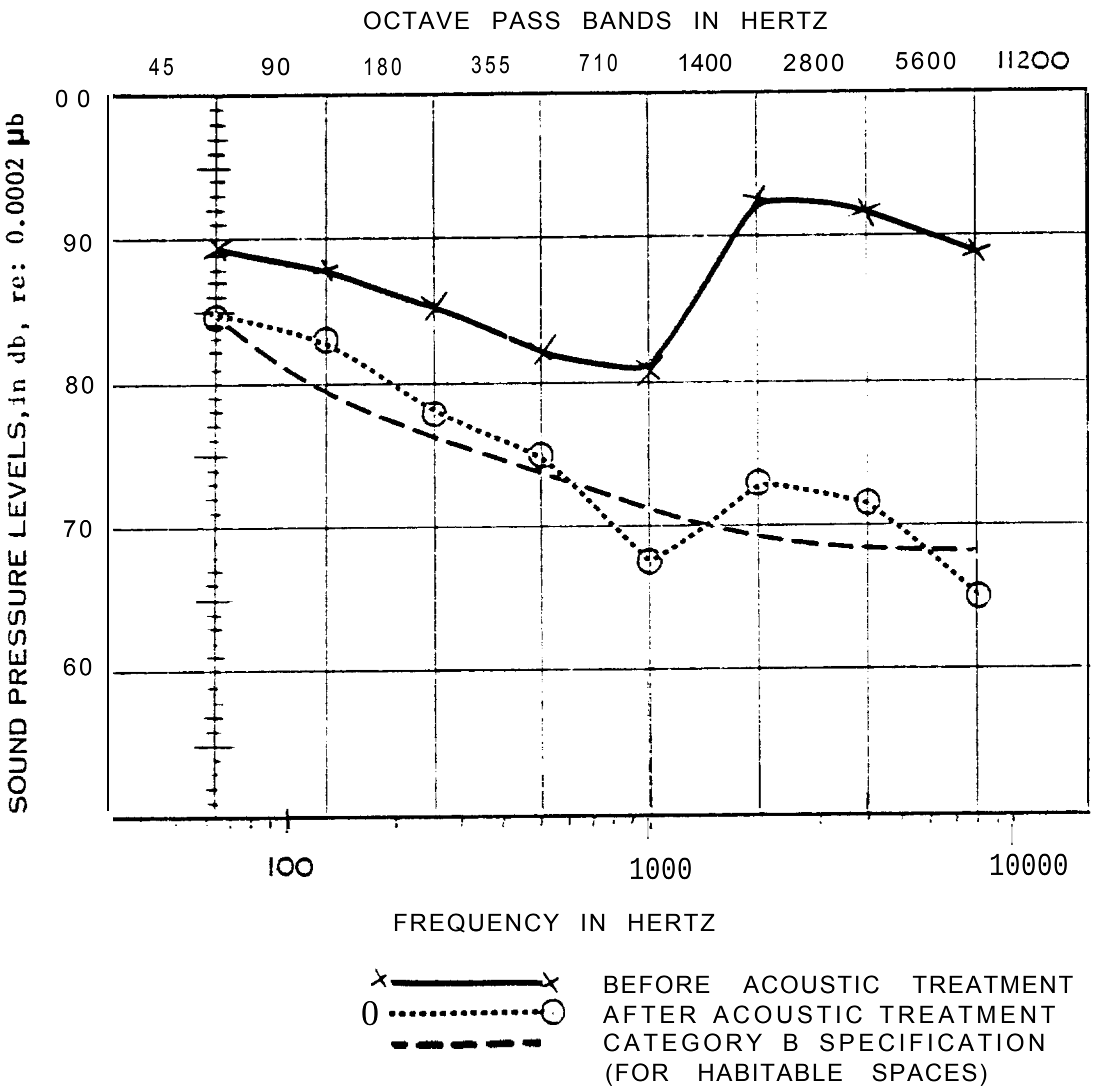


Figure II.A.7-13. EFFECTIVENESS OF ACOUSTIC TREATMENT OF AGEH-1

7.5 COMBAT SYSTEMS HUMAN FACTORS

(U) Past hydrofoil ships have been fitted with relatively simple combat systems, and hence, little effort was expended in human engineering their combat operating stations. Moreover, for the most sophisticated ship, the PHM-1, time and resources available, did not allow extensive human engineering effort during the design phase. Arrangement efforts consisted mainly of engineering to fit available equipments into space dictated by the relatively short preliminary design phase. While the basic equipments specified by the Navy had met human engineering standards extant at the time of their design, a live mockup was not used to verify the effectiveness of arrangements and man-machine interfaces for the PHM.

7.6 HUMAN FACTORS IN HYDROFOIL SHIP CONTROL

(U) Until the PHM program was initiated, Navy hydrofoil ship operating experience was vested in four ships. On these craft the formal application of human factors was limited, although their designs at least reflected good human engineering practices derived from judgment and the more obvious of the driving considerations. Also, because the detail design was in the hands of aerospace organizations, there was an initial bias towards useful aircraft concepts of craft control man/machine interfacing. The more obvious features to appear are the completely enclosed pilothouses, seated operators with console type controls grouped for convenient access and operation. Propulsion spaces were unmanned and all propulsion control and monitoring functions in the pilothouse. They provided adequately, if not optimally for all basic ship control functions, but were notably unsophisticated in areas concerning navigation and collision avoidance. TUCUMCARI was taken out of service after a serious grounding incident, an occurrence which is probably indicative of the fact that bridge ergonomics had not been brought up to a point that we now recognize as necessary for ships of this type.

(U) PHM-1, commissioned in 1975, is the first in a line of operational ships. Specifications levied certain human engineering requirements on the design as regards the customary standards for displays and arrangement of controls, as well as standards for operator visibility. All normal ship control functions are organized around a three-man conning crew in seated locations. A ship control console is remarkably similar in general arrangement to that recommended by the latest Destroyer Integrated Bridge studies. The size of the machinery installation has grown to the point where it was deemed necessary to have a separate EOS, but pilothouse has optional control of engine power levels.

(U) The array of bridge instrumentation on the PHM-1 is simple and minimal. Bridge operators have primary interest in the foilborne control and supporting hydraulic systems; therefore, all set up, monitoring, and warning devices are grouped in the pilothouse console. Two peloruses are arranged inside the pilothouse and are movable in a way that allows 360° observations without leaving the pilothouse, a feature that should be standardized for all hydrofoil ships. The overall arrangement permits normal route operations if desired with one ship control operator, the other two locations being nominally assigned to the OOD and the CO. A CIC is located aft and half a deck below the conning station. The navigation and radar features dedicated to ship control are standard for a Navy ship of this size.

(U) The separate EOS on PHM was designed as a one-man station, monitoring an unmanned machinery and electric plant. The operator does not have visibility into the machinery compartments, and casualty control sensors are available. An automated logging system serves both bridge and EOS as well as selected internal and external commuications circuits.

(U) The PHM appears to offer a reasonable and workable synthesis of human engineered elements considering the size and mission of the ship. One should recognize that there has not been any major coordinated program of ergonomic studies for hydrofoil ship control stations as has been carried on for surface ship bridges, and the types of navigation, collision avoidance, and tactical automated displays developed for the surface ship programs have not yet made an appearance in hydrofoil ships, although the technology is certainly available and the need exists for this type of ship to a greater extent than in conventional combatants. The PHM-1 should provide useful feedback for future designs.

REFERENCES

II.A.7-1 ISO/DIS 2631, "Guide for the Evaluation of Human Exposure to Whole Body Vibration", International Standards Organization (ISO) 1972

II.A.7-2 Boeing Document D312-80248-1, "Performance of PEGASUS (PHM-1) as Demonstrated in Sea Trials (U)", Rev. A, October 1975 (Conf.)

II.A.7-3 Boeing Document D2-133811-1, "Comparative Evaluation of Hydrofoil Craft (U)", July 1971 (Conf.)

II.A.7-4 Boeing Document D2-133810-1, "Comparative Evaluation of Hydrofoil Gunboat, TUCUMCARI, PGH-2 (U)", July 1971 (Conf.)

II.A.7-5 Boeing Document D2-133605-1, "Summary of PCH-1 Rough Water Trials Conducted During October 1966 (U)", 1967 (Conf.)

II.A.7-6 Boeing Document D2-144623-1, "First 1968 Rough Water Trials, Waves and Craft Motions - Mod 0 (U)", 1968 (Conf.)

II.A.7-7 Boeing Document D2-133705-1, "Hydrofoil Patrol Craft HIGH POINT (PCH-1) March and April 1969 Rough Water Trials - Waves and Craft Motions (U)", September 1969 (Conf.)

II.A.7-8 Boeing Specification 10-72108, 'Wave Height Measurement Instrument for PCH-1", 1968

II.A.7-9 Hogben and Lumb, "Ocean Wave Statistics', Her Majesty's Stationery Office, London, 1967

II.A.7-10 Edmondo, P., "Human Factors Evaluation of a Hydrofoil During Extended Transit and Exercise Operations', NSRDC Report 27-551 dated October 1973

II.A.7-11 O'Hanlon and McCauley, 'Motion Sickness Incidence as a Function of the Frequency and Acceleration of Vertical Sinusoidal Motion", Aerospace Medicine, April 1976

II.A.7-12 NAVSEA 0902-00-039-4010, "Ship System Specification for Building Patrol Combatant Missile (Hydrofoil) PHM-1 Class (PHM-3 Series), 11 June 1976.

II. STATUS OF VEHICLE TECHNOLOGY

A. TECHNOLOGICAL PERFORMANCE FEATURES

8. RELIABILITY/MAINTAINABILITY/AVAILABILITY (R/M/A)

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II.A. TECHNOLOGICAL PERFORMANCE FEATURES

8. RELIABILITY/MAINTAINABILITY/AVAILABILITY (RMA)

8.1 INTRODUCTION

(U) The state of the art in the area of RMA experience on hydrofoil ships is best exemplified by the two most recently produced, USS PEGASUS (PHM-1) and the commercial hydrofoil ship, JETFOIL. In May 1976, PHM-1 commenced its Operational Evaluation (OPEVAL), and there are five JETFOILS operating in the world with five more being built (two are in Hong Kong and three are in Hawaii). This discussion will focus on the RMA aspects of the PHM-1 design process and will present T&E RMA experience data from PHM-1 and JETFOIL. The PHM-1 experience data presented are current to Voyage 95 (Jan 1976); additional operating experience data accumulated during USN evaluation trials will be analyzed as it becomes available.

8.2 PHM RMA PROGRAM

(U) In October 1971 the United States awarded Phase I of a PHM lead ship design and construction contract to The Boeing Company. This phase was primarily a system definition phase wherein operability, reliability, maintainability, and availability goals, objectives, and requirements were established and are documented in the Ship System Requirements (SSR) and Ship System Description (SSD). Additionally, an Integrated Logistic Support Plan was prepared for managing, identifying, and developing PHM logistic resources within the framework of its operations and maintenance (O&M) concept.

Phase I was completed in December 1972. The Phase II contract, consisting of detail design, construction of two lead ships, development of logistic resources, and testing was awarded to The Boeing Company in February 1973. Program costs subsequently reduced the number of lead ships from two to one. RMA activities during this period are shown in Table II.A.8-1.

Table II.A.8-1 PHM PHASE II RMA ACTIVITIES

SYSTEM DESIGN	• FAILURE MODES & EFFECTS ANALYSES • MAINT. ENGR. ANALYSES • LEVEL OF REPAIR ANALYSES • RMA MODEL STARTED
CONSTRUCTION	• QUAL. TESTING • ACCEPTANCE TESTING • FAILURE REPORT/ANALYSIS
T&E/IOT&E	• FAILURE REPORT/ PROBLEM RESOLUTION • RMA INCENTIVE PROGRAM • MAINTENANCE DATA COLLECTION SYSTEM (MDCS) • RMA ASSESSMENT

8.3 SYSTEM RMA OBJECTIVES

(U) The NATO Circular of Requirements and U.S. Navy Plan For Use established four basic missions for the U.S. Variant consisting of a 16-Hour Foilborne (F/B) Sortie, a 120-Hour Hullborne (H/B) Transit, a 120-Hour General Patrol, and a 120-Hour Normal Patrol. Based on these missions, annual operating hours are shown in Table II.A.8-2. Mission reliability and availability objectives for the mature system were established as follows:

Reliability

a.	16-Hour Sortie	0.95
b.	120-Hour Combined Patrol	0.65
c.	120-Hour Transit	0.87

Availability 0.98

Maintainability requirements consisted of the following:

a. Access requirements per MIL-STD-1472.

b. Foilborne engine removal and replacement in 36 hours by 6 men.

c. Two-hour Mean Time to Repair (MTTR) for 15 mission critical equipment items having the highest failure rate.

All compartments, usable spaces, and voids shall be provided with access. Access closures are to be "quick-acting" type, except for access to unmanned spaces.

(U) The PHM-1 Maintenance concept is summarized in Table II.A.8-3, and the accomplishment of maintenance tasks is based on the following requirements:

Table II.A.8-2. PHM OPERABILITY OBJECTIVES

MISSION	MODE	F/B HRS.	H/B HRS.	TOTAL
SORTIE	F/B	432		432
TRANSIT	H/B	-	720	720
GENERAL PATROL	F/B 50% H/B 50%	300	300	600
NORMAL PATROL	F/B 10% H/B 90%	70	680	750
SUBTOTAL	—	802	1,700	2,502
STANDBY	SSPU ONLY	—	—	600
TOTAL ANNUAL	—	802	1,700	3,102

Table II.A.8-3 PHM MAINTENANCE CONCEPT SUMMARY

CATE-GORY	TYPE	FUNCTION	FREQUENCY AND (ELAPSED TIME)	LOCATION	PERSONNEL	TOOLS	SPARES SUPPLY
ORGANIZATIONAL	. PREVENTIVE MAINTENANCE	. INSPECTIONS • SERVICE	, EVERY 5 DAYS OK 120 OPERATIONAL HOURS -NORMAL	PHM	, OPERATORS (NO SPECIAL MAINTENANCE TRAINING)	. STANDARD HAND TOOLS • BUILT-IN MONITORING DEVICES	PHM 5 DAYS
ORGANIZATIONAL	, MINOR CORRECTIVE MAINTENANCE	. FAULT ISOLATE WITH BUILT-IN EQUIPMENT • EMERGENCY CORRECTIVE MAINTENANCE	, AS REQUIRED (1.0 HOURS MEAN 2 HOURS MAXIMUM FOR 90% OF MAINT. ACTIONS.)	PHM	, OPERATORS	. STANDARD TEST EQUIP.	
INTERMEDIATE	• PREVENTIVE MAINTENANCE . AVERAGE REPAIR	. EQUIPWENT TEAR-DOWN AND REPAIR IN PLACE AND AT BENCH	SCHEDULE UPKEEP AFTER 5 DAYS UNDERWAY SCHEDULED: . EVERY 30 DAYS UNSCHEDULED: . AS REQUIREI	MLSF OR BASE	. MLSF MAINTENANCE TEAM	. MAINTENANCE CONTAINER WITH : • SPECIAL TEST EQUIP. . PRECISION MEASURING EQUIP. . SPECIAL TOOLS . MLSFAND BASE SUPPORT . REPAIR SHIP	MLSF 90 DAY!
INTERMEDIATE	. EXTENDED REPAIR	, EXTENSIVE EQUIPMENT REMOVAL TO	SCHEDULED: . EVERY 90 DAYS UNSCHEDULED: , AS REQUIREI	MLSF REPAIR SHIP OR BASE	. PHM MLSF MAINTENANCE TEST		
DEPOT	• OVERHAUL	. MAJOR ELEMENT OVERHAUL . STRUCTURAL REPAIR	. EVERY 1.5 YEARS	SHIPYARD	. BASE OR SHIP YARD PERSONNEL (GENERALLY SKILLED - PHM TRAINING)	. DRY DOCK . LARGE CRANES . EXTENSIVE GENERAL REPAIR CAPABILITY	DEPOT 1 YEAR

UNCLASSIFIED

a. Three levels of maintenance:

Organizational - performed on-board by the ship's crew

Intermediate - performed by the Mobile Support Group (MSG) on-board PHM or a tender or a shore station

Depot - performed at a shipyard, overhaul facility, or at a contractor's plant

b. Normal shipboard maintenance actions performed by the crew (organizational) will be capable of being completed with standard hand tools and/or built-in test equipment. Repair tasks will be remove and replace actions.

c. Intermediate level maintenance and repair will consist of upkeep after each mission, a Technical Availability each month, and a Restricted Availability every third month.

d. Ship refurbishment and overhaul will not be required more frequently than once each 1.5 years.

e. Five-day operation without care or preventive maintenance extended to 7 days for tactical emergencies.

f. Desired Z-hour MTTR (Mean Time to Repair) for 90 percent of organizational level repair actions.

g. Emergency maintenance actions to include: on-board replacement of diesel engine pistons, cylinder liners, and rod bearings; removal and replacement of the hullborne and foilborne propulsors while the ship is in the water.

8.4 RMA ASSESSMENT METHODS

(U) Assessment of the PHM missions for RMA employed a NAVSEC-developed RMA simulator model (TIGER) (Reference II.A.8-2) and a Boeing-developed Logistic Resource (LR) model. In addition, an assessment was performed of all failures reported during PHM-1 Test and Evaluation and of the measures taken to prevent failure recurrence.

*See Reference II.A.8-1

(U) Assessment of a PHM mission required definition of the following operational considerations:

- Mission scenarios and timelines for each mission
- Maintenance concept to be employed for the assessment
- Equipment reliability relationships in terms of reliability block diagrams
- Equipment utilizations for each phase of each mission based upon mission scenarios and timelines

(U) The LR model was developed to provide logistic input data requirements for the TIGER Model. These LR data include:

- Equipment MTBFs and MTBMAs
- Equipment MTTRs for maintenance actions at each repair location (ship, tender, depot)
- Percent of failures reparable at each repair location for each equipment
- Recommended repair location for each corrective maintenance action on each equipment, depending on weight and cost considerations
- Logistic resources required for each corrective maintenance action on each equipment

(U) The PHM Maintenance Engineering Analyses (MEAs) were the basic source data for the LR Model.

8.5 RMA ASSESSMENT RESULTS

(U) Analytical RMA assessment results for the 16-Hour Sortie, the 120-Hour Patrol, and the 120-Hour Transit missions are based on mission assumptions shown in Table II.A.8-4, the mission timelines shown in Figure II.A.8-1, and mission equipment utilization shown in Table II.A.8-5. Each mission's reliability and availability were evaluated under the baseline support concept (Case 1 - Limited on-board spares and support equipment) and augmented organization repair (Case 2 - additional on-board spares, support equipment, and training). Additionally, the 120-hour patrol mission's reliability and availability were evaluated using prepositioned maintenance kits aboard fleet auxiliaries (e.g., fleet oilers) for augmented organizational level repairs in addition to the additional on-board resources (Case 3). Spares and support equipment selection for augmentation (Cases 2 and 3) considered selection of those spares and support equipment that would correct the greatest number of mission critical failures for the least weight and cost.

Table II.A.8-4 BASELINE MISSION ASSUMPTIONS

- 16-Hour Sortie
  - Defcon I + Emcon
  - Radius of Operation - 150 Nautical Miles
  - Air Surveillance
- 120-Hour Patrol
  - Defcon II Defcon I + Emcon
  - Refuel Every 24 Hours
  - Radius of Operation - 150 Nautical Miles
  - Air Surveillance
- 120-Hour Transit
  - Defcon III

(U) Table II.A.8-6* shows the RMA assessment for the 120-hour patrol mission. The predicted mission reliability under

*On page II.A.8-12.

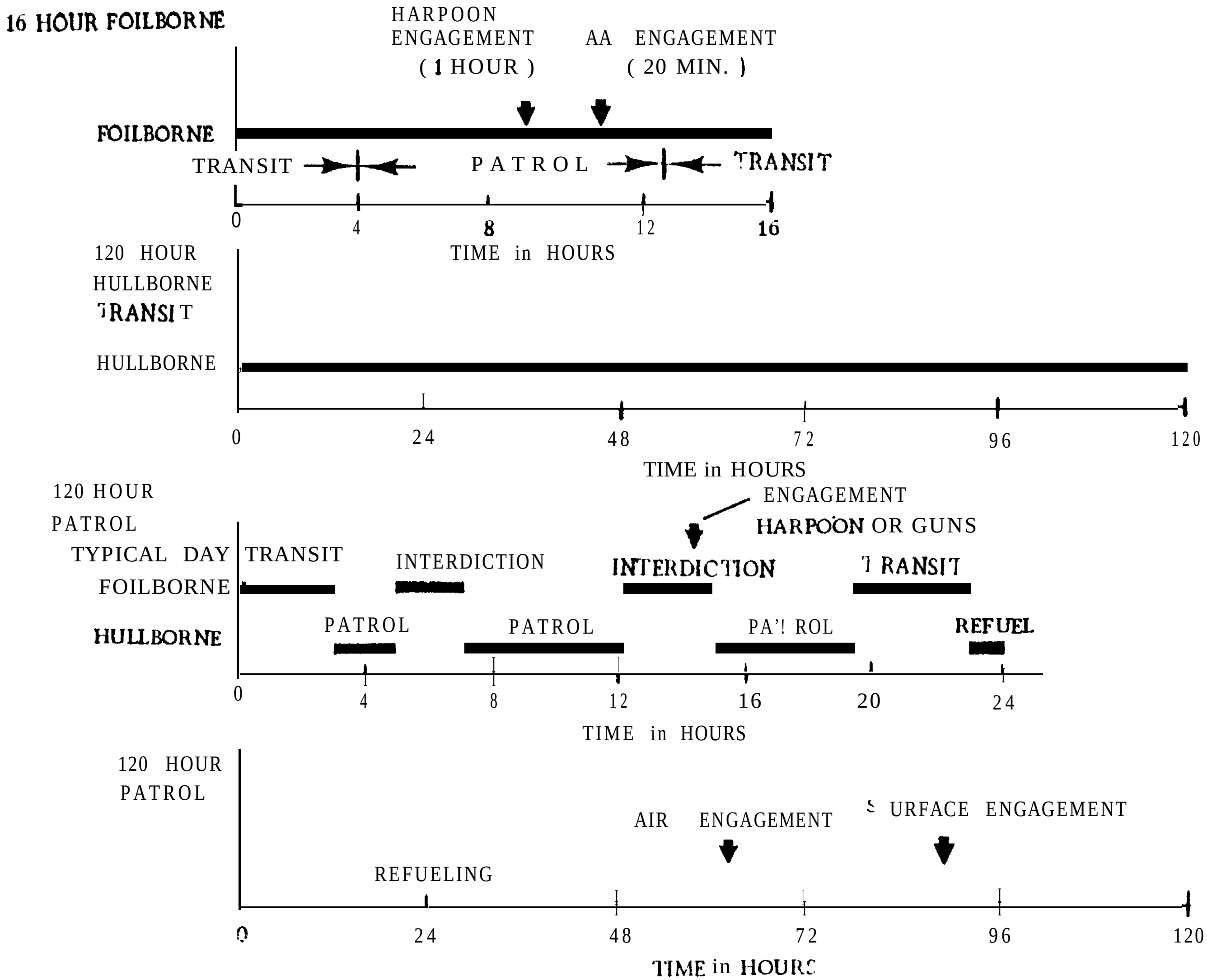

Figure II.A.8-1 MISSION TIMELINES

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Table II.A.8-5. MISSION EQUIPMENT UTILIZATION

MISSION EQUIPMENT	16 HR FOILBORNE SORTIE (%)	120 HR HULLBORNE TRANSIT (%)	FOILBORNE TRANSIT (%)	120 HOUR PATROL - MISSION PHASES: HULLBORNE PATROL (%)	FOILBORNE INTERDICTION (%)	FOILBORNE ENGAGEMENT (%)	HULLBORNE REFUELING (%)
COMMUNICATIONS ▷1							
VHF MR201-B	1	0.5	0.5	0	1	0	0
UHF U1402B (LOS)	1	0	0.5	0.1	1	5	0
U1402E (SATCOM)	0	0	0	0	0	0	0
HF 671T #1 #2	1	1	0	0.5	1	20	0
NAVIGATION							
GYROCOMPASS (IRU) SPEED LOG	100	100	100	100	100	100	100
DEAD RECKONING							
DEPTH FINDER	50	50	50	50	50	50	50
OMEGA	90	100	100	100	100	100	100
RADAR AN/SPS-63	5	50	5	5	5	5	0
WEAPON/SENSOR							
ESM	50	0	0	100	100	100	0
MK-94 FCS - STANDBY	50	0	100	100	100	100	0
RADIATE	1	0	.5	.5	1	100	0
IFF MK-12 INTERROGATE	1	0	.5	.5	.5	.5	0
TRANSPOND	1	0	.5	.5	.5	.5	0
HARPOON - FIRE CONTROL	0.5	0	50	50	50	▷2 100	0
MISSILES	8 MISSILES	0	0	0	0	4 MISSILES	0
76mm GUN READY		0	50	50	SO	▷2 100	0
FIRE	60 ROUNDS	0	0	0	0	60 ROUNDS	0
RBOC	12 ROUNDS	0	0	0	0	12 ROUNDS	0

▷1 PERCENT OF TIME TRANSMITTING, RADIOS ARE ON TO RECEIVE 40% OF THE TIME.

▷2 4 HARPOONS OR 60 ROUNDS. DEPENDING ON WHETHER SURFACE OR AIR TARGET.

the baseline (unaugmented) support concept is approximately 0.06 below the desired goal; however, augmentation of shipboard resources brings mission reliability above the desired goal. Taking advantage of the necessity for daily refueling to highline prepositioned maintenance kits to the hydrofoils enables reliability objectives to be considerably exceeded. This indicates an inherent capability to maintain high reliability over longer durations for a nominal investment should this capability be needed. Mission availability meets the desired objective (0.98) in all cases.

(U) Table II.A.8-7 shows the RMA assessment for the 16-hour foilborne Sortie. The predicted mission reliability with baseline (unaugmented) support resources is 0.023 below the desired goal. Augmentation improves the predicted to within 0.008 of the desired goal. Augmentation for this mission has a relatively small impact because of the short mission duration. Case 3 augmentation is not applicable to this mission since no underway refueling is required.

(U) RMA assessment for the 120-hour foilborne transit mission is shown in Table II.A.8-8. The predicted mission reliability with baseline (unaugmented) support resources is 0.03 below the desired goal; however, augmentation brings it well above the desired goal. Case 3 augmentation is not applicable to this mission since no underway refueling is required.

Table II.A.8-6 120-HOUR PATROL MISSION
RMA ASSESSMENT

SUPPORT CONCEPT	RELIABILITY GOAL	PREDICTED RELIABILITY	MISSION AVAILABILITY
Case 1 - Present O&M Concept	0.65	0.593	0.995
Case 2 - Augmented Organizational Repair by Additional Onboard Spares and STE	0.65	0.660	0.998
Case 3 - Augment Organizational Repair by Prepositioned Maintenance Kits Aboard Fleet Auxilaries	0.65	0.710	0.998

Table II.A.8-7 16-HOUR SORTIE MISSION
RMA ASSESSMENT

SUPPORT CONCEPT	RELIABILITY GOAL	PREDICTED RELIABILITY	MISSION AVAILABILITY
Case 1 - Present O&M Concept	0.95	.937	.993
Case 2 - Augmented Organizational Repair by Additioaal On-Board Spares and STE	0.95	.942	.999

Table II.A.8-8 120-HOUR TRANSIT MISSION
RMA ASSESSMENT

SUPPORT CONCEPT	RELIABILITY GOAL	PREDICTED RELIABILITY	MISSION AVAILABILITY
Case 1 - Present O&M Concept	0.87	0.84	0.992
Case 2 - Augmented Organizational Repair by Additional Onboard Spares and STE	0.87	0.90	0.998

(U) Case 2 augmentation would require additional spares, support, and training above the baseline per ship as follows:

a. Spares weight - 770 lbs
b. Spares cost - $57,500
c. Support equipment weight 198 lbs
d. Support equipment cost - $ 4,920
e. Training cost - $ 5,150

(U) Case 3 augmentation per squadron (six ships) is as follows:

a. Spares weight - 3,070 lbs
b. Spares cost - $716,900
c. Support equipment weight 90 lbs
d. Support equipment cost - $ 1,490
e. Training cost' - 11,845

8.6 TEST AND EVALUATION RMA RESULTS

(U) Actual trials and operating data for the PHM-1 and JETFOIL come from two sources:

- A Boeing intra-company system for recording and tracking failure and maintenance actions, called UERs (Unplanned Event Records). This system is used on the JETFOIL and has been used on PI-M-1 during the period from its first voyage (14 Feb 1975) to its deployment to Southern California (29 Sep 1975).

- A computerized system called "ASSIST" (Advanced Ships Information System - Technical) (See References II.A.8-3 and II.A.8-4) developed by DTNSRDC which has been used on PHM-1 since 30 Sep 1975 to track all unscheduled maintenance actions and design discrepancies on all systems.

8.6.1 JETFOIL RMA Experience

(U) Figure II.A.8-2 illustrates the mechanical reliability of the five JETFOILS in service in Hong Kong and Hawaii. In this case, reliability is defined as the percentage of time that a voyage takes place without a 15 minute departure delay. Only those cancellations and delays attributed to malfunction of the systems on the ship are counted. By way of comparison, the mechanical reliability of a number of mature aircraft is shown on the right-hand side.

8.6.2 PHM-1 RMA Experience

(U) Although a complete analysis of the data accumulated to date is still in progress, Figure II.A.8-3 shows some preliminary indications of the improvement in PHM-1 reliability. Because the ship, to date, has been primarily involved in debugging and testing and does not represent a mature system, in the RMA sense, it is difficult to extrapolate the data for a comparison with predicted data. But if one considers the mission of PHM-1 in its current phase of operation to be subsystem testing, then Figure II.A.8-3 illustrates a trend showing continual improvement as the testing continues. This figure shows the cumulative underway hours to date and the cumulative number of times one of the mission critical or mobility critical systems causes an abort or revision of the trials. For the 19 subsystems monitored on the first 95 voyages, this represents 33 times out of 1,805 possibilities (19x95) or 1.8 percent of the

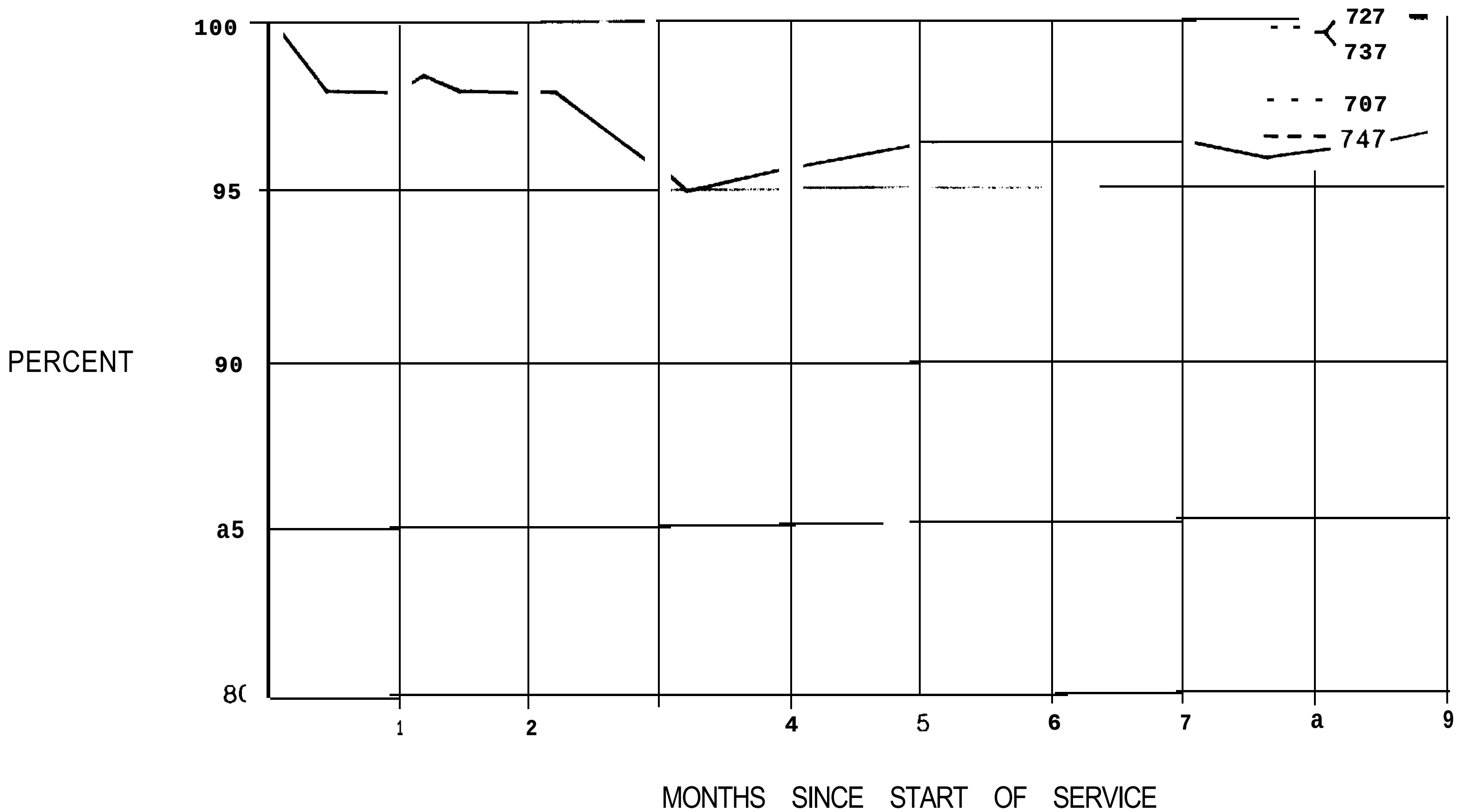

Figure II.A. 8-2. JETFOIL EQUIPMENT (MECHANICAL DEPARTURE) RELIABILITY

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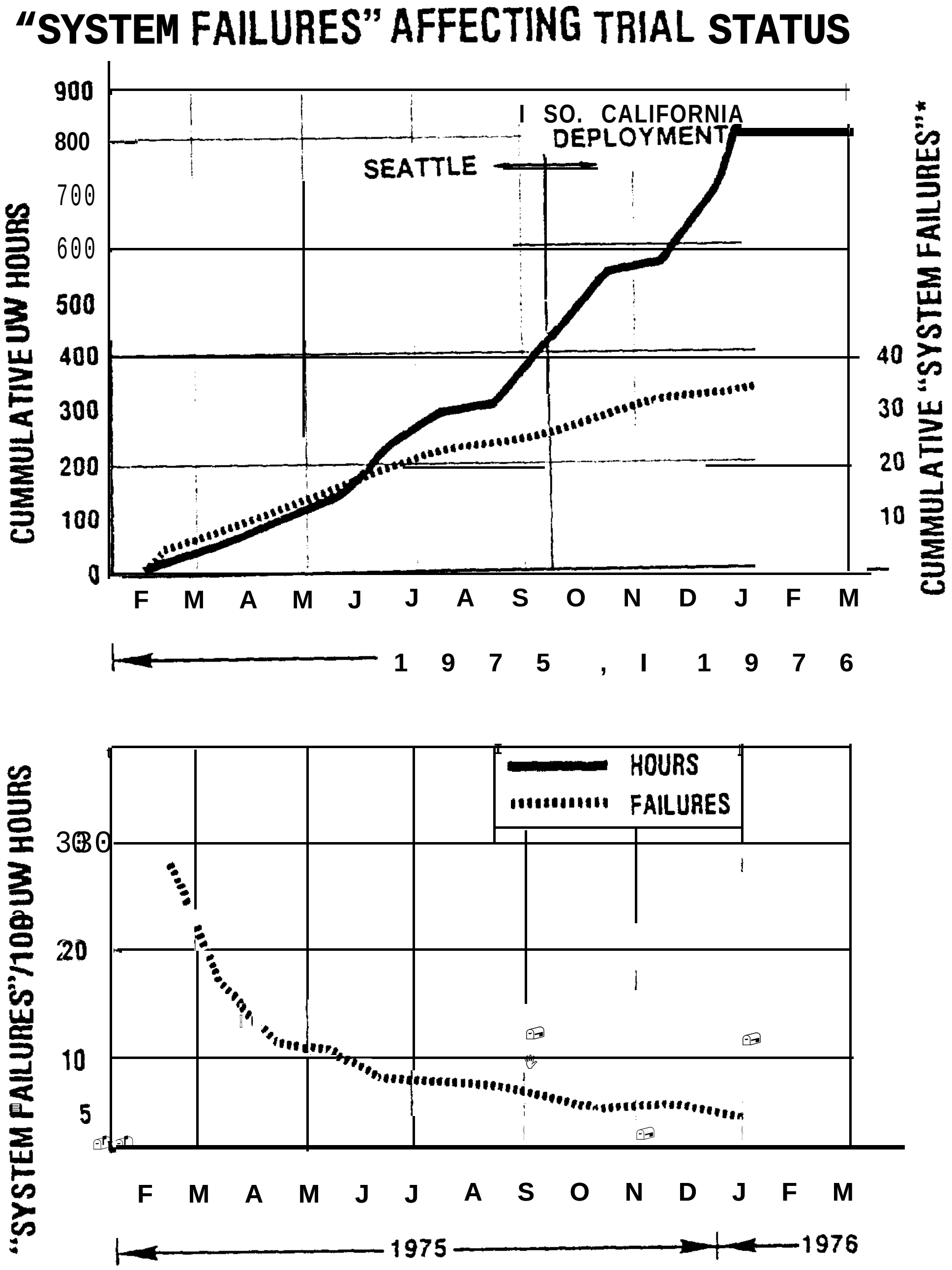

*"SYSTEM FAILURE" = CAUSES VOYAGE ABORT, TEST DISCONTINUATION OR TEST REVISION

Figure II.A.8-3. PHM-1 TEST AND EVALUATION SUMMARY time that a test had to be revised, discontinued, or a voyage aborted because of a subsystem failure.

(U) Figures II.A.8-4 and II.A.8-5 illustrate the top ten subsystems in terms of number of failures for the two periods prior to and since deployment of PHM-1 to Southern California (SOCAL) on 30 September 1975. Aside from foilborne propulsion failures, the subsystems with the highest failure experience are not hydrofoil peculiar. The design of PHM-1 has incorporated additional redundancy in these systems as depicted in Table II.A.8-9.

(U) Looking at the resources spent in maintaining the PHM-1, Figure II.A.8-6 illustrates the maintenance trend in terms of the number of maintenance man hours per operating hours during the Southern California Deployment.

(U) Comparison of the PHM-1 experience with comparable ship information was not possible because of the lack of such data for conventional surface ships. Therefore, similar data for a number of familiar aircraft are shown to illustrate the general trend. The PHM-1 is shown to the left of the ordinate, since her delivery to the Navy is not presently scheduled until October 1976.

(14 FEB - 29 SEP 1975)
(TEN HIGHEST SYSTEMS = 75% TOTAL FAILURES)

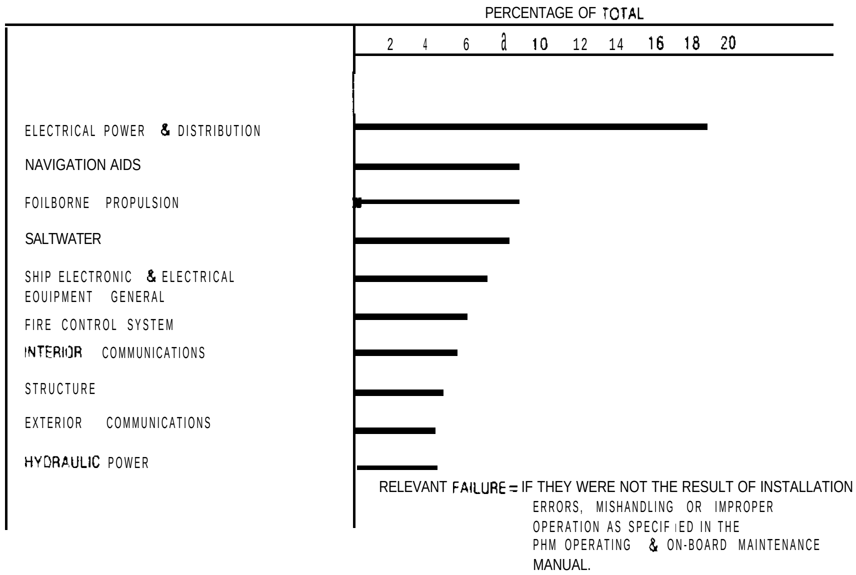

Figure II.A.8-4. PERCENT OF TOTAL RELEVANT FAILURES PRIOR TO SOCAL DEPLOYMENT

(30 SEP 1975 - 1 JAN 1976) TEN HIGHEST SYSTEM = 70% OF TOTAL FAILURES

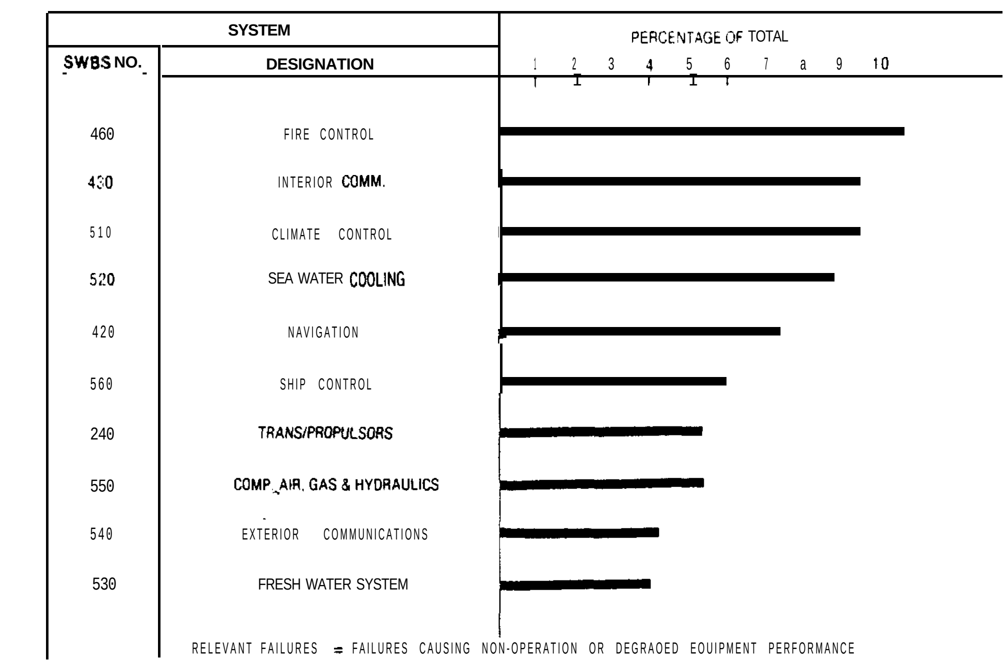

Figure II.A.8-5. PERCENT OF TOTAL RELEVANT FAILURES SINCE SOCAL DEPLOYMENT

)

Table II.A.8-9. PHM REDUNDANCY

SYSTEM	NUMBER REQUIRED	AVAILABLE REDUNDANCY
• ELECTRICAL SSPU's Generators Converters	One one TWO	Two Available Two Available Three Available
• HYDRAULIC POWER Pumps Packs Loops	Two to Four TWO Fore and Aft	Eight Available Four Available Dual Loops Fore and Aft
• HULLBORNE PROPULSION Diesels/Propulsors	One	Two Available
• BILGE Pumps	Four Pumps	Portable Pump
. SEAWATER Pumps	Three (H/B Only)	Five Available
. FRESH WATER Desalinator	One	16-Hour to 24-Hour Supply Available. Replenish at Refueling.
• COMPRESSED AIR	One SSPU	Two SSPU's Available and DC Air Compressor
• ENVIRONMENTAL CONTROL Chiller Loops	TWO	Four Available
• INTERNATL COMMUNICATIONS	Intercom backed by Sound-Powered Communications	

MAINTENANCE MAN-HRSIOPERATING HOUR

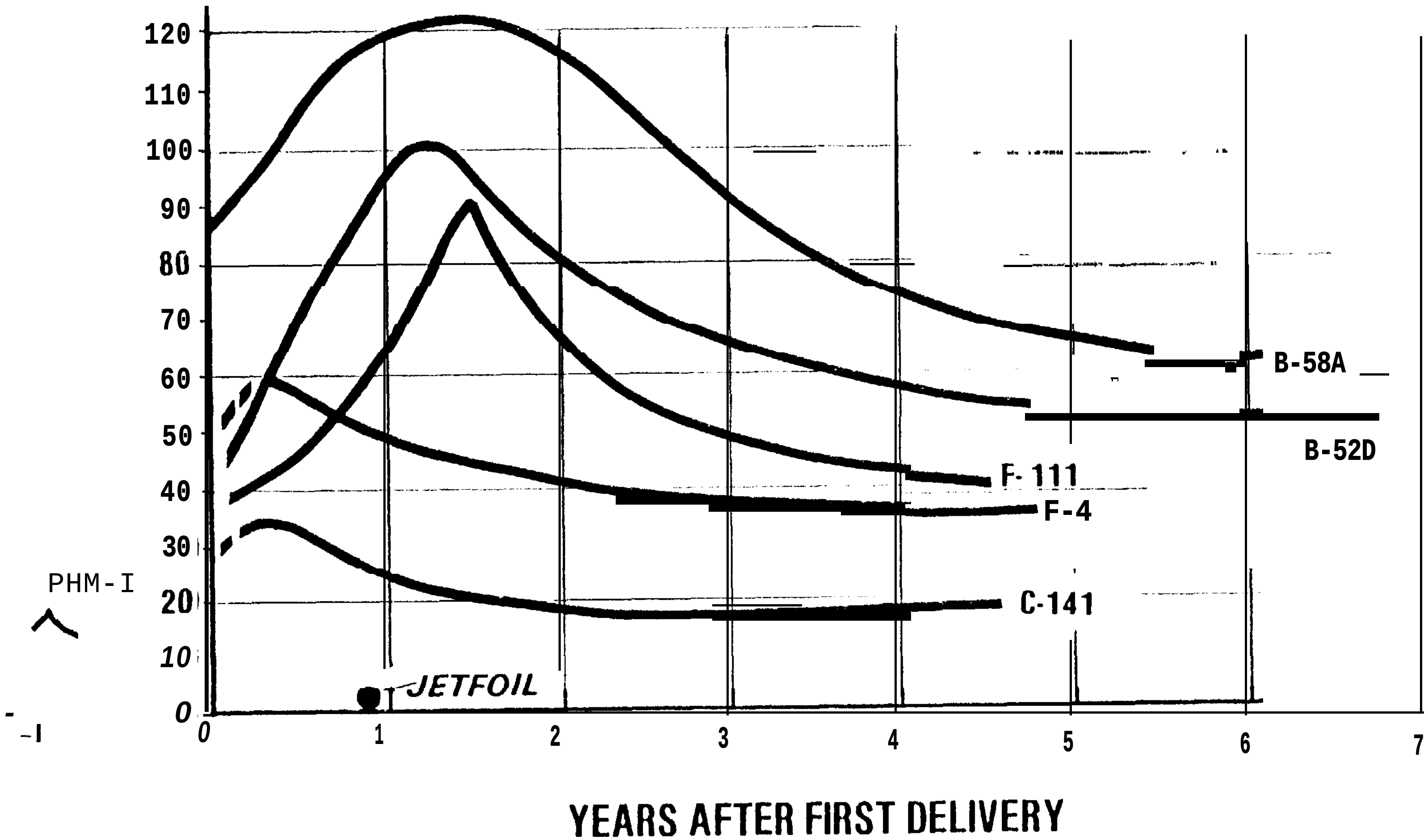

Figure II.A.8-6. MAINTAINABILITY-MAINTENANCE TREND

References

II.A.8-1 Final Report CCP-88 - US Variant PHM Reliability/Availability Analysis for Critical Subsystems, The Boeing Company Document No. D323-15003, dated 28 January 1976.

II.A.8-2 Luetjen, P., "TIGER Users Manual," Naval Ship Engineering Center Report 6112B-130-76 (Rev. D), June 1976.

II.A.8-3 "ASSIST" (Advanced Shjps Information System - Technical) Users Manual, dated 12 September 1975 (PRELIMINARY) (Final version to be published September 1976 by DTNSRDC).

II.A.8-4 Larsen, D.B., Johnson W.L., "O&M Experience Information Collection for Hydrofoil Test and Lead Ships" The Boeing Company Document No. D321-13008 dated 25 April 1975.

II. STATUS OF VEHICLE TECHNOLOGY

A. TECHNOLOGICAL PERFORMANCE FEATURES

9. UNIQUE FEATURES

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II.A TECHNOLOGICAL PERFORMANCE FEATURES

9. UNIQUE FEATURES

9.1 INTRODUCTION

(U) The unique features of a hydrofoil ship result in the ability of a relatively small (compared to a displacement ship), highly maneuverable ship with a high useful load fraction to operate at high speeds in high sea state with low motions.

(U) The features which give a hydrofoil ship these capabilities are discussed in detail in other sections and will be highlighted only in this section.

9.2 SPEED

(U) A hydrofoil ship operates in the hullborne mode from 0 to approximately 25 knots and from 25 to approximately 50 knots in the foilborne mode. Burst speeds to 70 or 80 knots are possible without sacrificing the efficient operation in the 40 to 50-knot regime by utilizing the recently developed TAP-2 foil concept (see Section II.A.1.5) and increasing the power available. Unlike other high performance ships, the speed loss of a hydrofoil ship in rough water is small, about 10 percent from smooth water to its design sea state.

9.3 RIDE QUALITY

(U) A hydrofoil ship for its size has unsurpassed ride qualities in rough water. While hullborne, the stabilizing effects of the strut-foil system give the hydrofoil ship the ride quality of a conventional ship 3 to 5 times larger. In the foilborne mode, the measured seaway induced motions are low. To give an idea of the magnitude of these motions, the 120-ton HIGH POINT operates routinely in Sea State 5 (significant wave height = 10 feet) at over 40 knots with vertical accelerations less than 0.1g rms, lateral accelerations less than 0.07g rms and pitch and roll angles less than 1.0 degree rms. (See Status of Performance Data, III.2.1.5.)

9.4 MANEUVERABILITY

(U) Hydrofoil ships while foilborne are highly maneuverable. Navy hydrofoil ships have demonstrated turn rates of 8 degrees per second at all foilborne speeds. This is equivalent to a turn diameter of less than 300 yards at 40 knots. In design sea state the demonstrated turn rate is slightly less, being about 6 degrees per second.

(U) In the hullborne mode the hydrofoil ship maneuvers much like any conventional displacement ship.

9.5 RELATIVELY SMALL SIZE

(U) To achieve the same performance in the same sea state, hydrofoil ships can be considerably smaller than conventional or other high performance vehicles. Concomitant with relatively smaller size are generally smaller crews and costs.

9.6 HIGH USEFUL LOAD FRACTION

(U) Hydrofoil ships have a high useful load fraction (military payload plus fuel/full load weight) which ranges from about 30 percent at 120 tons to about 48 percent at 1,300 tons. This useful payload can be allocated between weapons or fuel depending on the mission and range requirements. This makes hydrofoil ships capable of fulfilling multimission Naval tasks.

9.7 CONVENTIONAL HULL

(U) The hull of a hydrofoil ship is similar to that of conventional ships and therefore can be constructed and outfitted in any shipyard qualified for aluminum ship construction. This offers potential cost savings over construction by aerospace companies as shown by a comparative cost study. In this comparative study, the cost advantage of building a hydrofoil ship, less foils, in a shipyard becomes obvious. The man hours labor per ton to construct and outfit a hydrofoil ship hull in an aerospace facility and a shipyard are compared in Figure II.A.9-1. As anchor points in this study, the actual labor required to build one ship in an aerospace facility, and the actual labor required to build 5 PGMs are shown. The difference per unit between the actual labor based on five PGMs compared with 10 hydrofoil ships reflects the added complexity of a hydrofoil ship system.

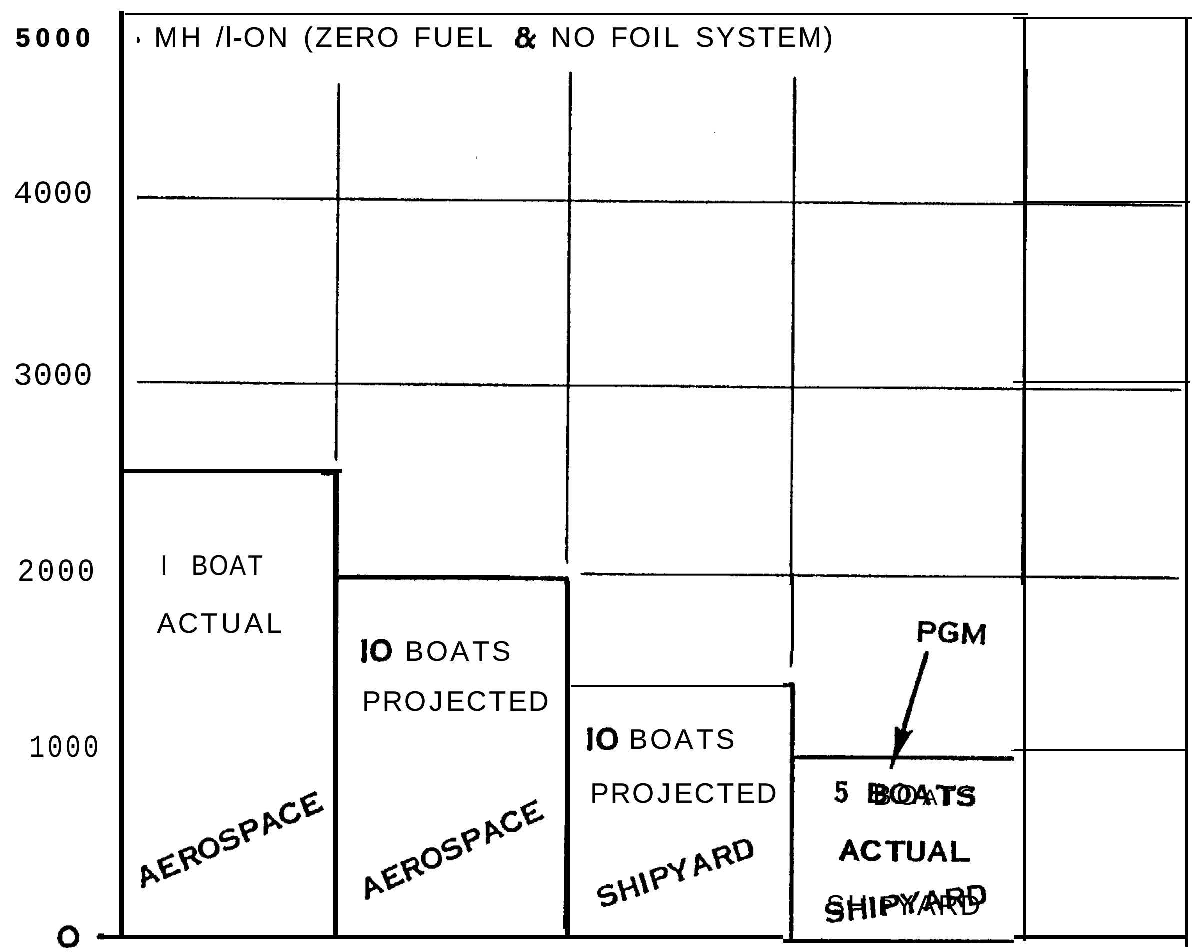

Figure **II.A.9-1.** HI-PERFORMANCE CRAFT: MANHOUR COSTS

II. STATUS OF VEHICLE TECHNOLOGY

B. SUBSYSTEMSAND DESIGN AND CONSTRUCTION FEATURES

1. HULL/AIRFRAME (CONTAINMENT SYSTEM)

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II.B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

1. HULL (CONTAINMENT SYSTEM) DESIGN FEATURES

1.1 INTRODUCTION

(U) This section will discuss the selection of the hydrofoil ship hull and the design features as they integrate and contribute to the total vehicle, while documenting the established features of existing and potential future hydrofoil hulls.

(U) The discussion will be developed in four major topics: General Containment Considerations, Hydrofoil Unique Hull Design Features, Hydrofoil Mission Related Features, and Structural Considerations.

(U) It should be noted at the outset that while the hydrofoil ship hull must satisfy requirements unique to the concept, the fulfillment of these requirements generally results in hull forms similar to traditional naval platforms. Thus, this discussion will address in the main the identification of the hydrofoil ship hull requirements, as the satisfaction of the requirements follows traditional naval architectural practices.

1.2 GENERAL CONTAINMENT CONSIDERATIONS

(U) Recent studies, Reference II.B.1-1, trended the vehicle densities for six prototype hydrofoil ships and for six recent design studies, Figure II.B.1-1. A measure of the efficient use of hull structure is the value of vehicle density (full load weight/total enclosed volume). For existing hulls, vehicle densities have generally increased with the maturing of the hydrofoil concept.

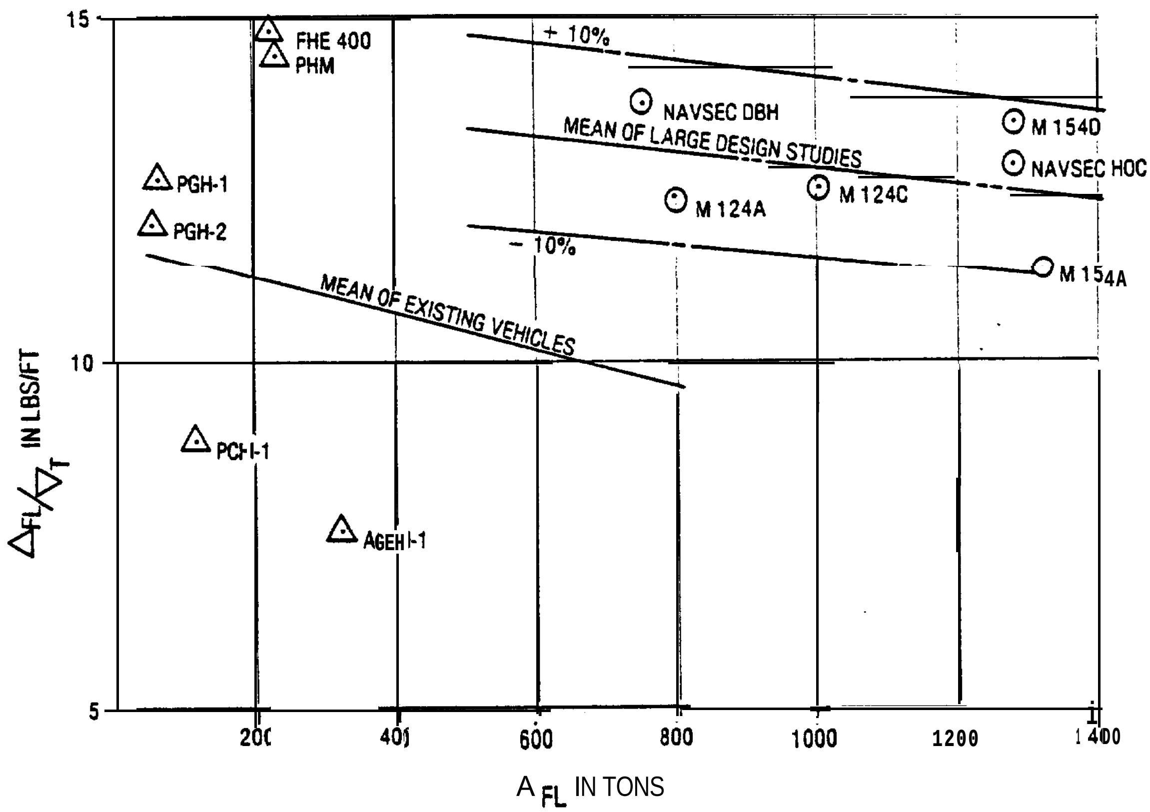

Figure II.B.1-1. VEHICLE DENSITY-BASED ON FULL LOAD DISPLACEMENT

Early USN R&D hydrofoil ships had low vehicle densities, while the most recently launched, the PHM, has a vehicle density of the order of 15 $lbs/ft.^3$ This latter figure compares favorably with naval displacement vehicles of the destroyer escort type which have densities on the order of 20-22 $lbs/ft.^3$ Heller and Clark, Reference II.B.1-2, attribute about 3 lbs/ft^3 difference in density to the use of all aluminum hulls in hydrofoil ships versus steel in conventional ships. Use of lighter weight equipment for foilborne performance considerations together with the smaller displacement of hydrofoil vehicles up until this time would account for the remaining differences in densities from conventional naval escort platforms.

(U) While it is difficult to quantify correct or acceptable values for vehicle densities, some keys are offered in terms describing existing hydrofoil vehicles. Operating crews, who must live on, operate, and maintain the ships, use the terms spacious, comfortable, tight, and cramped; while designers use terms like efficient, compact, and under-utilized. Of the prototype vehicles, the AGEH-1 is generally recognized as the most spacious; PCH-1 is termed comfortable; PGH-1, PGH-2, and PHM are described as compact, and the FHE-400 is touted for her volumetric efficiency.

(U) Acceptable values for future hydrofoil ships will predominantly be functions of crew size and equipment maintainability and repairability requirements. The question of crew size in general and the concern of providing the proper blend of habitability with minimum ship volume and weight constraints is shared by all advanced naval vehicle concepts. Access needs and inherent volume requirements for maintenance and repair of equipment are becoming better quantified as the hydrofoil concept matures. Work is underway at The Boeing Company directed towards assembling these data.

(U) Thus far, the discussion has dealt only with the gross vehicle parameter of total weight over total volume. As the 12 designs considered (in Figure II.B.1-1) had wide variations in fuel load percentages, the data were corrected for fuel weight and volume, Figure II.B.1-2. The corrected data show good agreement between the means for the existing vehicles and the design studies, although there is considerable scatter for the existing hydrofoil ships, with all three USN combatants (PGH-1, PGH-2, and PHM) falling above the mean. The two R&D ships (PCH-1 and AGEH-1) suffer from the lack of an installed weapon system.

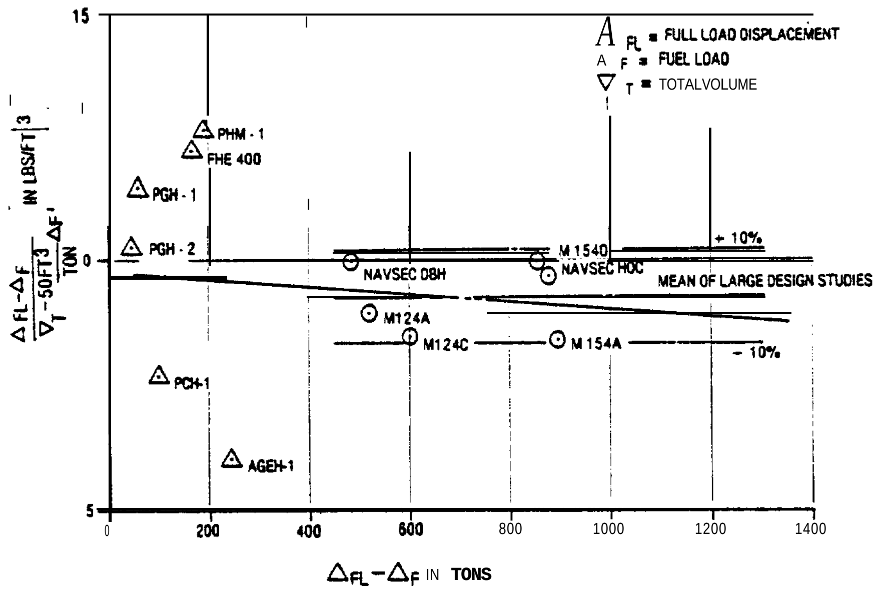

Figure II.B.1-2. VEHICLE DENSITY-BASED ON FULL LOAD DISPLACEMENT MINUS FUEL LOAD

(U) Finally, recognizing that the bulk of the lift systems was external to the hull, the data were again corrected (Figure II.B.1-3) by subtracting lift system weights. A trend of increasing density with platform displacement can be identified.

(U) Also identified in Figure II.B.1-3 is the apparent existence of a "volumetric growth margin" inherently built into all design studies, which is perhaps a partial explanation of why vehicles can grow in weight during the successive design phases without significantly growing in volume. To quantify the potential upper limit

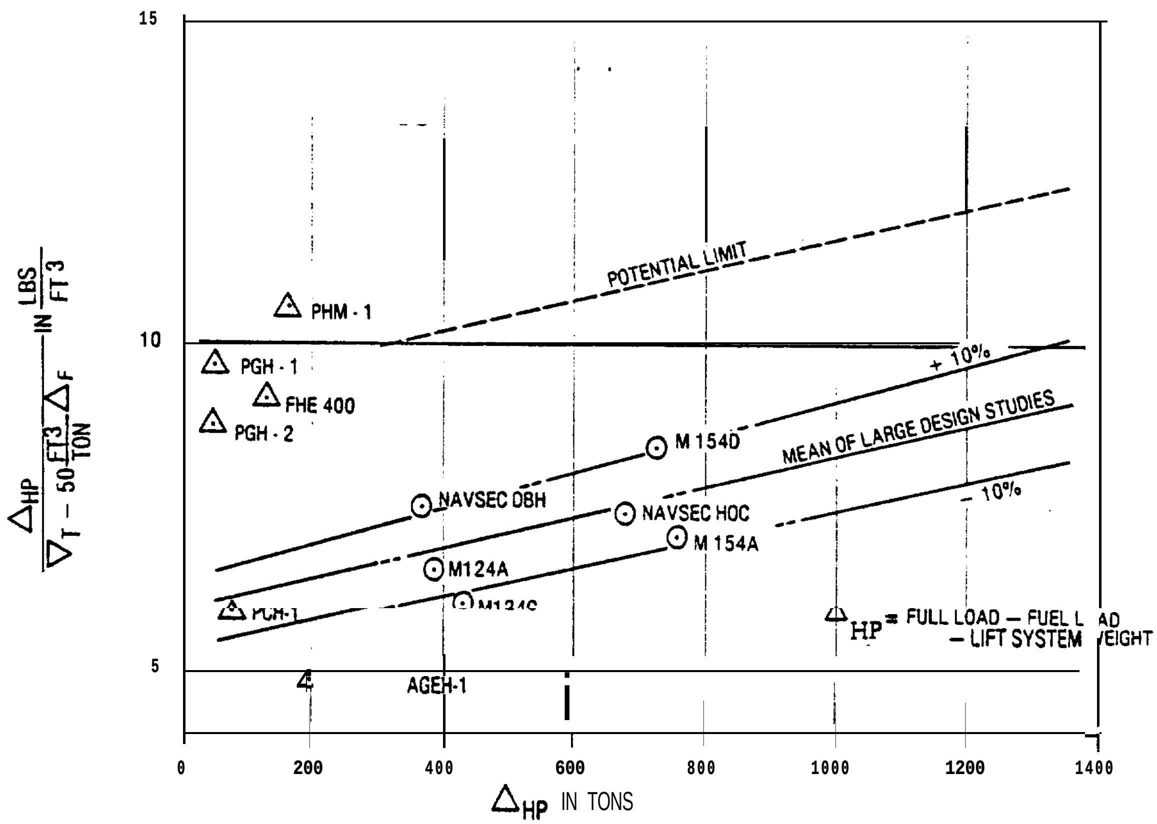

Figure II.B.1-3. VEHICLE DENSITY-BASED ON FULL LOAD DISPLACEMENT MINUS FUEL LOAD AND LIFT SYSTEMS

of vehicle density, a new line was drawn, Figure II.B.1-3, through the mean of the four most dense existing hydrofoil ships with a slope identified by the six recent design studies. A total vehicle density was then constructed by adding lift system weight from F.gure II.B.1-4 and fuel weight. (The mean trend line on Figure II.B.1-4 did not include the three fixed lift system designs, FHE-400, M154A, and M154D.) Figure II.B.1-5 resulted, which illustrates both potential total vehicle density and the effect of fuel load. The trends shown are considered valid for retractable lift system, propeller driven craft. Non-retractable lift system designs will have lower vehicle densities, as the bulk of the lift system is external to the containment volume, while waterjet powered craft will increase the vehicle

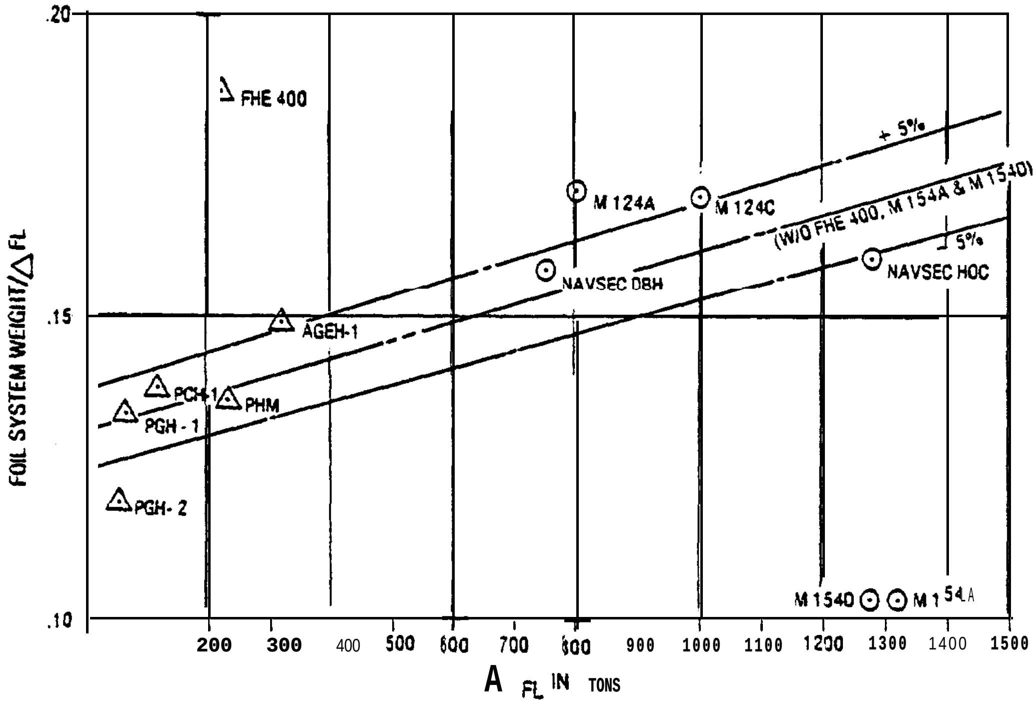

Figure II.B.1-4. DISTRIBUTION OF FOIL SYSTEM WEIGHT.

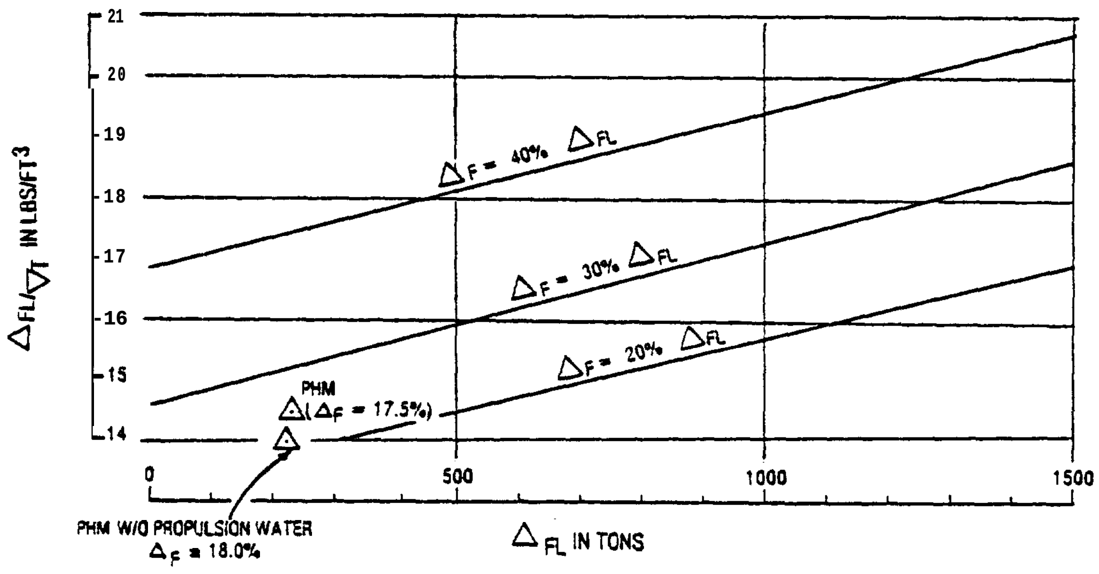

Figure II.B.1-5. POTENTIAL VEHICLE DENSITY - BASED ON FULL LOAD DISPLACEMENT density by a minor amount due to the relatively dense onboard propulsion water. PHM, with a fuel load of 17.5% of full load as built, is shown for reference. Correcting the PHM density for on-board propulsion water associated with the waterjets, brings it into good agreement with the indicated potential trends.

(U) While total vehicle trends can be identified by the preceding, distribution between hull girder and superstructure volume is shown in Fgiure II.B.1-6. There are pros and cons for designing to either side of the mean distribution shown.

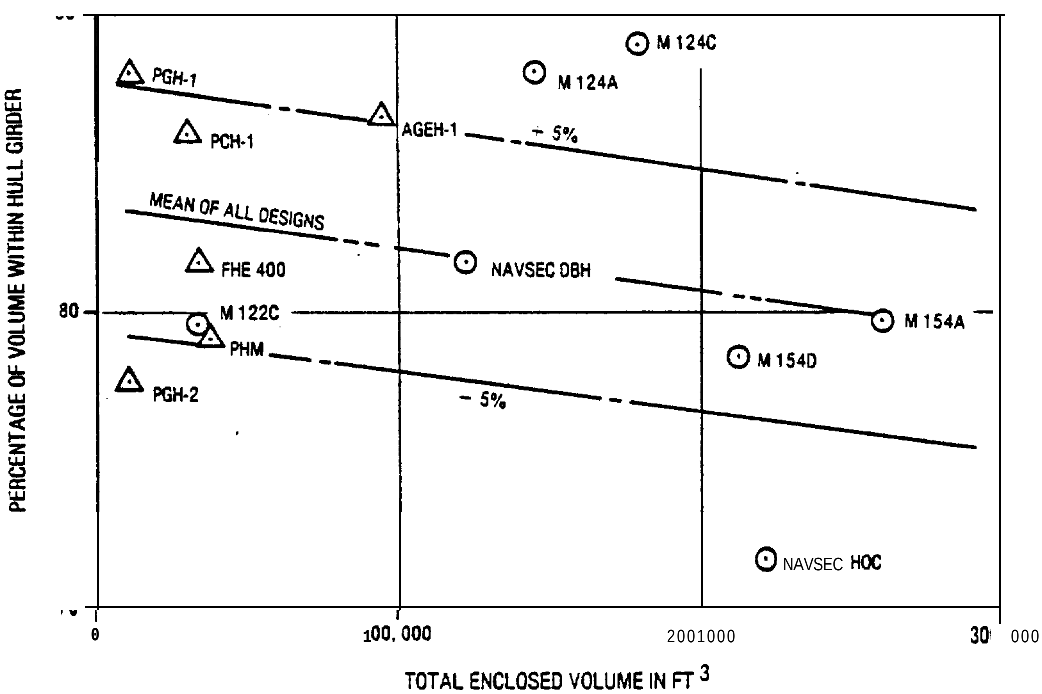

Figure II.B.1-6. DISTRIBUTION OF HULL GIRDER AND SUPERSTRUCTURE VOLUME

1.3 HYDROFOIL UNIQUE HULL DESIGN FEATURES

(U) Hydrofoil ship unique hull design features are defined as those hull requirements which are necessary to the hydrofoil concept without regard to the mission of the total vehicle.

These features are a balance of distributed hullborne loads and concentrated foilborne conditions; hydrodynamic performance to insure takeoff to foilborne; and, when required, the geometric interaction necessary for lift system retraction.

1.3.1 Load Distribution

(U) Most discussions in regard to hydrofoil load distribution center on the distribution of lift in foilborne mode between the forward and aft lift system arrays. The terms conventional, tandem, and canard are used to classify hydrofoil craft by lift system distribution. Figure II.B.1-7, taken from Reference II.B.1-3, illustrates the generally accepted limits for each type. Existing hydrofoil ships have successfully utilized both airplane and canard configuration. The AGEH-1 and PGH-1 utilize the airplane configuration, while PCH-1, PGH-2, PHM, and the Canadian FHE-400 utilized the canard configuration. Future larger hydrofoils with lesser strut length-to-ship length ratios and higher foil span-to-ship beam ratios will tend to employ tandem distributions. The final lift system distribution choice involves overall arrangement and weight distribution considerations including machinery and combat system element locations; retractability, if required of the struts and foils; and foilborne hydrodynamic considerations relative to dynamic stability and control, maneuverability, and wake effects of the forward foil on the aft foil.

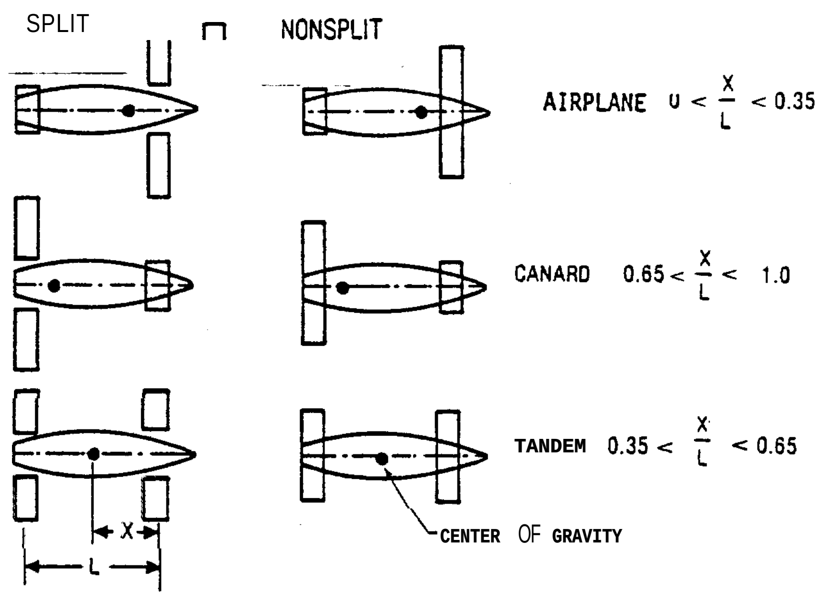

Figure II.B.1-7. DEFINITION OF FOIL AREA DISTRIBUTION

(U) Not often recognized, however, is the requirement of the hull form to match the selected vehicle load distribution with minimal changes in trim.

(U) The single hull parameter which best defines the solution is the location of the longitudinal center of buoyancy (LCB) for the displacement of interest. Figure II.B.1-8 illustrates typical values of LCB suitable for the various foil lift classifications.

(U) For level trim hullborne, the LCB location must match the location of the longitudinal center of gravity (LCG). It should be noted that on retractable system designs, lowering the foils will move the LCB and LCG for the total vehicle. For this reason, hullborne level trim conditions cannot, as a rule, be precisely satisfied both foils up and down, although experience has shown that acceptable limited excursions in trim can be attained under all conditions of loading and lift system position.

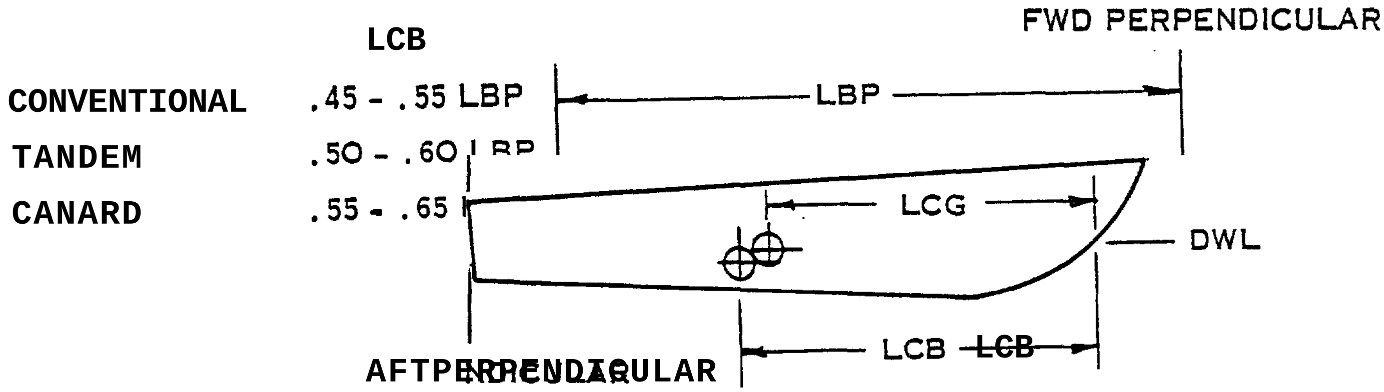

Figure II.B.1-8. TYPICAL LCB LOCATIONS FOR HYDROFOIL CRAFT

(U) To present an illustration of the hull forms characteristics suited for each type of distribution, the following figures taken from Reference II.B.1-1 are shown. The data in each figure have been normalized to a 1,000-ton nominal hull displacement for comparison. The figures will also be utilized in the discussion of lift system retraction following. Figure II.B.1-9 illustrates the AGEH-1 hull form, with a conventional (90/10) distribution. To achieve the required LCB location, a full sectioned hull was provided forward, with rather extreme tapering of the hull sections aft. Lowering the lift system elements (mains athwartships, and tail in the forward and aft plane) tended to move the total vehicle LCB and LCG forward to a match with the foilborne center of lift.

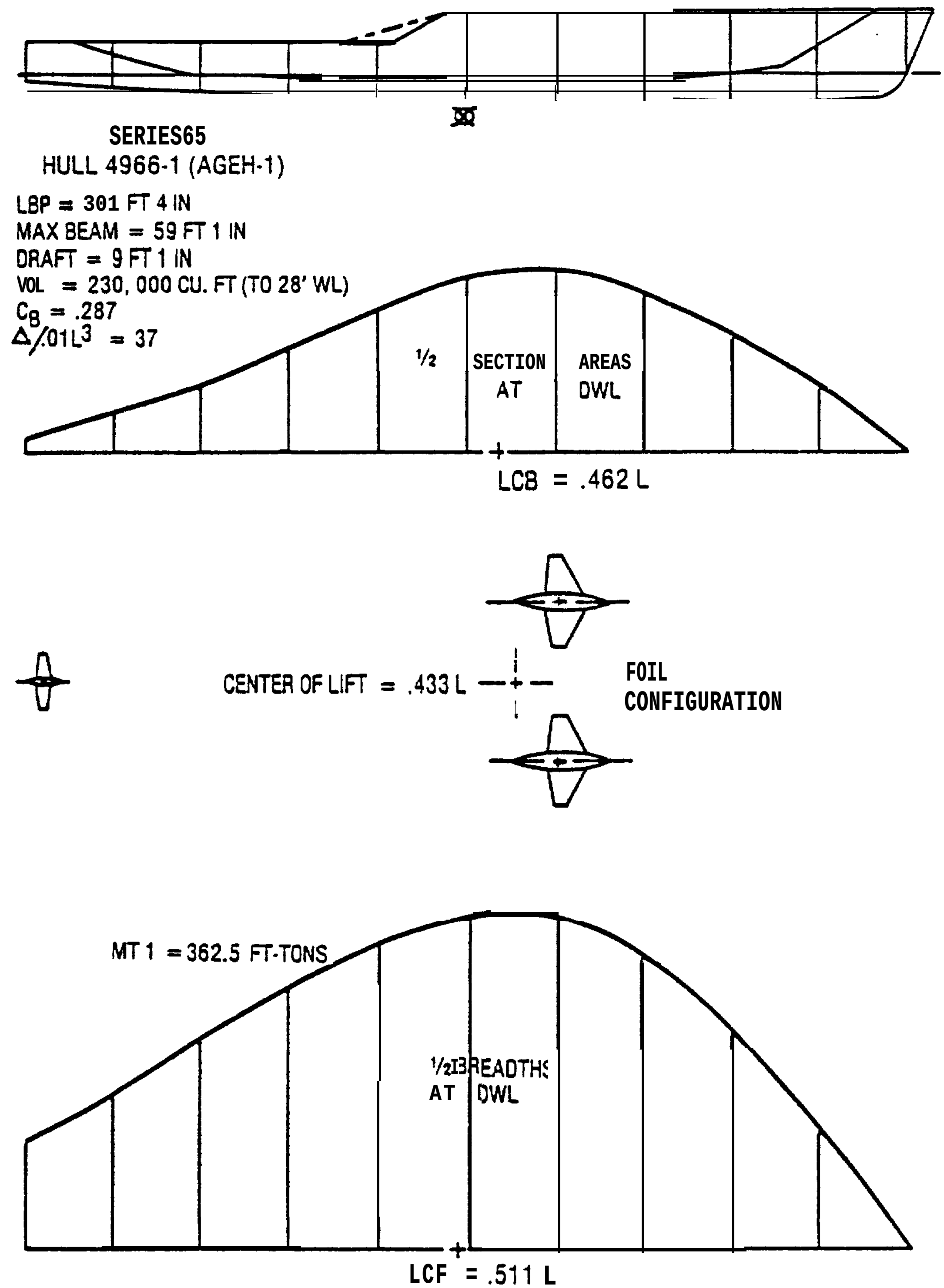

Figure II.B.1-9. AGEH-1 HULL FORM AND CONVENTIONAL F/S CONFIGURATION WITH 90/10 LOAD DISTRIBUTION

Figures II.B.1-10 and II.B.1-11 illustrate two recent Grumman Aerospace Corp. designs for tandem lift system hulls. Design M124, Figure II.B.1-10, has a 40/60 distribution; while Design M154, Figure II.B.1-11, has a 50/50 distribution as illustrated, for which a retraction scheme can be developed at the expense of complicated mechanical arrangements. A 40/60 distribution is more practical. In both of these designs, having satisfied the distribution requirement, hull sections were chosen primarily for machinery arrangement, hullborne speed, and seakeeping requirements; resulting in rather fine lines forward with traditional sections aft. Due to the lift system distribution, there is little excursion in LCG or LCB upon lowering of the foils. Final LCG and LCB values selected in the foils extended condition were a function of second order hydrodynamic performance conditions. Finally, we see Figure II.B.1-12, a canard foil system hull derived from the AGEH-1 hull. The 30/70 lift system distribution results in a hull requirement for proportional fine section forward with extremely full sections aft. Lowering the lift system elements (both in the forward and aft plan) moves the total vehicle LCG and LCB forward.

1.3.2 Foil System Retraction

(U) All USN hydrofoil ships have had retractable lift systems. AGEH-1 and PGH-1 with conventional distributions, have split forward arrays which are retracted athwartships, and a single tail strut and foil pivoted over the transom in the fore and aft plane. All elements are lifted clear of the water for inspection and maintenance.

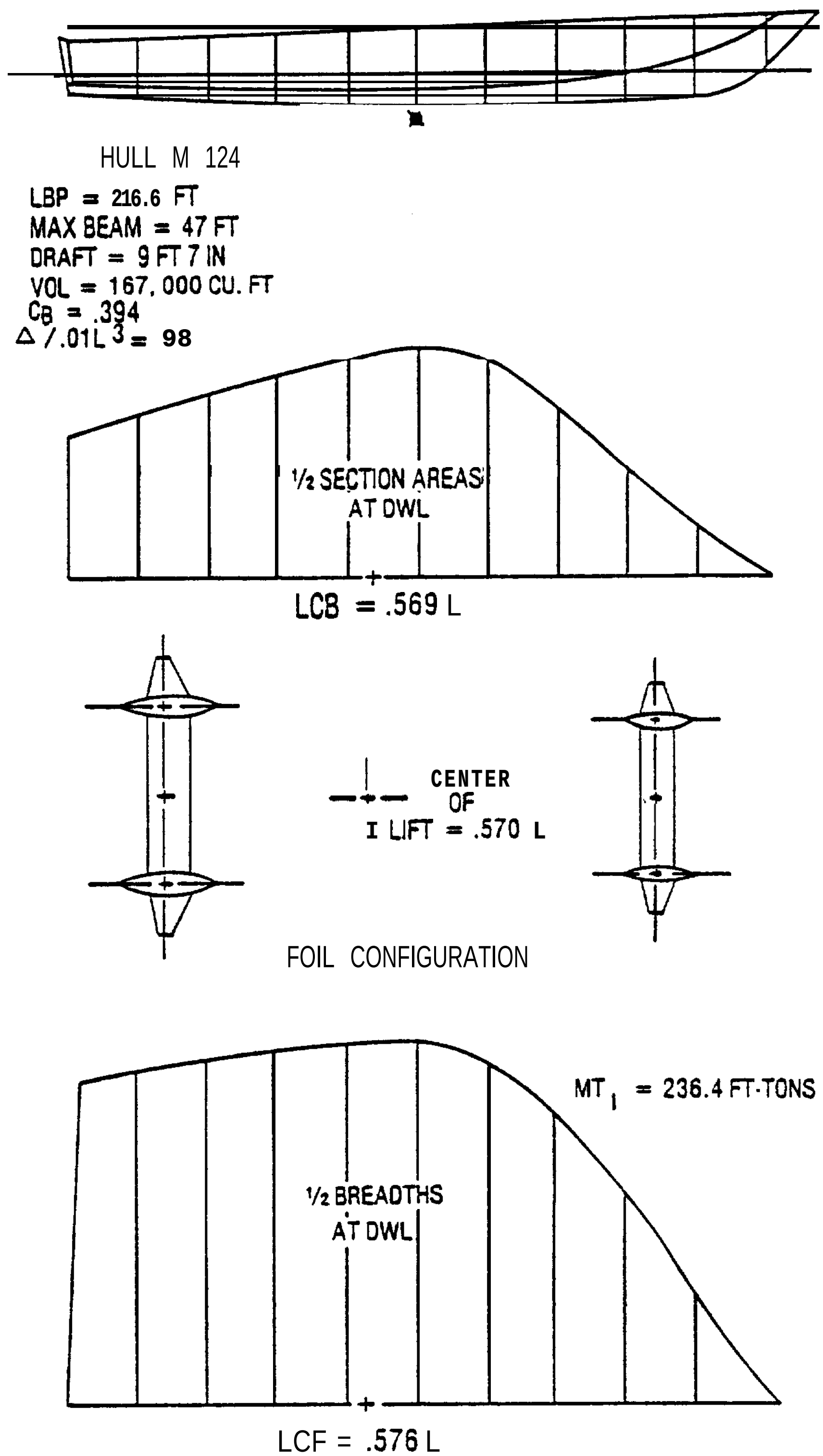

Figure II.B.1-10. GAC M124 HULL FORM AND TANDEM F/S CONFIGURATION

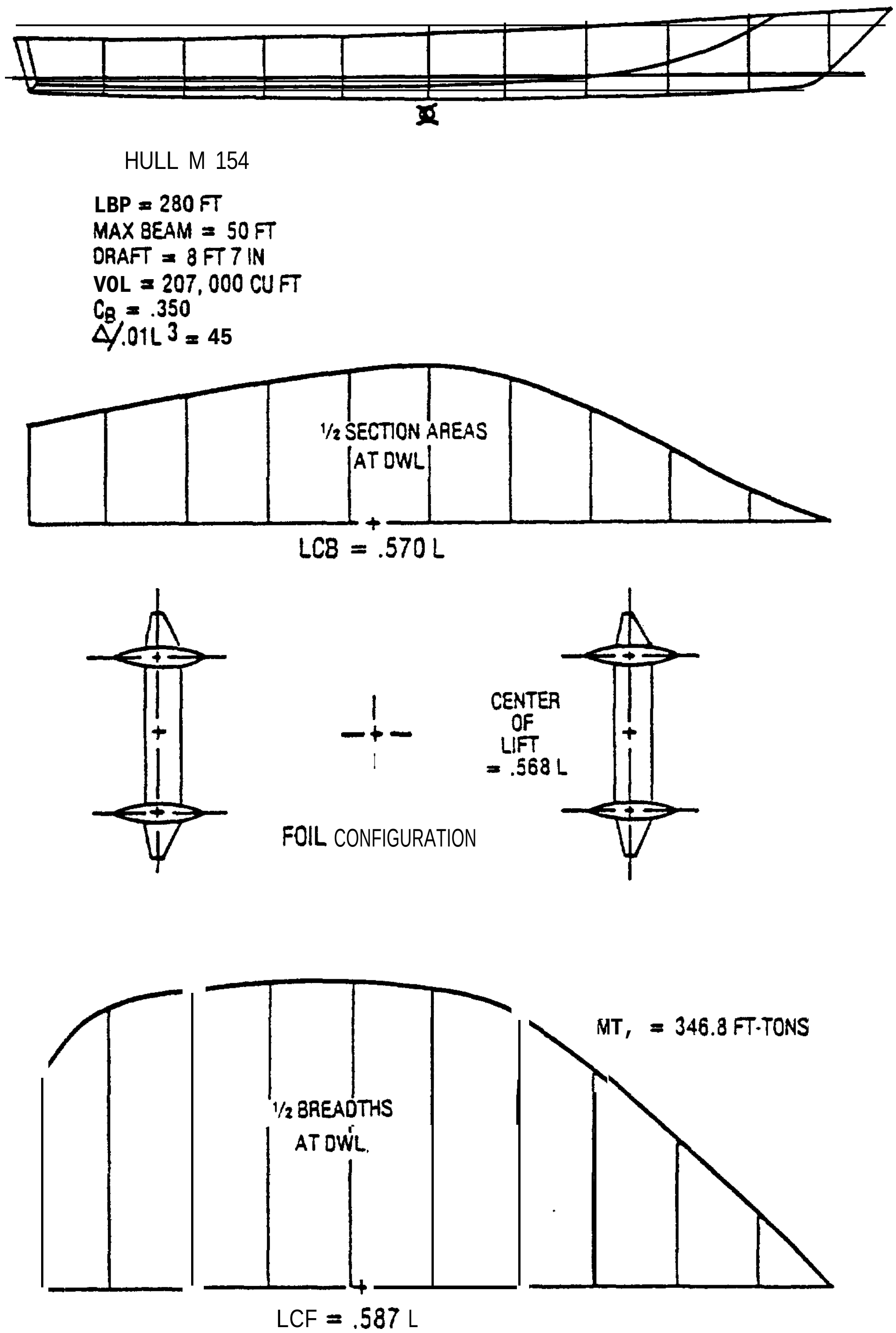

Figure II.B.1-11. GXC M1.54 HULL FORM AND TANDEM F/S CONFIGURATION WITH 50/50 LOAD DISTRIBUTION

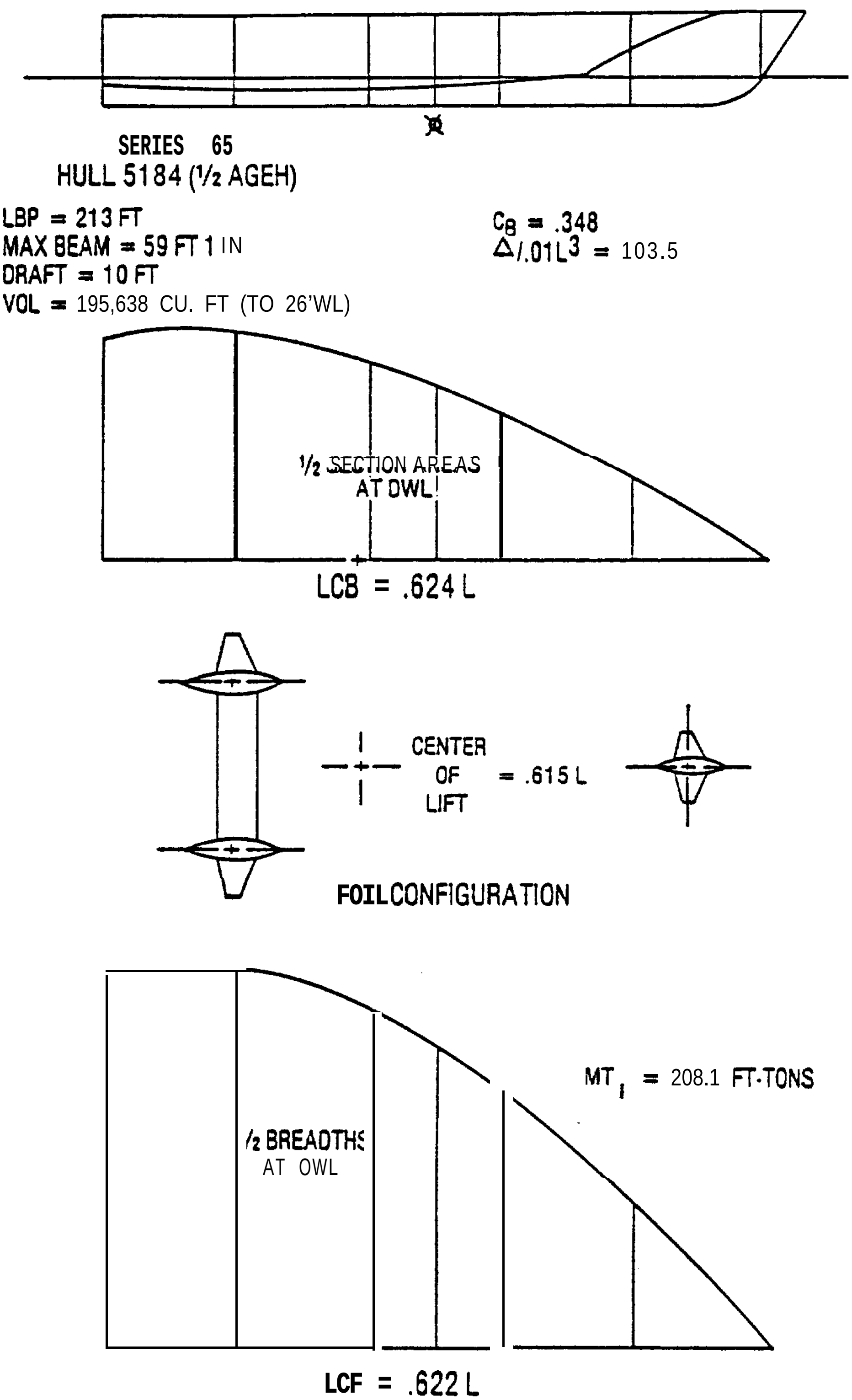

Figure II.B.1-12. AGEH-1 DERIVED HULL FORM AND CANARD F/S CONFIGURATION WITH 30/70 LOAD DISTRIBUTION

(U) The lift system elements on PCH-1 are retracted vertically, but remain wet. This procedure, while reducing hull-borne draft, does not facilitate lift system inspection and/or maintenance. The PGH-2 with a canard distribution has a mirror image of the PGH-1 retraction with split aft arrays retracted athwartships and the single forward array pivoted over the bow.

(U) The PHM, with a canard distribution, has a single foil aft supported by two struts retracted over the stern; the single forward strut and foil forward swings over the bow.

(U) Generally, each of these retraction schemes has imposed no severe requirement on the hull arrangements. The reason is explained by reference to Figure II.B.1-7. The parameter X is defined as the distance from the craft LCG to the forward foil array and the parameter L is the distance between arrays. Both parameters can be varied in proportion maintaining the same distribution. With athwartship retraction of either the forward or aft elements (AGEH-1, PGH-1, and PCH-2), the location of the other array can be located for convenience in establishing the retraction geometry and mechanisms, and the longitudinal location of the athwartship retracted elements adjusted by varying "X" with "L".

(U) In establishing the retraction geometry for the PHM, the location of the critical single forward strut and foil was developed, and the location of the aft array was determined by again varying "X" and "L". This procedure resulted in the aft array passing the stern with greater than needed, although acceptable, clearance.

(U) Experience with all retraction methods today has been favorable, with the following minor notations. Retracting the main elements athwartships (AGEH-1, PGH-1, and PGH-2) have imposed additional requirements on static stability which have been met. Pivoting a single strut and foil (PGH-2 and PHM) necessitates a bow closure door which was a source for several failures on PGH-2. An improved bow door design was developed for PHM based on the PGH-2 experience.

(U) Retraction arrangement for future larger hydrofoil ships will not be as readily achievable as on past designs. There are several reasons, but most are related to achieving higher hydrodynamic performance in both foilborne and hullborne modes. For a given foil loading, foil dimensions increase by the 1/2 power of displacement, while hull dimensions increase by the 1/3 power. Foil efficiency is increased with increases in aspect ratio of the planform. Thus, as future vehicle size increases, both foil dimensions relative to hull dimensions and aspect ratio will increase, eliminating the possibility of split foil arrays or single strut and foil combinations as found on the AGEH-1, Figure II.B.1-9. Athwartship retraction will not be possible without a centerline break joint on the foil. With larger relative foil spans, minimum operational beam will be achieved with near tandem distributions. The most practical retraction geometry is to retract the forward array over the bow and the aft array over the stern, with the shortest hull (relative to strut length) with an LCB closest to amidships offering the easiest solutions.

(U) Better hullborne performance, however, is achieved with longer hulls, while good seakeeping ability results in LCB locations about 7% of the hull length aft of amidships. With these additional requirements the lift system distribution will favor loading the aft array. Thus, the total mission requirement of the vehicle has an influence on lift system distribution by reason of practical retraction arrangements.

(U) Hull length has an influence on trim excursions between foilborne and hullborne modes. The measuring parameter is MT_1 or the moment required to trim the craft 1 inch hullborne. Typical MT1 values are shown on Figures II.B.l-9 to II.B.1-12 and illustrate that resistance to trimming is primarily linear with hull length. Thus, the designer has a slightly easier task balancing foilborne and hullborne trims with the longer craft.

1.3.3 Takeoff Hydrodynamic Performance

(U) Historically, the analysis of the hydrodynamic performance of hulls during the takeoff transition was initially based on seaplane technology, as reflected in early hydrofoil hullform selections. As the hydrofoil technology matured, it was recognized that the dynamic attitude of the seaplane (thrust over drag vectors producing a bow down trim) and higher takeoff speeds of the aircraft were not appropriate to the hydrofoil conditions. Thus, hydrofoil designers turned to planing craft technolgoy for both design data and analysis techniques. Although hydrofoil design is presently considered by some to be a branch of planing craft naval architecture, it is more precisely defined as a separate, but similar, field of technology. The hydrofoil hull in takeoff differs from the planing hull as follows: being constantly unloaded, it has no fixed design displacement; it is subjected to high hull trimming moments from the position of drag vector from the lift system and thrust vectors on propeller driven craft; it rarely, if ever, achieves a positive attack angle of the aft underbody (necessary for the definition of planing); and, in general, it experiences maximum drag values at forward velocities other than those experienced in planing craft. Planing craft literature, however, serves as a valuable source of initial design data and suggestions for improvement of analysis techniques. Typical Reference II.B.l-4, a recent paper, contains analysis techniques (and excellent propeller data) which may have application to hydrofoil technology, although the planing craft illustrations are not directly applicable.

(U) To illustrate the relative contribution of the hull to the total hydrofoil drag during the takeoff transition, some typical cases will be shown based upon actual hull model test data found in Reference II.B.l-5. This reference describes the design Ml22 hull configuration chosen and, subsequently, model tested in 1971 by Grumman Aerospace Corp. The extensive towing tank tests completed by Grumman Aerospace Corp., Reference II.B.l-6, provide an adequate data base for valid prediction of hull drag and pitch for a considerable range of design displacements and loading conditions. "Design"* displacement of M122 was 172.8 tons with a hull length (LBP) of 120 ft, yielding a displacement-to-length ratio:

$$\Delta/(.01L)^3 \text{ of } 100 \text{ tons/ft}^3$$

Anticipated takeoff speed was 25 knots.

(U) Typical residuary resistance coefficients

$$C_R = R_R/\tfrac{1}{2}\rho S V^2$$

for M122 are shown in Figure II.B.1-13. These data are expanded and added to frictional drag for two illustrative hull sizes of 100 and 1,065 tons, Figures II.B.1-14 and II.B.1-15, both for 25-knot takeoff conditions. Note that maximum hull drag occurs at similar forward velocity, but at dissimilar Froude numbers

$$F_n = V/(gL)^{\frac{1}{2}}$$

Planing craft theory would predict maximum hull drag at a constant Froude number (between .4 and .5) independent of vehicle displacement. For the larger craft (1,065 tons), a higher takeoff speed of 35 knots was considered, Figure II.B.1-16. A standard unloading with hull displacement proportional to takeoff speed squared

$$\Delta_H = \Delta_D \left[1 - \left(\frac{V}{V_{TO}}\right)\right]^2$$

was used in this analysis.

*Hull "Design" Displacement by Grumman Aerospace Corp. Standard practice for hull development is full load displacement minus one-half fuel load.

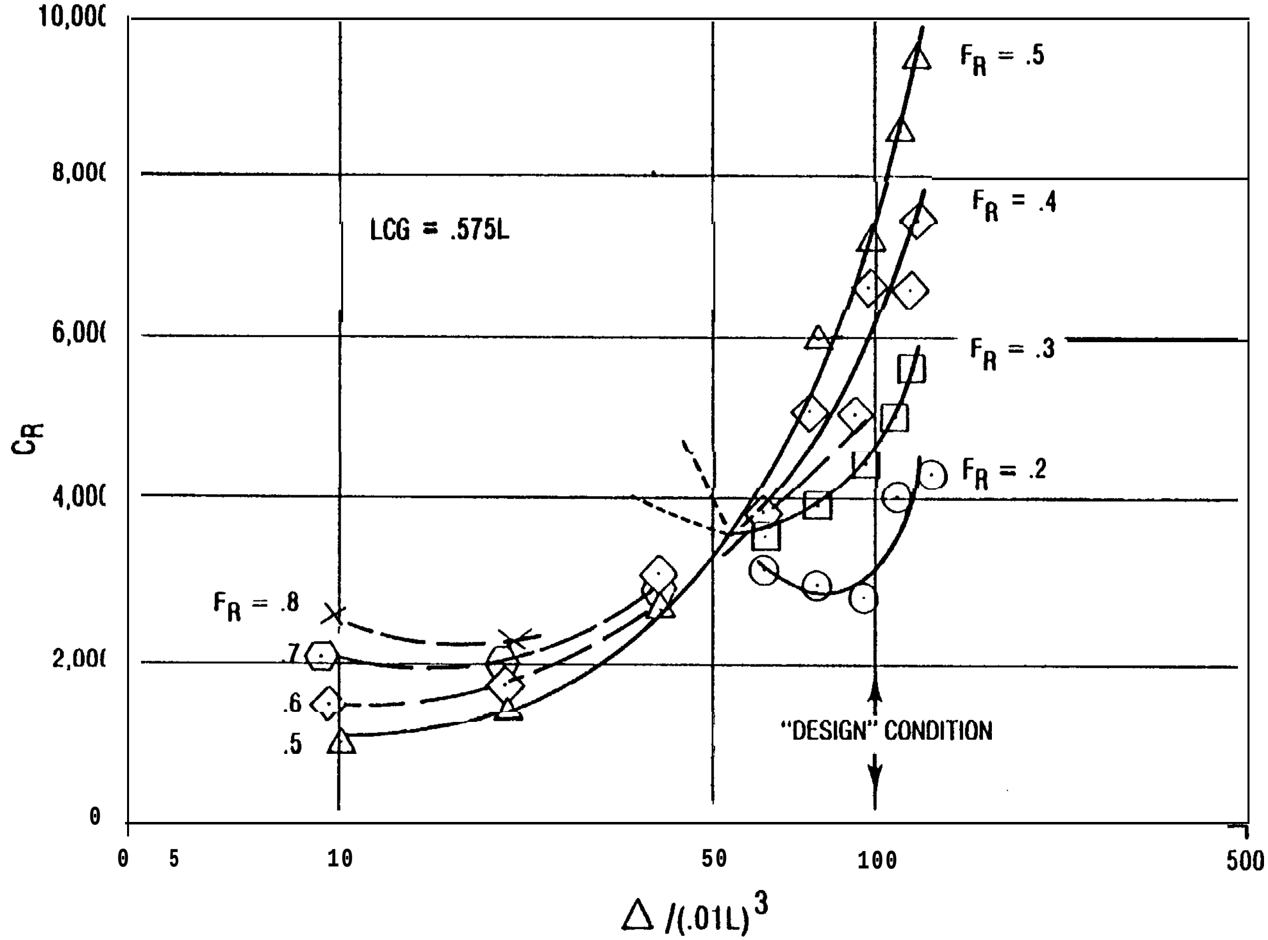

Figure II.B.l-13. TYPICAL RESIDUARY RESISTANCE COEFFICIENTS FOR M122/124

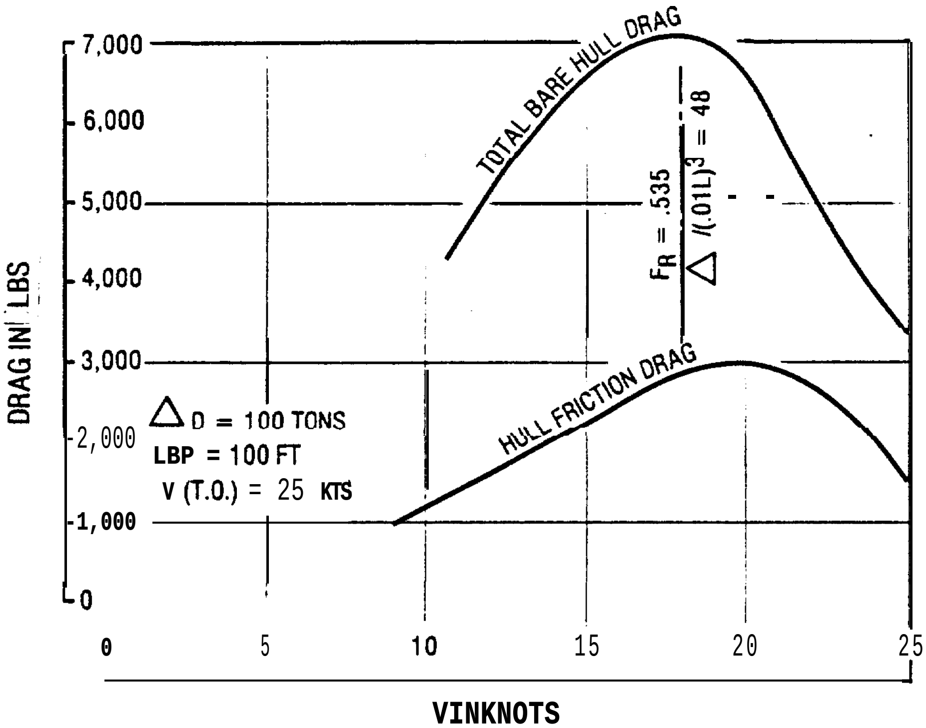

Figure II.B.1-14. M122 BARE HULL DRAG FOR 100-TON, 25-KNOT TAKEOFF SPEED DESIGN

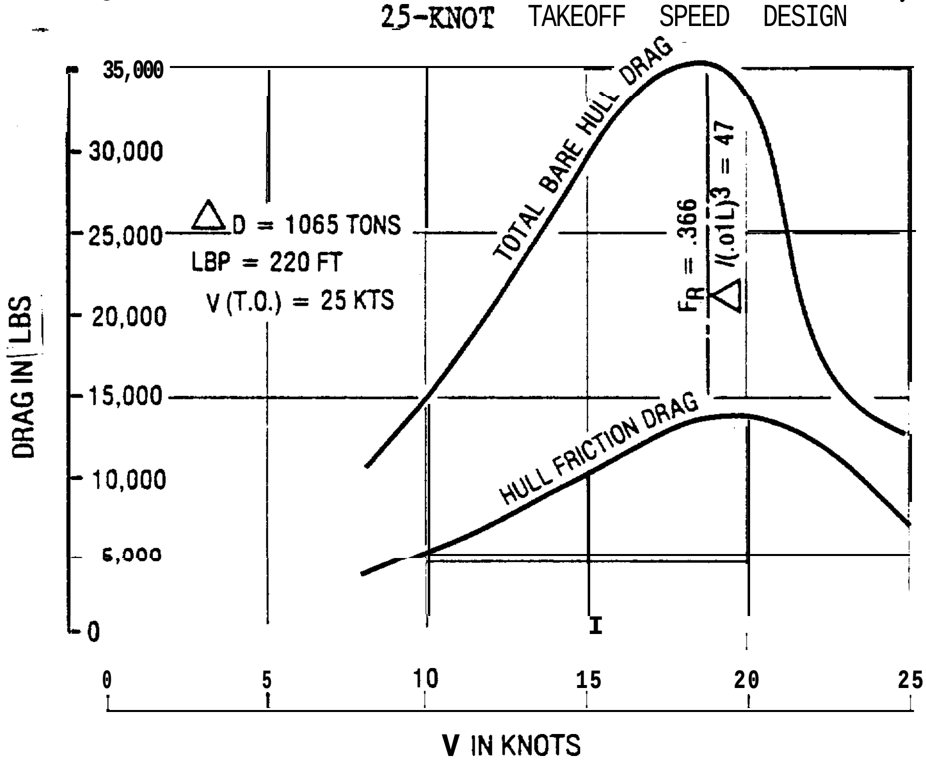

Figure II.B.1-15. M122 BARE HULL DRAG FOR 1065-TON, 25-KNOT TAKEOFF SPEED DESIGN

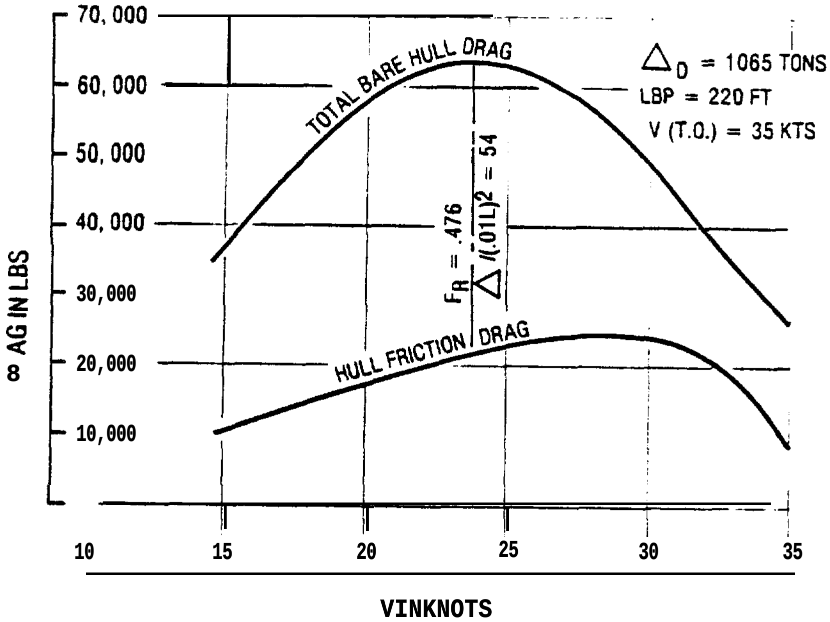

Figure II.B.1-16. M122 BARE HULL DRAG FOR 1065-TON 35-KNOT. TAKE-OFF SPEED DESIGN

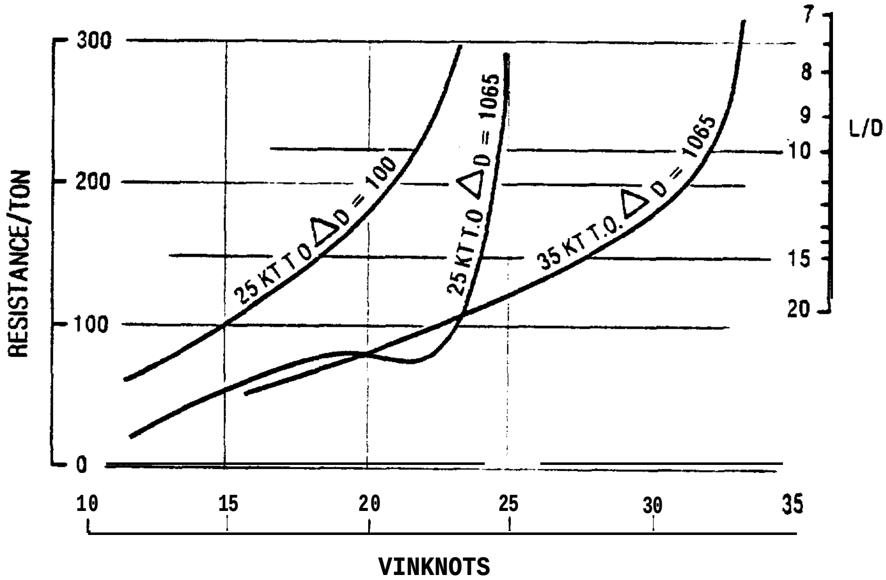

Figure II.B.1-17. M122 BARE HULL RESISTANCE PER UNIT DISPLACEMENT AND L/D

(U) Figure II.B.1-17 compares the hull resistance per ton, and corresponding "lift-to-drag" (L/D) ratios for the three examples. At 25-knot takeoff conditions, the relative hull resistance of the smaller craft (100 tons) is about twice the resistance of the larger (1,065 ton) craft. Comparing takeoff speed conditions, for the same displacement, hull resistance is similar up until about 23 knots, where hull "L/D" ($\approx$ 20) is greater than to be expected from the foil lift system at this speed. This illustrates that, as hydrofoils grow in size and length, increasing takeoff speed has certain advantages, primarily if it is desirable to optimize the lift system hydrodynamic design for maximum foilborne speeds. Foil efficiency at takeoff speed can be compromised to achieve better maximum speed efficiency, and the transfer of lift from the hull to the lift system delayed in compensation. This can be accomplished because hull "L/D" ratios are a function of the Froude speed relationship, while foil system "L/D" ratios are a function of absolute velocity. Indeed, early historic concerns about getting "over the hump" at takeoff will diminish with increasing vehicle size.

(U) Note on Figures II.B.1-14 through II.B.1-16, the hull drag value identified at takeoff at zero hull displacement. This drag component is caused by spray and water adhesion with the keel transiting from the still water surface. While this phenomenon had been previously suspected, it was positively identified for the first time in Reference II.B.1-6, and has been verified in subsequent model tests conducted by Grumman Aerospace Corp.

(U) The final discussion is the effect of dynamic trim during takeoff. Because the hull can be subjected to wide variations in trimming moments due to the drag of lift system components (causing bow down trim), differential lift from the forward and aft foils, and acceleration thrust excursions (causing bow up trim on propeller driven craft), it is desirable to provide hulls which are relatively insensitive in trim and drag variation to these effects. Analytically, the trimming moments are treated as hull static moments providing a shift in the craft longitudinal center of gravity (LCG). Figure II.B.l-18 illustrates the achievement of this objective for a previously discussed typical hydrofoil hull. Corresponding trim excursions were on the order of one degree maximum.

1.4 HYDROFOIL MISSION RELATED FEATURES

(U) Mission related features are defined as those hull requirements dictated by the mission of the total design. Included within these features are:

- Hullborne Speed
- Hullborne Seakeeping
- Weapon System Arrangement
- Subdivision
- Foilborne/Hullborne Range
- Retraction Necessity
- Foilborne Maneuvering
- Operating Environment
- Mission Duration

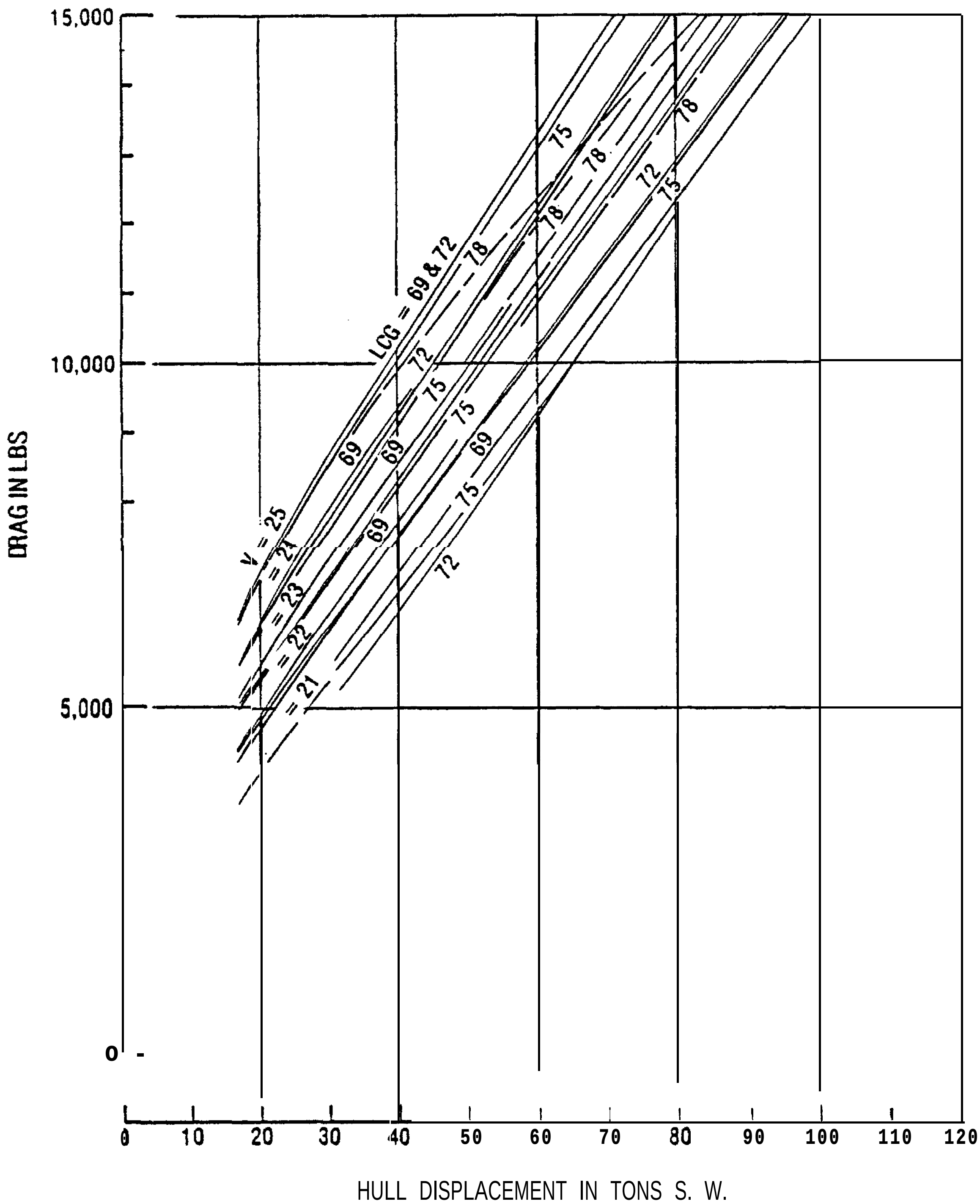

Figure II.B.1-18. M122 HULL TAKEOFF DRAG SPEED AND LCG VS Δ

(U) While none of these features is necessary to the hydrofoil concept, each contributes to the military worth of the hydrofoil ship and, in some measure, affects the solution of hydrofoil unique features discussed in the preceding section.

1.4.1 Hullborne Speed

(U) Historically, hullborne speeds of hydrofoil ships have received minor consideration. What could be achieved without difficulty was accepted with little question. Hullborne speed (and range) ability were sacrificed to achieve the best foilborne performance resulting in effective vehicle speed gaps of as high as 25 knots between maximum pure hullborne speeds and minimum continuous foilborne speeds.

(U) Future larger hydrofoil ships can be designed to achieve high hullborne speeds at fuel economies not unlike conventional hull ships as shown in Reference II.B.l-1. Figure II.B.1-19 compares the bare hull resistance of the four representative hydrofoil ship hulls discussed in the preceding section. All results are based on hull model tests.

(U) While increases in hullborne speed are achieved with high length-to-beam ratios, adequate transverse stability can be maintained; and as was shown in Section II.A.3, without increase in hull weight.

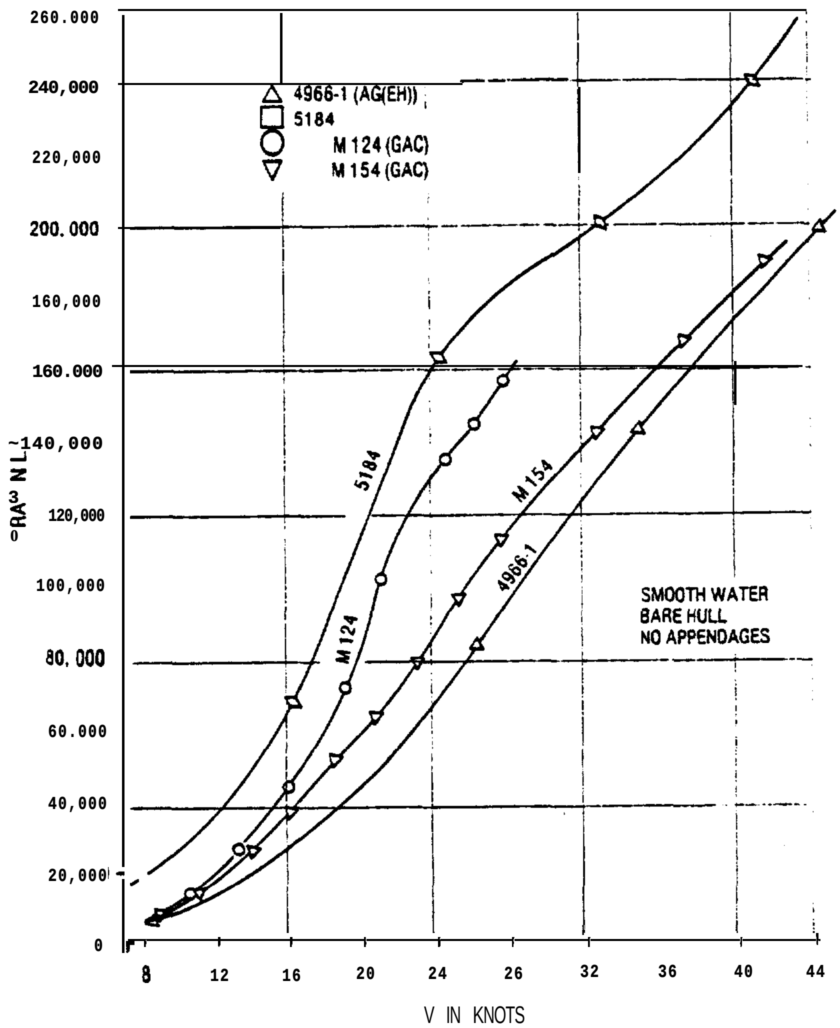

Figure II.B.1-19. COMPARISON OF HULL DRAG AT Δ = 1000 TONS

(U) With proper design attention, mission effective speeds over the entire velocity profile from zero to maximum foilborne speeds can be achieved.

1.4.2 Hullborne Seakeeping

(U) With increasing attention to higher hullborne speeds, greater emphasis will be placed on seakeeping at these speeds. Good seakeeping is achieved with higher length-to-beam ratios, fine entrance bow section, sufficient freeboard, and attention to longitudinal weight distribution. With decreasing emphasis on takeoff drag as discussed in Section 1.3, these features can be designed into future hydrofoil hulls.

(U) Recent seakeeping tests, Reference II.B.l-7, demonstrated the potential ability of a nominal l,OOO-ton hydrofoil ship hull to achieve speeds of 25 knots in sea state 6 without slamming and propeller unwetting.

(U) Yet to be fully documented are the effects of lift system damping on hull motions with the lift system extended at high hullborne speeds. Canadian studies indicate that, due to the motion damping effect of the foil system, the hullborne drag in sea states can be less with the foils down than with the foils retracted depending upon the ship size.

1.4.3 Weapon

(U) Dictates of good weapon system arrangement favor maximum weather deck space and minimal superstructure, tending to increase hull structural weight. Radar and radio frequency antennas favor high installation locations, adversely effecting transfer stability in wind. Counter to this is the increase in antenna height during foilborne operation.

(U) Missile blast effect concerns and armament reload and magazine locations relative to armament desires are not unlike conventional military platforms.

1.4.4 Subdivision

(U) Section II.A.3 discusses both the criteria and experience of existing hydrofoil ships in achieving adequate subdivision. Future hydrofoil ships are expected to maintain the same level of subdivision as on conventional Navy platforms. Hydrofoil ships, as with conventional ships, are less sensitive to subdivision standards with increasing slenderness ratio of the hull.

1.4.5 Fuel Tankage

(U) Increasing fuel percentages (of full load) of hydrofoil ships introduces the necessity of both providing sufficient tankage and the control of utilization of the fuel to *maintain* acceptable foilborne and, to a lesser extent, hullborne longitudinal distribution. Generally, this can be achieved by providing fuel tanks in a quantity defined by the following empirical relationship:

No. of Fuel Tanks* = (22-28) (Fuel Load/Full Load)

Number and location of the tanks have a second order effect on damaged stability.

1.4.6 Retraction Necessity

(U) Section II.B.1-3 described the hydrofoil unique requirement and ability to retract the lift system. The necessity of such retraction is a mission consideration. There are many pros and cons to the issue of retraction necessity which will not be answered here.

(U) The retraction of the lift system reduces the operational draft of the vehicle and reduces channel requirements, but not the operational beam of the ship. Marine growth on retractable

*Port and starboard pairs are considered to be one tank. For port, centerline, and starboard tanks the multiplier is reduced to 15-21.

foils is reduced. Lift system maintenance and drydocking is easier with retraction.

(U) Retraction results in potentially more complex machinery arrangements, greater hydraulic power requirements, hull system integration concerns, and greater lift system weights. Retraction time has minor significance in the assessment of these penalties.

(U) Fixing the lift system also introduces the possibilities of reducing strut length. Combined with 50/50 tandem distribution, this potential arrangement would offer the lowest draft and submerged beam combination. Hull length would not be restricted by any static stability considerations.

1.4.7 Foilborne Maneuvering

(U) Maximum foil span together with foil submergence define the maximum allowable roll angle in a coordinated turn maneuver. Typically, a 90-ft span foil at 12½ ft submergence rolling 12½° keeps the foil tip 30 in. below the water surface. At 45 knots under these conditions, the turn rate if 5½°/sec and the corresponding turning radius would be 800 ft.

1.5 STRUCTURAL CONSIDERATIONS

(U) Hull loading criteria both in impact and overall bending are discussed in Section II.A.5. The discussion contained herein will focus on experienced and expected trends in hull weight to meet the criteria.

(U) In general, the hull load criteria are based on three distinct operating conditions. Hullborne, as in conventional craft, the longitudinal bending moment in waves is *the* governing overall criterion. However, the longitudinal bending moment foil-borne developed by the lift from the struts transmitted into the hull at two longitudinal locations normally exceeds the hullborne bending moment. Experience has shown the criteria hull loading conditions are impact pressures developed from direct wave impact on the hull while foilborne in extreme seas or from crash landings at maximum speed by direction or after loss of foil system lift.

(U) Experience has shown that hull weight is primarily a function of total hull volume and peak local hydrodynamic impact pressures on hull bottom, sides, decks, and superstructure. Figure II.B.1-20 shows actual and expected hull structural weight trends based on existing hydrofoil ships and design studies. Shown are WBS* Groups 110 to 140 (shell plating and frames, bulkheads, decks, and platforms) and Group 110 alone. A trend of increasing structural density with shorter craft length is indicated - counter to the expected trend for conventional craft. This reflects the fact that impact pressure sizes the plating thickness, rather than bending moment. This is illustrated in Figure II.B.1-21 for existing craft, which shows the gross ratio of bottom impact area (length x hull beam) divided by hull girder volume as a function of hull girder volume.

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*Reference II.B.1-8

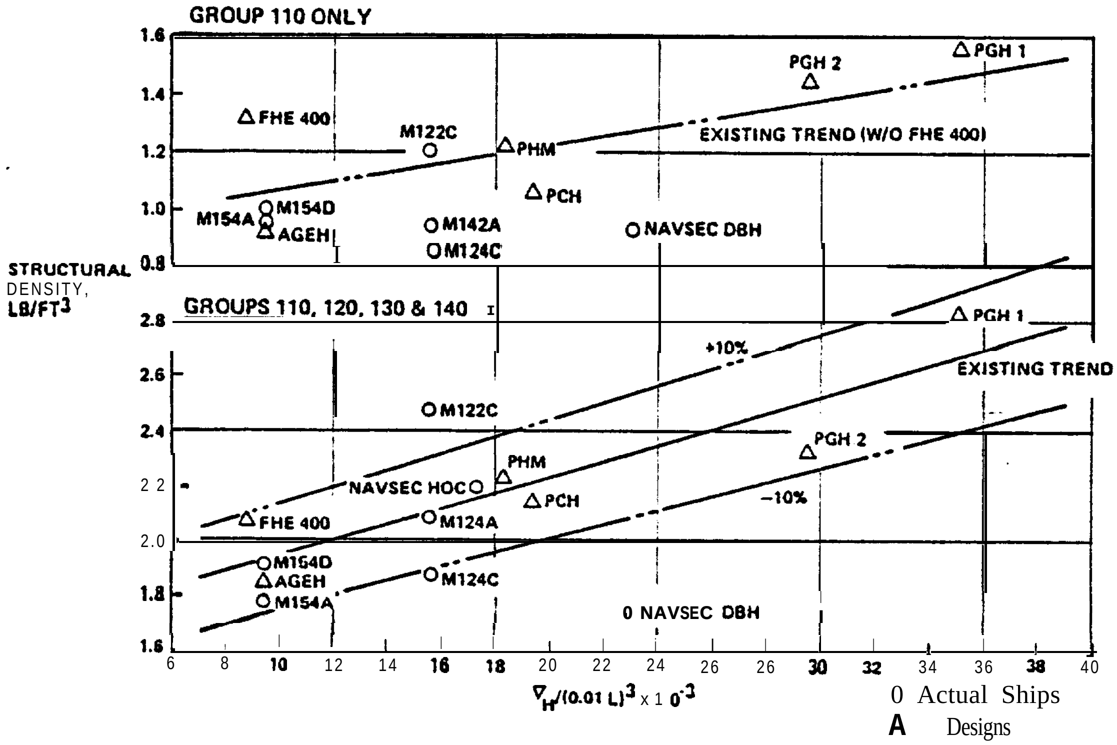

Figure II.B.l-20. HULL GIRDER WEIGHTS (U)

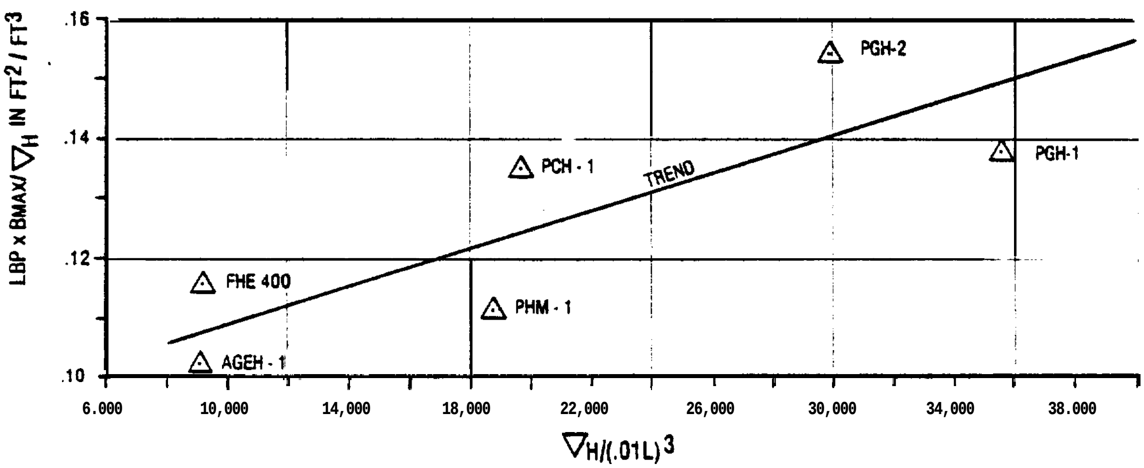

Figure II.B.1-21. TREND IN HULL IMPACT AREA BY HULL GIRDER VOLUME FOR EXISTING HYDROFOIL SHIPS (U)

(U) Figure II.B.1-22 illustrates that WBS Group 110 weights can be expressed as a relatively constant value of the gross length times beam parameter. Correcting this relationship by a form factor accounting for the tapering of the hull forward and aft (main deck area, rather than length times beam) would reduce the scatter in Figure II.B.1-22. Also shown is a probable difference in Group 110 weights for single and double (continuous second deck) designs.

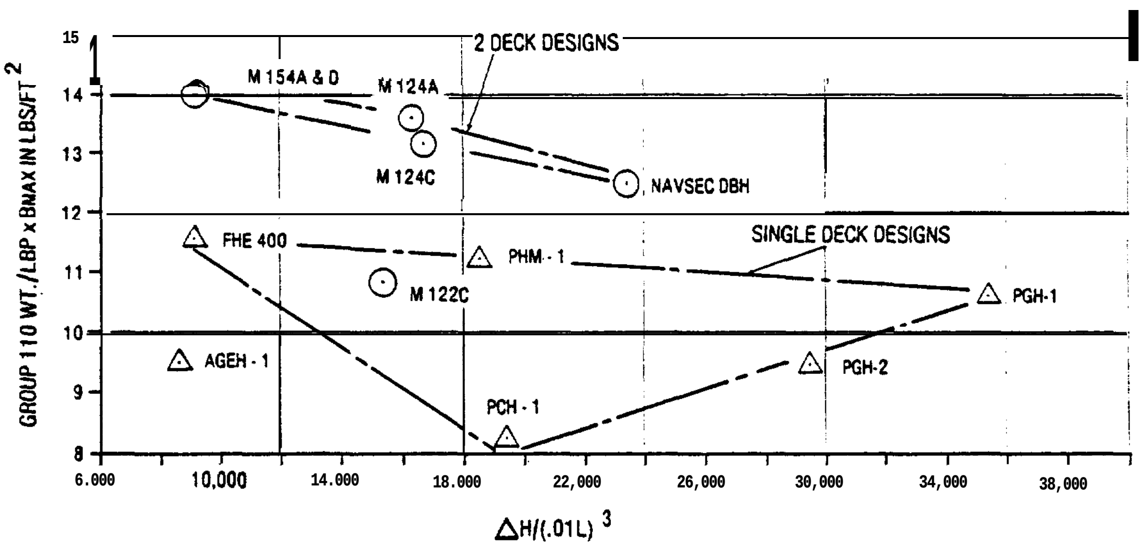

Figure II.B.1-22. GROUP 110 WEIGHTS

(U) Superstructure weights (WBS Group 150) are shown in Figure II.B.1-23, indicating an expected increase in structural efficiency with increasing volume. To be noted are the relative structural efficiencies of the basic hull girder, Figure II.B.1-20 and the superstructure.

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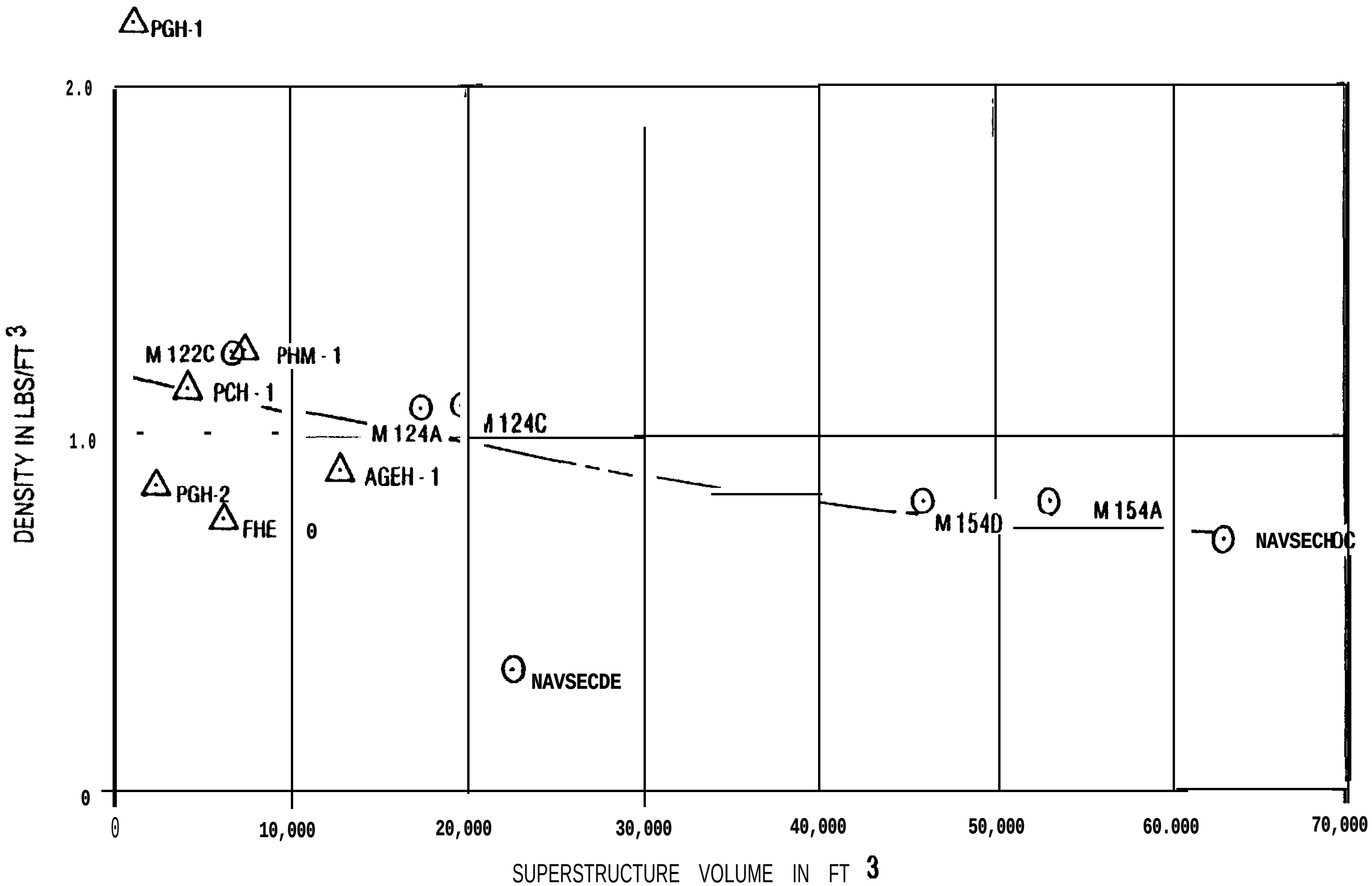

Figure II.B.1-23. SUPERSTRUCTURE WEIGHTS (U)

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II.B.1-2 "The Outlook for Lighter Structures in High Performance Marine Vehicles" - Heller and Clark, AIAA/SNAME, February 1974.

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II.B.1-4 "Small-Craft Power Prediction" - Blount and Fox, Marine Technology, January 1976

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II.B.1-7 "Model Tests of the M-154 Hydrofoil Hull" - Chiocco, Stevens Institute Report DL-75-1806, January 1975.

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II. STATUS OF VEHICLE TECHNOLOGY

B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

2. PROPULSION SYSTEM

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II.B SUBSYSTEM AND DESIGN AND CONSTRUCTION FEATURES

2. PROPULSION SYSTEM

2.1 INTRODUCTION

(U) The purpose of this section is to present a state-of-the-art assessment with respect to the design and construction features of hydrofoil propulsion subsystems. As a general rule, only the design and construction features of U.S. Navy hydrofoils are presented herein. The U.S. Navy has, through a systematic research and development effort, arrived at certain design criteria which differ significantly from usual commercial problems. Therefore, only in specific instances will craft other than U.S. Navy vehicles be included in the discussion.

(U) The discussions herein are not solely restricted to those features which are unique to hydrofoil propulsion systems. Some data presented herein are applicable to other types of craft; however, these sections containing "common" information are important to the overall development of the discussions on the various propulsion subsystems and components. The deletion of this information would detract from the value of the discussion of hydrofoil subsystems and components.

(U) The selection of the crucial propulsion system components was relatively straightforward as the engines, transmissions, and propulsors stand out as the main choices for review because they are the primary components of the propulsion system. The system interfaces have presented a much more difficult problem, as there are many vital support systems which the primary propulsion components must depend on for continual operation. A number of system interfaces are discussed and these are considered the most essential ones to the success of the hydrofoil propulsion system.

(U) This section develops the problems and constraints which must be dealt with during the design of a hydrofoil propulsion system.

2.2 DESCRIPTION OF PRINCIPAL PROPULSION SYSTEM COMPONENTS AND THEIR DESIGN STANDARDS

2.2.1 Gas Turbines

2.2.1.1 Existing and Future Gas Turbines

(U) All the U.S. Navy hydrofoil ships which have been built to date use marinized gas turbine engines exclusively for the foilborne propulsion system. Table II.B.2-1 is a list of the U.S. and Canadian Navy hydrofoil ships which have been built plus information about various aspects of their propulsion systems.

(U) Table II.B.2-2 is a list of currently available gas turbine engines which could be used as a prime mover for a hydrofoil ship's propulsion and/or auxiliary power.

(U) Table II.B.2-3 is a list of gas turbine engines which are currently in development and which may be available for use in the future. The successful development of these engines will facilitate power plant selection in that the gaps which presently exist in the power spectrum (approximately 5,000 to 12,000 shp and from 23,000 to 40,000 shp) will be partially filled by the GTPF 990 and the FT9A-2 engines, respectively.

Table II.B.2-1. CANADIAN AND U.S. NAVAL HYDROFOILS

Characteristica	PCH-1 (Mod 1) (High Point)	ACEH-1 (Plainview)	PGH-1 (Flagstaff)	PCH-2 (Tucumcari)	PHM-1 (Pegasus)	Denison	Canadian FHE 400 (Bras D'or)
Foilborne propulsion	Two Gas Turbine3 RR-Proteus	Two Gas Turbines GE LM1500	One Gas Turbine RR-Tyne	One Gas Turbine RR-Proteus	One Gas Turbine GE LM2500	One Gas Turbine GE LM1500	One Gas Turbine P&W FT4A-2
Continuous rhting	3,600 shp (each) @ 5,000 rpm	14,000 bhp (each) @ 5,000 rpm	3,600 shp @ 14,500 rpm	,200 shp @ ,545 rpm	16,000 bhp 3 3,000 rpm	14,000 bhp @15,500 rpm	22,000 shp @ 3,600 rpm
Thrust producer	Four 5-bladed, counter-rotating, fixed pitch, eubcav props, 32.4" Dia., 1,484 rpm, one tractor & one pusher prop on each pod	Two 4-bladed, fixed pitch, super cav props, 62.4" Dia., 1,345 rpm	One 3-bladed var pitch, super cav prop, 45" Dia., 1,115 rpm	One waterjet, double suction, cntfgl flow, Byron Jackson-WDS,28" Dia. implr., ,350 rpm	One waterjet 2 stage-axial flow, Aerojet-AJW-18800-1, 24.4" Dia. indr., 690 rpm, 30" Dia. implr.) 1,570 rpm	One 3-bladed, fixed pitch, super cav prop, 40" Dia., 2,250 rpm	Two 3-bladed, fixed pitch, super cav pops, 48" Dia., 2,000 rpm
Transmission	Initial planetary reduction gear on eng., subq. reduction via single mesh rt. angle spiral bevel gear set (one on each end of retractable struts), lower set splits pwr to fwd and aft props	Single helical reduction gear (w/idler in hull, dual mesh spiral bevel gearbox at the top of each retractable strut and in pod.	Hull-mtd reduction gear trans-mits power to bevel gearbox at top of retractable & steerable tail strut, pod contain: spiral bevel gear plus planetary reduction gear	Direct drive, eng. mounted planetary reduction gear	Double helical reduction gear w/coax output shafts	Double helical reduction gearbox in hull, dual mesh rt. angle spiral bevel gearbox at top of retractable & steerable strut and in pod	Helical step-up plus rt. angle spiral bevel combo. gearbox transmits power to rt. angle spiral bevel gear at the top of fixed struts and star reduction gearbox in pod. The engine output shaft drives a 1:2 helical step-up gearbox mounted on the No. 1 (main) deck centerline abaft the engine. Power output is split into a pair of adjacent right-angle, dual-mesh, spiral-bevel (mitre with hunting tooth) gear trains each driving through dual downshaft assemblies within the inboard fixed struts on each side. Another similar but reversed right-angle spiral bevel gearbox, a 4.16:1 compound star reduction gear and the propeller shaft assembly are mounted within each pod located at the bottom of the struts. (See Figure II.B.2-21.)

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Table II.B.2-1. CANADIAN AND U.S. NAVAL HYDROFOILS (Continued)

Characteristics	PCH-1 (Mod 1) (High Point)	AGEH-1 (Plainview)	PGH-1 (Flagstaff)	PGH-2 (Tucumcari)	PHM-1 (Pegasus)	Denison	Canadian FHE 400 (Bras D'or)
Hullborne propuleion	One diesel DD-12V-71T	Two diesels DD-12V-71T	Two diesels DD-6V-53N	One diesel DD-6V-53N	Two diesels MTU 8V331TC80	On8 gas turbine GE T-5&3	One diesel Paxman 16YJCM
Continuoue rating	540 ahp @ 2,100 rpm	500 bhp (each) @ 2,100 rpm	160 bhp (each) @ 2,600 rpm	160 bhp @ 2,600 rpm	661 bhp (each) @ 2,200 rpm	795 bhp @ 19,500 rpm	2,200 bhp @ 1,500 rpm
Thrust producer	One 3-bladed, fixed pitch, tractor type, aubcav prop, 43"Dia., 800 rpm	Two 5-bladed, fixed pitch, tractor type, suboav props, 48" Dia., 525 rpm	Two water-jet, single stage-axial flow, Beuhler 165-1-C, 16.5" Din. implr., steerable nozzle and reversing bucket	One uater-jet, single stage-axial flow, Beuhler 165-1-B, 15.7" Dia. implr., steerable nozzle and reversing bucket	Two uater-jets, single stage axial flow, Aerojet-AJW Boo-1, 26.4" Dia. implr., 903 rpm, steerable nozzle and reversing bucket	Two water-jets, 3 stage, axial flow, Beuhler pump, 12" Dia., 2,250 rpm, steerable nozzle and reversing bucket	Two 3-bladed, var pitch(reversible, variable pitch plus feathering), 84" Dia., 315 rpm
Transmission	Eng. std. clutch transmit power to rt. angle spiral bevel gear aet in upper and lower end of retractable and steerable (360°) out-drive unit	Eng. mtd. clutch transmits power to rt. angle spiral bevel gear ret In upper and lower end of retractable and steerable (±60° fwd and aft) out-drive unit	NO reduction gear-direct drive	RPM reduction via pulley and belt drive	Engine mounted helical reduction gear and clutch	Initial reduction gaar on eng., subq. reduction via rt. angle spiral bevel gearbox (inbd), then to one port and stbd rt. angle spiral havel gearboxes	Helical step-up plus rt. angle spiral bevel gearbox combo transmits power to rt. angle spiral bevel gearbox at the top of No. 2 deck plus planetary reduction gearbox in pod

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Table II.B.2-2. GAS TURBINE CHARACTERISTICS

Production Gas Turbine Engines; Ambient Air Temperature=100°F, 4"&6" ducting losses

Manufacturer Model No.	Max. Intermittent Rating MHP (1) (HP)	Rated Speed RPM	SFC at Rated Output kg/MHP-hr (lb/HP-hr)	Air Consumption kg/sec (lb/sec)	Weight kg (lb)	Spec. Weight kg/MHP (lb/HP)	ngine glume ft^3)
AVCO/Lycoming							
TF14B	364 1345)	18,500	.28 (.62)	5.0 (11.0)	17.3 920) (2)	.31 .68)	.09 38.5)
TF25C	282 2250)	14,500	.29 (.64)	9.8 (21.7)	36.6 1183) (2)	.24 .52)	.24 43.7)
TF35C	797 2758)	14,500	.25 (.56)	10.8 (23.9)	77.4 1273) (2)	.21 .46)	.29 55.5)
TF40	324 3278)	15,400	.25 (.56)	11.3 (24.9)	01 1325) (2)	.18 .40)	.29 t5.5)
Allison							
501-KF	833 3780)	13,820	.24 (.54)	5.9 35)	1134 (2500)	.30 .66)	.10 180)
General Electric							
LM-1500	2,675 12,500)	5,500	.24 .53)	1.8 70)	3651.5 (8,050)	.29 .64)	3.6 333)
LM-2500	2,612 22,300)	3,600	19 .43)	9.0 130)	4672.1 (10,300)	.21 .46)	3.9 1,091)
Garrett							
GTP831 (3)	82 475)	41,730 ± 200	34 .76)	.2 7)	680.4 (1500)	1.42 (3.16)	89 31.6)
Solar							
T-1000	1020 (1006)	22,300	.28 (.63)	5.8 (12.7)	567 (1250)	.56 (1.24)	2.3 (80.2)
Pratt&Whitney							
FT-4C	40,560 (40,000)	3600	.20 (.45)	125.2 (276)	11,340 (25,000)	.280 (.625)	24.36 (860)

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Table II.B.2-2. GAS TURBINE CHARACTERISTICS (Continued)

Manufacturer Model No.	Max. Intermittent Rating MHP (1) (HP)	Rated Speed RPM	FC at ated Output g/MHP-hr lb/HP-hr	Air Consumption kg/sec (lb/sec)	Weight kg (lb)	pec. sight g/MHP (lb/HP)	Engine Volume m^3 (ft^3)
Rolls Royce							
Proteus	3448 (3,400)	5,000	.32 (.705)	18.9 (41.7)	1414.3 (3118)	41 .92)	4.6 (162)
Tyne	4969 (4,900)	15,000	.21 (.476)	20.4 (45)	3084.5 (6800)	62 1.39)	7.65 (270)
Olympus TM	22,308 (22,000)	N.A.	.23 (.51)	N.A.	4753.7 (10,480)	21 .48)	85.3 (3012)
United Aircraft of Canada							
ST6J-70	507 (500)	1210	.37 (.82)	N.A.	158.8 (350)(4)	.31 (.70)	.37 (12.95)
ST6L-77	558 (500)	21000	.31 (.69)	N.A.	138.8 (306)(4)	.20 (.44)	.31 (10.91)
ST6T-75 (Twin-Pat)	1115 , (1100)	4200	.33 (.745)	N.A.	331.1 (730)(4)	.23 (.52)	1.5 (53.91)

(1) The maximum ntermittent powe ratings flect applications for displac nent hull operations uti izing 100°F ambient air emperature and s andard 4 1 6 inches of water duct losses., Applicat n of these ngines at a higher shor duration rating ould be c sidered dependent on identification of the pecific shi 3 power profile requirement In some cases his could esult in as much as a 20% increase in the tings notec

(2) Includes sta dard accessories (air inle lube oil system, electrical s stem, acces ry drive sy tern, start system, fue system, control nd governing system),

(3) Industrial/l rine Engine

(4) Drv Weights

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Table II.B.2-3. GAS TURBINE CHARACTERISTICS

Advanced Gas Turbine Engines in Development: Ambient Air Temperature= 100°F Sheet 1 of 1

Manufacturer Model No.	Max. Intermittent Rating MHP (1) (HP)	Rated Speed RPM	SFC at nted Output kg/MHP-hr lb/HP-hr)	Air Consumption kg/sec (lb/sec)	Weight kg (lb)	pec. aight g/MHP lb/HP)	Engine Volume m^3 (ft^3)
AVCO/Lycoming ACT 1500	521 1500)(1)	22,500	.19 (.42)	i.8 12.7)	07.2 (2000)(2)	60 (1.33)	1.17 (41.2)
Garrett CTPF 990	5070 (5000)	3600	.22 (.49)	18.1 (39.8)	2358.7 (5200)(2)	.465 (1.04)	5.95 (210)
General Electric LM-5000	46,644 (46,000)	3600	.18 (.40)	137 (302)	8958.6 (19,750)	.192 (.429)	64.97 (2,294)
Pratt&Whitney FT9A-2	40,560 (40,000)	7260	.18 (.40)	96.2 (212)	9661.7 (21,300)	.238 (.533)	23.0 (813.6)
Rolls Royce TF-41 Spey	12,168 (12,000)	4730	.19 (.43)	47.2 (104)	5443.2 (12,000)	.447 (1.00)	20.4 (720)

(1) Rating is 59°
(2) Includes i ernal gearbox

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2.2.1.2 Desirable Engine Characteristics

(U) A gas turbine engine for hydrofoil applications should be efficient, light in weight, reliable, and provide adequate performance at all ship design conditions. A minimum weight propulsion plant is desired, but some compromise must be made, since high-efficiencies (which save on fuel weight) can often be obtained only at the cost of increased plant weight. The measure of weight efficiency is the power plant specific weight (weight/power). Tables II.B.2-2 and II.B.2-3 illustrate the range of values which are currently available or which are anticipated for various gas turbine engines currently under development.

(U) The volume of the power plant should also be minimal,. since the ship weight is proportional to the required power plant volume. The measure of volumetric efficiency is the power density (power/volume). To provide estimates of engine volume for several types of engines, Figure II.B.2-1 has been prepared showing engine power density versus engine power for experimental and current production diesels, and current production (or near production) gas turbines. Note that this data is for just the engines and engine mounted auxiliaries, and does not include intake and exhaust ducting which for the gas turbine can occupy far more volume than the engine.

2.2.1.3 Engine Physical Characteristics

(U) The gas turbine cycle of interest to the hydrofoil designer is the simple type rather than one of the various regenerative cycles, which are too heavy to be of interest. When the

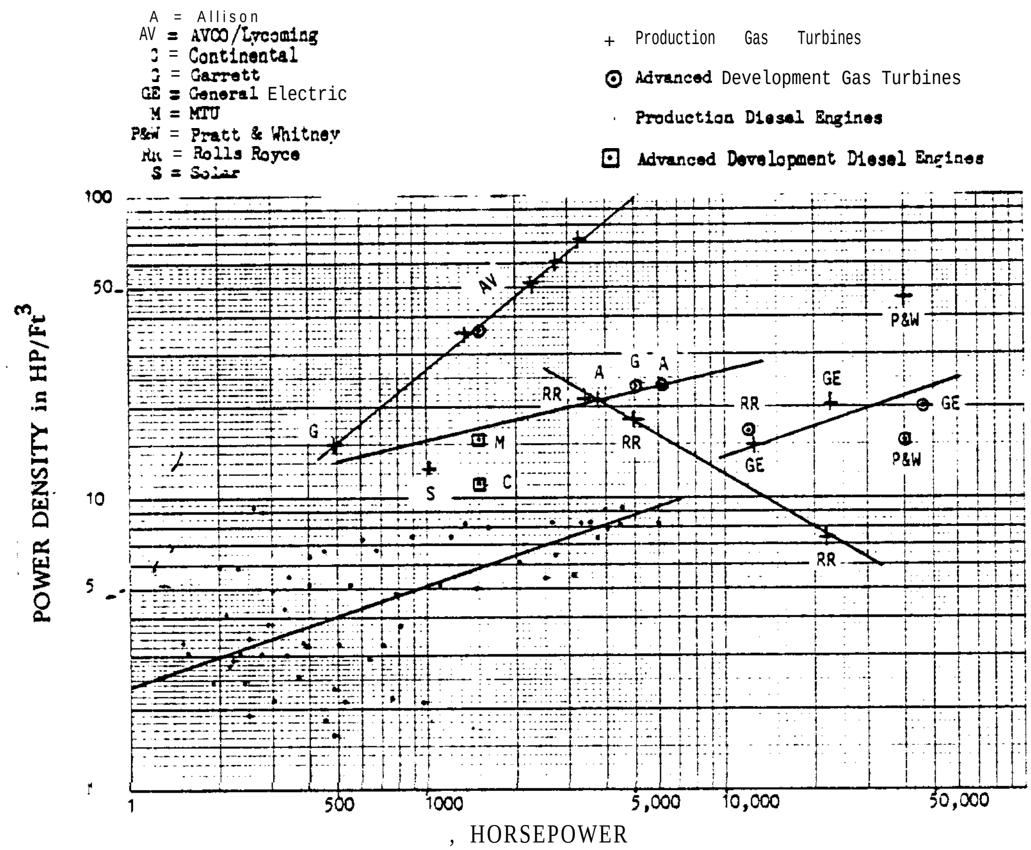


Figure II.B.2-1. POWER DENSITY (POWER/VOLUME) VERSUS POWER FOR VARIOUS ENGINE TYPES

high pressure turbine is mechanically connected to the power turbine, it is known as a solid-shaft design. Such a design is not suited to applications wherein the output speed is not constant, since a 20% speed variation will cause the compressor to stall.

(U) The split-shaft design is mechanically more complex, but it permits the compressor to run at a steady speed while. the power turbine is free to vary with the load. In addition, the starting effort is less because the compressor-gas generator section can be brought up to speed without rotating the power turbine and its connecting power train. Other variations of the split-shaft design involve variable inlet vanes and twin-spool arrangements, which serve to improve engine stability and control over a wide performance range.

2.2.1.4 Engine Performance Characteristics

(U) The performance of the gas turbine is affected by its internal design, its installation in the ship, the ambient operating conditions, and the loads imposed on it by the drive train.

(U) The two most important internal design parameters of the gas turbine are pressure ratio (R) and turbine inlet temperature (TIT). The effects of varying each of these parameters are shown in Figures II.B.2-2 and II.B.2-3. As is evident from Figure II.B.2-3 simultaneous increases in pressure ratio and turbine inlet temperature result in greater engine efficiency (lower SFC) and from Figure II.B.2-2, the increase in turbine pressure ratio and inlet temperature results in more compact engines (higher specific power, power/mass flow rate of air). The curves in these figures are based on equations derived from the basic Brayton Cycle, which describes the gas-turbine cycle. The assumptions used in developing Figures II.B.2-2 and II.B.2-3 are: a simple gas turbine cycle; ambient temperature of $60^{\circ}F$, 0 percent humidity; compressor efficiency of 0.89; turbine efficiency of 0.90; combustor efficiency of 0.98; and heating value of fuel of 18,500 Btu per pound.

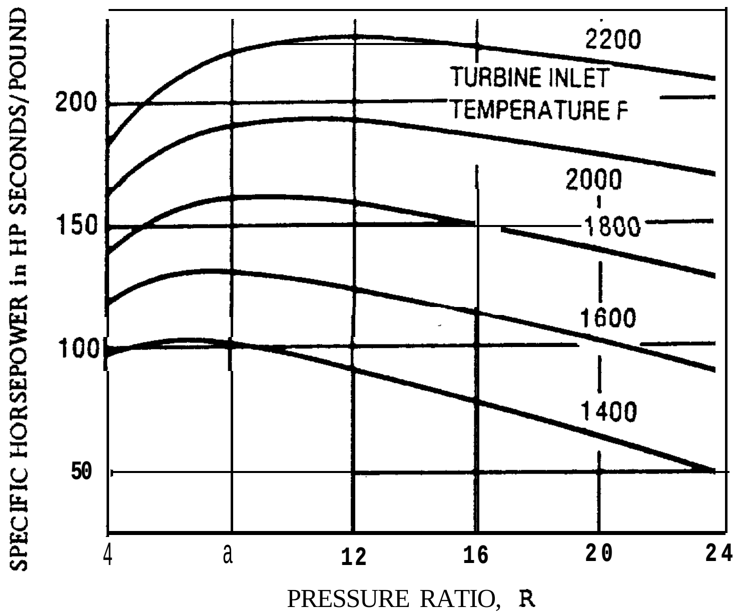


Figure II.B.2-2. SPECIFIC HORSEPOWER VERSUS PRESSURE RATIO

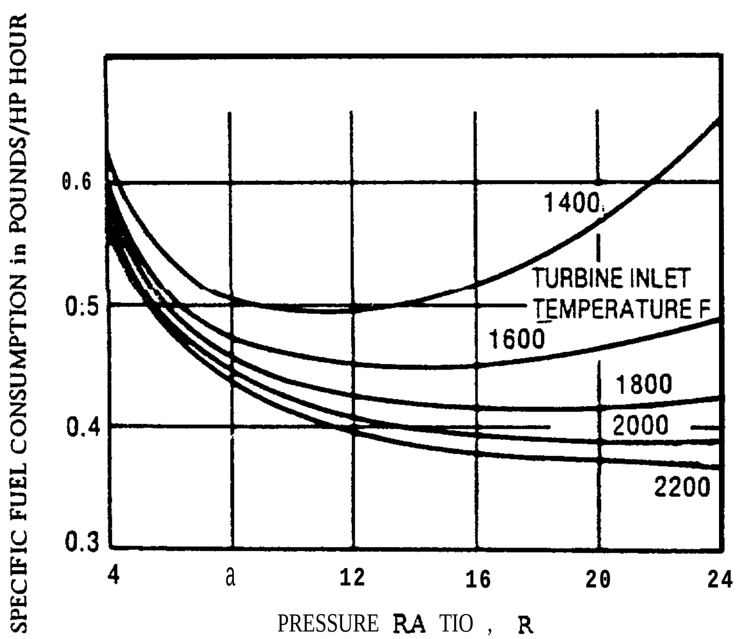


Figure II.B.2-3. SPECIFIC FUEL CONSUMPTION VERSUS PRESSURE RATIO

(U) Design limits are imposed by material strength and resistance to corrosive action at elevated temperatures. Present TIT temperatures of 2,500°F are being attained by transpiration and by internally air cooling the metal blades down to temperatures around 1,500°F. Metal temperatures above 1,500°F are avoided because they bring about an increase in the rate of sulfidation occurring on the turbine blades and other hot sections of the engine. Sulfidation deposits are due to a combination of salt in the ingested air and impurities in the fuel, such as sulfur and vanadium.

(U) Blade air cooling requires air flow from the compressor that reduces the overall efficiency of the engine. Further increases in TIT, with resultant increases in engine efficiency and power, appear obtainable only with materials that can withstand those temperatures without recourse to air cooling. At present, development work is being conducted with ceramic materials tolerant of 2,800°F.

(U) The effects of ambient temperature on turbine performance are shown in Figure II.B.2-4. These curves are obtained from basic cycle relationships under an assumed constant engine rpm and efficiency.

(U) Limitations in the structural strength of the engine dictate a power limit in actual operation. This limit is obtained by power-regulating the turbine through fuel control. Because of this requirement, actual engine curves are held to a maximum power level occurring at an ambient temperature of about -7°C.

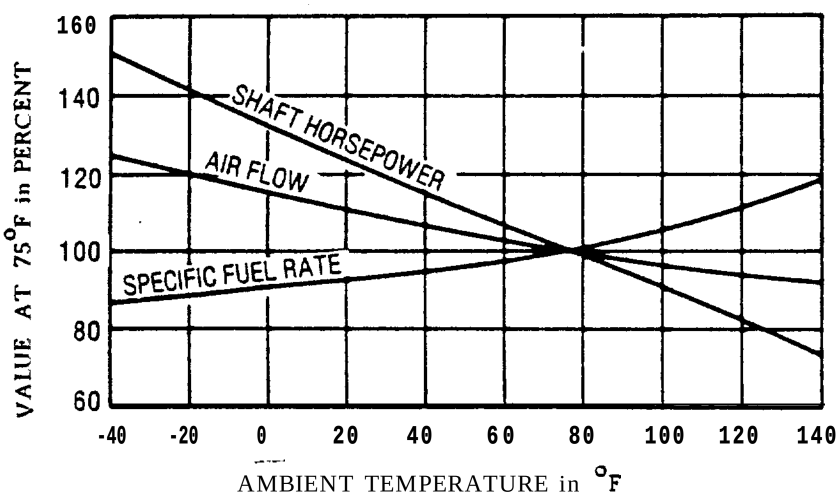


Figure II.B.2-4. TYPICAL EFFECT OF AMBIENT TEMPERATURE

(U) Gas turbine engine performance can also be adversely affected by inlet and exhaust duct pressure losses and variations in humidity, which alter the specific heat and density of the air.

2.2.1.5 Specific Fuel Consumption

(U) Specific fuel consumption (SFC) reflects the thermodynamic efficiency of the power plant. Its determination is basic to accurate estimation of the fuel required for operation in various sea states and at different ranges. For this purpose, curves relating SFC to brake horsepower level and ship speed are required.

(U) The SFC of a gas turbine varies with power-turbine rotary speed (rpm) and power level. To determine the fuel rate accurately, it is necessary to use the propulsor performance curve to find corresponding values of rpm and power level for each ship speed and gross weight. If such curves are not available in the preliminary stages of design, approximations of propulsor performance curves can be derived by making certain assumptions. When the propulsor is a waterjet, for example, it can be assumed that turbine speed remains constant with varying power absorption. The error introduced by using this assumption should not exceed 10%.

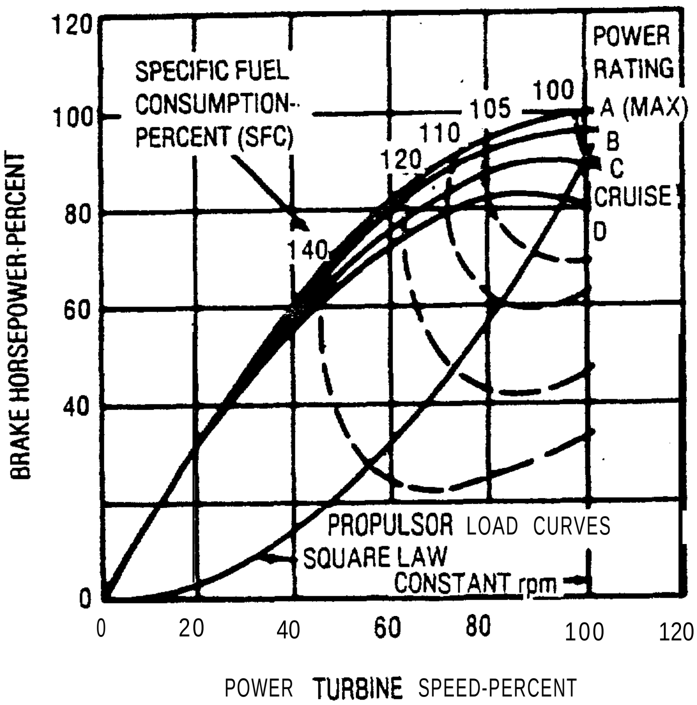
(U) For variable-pitch water propellers, a more generally applicable assumption can be used in place of the normal cube relationship; that is, that the power absorbed by the propeller is approximately proportional to the second power of the propeller rpm. A non-dimensional curve of this type is shown in Figure II.B.2-5.

(U) Data relating SFC to power level can usually be obtained from the manufacturer's performance curves for the engine selected. In the absence of such data, the non-dimensional curve of Figure II.B.2-5 can be used. The power turbine speed is chosen for minimum SFC at the cruise power requirement. The SFC for various power levels can be taken from along the indicated rpm curve. If the actual propulsor rpms for various power levels are known, the curve of propulsor rpm vs bhp can be superimposed on the turbine performance curve and the SFC read along that curve. In this latter case,

$$n = r_T n_e$$

where

n = propulsor rotary speed in rpm



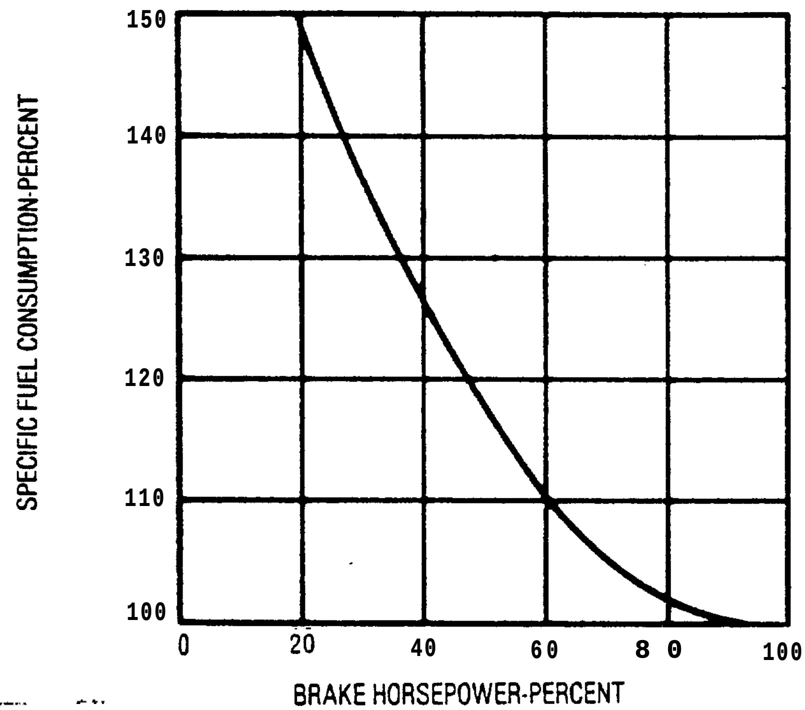
(Reference II.B.2-1)

Figure II.B.2-5. POWER VERSUS POWER TURBINE SPEED (TYPICAL MARINE GAS TURBINE ENGINE)

n_e = power turbine speed in rpm

r_T = transmission reduction ratio

(U) Information relating SFC to brake horsepower can be presented more conveniently as shown in Figure II.B.2-6, again in non-dimensional form. This curve, when used in conjunction with a power-speed curve, relates the specific fuel consumption to the speed of the hydrofoil. This information is useful in determining range and endurance under various operating conditions.



(Reference II.B.2-1)

Figure II.B.2-6. SPECIFIC FUEL CONSUMPTION VERSUS BRAKE HORSEPOWER (TYPICAL MARINE TURBINE ENGINE, BASED ON LOAD CURVE FROM FIGURE II.B.2-5)

(U) A survey of SFC for diesel and gas turbine engines was conducted to determine SFC figures for production engines (1976) and projection for the developmental engines (≈ 1980).

(U) Specific fuel consumption on currently available and projected marine and vehicular lightweight, high-speed diesels and simple-cycle, aircraft-derivation, marinized gas turbines is shown as a function of horsepower in Figure II.B.2-7 together with projections of SFC for gas turbines in the years 1980+.

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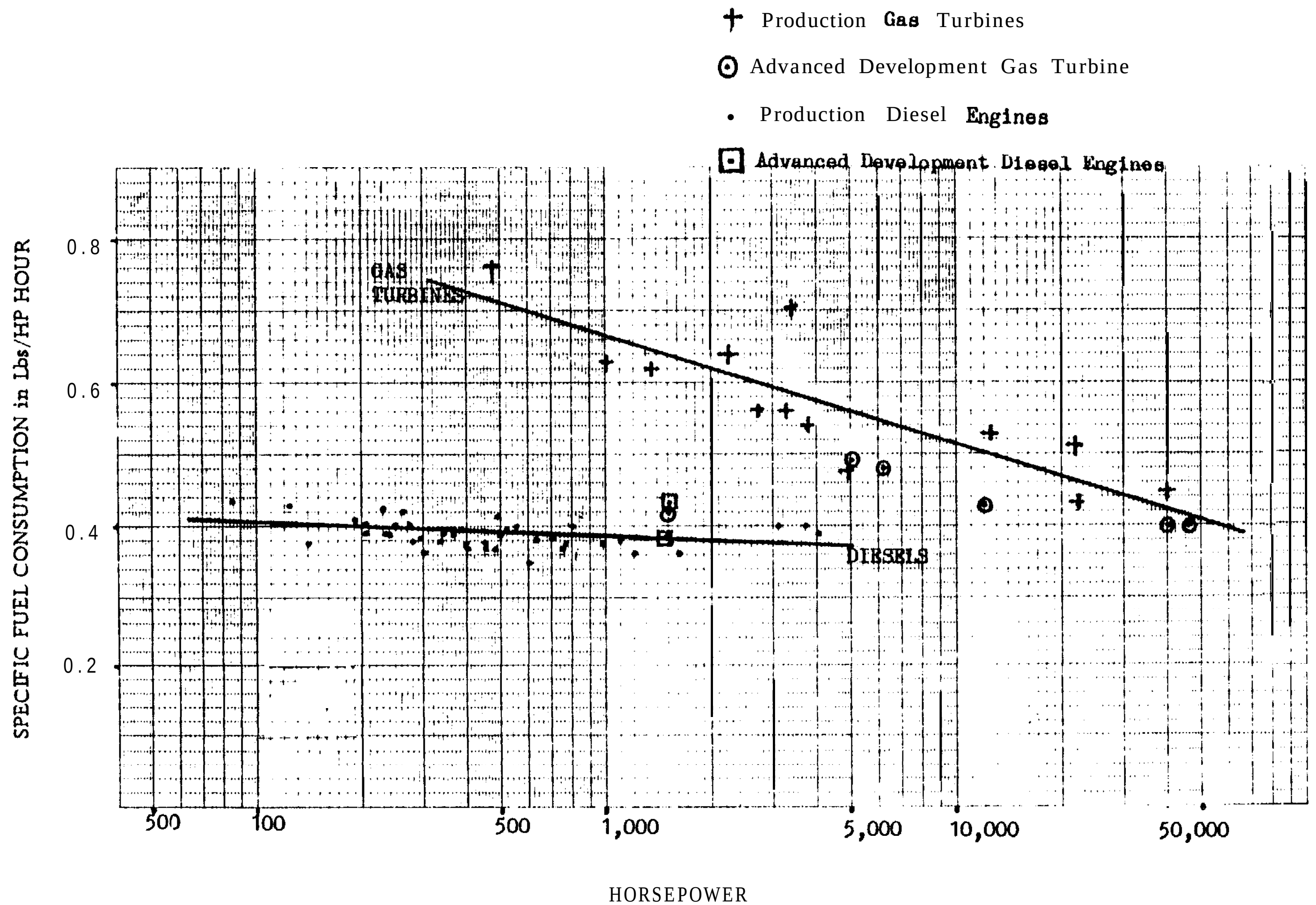

Figure II.B.2-7. SPECIFIC FUEL CONSUMPTION VERSUS HORSEPOWER FOR DIESEL AND GAS TURBINES; 1974 PRODUCTION AND 1980-k PROJECTIONS

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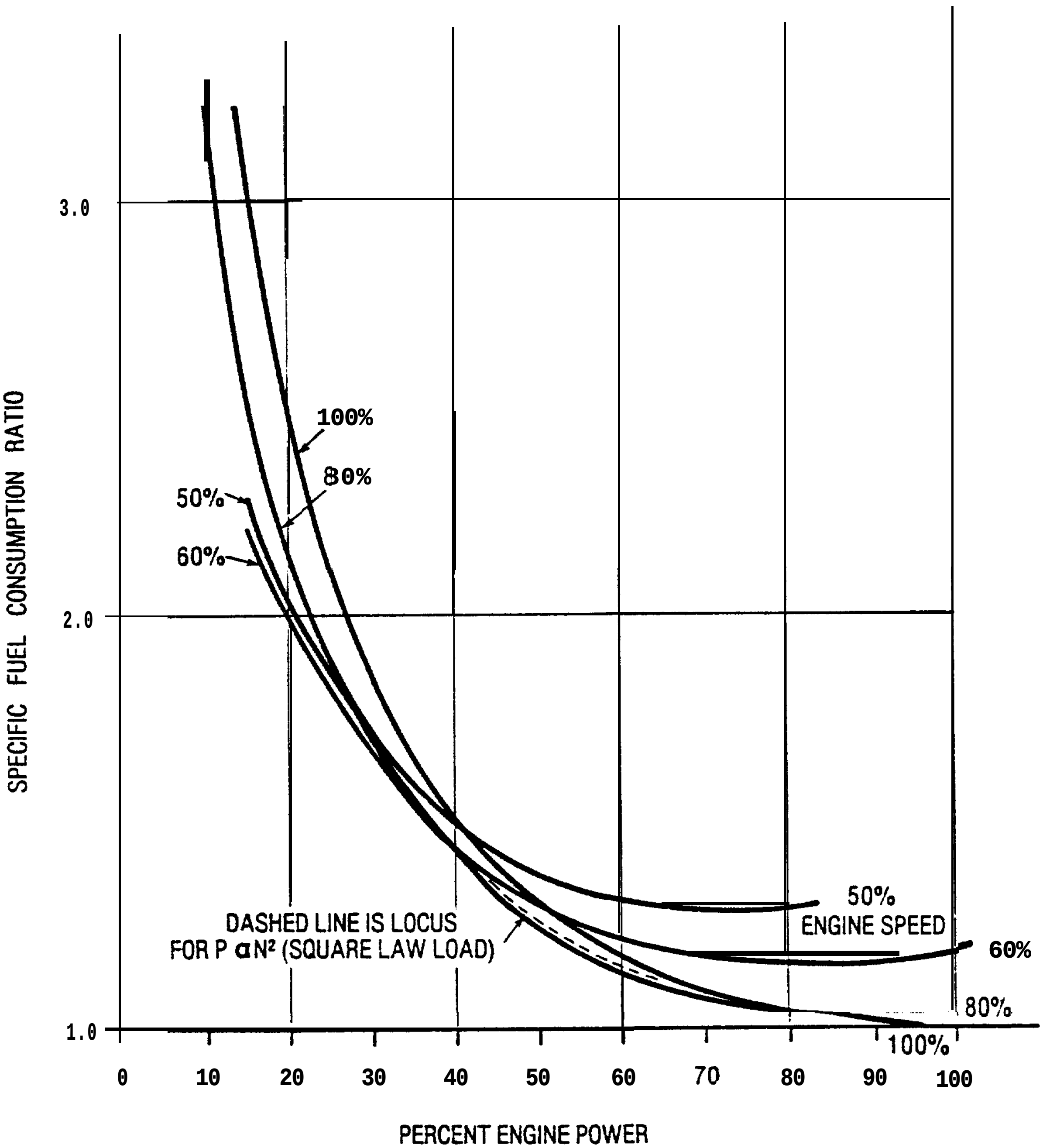
(U) These data indicate a fairly well-defined trend for production (or nearly-in-production) gas turbines resulting in typical SFC figures at rated maximum intermittent power from .63 lb/hp-hr at 1,000 hp to about .43 lb/hp-hr at 22,300 hp (for the LM-2500). The three largest engines FT-4C, LM-2500, and FT9A-2 (expected) are shown mainly to indicate the decreasing trend to SFC with increasing horsepower. The LM-2500 and FT9A-2 also illustrate that low SFC of approximately .4 lb/hp-hr is already being achieved through increased compression ratios and turbine inlet temperatures for these large 20,000 hp and larger engines.

(U) Achievement of these performance figures for smaller single-cycle gas turbine engines is expected, in the 1980s, to result in decreases of about 20-25% in SFC. Thus, at 1,000 hp, an SFC of .50 lb/hp-hr will probably be realized.

(U) The specific fuel consumption ratio of a typical simple-cycle, gas turbine in the 3,000 hp range as a function of percent maximum power and speed is shown in Figure II.B.2-8. This figure indicates a rapid increase in specific fuel consumption, especially for engine power levels below about 50%. In contrast to the specific fuel consumption curves for a diesel and rotary engine, there is less of a variation on SFC due to engine speed; e.g., for engine speeds from about 60% to 100%, the curves are fairly closely grouped together.

(U) Along the square-law load characteristic, the increase in SFC is a factor of 1.7 to 1.9 for 30% engine power and



[Condition: Sea Level, 15°C (59°F)]

Figure II.B.2-8. SPECIFIC-FUEL-CONSUMPTION RATIO FOR A TYPICAL SIMPLE GAS-TURBINE ENGINE IN THE 3,030 MHP (3000 HP) RANGE engine speeds from 100% to 50%. By comparison, diesel engine part-power SFC for about the same conditions is about 1.07 less. Thus, for part-power application, diesel engines perform very well in terms of low specific fuel consumption. With gas turbines, however, part-load performance is obtained only at the expense of a high specific fuel consumption.

2.2.1.6 Engine Design Standards

(U) For most U.S. Navy applications, a gas turbine engine is required to be rated and qualified by the procedures and requirements of MIL-E-17341 (Reference II.B.2-2). This is a good rating and qualification procedure which allows all engine candidates to be evaluated and compared to the same standard power profile which is independent of ship application. Qualification to the rating procedure of MIL-E-17341, for a particular engine, demonstrates the mechanical integrity, a rated power and corresponding fuel consumption (SFC), and a guaranteed level of MTBF (i.e., all failure events for a single engine).

(U) In addition to the qualification to MIL-E-17341, the actual engine ratings for a particular ship application should be determined based upon an anticipated power profile for the ship. Reference II.B.2-3 is a NAVSEC procedure which should be used to determine the gas turbine engine power ratings. The rating procedure recognizes that U.S. Navy high performance ships normally operate on an aircraft type power profile with high power settings required for takeoff transients and lower cruise power for the remainder of the time. Reference II.B.2-3 outlines a procedure for rating a gas turbine engine based on predicted operating time-at-temperature. Basing the rating procedure on time-at-temperature tends to maximize the utilization of the performance capability of a gas turbine engine.

2.2.2 Diesel Engines

2.2.2.1 Existing and Future Diesel Engines

(U) All the U.S. Navy hydrofoils which have been built to date use diesel engines exclusively for the hullborne propulsion system. Table II.B.2-1 is a list of the U.S. and Canadian Navy hydrofoils which have been built to date, plus information regarding various aspects of their propulsion systems. Diesel engines have been chosen for hullborne prime movers because of their lower cost, flexibility of operation, and above all, their high efficiency which results in increased ships endurance over that obtainable from a gas turbine hullborne prime mover.

(U) Table II.B.2-4 is a list of currently available lightweight, high-speed diesel engines which could be used as a prime mover for a hydrofoils hullborne propulsion and/or auxiliary power.

(U) Table II.B.2-5 is a list of lightweight, high-speed diesel engines which are currently under development and which may be available for use in the future. The successful development of these engines will facilitate power plant selection in that a larger variety of engines will be available to select from.

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Table II.B.2-4. PRODUCTION, LIGHTWEIGHT, HIGH-SPEED DIESEL ENGINES

Manufacturer Model No.	Displacement Liters (in3)	No. of Cylinders	Max. Cont. Rated MHP (HP) (2)	Rated Speed RPM	Rated MEP kg/cm2 (psi)	SFC at Rated Output kg/MHP-hr (lb/HP-hr)	(1) Weight kg (lb)	Spec. Weight kg/MHP (lb/HP)	Engine Volume m3 (ft3)
Caterpillar									
3203 NA	10.4 (636)	V-8	152 (150)	2400	5.5 (78)	.169 (.378)	816 (1800)	5.37 (12.0)	1.28 (45.3)
3304 NA	7.0 (425)	I-4	86 (85)	2000	5.6 (79)	.196 (.438)	993 (2190)	11.55 (25.76)	1.39 (49.0)
3304 T	7.0 (425)	I-4	127 (125)	2000	8.2 (116)	.193 (.430)	1016 (2240)	8.00 (17.92)	1.39 (49.0)
3306 T	10.5 (638)	I-6	193 (190)	2000	8.3 (118)	.183 (.410)	1252 (2760)	6.49 (14.53)	2.21 (78.0)
3306 TA	10.5 (638)	I-6	238 (235)(2) 218 (215)(3)	2000	10.3 (146)	.175 (.391)	1486 (3275)	6.24 (13.94) 6.82 (15.23)	2.19 (77.2)
3406 PC-T	14.6 (893)	I-6	254 (250)	1800	8.6 (123)	.180 (.402)	2046 (4510)	8.06 (18.04)	3.77 (133.0)
3406 PC-TA	14.6 (893)	I-6	279 (275)(3)	1800	9.5 (135)	.182 (.407)	2046 (4510)	7.33 (16.40)	3.77 (133.0)
3408 DI-T	18.0 (1099)	V-8	304 (300)	1800	8.4 (120)	.163 (.365)	2371 (5228)	7.80 (17.43)	3.98 (140.7)
3408 PC-TA	18.0 (1099)	V-8	370 (365)(3)	1800	10.3 (146)	.174 (.390)	2371 (5228)	6.41 (14.32)	3.98 (140.7)

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Table II.B.2-4. PRODUCTION, LIGHTWEIGHT, HIGH-SPEED DIESEL ENGINES (Continued)

Manufacturer Model No.	Displacement liters (in³)	No. of cylinders	Max. cont. rated HP (HP) (2)	Rated speed RPM	Rated BMEP kg/cm² (psi)	BSFC at Rated Output kg/MHP-hr (lb/HP-hr)	(1) Weight kg (lb)	Spec. Weight kg/MHP (lb/HP)	Engine Volume m³ (ft³)
Caterpillar									
3412 DI-T	27.0 (1649)	V-12	456 (450)	1800	8.4 (120)	.166 (.371)	3810 (8400)	8.36 (18.67)	6.97 (246.2)
3412 PC-TA	27.0 (1649)	V-12	527 (520)(3)	1800	9.8 (139)	.177 (.395)	3810 (8400)	7.23 (16.15)	6.97 (246.2)
D-346 TA	19.5 (1191)	V-8	487 (480)(2)	1800	12.4 (177)	.166 (.370)	4218 (9300)	8.66 (19.38)	8.24 (290.8)
D-348 TA	29.3 (1786)	V-12	761 (750)	1800	12.6 (179)	.165 (.368)	5119 (11285)	6.73 (15.05)	9.71 (342.7)
D-349 TA	39.0 (2382)	V-16	984 (970)	1800	12.6 (179)	.169 (.377)	6713 (14800)	6.82 (15.26)	13.05 (460.9)
Cummins									
KTA 3067	50.3 (3067)	V-16	1622 (1600)	2100	13.8 (197)	.162 (.362)	6940 (15300)(5	.28 49.56)	5.63 (198.8)
KTA 2300	37.7 (2300)	V-12	1217 (1200)	2100	13.8 (197)	.162 (.363)	5652 (12460)(5	4.64 (10.38)	4.57 (161.3)
KT 2300	37.7 (2300)	V-12	791 (780)	1950	13.8 (197)	.168 (.376)	5538 (12210)(5	7.00 (15.65)	4.57 (161.3)
KTA 1150	18.8 (1150)	I-6	608 (600)	2100	13.8 (197)	.156 (.349)	1724 (3800)(5)	2.84 (6.33)	2.35 (83.1)

Table II.B.2-4. PRODUCTION, LIGHTWEIGHT, HIGH-SPEED DIESEL ENGINES (Continued)

Manufacturer Model No.	Displacement Liters (in3)	No. of Cylinders	Max. Cont. Rated MHP (HP)(2)	Rated Speed RPM	Rated BMEP kg/cm² (psi)	BSFC at Rated Output kg/MHP-hr (lb/HP-hr)	(1) Weight kg (lb)	Spec. Weight kg/MHP (lb/HP)	Engine Volume m³ (ft³)
Cummins									
KT 1150	18.8 (1150)	C-6	406 (400)	1950	9.9 (141)	.165 (.368)	1678 (3700)(5)	4.13 (9.25)	2.20 (77.6)
VTA 1710	28.0 (1710)	V-12	811 (800)	2100	12.4 (176)	.179 (.400)	3624 (7990)	4.47 (9.99)	6.17 (217.8)
VTA 1710-M2	28.0 (1710)	V-12	710 (700)	2100	10.8 (154)	.170 (.381)	3624 (7990)	5.10 (11.41)	6.17 (217.8)
VTA 1710-M1	28.0 (1710)	V-12	645 (635)	2100	9.8 (140)	.170 (.381)	3565 (7860)	5.53 (12.38)	6.17 (217.8)
V 1710 M	28.0 (1710)	V-12	487 (480)	2100	7.5 (106)	.186 (.415)	3089 (6810)	6.34 (14.19)	5.86 (206.9)
NT 855	14.0 (855)	I-6	385 (380)	2100	10.8 (153)	.177 (.396)	1780 (3925)	4.62 (10.33)	3.11 (109.9)
NT 855 M-1	14.0 (855)	I-6	340 (335)	2100	10.4 (148)	.171 (.382)	1780 (3925)	5.24 (11.72)	3.11 (109.9)
NT 855 M	14.0 (855)	I-6	243 (240)	2100	7.5 (106)	.176 (.393)	1558 (3435)	6.41 (14.31)	2.78 (98.2)
VTA 903 M	14.8 (903)	V-8	456 (450)	2600	10.7 (152)	.170 (.379)	1678 (3700)	3.68 (8.22)	1.92 (67.7)
VT-903M	14.8 (903)	V-8	406 (400)	2600	9.5 (135)	.168 (.376)	1452 (3200)	3.58 (8.00)	1.77 (62.5)
VT 903M-1	14.8 (903)	V-8	345 (340)	2800	7.5 (107)	.174 (.389)	1338 (2950)	3.88 (8.68)	1.77 (62.6)

Table II.B.2-4. PRODUCTION, LIGHTWEIGHT, HIGH-SPEED DIESEL ENGINES (Continued)

Manufacturer Modal No.	Displacement liters (in³)	No. of Cylinders	Max. Cont. Rated MHP (HP)(2)	Rated Speed RPM	Rated BMEP kg/cm² (psi)	BSFC at Rated Output kg/MHP-hr (lb/HP-hr)	(1) Weight kg (lb)	Spec. Weight kg/MHP (lb/HP)	Engine Volume m³ (ft³)
Cummins									
V 903 M	14.8 (903)	V-8	299 (295)	2600	7.0 (99.5)	.171 (.382)	1270 (2800)	4.25 (9.49)	1.68 (59.2)
V 555 M	9.1 (555)	V-8	233 (230)	3300	7.0 (100)	.189 (.423)	839 (1850)	3.60 (8.04)	1.13 (39.8)
V 504 M	8.3 (504)	V-8	205 (202)	3300	6.7 (96)	.180 (.402)	771 (1700)	3.76 (8.42)	0.97 (34.4)
Detroit Diesel									
6-7 TI	7.0 (425)	I-6	254 (250)	2100	8.5 (121)	.179 (.40)	1429 (3150)(6)	5.63 (12.60)	2.09 (73.8)(6)
6V-53 TI	5.3 (318.4)	V-6	284 (280)	2300	8.7 (124)	.170 (.38)	826 (1820)	2.91 (6.50)	0.89 (31.4)
8V-53	6.9 (424)	V-8	264 (260)	2300	6.1 (87)	.188 (.42)	1043 (2300)(6)	3.95 (8.85)	0.80 (28.1)(6)
8V-71 TI	9.3 (567.4)	V-8	553 (545)	2100	12.7 (180)	.179 (.40)	1905 (4200)(6)	3.44 (7.70)	3.01 (106.2)(6)
12V-71T	13.9 (851)	V-12	507 (500)	2100	7.8 (111)	.174 (.39)	2921 (6440)(6)	5.76 (12.88)	4.26 (150.5)(6)
12V-149 TI	29.3 (1788)	V-12	1115 (1100)	1300	9.0 (128)	.171 (.383)	4536 (10000)	4.07 (9.09)	6.11 (215.7)
16V-149 TI	39.1 (2384)	V-16	1486 (1465)	1900	9.0 (128)	.171 (.383)	5443 (12000)	3.66 (8.19)	8.23 (290.7)

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Table II.B.2-4. PRODUCTION, LIGHTWEIGHT, HIGH-SPEED DIESEL ENGINES (Continued)

Manufacturer Model No.	Displacement Liters (in^3)	o. of ylindera	lax. Cont. lated HP HP)(2)	lated Speed PM	lated MEP g/cm^2 psi)	WC at ated utput g/MHP-hr lb/HP-hr)	(1) Weight kg (lb)	Spec. Weight kg/MHP (lb/HP)	Engine Volume m^3 (ft^3)
MTU									
6V331TC81	9.9 1214)	-6	80 671)	2340	13.1 (186.2	I.A.	1580 (3483)	2.32 (5.19	2.87 (101.3)
8V331TC81	6.5 1617)	-8	Do (888)	2340	13.1 (186.2)	I.A.	1920 (4233)	2.13 (4.77)	31.38 (119.3)
12V33 1 TC81	9.8 2429)	-12	360 (1341)	2340	13.1 (186.2)	I.A.	2910 (6415)	2.14 (4.78)	4.61 (162.8)
12V538TB91	4.5 3936)	-12	2700 (2663)	1900	19.8 (281.6)	I.A.	5250 (11574)	1.94 (4.35)	9.15 (323.1)
16V538TB91	86.0 (5248)	-16	3600 (3551)	1900	19.8 (281.6)	I.A.	6720 (14815)	ii.87 (4.17)	12.32 (435.0)
16V538TB92	86.0 (5248)	i-16	4000 (3945)	1900	22.0 (312.8)	I.A.	6720 (14815)	1.68 (3.76)	12.32 (435.0)
20V538TB91	107.5 (6560)	v-20	4500 (4438)	1900	19.8 (281.6)	I.A.	8900 (19621)	1.98 (4.42)	13.65 (482.0)
12V652TB81	78.3 (4778)	v-12	2055 (2027)	1760	16.0 (227.5)	N.A.	4850 (10692)	2.36 (5.27)	9.54 (336.9)
16V652TB81	104.3 (6364)	v-16	2750 (2712)	1485	16.0 (227.5)	N.A.	6235 (13746)	2.27 (5.07)	11.97 (422.7)
12V956TB91	114.7 (6999)	v-12	3400 (3353)	1575	17.7 (251.7)	N.A.	8550 (18849)	2.51 (5.62)	11.40 (402.5)

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Table II.B.2-4. PRODUCTION, LIGHTWEIGHT, HIGH-SPEED DIESEL ENGINES (Continued)

Manufacturer Model No,	)isplacement .iters (in^3)	3. of ylinders	ax. Cont. sted MHP (HP)(2)	ated peed P M	Rated BMEP kg/cm^2 (psi)	BSFC at Rated Output kg/MHP-hr (lb/HP-hr)	(1) Weight kg (lb)	Spec. Weight kg/MHP (lb/HP)	Engine Volume m^3 ft^3)
MTU									
16V956TB91	152.9 (9330)	V-16	4500 (4438)	1575	17.7 (251.7)	N.A.	1510 25374)	2.56 (5.72)	15.63 551.9)
20V956TB92	191.1 (11661)	V-20	6000 (5918)	1600	17.7 (251.7)	N.A.	4900 32849)	2.48 (5.55)	20.01 (706.6)
Napier Deltic									
CT18-50K	88.2 (5384)	Δ-18	4056 (4000)	2100	9.8 (140)	.174 (.39)	144 15750)	.76 (3.94)	4.23 (502.4)
CT18-42K	88.2 (5384)	Δ-18	3752 (3700)	2100	9.1 129.6	.179 (.40)	7144 (15750)	1.90 (4.26)	14.23 502.4)
T18-37	88.2 5384)	Δ-18	3143 (3100)	2100	N.A.	.179 (.40)	6183 (13630)	1.97 (4.40)	15.90 561.5)
18-39K	88.2 (5384)	y-18	2535 (2500)	2100	N.A.	N.A.	5806 (12800)'	2.29 (5.12)	13.01 (459.4)
Waukesha									
H866DSIM	14.2 (866)	V-8	393 (388)	1900	10.5 (149)	N.A.	1497 (3300)	3.18 (8.51)	3.39 (119.8)
F674DSIM	11.0 (674)	I-6	335 (330)	1800	12.2 (173)	N.A.	1055 (2326)	3.15 7.05)	2.14 (75.5)
F674DSM	11.0 (674)	I-6	293 (289)	1800	10.7 (152)	N.A.	954 (2103)	3.26 (7.28)	2.14 (75.5)

Table II.B.2-4. PRODUCTION, LIGHTWEIGHT, HIGH-SPEED DIESEL ENGINES (Continued)

Manufacturer Model No,	Displacement Liters (in^3)	No. of Cylinders	Max. Cont. Rated MHP (HP)(2)	Rated Speed RPM	Rated BMEP kg/cm^2 (psi)	BSFC at Rated Output kg/MHP-hr (lb/HP-hr)	(1) Weight kg (lb)	Spec. Weight kg/MHP (lb/HP)	Engine Volume m^3 (ft^3)
F674DM	11.0 (674)	I-6	23 (220)	2000	8.6 (122)	N.A.	930 (2050)	4.17 (9.32)	2.14 (75.5)
F476DSM	7.8 (476)	I-6	212 (209)	2000	9.9 (141)	N.A	828 (1825)	3.91 (8.73)	1.46 (51.4)
F476DM	7.8 (476)	I-6	157 (155)	2000	7.7 (110)	N.A	764 (1685)	4.87 (10.87)	1.46 (51.4)

(1) Except as noted, the engine weights for Caterpillar, Cummins, and Napier Deltic, include the gearbox. Engine weights for MTU and Waukesha do not include gearbox weight.
(2) This rating assumes raw water intercooling.
(3) This rating assumes Jacket water intercooling.
(4) Includes wt of gearbox
(5) Does not include wt of gearbox
(6) Includes 2 to 1 reverse reduction gear

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Table II.B.2-5. ADVANCED-DEVELOPMENT, LIGHTWEIGHT, HIGH-SPEED DIESEL ENGINES

Manufacturer Model No,	Displacement Liters (in^3)	0. of yiinders	lax. cont. lated IHP HP)	lated peed PM	Rated BMEP kg/cm^2 (psi)	BSFC at Rated Output kg/MHP-hr (lb/HP-hr)	(1) Weight kg (lb)	Spec. Weight kg/MHP (lb/HP)	Engine Volume m^3 (ft^3)
Continental									
AVCR-1360-2	22.3 (1360)	V-12	1521 (1500)(1)	2600	23.6 (336)	.190 (.425)	2030 (4475)	1.33 (2.98)	3.65 (129)
MTU									
MB873	2463 (2429)	V-12	1521 (1500)(1)	2600	21.5 (306)	.179 (.40)	1941 (4280)	1.28 (2.85)	2.72 (96)

(1) Tank engi rating - Gross Horsepower (ldition of cessory drives can reduce t al by as uch as 10%)

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2.2.2.2 Desirable Engine Characteristics

(U) Gas turbines offer an alternative to diesels for hullborne operation, but unfortunately the smaller gas turbines are not nearly as efficient as diesels, particularly at part load. The weight of the extra fuel required because of this poorer fuel economy soon overrides the gas turbine weight advantage if the ship must cruise any significant distance hullborne. Figure II.B.2-9 shows the range as a function of weight at which the total engine plus fuel weights are equal. The figure illustrates that the diesel plant is lighter for long hullborne ranges.

(U) A minimum weight plant is desired, but some compromise must be made, since high efficiencies (which save on fuel weight) can often be obtained only at the cost of increased plant weight. The measure of weight efficiency is the power plant specific weight (weight/power). Tables II.B.2-4 and II.B.2-5 illustrate the range of values which are currently available or which are anticipated for various diesel engines currently under development.

(U) The volume of the power plant should be minimal, since the ship weight is proportional to the required power plant volume. The measure of volumetric efficiency is the power density (power/volume) which may be expressed in $hp/ft^3 (mhp/m^3)$. To provide estimates of engine volume for several types of engines, Figure II.B.2-1 has been prepared showing engine power density versus engine power for experimental and current production diesels. Note that these data are just the engines and engine mounted auxiliaries, but do not include intake and exhaust ducting.

Assumption .

Installed weight of FT-40 = .68 tons (continuous power = 3350 hp)
Installed weight of DD16V-149TI = 5.4 tons (continuous power = 1465 hp)

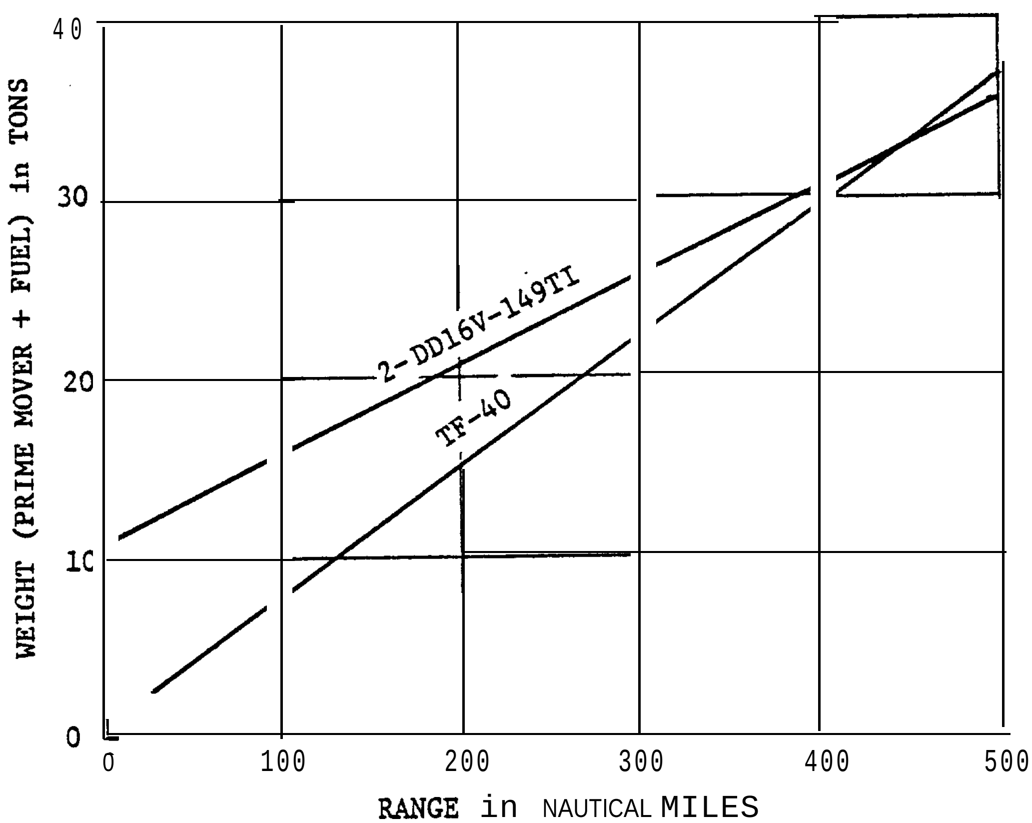

Figure II.B.2-9. COMPARISON OF DIESELS AND GAS TURBINES FOR HULLBORNE POWER PLANT

2.2.2.3 Specific Fuel Consumption

(U) A survey of specific fuel consumption (SFC) for diesel and gas turbine engines was conducted to determine SFC figures for production engines. Tables II.B.2-4 and II.B.2-5 both have columns which list the SFC for various engines. Specific fuel consumption on currently available marine lightweight, high-speed diesels along with simple-cycle, aircraft-derivation, marinized gas turbines are shown as a function of horsepower in Figure II.B.2-7.

(U) Data relating SFC to power level can usually be obtained from the manufacturer's performance curves for the engine selected. These curves may be similar to any of the three different types illustrated by Figures II.B.2-10 through II.B.2-12. From these curves, the SFC at part-load can be determined. Part-load, specific fuel consumption estimates are important when comparing the performance of various types of engines (diesel or gas turbine) in terms of fuel consumption, particularly where a single engine is used at several widely differing power levels.

2.2.3 <u>Transmissions</u>

2.2.3.1 Components Used On Existing Hydrofoils

(U) The primary function of the transmission system is to transmit power between two points. A secondary function is to change speed and torque, as well as direction of motion of the rotating components used to transmit power. Figures II.B.2-13 through II.B.2-23 illustrate various mechanical transmission arrangements,

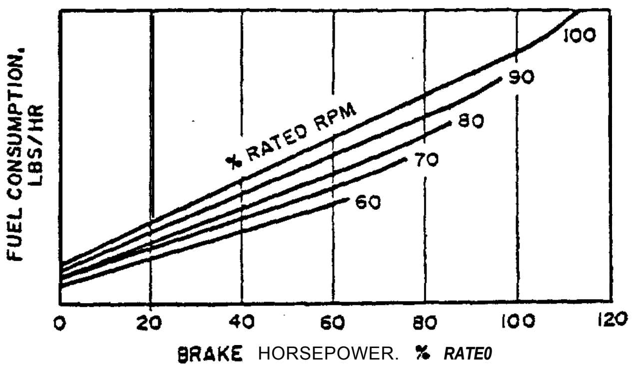

Figure II.B.2-10. DIESEL FUEL CONSUMPTION VERSUS HORSEPOWER

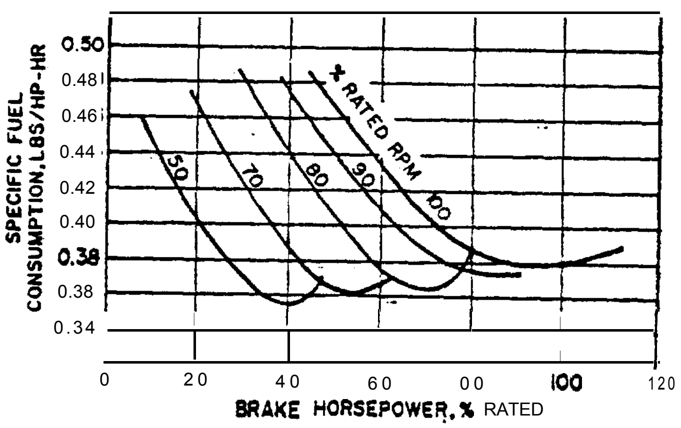

Figure II.B.2-11. DIESEL ENGINE "FISHHOOK" CURVES, SPECIFIC FUEL VERSUS BRAKE HORSEPOWER

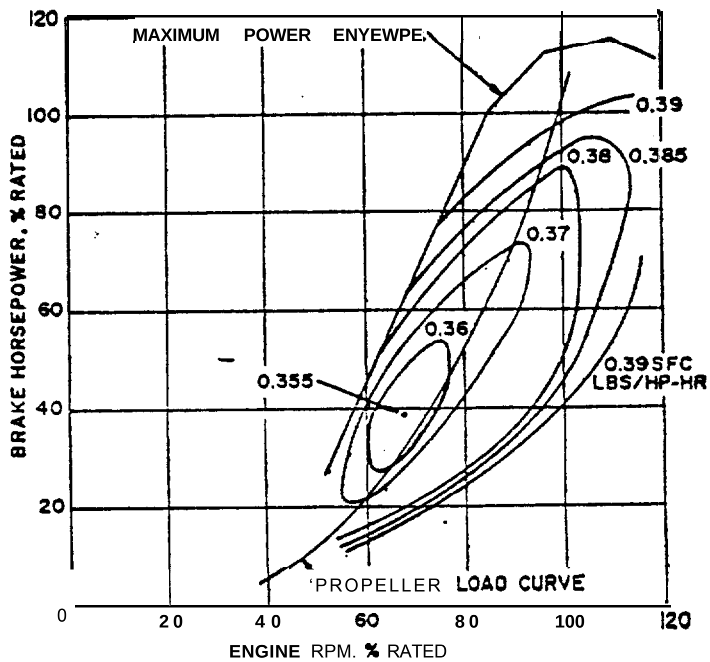

Figure II.B.2-12. TYPICAL SPECIFIC FUEL CONSUMPTION MAP FOR DIESEL ENGINE

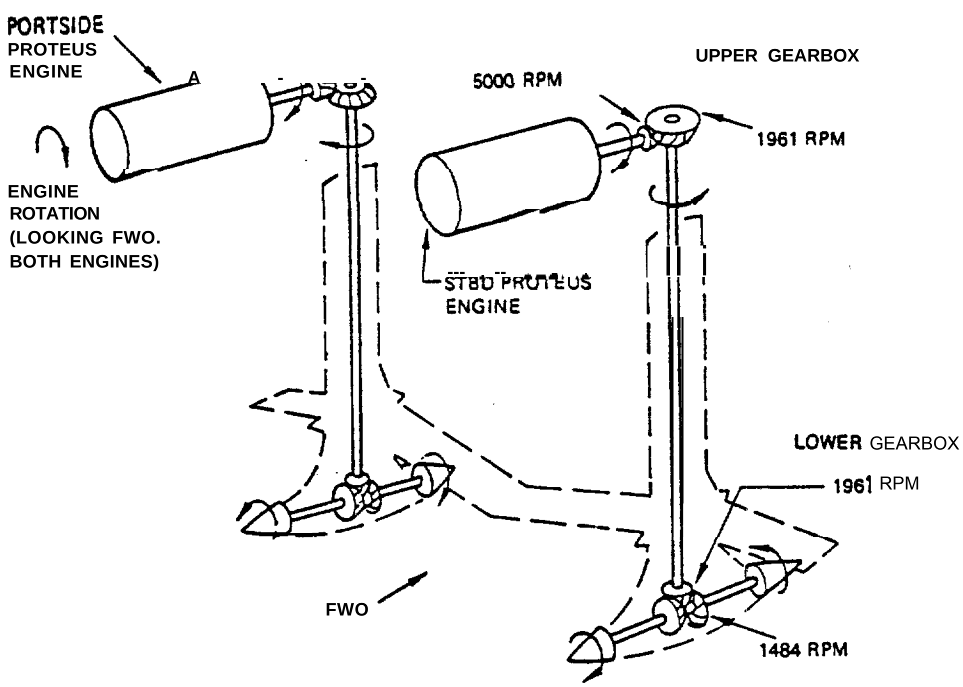

Figure II.B.2-13. PCH-1 (MOD 1) FOILBORNE TRANSMISSION SYSTEM

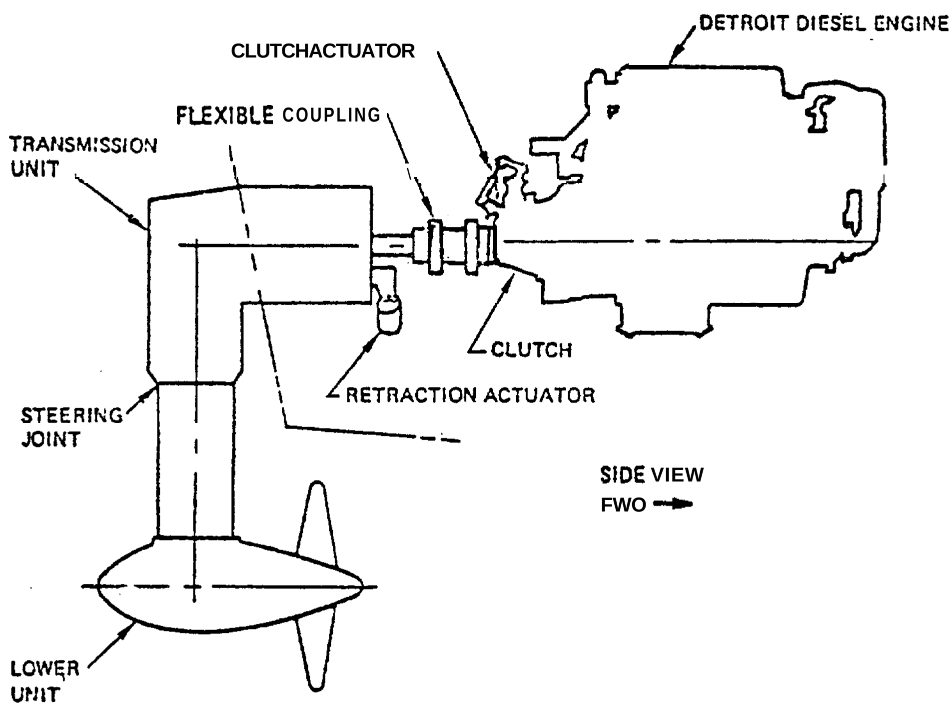

Figure II.B.2-14. PCH-1 (MOD 1) HULLBORNE TRANSMISSION SYSTEM

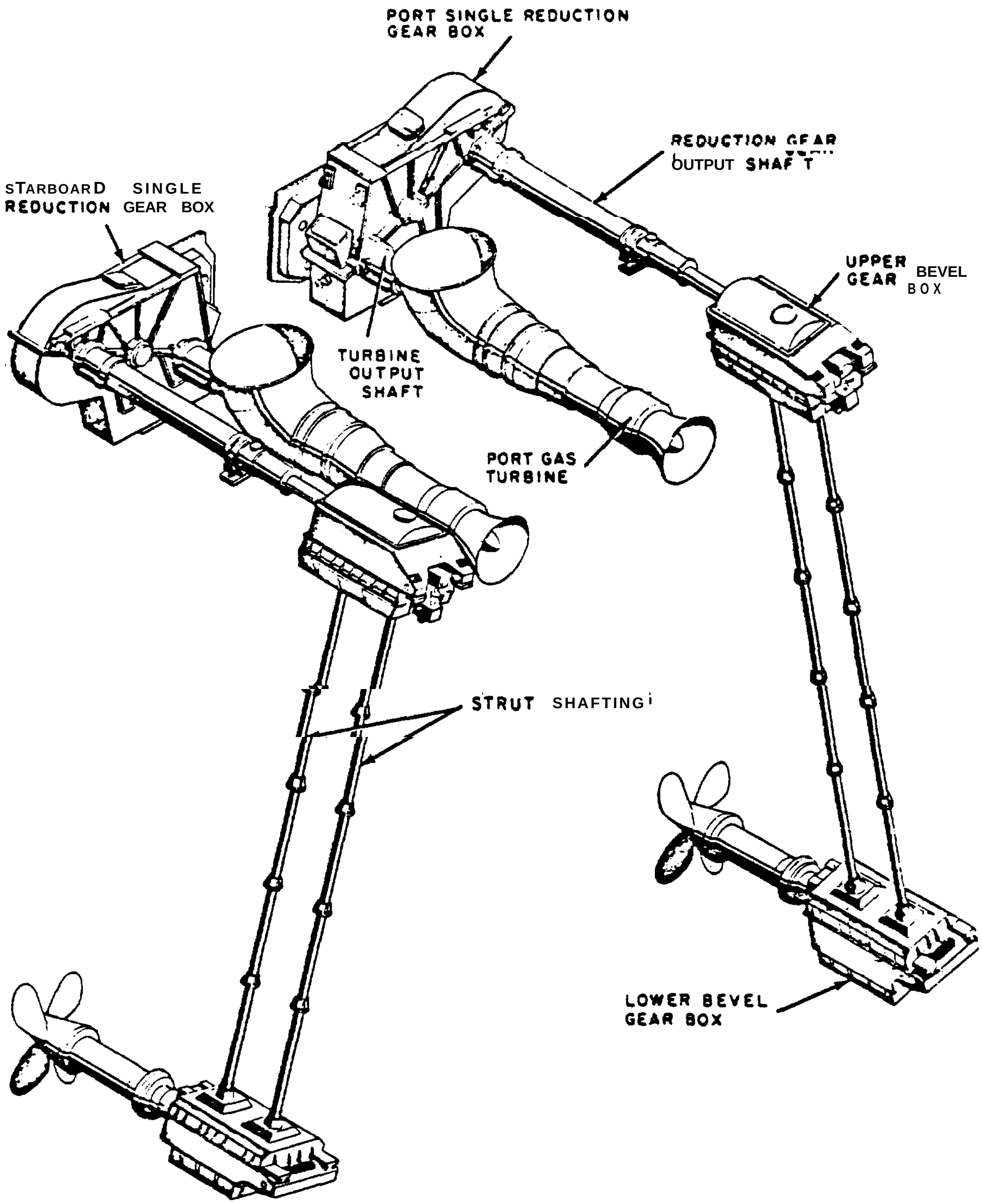

Figure II.B.2-15. AGEH-1 FOILBORNE TRANSMISSION SYSTEM

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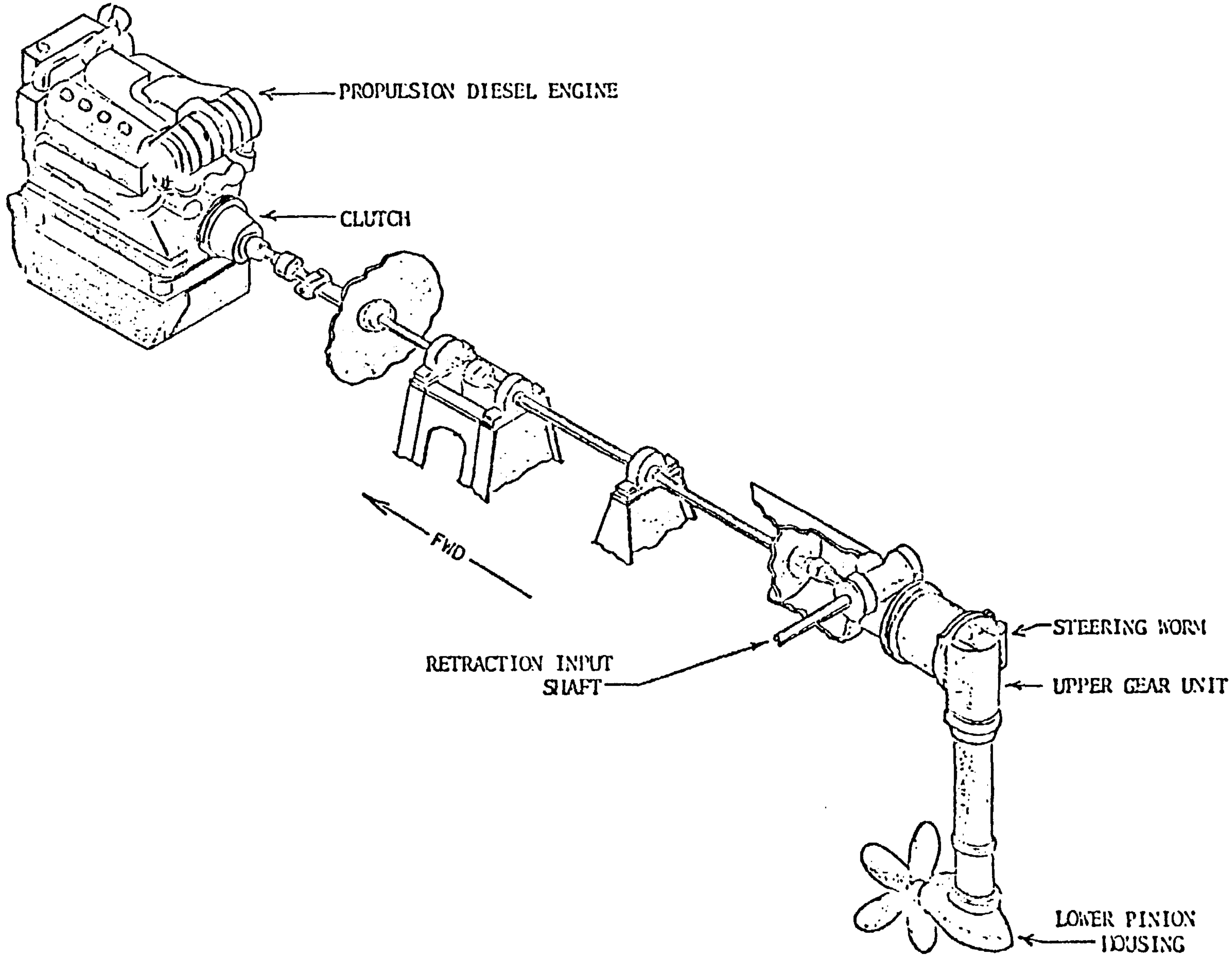

Figure II.B.2-16. AGEH-1 HULLBORNE TRANSMISSION SYSTEM

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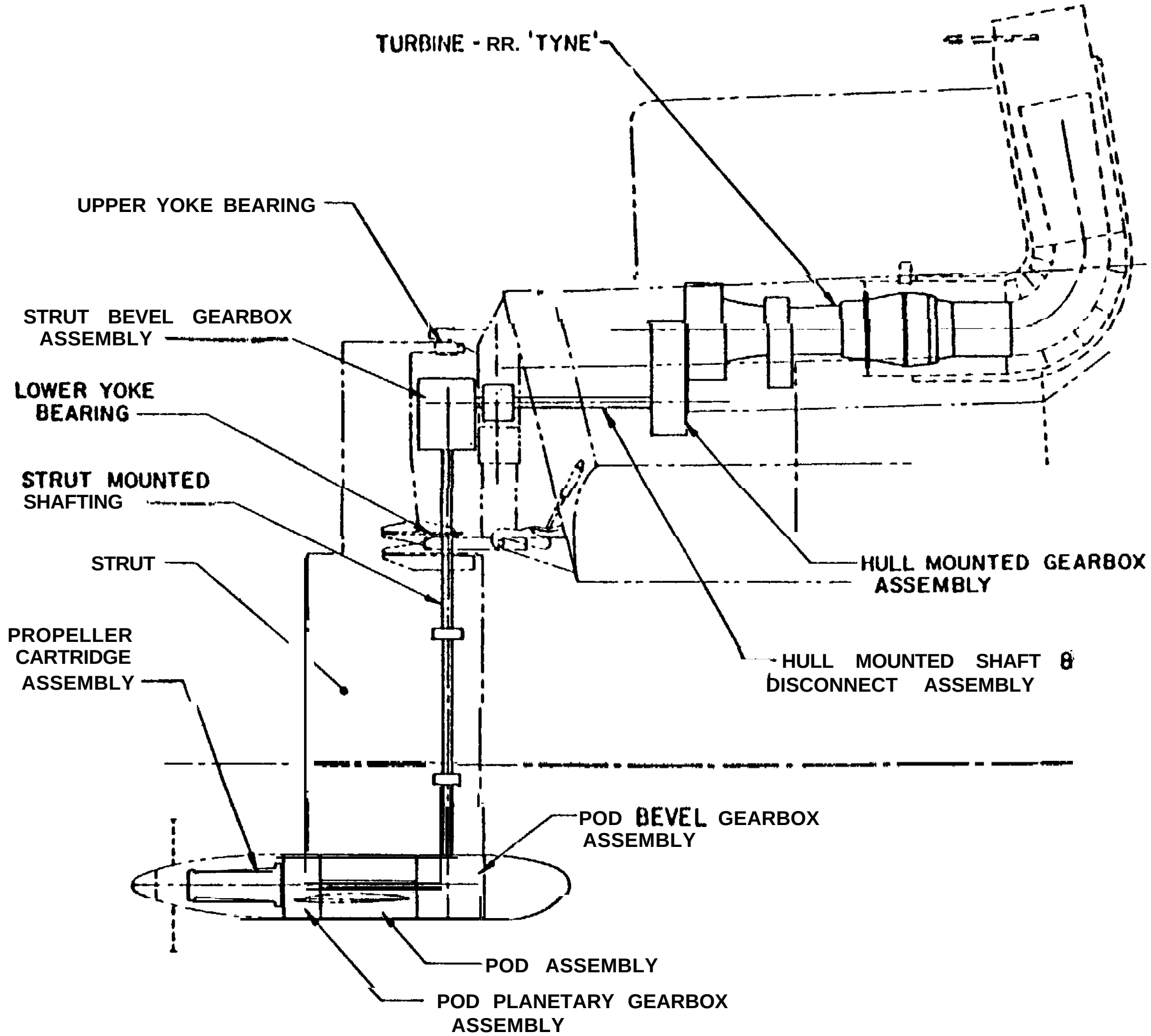

Figure II.B.2-17. PGH-1 FOILBORNE TRANSMISSION SYSTEM

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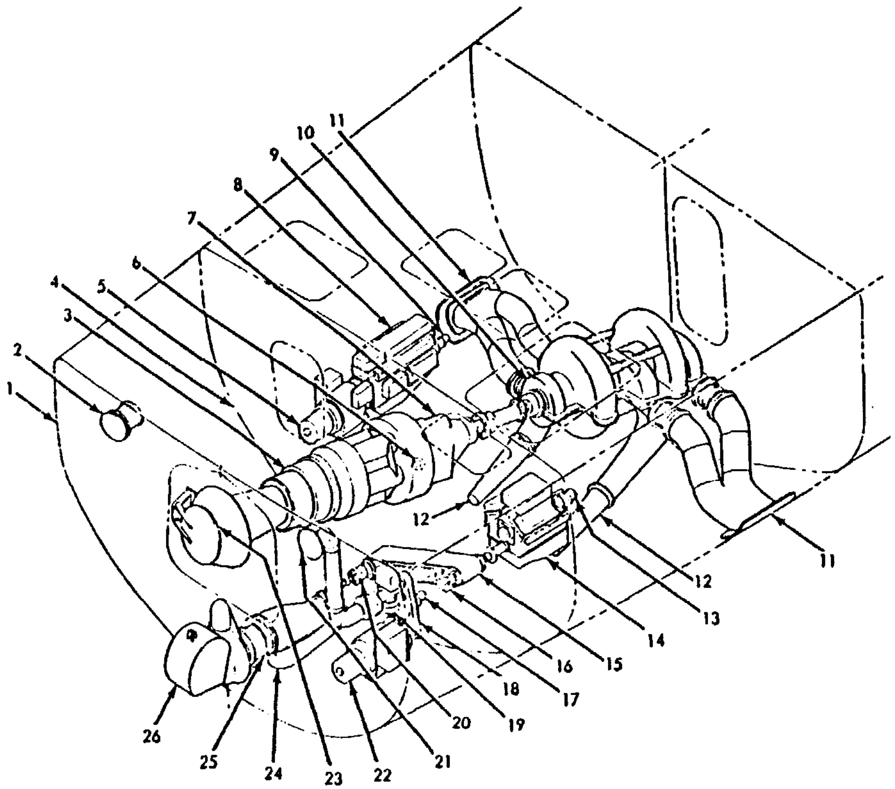

1. AFT MACHINERY COMPARTMENT
2. AFT MACHINERY COMPARTMENT VENTILATION DOOR AND FAN
3. FOILBORNE PROPULSION GAS TURBINE ENGINE
4. BULKHEAD 20
5. SHIP SERVICE ELECTRICAL SYSTEM MAIN GENERATOR
6. FOILBORNE HYDRAULIC SYSTEM MAIN PUMP
7. FOILBORNE PROPULSION TURBINE REDUCTION GEARBOX
8. SHIP SERVICE DIESEL ENGINE
9. SHIP SERVICE HYDRAULIC SYSTEM MAIN PUMP
10. FOILBORNE PROPULSION PUMP
11. FOILBORNE PROPULSION PUMP WATER INTAKES (P/S)
12. FOILBORNE PROPULSION WATER DISCHARGE NOZZLES (P/S)
13. FOILBORNE HYDRAULIC SYSTEM STANDBY PUMP
14. HULLBORNE PROPULSION DIESEL ENGINE
15. HULLBORNE PROPULSION PUMP DRIVE BELT
16. HULLBORNE STEERING SYSTEM HYDRAULIC PUMP
17. SHIP SERVICE STANDBY HYDRAULIC PUMP
18. SHIP SERVICE STANDBY HYDRAULIC PUMP AND GENERATOR DRIVE GEARBOX
19. SHIP SERVICE TURBINE
20. HULLBORNE PROPULSION PUMP DRIVE SHAFT
21. SHIP SERVICE TURBINE EXHAUST DOOR
22. SHIP SERVICE ELECTRICAL SYSTEM STANDBY GENERATOR
23. FOILBORNE PROPULSION TURBINE EXHAUST COOR
24. HULLBORNE PROPULSION PUMP WATER INTAKE
25. HULLBORNE PROPULSION PUMP
26. HULLBORNE PROPULSION THRUST REVERSING BUCKET

Figure II.B.2-18. PGH-2 FOILBORNE AND HULLBORNE TRANSMISSION SYSTEMS

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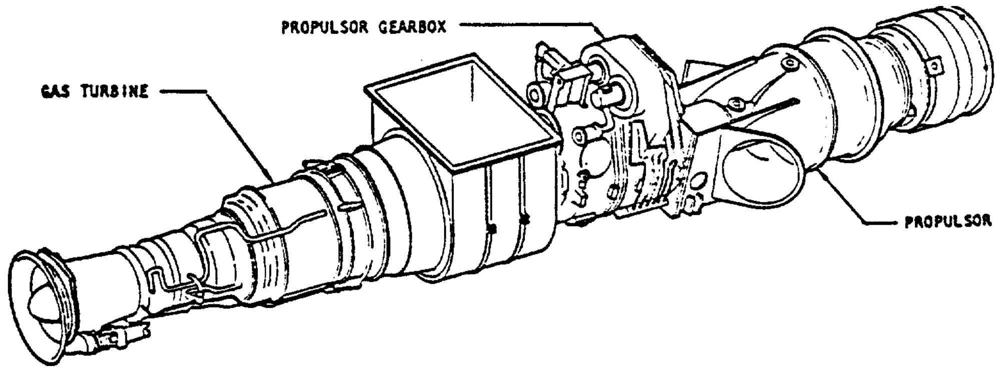

Figure II.B.2-19. PHM-1 FOILBORNE PROPULSION SYSTEM

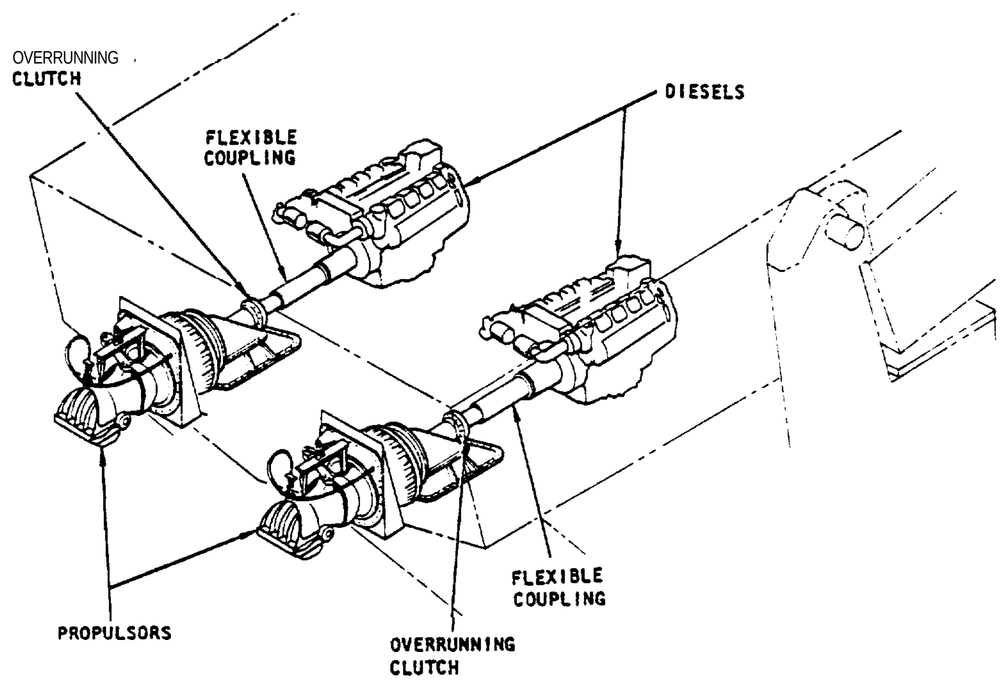

Figure II.B.2-20. PHM-1 HULLBORNE PROPULSOR SYSTEM

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II.B.2-41

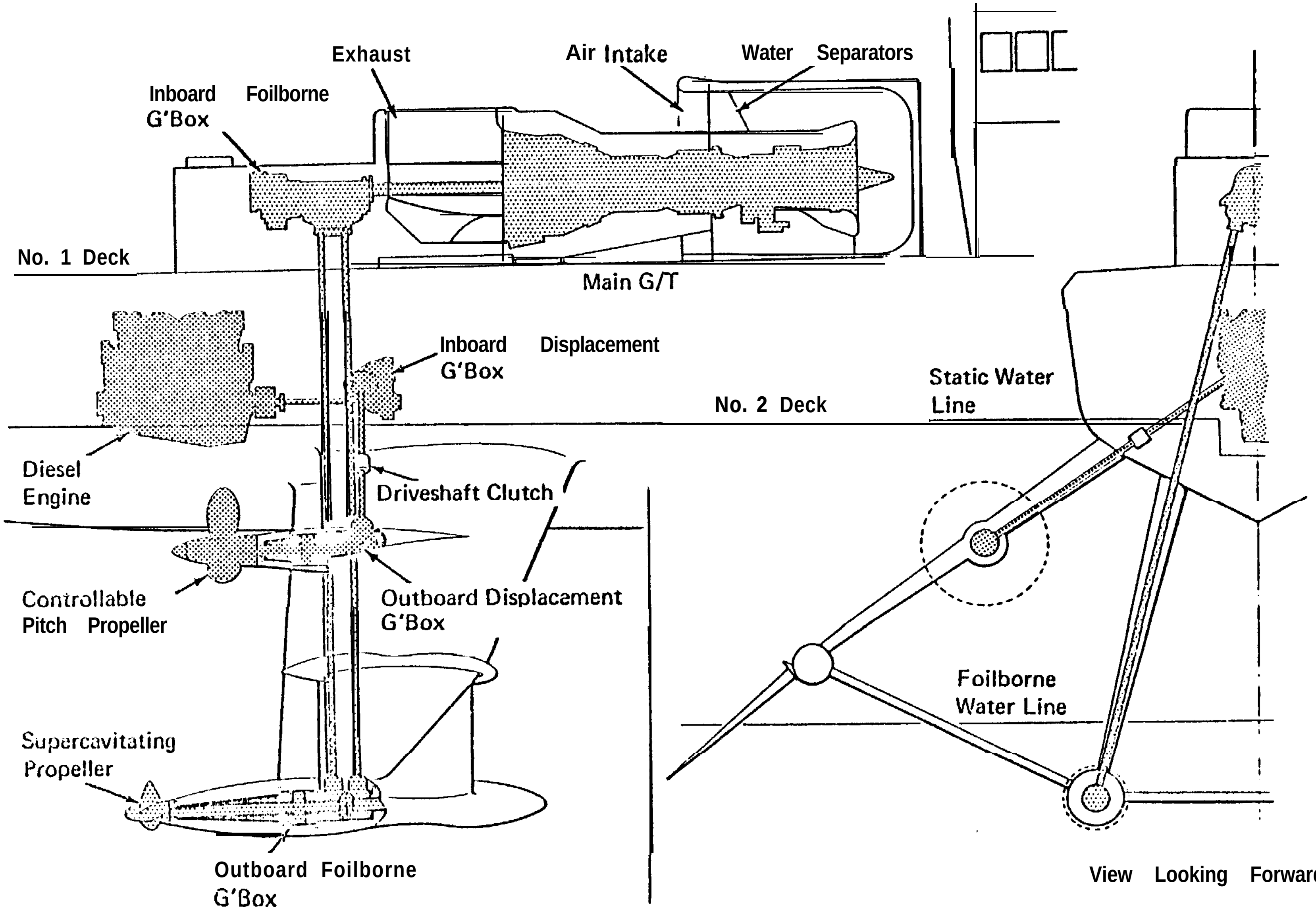

Figure II.B.2-21. FHE-400 PROPULSION SYSTEMS

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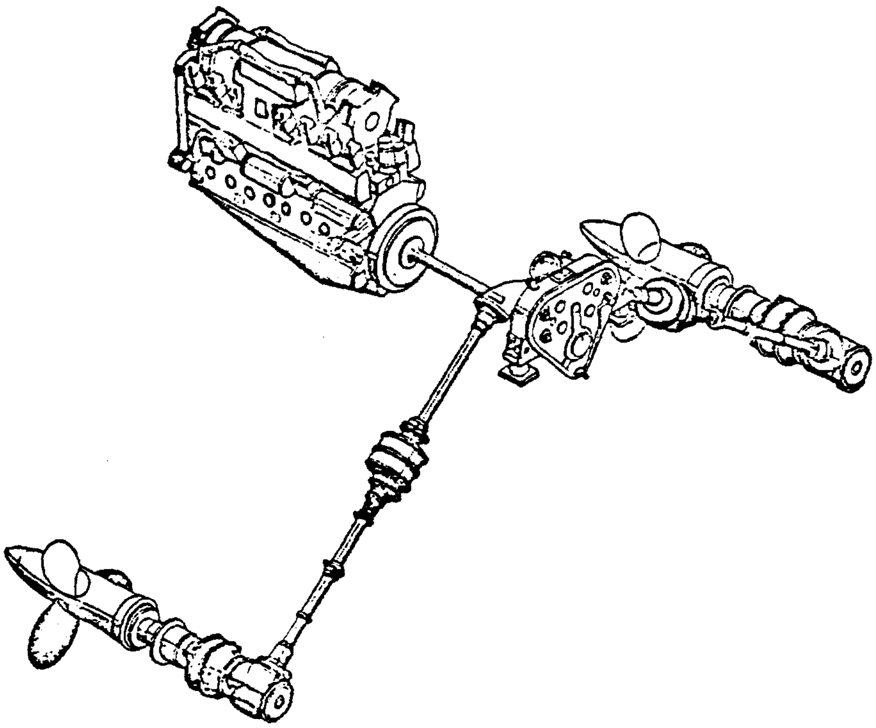


Figure II.B.2-22 FHE-400 HULLBORNE TRANSMISSION SYSTEM

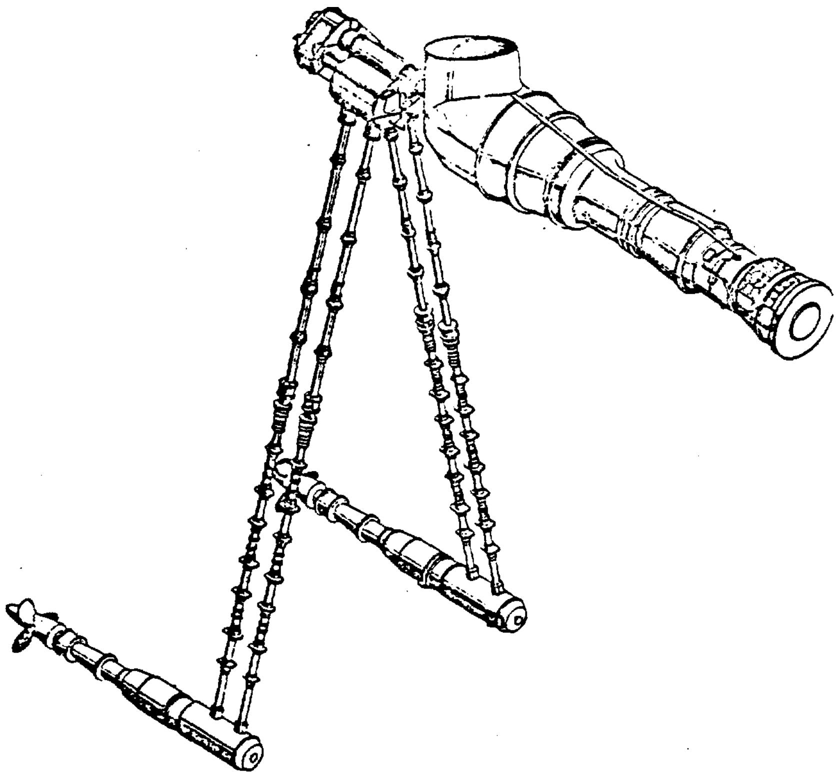


Figure II.B.2-23. FHE-400 FOILBORNE TRANSMISSION SYSTEM

and Table II.B.2-1 provides a verbal description of the transmission systems which have been used on U.S. Navy and Canadian hydrofoil ships up to this time.

(U) In the selection of a transmission system and components, a low weight-horsepower ratio is of prime importance. Of secondary importance is high efficiency, flexibility, and simplicity. Other desirable characteristics include maintainability, low volume, and low noise levels.

(U) Numerous mechanical, fluid, and electrical power transmission systems are available. Of these, particular consideration will be given below to gear, electromechanical, and superconducting electric systems.

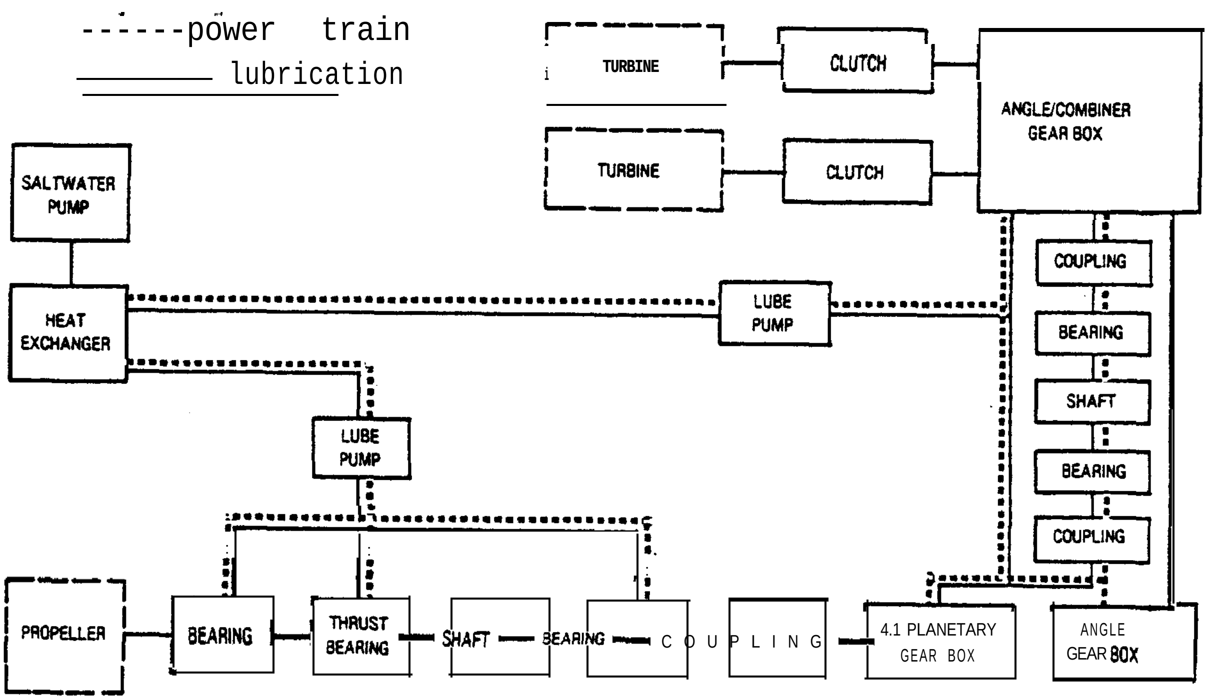
2.2.3.2 Available Transmission Systems

2.2.3.2.1 Mechanical System

(U) Figure II.B.2-24 is a schematic diagram of a typical mechanical gear system comprised basically of gearboxes and shafting. Refer to Figure II.B.2-15 again for an example of the propulsion system layout for a hydrofoil ship with a typical mechanical transmission system. The shafting is used to transmit power from one point to another, while the gearboxes are used to change speed, torque, and direction of rotation. Support components include bearings, couplings, clutches, and a lubrication and cooling system.

(U) The major components of a gear system are the gearboxes. For parallel shaft application, gear and pinion or epicyclic arrangements (Figure II.B.2-25) are used. Gear and pinion arrangements can vary in the number of branches and number of reductions. Epicyclic arrangements can be either planetary, star, or solar. The planetary arrangement results in the smallest gearbox. Table II.B.2-6 provides basic data on the various epicyclic arrangements.

(U) For intersecting shaft applications, angle gearboxes are used. These boxes can accommodate shafts intersecting at any angle, but are normally designed for right angle intersections.



(Reference II.B.2-1)

Figure II.B.2-24. TYPICAL GEAR BOX

Sets of angle gears can be gauged to reduce the loading experienced by any one gear mesh and allows the negation of torque reactions occurring in long shafting runs.

(U) The use of high-strength materials and precision grinding techniques common to the aircraft and helicopter industry permits gear systems to be the lightest and most compact of the available transmission systems.

(U) Gear systems are the traditional means of transmitting power on ships. Gear pinion arrangements are available up to 30,000 hp per mesh, with a 15:1 reduction ratio and 99% efficiency per mesh. Epicyclic transmissions have been used in several marine

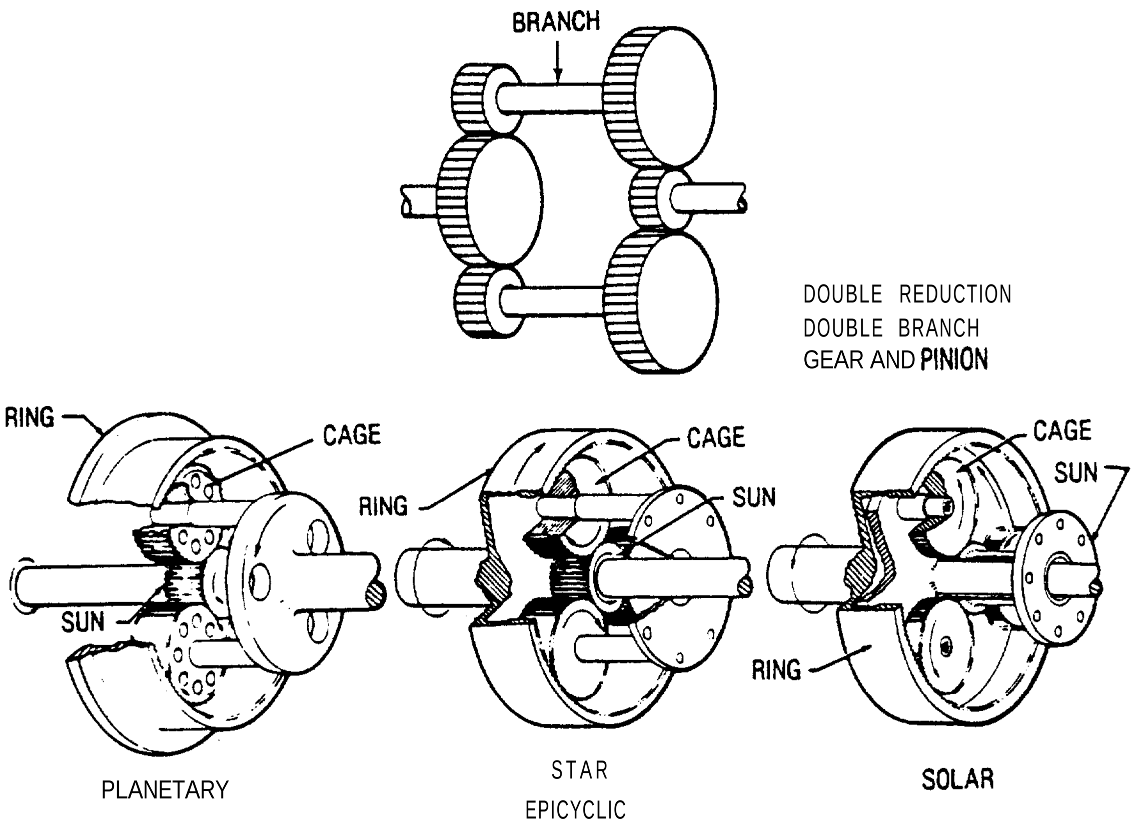


Figure II.B.2-25. GEARBOX ARRANGEMENTS

(Reference II.B.2-1)

systems up to 16,500 hp, with an overall efficiency of 98%. A prototype of a 40,000 hp planetary reduction gear with a 4:1 reduction has been built and successfully tested. Reduction ratios available are given in Table II.B.2-6. For angle gearboxes, gear size and horsepower capacity are presently limited to the capacity of the machinery used to rough-cut the gear teeth. A 3,600 rpm, 15,000 hp per mesh gear can be manufactured on a production basis; up to 25,000 hp per mesh is also achievable, but at an extremely high manufacturing cost. Reduction ratios up to 10:1 can be designed with 98% efficiency.

Table II.B.2-6. CHARACTERISTICS OF EPICYCLIC GEARS

Arrangement	Fixed Member	Input	output	Overall Gear Ratio M_o	Range of Overall Gear Ratios
Planetary	Ring	Sun	Cage	$N_R/N_S + 1$	3:1 - 12:1
Star	Cage	Sun	Ring	N_R/N_S	2:1 - 11:1
solar	Sun	Ring	Cage	$N_S/N_R + 1$	1.2:1 - 1.7: 1

N_R = number of teeth in ring gear

N_S = number of teeth in sun gear

(Reference II.B.2-1)

2.2.3.2.2 Electromechanical System

(U) Electrical systems may be well suited to large hydrofoil ships, since their transmission components are simple as compared with those of a mechanical system. In electrical systems, ducts or wires with appropriate switchgear is all that is necessary to channel power from one area to another, whereas mechanical systems require complex arrangements of clutches, gears, and shafting to accomplish the same results. However, there are severe technological limits which presently exist in regard to weight and size of electrical system components. These limits are being reduced with the development of advanced cooled and super-cooled electrical machinery development programs.

(U) Electric drives utilize a prime mover and a generator powering a motor through connecting electric cables, switchgear, and controls.

(U) The electric cable connectors between the generator and motor are lightweight and flexible and require almost no maintenance.. Operation is relatively lubrication free, thus minimizing the generation of fumes and, in turn, minimizing.ventilation requirements. Required speed output can be provided with proper sizing of the motor and generator. Motors and generators are bulky and heavy. Electric motors are, at best, 90% efficient and therefore require extensive cooling to dissipate power losses. In applications where reversing capability is required or a large number of remote outputs from a central input is desired, electrical systems warrant consideration.

(U) Shipboard systems are available up to 40,000 hp and through the development of supercooling may approach a specific weight of 15.5 lbs/hp. This compares with mechanical systems of 2 to 5 lbs/hp.

2.2.3.2.3 Superconducting Electric

(U) At very low temperatures (in the order of 4.2°K) the electrical resistivity of certain materials disappears. These materials, called superconductors, have current carrying capacities of up to three orders of magnitude higher than conventionally used copper, thus opening the possibility of designing electrical machinery offering substantial weight and volume reductions over conventional machinery.

(U) For a shipboard installation, a constant-speed prime mover drives a synchronous generator with a superconducting field winding. Cooling of the superconducting field is provided by circulation of liquid helium. A vacuum region surrounding the windings and thermal radiation shield serves as the principal means of insulation. A cycloconvertor, which changes the output frequency, is the primary means of speed reduction and control. A synchronous motor, similar to the generator, completes the system. This motor operates at a synchronous speed for a fixed frequency and, as the output frequency from the cycloconvertor varies, so does the speed of the motor.

(U) An equally important part of the system is the refrigeration plant. This plant provides liquid helium to the generator and motor to maintain the low temperatures required for superconductivity. Other components include a transmission bus to transmit the generated electricity to the cycloconvertor and motor, a braking resistor for dynamic braking, and miscellaneous switches and controls.

(U) The primary advantages of this system are the same as those for an electromagnetic system. The flexibility of the system allows the prime mover to be located anywhere on the ship and to transmit power to any number of motors without significantly affecting the size and complexity of the transmission system. In addition, the system weight estimate predicts a lightweight system, having a total specific weight of from 0.85 to 5.0 lbs per hp and an efficiency of about 95%. The refrigeration plant requirements are low, and plant weight is about 10% of the total system weight.

(U) At present, the state-of-the-art has not developed sufficiently to permit use of a superconducting electric transmission in a hydrofoil. The largest generator built to date is 6,700 hp (References II.B.2-4 and II.B.2-5). It is about 5 ft long by 3-1/2 ft in diameter. Additional development work on higher horsepower equipment is planned in England, Germany, and the United States. The U.S. Navy R&D plan includes step-by-step development up to 30,000 hp. These systems, if funded, would provide usable systems in the 1980 timeframe.

2.2.3.2.4 Comparative Data

(U) Table II.B.2-7 summarizes pertinent information on transmission systems.

(U) The mechanical gear system is at present the only lightweight, efficient system available in high horsepower ranges. As a result, the discussion of system components in the following sections will be limited to the components of a mechanical gear system.

Table II.B.2-7. CHARACTERISTICS OF TRANSMISSION SYSTEMS

System	Efficiency	Capacity (HP) **	Specific Weight (pounds/HP)
Mechanical*	97.0%	40,000	2.0-5.0
Superconducting electric	95%	6,700	.85-5.0***
Hydraulic	75%	4,000	a.8
Electra-mechanical	90%	40,000	15.5

• Typical ***system*** design with planetary gear box.

** All systems would demand a developmental stage to establish design reliability at powers quoted thereby establishing weight.

*** Depending upon refrigeration requirements and redundancy of critical sub-systems.

2.2.3.3 Component Design Standards

2.2.3.3.1 Gearboxes

(U) High-speed, heavy-duty applications demand the use of helical and/or spiral bevel gears. These gears run more quietly and have lower impact loads than other types because the contact surfaces between gears overlap, transferring the load gradually from one tooth to the next. Straight-tooth gear (spur), on the other hand, carry the entire load on only one tooth at a time, generating noise and instantaneous high loads. Double helical gears are most common in high-power, parallel, and concentric shaft applications. The two opposite sets of helix-tooth forms on each gear produce counterbalancing axial forces and eliminate the need for thrust bearings in the gearbox. With helical gears, wider total face widths can be achieved as compared with those of other gears. Spiral bevel gears are used to transmit power between intersecting shafts.. The thrust loads they produce must be absorbed by suitable thrust bearings.

(U) The gear case bearings and shafts must be compatible with the types of gears being used. Correct mounting is necessary to insure smoothness of operation, resistance to wear, and the maximum of strength and efficiency. The use of the vibration criteria of MIL-STD-167 (Reference II.B.2-6) will help insure continual smoothness of operation and less vibration associated component failures. Inspection of at least one gear of each pair without disassembling the gearbox is highly desirable. This allows setting the gears in assembly and for periodic inspection in service.

(U) The location of lubrication oil jets in the gearbox, provisions for draining, and the inclusion of local traps that can provide local lubrication on start-up before normal system flow is achieved, should be carefully designed into the internal gear case. Excessive wear and premature failure of components can result if lubricating oil is allowed to flow through successive gear meshes or bearings without filtration. Suspended material eroded from one gear set acts as an abrasive to speed wear on subsequent components it contacts.

(U) For initial estimating purposes, the weight of gearboxes can be taken as 0.30 lbs per hp for right-angle gears and 0.10 lbs per hp for planetary gears, based on a 10,000-hour life. These numbers will vary greatly, depending on the gearbox life service and construction. A procedure determining the weight and size of the gearbox, in greater detail, is outlined in Chapter III-B of Reference II.B.2-7 and is based on information presented in References II.B.2-8 through II.B.2-10. Reference II.B.2-11 also provides a preliminary design procedure for sizing high performance marine propulsion gearboxes for the 2,000-ton Surface Effect Ship, but this procedure can also be used for sizing hydrofoil transmission systems. Table II.B.2-8 presents the relative weights for gearing for different application and is an indication of the relative conservatism of gearbox design.

Table II.B.2-8. RELATIVE WEIGHTS FOR GEARBOXES

Application	* Relative Weights	Typical Construction
Aircraft	1.0	Magnesium and aluminum
Hydrofoil	1.2	Lightweight steel or aluminum
Commercial	2.0	Cast or fabricated steel

*Includes gearing, shafts, bearings, and immediate support structure but does not include accessories, such as lubrication.

(From Reference II.B.2-1)

2.2.3.3.2 Gear Tooth Design

(U) Standards published by the American Gear Manufacturers Association (AGMA) establish national industry-wide standards for gear design. These standards establish as a minimum, tooth proportions and profiles, surface durability, strength, and inspection and material requirements for various gear configurations. Since these standards are revised from time to time, the designer should assure himself that he is using the latest issue. AGMA quality 12 is usually used in design of high performance bevel gear systems.

(U) Additional nationally recognized engineering and manufacturing data for various types of gearing are also contained in the Gear Handbook (Reference II.B.2-12) written by D.W. Dudley.

(U) The spiral bevel gear tooth generation, most common in this country and which has been recommended for and used in existing hydrofoils, is the Gleason System. The general features of the system are the subject of a section of Gleason's Bevel and Hypoid Gear Design Handbook (Reference II.B.2-13).

(U) Reference II.B.2-14 contains a detailed reference listing of specifications, standards, and publications which are applicable to the various areas which are discussed. This document is considered a good reference for design information applicable to various transmission related components.

(U) Several U.S. companies have been involved in high performance hydrofoil transmission system design, development, and operatioh and have consequently developed recommended characteristics for high performance bevel gear transmission systems. These characteristics are considered to be within the state-of-the-art with regard to machinery design and manufacturing practices. Table II.B.2-9 illustrates a comparison of the transmission characteristics which various organizations have proposed for a large hydrofoil. The various characteristics are also compared with the characteristics of the AGEH-1 which have been demonstrated as obtainable. The last column of Table II.B.2-9 shows recommended characteristics for a large hydrofoil type foilborne propulsion transmission. These characteristics were developed from the various studies noted in Table II.B.2-9, which have met the criteria of either having been previously proven in a similar application, or being declared amenable to conventional design approaches.

2.2.3.3.3 Shafting

(U) Shafting is used to transmit power from the power plant to the propulsor. Unlike commercial vessels which may use solid mild steel shafting, naval vessels have used high-strength hollow steel shafting due to the ship's weight sensitivity. Ideally, solid shafting should be used in areas exposed to the seawater because this environment causes fretting and corrosion and reduces the fatigue limit of the shafting. With a solid shaft, a smaller percentage of the metal would be in contact with the seawater as compared to a hollow shaft. Solid shafting should be used at the bearing and couplings to minimize the size of these components.

Table II.B.2-9. BEVEL GEAR TRANSMISSION CHARACTERISTICS AND PARAMETER COMPARISON

BEVEL GEAR TRANSMISSION CHARACTERISTICS AND PARAMETER COMPARISON [3]

PARAMETER	GE STUDY FOR HYDRONAUTICS/ NAVSEC-DBH REPORT APPENDICES G&H-DEH RECOMMENDATIONS	DIEHL AND LUNOGAARO. INC. [1] REPORT ND. 7418-1-LHF RECOMMENDED CRITERIA	NAVSHIPS 0943-002-3010 [2] and D&L REPORT No. 7418-1 [1] 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.
100th 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 elax. [4]
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 35 @ 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

[1] Reference II. B.2-16

[2] Reference II. B.2-17

[3] Reference II. B.2-15

[4] Gleason Works presently recommends maximum pitch line velocity of 25,000 FPM

Table II.B.2-9. BEVEL GEAR TRANSMISSION CHARACTERISTICS AND PARAMETER COMPARISON (Continued)

PARAMETER	GE STUDY FOR HYDRONAUTICS/ NAVSEC-DBH REPORT APPENDICES G&H DEH RECOMMENDATIONS	DIEHL AND LUNDGAARD, INC. REPORT NO. 7418-I LHF RECOMMENDED CRITERIA	AGEH-1 AS BUILT	RECOMMENDED CHARACTERISTICS FOR A LARGE HYDROFOIL FOILBORNE PROPULSION TRANSMISSION
Gear arterial	Carburized AISI 9310	---	AISI 9310/AMS 6260	Carburized AISI 9310/AMS6260
Method oi gear manufacture	Gleason method (Cut, double carburized. HT to AC 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 CEVH 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

(U) The basic design criteria for shafting are discussed in Volume II of Reference II.B.2-14. Reference II.B.2-14 indicates that the conventional stress analysis formulas applicable to torsion, compression, column phenomena, and buckling from torsion or bending are considered adequate for hollow shafting design, and that there is no apparent need to develop new design criteria as long as all stresses are kept within conservative limits. Hollow and solid shafting of various materials are compared in the summary design section of Volume I, Reference II.B.2-14.

(U) The design criteria for strut shafting are discussed in Reference II.B.2-16. The design of hydrofoil strut shafts for rigid struts is fairly straightforward. The design of shafting for flexible struts is a more difficult problem, but has been successfully demonstrated on several existing hydrofoils. Reference II.B.2-16 also presents a recommended design procedure for flexible strut shafts.

(U) The specific weight per foot of solid steel shafting can be roughly approximated as 0.002 lbs per hp.

2.2.3.3.4 Couplings

(U) Couplings are needed to make semi-permanent connections between shafts. Basically, shaft couplings can be classified as rigid or flexible. Rigid couplings can be used to connect two components that are accurately located with respect to each other and do not move during operation. In view of the flexibility of hydrofoil struts, flexible couplings may be required to connect components located any distance apart.

(U) Flexible couplings can accommodate small amounts of lateral and angular misalignment, thus avoiding the stress that would occur if rigid couplings were used. Additionally, flexible couplings are capable of absorbing minor impacts due to fluctuations in shaft torque and speed. General information on some types of flexible couplings is given in Table II.B.2-10. These values will vary depending on the individual application and manufacturer. Gear couplings are generally used for applications over 10,000 hp and their flexibility should be adequate for hydrofoil applications over 10,000 hp. Diaphragm type couplings, which require no lubrication, are now available up to 20,000 hp.

Table II.B.2-10. TYPES OF FLEXIBLE COUPLINGS

(Reference II.B.2-1)

Type	Maximum Misalignment	
	Parallel	Angular
Gear	0.02 inches	1 ½ degrees
Chain	0.04 inches	2 degrees
Flexible	0.08 inches	1 degree
Diaphragm	~	2 degrees

(U) An approximation of coupling specific weight is 0.0018 lb/hp. The length is approximately 2 times the solid shaft diameter, and the outside diameter is approximately 1.7 times the solid shaft diameter.

2.2.3.3.5 Clutches

(U) Clutches are used to engage or disengage a rotating element from a prime mover without starting or stopping the prime mover. The clutch will generally be located between the prime mover and the gearbox, which allows the prime mover to rotate without driving the propulsor. Clutches considered for hydrofoil use transmit torque by three basic means:

- Positive: positive tooth or jaw
- Friction: disc or drum
- Eddy-current: electromagnetic field

(U) These clutches may be actuated electrically, hydraulically, or pneumatically. Specialized variations of these clutches include centrifugal, overrunning, synchro self-shifting, and synchromesh clutches. Centrifugal clutches engage automatically at a predetermined speed. Overrunning clutches drive in one direction only.

(U) The synchromesh clutch may be most suitable for main propulsion systems. 150 psi oil (or 100 psi air) is required for actuation and 50-watt, 115-volt electricity is required for control. Because of its normally positive engagement, this clutch does not require cooling. Maintenance and lubrication are minimal. Since the size of the clutch is a function of the torque transmitted, the unit should be located on the highest-speed shaft.

(U) An approximation of synchromesh clutch weight is 0.0045 lbs/in. lb of torque.

2.2.3.3.6 Bearings

(U) Marine line-shaft bearings are generally of the journal type (hydrodynamic) and depend on a film of oil lubrication (gravity-fed or forced) to reduce friction. They are usually conservatively designed and ruggedly constructed. Ball and roller bearings may be used with a resultant decrease in weight and in friction loss; there is also, however, a decrease in reliability and an increase in required maintenance when compared to the standard marine journal type. There is also an upper limit as to load carrying capability.

(U) Since bearings are likely to have the shortest life of any part of the transmission, ease of replacement must be a prime consideration. This may be achieved by using a special shaft design or split bearings. Bearing spacing must be determined through a complex vibrations analysis (see Reference II.B.2-18). An approximation of the number of bearings can be obtained by dividing the shaft weight by the bearing capacities. A maximum bearing spacing of 22 times the shaft diameter should be the limit. For light loads ball bearings can be used; for heavier loads roller bearings should be used.

(U) If heavy loads and increased temperatures are encountered, forced-oil lubrication is required.

(U) The outside diameter of a line shaft bearing and housing will be about 2½ times the solid shaft diameter, and the length will be about equal to the solid shaft diameter. An approximation of specific weight is 0.0004 lb/hp.

(U) For propeller-driven ships, two thrust bearings are required per propeller shaft. As are line-shaft bearings, thrust bearings are usually conservatively designed and ruggedly constructed oil bearings. The use of aluminum housings can reduce the weight of these bearings by about 30%. The thrust loads and speeds encountered in a hydrofoil propulsion system permit the use of roller thrust bearings. Current heavy duty, high speed roller thrust bearings have a practical limit of over 100,000 lbs thrust at speed up to 1000 rpm. The lubrication system for this type of bearing requires particular attention to insure a satisfactory oil film and heat dissipation.

(U) Alternate means of supporting the thrust load are oil bearings in which the thrust load is supported on a film of lubrication. The efficiency of these bearings is about 99.7%. Forced-oil lubrication is required to maintain the film and dissipate heat. The height and width of these types of thrust bearings with aluminum housing is approximately three times the solid shaft diameter. The length is about 1.5 times the width. Oil film bearings are considerably heavier than roller bearings, having an approximate specific weight of 0.17 lb/hp.

(U) For waterjet-driven ships, the thrust bearing would be an integral part of the pump, and is not considered a part of the transmission system.

2.2.3.3.7 Lubrication

(U) A lubrication system is required for cooling and for reduction of friction in gearboxes and thrust bearings. The cooling requirements determine the size of the lubrication systems, which includes pumps, reservoir, heat exchanger, piping, valves, and filters.

(U) Adequate filtration of the lubrication oil is mandatory to transmission longevity. The filter should have sufficient capacity for the required flow rate as well as storage for the trapped contaminants. Provisions for easy cleaning or filter cartridge replacement are conducive to frequent servicing.

(U) The heat exchanger is the largest component in the system. Either air or seawater can be used for cooling. With an oil-air heat exchanger, fans are required to ensure a sufficient air flow. A more conventional approach would be the proven, compact internal oil-seawater exchanger, with a pump and piping system providing the supply of seawater to the heat exchanger.

2.2.3.4 Transmission Problem Areas

(U) Many of the problems associated with bevel transmission, which have been experienced by U.S. Navy hydrofoils, have been attributed to support systems and not the ability of the gears to carry the load. Table II.B.2-11 lists various large Zee-drive hydrofoil transmissions, their power ratings, and operating hours and major problems encountered.

Table II.B.2-11. HYDROFOIL ZEE-DRIVE TRANSMISSION

(Reference II.B.2-19)

SHIP	POWER	YEAR DELIVERED	TOTAL FOILBORNE HOURS AS OF 15 AUGUST 1974	MAJOR PROBLEMS AND COMMENTS
DENISON	13,000 HP	1962	416	Minor bearing and lubrication problems during builders trials and de-bugging. Water leaks in the strut caused some beating failures. Trouble free after delivery IO Navy.
HIGH POINT	3,500 HP	1963	970	Water in transmission system due to seal leaks and salt water inlet piping leaks. Ball bearing retainers laded due to corrosion at 330 houtr. Refurbished transmission. Operated trouble free until Mod I overhaul at 690 houtr. Trouble free since Mud I overhaul.
FLAGSTAFF	3,800 HP	1968	672	During the first 351 hours. systems was essentially de bugged on the ship rather than in bench tests. Major failures were a fatigue crack in web of an idler gear due IO stress analysis error, and repeated bearing failures in some axial bearings with insufficient clearance to allow for thermal growth. Since these deficiencies were corrected, transmission has operated 650 foilborne hours and 300 hiyh speed hullborne taxiing hours trouble free.
BRAS d'OR	24.000 HP engine split to IWO 12,000 HP ZEE drives.	1968	100	Major design problems eliminated by extensive bench testing. Minor lubrication problem on down shaft bearings corrected early in trials. No problems after this. An additional 100 hours were placed on the transmission during high speed hullborne operations.
PLAINVIEW	17,000 HP	1969	196	Coupling wear due IO misalignment. New coupling designed IO take large misalignments being installed. Major gear bones have been trouble free.

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(U) Figure II.B.2-26 presents the service experience for the Zee-drive transmission in greater detail as it illustrates failures per 1,000 foilborne operating hours for the lube system, gearboxes, shafts, etc., and is indicative of the learning process during that period of technology development. Note that the AGEH-1 system, using higher power levels than the previous ships and with an updated transmission configuration, has performed well in the basic mechanical area, but has a high incidence of lube oil system casualties.

2.2.3.5 Gear Manufacturing Limitations

(U) The maximum available gear diameter which can be generated is limited by the present industrial manufacturing facilities. Table II.B.2-12 presents the current limitations on gear diameters. Larger machine tools are available in the free world, but are not as accurate, especially at larger sizes. Grinding accuracy is essential for high speed, heavily loaded gears.

(U) Table II.B.2-12 has demonstrated that the gear generator is the primary limitation. It is conceivable that larger bevel gears could be produced without a generator. This manufacturing process is expected to be:

- Rough slot on boring mill to remove approximately 80% of tooth space
- Soft grind rough tooth shape
- Carburize
- Hard grind final tooth shape

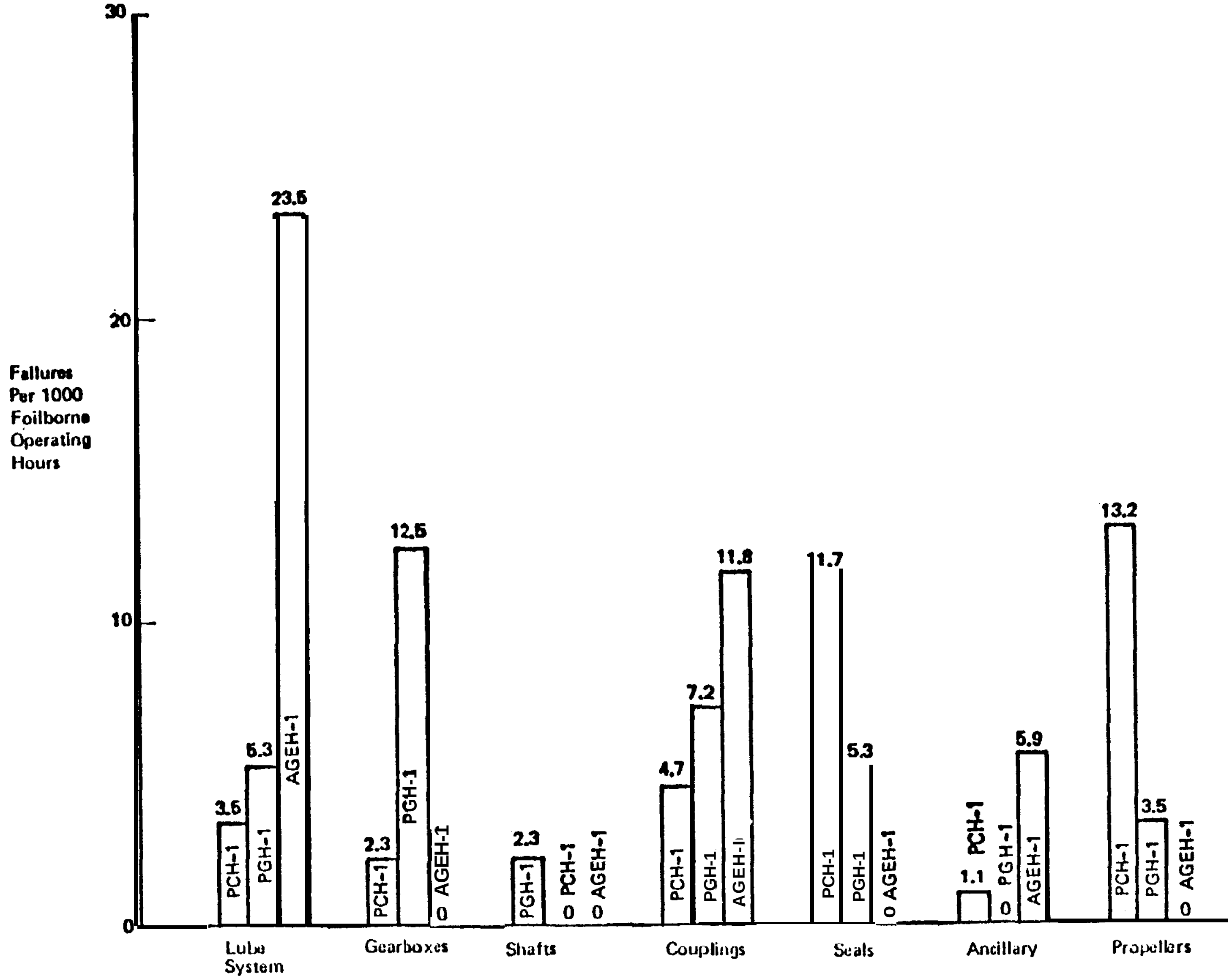

Figure II.B.2-26. FAILURE RATE BY COMPONENTS

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Table II.B.2-12. CURRENT MANUFACTURING LIMITATIONS ON BEVEL GEAR DIAMETERS

Reference II.B.2-16

Machine	Gear Ratio	Approximate Diameter Limit
Gleason Model 26 Generator	1x1	26"
	1.5x1	28"
	2x1	30"
	10x1	33 "
Gleason Model 137 Grinder	1x1	34"
	2x1	36"
* Gleason Model 650 Hypoid Generator	1x1	34"**
	2x1	34"
	10x1	34"
Gleason Model 655 Hypoid Generator	1x1	25 "
	2x1	31.5"
	4x1	3 4 "
	10x1	35"

* This machine is expected to become operational later this year. The limitations of the machine have not yet been fully determined.

** Must be followed by grinding operation on Model 137.

(U) This process is more suitable to a one-of-a-kind program, rather than for a reliable, multiship program. Therefore, it is not recommended as a possible alternative here.

2.2.3.6 Transmission System Testing

(U) There is a certain amount of design risk associated with a new hydrofoil transmission system. This risk is somewhat greater than a new design for a conventional naval vessel, but less than that associated with a developmental transmission. Since hydrofoil transmission design has not yet reached the confidence level enjoyed by conventional naval vessels, proper testing is bound to uncover some deficient areas in the new system. Discovering a deficiency of this type could be untimely if it occurred during or after sea trials of a new ship. Therefore, the basic objective of testing a new hydrofoil transmission system would be to advance it to the higher confidence level enjoyed by conventional vessel designs, long before the transmission system hardware is installed on the ship.

(U) Test methods for the transmission system will vary acording to how close the design approaches the developmental stage and how much funding is available. Test methods could include such tests as individual component testing, back-to-back torque speed testing for gearboxes, shore-based system testing or at-sea system tests, where the transmission system is installed and tested on a waterborne craft. It is obvious that the quality of the test results is directly related to how closely the test method(s) approach actual shipboard installation. Successful and meaningful tests do not just happen, they must be planned and developed sufficiently in advance of actual shipboard installation to prevent major and time-consuming changes (if they are required) from delaying delivery of the ship. In any event, they are considered mandatory in any new transmission system development. MIL-G-17859 can be used as a guide for the types and duration of testing, quality assurance, and inspection procedures which should be invoked.

2.2.4 Propulsors

2.2.4.1 Components on Existing Hydrofoils

(U) No one particular type of hullborne or foilborne propulsion system design can be said to be standard for U.S. Navy hydrofoil ships. Several different combinations of propulsors have been used on the hydrofoils which have been constructed. The propulsion systems for each ship have been individually designed to meet the requirements of each specific ship. Table II.B.2-1 illustrates the various types of hullborne and foilborne propulsors which have been used on U.S. Navy and Canadian Navy hydrofoil ships.

2.2.4.2 Physical Characteristics of Propulsors

(U) Compared with conventional ships, the hydrofoil places unusual requirements on the propulsor because of the resistance hump at takeoff. A propulsor which is optimized for top foilborne speed may be inadequate at takeoff, and vice versa. However, suitable compromises have been demonstrated and optimized.

(U) In general, propulsors are compared on the basis of the efficiency achieved and of the weight and space required for the propulsor and transmission. Reliability is also a consideration. In addition, for ships involved in ASW missions, the noise radiated by the propulsor is an important evaluation factor. More data on radiated noise of propellers and waterjets are required in order to better select a propulsor based on minimum noise over the speed range.

(U) The relative efficiency between a propeller or a waterjet propulsion system is illustrated in Figure II.B.2-27 by a comparison of propulsive coefficient and shaft horsepower per ton, to the ship's speed. It is readily evident that the low propulsive efficiency of the waterjet represents a severe performance penalty.

2.2.4.3 Propeller Performance Characteristics

(U) Propelling high speed ship, i.e., ships with speeds greater than about 50 knots, at acceptable efficiencies with subcavitating propeller designs is not practical. The propeller would be cavitating at speeds greater than about 45 knots. Just like in supersonic flight, new approaches have been taken. Past a certain speed depending on a variety of conditions, cavitation must be lived with. If the imploding forces associated with cavitation exist, then one solution is to arrange that the collapse of the cavities takes place away from the blades or structure. Development along these thoughts has resulted in supercavitating propellers and hydrofoils. These systems accept the losses due to the presence

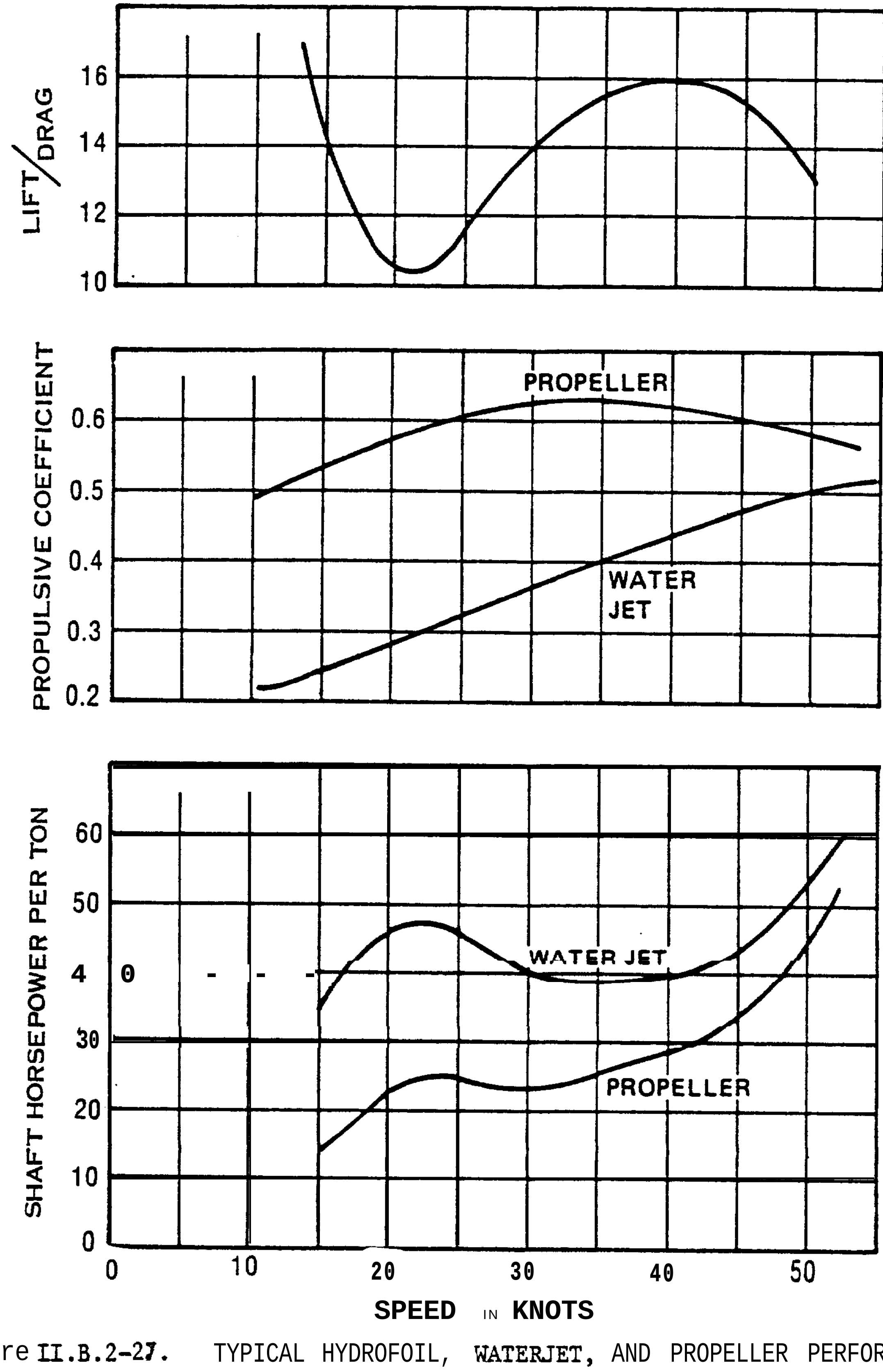


Figure II.B.2-27. TYPICAL HYDROFOIL, WATERJET, AND PROPELLER PERFORMANCE of the cavity, but circumvent structural and material problems. The supercavitating propellers are run at a sufficiently high speed that a well-defined cavity is formed on the suction face and does not collapse until well downstream of the blade. While supercavitating efficiencies are generally lower, they nevertheless persist into the higher speed regimes.

(U) Supercavitating propellers take on profiles (Figure II.B.2-28) that represent considerable departures from subcavitating propeller practice. There are two factors that dictate these shapes. The first is fluid dynamics, or the requirements that the cavity forms cleanly and collapses clear of the blade. The second is structural. From the minimum blade loss viewpoint it would be desirable to have as thin a blade section as possible; however, the propeller thrust is transferred through the blades to the hub and then to the shaft and vessel. To support these loads, the blades must have an appreciable cross section.

(U) Conventional subcavitating marine propellers are not suitable for very high speed propulsion. Operating speeds over 45 knots are practical only for short periods. Sustained operation at such speeds will result in excessive cavitation erosion damage to the propellers and probably also to any ship structure in the propeller wake. By contrast, supercavitating and superventilated propellers are designed to operate with the back or suction side completely enclosed within the vapor cavity. For a super-ventilated propeller, a cavity is ensured by introducing air to the backs of

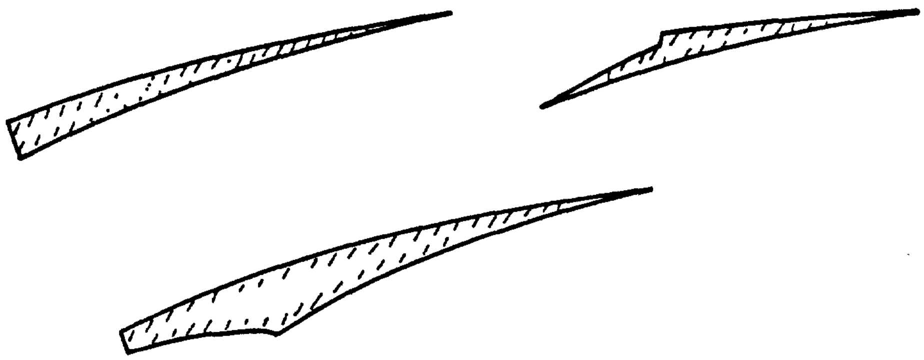


Figure II.B.2-28. SAMPLE SUPERCAVITATING BLADE SECTIONS

the blades. Supercavitating type propellers can operate fully or partially submerged. Partially submerged propellers *are* almost *al*-ways superventilated, while fully submerged propellers can be either supercavitating or superventilated.

2.2.4.3.1 Propeller Design Standards

(U) In summary, it is reasonable to state, as Kruppa does (Reference II.B.2-20) that all supercavitating propellers tested as models or run at full scale to date, have to be regarded as empirically designed.

(U) Since 1969, there is no evidence of any significant *major* advancements in the state-of-the-art in available technical literature. Data becoming available from the SES 100B test craft seem to indicate that the design methods in use have not proved adequate in predicting full-scale supercavitating propeller performance, even after design modifications have been made from model data and experience.

2.2.4.4 Waterjets

2.2.4.4.1 Waterjet Physical Characteristics

(U) Waterjet propulsors have been employed successfully in high speed displacement craft, hydrofoils, and in one of the current 100-ton SES test craft. As in any propulsive device, the waterjet produces thrust by accelerating a working fluid (water) to achieve a net change in the momentum of the fluid equal to the thrust generated. The basic components of a waterjet propulsion system are:

- An inlet to ingest water and usually an associated inlet diffuser to reduce the velocity and increase the pressure of the fluid.
- A duct which transfers the ingested water to the pump and can also further diffuse the flow.
- A pump driven by a suitable prime mover, which increases the pressure and velocity of the water.
- A discharge nozzle which further increases the water velocity and can be movable for purposes of steering control. The components of a typical hydrofoil waterjet propulsion system are shown schematically in Figure II.B.2-18.

Pump Configuration:

(U) Pumps are normally divided into three classes, which are characterized by the direction of flow through the impeller as (1) radial flow (or centrifugal), (2) mixed flow, and (3) axial flow (or propeller). They can also be classified according to the head developed as (1) high head, (2) intermediate head, and (3) low head.

(U) These qualitative classifications are somewhat overlapping. For a flow rate (Q) that is relatively low, and a head (H) that is relatively high, a centrifugal pump is usually used. For a relatively high flow rate and low pump head, an axial inducer pump is used. For higher pump heads, multistage centrifugal or axial pumps can be used. To obtain higher pump speeds at low inlet suction pressures, a double-suction centrifugal pump is sometimes used. An inducer pump will invariably be used as a first stage of a multiple-stage axial pump and inherently has the highest suction performance of any impeller type. Additionally, a two-speed, coaxial-shaft two-stage pump is sometimes used to achieve high suction performance with a low rpm stage and high pressure with a high rpm stage. These various multiple-stage pumps are schematically illustrated in Figure II.B.2-29.

Available Pumps:

(U) Waterjets are in production or under development in the power range from less than 101 mhp (100 hp) to 40,560 mhp (40,000 hp). A summary of characteristics of some waterjets in production in 1975 has been prepared in Table II.B.2-13, and the specific weights versus horsepower are plotted in Figure II.B.2-30. The principal purpose of this compilation is to determine typical waterjet specific weights, volume, and rotational speeds for power plant sizing purposes.

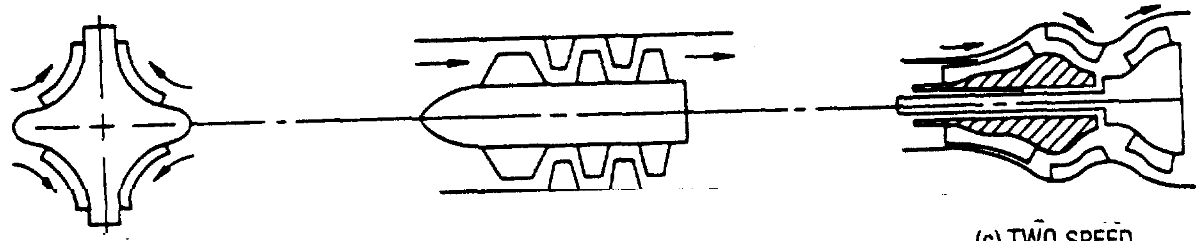


Figure II.B.2-29. VARIOUS MULTIPLE-STAGE PUMPS

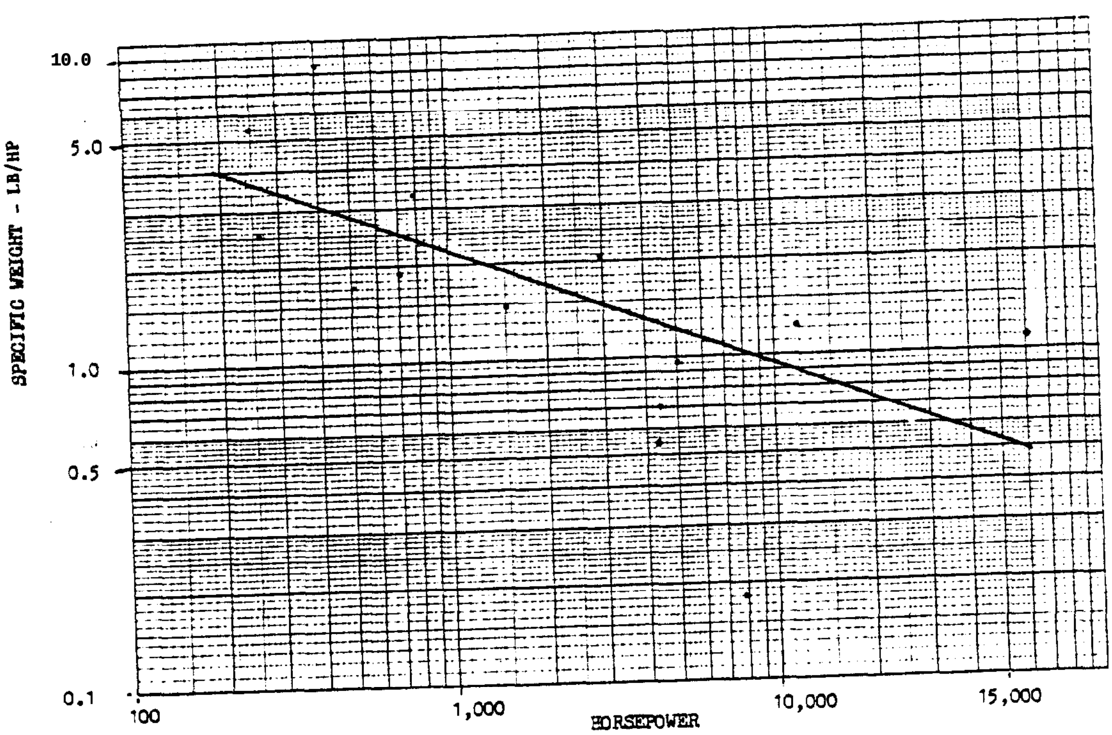


Figure II.B.2-30. SPECIFIC WEIGHTS (WET) OF WATERJETS IN PRODUCTION

Table II.B.2-13. CHARACTERISTICS OF PRODUCTION AND DEVELOPMENTAL WATERJETS (1976)

Manufacturer and Model Number	Range of Performance Characteristics								
	Maximum Input MHP (HP)	Pump Speed RPM	Static Thrust Kg (lb)	Flowrate liters/min (GPM)	Pump Efficiency %	Volume Pump Overall M^3 (ft^3)	Weight (dry) Kg (lb)	Weight (Wet) Kg (lb)	Spec Wt. (wet) Kg/MHP (lb/HP)
Aerojet AJW-250	249 (246)	1,550	2,245 (4,950)	N.A.	N.A.	1.83 (64.6)	365 (805)	601 (1,325)	2.41 (5.39)
Aerojet AJW-400	406 (400)	730	2,753 (6,070)	107,494 (28,400)	71%	2.34 (62.7)	953 (2,100)	1,520 (3,350)	3.74 (8.38)
Aerojet AJW-800 (PHM-HB pump)	801 (790)	900	4,740 (10,450)	116,200 (30,700)	90%	3.79 (134)	644 (1,420)	1,207 (2,660)	1.51 (3.37)
Aero jet AJW-3,000	3,001 (2,960)	a m	11,340 (25,000)	227,100 (60,000)	84%	4.68 (165.2)	1,302 (2,870)	2,799 (6,170)	.93 (2.08)
Aerojet AJW-4,500	4,502 (4,440)	5,200	9,979 (22,000)	95,382 (25,200)	86.6%	2.38 (84)	998 (2,200)	1,402 (3,090)	.31 (.70)
Aerojot AJW-8,000 (SES 100A pump)	8,000 (7,890)	4,465	11,612 (25,600)	77,593 (20,500)	87%	1.51 (53.3)	399 (880)	649 (1,430)	.08 (.18)
Aero jet AJW-12,000	11,965 (11,800)	1,023	25,402 (56,000)	253,595 (67,000)	87%	5.21 (184)	4,001 (8,820)	6,500 (14,330)	.54 (1.21)
Aerojet AJW-18,000 (PHM-FB pump)	16,224 (16,000)	3,040	35,834 (79,000)	355,790 (94,000)	87%	16.0 (564.8)	5,702 (12,570)	8,002 (17,640)	.49 (1.10)
Aerojet (2K SES pump)	40,560 (40,000)	4,098	65,908 (145,300)	480,317 (126,900)	83.1%	N.A	N.A	N.A.	N.A.

UNCLASSIFIED

Table II.B.2-13. CHARACTERISTICS OF PRODUCTION AND DEVELOPMENTAL WATERJETS (1976) (Continued)

Manufacturer and Model Number	Range of Performance Characteristics								
	Maximum Input MHP (HP)	Pump Speed RPM	Static Thrust Kg (lb)	Flowrate liters/min (GPM)	Pump Efficiency %	Volume Pump Overall M^3 (ft^3)	Weight (dry) Kg (lb)	Weight (Wet) Kg (lb)	Spec wt. (wet) Kg/MHP (lb/HP)
Jacuzzi 14YJ	264 (260)	3,000	1270 (2,800)	N.A.	N.A.	.27 (9.4)	245 (540)	302 (665)	1.14 (2.56)
Jacuzzi 20J-HP	710 (700)	2,400	1474 (3,250)	N.A.	N.A.	.76 (26.9)	499 (1,100)	601 (1,325)	.85 (1.89)
Rocketdyne Powerjet 16	1,521 (1,500)	2,2m	3,357 (7,400)	68,887 (18,200) (2)	N.A.	1.49 (52.6)	885 (1,950)	998 (2,200)	.66 (1.47)
Rocketdyne Powerjet 20	4,360 (4,300)	2,250	8,165 (18,000)	87,623 (23,150) (4)	N.A.	1.44 (50.9)	777 (1,712)	1.055 (2,326)	.24 (.54)
Rocketdyne Powerjet 24	5,070 (5,000)	1,750	8,845 (19,500)	170,325 (45,000) (3)	N.A.	4.19 (147.9)	1,769 (3,900)	2,177 (4,800	.43 (.96)

(1) Weight without steering and reversing bucket
(2) Flowrate at 2000 rpm and at 30 knots
(3) Flowrate at 1640 rpm and at 30 knots
(4) Flowrate et 2080 rpm and at 30 knots

(U) Figure II.B.2-31 shows the power density (power/volume) of typical 1975 production (or close to production) waterjets in the power range from 202 to 18,252 mhp (200 to 18,000 hp). The waterjet volumes on which these data were computed are based on a rough estimate of total waterjet installation volume including the ducting inside and outside the craft. If the exact waterjet volumes were used, the values of Figure II.B.2-31 would increase by an estimated factor of about 2.

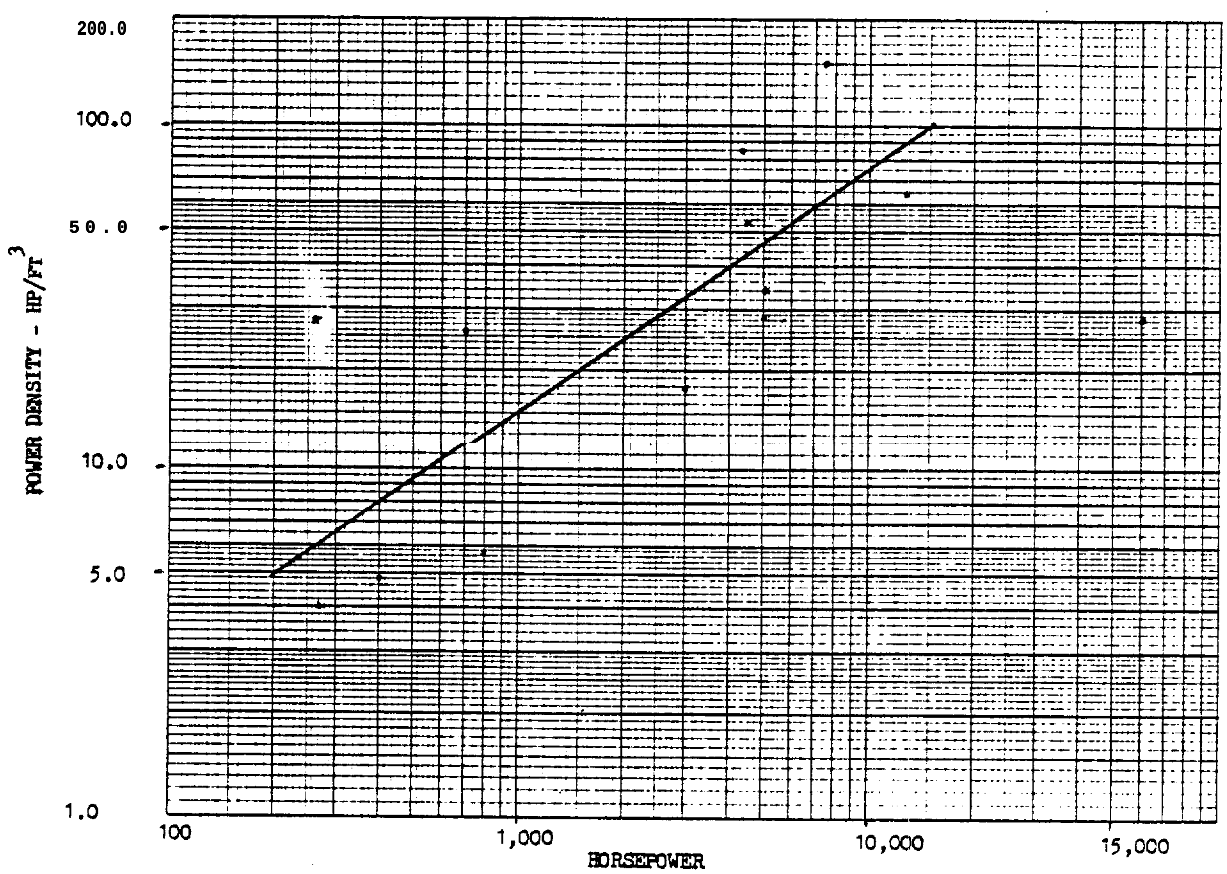


Figure II.B.2-31. POWER DENSITY OF WATERJETS IN PRODUCTION

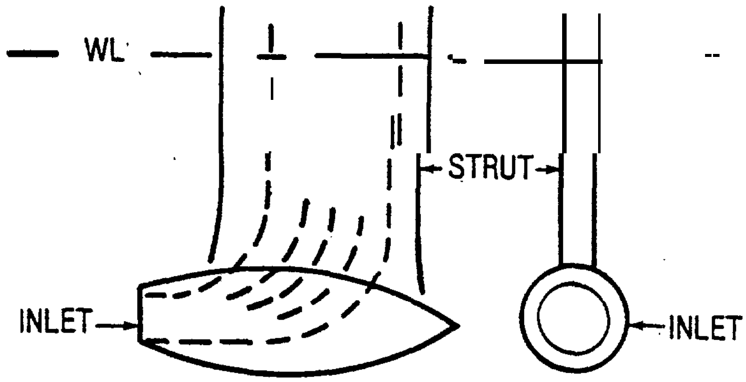
Types of Inlets:

(U) Two basic types of inlets used for a waterjet are: (1) flush or semi-flush and (2) pod-strut or ram inlet.

(U) Figure II.B.2-32 illustrates a typical inlet of the pod-strut type which usually has the opening away from the ship's hull and which is generally restricted to a foilborne propulsion system. Figure II.B.2-33 illustrates typical flush type inlets which have the inlet opening adjacent to or buried within the hull. This type of inlet is generally restricted to the hullborne propulsion systems .

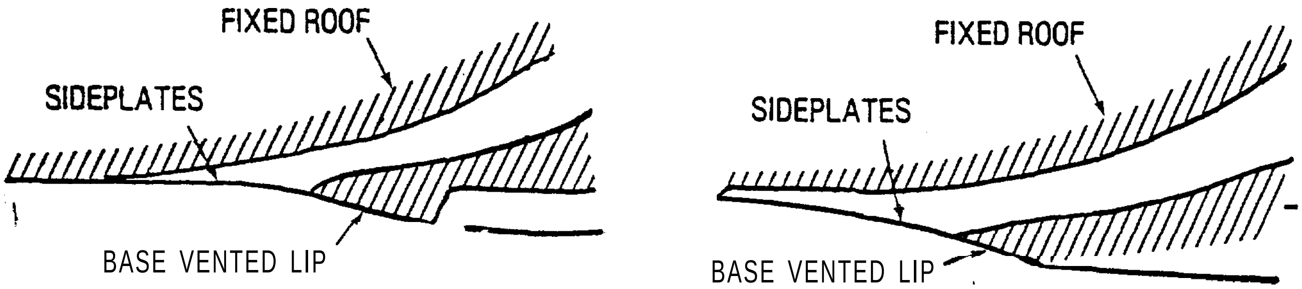
(U) This use of pod-strut type inlets seems natural for hydrofoils, which have struts for hydrofoil support. Typical modern hydrofoil configurations are canards, with one small foil forward and two foils aft or one large aft foil with two struts. The use of two aft struts permits the use of two inlets and independent waterjet systems, a desirable feature. For many hydrofoil systems, pods are required at strut-foil intersections to avoid cavitation or to house foil actuators. The existing pods and struts can also be used to house inlet systems, although some increase in pod and strut size may be required, and some interference of inlet and machinery may result. A semi-flush inlet could be used below the foil, but the ducting into the strut would probably require a large pod-like fairing, negating any possible benefits.

(U) For hydrofoils with deep foil submergence, the entire inlet may be located in the strut, eliminating the need for



FIXED AREA, POD ONLY INLET
(FULLY WETTED POD AND STRUT)

Figure II.B.2-32. TYPICAL POD STRUT TYPE IX-LET



A. FIXED AREA, FLUSH INLET

B. FIXED AREA, SEMI—FLUSH INLET

Figure II.B.2-33. TYPICAL FLUSH TYPE INLET a pod. For most hydrofoils, however, the strut length which remains submerged in rough water is usually rather small, necessitating a thick, high-drag strut to provide adequate submerged inlet area. A pod inlet will therefore be required, perhaps in combination with a strut inlet, for most hydrofoil ships. The use of variable area pod inlets are not recommended, as they are complex and untried.

(U) For the hullborne mode of hydrofoil propulsion where the inlet can be expected to remain fully submerged and non-ventilated at all times, flush type inlets are clearly desirable, not only because of their lower drag, but also because of their ability to ingest some portion of the boundary layer. Both factors will lead to greater waterjet system performance. The amount of the total boundary layer ingested is a function of inlet size, aspect ratio, location, ship beam, and other factors.

2.2.4.4.2 Waterjet Performance Characteristics

(U) The most significant single performance parameter of the system is the propulsive efficiency at the design point. The propulsive efficiency is sensitive to unavoidable hydrodynamic energy losses in the jet and in the individual subsystems. Internal losses are caused by friction, flow turning and separation, flow splitting, and diffusion. External losses are caused by external diffusion losses and inlet drag. An additional penalty is incurred by friction on the increased wetted area of the hull which must be enlarged to incorporate the waterjet for the hullborne system.

(U) Most of the design effort is devoted to the avoidance of flow phenomena that lead to energy losses. These phenomena are flow separation, cavitation, and ventilation. Little can be done to avoid the viscous friction losses.

(U) The formation of vapor cavities increases the probability of ventilation of the cavity from nearby sources of air. Ventilation is generally restricted to the hullborne propulsion system.

(U) Ventilation occurs when a continuous air supply is established to a low-pressure region in the flow. Ventilation may be induced by cavitation or by flow separation. Ventilation is a potential problem in designing the inlet. If ventilation at the inlet occurs in such a way that continuous air ingestion results, the system may be rendered practically inoperative.

2.2.4.4.3 **Waterjet** Design Standards

(U) Design of the inlet and diffuser system has presented a considerable challenge to designers. Theoretical procedures have been developed by a number of agencies for design and analysis of inlets and diffusers. The correlation of theory and test data has been partially documented in References II.B.2-21 through II.B.2-28. In each case, there has been some measure of success, and each theory has been improved by an adjustment of empirical data.

(U) The design of the pump and its components has been somewhat less complicated than the design of the inlet system.

Pump components are sized for stresses imposed by fluid pressures and momentum forces, external interface loads, and acceleration loads. The loads selected for structurally sizing each component are taken at the most extreme load condition that can exist for each component. The design safety factors used are based on stresses caused by the structural design loads, number of stress cycles experienced during the design life, and guaranteed minimum available material properties.

(U) The pump housing is designed for the following types of loads: (1) internal pressure, (2) separating loads, (3) momentum loads, (4) thrust and mount reaction loads, and (5) acceleration loads. The structural sizing of the pump housing is based on the basic considerations of strength and stiffness.

(U) Selection of materials for a waterjet pump assembly is specifically oriented toward seawater service and marine environment. The factors to consider in selecting materials are salt water corrosion, electrolytic corrosion, cavitation resistance, resistance to high-velocity seawater impingement, and mechanical properties. The length of service, the configuration of the particular component, future design growth (size and stress parameters), fabrication technology, and material costs are also considered.

(U) Concurrently with the design process should ideally be a model test program. The complex flow fields associated with waterjets include viscous boundary layer flow, free-surface phenomena, vapor cavitation, and ventilated flow. The performance of a waterjet system is therefore a product of the interrelationships of the components and the flow phenomena. Appropriate experimental facilities provide simulation of the flow conditions for individual components and combinations of components of the system allowing performance to be evaluated. This type of program provides an opportunity for design changes to be made which will improve system performance.

(U) In addition to model testing, there is an essential requirement for a full-scale test program prior to installation of the components on the ship. Although model testing helps prove out a potential design extending existing technology to larger pump sizes will generally require a period of debugging during which time the confidence level of the pump is increased to a more acceptable level. This period of debugging is ideally performed at a land-based test site where test conditions can be controlled and meaningful data collected. Ideally, this debugging period would take place prior to the ship trials so that sufficient time would be available to correct any defects which are discovered. Unfortunately, this is not always possible, as was the case of the recently completed waterjet pump for the PHM-1. Delays in the establishment of an adequate land-based test site forced concurrent land-based testing and ship board trials. The unfortunate result of the concurrent testing is that the problems which have developed have caused some delays in the ships test and acceptance trials. This current example helps reinforce the argument in favor of land-based testing prior to installation of the pump into the ship.

(U) In addition to a test program for the first of a kind production waterjet pump, new design and manufacturing standards are required and are presently being developed. These new standards are to cover (at a minimum) the areas of design, performance, metallurgy, manufacturing, quality assurance, and quality control. These new standards are presently being developed by NAVSEC and will be issued in the form of a MIL-SPEC.

2.2.4.4.4 Recent Waterjet Failures

(U) In recent waterjet propeller hydrofoil ships, Boeing JETFOIL and PHM-1, problems of the type to be expected in a developmental program have occurred during the test and introduction phases. The JETFOIL experienced inability to produce design thrust at the design point. The system was analyzed and internal pump flow changes were initiated (stator angle) to better line up the flow from the exit of the first stage impeller into the stator, thereby reducing swirl with a consequent improvement in performance. Cavitation erosion has been experienced in some internal flow passages within the PRM-1 pump. A change has been made to a more cavitation-resistant material. Inlet duct and pump inducer housing fatigue failures have been corrected by structural stiffening combined with additional material changes.

(U) The speed range of the presently anticipated hydrofoils, dictates an optimum jet velocity ratio (V_j/V_i) thereby limiting the performance that the waterjet system contributes to overall plant efficiency. There are numerous Navy funded programs which are attempting,, to make waterjet system efficiency, including inlets, diffusers, pumps, and nozzles, more in line with cavitating propeller performance. Some of these programs, if funded, will yield higher efficiencies but are still bounded by the hydrodynamic constraints of the generic system. Nonetheless, the intrinsic reliability of the system, keynoted by reduced numbers of moving, highly stressed parts still makes waterjet systems viable candidates for hydrofoil propulsion systems. Trade-off studies have to be performed in the early stages of design to compare propellers and waterjets using reliability, performance, weight, space, and cost as criteria.

2.3 KEY INTERFACES BETWEEN PROPULSION SYSTEM AND OTHER VEHICLE SYSTEMS

(U) Installation and interface guidelines are given in Reference II.B.2-30.

2.3.1 Air Inlet/Demisting/De-icing Systems

(U) The inlet ducting brings combustion and cooling air to the engine. Air intakes are large, and adequate space allowance must be made for them. An essential consideration in arrangement is to minimize pressure losses by maintaining low duct velocities and smooth runs.

(U) Engine cooling air is usually about 10 percent of the combustion air requirements. Acceptable inlet duct velocities are 50 to 90 ft/s. From these data the duct cross-sectional area can be determined. Typical values of ducting pressure drop for the ducting alone are between 0.5 and 1.0 inches of water.

(U) Installed in the inlet duct are a screen and inlet filter, or demister, which prevent foreign objects and water spray from entering the engine. Typical pressure drops for those two components are 0.5 inch to 2.5 inches of water.

(U) Basically, there are two methods of water removal, inertial demisters and knit mesh demisters. Inertial demisters consist of turning vanes, the water is thrown outward in turning and clings to the surface of the vanes due to the centrifugal effect. The principal advantage of the inertial demister is that it is relatively small and does not require a great deal of attention; however, water removal efficiency at low air flows drops off quite rapidly. The knit mesh demister filters and coalesces the water particles. The efficiency of the knit mesh demister remains high over the entire air flow range, and pressure drops are lower than with inertial demisters (1.5 to 3 inches of water versus 2.5 to 3.5 inches of water). The disadvantages of the knit mesh demisters are that they are heavier and require more space and maintenance than inertial demisters. Approximately 1 sq ft of knit mesh demister is required for every 200 hp of engine being served.

(U) Several applications consider both types to assure maximum demister efficiency over a wide span of inlet velocities and moisture particle size.

(U) The internal duct material should be resistant to corrosion caused by the saltwater-laden air. Aluminum and stainless steel are recommended. For weight-estimating purposes, it is appropriate to use figures for insulated duct of 6 **lbs/sq** ft of duct surface area for large turbines and 4 **lb/sq** ft for turbines below 5,000 hp. In selecting duct size, consideration should be given to the possiblity of removing the gas generator section through the inlet duct. This method is frequently adopted, as it provides quick and easy access from the weather deck to the engine room. The inlet duct should be oriented to preventing the ingestion of salt spray and exhaust gases. Inlets preferably face inboard or aft and are located below the exhaust stacks. Louvers can be used to advantange in reducing ingestion.

(U) A flexible joint connects the inlet duct to the turbine inlet and to the chamber around the engine, which directs air over the engine for cooling. This joint provides for engine thermal expansion. Adequate space should be provided for the intake plenum in front of the engine. It is desirable to have a separate plenum for each engine because intake flow-pattern distortions result when two engines compete for air.

(U) Under circumstances where freezing temperatures are anticipated, provisions should be made for de-icing and possibly for bypassing the inlet filter-separator by a blow-in door. Hot compressor-bleed air is generally used to provide sufficient heat to prevent the formation of ice. An electric heating system applied to the engine inlet fairing can also be used. The electric power requirement is about 1 kw per 3,000 hp. These features are optional on the engine itself.

(U) In design, consideration is also given to missile firing efflux and air inlet location of the gas turbine engine. Pressure, temperature, and chemical analyses are performed on the missile efflux to assure adequate gas turbine engine margins.

2.3.2 Exhaust Ducting

(U) The ducting must be designed to minimize duct pressure loss, resist exhaust gas temperatures on the order of 1,000°F, and provide attenuation of exhaust noise.

(U) The duct is sized to maintain exhaust gas velocities of 100 to 200 ft/s. The exhaust gas includes both engine exhaust and engine external cooling air. The cooling air is drawn into the exhaust duct by an eductor or a fan. The fan has the advantage of permitting engine cooling after shutdown.

(U) As with the inlet ducting, the exhaust ducting is rigidly supported by the ship's structure, and a flexible connection to the engine is required to accommodate engine thermal expansion. The duct itself is usually thermally and acoustically insulated. Silencers can be installed for additional sound attenuation. For weight-estimating purposes, it is appropriate to use figures for insulated duct of 7 lbs/sq ft of duct surface area for large turbines and 5 lbs/sq ft for turbines below 5,000 hp.

2.3.3 System Interfaces to Engine

(U) On the larger horsepower engines, certain portions of support systems can be mounted outside the engine enclosure and be connected to the remaining portions of the same system that are engine-mounted.

(U) For the lube oil system, these off-engine components may include lube oil tanks, lube oil/seawater coolers, duplex filters, mist precipitators, control valves, seawater pumps, and associated piping.

(U) The electrical system provides sensing, protection, ignition, and control services to the engine. Control power is normally obtained from the ship auxiliary power system. About 1 kw is required for a typical 39,000-hp engine.

(U) An engine starter is required to motor the gas generator to a minimum speed before the fuel is ignited. Once the fuel is ignited, it continues to burn of itself, and the engine starter is turned off. Starting time required is about 1 to 2 minutes.

(U) Starting systems can be hydraulic, pneumatic, or electrical. Larger engines, such as the LM 2500 and the FT 4, are restricted to use of hydraulic and pneumatic starters. For these large engines pneumatic starter-system requirements are about 160-200 lb/min of air at 38/41 psi. This air can be supplied by one auxiliary power unit (APU), which can also be used to drive the ships emergency generator. Once one engine is operating, a second engine can be started by using bleed air from the first. The weight of the air starter for this system is about 30 lbs. If the APU is part of the emergency generator, only piping and valve weight need be considered in addition to starter weight. If bottled compressed air is required for backup, however, the weight requirement may be as high as 2,000 lbs.

(U) The weight of a hydraulic starter system for these large engines is about 2,700 lbs. This includes a 100-hp electric motor. It does not include the weight of the seawater in the hydraulic oil cooler. Starters on turbines below 10,000 hp are usually electrical and are included in the engine weight.

(U) Another function of the starter motor is to turn the gas generator during engine washing. For this purpose, a distilled water supply to the engine is required. Wash-water requirements for the LM 2500 (using Ajax detergent) are 180°F distilled-water at 46 psig and 15 gpm. About 120 gallons of water are required for a complete wash/rinse cycle, which should be undertaken at least monthly or whenever engine conditions warrant.

(U) A vent and drain system is required to provide drainage to the inlet and exhaust ducts, lube oil pumps, and fuel system (the lube oil and the fuel drain to their respective waste tanks).

2.3.4 Fuel Systems

(U) The fuel system consists of all the piping, valves, pumps, heaters, purifying equipment, and tanks necessary to remove any accumulation of water or sediment that enters the fuel during transfer or while onboard, to heat the fuel to the proper operating viscosity and to deliver it under pressure to the engine.

(U) Fuel is pumped from the storage tanks to the settling tank, which is equipped with a floating suction system and a drainage system to remove accumulated water and sediment. The storage tank may be designed to act as a settling tank as well. Some heating by steam or electric coils may take place here to bring the fuel above the cloud point prior to centrifuging. After centrifuging, the purified fuel (99.5% water removal by volume) is pumped into the day tank, which is best located above the engines to provide a gravity supply in case of an emergency. Heat is also applied here, if required, to bring the fuel to proper engine inlet viscosity, and a booster pump provides the fuel with a positive head (12 psig min.> to the engine. A series of filters removes impurities down to 20 microns before the fuel enters the engine-mounted systems.

(U) The maximum temperature the fuel is permitted to reach in any of these heating phases is 150°F, which is close to the flash point.

(U) Fuel for the gas turbine should have a kinematic viscosity of less than 6 centistokes for cold starting and of 12 centistokes for running, to minimize smoking. The figures vary with the engine manufacturer. A JP-5 fuel system, wherein fuel cleanliness is maintained to aircraft standards, is the simplest and lightest, since JP-5 has a kinematic viscosity of 4 centistokes at 28°F. Most of the larger horsepower engines are capable of burning heavier distillates, but only after the fuel is heated and purified. Navy diesel fuel marine has a kinematic viscosity of 65 at 28°F and of 10 at 100°F.

(U) For initial estimating purposes, the specific weight of a Navy diesel fuel marine system consisting of piping, heaters, purifiers, filters, and pumps can be taken to be about 0.40 lbs/hp. If aircraft purity JP-5 can be delivered, there is no requirement for purifiers, filters, or a heating system, and the specific weight would be about 0.15 lbs/hp. If the JP-5 system requires that purifiers and filters be installed, the specific weight would be about 0.25 lbs/hp.

2.3.5 Lubricating Oil Systems

(U) The primary purposes of any lubrication are to separate moving surfaces, to reduce friction and wear, and to remove heat from the gears and bearings. In addition, reducing friction and wear reduces heat generation and thus energy loss.

(U) The present trend toward higher gear loads at higher speeds has resulted in critical requirements on gear train lubricants. High loads create high contact pressures, which increase the difficulty of maintaining tooth-separating lubricant films. As speeds and transmitted power increase, the resultant head must be rapidly removed from the tooth surfaces to prevent the breakdown of lubricant films. The basic axiom for the lubrication of high-speed gearing is: Reduce the causes that develop heat. The basic contact action between gear teeth is a combination of sliding and rolling. The heat generated in this motion is what must be removed.

(U) The lubrication system must be designed first to deliver the oil to the locations where heat is generated in sufficient quantity to lubricate sliding surfaces and to prevent any portion of the transmission or its components from reaching a temperature that might impair their continued ability to operate at full load and without premature failure. The lubrication system must then transfer the heat in the oil to some cooling medium prior to the oil being returned to the gear sets. In addition, the design must prevent oil leakage out, or contaminant leakage in, must remove foreign particles by filtration, and must provide means for filling and draining the lubricant and for checking the oil level or supply rate. In most cases, breathers are required to prevent pressure buildup in the transmission, and warning systems or alarms are needed for pressure drop, temperature rise, or presence of metallic debris.

(U) The placement, size, and design of the spray nozzles are an important part of lubrication system design. In general, a nozzle can be developed that will have a satisfactory spray pattern or trajectory for use on either the incoming or outgoing side of the mesh. For cooling, the outgoing side is preferred; for lubrication, the incoming side is best. The highest load capacity is usually obtained with nozzles on the incoming side, but for wide-face, high-speed gears, caution must be used to avoid oil trapping.

(U) Additional information regarding system design and present hydrofoil lubrication systems is outlined in Volume 11 of Reference II.B.2-14 and II.B.2-29.

2.3.6 Structural

(U) Small turbines are often sufficiently lightweight to be cantilevered off the gearboxes or flanges of the equipment they drive. The mounting system for a larger engine is much more complex and is generally supplied by the engine manufacturer. The foundation, the system interface, must be able to accept the weight and torque reaction of the engine and must conform to the attitude limits set by the manufacturer. Some typical limits are:

Permanent trim - 13° up either end

Permanent list - 15° either side of vertical

Momentary trim - 10° beyond permanent trim for 10 sec.

Momentary list - 45° beyond permanent list for 10 sec.

(U) The struts and pods for a propeller-driven hydrofoil must also be capable of accepting the weight and torque of the shafting and transmission system plus the thrust reaction from the propeller.

2.4 INTERDEPENDENCIES BETWEEN PROPULSION SYSTEM AND GROSS CHARACTERISTICS AND PERFORMANCE FEATURES

(U> There are many interdependencies between the propulsion system and the gross ship characteristics such as size, weight and displacement, and performance features such as speed and endurance. The interdependency which probably has the most impact on the gross ship characteristics and performance features is that of machinery arrangement.

(U) The arrangement of the propulsion system on a hydrofoil is governed by the following minimum principles:

- Compatibility of machinery weights with ship stability. The propulsion plant is normally located over the main foil system which is usually mounted aft for proper weight distribution.
- Minimum volume consistent with adequate access for installing, operating, and servicing the propulsion plant.

- Suitability of machinery layout for minimum manning requirements.
- Shafting location between the propulsion engine(s) and the propulsor(s), usually governed by sea state considerations.

(U) In addition, there are interdependencies between the principles noted above and other unlisted principles which also contribute to a successful configuration. This includes such things as ship's displacement, speed, and endurance. It is logical to assume that an arrangement which includes the minimum acceptable machinery volume will normally result in the minimum machinery weight. The machinery weight (see Table II.B.2-14) which can account for as much as 15% of the total ship displacement, influences the ship's draft which, in turn, influences the ship's resistance, which influences the ship's speed and endurance, both of which are two of the most critical operational requirements. The design of a hydrofoil to obtain optimum performance is an iterative process which continually refines total ship design (hull, machinery, electrical, combat systems, etc.) and will normally result in an acceptable ship configuration which will successfully meet its operational requirements.

(U) Although the discussion above has been very general, it does provide an insight into how much impact the propulsion system has on the rest of the ship. Some additional examples of interdependencies are discussed below. These examples will show how relatively small areas of design concern can have a very definite impact on the ship size and displacement.

Table II.B.2-14. HYDROFOIL PROPULSION PLANT WEIGHT INFORMATION

Full Load Weight (tons)	AGEH-1 320	*PHM-1 231	PCH-1 MOD 1 126	Denison 79	PGH-1 69	PGH-2 57
SWBS-200 Total 200 wt. (tons)	42.37	33.08	18.05	11.35	9.32	6.95
% F.L. Weight	13.25	14.30	14.30	14.36	13.59	12.1
Total wt. F.B. plant(tons)	34.8	20.8	13.1	9.99	6.7	5.8
% F.L. Weight	10.87	8.99	10.4	12.61	9.75	10.01
Total F.B. plant wt/F.B. power-(lb/HP)	2.78	2.91	4.74	1.60	4.16	4.03
Total wt. H.B. plant (tons)	7.6	12.3	4.2	1.4	2.6	1.2
% F.L. weight	2.37	5.32	3.32	1.72	3.84	2.09
Total H.B. plant wt./H.B. power-(lb/HP)	17.0	20.83	17.38	3.83	18.46	16.78
SWBS-230 Total wt. propulsion units (tons)	10.14	9.48	5.04	3.07	2.11	2.23
% total 200 Weight	23.92	28.66	27.95	27.06	22.68	32.08
SWBS-240 Total trans & propulsor sys. (tons)	21.38	8.59	6.07	6.62	3.15	1.56
% tot81 200 Weight	50.46	25.96	33.66	58.33	33.83	22.43
SWBS-250 support systems (tons) except fuel and lube oil	3.92	3.54	3.18	.82	1.33	.83
% tot.1 200 Weight	9.25	10.71	17.63	7.21	14.28	11.91
SWBS-260 Total propulsion support system (tons) (fuel and lube oil)	6.93	1.36	1.25	.69	2.19	.32
% total 200 Weight	16.37	4.10	6.92	6.8	23.49	4.57
SWBS-290 Special purpose System (tons)	N/A	10.12	2.50	.15	.53	2.02
% total 200 Weight	N/A	30.85	13.85	1.34	5.72	29.01

* Preliminary

(U) The location of the propulsion plant is dependent upon the necessity of providing a reasonable length of shafting to the propulsors. The conventional method of routing shafting down through the struts into the pods is the most acceptable method of transferring power to the propulsor. In this case, the propulsion plant must be located within a reasonable distance from the struts to minimize weight of shafting between the propulsion plant and strut.

(U) A waterjet propulsion system has totally different requirements, because the inlet system is housed within the strut system and requires an inlet pod. In general, the strut size must be larger than it would normally be for purely structural reasons because of the water path requirements. As a result, structural weight and drag will normally be increased over a configuration which does not incorporate a waterjet inlet system. An additional penalty which the waterjet system imposes is that of the weight of the water within the waterjet system. Propulsor arrangement with respect to strut location significantly affects the amount of water weight which the ship must carry. It is evident that an inlet system must be judged not only on its hydraulic qualities, but also on those qualities affecting arrangement, weight, and drag.

(U) The size of the ship's propellers must not only be designed to be efficient at hump speed, but at cruise speed also. The use of high speed subcavitating propellers, in which the loading of the screw must be kept as low as possible, results in large diameters and low propeller revolutions. On the other hand, the application of fully cavitating propellers permits an increase in the loading, thus leading to smaller propeller diameters and higher revolutions at the penalty of decreased propeller efficiency. The use of supercavitating propellers, with their higher rotational speed, tends to reduce the transmission size and weight. In turn, smaller transmission size tends to reduce the pod size and the hydrodynamic drag.

(U) Another consideration of propeller selection is the trade-off associated with propeller diameters. Ideally, a larger propeller is capable of producing more thrust, but if the propeller diameter is too large and pierces the water surface during operations at high sea states, not only is its efficiency reduced, but it is undesirable from the blade strength and vibration point of view. The selection of a nonsurface-piercing propeller may result in the selection of a propeller which has a diameter which is less than ideal, but which is compatible with the ships operational flight height requirements.

(U) Another problem which has not yet been addressed is that of the interaction between the hull and propeller when the ship is hullborne. The propeller of an actual ship does not work in undisturbed water as in an open water propeller model test, but in water disturbed by the wake current (motion of the water immediately surrounding the ship relative to undisturbed water) where it experiences a change in the relation between thrust and torque from the open water condition. In addition, the propeller acts on the ship by increasing the water velocity near the stern and creates an augmentation of resistance. These factors, which reduce propeller thrust, are reduced to an acceptable level by model testing and locating the actual propeller in a position where the losses are minimal.

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ADVANCED NAVAL VEHICLE CONCEPT EVALUATION

PART I
TECHNICAL ASSESSMENT

HYDROFOIL (U)

VOLUME II

DAVID TAYLOR NAVAL SHIP RESEARCH & DEVELOPMENT CENTER

EDITED BY: R. JOHNSTON
W. O'NEILL
D. CLARK

31 AUGUST 1976

NATIONAL SECURITY INFORMATION
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II. STATUS OF VEHICLE TECHNOLOGY

(CONTINUED)

B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

3. ELECTRICAL AND AUXILIARY SYSTEM
(VEHICLE SUPPORT SYSTEM, NOT INCLUDING SUPPORT FOR LIFT SYSTEM)

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II.B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION

3. ELECTRICAL AND AUXILIARY MACHINERY SYSTEMS

3.1 INTRODUCTION

(U) This electrical and auxiliary machinery survey covers most of the subsystems in the Group 300 and 500 series of the Ship Work Breakdown Structure (SWBS), respectively. For this status evaluation, the following auxiliary machinery subsystems are addressed: sea water, fresh water, fuel system, climate control, and air, gas, and miscellaneous fluids. In the electrical system breakdown, the power generation (SWBS Group 310) will be pinpointed.

(U) The weight of these systems, Group 500 less Group 567 (Hydrofoil Lift System) and Group 300, as a percentage of the full load weight is shown in Figure II.B.3-1. As can be seen, these equipment are about 7-11 percent of the full load weight. In general, much of the equipment used on existing hydrofoil ships is the same as that used on conventional surface ships. The weight trend for the Auxiliary Systems (SWBS 500 less 567 Lift System) is shown in Figure II.B.3-2. The hydrofoil ships weight trend is, in general, consistent with that of conventional ships, but, because of a number of hydrofoil ship specific requirements, many new approaches and innovations have been investigated. Where required, aircraft technology has been tied in (or redesigned) to marine technology to produce the desirable end product.

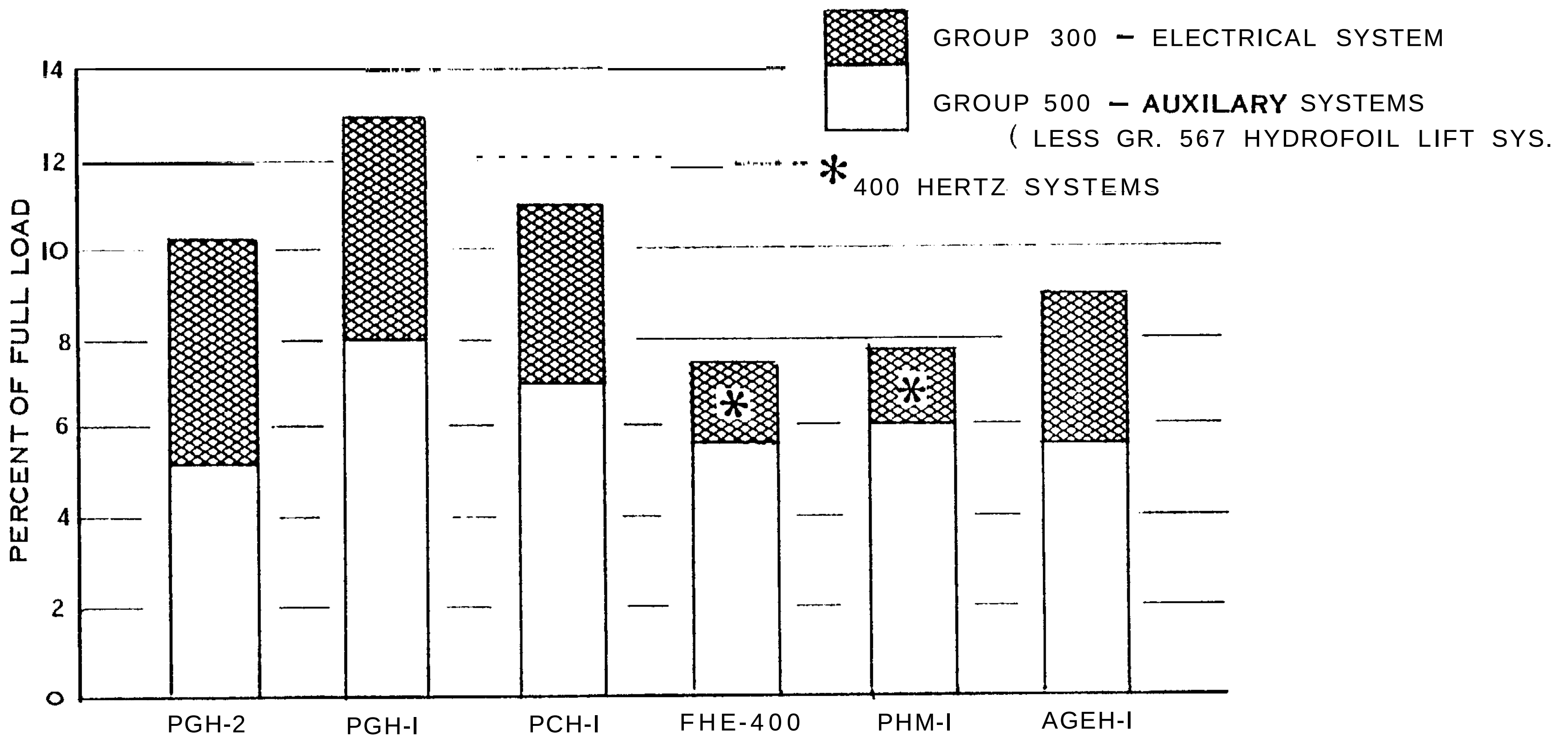


Figure II.B.3-1. SWBS GROUPS 500 LESS 567 AND 300 WEIGHT IN PERCENT OF FULL LOAD WEIGHTS

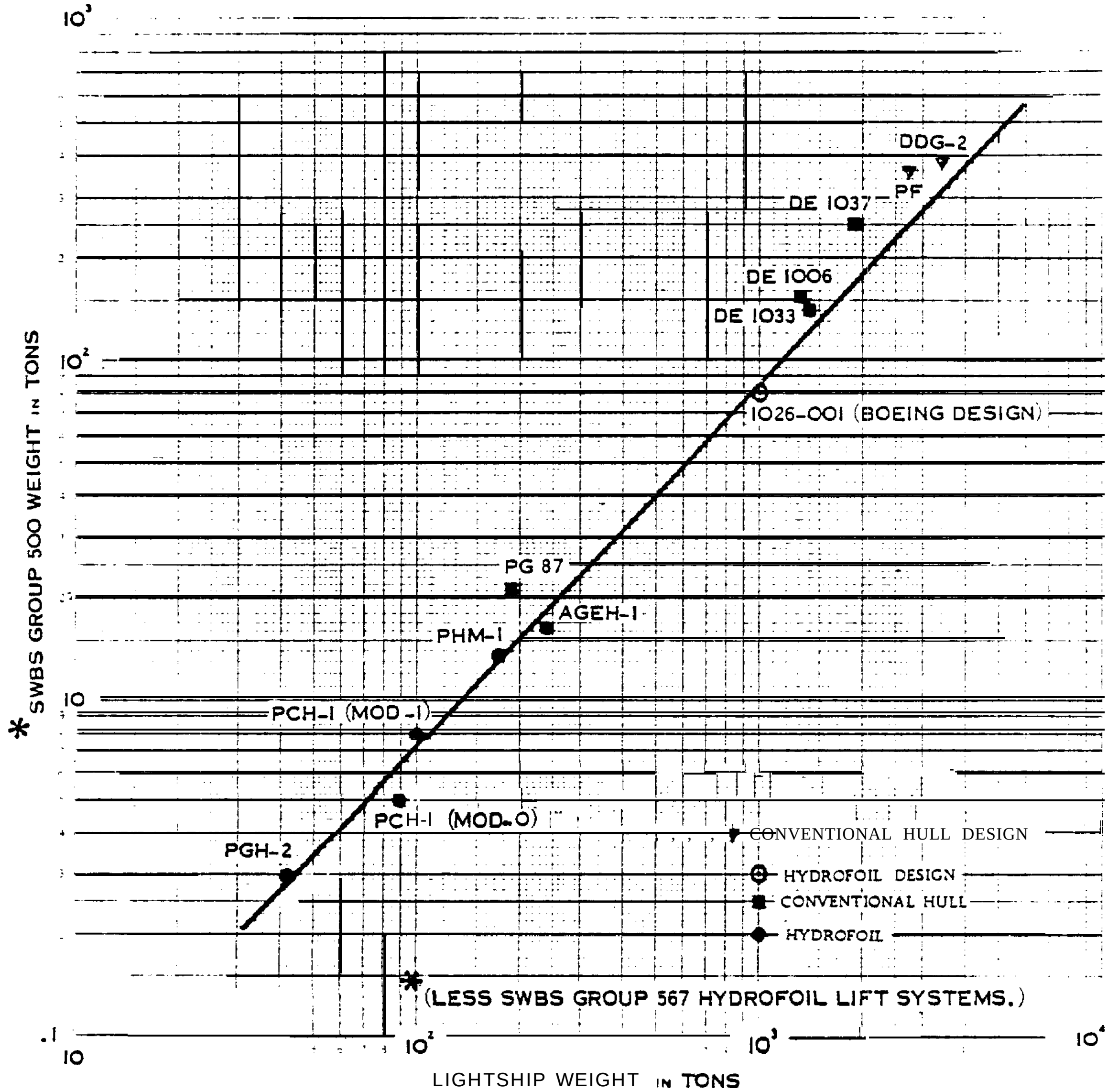


Figure II.B.3-2. HYDROFOIL WEIGHT TRENDS FOR AUXILIARY SYSTEMS (LESS HYDROFOIL LIFT SYSTEM)

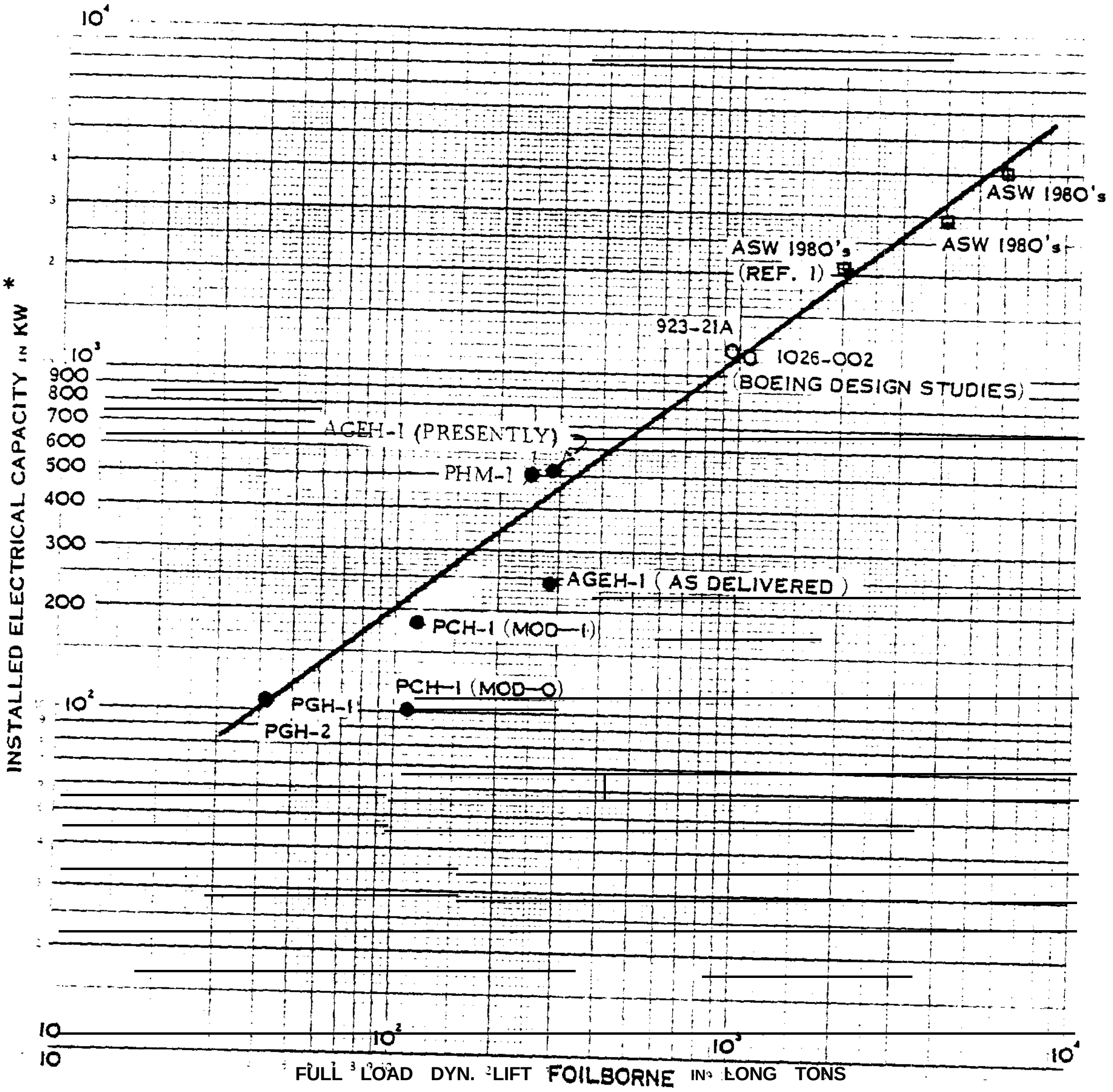
(U) Innovations examined by hydrofoil ship technology include:

- Lightweight electrical power generation (400 Hz)
- Combined heating, ventilation, and air conditioning systems
- Piping systems of non-corroding light weight non-metallic material
- Fully automatic fire sensing and extinguishing systems for unmanned machinery spaces
- Modular type hydraulic system packages with new leakproof automatic tubing welding techniques
- Modern pollution control of sewage and waste

The following discussion is organized in accordance with the SWBS, and the above innovations are discussed in detail in each section.

3.2 ELECTRICAL SYSTEMS (SWBS GROUP 300)

(U) Production of electrical energy on hydrofoil ships comes from either diesel engines or gas turbines driving electrical generators. To reduce weight, gas turbine generators are prevalent, although their fuel consumption rate is higher. Conventional 60-HZ generating plants are used in most hydrofoil ships because of reliability and long and intimate utilization in the military services. The trend of installed electrical capacity as a function of ship size is shown in Figure II.B.3-3 with estimates for ASW surface ships projected for the 1980s indicated. As shown, the hydrofoil ships built to date follow the trend quite well. Higher electrical frequencies, 400-Hz for example, are now being introduced because of their overall lighter weight and smaller volume. Hardware is essentially marinized derivations of equipment developed for aircraft.



* Installed electrical capacity assumes 100% redunancy over the maximum functional load.

O HYDROFOIL DESIGNS
● HYDROFOIL SHIPS
□ PROJECTED CONVENTIONAL SHIPS

Figure II.B.3-3. TREND IN ELECTRIC PLANT CAPACITY

(U) All the present hydrofoil ships utilize 60-Hz and 400-Hz power along with 24/28 VDC power. Voltages utilized vary from 115 to 450 volts. Conventional shipboard generating and control systems prevail. Due to the weight sensitivity of these craft, the lighter weight of 400-Hz frequency power generation system is coming into more predominant use. The primary electrical system of PHM-1 is principally 400-Hz frequency power. In contrast to other hydrofoil ships, only 10 percent of the electrical power on PHM-1 is 60-Hz frequency power. The utilization of 400-Hz as demonstrated on PHM-1 results in 1/3 to 1/2 the weight of a 60-Hz system as illustrated in Table II.B.3-1.

(U) Although 400-Hz power seems to be "here to stay," more development will be required for the future larger craft whose electrical requirements will be greater by a factor of 5 or more.

3.3 HEATING, VENTILATION, AND AIR CONDITIONING (SWBS GROUP 510)

(U) Heating, Ventilation, and Air Conditioning (HVAC) systems have varied on all the hydrofoil ships built to date. Conventional and unconventional systems have been installed and operated with varying degrees of success and failure. The latest system, on PHM-1, appears to be a compact integrated system which has to be evaluated fully. The weight trend demonstrated to date is illustrated in Figure II.B.3-4.

(U) The combined heating and air conditioning system installed on PHM-1 produces a fully integrated environmental control system which produces cooling, heating, or ventilation for manned

Table II.B.3-1. SWBS GROUP 300 WEIGHTS

SHIP	ELECTRIC PLANTWEIGHT (LBs)	INSTALLED CAPACITY (KWs)	ELECTRIC PLANT SPECIFIC WEIGHT (LB/KW)
AGEH-1	20,744	250	83
PHM-1"	18,598	500	37
PCH -Mod 0	10,315	106	97
PCH - Mod1	13,642	175	78
PGH-1	6,751	125	54
PGH-2	7,930	125	63

*Has both 400 Hz and 60 Hz power.

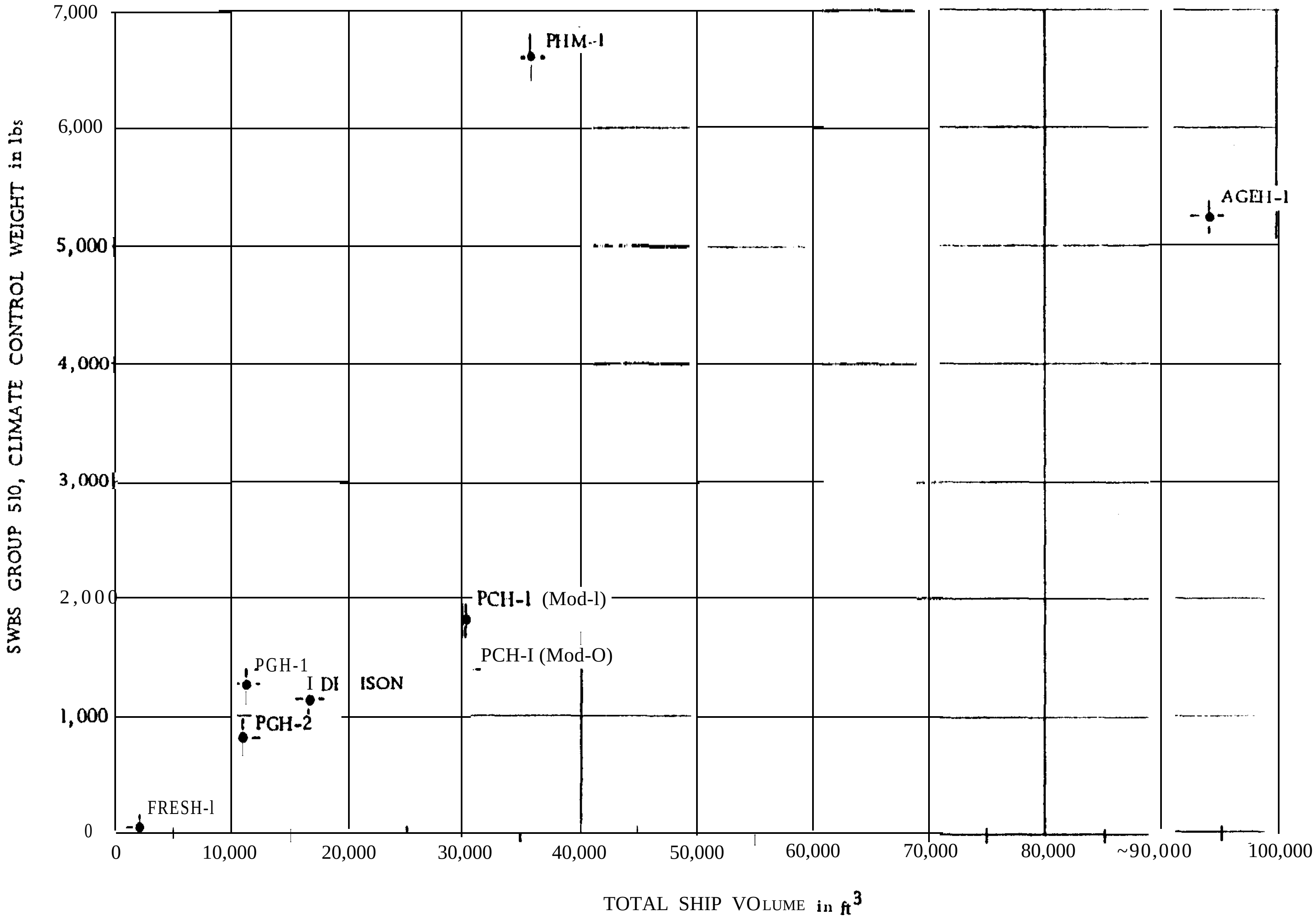


Figure II.B.3-4. TREND IN HEATING, VENTILATION, AND AIR CONDITIONING WEIGHTS

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space and heating and ventilation for unmanned spaces. Individual air terminal units are installed in each space, and each space is individually temperature controlled; heated, cooled, or ventilated.

3.4 SEA WATER SYSTEM (SWBS GROUP 520)

(U) The water systems installed on hydrofoil ships are typical of similar systems on conventional surface craft. They perform the same functions, i.e., cooling water for engines and generator sets, fire mains, conversion to potable water, and other uses. Aluminum piping has been used historically because of light weight. However, severe corrosion has caused "down time" and costly replacement. Also the use of aluminum for critical systems (e.g., fire mains) poses a hazard because of its low melting point. Figure II.B.3-5 depicts the general weight trend of sea water systems as a function of total ship volume.

(U) An advance which has been achieved, under sponsorship of the Advanced Hydrofoil Development Program, is the use of Glass Reinforced Plastic (GRP) piping in lieu of metallic piping. This material does not corrode, is light, cheap, easily procured and installed, strong, and has infinite life in the sea atmosphere. The entire PHM-1 sea water system was designed with GRP piping. The AGEH-1 piping system is being replaced with GRP piping. Table II.B.3-2 shows properties of this new material and Table II.B.3-3 shows cost relationships of installed systems.

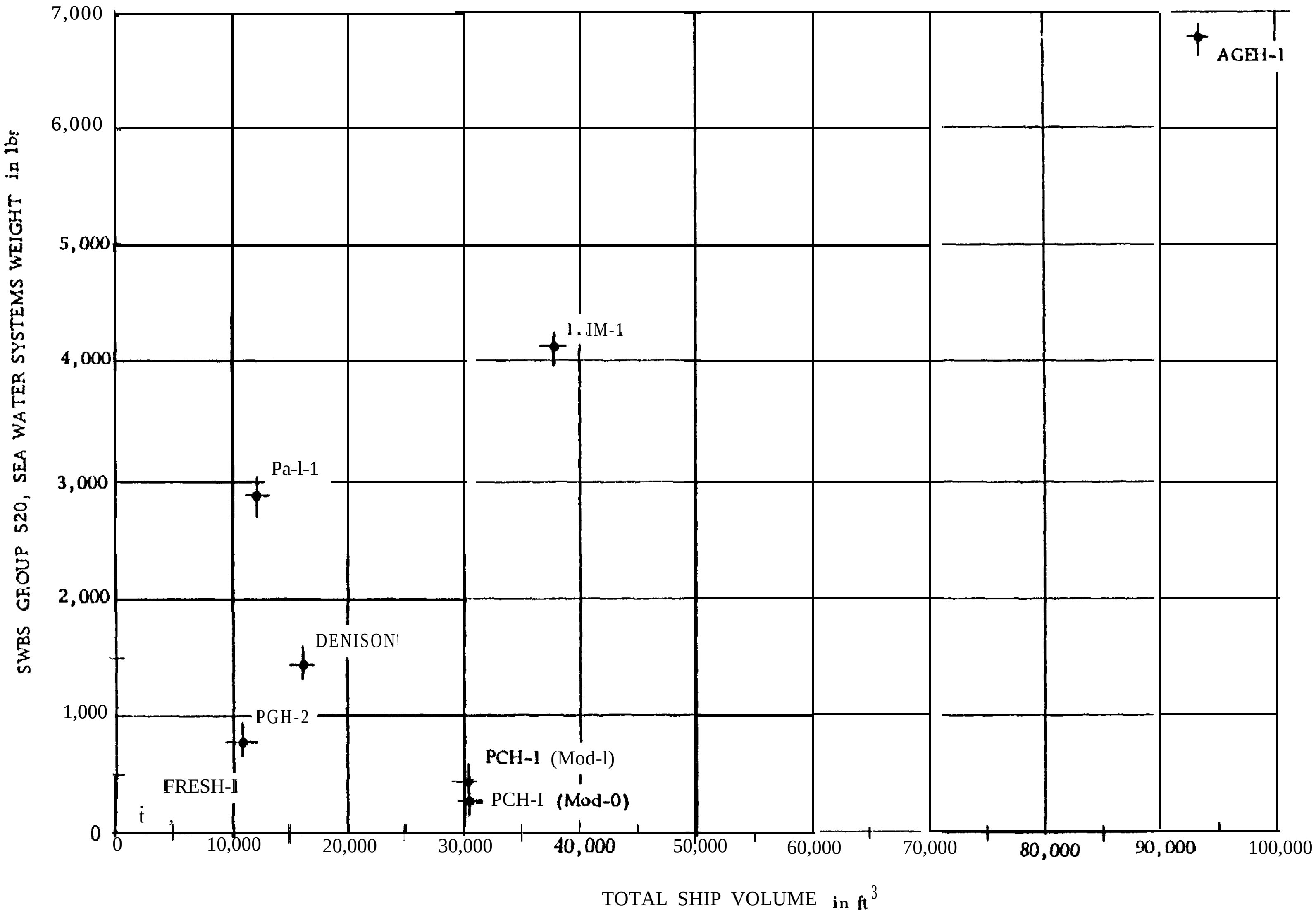

Figure II.B.3-5. SWBS GROUP 520 WEIGHT TREND

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Table II.B.3-2. MATERIAL, PROPERTIES FOR 2-INCH SEA WATER PIPING

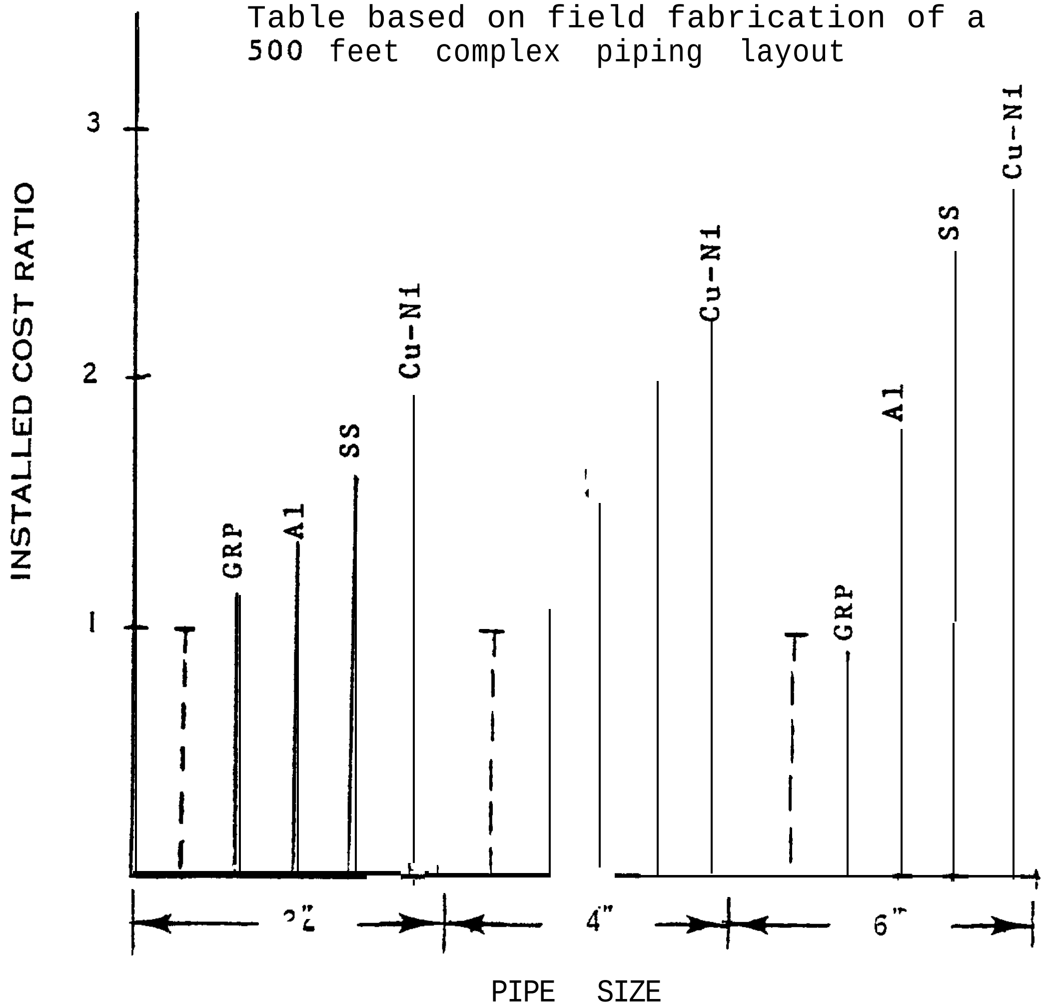
Properties	GRP Thermoset	Aluminum Alloy 6061-T6 (Sch. 10)	CU-Ni 90/10 (Class 200)	Titanium Unalloyed (Sch. 10)	Stainless Steel Type 316 (Sch. 10)
Pressure Rating at 200°F (psi)	220	150	200	200	240
Tensile Strength at 75°F (psi)	10,000	38,000	44-60,000	40430,000	90,000
Modulus of Elasticity in tension at 75°F (psi)	$1.1x10^6$	10.0x106	$18.0x10^6$	$16.0x10^6$	$28.0x10^6$
Thermal Conductivity ($Btu/hr/ft^2/°F/in$)	2.03	1,070.0	324.0	126.0	112.8
Joining Techniques	Fully bonded	tapered joint	Welded joints	Welded & brazed joints	Welded joints	Welded joints
Weight/foot (lbs)	0.60	0.91	2.32	1.52	2.70
Available Nominal Size Range (in)	1-12	1/2-6	1/4-12	1/8-6	1/2-36
Cost Per Foot $(1976)	2.64	3.80	a.00	16.00	7.60

GRP - Fiberglass filament wound thermoset material

Table II.B.3-3. INSTALLED COST COMPARISON OF VARIOUS PIPING MATERIALS

Cost ratio based on Schedule 40 carbon steal as unity

Table based on field fabrication of a 500 feet complex piping layout



(U) Recent studies showed that if this material were used to replace conventional Cu-Ni piping in a newly designed class of 3,600-ton combatant ship, the savings per ship would be 22 tons in weight and $120,000.

3.5 FRESH WATER (SWBS GROUP 530)

(U) Production of potable water is accomplished by conventional means of distillation or evaporation of sea water by heat normally supplied by the exhaust gas of diesel engines. Insufficient and unsteady heat supply by this means has produced an unsatisfactory supply of potable water. Corrosion of piping and sludge accumulation in aluminum piping has caused bad water supply.

(U) Non-metallic piping and non-metallic supply tank (GRP material) satisfactorily resolved this situation on FLAGSTAFF. Electric heat used in the distiller on PHM-1 and non-metallic piping appear to be satisfactory. However, a new lighter and more efficient concept will be installed on AGEH-1 for evaluation. The reverse osmosis principle for desalination of sea water uses 1/4 of the energy required by a conventional distillation unit and weighs less than 1/2 of the comparable conventional unit. The weight trend for the Fresh Water System on existing ships is illustrated in Figure II.B.3-6.

3.6 FUEL SYSTEM (SWBS GROUP 540)

(U) The fuel system for hydrofoil ships has to be designed to produce clean fuel to the gas turbines, which are the primary source of power. Gas turbines are not forgiving to ingesting

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II.B.3-14

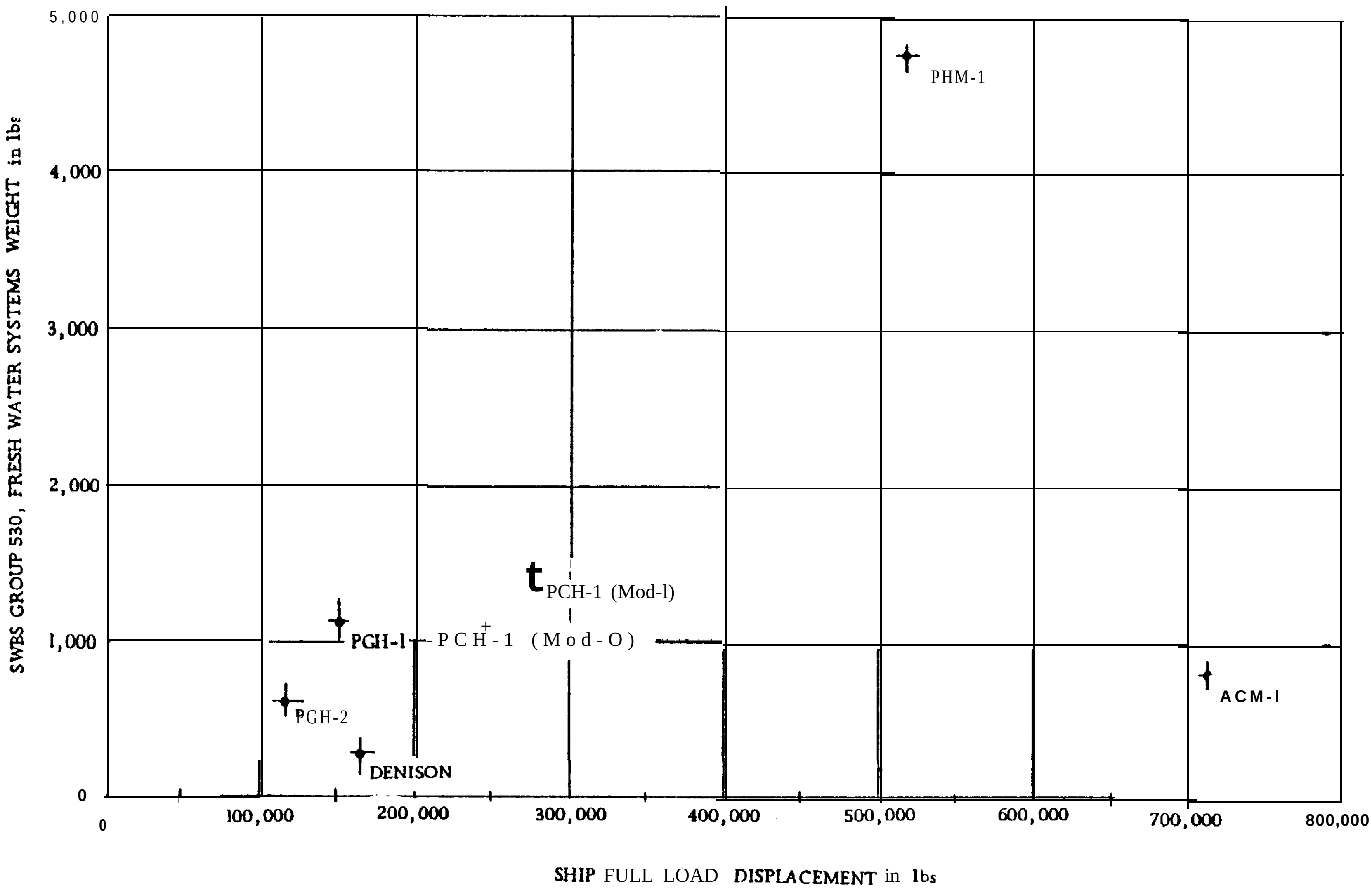

Figure II.B.3-6. SWBS GROUP 530 WEIGHT TREND

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dirty fuel, so the systems have to incorporate good "clean-up" facilities. Two-stage fuel filtering, prior to delivery to machinery, is provided. Most of the systems contain prefilters for dirt removal (down to 5 microns) and coalescent filters - separators for water removal. A stripping system is provided for water and sludge removal from fuel tanks.

(U) A typical system is shown in Figure II.B.3-7.

(U) Present systems are satisfactory for use with high grade fuels such as JP-5 and marine diesel types. The weight trend for existing ships is shown in Figure II.B.3-8.

3.7 FIRE PROTECTION OF HYDROFOIL SHIPS (SWBS GROUP 555)

(U) High performance craft such as hydrofoil ships, surface-effect ships, and gunboats present special problems in fire protection. These problems are weight restrictions, and potential sources of intense combustion including vulnerability of the light-weight aluminum plating and structures, relatively large and complex fuel, hydraulic, and lubricating oil systems of these craft, and the high-performance machinery and electrical power systems. A firefighting system for such craft must feature rapid and reliable detection of fires, rapid (automatic or manual) release of an extinguishing agent, and automatic initiation of such actions as are necessary to contain and smother any reignition. Two factors influencing the design of fire-protection systems for these special craft are the small number of personnel in the crews and the vulnerability

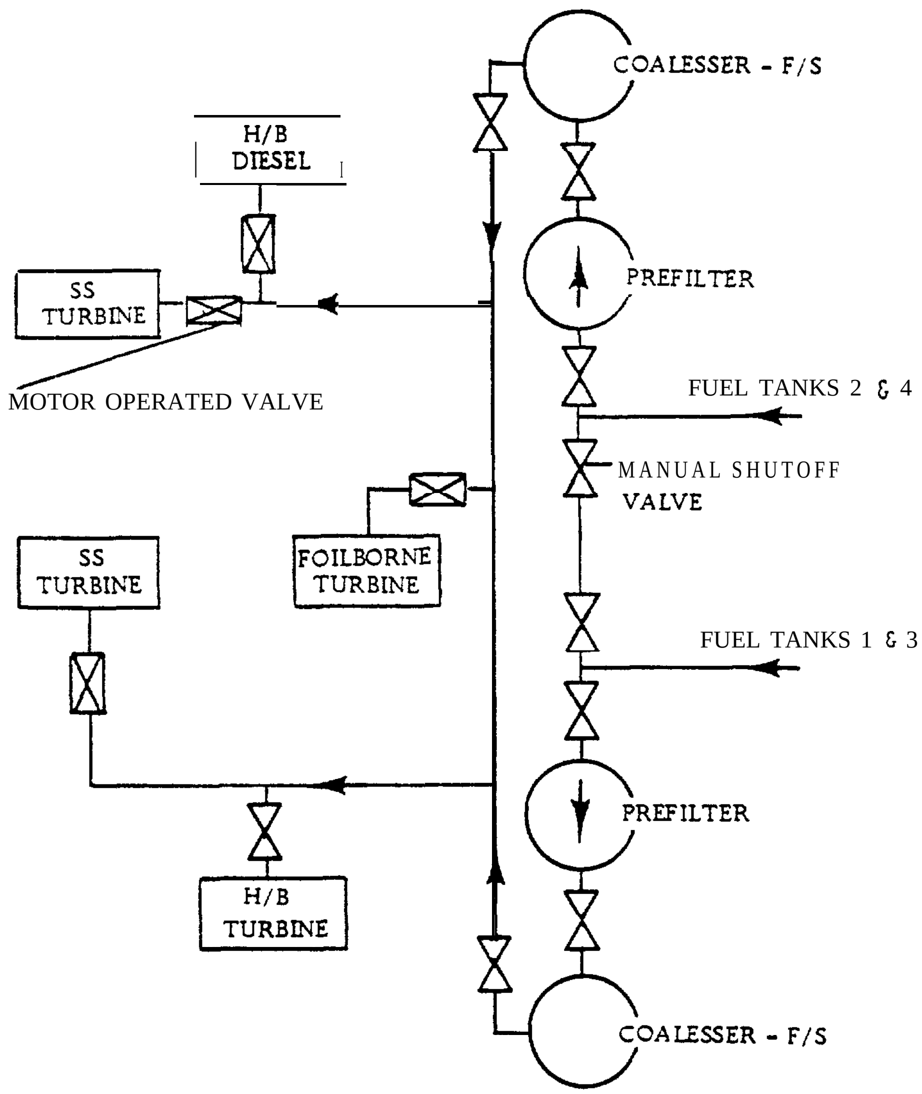

Figure II.B.3-7. TYPICAL HYDROFOIL SHIP FUEL FILTER SYSTEM

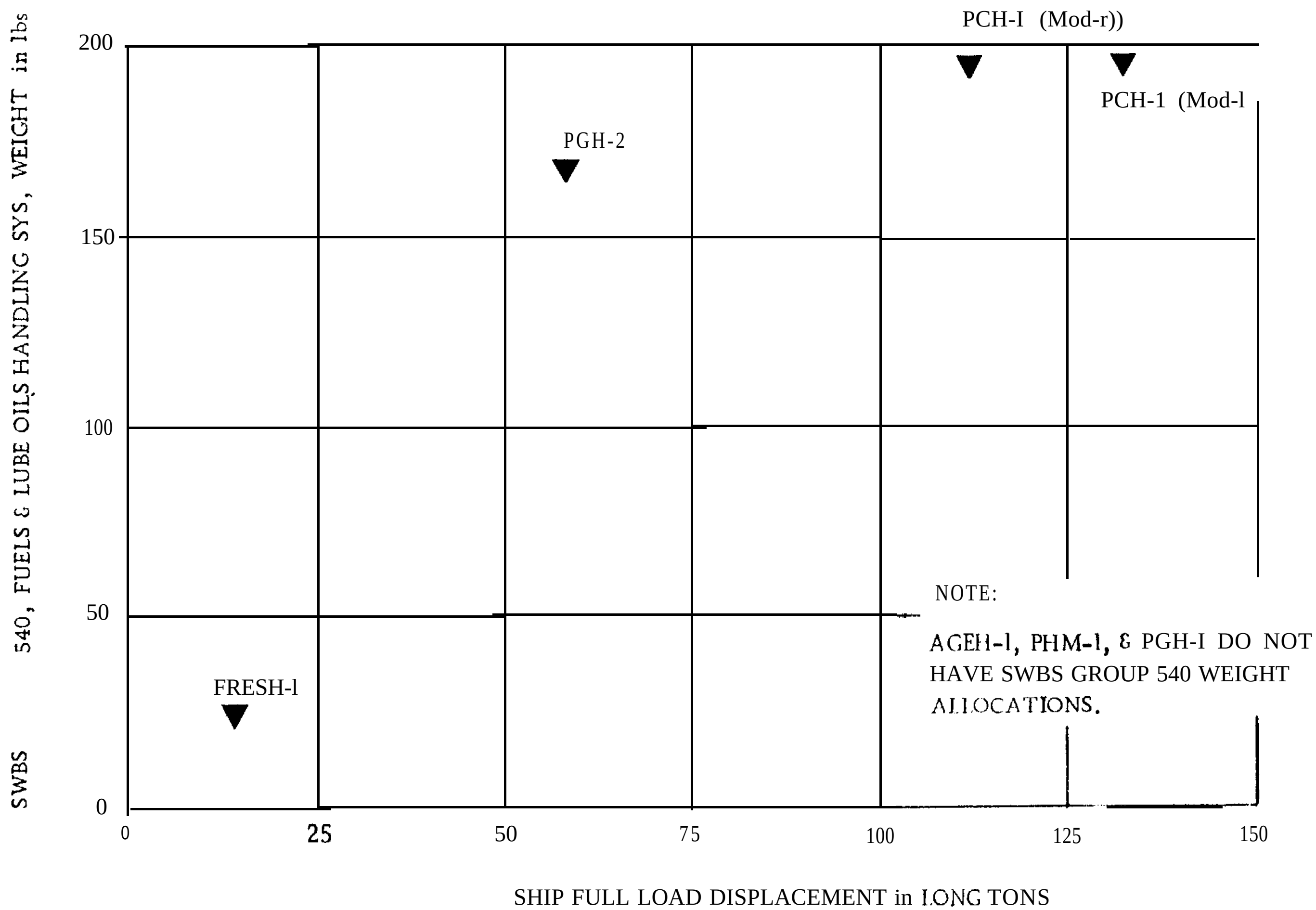

Figure II.B.3-8. SWBS GROUP 540 WEIGHT TREND

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of the structure and of the complex machinery and control systems. These factors rule out dependence on conventional hose parties for extinguishing fires.

(U) All military hydrofoil ships are equipped with a Freon 1301 (commonly called "Halon") system for protecting the machinery spaces, which are designed for unmanned operations. This material was first used in hydrofoil ship machinery spaces because of the unmanned operational concept used in hydrofoil ships. Halon decomposes (when exposed to fire) to extinguish a fire burning in the vapor phase as liquid fuels do. However, Halon will not prevent the fire from reflashing, since it produces a negligible cooling effect. Therefore, this system is normally backed up with CO_2, purple "K" or water systems. High expansion foam is also being evaluated on the AGEH-1 as a back-up extinguishing agent for machinery space fires. The USS PEGASUS (PHM-1) and USS PLAINVIEW (AGEH-1) are the most representative of the state of the art of fire protection systems on hydrofoil ships and will be described in detail.

3.7.1 PHM-1 Fire Protection Svstem

(U) On the 235-ton PHM-1 craft the five machinery spaces are protected by Halon 1301 system which is automatically released when the system is triggered by at least two sensors. Each machinery space has both primary and secondary Halon containers for fire protection. To assure maximum effectiveness, louvers and vents are automatically closed and ventilation fan shutdown is effected upon extinguishing action. Three types of fire detection sensors are used: smoke, thermal, and optical detectors.

(U) A sea water fire fighting system is also installed with a main deck forward port side fire plug and a main deck aft starboard side fire plug.

(U) Portable dry powder (potassium bicarbonate) and CO_2 extinguishers are located throughout the ship, i.e., pilothouse deckhouse, and various platform deck areas.

(U) The magazine sprinkler is supplied from the sea water system.

3.7.2 AGEH-1 Fire Protection System

(U) The fire protection system developed for installation in the machinery spaces of USS PLAINVIEW (AGEH-1) is the first of its kind to be installed in a naval ship. It is a dual system consisting of a primary extinguishing system using Halon 1301 backed up by a high-expansion foam system. The high-expansion foam system has not been previously installed on board a naval ship. The use of these two systems in combination is unique.

(U) This system is based principally on the integrated and coordinated functioning of three shipboard subsystems: a detection and alarm system, an improved Freon flooding system, and an installed high-expansion foam system. The system, which is scheduled for evaluation in FY 1977, will provide a comprehensive approach to fire protection which will ensure:

- Effective protection of personnel and material
- Rapid detection and response
- Automatic initiation of Halon flooding

- Remote operation of firefighting systems for all machinery spaces
- Minimal damage to equipment

(U) Living and habitable spaces are considered to fall under Class A fire protection for which water or certain dry chemicals are prescribed. All of the present military hydrofoil ships have sea water fire protection systems. In addition, purple "K" and CO2 and protein foam are used on the craft. Detection is principally based on thermal detectors which sound an alarm upon activation. CO2 extinguishers are used for areas containing electronic equipment.

(U) It must be noted that the Navy has not to this date developed standards for fire detectors, sensors, sensitivity and maintenance, or location of these devices.

(U) Reliance is made on recommendations by organizations such as:

- National Fire Protection Association
- Factory Mutual Research Corp.
- Underwriters Laboratory

(U) In summary, hydrofoil ships and other weight critical advanced craft are depending upon Halon gas as the primary fire extinguishing agent for machinery room fires. A secondary system is required as a back-up, and expanded foam appears to be a strong candidate. Very quick and positive detection is necessary for automatic activation of the extinguishant.

3.8 HYDRAULICS (SWBS GROUP 556)

(U) Hydraulic systems for hydrofoil ships utilize aircraft philosophy in design and configuration. Lightweight components and systems are required. High operating pressures (3,000 psi) are prevalant in these functional systems. Redundancy is required for functional and safe operation.

(U) The hydraulic systems of all hydrofoil ships perform basically similar functions. The primary need for hydraulic power is to provide the "muscle" for the actuation of the foil system during foilborne operation (incidence, flap, or a variation of either), extension and retraction of the foil/strut assemblies, and for steering. Secondary requirements of hydraulic power are for the ship service function during both foilborne and hullborne modes of operation.

(U) During the past 30 years, the size and operational requirements of hydrofoil ship and aircraft hydraulic systems have increased appreciably. Figure II.B.3-9 compares the growth of the hydraulic horsepower capacity of aircraft and hydrofoil ships built since the end of World War II. Differences of design speeds for both types of craft can appreciably change the hydraulic horsepower requirements. This is most noticeable with the supersonic transport (SST), which is lighter than the Boeing 747 aircraft, but has higher hydraulic power demands because of its high speed. In the flying condition for the aircraft, all hydraulic pumps are operational, whereas for the hydrofoil ships only those pumps that are driven by the foilborne propulsion engine are operational. Hydrofoil ship

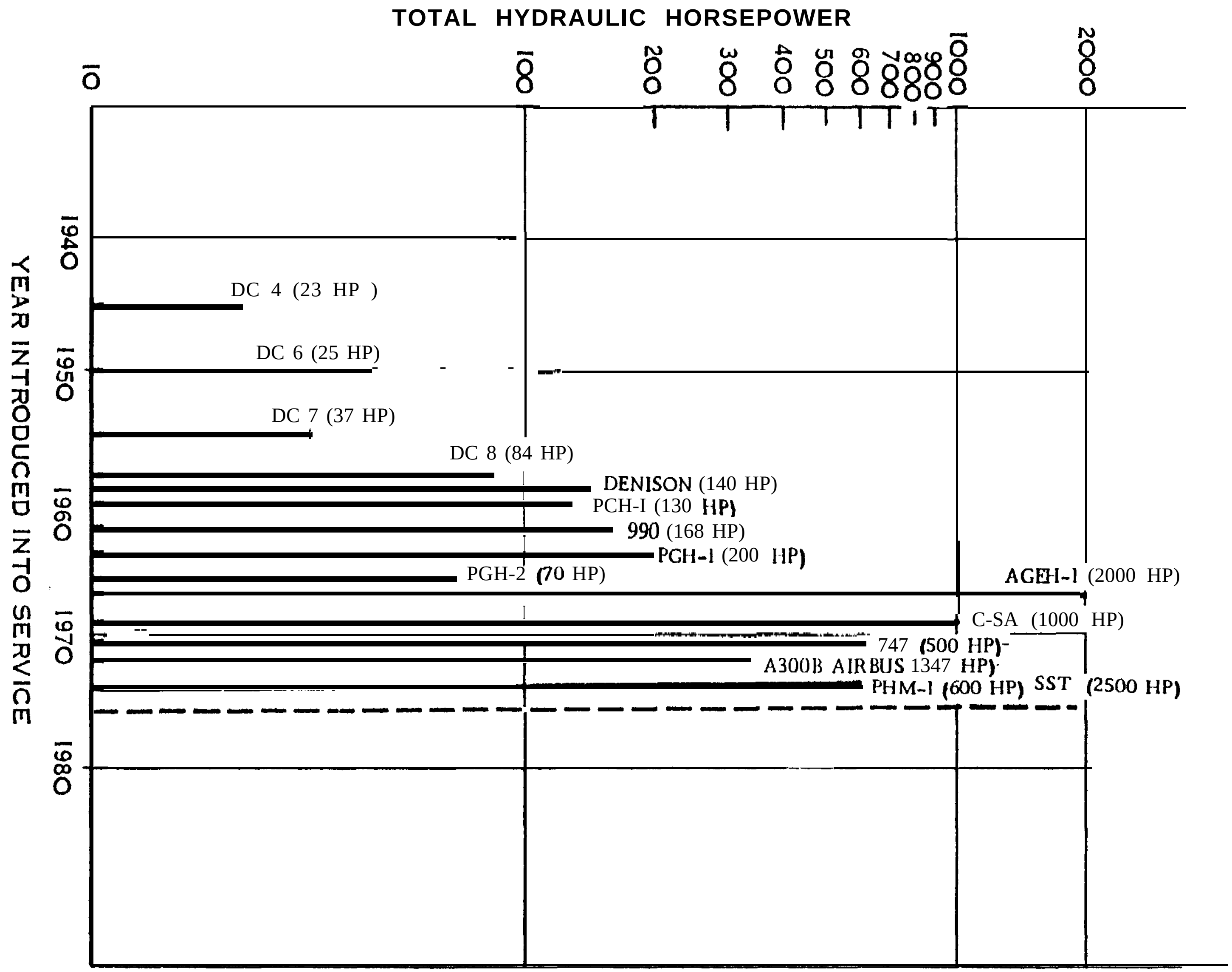

Figure II.B.3-9. MAXIMUM HYDRAULIC HORSEPOWER IN AIRCRAFT AND HYDROFOIL SHIPS

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hydraulic pumps driven by the hullborne propulsion system are nonoperational during the foilborne mode. Pumps driven by ship service generator engines may operate for both hullborne and flight modes.

(U) AGEH-1 and PGH-1 are controlled in the foilborne condition by changing the angle of attack of the entire foil assembly (incidence control). PHM-1, PCH-1, PGH-2, and DENISON are controlled in the foilborne conditions by flap control.

(U) Hydraulic power requirements for incidence control or flap control on various craft (with 100% redundancy) are compared in Figure II.B.3-10. It is interesting to note the position of the Canadian hydrofoil FHE-400 on this plot. This craft had both incidence and flap control for foilborne operations.

(U) For instance, the curve shows that AGEH-1 has over 2,000 hydraulic horsepower available'for incidence control operations. If incidence control could be replaced by flap control, the horsepower requirements would be reduced to approximately 500 horsepower.

(U) Figure II.B.3-11 shows how the aircraft hydraulic pumps have become lighter in weight and cheaper within the last several decades. The hydrofoil craft have been able to use the most advanced aircraft. pumps by "ganging" to produce sufficient output for hydrofoil demands.

(U) Along with pumps, new strong, lightweight tubing is available with welding utilized to eliminate leakage. Fire resistant

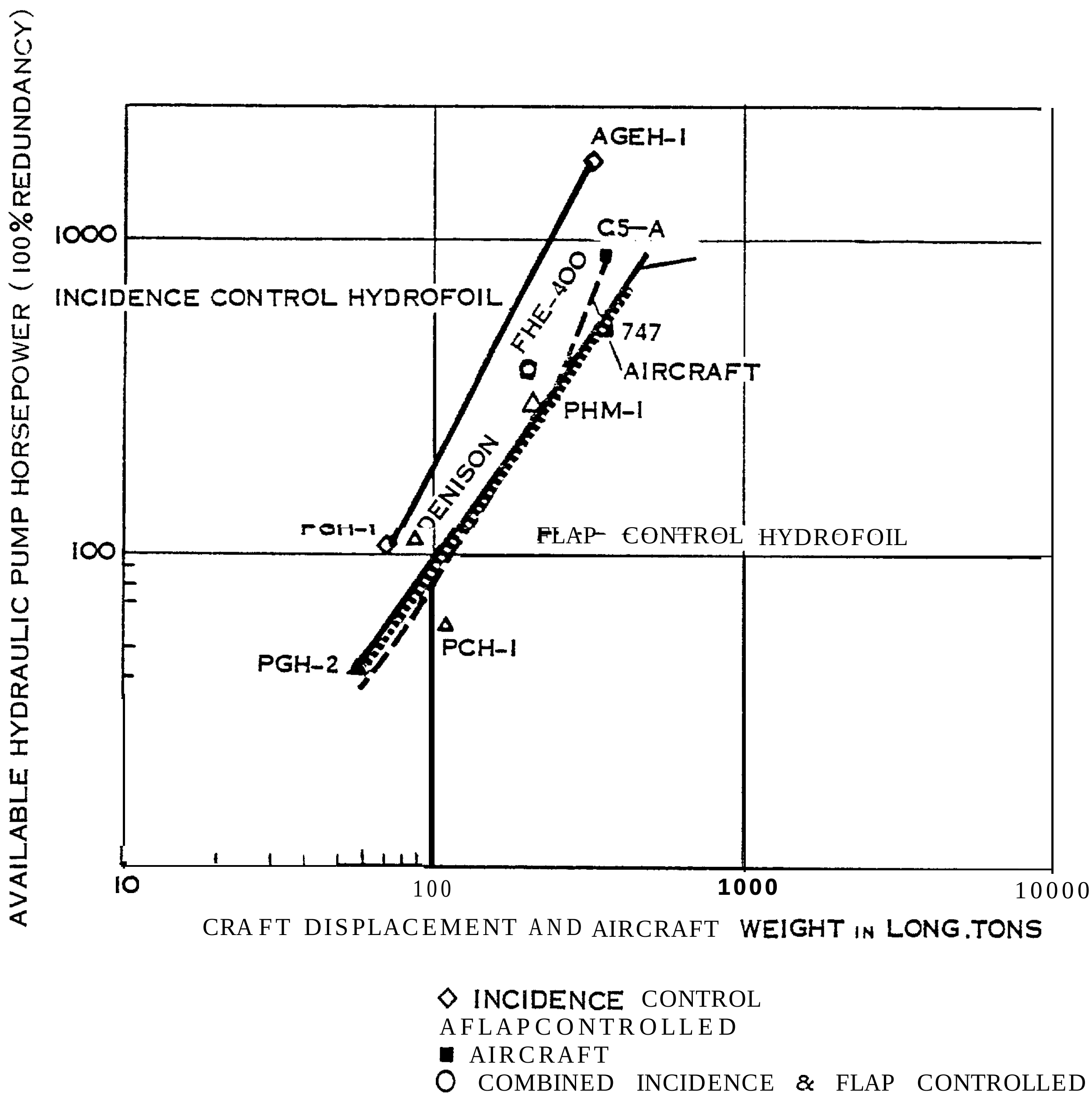
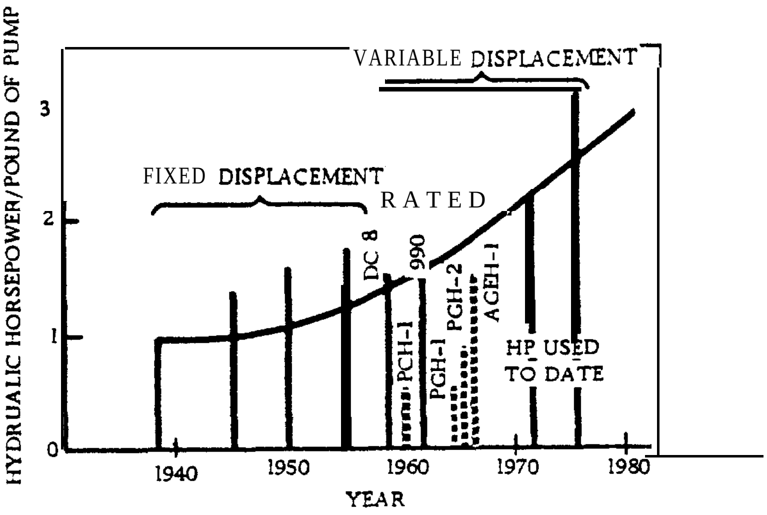
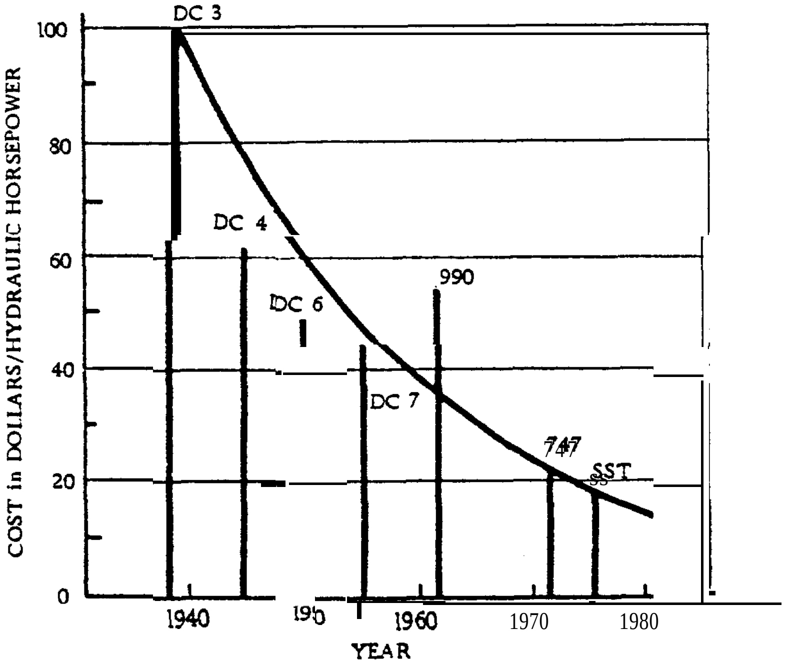


Figure II.B.3-10. HYDROFOIL HYDRAULIC HORSEPOWER FLAP CONTROL AND INCIDENCE CONTROL



(a) PUMP YEAR



(b) INSTALLED HYDRAULIC POWER COST

Figure II.B.3-11. HYDRAULIC PUMP WEIGHT AND POWER COST fluids are available. "Manifolding" produces easier servicing and repairing. The systems, although normally separated in their functioning, have crossover features for redundancy and power transfer.

(U) Present modifications to the AGEH-1 Hydraulic System shown schematically in Figure II.B.3-12, will produce a new lightweight "aircraft designed" system with the following principal features:

1. Utilization of strong lightweight steel tubing with welded connections maximized to reduce weight and reduce potential leakage and increase efficiency.

2. Utilization of modularization, i.e., manifolding concept to centralize flexible fitting connections, filters, test fixture connections, etc. to provide simplified and faster component replacement while minimizing leakage points.

3. Utilization of proven aircraft type lightweight pumps to increase redundancy and easy pump replacement.

4. Utilization of several independent systems with interconnecting power-transfer capability to increase reliability and operational capability.

5. System designed to utilize the new fire resistant synthetic hydrocarbon hydraulic fluid MIL-H-83282.

(U) Since the capacity of the new AGEH-l's hydraulic system exceeds that which will be required to actuate flaps on a 1,000-ton hydrofoil, it will act as the forerunner of the hydraulic system for larger hydrofoil ships. The system will be thoroughly checked at-sea on the AGEH-1 and form the design basis for the hydraulic system for large hydrofoils.

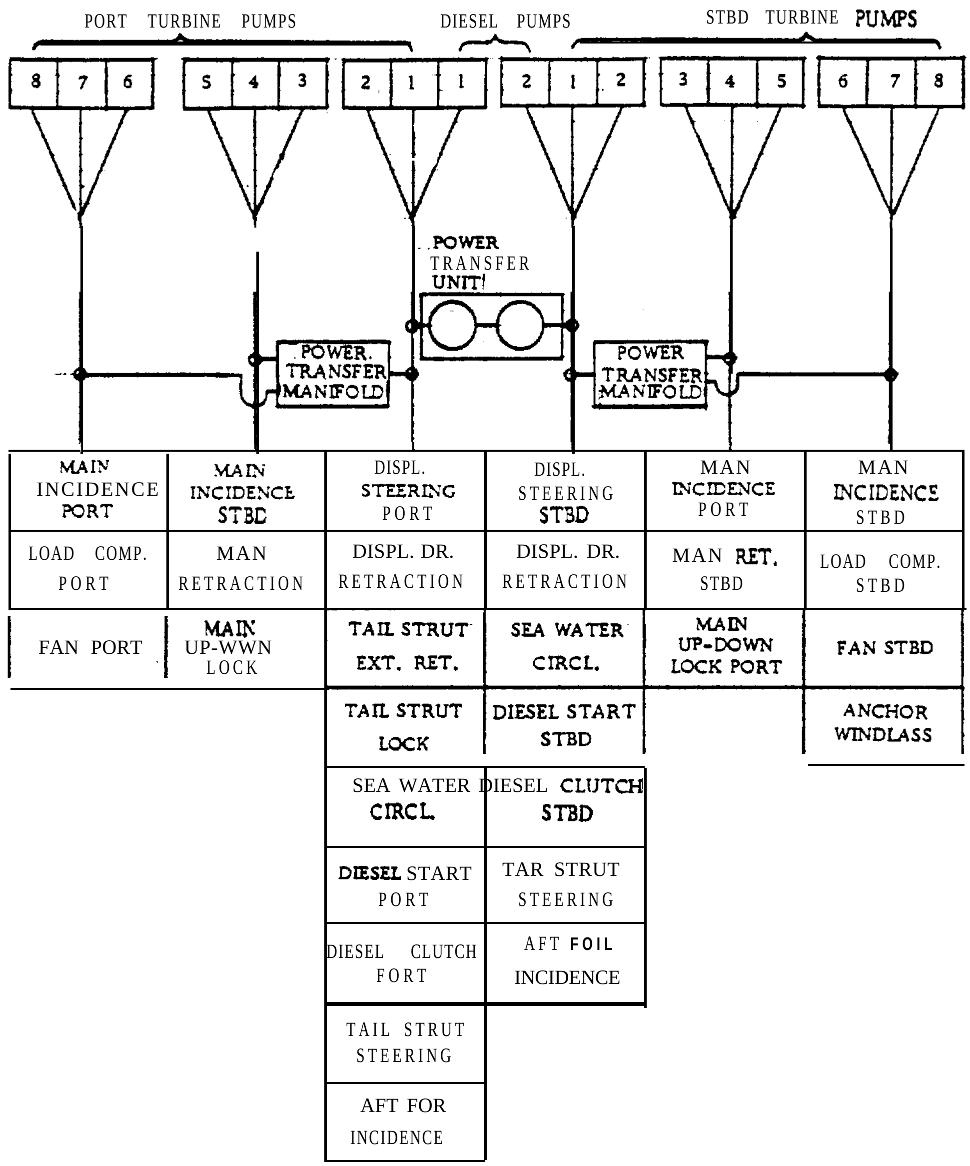


Figure II.B.3-12. SINGLE LINE HYDRAULIC SYSTEM DIAGRAM FOR AGEH-1

3.9 POLLUTION CONTROL (SWBS GROUP 590)

(U) To date, the pollution control efforts on hydrofoils consist of two basic systems: the treating of waste water and sewage. Both systems on the PHM-1 discharge to a common receiving facility. The normal arrangement for underway operations is to process and store the sewage and dump the waste water overboard. At dockside the waste water is discharged to the shoreside receiving facility. However, as hydrofoils become larger, systems to service garbage, paper, oily wastes and sewage will have to be utilized.

(U) The sewage system (on the 235-ton PHM-1) operates on the principle of volume reduction of human waste products through evaporation of water. This system will service 21 men for about 15 days, Water and waste are pumped to an evaporator by a macerating pump. The slurry is heated in the evaporator and water vapor, and gases are vented to the atmosphere. When the evaporator is full, it is emptied. Under permissible conditions the evaporator sludge may be dumped overboard or otherwise removed at a dockside facility (See Figure II.B.3-13). The weight of this system is approximately 1,565 lbs, volume approximately 68.86 ft^3 and power requirement about 5 KW.

(U) For larger craft, e.g., as proposed for a 500 ton ACV, a total system is shown in Figure II.B.3-14. This system is a closed loop sewage treatment processing plant using the sterile filtered effluent as a flushant for toilets and urinals. Excess accumulated water is removed by venting the vapor phase discharge

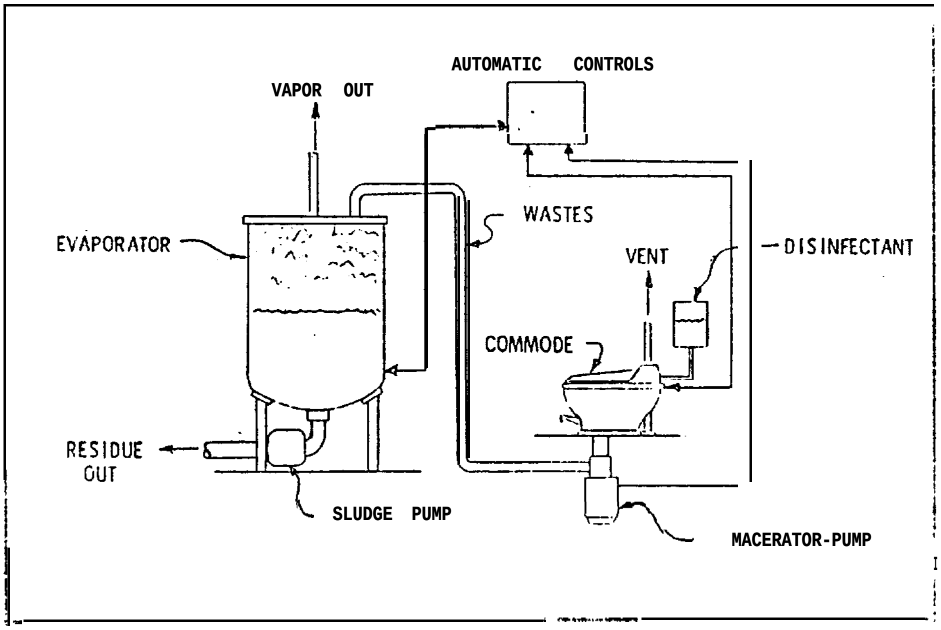


Figure II.B.3-13. SEWAGE TREATMENT SYSTEM

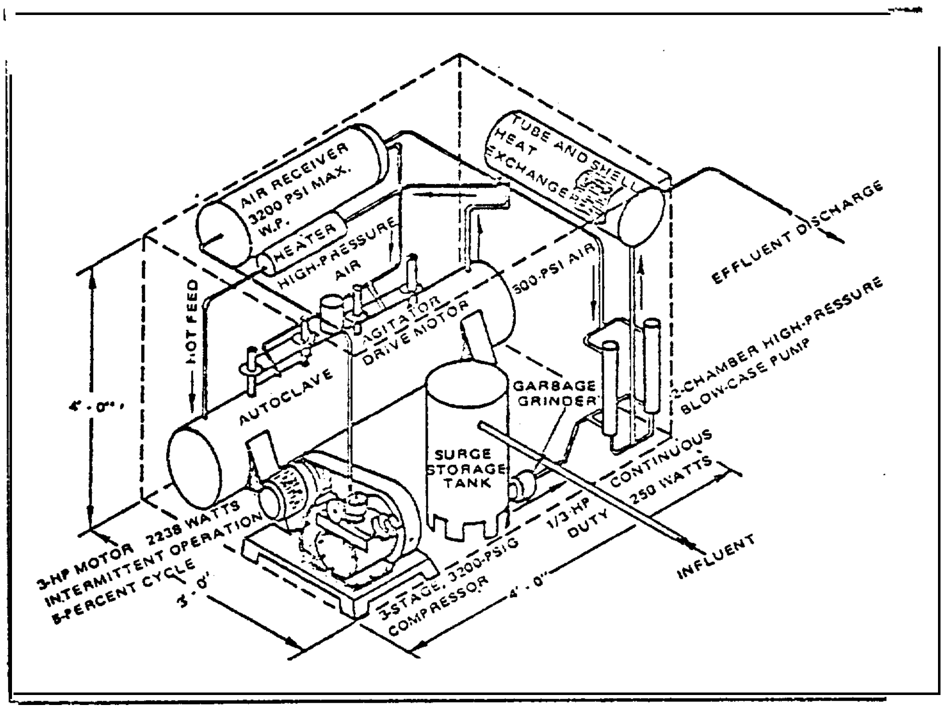


Figure II.B.3-14. SCHEMATIC VIEW OF SHIPBOARD WET-OXIDATION SYSTEM FOR WASTEWATER TREATMENT from the reactor to the exhaust of an APU. This system is purported to be capable of handling sewage, paper, oily wastes and garbage produced by a crew of 30/40 men for extended mission time. This treatment plant occupies a volume of about 48 ft.^{3} weighs about 2500 lbs and has an average power consumption of approximately 670 watts.

II. STATUS OF VEHICLE TECHNOLOGY

B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

4. MANNING CONCEPT AND HUMAN SUPPORT SYSTEM

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II.B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

4. MANNING CONCEPT AND HUMAN SUPPORT SYSTEM

4.1 INTRODUCTION

4.1.1 Definition

(U) For the purpose of this discussion, the term MAN-POWER refers to the gross quantitative manning (officer, enlisted, and civilian) requirements of a ship or a system and the impact of the total procurement of the ship or system on Navy manning resources. The term PERSONNEL refers to the qualitative manning requirements of a ship or a system, and includes such factors as rank or rating/paygrade and selection criteria. TRAINING refers to all training requirements and pipeline schedules for a ship or a system: Formal classroom, simulator, factory, and on-the-job as well as cross-training requirements.

(U) The major function of the manpower, personnel, and training (M,P&T) task has been described as the prediction, development, and evaluation of personnel and training related to the selection, acquisition, training, assignment and efficient and economical use of human resources to operate, maintain, and support new ship, weapon, and support systems.

4.1.2 History of the Hydrofoil Ship M,P&T Effort

(U) M,P&T analyses of varying depth and scope have been conducted for all Navy hydrofoil system programs at some time during their RDT&E cycle. Of particular interest are the following milestones (dates are for calendar years):

- (1962) - PCH-1 M,P&T requirements analysis
- (1964) - AGEH-1 M,P&T requirements analysis
- (1967) - AGEH-1 training guides
- (1968) - PGH-1 training guides
- (1970-71) - M,P&T analyses for the Patrol Hydrofoil Ship System (PXH), a conceptual forerunner to the PHM
- (1972) - Manning estimates and trade-offs for a large hydrofoil (DBH)
- (1972-Present; ongoing) - Various PHM M,P&T analyses
- (1973) - Study of retention rates for hydrofoil ship enlisted personnel
- (1973) - Manpower studies in support of large hydrofoil ship mission and feasibility design studies
- (1973) - Analysis of various potential means of reducing manning for advanced hydrofoil systems
- (1974) - Ship Manpower Documents for PGH-1 and AGEH-1
- (1975) - Ship Manpower Document for PCH-1
- (1975) - Study of essential manning and combat systems concepts for 1983 and 1990 large multi-mission hydrofoil. (Reference II.B.4-1)

4.2 MANPOWER AND PERSONNEL

(U) Table II.B.4-1 presents the officer and enlisted complements for the Navy's past and current hydrofoil ships. These data are plotted quantitatively on a bar graph showing complement/

Table II.B.4-1. NAVY HYDROFOIL COMPLEMENTS

PGH-1 •	PGH-2*	PCH-1 MOD 0*	CH-1 MOD 1**	AGEH-1**	PHM**
LT	LT	LT	LT LTJG	LT LTJG LTJG ENS	LCDR LT LTJG LTJG
BMCM QM1 SK1 ET1 RM2 GMG2 GMGSN ENC EN1 EN3 EM1 IC2 1 OFF/ 12 ENL	BM2 QMC SK2 ET1 RM2 GMG2 GMGSN ENC EN1 ENFN EM1 IC2 1 OFF/ 12 ENL	BMC SN QMC OS2 ETR2 MS2 EN1 EN2 EN3 EM2 IC2 Plus Mobile support Group ENC FTG2 ETR2 ENFN SK2 YN2 1 OFF/11 ENL Plus 6 ENL for Support (Total 17 ENL)	BM2 SMSN QMC OS1 OS3 ETN2 ETR2 FTG2 MS2 NC EN1 EN2 EN3 ENFN EM2 EMFN HT3 IC3 SK2 YN2 2 OFF/ 20 ENL	BM2 QMC OS1 ET1 ETR3 RM2 MS2 SN SN QMSN MSSN ENC EN1 EN2 N 3 EN3 HT2 EM1 EMFN IC2 FN SK2 YN2 4 OFF/ 23 ENL	QMC BM1 OS1 OS2 RM1 MS2 SMSN GMG1 FTGC FTG2 ET1 NC EN1 ENFN EN2 EM1 IC2 4 OFF/ 17 ENL
		NOTE: The Mobile Support Group is part of the manpower authorization for the PCH MOD 0.		NOTE: An Interim Mobile Logistic Support Group (IMLSG) located in 6 VANS is assigned to PHM-1. Its complement is 1 OFF/28 NL.	

• Based on manpower authorization (OPNAV 1000/2).

• * Based on latest Ship Manpower Document (SMD).

displacement (Figure II.B.4-1). It is important to note the different mission hydrofoil ships and the impact on the complement. The PCH-1 (MOD 0 & 1) and AGEH-1 are research and development platforms with no requirement for manning weapons systems (except for one-time-only tests). The PGH's are patrol gunboats and the PHM is a patrol missile/gunboat. The R&D hydrofoil ships are normally operated during day-time hours only and utilize a 2-section watch for foilborne operations. PGH-1 has a short mission scenario and utilizes a 3-section watch. The PHM has a five-day mission scenario and utilizes a 2-section watch. Figure II.B.4-2 shows Navy hydrofoil ships enlisted complement/displacement for operations/administration, engineering, and weapons department personnel. (PHM Interim Mobile Logistic Support Group (IMLSG) personnel are not shown.)

(U) All of the current hydrofoil ships discussed above are dependent on shore support for assistance with maintenance and supply as well as administration. PCH-1 had a six man Mobile Support Group. This group was merged with the shipboard complement for MOD 1. When it is realized that PHM has an assigned Mobile Logistic Support Group, Figures II.B.4-1 and II.B.4-2 show how hydrofoil ships manning requirements increase as displacement increases. The Personnel and Training Analysis Office of NAVSEA conducted several studies to support the large hydrofoil feasibility effort (References II.B.4-2 and II.B.4-3). Throughout this section when reference is made to the Hydrofoil Ocean Combatant (HOC) it is based on those studies. HOC will utilize

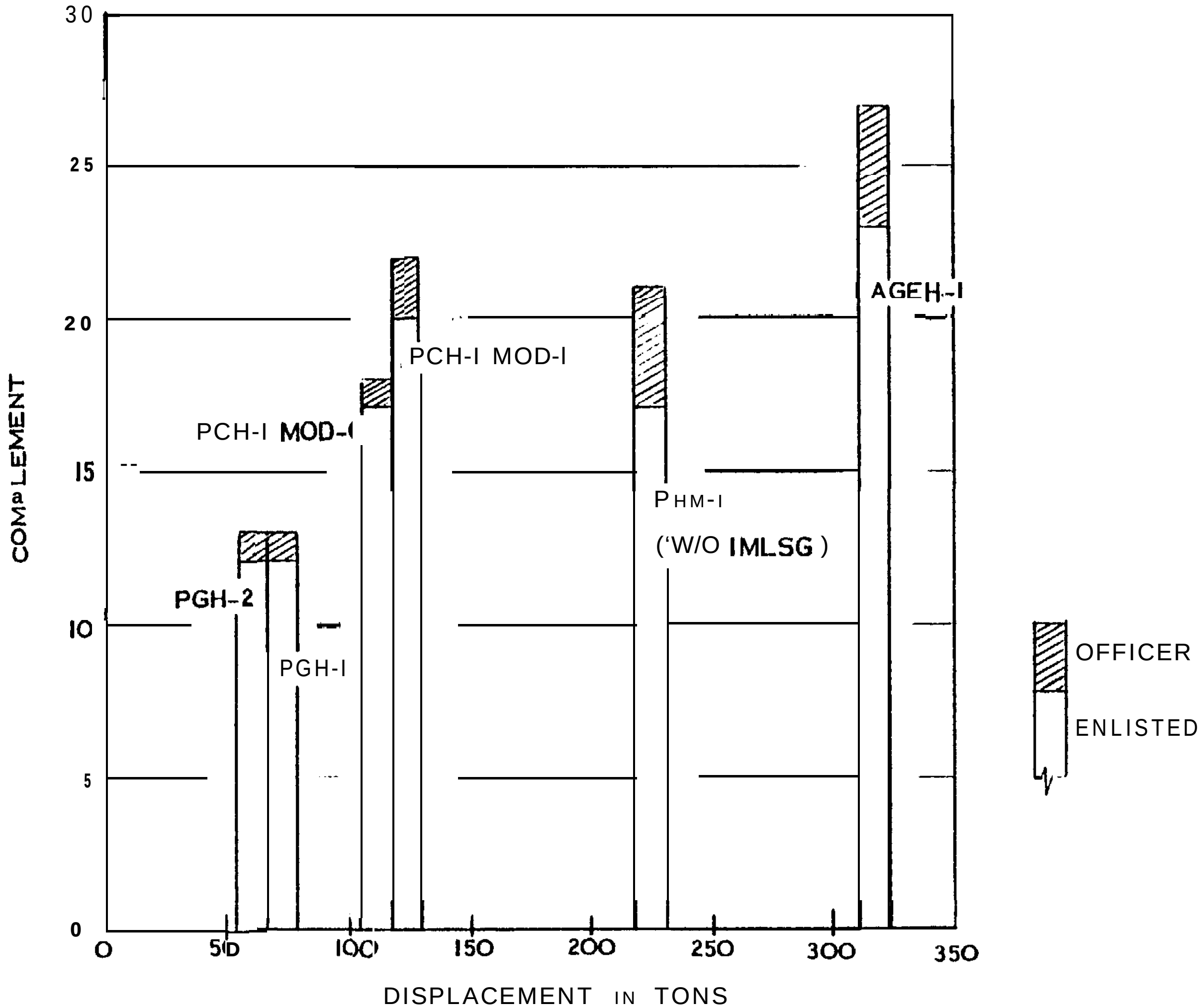

Figure II.B.4-1. NAVY HYDROFOIL COMPLEMENT/DISPLACEMENT

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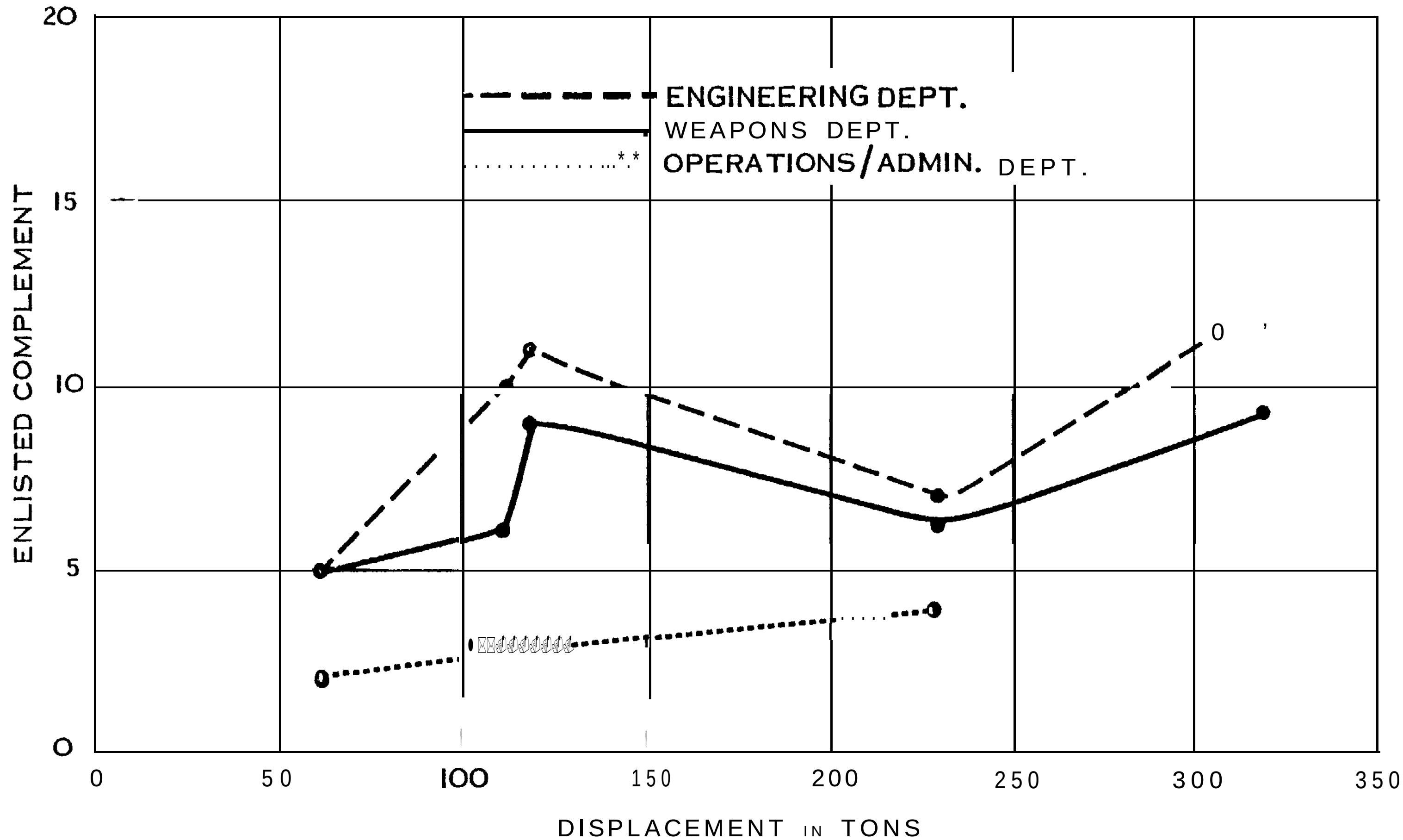

Figure II.B.4-2. NAVY HYDROFOIL COMPLEMENT/DISPLACEMENT BY DEPARTMENT shore support personnel and facilities and existing Fleet assets (e.g. tenders) for maintenance, supply, and administration support. A unique, dedicated HOC support group is not envisioned.

Manning standards include such items as:

- Conditions of Manning Readiness. This is a description of preparedness relative to the general degree of readiness in effect. For example, during Condition I (Battle Readiness) all personnel will be continuously alert at an assigned General Quarters watchstation. During Condition III (Wartime Cruising Readiness) operational systems will be manned and operating as necessary to conform with prescribed operational requirements (the ROC- Required Operational Capabilities). Accomplishment of underway maintenance in accordance with the prescribed maintenance concept is also expected during Condition III.

- Various Prescribed Ship Manpower Document (SMD) Standards. They include such factors as a productive allowance, a service diversions and training allowance, and the Navy Standard Workweek (watchstanders: 74 hours at-sea, 45 hours in-port; non-watchstanders: 66 hours at-sea, 41 hours in-port).

(U) Manning for the current hydrofoil ships has generally conformed to manning standards. In some instances the manning standards have had to be modified in order to make allowance for the unique operational scenario. For example, due to the R&D mission of PCH-1 and AGEH-1, an average Navy Standard Workweek had to be determined using the in-port and at-sea standard workweeks in proportions comparable to the craft in-port to at-sea time ratio. However, the anticipated mission scenario for HOC indicates that modification of manning standards will not be required. Following the example mentioned, HOC will be able to utilize the Navy standard at-sea workweeks instead of requiring a weighted average between at-sea and in-port workweeks.

(U) There are no unique manning requirements for hydrofoil ships when compared with conventional displacement surface ships. The current hydrofoil ships have been successfully manned using standards and requirements established for conventional ships. This has been verified by the interchangeability of hydrofoil shipboard crewmembers with personnel from support facilities. This was demonstrated by PGH-2 during its tour to Europe: PGH-2 was able to utilize personnel from a LST on those occasions when its own crewmembers were not available. While using these LST personnel PGH-2 was still able to fulfill all mission requirements. This also helped to verify an earlier determination that higher qualifications requirements (e.g., more stringent selection criteria) are not required for hydrofoil crewmen than for conventional ship crewmen. Experience with current hydrofoils confirms that standard selection criteria using BUPERS Occupational Standards are satisfactory for hydrofoil ship manning requirements.

(U) A 1973 study on Navy retention of hydrofoil ship enlisted personnel showed that, in general, the retention rate for hydrofoil ships is better than the average Navy-wide retention rate. However, it must be realized that the hydrofoil enlisted population is relatively small. Figure II.B.4-3 shows the hydrofoil ship/Navy-wide retention rates for all enlisted personnel. Figure II.B.4-4 shows hydrofoil ship/Navy-wide retention rates for specific ratings (only those ratings for which the hydrofoil ship population was in excess of five). For all ratings except one (ET), the hydrofoil ship retention rate exceeds the Navy-wide average. For some ratings the hydrofoil ship retention rate is almost double that of the Navy-wide average for the specific rating.

(U) In December 1973 a study was made to determine an estimate of the manning requirements for a large (approximately 1,000-ton) hydrofoil ship. (This study was conducted to provide inputs to Reference II.B.4-3.) This M,P&T effort, conducted by the Personnel and Training Analysis Office (NAVSEA-047C1), indicated that an estimated 7 officers and 76 enlisted men would be required. The estimate took into consideration such factors as a proposed operational and mission scenario as well as a maintenance concept. Determination of HOC manning requirements will also take these factors into account during utilization of the Ship Manpower Document (SMD) approach.

(U) This estimate of manning requirements for a 1,000-ton hydrofoil ship presents a typical complement for the HOC. While

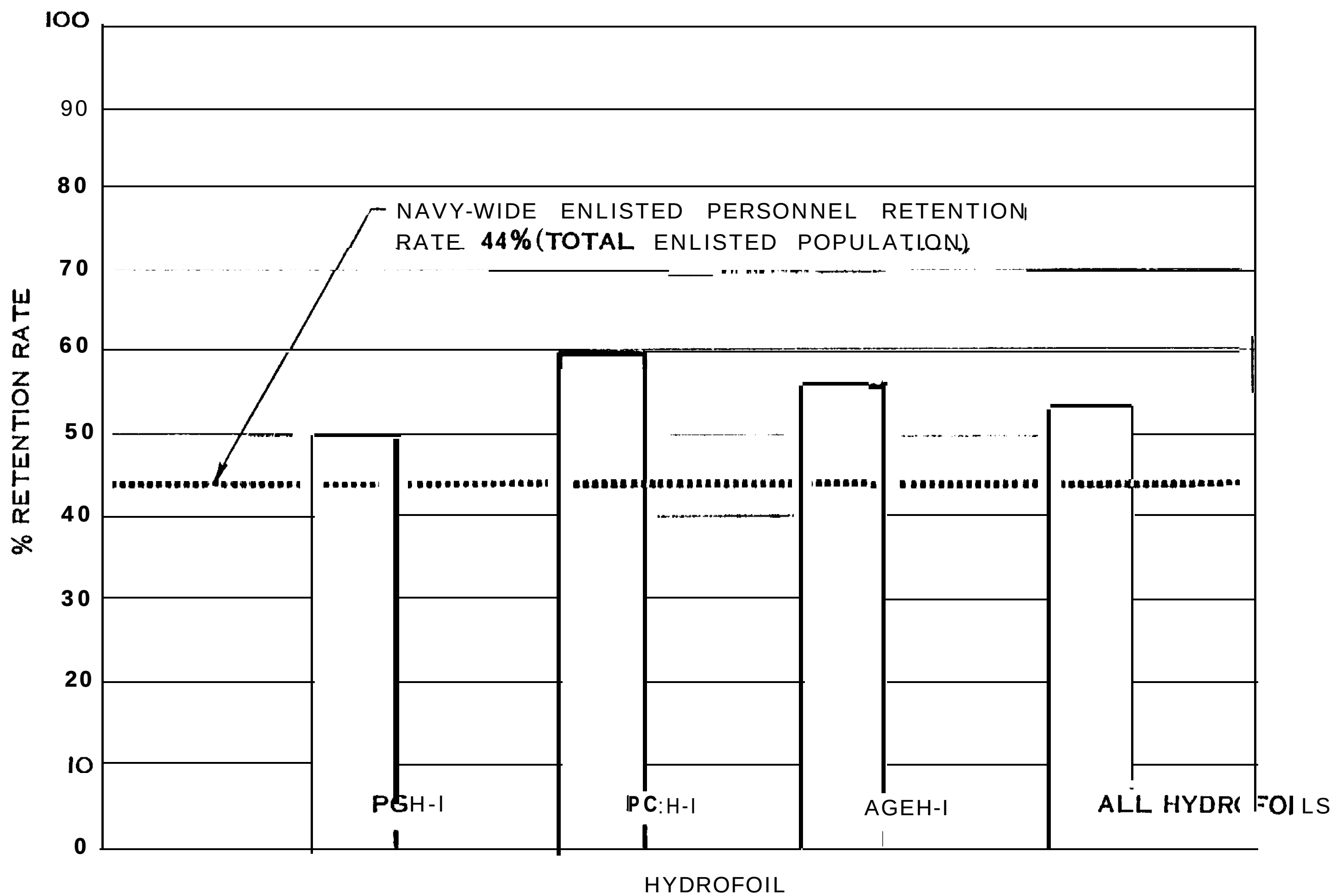

Figure II.B.4-3. NAVY RETENTION OF HYDROFOIL SHIP ENLISTED PERSONNEL
(Based on a January 1973 Study)

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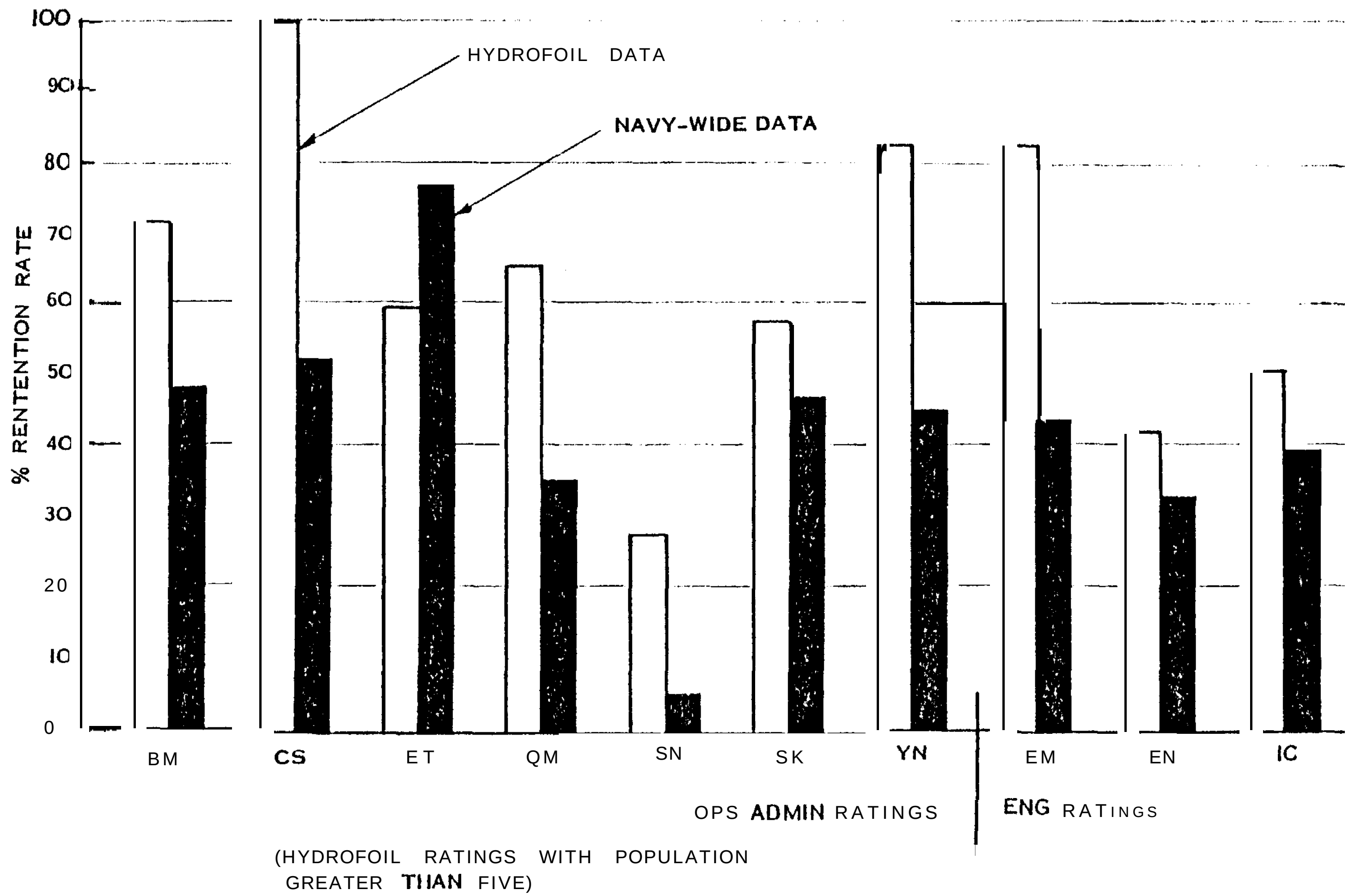

Figure II.B.4-4. NAVY RETENTION OF HYDROFOIL SHIP ENLISTED PERSONNEL BY RATING (Based on a January 1973 Study) the final HOC complement will undergo several changes and refinements during the development cycle, it provides some idea of the quantitative manning requirements (numbers in parentheses are quantity):

- OFFICERS:

  Lieutenant Commander - LCDR (1)
  Lieutenant - LT (2) Lieutenant, Junior Grade - LTJG (4)

TOTAL OFFICERS = 7

- ENLISTED:

  Administrative Division (Total 5):
  Yeoman - YN (1)
  Personnelman - PN (1)
  Quartermaster - QM (3)

  Operations Department (Total 21):
  Operations Specialist - OS (5)
  Electronics Warefare Technician -EW (2)
  Radioman - RM (6)
  Signalman - SM (2)
  Boatswain's Mate - BM (6)

  Combat Systems Department (Total 26):
  Sonar Technician - ST (6)
  Torpedoman's Mate - TM (2)
  Fire Control Technician - FT (8)
  Gunner's Mate - GM (2)
  Data Systems Technician - DS (4)
  Electronics Technician - ET (3)
  Interior Communication's Electrician - XC (1)

  Engineering Department (Total 15):
  Engineman - EN (10)
  Electrician's Mate - EM (2)
  Hull Maintenance Technician - HT (1)
  Machinery Repairman - MR (1)
  Fireman - FN (1)

  Supply Department (Total 9):
  Storekeeper - SK (2)
  Ship's Serviceman - SH (1)

Hospital Corpsman - HM (1)
Mess Management Specialist - MS (4)
Seaman - SN (1)

TOTAL ENLISTED = 76
TOTAL OFFICERS & ENLISTED = 83

(U) The SMD approach, using standards, procedures, and techniques already available will also be utilized to determine qualitative personnel requirements (e.g., paygrade levels) for the HOC. Existing qualifications standards for officers (Navy officer Manpower and Personnel Classifications Manual) and enlisted men (Occupational Standards Manual) will be utilized in the personnel rank and rating/rate determination process. Personnel Qualifications Standards (PQS) will be utilized where available for specific billet requirements.

(U) Variations in complement size will affect the ability of the crew to operate and maintain various systems, to efficiently operate the ship, and to enable fulfillment of mission requirements. The complement size, as determined through the SMD, is affected by the following requirements:

- Operational manning (watchstanding)
- Maintenance manning
- Utility tasks
- Administrative support
- Various standard allowances

(U) Operational manning has the largest impact on complement size. Changes in complement size will primarily change crew ability to stand watches on operational systems, such as engineering and CIC. However, the ability to perform preventive, corrective, and facility maintenance will also be affected, as will the ability to fulfill other manning-determinant requirements (but to a lesser extent). The availability and capabilities of off-ship support personnel and facilities can greatly reduce maintenance requirements, thereby enabling a reduction in on-board complement size.

(U) Reducing the complement size while retaining the ability to man all required systems, perform necessary maintenance and fulfill all operational/mission requirements is a major hydrofoil manning goal. A draft study prepared in 1973 investigated various means of reducing manning requirements for advanced hydrofoil systems. Among the items discussed that will be considered for applicability to a larger hydrofoil ship are:

- Utilization of available equipment and new equipment currently under development. For example, integrated and/or automated systems to reduce the number of watchstations.
- New shipboard procedures and requirements that could result in reduced manning requirements. For example, reduction of underway maintenance requirements (deferring some underway preventive maintenance to the intermediate level).
- Use of such techniques as cross-training and cross-utilization to enable an individual crewmember to operate and/or maintain two or more specialized systems/equipments.

4.3 TRAINING

(U) Table II.B.4-2 identifies the hydrofoil-unique contractor (factory) training, courses that were provided for the initial crews of PCH-1, PGH-1 and PGH-2, AGEH-1, and PBM-1. This does not include prerequisite training requirements. (Prerequisite training includes existing Navy training required to qualify a crewman to attend a hydrofoil-unique training course.>

(U) Table II.B.4-3 indicates the extent of cross-training on the current hydrofoil ships. This cross-training, and cross-utilization, has been required to enable reduction of the shipboard complement. It has been successfully incorporated into the manning philosophy of the current hydrofoil ship.

(U) The HOC presents no unique problems in the determination of training requirements. OPNAVINST 1500.8H of 3 July 1975 provides an outline for the Navy Training Plan (NTP). This outline will be followed in preparing the HOC NTP, which will consider such factors as:

- Numbers of personnel to be trained
- Initial training requirements (for example, factory/contractor training)
- Follow-on and replacement training (for example, formal Navy training courses developed from contractor courses)
- Training logistic support requirements (for example, training equipment, devices, guides, manuals)

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Table II.B.4-2. HYDKOFOIL - UNIQUE CONTRACTOR (FACTORY) TRAINING COURSES*

PCH-1	AGEH-1	PGH-1	PGH-2	PHM-1
• Orientation	• Orientation	• Orientation	• Orientation	• Familiarization/ Orientation
• Transmission	• Ancillary Equipment Systems	• Electrical and Electronics Systems	• Electrical and Hydraulic Systems	• Navigation/IC Slgnalllng Systems
• Hydraulics	• Navigation Equip- ment Systems	• Propulsion and Mechanical Systems	• Communication and Navigation Systems	• Auxiliaries
• Autopilot	• Propulsion Equip- ment Systems	• Piping, Heating and Ventilation Systems	• Autopilot Equip- ment Sys terns	• Electrical Plant
• Navigation and Fire Control	• Electrical and Power Distribution Equipment Systems	• Operational Underway Training	• Propulsion Equip- ment Systems	• Ship Control Systems
• Interlocks	• Operational Under- way Training		• Operational Under- way Training	• Propulsion Plant and Engineer's Operating Station
• Procedures				• Command and Control ESM and Radio Systems
				. Damage Control Team Training
				• Underwdy Training

* Most courses include training on system operation and maintenance, where applicable.

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Table II.B.4-3. CROSS-TRAINING ON NAVY HYDROFOIL SHIPS

PCH-I BILLET/COURSES	AGEH-1 BILLET/COURSES	PCH-I BILLET/COURSES	PGH - 2 BILLET/COURSES	PHM-I BILLET/COURSES
EN's/ -Transmissions -Hydraulics -Autopilot IC2/ -Hydraulics -Autopilot -Navigation and Fire Control ETR2/ -Hydraulics -Autopilot -Navigation and Fire Control -Interlocks	EN's/ -Ancillaries -Propulsion EM1/ -Propulsion -Electrical and Power Distribution ET's/IC2/QMC -Navigation -Electrical and Power Distribution	BMCM/GM's/ -Piping, Heating and Ventilation ET1/QM1/IC2/ -Electrical and Electronics	EN's/EM1 -Electrical and Hydraulic - Propulsion ET1/ -Communication and Navigation -Autopilot QMC/IC2 -Communication and Navigation	ENC/ -Propulsion and EOS -Electrical Plant EN1/ -Propulsion and EOS -Auxiliaries EM1/ -Electrical Plant -Damage Control ET1/ -Navigation and Signalling -Ship Control -C&C, ESM, Radio FT's/ -Ship Control -C&C, ESM, Radio IC2/ -Electrical Plant -Propulsion and EOS -Navigation and Signalling RM1/ -C&C, ESM, Radio OS's/ -Navigation and Signalling GMG1/ -Electrical Plant -Ship Control -Damage Control

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(U) The reduced HOC manning will necessitate the requirement for special skills and cross-training of several on-board billets. Special skills and training may also be required of off-ship personnel responsible for HOC intermediate and depot level maintenance. These requirements can be readily determined and outlined within the framework of the NTP.

(U) Development of a training pipeline analysis also presents no unique problems for HOC. This analysis will delineate, for each HOC billet, the schedule for sending the various HOC crewmen to the training courses they require. It will include prerequisite training to qualify a crewman to attend unique HOC system courses.

4.4 HUMAN SUPPORT

(U) In the discussion of human support standards and characteristics of existing hydrofoil ships as well as those envisioned for future hydrofoil ships, an analysis of volume and deck space allocation is the most appropriate to show the interdependency with the total vehicle. However, a discussion of the area of habitability standards should include not only a discussion of the volume associated with crew living but also should include at least qualitative statements on the support system equipment and space required. The support system space is that space required by the following:

- potable water supply system
- air conditioning/heating system
- waste disposal system

- galley equipment
- illuminating networks

(U) The minimum allocation of space to the above areas is well established by the NAVSEC 1965 Habitability Standards, and is dictated by the present technology level; therefore, the support system space allocation is not considered a variable for a given ship and complement size for either an advanced ship or a conventional ship design. The support system equipment used on existing hydrofoil ships is readily available and, as shown on Figure II.B.4-5, plays a small part in the determination of vehicle size.

(U) The Naval Ship Engineering Center (NAVSEC), Hyattsville, Maryland, has developed several methods of analyzing the distribution of space onboard ship; the most prominent of which is the "Ship Space Classification System" of Reference II.B.4-3. The System also assists the ship designer in achieving adherence to the NAVSEC 1965 Habitability Standards which must be met in all new ship construction.

- Group 1 spaces --- Military Mission 15-20%
- Group 2 spaces --- Ship's Personnel 18-30%
- Group 3 spaces --- Ship Operation 50-75%

(U) Figure II.B.4-6 displays typical volume allocations. Allocation of space to groups, in itself, does not provide the analyst with a direct correlation to the habitability of a ship.

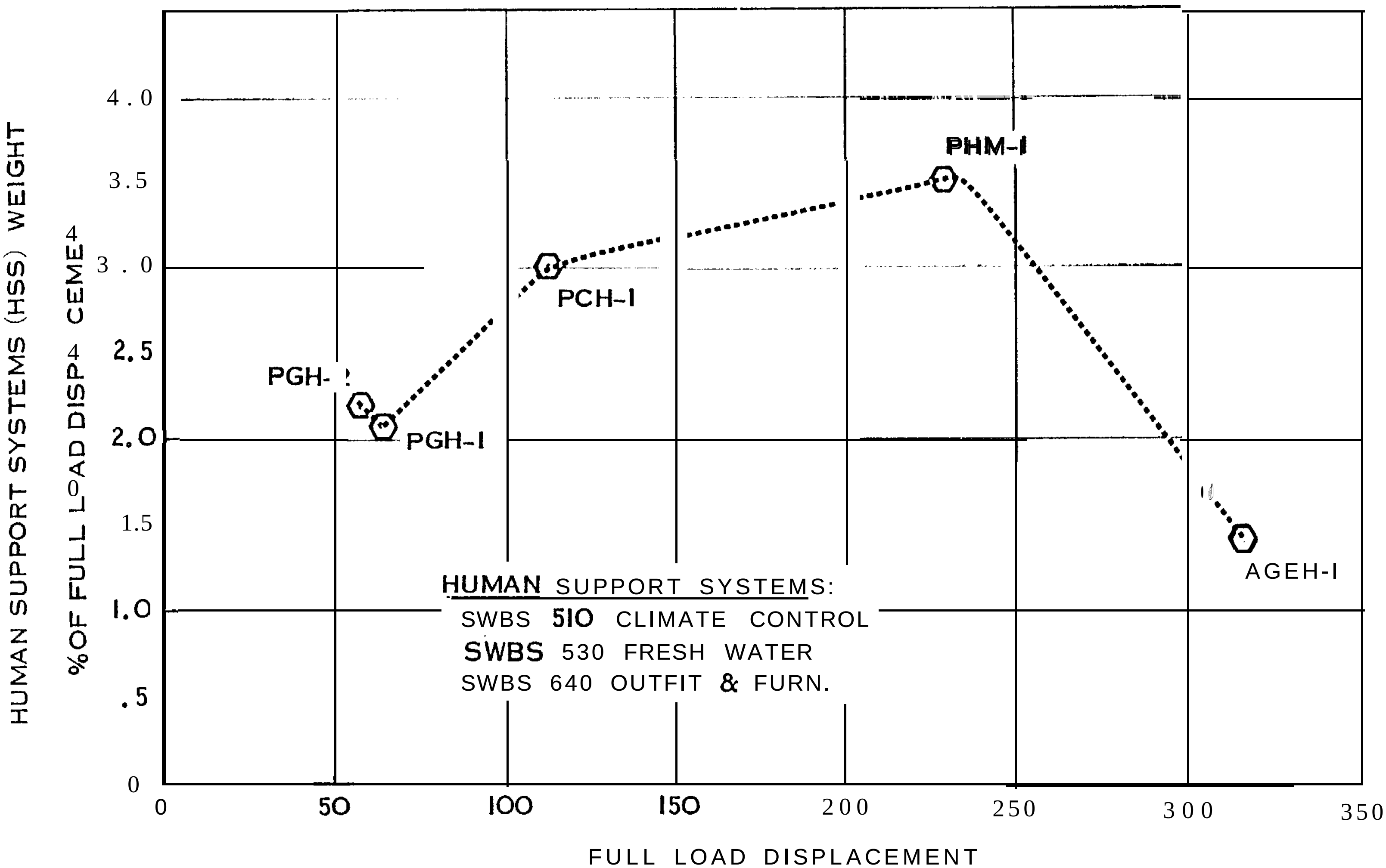

Figure II.B.4-5. HUMAN SUPPORT SYSTEM (HSS) WEIGHT

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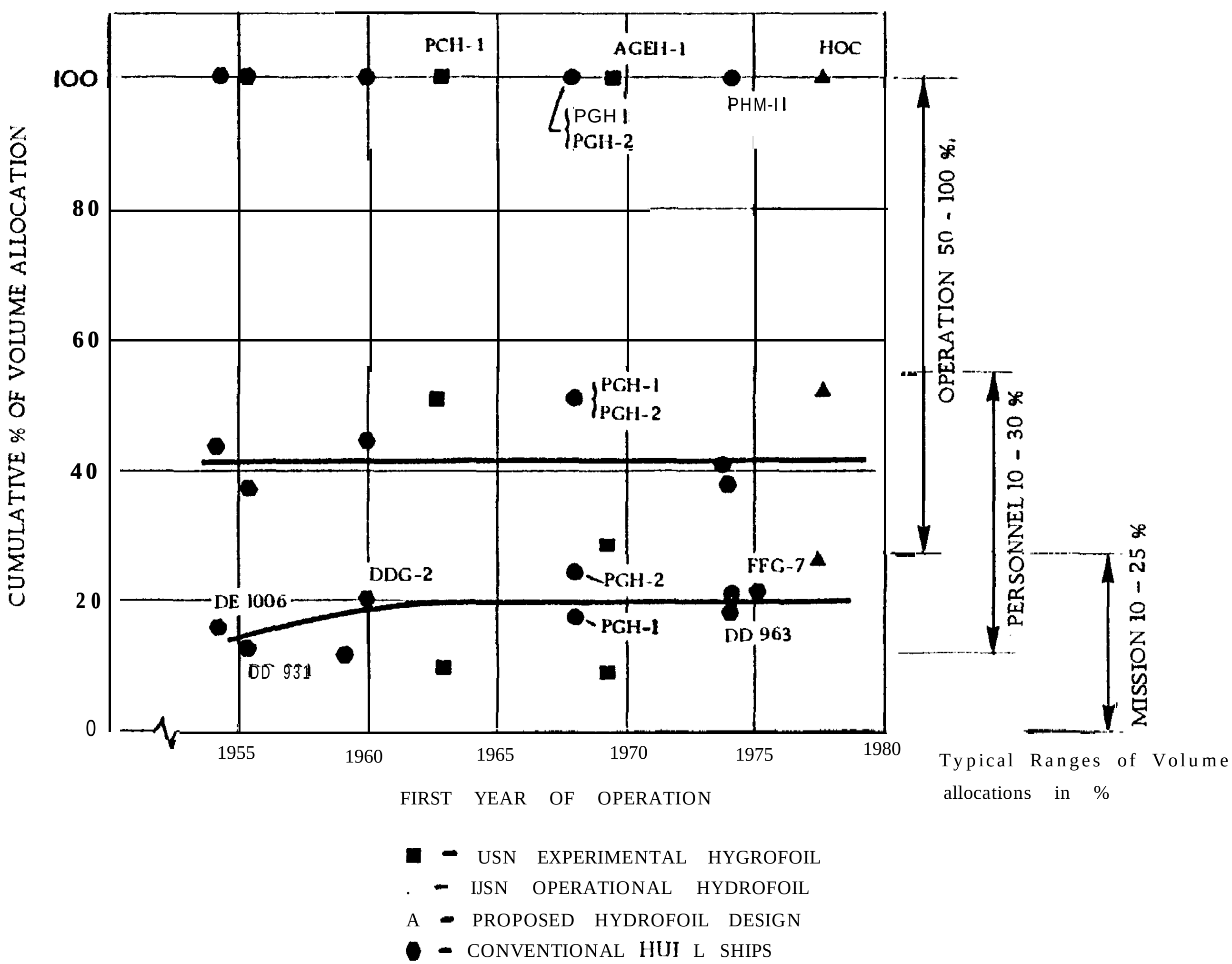

Figure II.B.4-6. SHIPBOARD VOLUME ALLOCATION

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Consideration of total ship volume and the ship's complement allow the analyst to determine the cubic feet per man and square feet per man which do serve as good indicators of habitability. Figure II.B.4-7 reflects the trend toward increasing space for personnel on conventional combatants and also displays the allocation of space among hydrofoil ships of considerably smaller displacement. The proposed HOC design, approximately 1,300 metric tons, incorporates volume allocations consistent with its conventional counterparts. Figure II.B.4-8 displays a breakdown of the three major contributors to Group 2 and shows that hydrofoil ships, despite their small size and shorter design mission durations, have maintained acceptable habitability.

(U) In summary, hydrofoil ships have been and can continue to be built without the need to reduce U.S. Navy human support standards to achieve required mission performance.

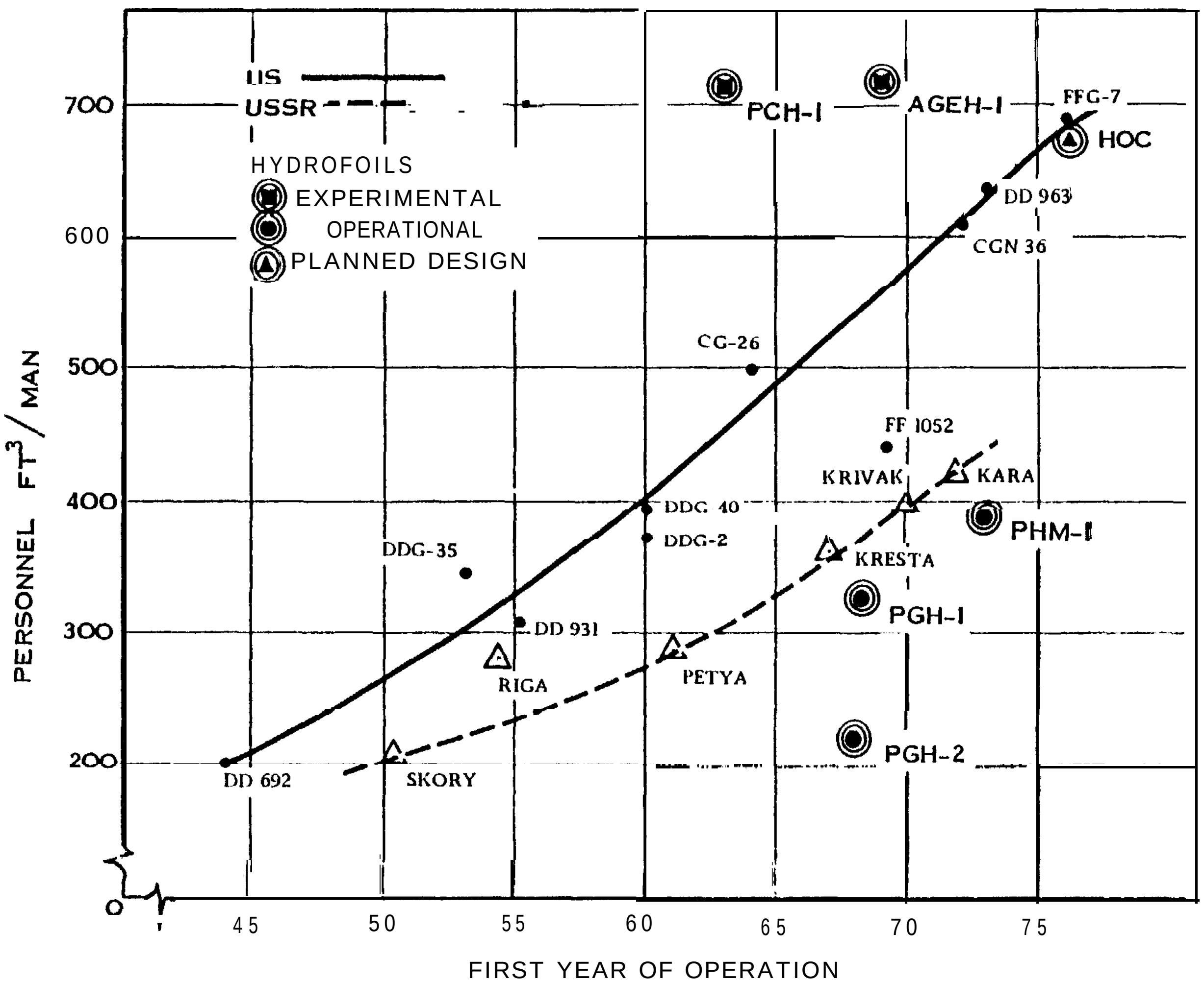

Figure II.B.4-7. HABITABILITY TREND

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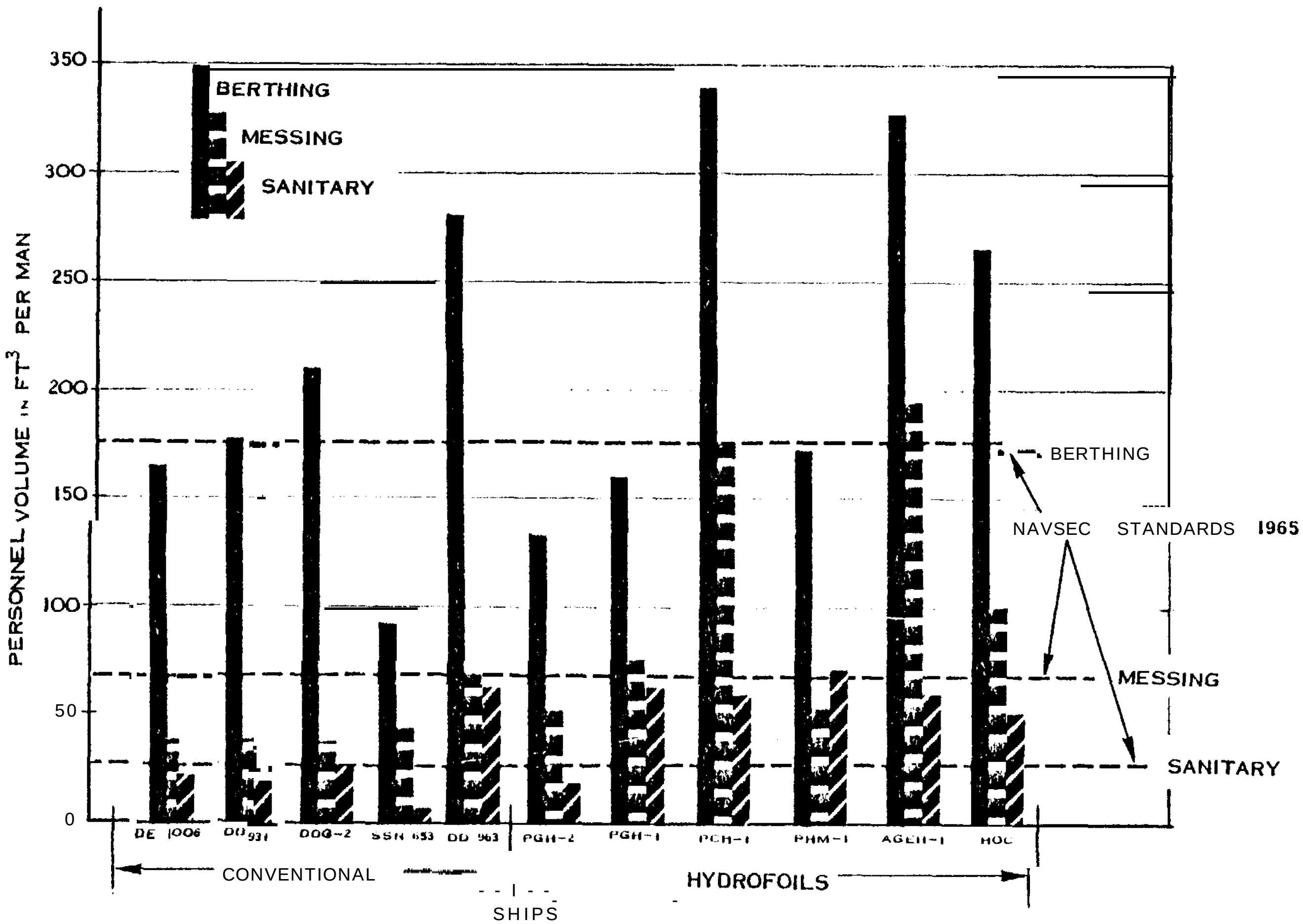

Figure II.B.4-8. DISTRIBUTION OF PERSONNEL VOLUME

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REFERENCES

II.B.4-1 "The Essentially Manned Advanced Surface Combat System," NELC TD 428, 1 May 1975.

II.B.4-2 The Personnel and Training Analysis Office (NAVSEC-047C1). "Preliminary Estimates of Manning Tradeoff and Manning Life Cycle Costs for Three Developmental Big Hydrofoils (DBH) - 3 Concept Designs," Ser 90-6, 6 June 1972, 10-U02085.

II.B.4-3 The Personnel and Training Analysis Office (NAVSEC-047C1). "Deepwater Escort Hydrofoil (DEH) Study, An Analysis of Missions, Combat Systems and Ship Concept Design" (U) (SECRET).

II.B.4-4 , "Proposed U.S. Navy Ship Space Classification Manual," Naval Ship Engineering Center, December 1969

II. STATUS OF VEHICLE TECHNOLOGY

B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

5. LIFT SYSTEM

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II.B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

5. LIFT SYSTEM

5.1 INTRODUCTION

(U) This section discusses the major design considerations, limitations, and engineering compromises inherent in the design of hydrofoil struts and foils.

(U) The lift system design process is typically one of iteration among performance requirements, hydrodynamics, structures, propulsion, hull configuration, weight, etc. A representative diagram of the design process is shown in Figure II.B.5-1. As can be seen, it is a very involved process with many repeated interactions between the requirements of different disciplines before arriving at the best balanced design.

(U) Basically, there are two approaches to the design of a lift system. The first is where the payload range and speed are specified, in which case the design process results in a minimum size ship to meet the requirement. The second is where the power plant is dictated, in which case the design process results in a ship with a possible maximum payload and range with the specified power plant, consistent with design speed and other requirements. The former case is adopted in this section since it is more realistic.

(U) Once the operational requirements have been established, either a single or a series of configurations are chosen for the appropriate design phase. Trade-off studies follow which interrelate

TYPICAL LIFT SYSTEM DESIGN PROCESS
(FIGURE 1)

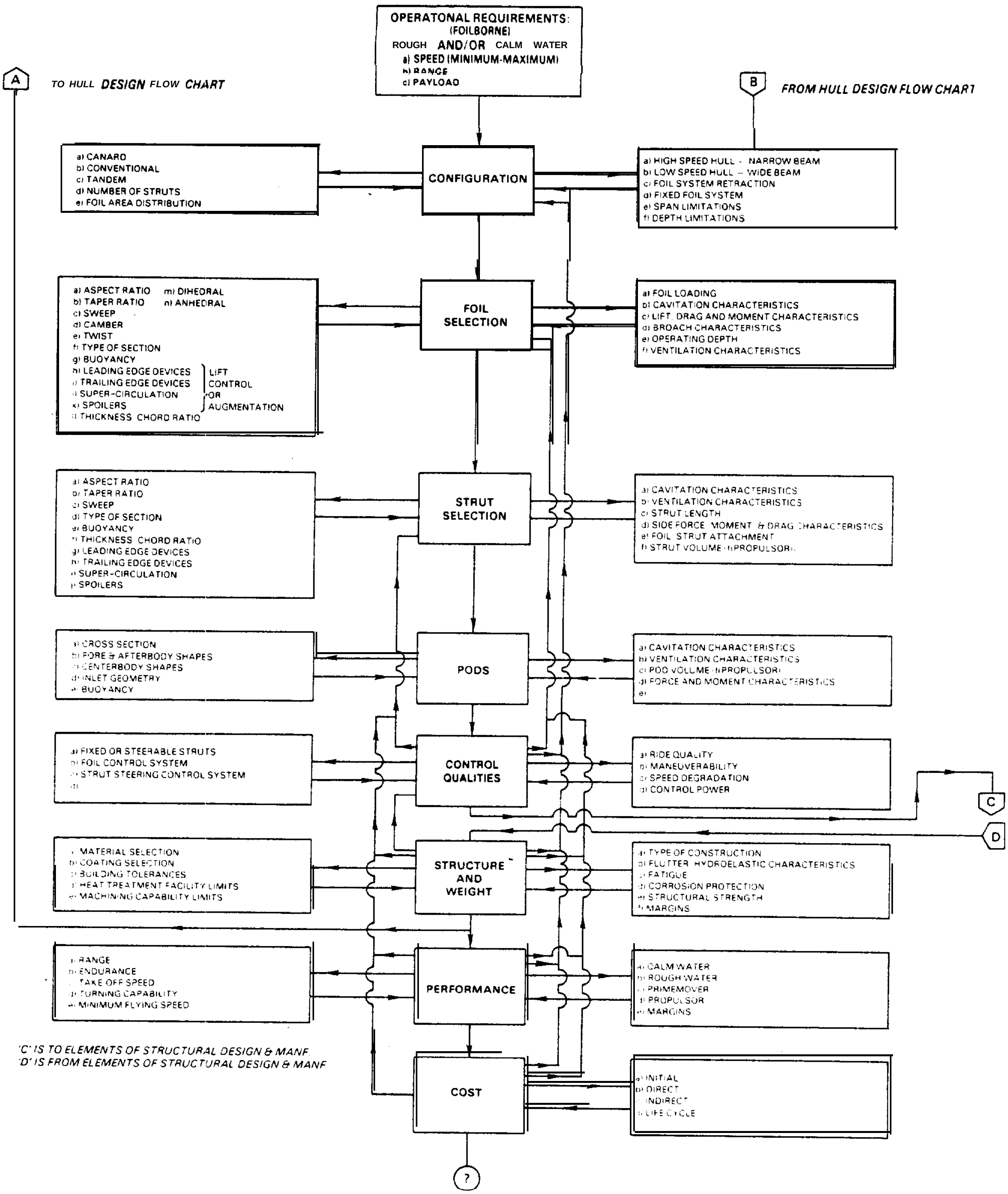

Figure II.B.5-1. TYPICAL, HYDROFOIL SHIP DESIGN PROCESS the hydrodynamic, structural, and propulsive areas that eventually determine a baseline configuration. A single configuration will then be chosen for contract design which will be subject to more trade-off studies and refinements, where cost and producibility are major considerations. The amount of refinement undertaken within the different disciplines in Figure II.B.5-1 is thus dependent upon the design stage and funds available.

(U) What follows will be a brief discussion of the factors and their effects on the major design decisions for lift systems required in the design process shown in Figure II.B.5-1. A summary of lift systems for several Navy hydrofoil ships is presented in Table II.B.5-1.

5.2 CONFIGURATION AND LOAD DISTRIBUTION

(U) Selection of the strut/foil configuration and load distribution are so interrelated that they are treated together. A hydrofoil ship is classified as having a canard, tandem, or airplane configuration depending on relative distribution of load between the forward and rear lifting surfaces. Reference II.B.5-1 arbitrarily defines a canard configuration as one in which less than 35% of the weight is carried on the forward foil, an airplane as one in which less than 35% of the weight is carried on the rear foil, and tandem as a distribution between these limits.

(U) Selection of the lift system configuration is influenced not only by hydrodynamic criteria, but also by external

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Table II.B.5-1

LIFT SYSTEMS FOR SEVERAL NAVY HYDROFOIL SHIPS

FOIL GEOMETRY	AGEH-1		PHM-1		PCH 1 (MOD 0)		PCH-1 (MOD-1)		PGH-1		PGH-2		FRESH-1	
	FWD	AFT	FWD	AFT	FWD	AFT	FWD	AFT	FWD	AFT	FWD	AFT	FWD	AFT
FOIL SECTION (NACA)	16-(.425)(.08)		16-206.5		16-309		16-309		16-(.27)(.077)		16-306		CAMBERED PARABOLIC	
S AREA (m^2)	41.80	5.56	13.10	28.10	6.10	13.90	6.10	16.06	6.50	3.25	3.35	7.34	.71	1.42
AR ASPECT RATIO	3.0	3.0	5.5	7.5	6.1	6.6	6.1	7.65	5.5	5.5	7.3	7.3	3.0	3.0
b FOIL SPAN (M)	7.92	4.09	8.50	14.51	6.10	9.60	6.10	11.09	4.23	4.23	4.94	5.18	1.44	1.44
C_R ROOT CHORD (M)	4.06	2.09	2.37	1.94	1.60	1.45	1.60	1.45	1.18	1.18	1.10	1.15	.74	.74
C_T TIP CHORD (M)	1.22	.63	.71	1.94	.40	1.45	.40	1.45	.36	.36	.25	.27	.25	.25
λ TAPER RATIO	.30	.30	.30	1.0	.25	1.0	.25	1.0	.30	.30	.23	.23	.30	.30
t/c THICKNESS RATIO	.08	.08	.065	.065	9%	9%	9%	9%	.077	.077	.06	.06	10%	10%
$\Lambda_{c/4}$ SWEEP ANGLE OF QUARTER CHORD (°)	35.2°	35.2°	11°	0°	15°	0°	15°	0°	11.72°	11.72°	9.74°	6°	17.1°	17.1°
Γ DIHEDRAL ANGLE (°)	0°	0°	0°	12°	0°	0°	0°	12° INBD 6° OUTBD	0°	0°	0°	13°	0°	0°
F_S FLAP AREA (TOTAL) (m^2)	N/A	N/A	3.28	5.72	1.30	3.13	1.30	3.13	N/A	N/A	1.40	4.88	.23	.46
L/A LOADING (kN/m^2)	64.90	47.94	64.16	51.71	53.87	50.00	68.76	57.22	64.93	59.75	52.62	52.62	76.61	76.61
% OF WEIGHT DISTRIBUTION	90%	10%	34.6%	65.4%	30.2%	69.8%	34.5%	65.5%	70%	30%	31%	69%	33.3%	66.7%
MATERIAL	HY-80 & HY-100 STEEL		17-4PH STEEL		HY-80 & HY-100 STEEL		HY-80 & HY-130 STEEL		6061 T652 ALUM		17-4PH STEEL		17-4PH STEEL	
CONFIGURATION	AIRPLANE		CANARD		CANARD		CANARD		AIRPLANE		CANARD		CANARD OR AIRPLANE	

REFERENCE: HYDROFOIL DESIGN DATA LOG DTNSRDC; TO BE PUBLISHED

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physical limitations and performance at off-design conditions. These constraints include:

1. Foil span
2. Navigational draft hullborne - foils down
3. Structural considerations
4. Center of gravity shift
5. Weapons suite and machinery arrangement

(U) Although the above will not be discussed at length in the interest of brevity, a few remarks in the next paragraphs are worthwhile, since the majority of issues raised have been competently addressed in voluminous proprietary and other documentation.

5.2.1 Span

(U) From a hydrodynamic efficiency consideration, the span of a hydrofoil should be as high as practical. This is particularly true at takeoff and lower flying speeds as is shown in Figure II.B.5-2. Structural and other considerations, however, limit the practical span of a hydrofoil. Foil span in some studies (References II.B.5-1, II.B.5-2, and II.B.5-3) has been limited to 100-108 ft in order to allow the ships to pass through the Panama Canal. Also, it is recognized that a substantial overhang spanwise on either inverted 'T' (single strut) or inverted 'Π' (two struts) foils could create serious docking difficulties in that the foils might find conflict with dockside cranes, buildings, and vehicles, etc. Figure II.B.5-3 shows the rear foil span for a canard configuration

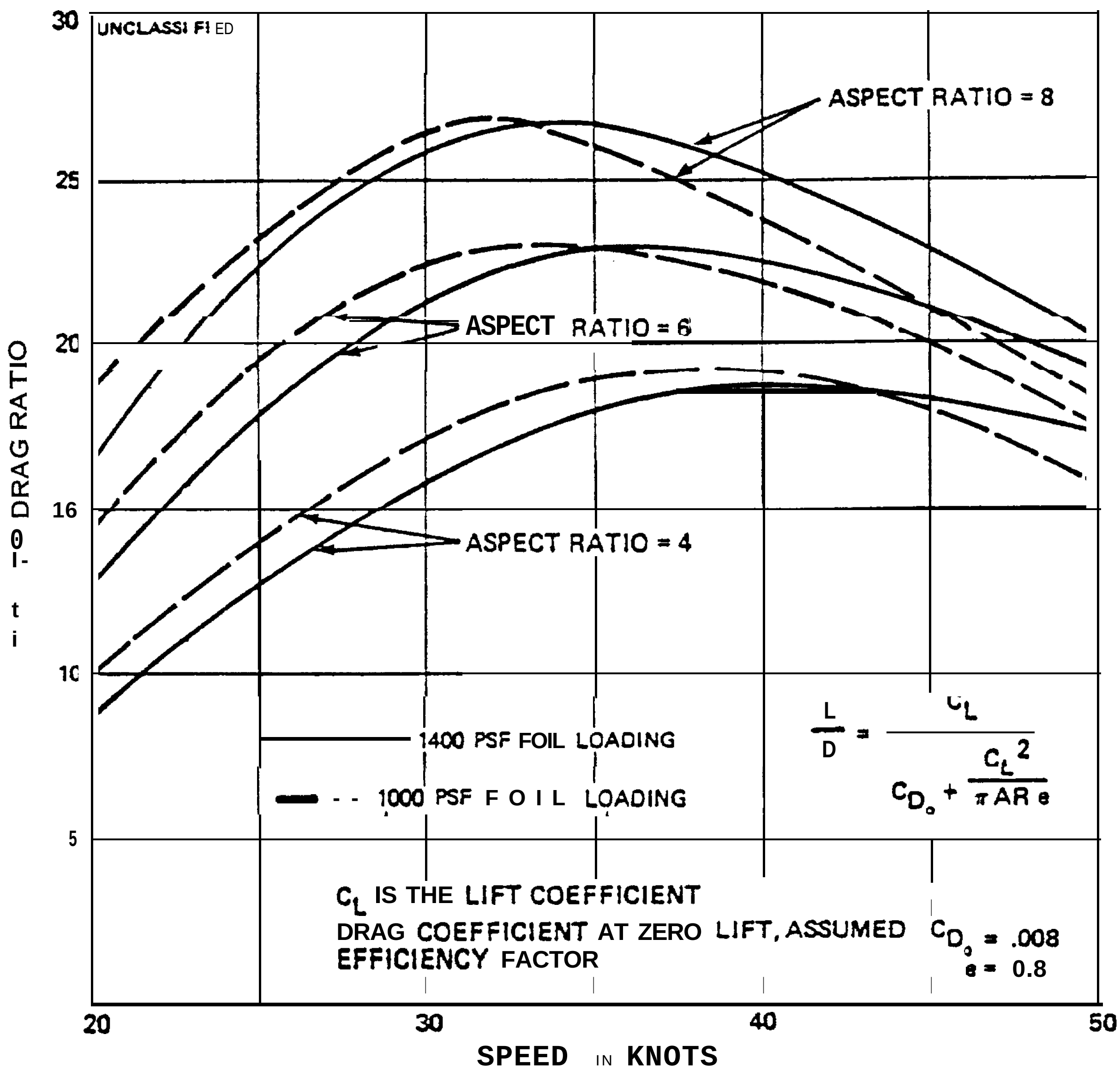
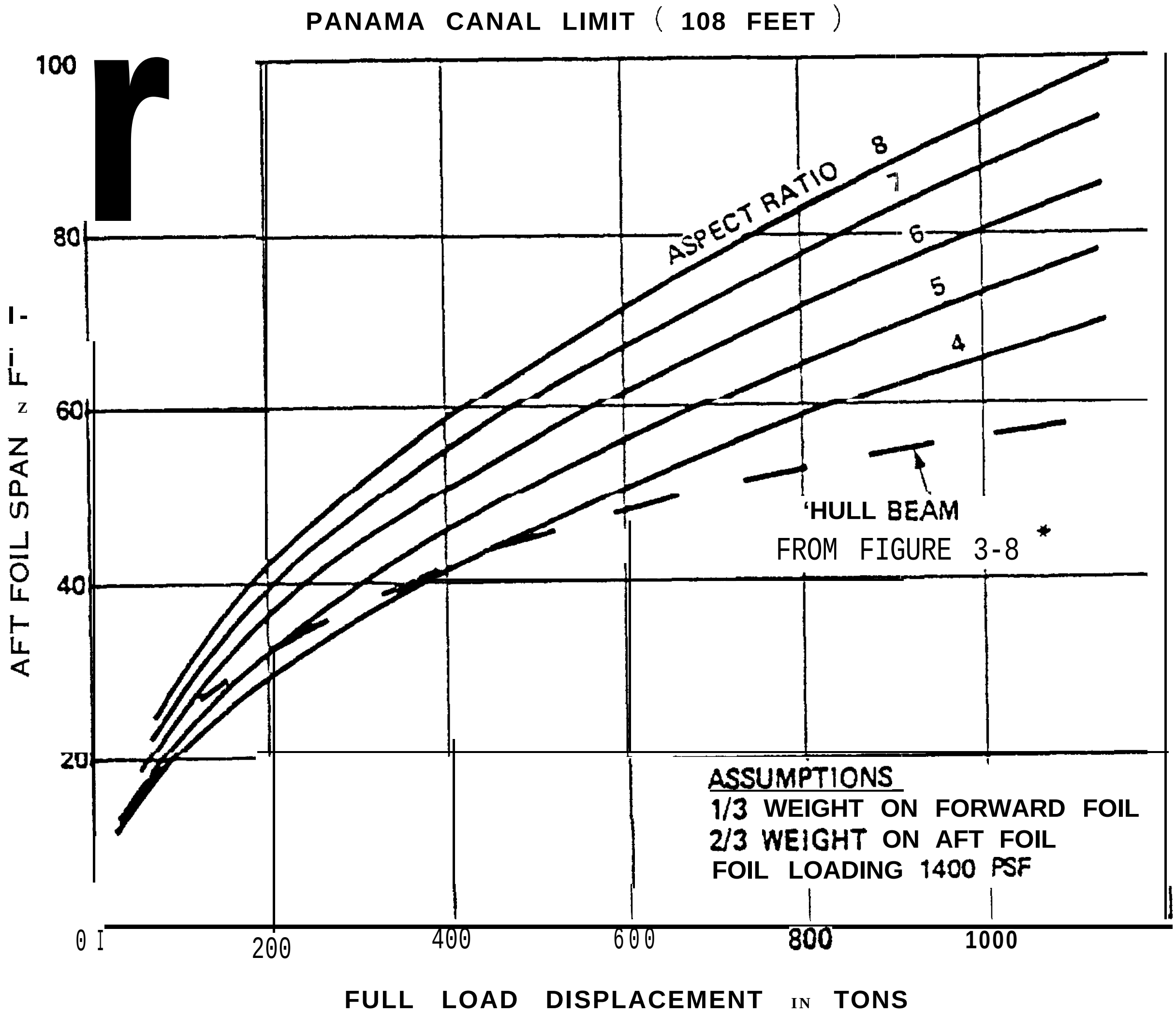


Figure II.B.5-2. FOIL EFFICIENCY AS A FUNCTION OF SPEED



* Reference II.B.5-1

Figure II.B.5-3. AFT FOIL SPAN AS A FUNCTION OF SHIP DISPLACEMENT (U) as a function of displacement for different aspect ratio foils. By going to a 50%-50% tandem configuration, the span would be reduced by 13% and the overhang by about 25%. For this reason, large hydrofoil ships are being driven more toward the tandem configuration rather than either the canard or airplane configuration. The major consideration which limits the degree to which one can go to a tandem configuration is the hull shape and weight distribution due to the arrangement of machinery and weapon systems and the requirement for retraction which will be discussed next.

5.2.2 Navigation Draft (Retraction)

(U) Hydrofoil ships with their foils down have a considerable draft relative to displacement hulls of the same displacement. For a 1,000-ton hydrofoil ship, this draft will be approximately 35 ft, about 2/3 of which is the amount the lift system projects below the keel. In order to reduce this draft and to make the lift system and propulsion gearboxes accessible for maintenance without drydocking, it is necessary to retract the foils out of the water. For larger hydrofoil ships, this is most easily done by swinging the foils up behind the transom and up over the front of the bow. Design studies for large hydrofoil ships indicate a weight penalty for dry retraction is between 10 and 20% of the full load weight of the ship. Retraction also complicates the transmission design. Although the penalty for retraction is high, considerations of draft, drydocking, and maintenance will probably dictate dry retraction. All projected performances of a large hydrofoil ship in this state-of-the-art summary are based on ships which have dry retraction.

5.2.3 Structural Considerations

(U) Two strut arrangements to support the lifting surface have been used in hydrofoil ships. The simplest and applicable to relatively small foils is the inverted 'T' configuration in which a foil is mounted at the end of the strut. The cantilever overhang of the foil creates large bending moments which limits the practical aspect ratio which can be used for such a system. The other type of foil is a continuous foil which is supported by two struts. The struts are generally located one on each side of the ship. This configuration is called the inverted 'Π' configuration. Large cantilevers are avoided and the effective aspect ratio of the center span due to the end plating effect of the struts is quite high. Since the struts are restrained in torsion at both ends, they are stiffer in torsion and resist the tendency to hydroelastic instability (flutter and divergence) better than the inverted 'T' configuration. For the above reason, inverted 'Π' configurations for both the forward foil and after foil as illustrated in Figure II.B.5-4 are favored in the design of large hydrofoil systems.

5.2.4 Center of Gravity Shift

(U) As hydrofoil ships use fuel and deliver weapons, the center of gravity can shift and alter the load distribution.

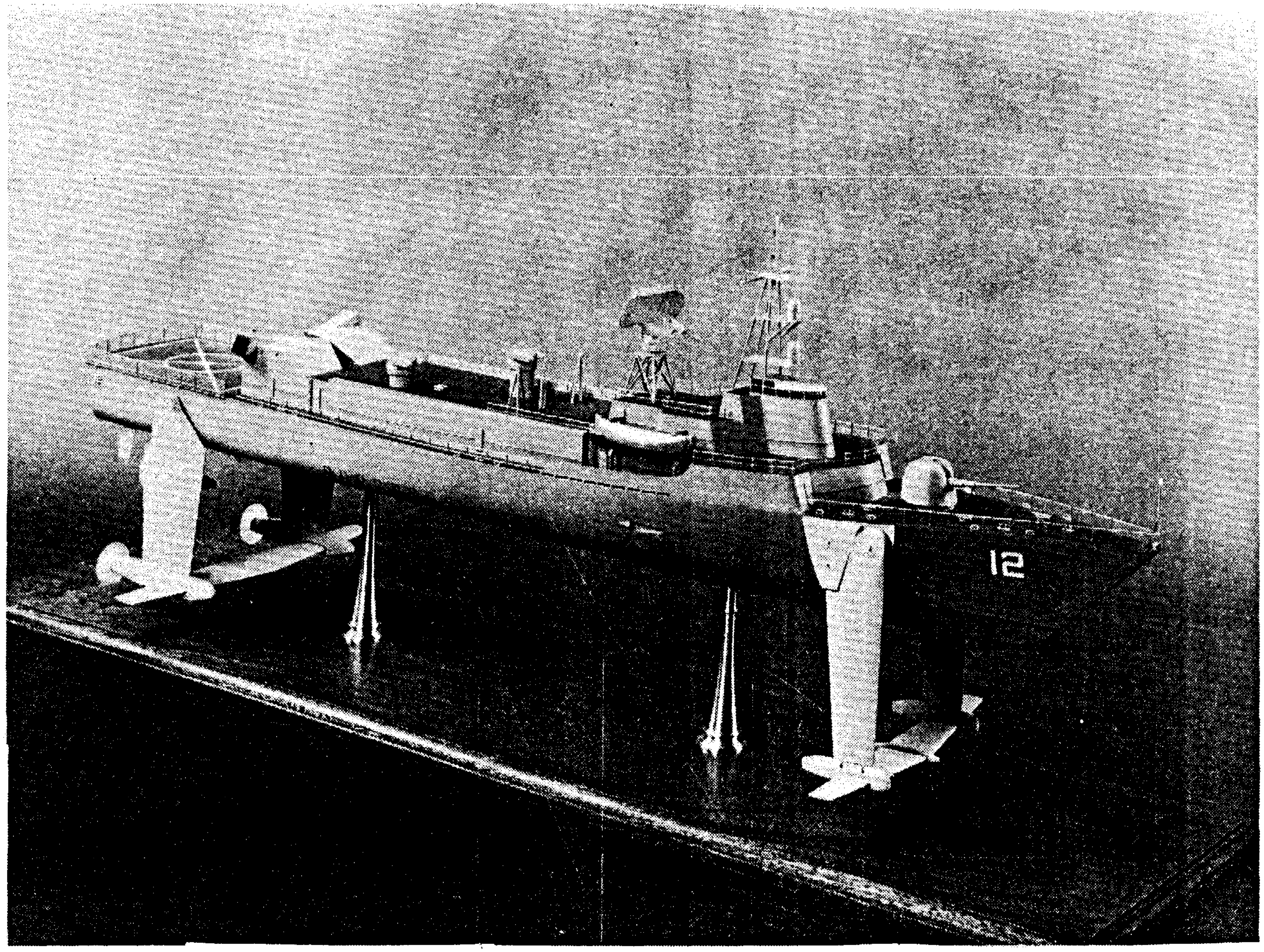


Figure II.B.5-4. TYPICAL LARGE HYDROFOIL DESIGN

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The closer the load distribution between the forward and aft foil is to tandem, the less effect this has. For instance, for a 10-90 distribution, a shift in the center of gravity (CG) location of 1% of the longitudinal spacing of the foils changes the forward foil loading 10% while for a 50-50 distribution, the same shift in CG location changes the forward foil loading only 2%. None of the Navy's present hydrofoil ships have been adversely affected by the normal shift in CG location due to fuel burnoff or weapon delivery.

5.2.5 Weapon Suite and Machinery Arrangement

(U) The designer is restrained in selecting the foil load distribution, and thus foil configuration, by practical hull shape, machinery, and weapon suite arrangements. Engines must be near the struts which transmit the power to the struts, and certain weapon systems such as missile launchers must be aft to minimize the danger of obnoxious fumes and visibility restriction. These considerations limit the flexibility in selecting the load distribution to meet other considerations.

5.3 FOIL DESIGN

(U) Foil design is very similar to wing design except the hydrodynamicist has to cope with cavitation, whereas the aerodynamicist has to cope with compressibility. Although both are physically unrelated, the restrictions imposed upon foil design by cavitation are analogous to those imposed by Mach number effects on wing design. Thus, a cavitation bucket looks very similar to a Mach force-divergence bucket. Cavitation occurs when the local static pressure drops to vapor pressure and the fluid then boils and vapor cavities are forced. If these cavities collapse on the surfaces of the lift system, severe erosion can take place.

(U) The prediction of hydrodynamic forces and moments use aerospace technology applied by the utilization of many computer programs which assist in optimizing design performance. These programs optimize lifting surface theory and pressure distribution.

5.3.1 Foil Loading

(U) Foil loading, dynamic lift divided by foil planform area, is first established by takeoff speed and/or minimum specified flying speed. The maximum lift coefficient which can be achieved by a foil is generally around 1.0. About 20% to 30% of this is reserved for control forces needed at takeoff, to counter the seaway, maneuvering and takeoff trim requirements.

(U) Figure II.B.5-5 shows the relationship of foil loading to takeoff speed. The limits are based on lift coefficients of 0.7 and 0.8. The minimum stable flying speed shown in Figure II.B.5-5 generally corresponds to a speed a few knots below the speed of minimum drag. Generally, this corresponds to a lift coefficient between 0.5 and 0.6, which provides sufficient lift margin needs to assure necessary control forces to trim the ship, alternate seaway disturbances and provide maneuvering transient forces and moments.

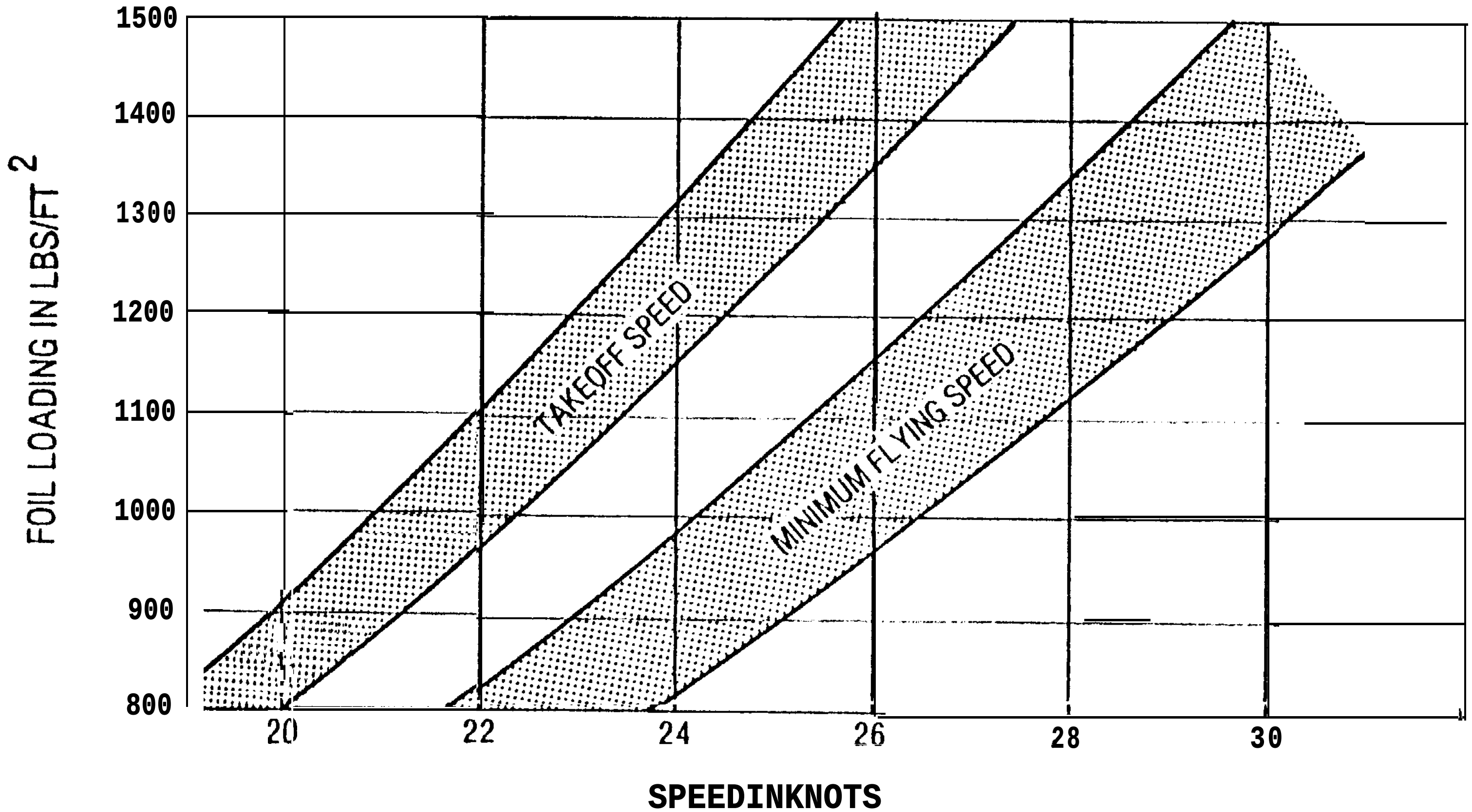

Figure II.B.5-5. FOIL LOADING - TAKEOFF AND MINIMUM FLYING SPEED RELATIONSHIP

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(U) The initial foil loading may have to be adjusted downward to assure cavitation-free operation at low speeds which will become apparent in the discussion on cavitation in the next paragraph.

5.3.2 Foil Section Selection

(U) Cavitation - the foil section is selected to give a relatively flat pressure distribution to avoid local pressure peak which causes cavitation. The 16 series and 64 series foils have this characteristic. The 16 series has been used for Navy hydrofoils primarily because of the extent of data available. There is some evidence that an improvement in performance in flap controlled foils can be realized by the use of 64 series. The cavitation characteristics of a foil are determined as follows:

(U) The operating foilborne loading speed envelope is plotted as shown in Figure II.B.5-6. Twenty percent margin on this loading is added for transient changes in a seaway and about a 5-knot speed margin is added to account for tolerances. A foil section is then sought which encompasses this envelope within its cavitation-free operation. The cavitation boundaries of foil sections are determined analytically by using programs such as developed by Brockett in Reference II.B.5-4, which shows good correlation with model tests as shown in Figure II.B.5-7. Figure II.B.5-8 shows the typical cavitation boundaries of swept-tapered 16 series foils for two different cambers. The areas of the foils where cavitation occurs

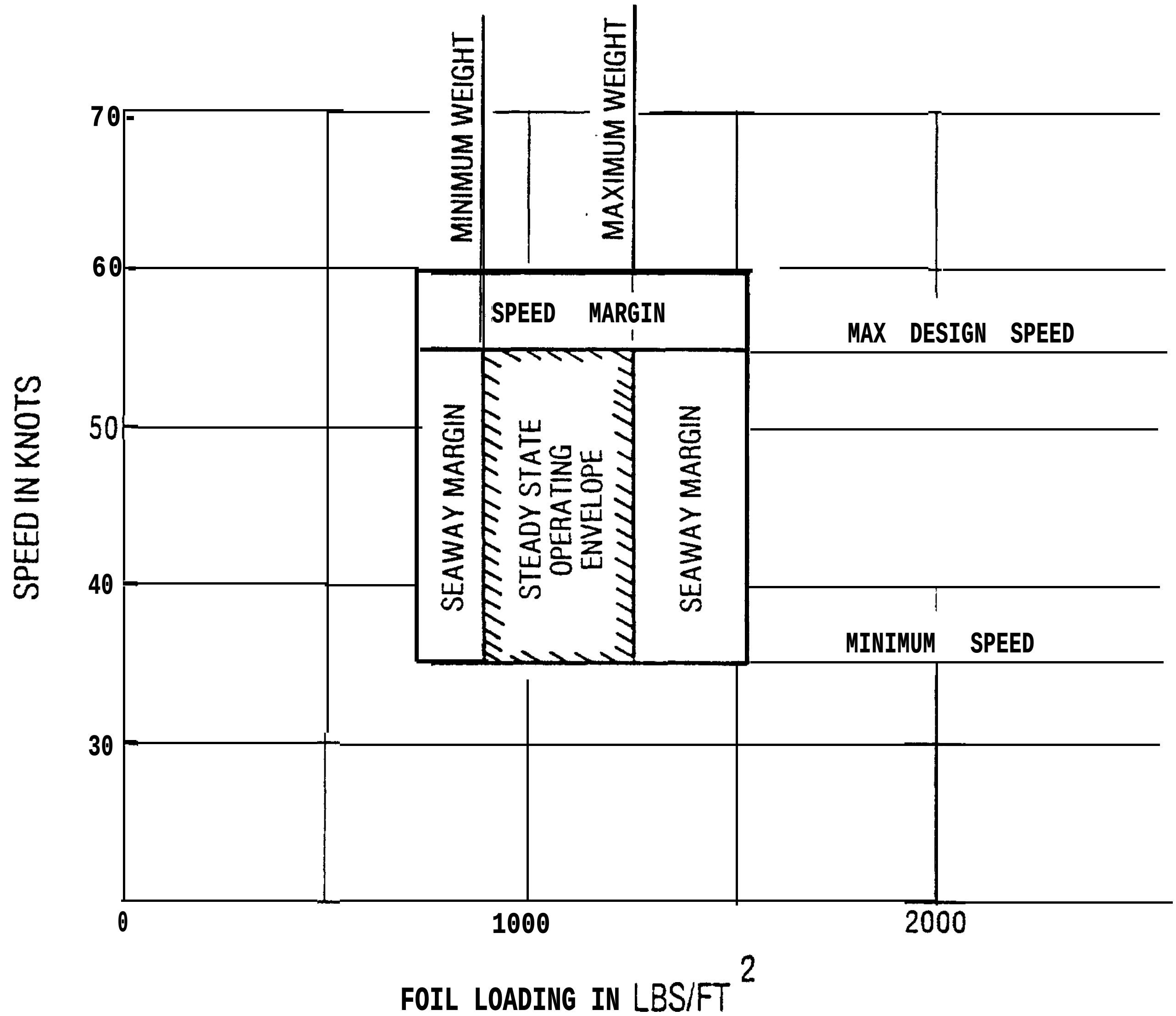

Figure II.B.5-6. FOIL LOADING - SPEED ENVELOPES

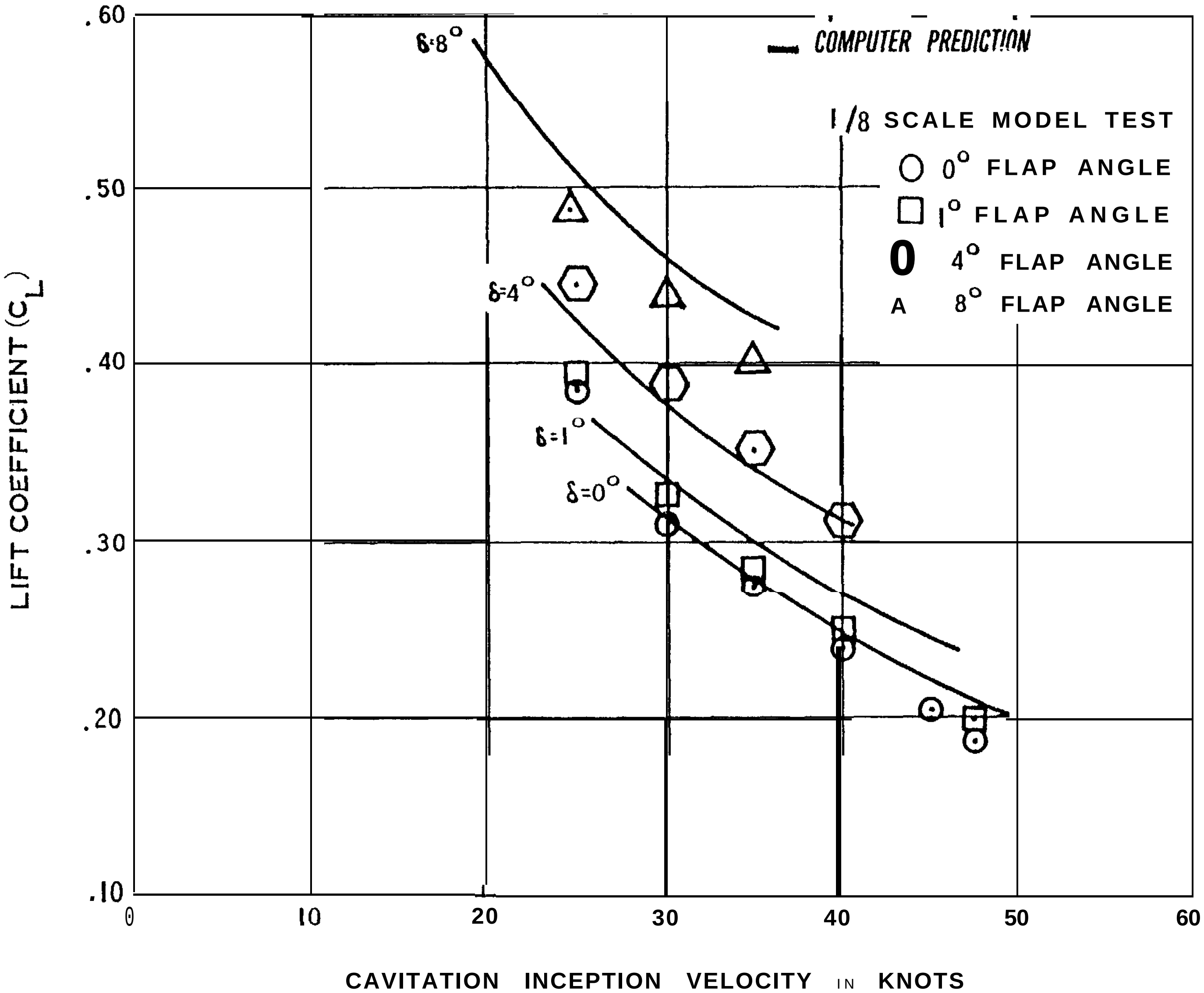

Figure II.B.5-7. COMPARISON OF PREDICTED AND EXPERIMENTAL LEADING EDGE CAVITATION INCEPTION RESULTS (PCH-1) FORWARD FOIL

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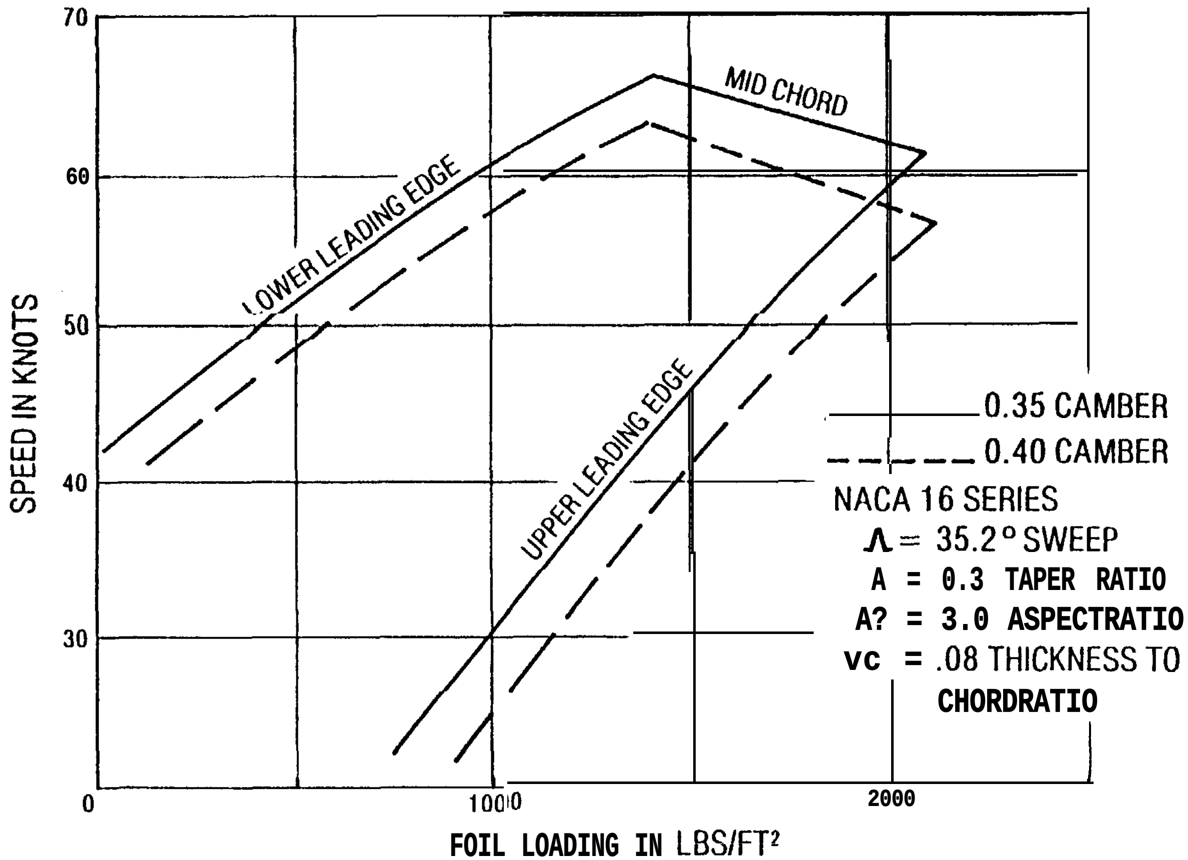

Figure II.B.5-8. TYPICAL CAVITATION BOUNDARIES OF SWEPT-TAPERED 16 SERIES FOILS FOR TWO DIFFERENT CAMBERS

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on each boundary is stated on the figure. These boundaries can be exceeded considerably before there are major changes in the ability of the foil to generate lift. For reference, the maximum loading obtainable on the foil is also shown in Figure II.B.5-9.

(U) When the cavitation curves of Figure II.B.5-8 are superimposed on the foil loading envelope, the operating cavitation characteristics of the foil system can be determined. Figure II.B.5-9 shows such a superimposition. This figure shows that for a 0.35 camber, the foil will cavitate slightly at minimum speed and maximum weight, particularly, intermittently in a seaway. If the camber is increased to 0.40, however, the entire steady state envelope will fall within the cavitation-free area, and only slight intermittent cavitation will occur in a seaway. The same result could have been achieved by lowering the foil loading slightly. Decreasing the foil loading, however, increases foil size and weight. In selecting a foil section, the designer can opt for either speed margin or growth margin to allow an increase in ship weight (increased foil loading). Since most ships tend to grow in weight with time, the latter is the preferred option.

5.3.2.1 Camber

(U) The camber of a foil is normally chosen so as to give the required lift coefficient at zero angle of attack near the maximum design speed so as to keep the pressure distribution

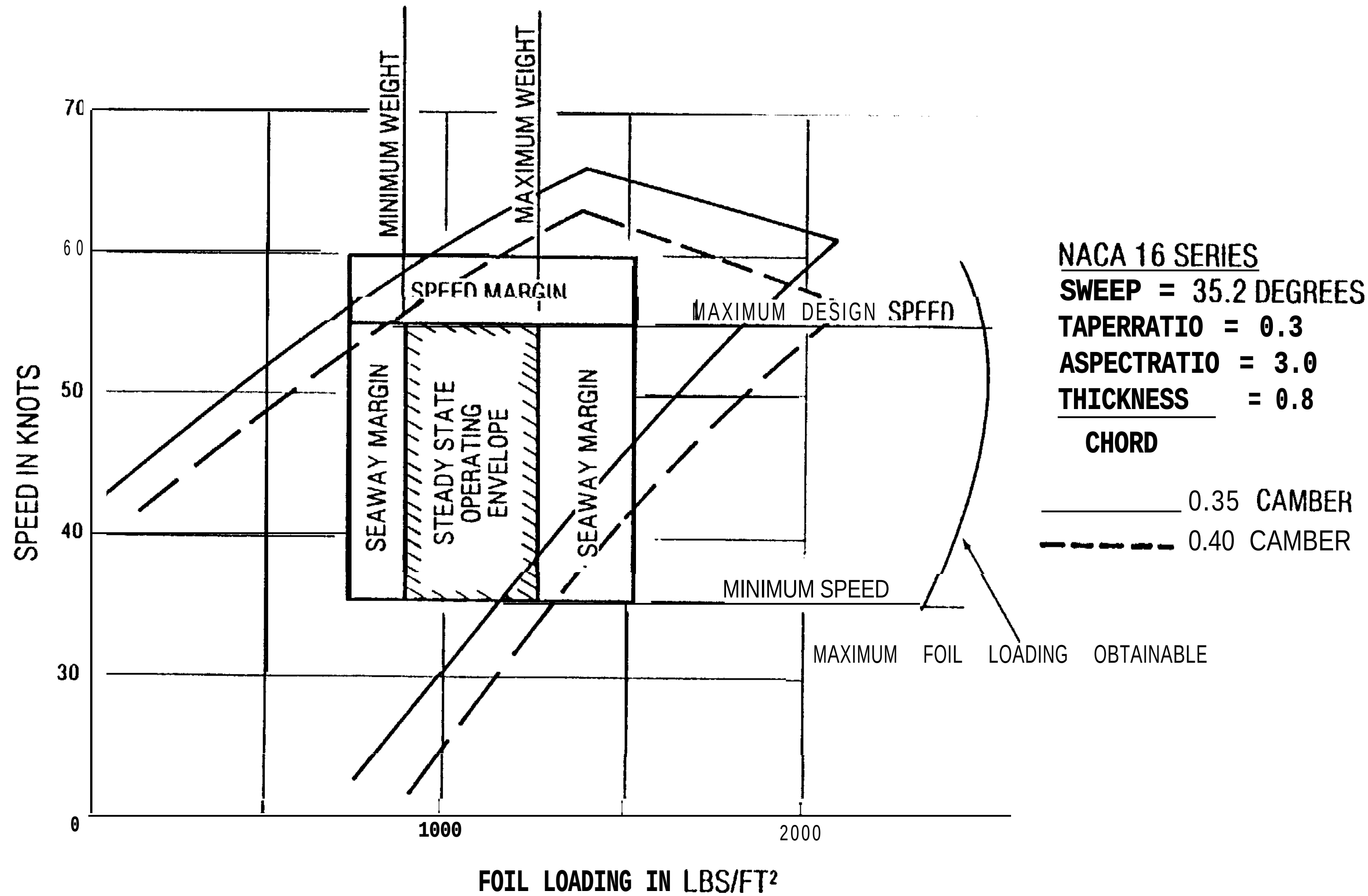

Figure II.B.59. FOIL LOADING - SPEED ENVELOPE WITH CAVITATION BOUNDARIES OF TWO DIFFERENT FOILS SUPERIMPOSED

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nearly uniform. By doing this, local pressure peaks near the leading edge due to angle of attack are minimized at maximum speed, and thus the tendency to cavitate at the leading edge is minimized.

5.3.2.2 Sweep

(U) Effect of sweep on incipient cavitation speed is shown in Figure II.B.5-10. The use of sweep allows the use of thicker sections for a given incipient cavitation speed, or alternatively extends the use of existing sections to higher design speeds. In this respect, it is interesting to note that, according to Reference II.B.5-5, the XCH-4 achieved 79 knots without any apparent evidence of harmful cavitation with a set of subcavitating NACA 65-206 foils employing a leading edge sweep of 45°. Sweep of the leading edge also tends to shed debris which is encountered by hydrofoils.

5.3.2.4 Taper Ratio

(U) Taper ratio is the ratio of the root chord to the tip chord of a foil. A foil is tapered to improve spanwise load distribution and reduce the gradient of the tip vortex. For unswept wings, a taper ratio of about 0.45 is optimum. For swept wings, more taper is required to get the optimum lift-to-drag ratio. Tapering places more load toward the center of the foil or nearer the strut and, therefore, decreases the bending load for a given lift.

5.3.2.5 Twist

(U) Twist is defined as the variation in the angle of incidence along the span. Twist and camber modification can be

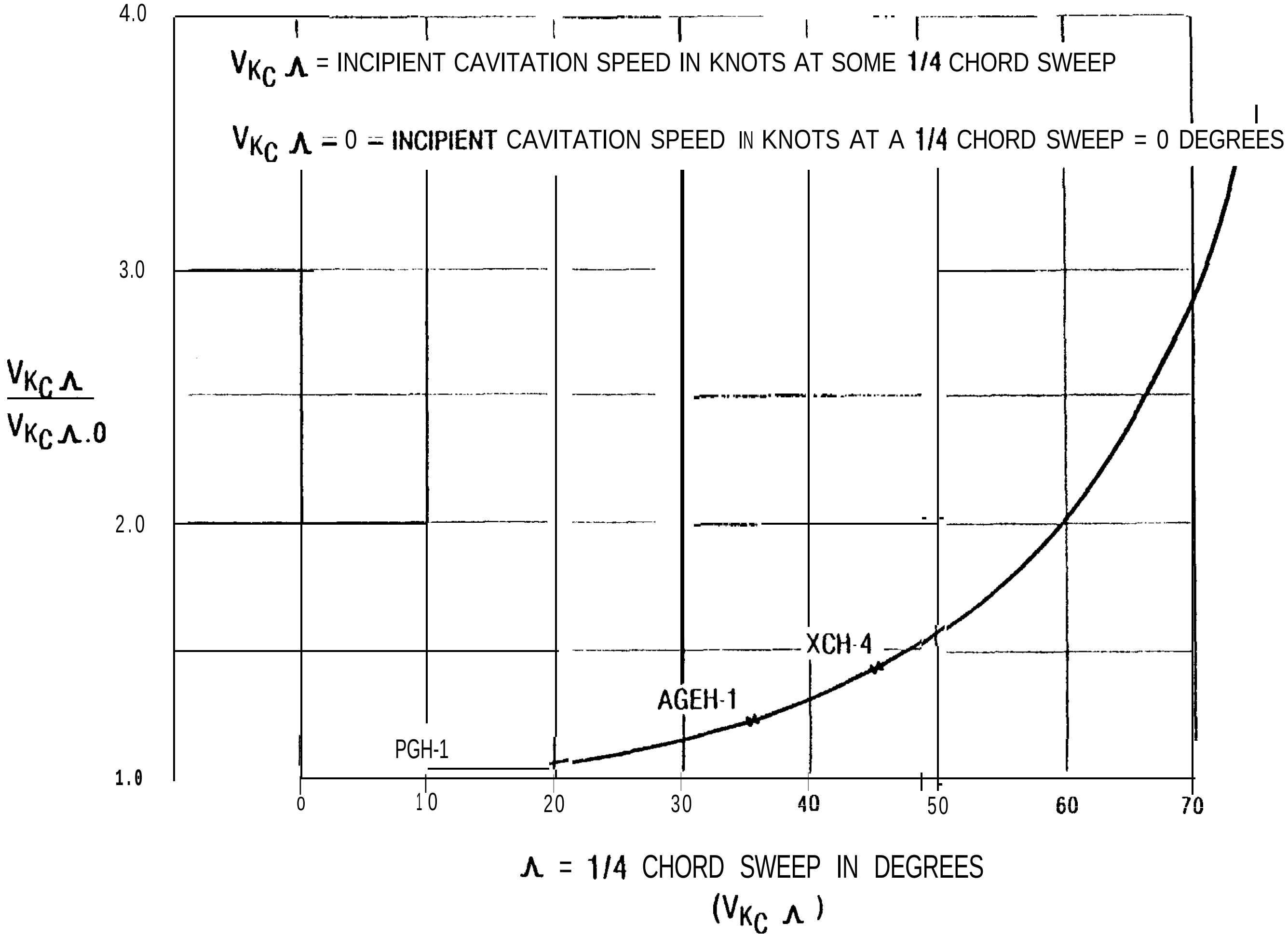

Figure II.B.510. RATIO OF INCIPIENT CAVITATION SPEED WITH SWEEP TO NONSWEPT SPEED VERSUS QUARTER CHORD SWEEP ANGLE - FOR SUBCAVITATING FOILS

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used to improve the spanwise load distribution much the same as taper ratio. Since it is simpler to manufacture a foil with taper than it is to make a foil with variable camber or twist, most foils are designed with no twist.

(U) Table II.B.5-2 summarizes the effects of lift system geometry on drag, lift cavitation, structures, and ride quality of a hydrofoil.

5.3.3 Control

(U) Historically, there have been continual debates over the optimal methods by which to achieve lift control for a hydrofoil. Only two systems have been used in Navy hydrofoils to date, the first being flap control and the second being incidence control. The power to operate these lift control devices, control power, is a function of hinge moment, control rate, efficiency of the powering system, the distance through which the control travels, and inertial effects. Hinge moment is a combination of the residual moment and the moment due to steady lift and unsteady lift which are both dependent upon pivot location. The residual moment is a function of the foil camber and section. Steady lift refers to that in calm or smooth water, which is purely related to speed so that for any given speed the foil or flap has one particular setting. Unsteady lift and moments are those associated with the acceleration and rate of altering the lift control devices, pitch angle, and heave required to decouple the craft's motion from the seaway. Thus, the control

Table II.B.5-2. FOIL DESIGN CRITERIA

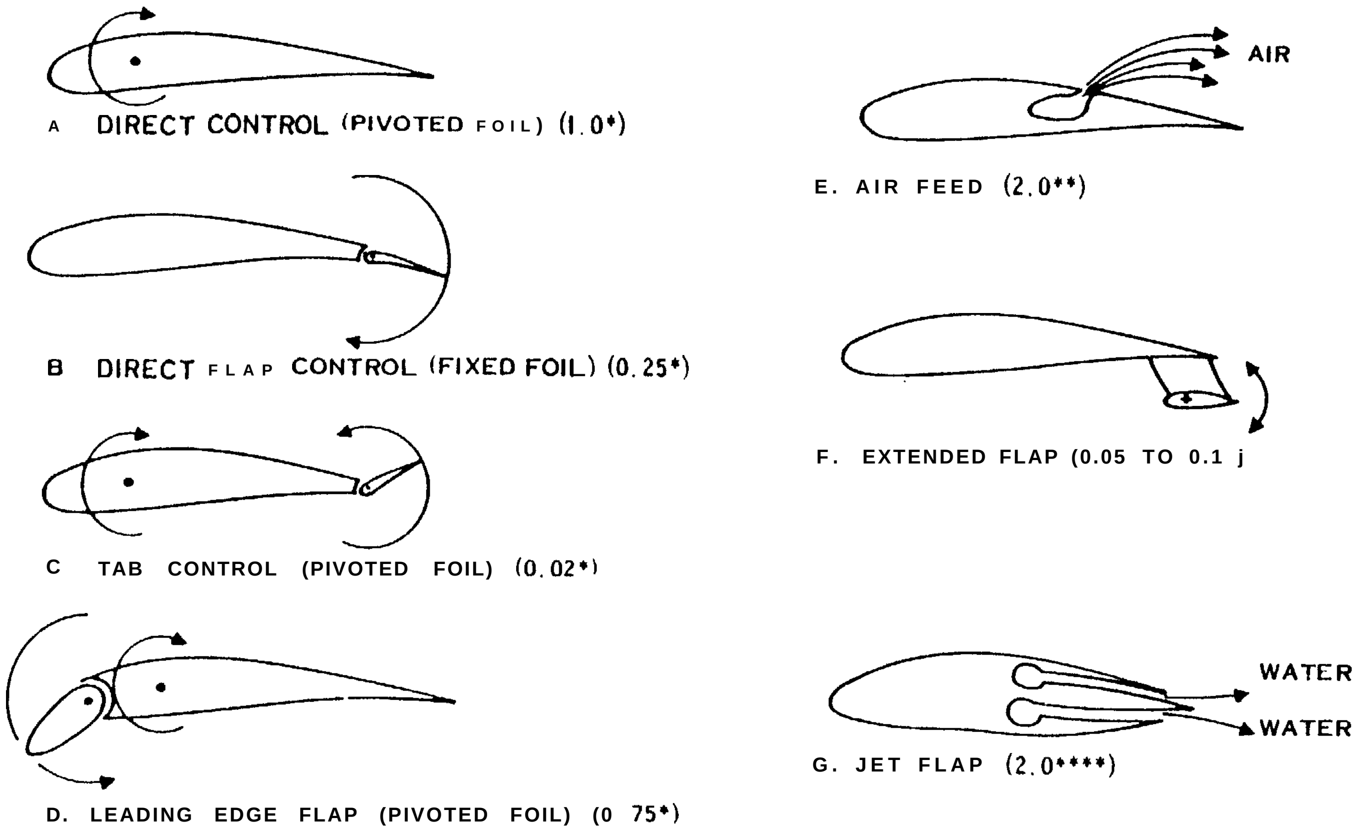
CHARACTERISTIC CRITERIA	FOIL AREA LOADING $(\frac{W}{S})$	ASPECT RATIO (AR)	SWEEPBACK (Λ)	TAPER (λ)	FOIL SECTION (t/c, τ, Profile)	TWIST $(\alpha_{ox\eta})$
DRAG	a) Minimum at cruise b) Limit at take-off c) Limit at top speed	a) Reduce foil induced drag b) Penalty if additional strut/pod is required	a) Affects spanwise load distribution b) Increased allowable thickness with increased sweepback	a) Improve spanwise loading, reduce induced drag 1) For unswept foil taper ratio of 0.45 is optimum. 2) Increasing sweepback, more taper is required. 3) Effect of taper and sweep can be modified by twist and camber variations.	a) Drag at take-off b) Drag at design speed	) Modify spanwise loading 1) Compensate for downwash on other foils. 2) Prevent tip "stall"
LIFT	a) Provide adequate lift for take-off at desired speed.	a. Affects lift curve Slope	a) Reduces available lift for given area.	a) Negligible change with taper ratio.	a) Considerable effects on max. obtainable C	) Changes lift curve slope characteristics.
CAVITATION	a) Limit loading at top speed b) Adequate load range all speeds and weight c) Avoid leading edge cavitation at min. foilborne speed.		a) Increased allowable thickness with increased sweepback.	a) Increased taper increases section lift coefficient near tip (effect is modified by twist and camber variation).	a) Max loading at top speed. b) Minimum foilborne speed. c) Manufacturing tolerances.	) Affects spanwise position of critical section.
STRUCTURAL	a) Foil weight b) Ease of retraction. c) Obstruction to maneuvering and docking.	a) Foil weight b) Ease of retraction c) Maneuvering, docking d) Span limitation	a) Shed debris b) Foil weight	a) Decreases foil bending moment with increase taper. b) Critical torsion-bending flutter speed increased. c) Decreased foil weight.	a) Section modulus	) Adversely affects weight.
RIDING QUALITY	a) Better with high loading	a) Better with low aspect ratio	a) Better with high sweep		a) Better with thin section.	
RELEVANT REQS.	V_{KD}, V_{KMR}, V_{KME}, V_{KTO}, W_S	V_{KTO}, V_{KME}, V_{KMR} V_{KD} W_S	W_S, V_{KD}, V_{KME}, V_{KMR}, V_{KTO}	W_S, V_{KTO}, V_{KME}, V_{KD}	V_{KD}, V_{KTO}	
RELATED CHAR	AR, λ, Λ, foil section	λ, Λ, material, structure	AR, λ	Λ, AR, $\alpha_{ox\eta}$ spanwise section	$\frac{W_F}{S}$, AR, Λ, λ, $\alpha_{ox\eta}$	, λ, section

For symbol defioition, sek page II.B.5-55.

power assessment requires a good understanding of the craft dynamics and sea state in which it is to operate. Several proprietary control simulations have been undertaken and Figure II.B.5-11, extracted from a study completed by Bolt, Beranek, and Newman (Reference II.B.5-6) for the David W. Taylor Naval Ship Research and Development Center, summarizes the relative control power of various lift control schemes, including any steady state drag increment. Model tests to obtain the characteristics of a trailing edge tab and an extended flap are currently planned to evaluate the viability of these concepts for the large hydrofoil ship. Upon completion of these tests, it is planned to modify the PCH-1 or AGEH-1 to incorporate the most promising scheme for at-sea, full-scale trials.

5.3.3.1 High Lift Devices

(U) High lift devices can be used to increase the maximum lift coefficient at takeoff and low speeds so as to either lower these speeds or,since these speeds determine the foil loading, to increase the foil loading and thus reduce the size of the foils. High lift devices include trailing and leading flaps, slats, and circulation control. Flaps increase the wing area in the more sophisticated types and substantially increase the lift on a aerosoil or hydrofoil. Slats increase the operating angle of attack range on an aerofoil or hydrofoil before the stall occurs. Table II.B.5-3 summarizes the various configurations of high lift devices aerodynamically tested. While the possibility of using slots is acknowledged,



NUMBERS IN PARENTHESIS ARE RELATIVE CONTROL POWER REQUIRED. INCLUDING STEADY STATE DRAG PENALTY.

- Rasod on Bolt, Beranek, and Newman report 2511, "Hydrofoil Design for Minimum Power. "

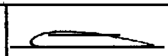
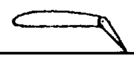
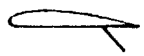
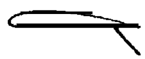
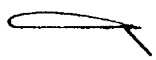
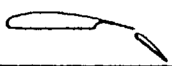
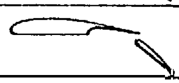
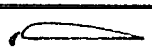
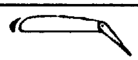
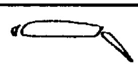
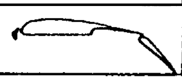
**Based on 1965 NSRDC-SUPRAMAR Tank Tests.

. **Based on Thr Boeing Co. estima tes.

* ***Based on Oceanics, Inc. Report 6413, "Use 01 Jet Flapped Hydrofoils as Ships Antipitching Fins. "

Figure II.B.5-11. LIFT CONTROL SCHEMES

Table II.B.5-3. HIGH LIFT DEVICES*

Designation	Diagram	$C_{L_{max}}$	α at $C_{L_{max}}$ (degrees)	L/D	$C_{m_{ac}}$	Reference
Basic airfoil Clark Y		1.29	15	7.5	-.085	TN 459
.30c Plain flap deflected 45°		1.95	12	4.0	–	TR 427
.30c Slotted flap deflected 45°		1.90	12	4.0	–	TR 427
.30c Split flap deflected 45°		2.16	14	4.3	-.250	TN 422
.30c hinged at .80c Split flap (Zap) deflected 45°		2.26	13	4.43	-.300	TN 422
.30c hinged at .90c Split flap (Zap) deflected 45°		2.32	12.5	4.45	-.385	TN 422
.30c Fowler flap deflected 40°		2.82	13	4.55	-.660	TR 534
.40c Fowler flap deflected 40°		3.09	14	4.1	-.860	TR 534
Fixed slot		1.77	24	5.35	–	TR 427
Handley Page automatic slot		1.84	28	4.1	–	TN 459
Fixed slot and .30c plain flap deflected 45°		2.18	19	3.7	–	TR 427
Fixed slot and .30c slotted flap deflected 45°		2.26	18	3.77	–	TR 427
Handley Page slot and .40c Fowler flap deflected 40°		3.36	16	3.7	-.740	TN 459

NACA 7 by 10 ft tunnel data   AR=6 R-609,000

*For symbol definition, see page II.B.5-55.

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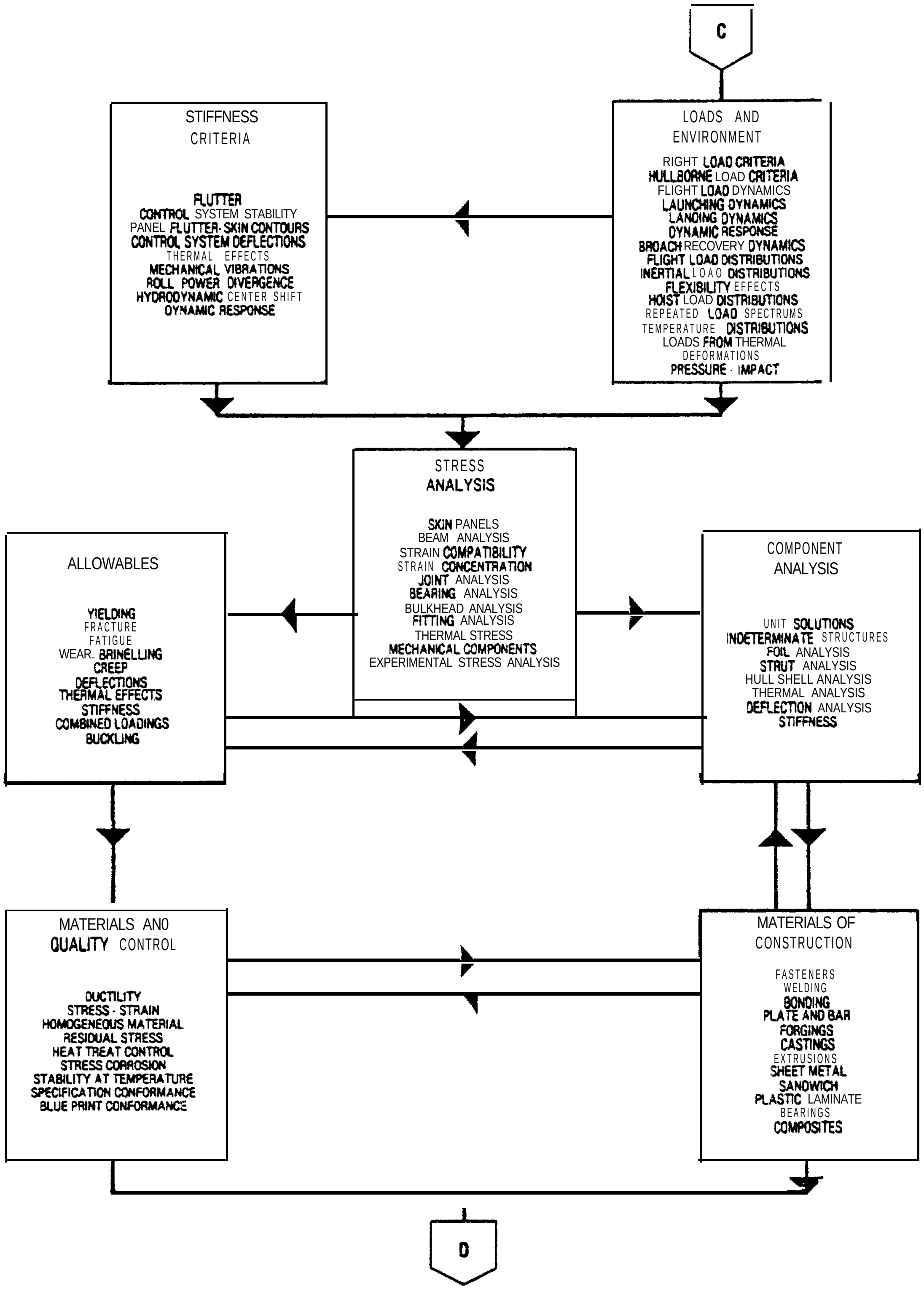
they have not yet been employed by the hydrofoil community because there has been no necessity to do so. France is presently building a 70-knot experimental hydrofoil with a subcavitating foil system with Fowler flaps. These flaps are apparently used to keep the takeoff speed in the 30- to 35-knot range. Trailing and leading edge devices allow the use of higher foil loadings which increase the hydrodynamic efficiency or L/D at design speed. Another means of increasing the maximum lift of a foil is circulation control, where fluid is either sucked from, or blown into, the boundary layer to delay separation and thereby increase the maximum lift coefficient attainable. Circulation control has been demonstrated on aircraft, but not yet on hydrofoils. These devices suffer from mechanical complexity, and their mechanisms could be troublesome in the seawater environment. Nevertheless, just as it was maintained that airplanes would not go to their present complex systems, the same is being said of hydrofoil ships. The use of such devices is inevitable if a wide foilborne speed range is required.

5.3.4 Structural Design and Manufacture

(U) The key areas in the structural design and manufacture are shown in Table II.B.5-4, which is essentially applicable to the structural design of the whole ship. Many computer programs exist in the stress analysis and component analysis areas which, although developed for air vehicles, are directly applicable to hydrofoil ships.

Table II.B.5-4. ELEMENTS OF STRUCTURAL DESIGN AND MANUFACTURE



(U) Single foil weight versus aspect ratio is shown in Figure II.B.5-12. As can be seen, the aspect ratio has a significant effect on the foil weight, as does design speed takeoff speed and foil loading. Cavitation avoidance requires the use of thinner foils with increase in design speed given the constraints imposed by Reference II.B.5-2, and this is reflected in Figure II.B.5-12. Although previous mention has been made that the spanwise bending moment essentially determines the skin thickness, it is possible with thinner section foils and/or low aspect ratio foils designed for high speed that the chordwise bending moment becomes the critical design factor. However, lower aspect ratio foils tend: to require much less skin thickness to react the bending loads, and in certain circumstances, the skin thickness is governed by the necessity to avoid buckling. Thus, the foil weight does not continually decrease with aspect ratio, and there is an aspect ratio which has minimum weight.

(U) The following types of foil construction have been used with varying degress of success:

1. Solid foils
2. Spar/rib construction

(U) Solid foils have had the greatest success in meeting manufacturing tolerances to date. However, this type of construction is obviously impractical for hydrofoil ships displacing beyond 100 tons. For the larger displacements all welded aircraft type spar-rib-skin construction is desirable to assure minimum contour deviation.

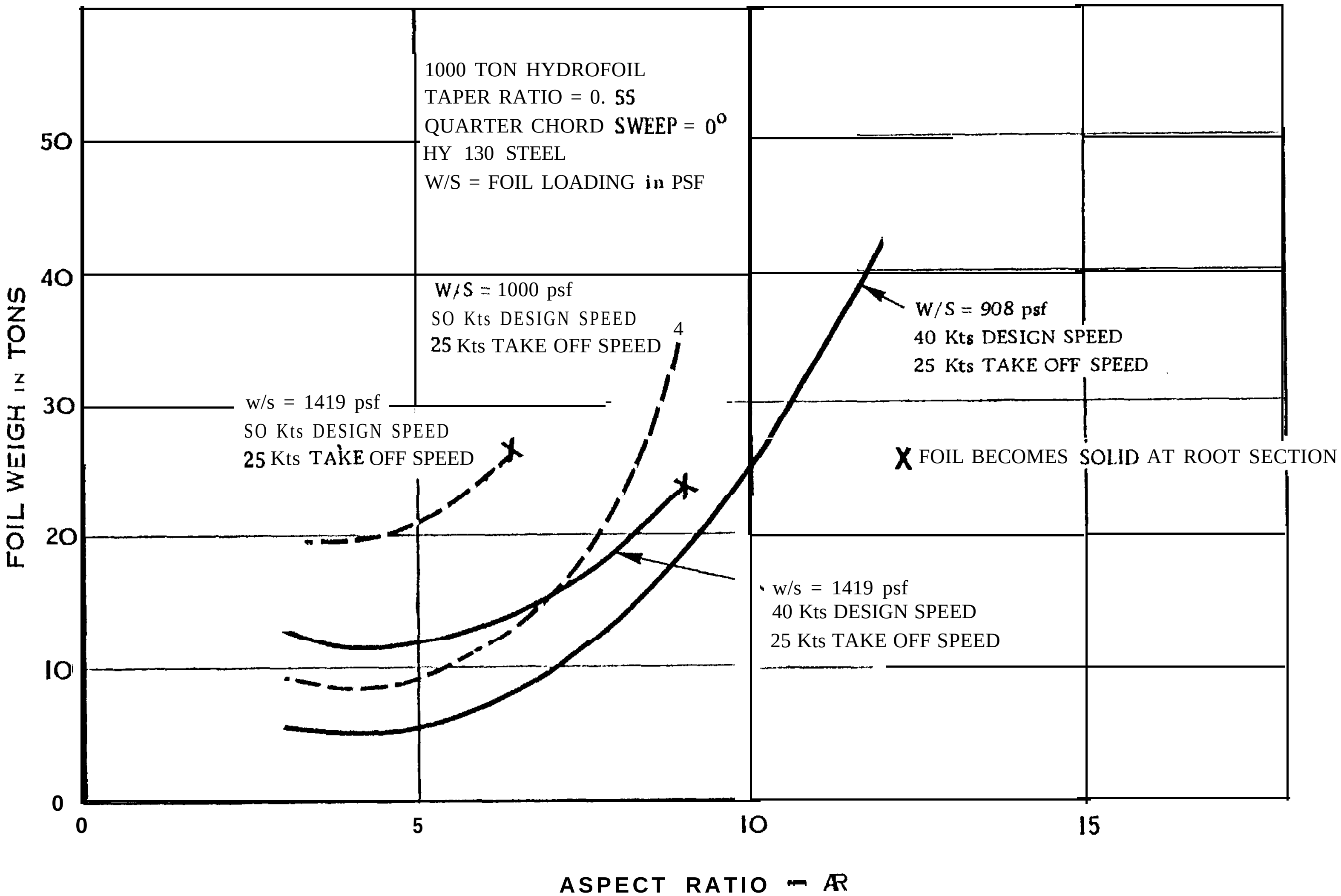


Figure II.B.5-12. SINGLE FOIL WEIGHT VERSUS ASPECT RATIO FOR VARIOUS FOIL LOADINGS (W/S IN LB PER SQ FT) AND SPEEDS

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The leading edges and trailing edges are machined from solid material. HY-130 and titanium *are* currently favored *as* the material for use on the lift systems. A following section provides a discussion of typical foil or strut construction for an HY-130 strut. Construction techniques may vary depending on the properties of the material employed.

(U) Within the timeframe addressed by this study, the use of composite materials is inevitable. Studies have been completed showing considerable weight savings using composite structures. Typical results from one such study (Reference II.B.5-7) are presented in Figure II.B.5-13. Such a saving can be reflected in the design either as increased payload or fuel load. Currently, a composite flap for the PCH-1 is being constructed for at-sea evaluation of a composite structure and should pave the way for more extensive application of this promising material.

(U) Figure II.B.5-14 shows a typical configuration for a large hydrofoil ship. The drawing is sectioned for a finite element analysis. However, spars and ribs would be spaced as approximately shown with suitable cutouts for actuators, hinges, etc.

5.4 PODS AND NACELLES

(U) Pods and nacelles are used for the following purposes:

a. To alleviate the adverse pressure field resulting from the strut foil intersection.

b. To provide space for actuators driving the flap foil or combination control system.

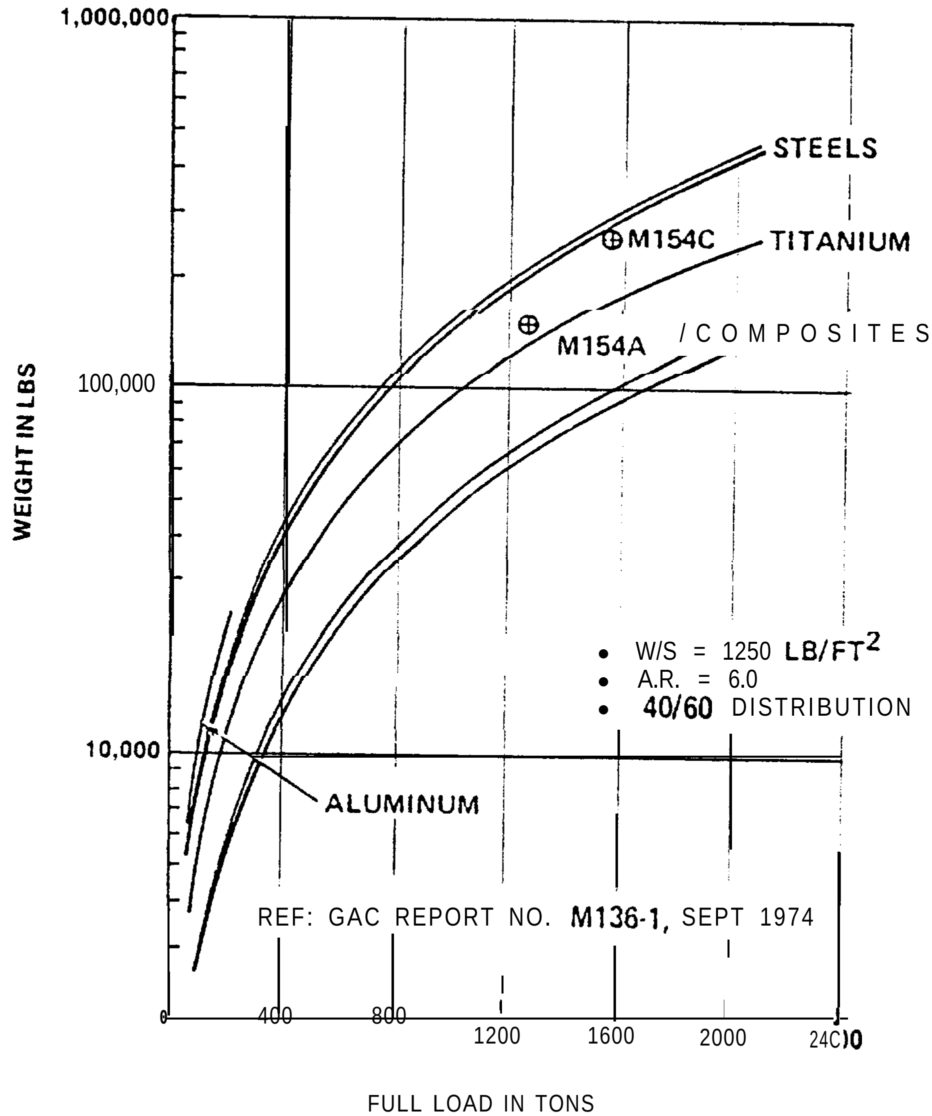

Figure II.B.5-13. FOIL WEIGHTS (PER SHIP SET)

- MATERIAL HY-130
- WT/FOIL = 156,600 LB

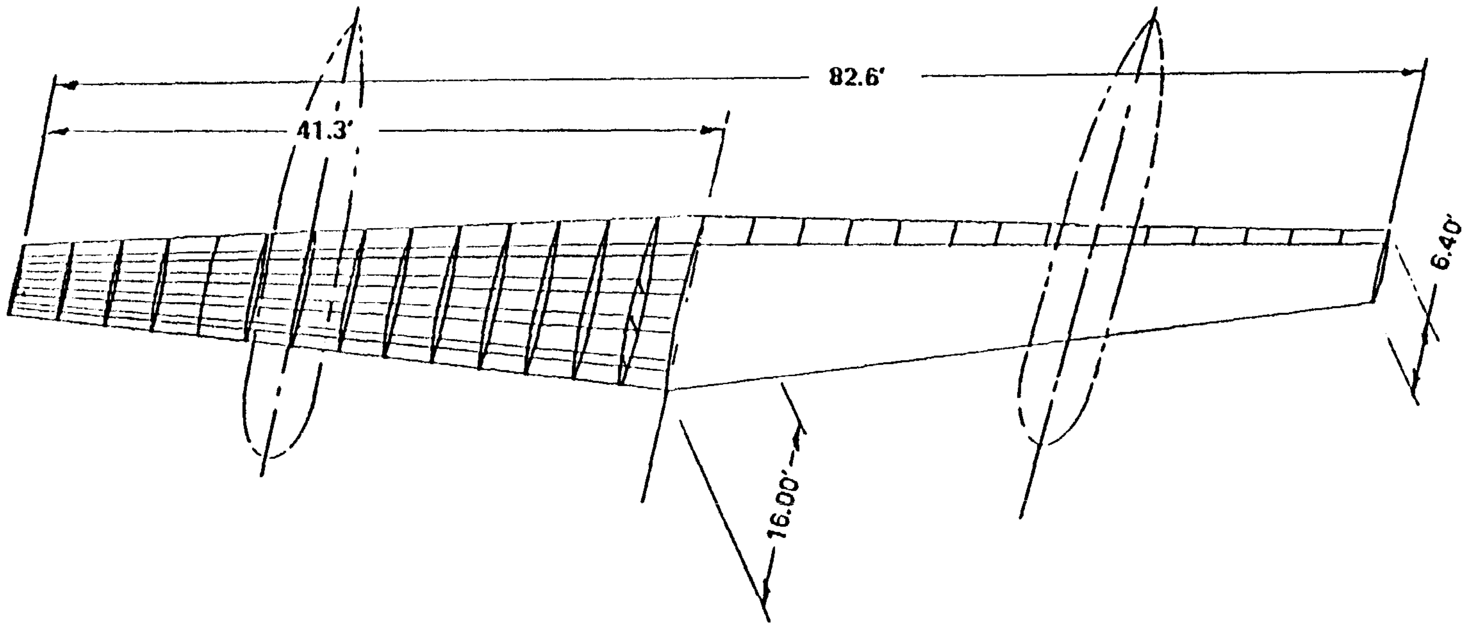

Figure II.B.5-14. TYPICAL HOC FOIL STRUCTURE

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c. To house underwater weapon sensors such as sonar transducers.

d. To house propulsion machinery including right angle and reduction gearboxes associated with mechanical drives.

e. To provide an inlet for the waterjet propulsor.

(U) Pod design is well understood. In the case of rectangular cross-section pods, a modified 16-series section gives cavitation-free performance, and the thickness-to-chord ratio for this becomes a function of design speed. For circular cross-section pods, successful cavitation-free performance requires the use of elliptical forebodies and ogival afterbodies whose length to diameter ratios are predicated upon the design speed.

(U) In order to get a realistic approximation of the hydrodynamic forces acting on the pod or nacelle to size the skin thickness, the latter is either treated as a yawed cylinder or as an extension of a strut. Also, any underwater explosion requirement may affect the structural design of the pod or nacelle. In the PCH-1, Mod 0, the mechanical drive gearbox formed part of the pod external contour. This proved to be a poor design, as the gearbox had to transmit the foil loads to the strut through this pod. Any leak in the pod allows salt water to get into the gearbox. Other ships have a separate gearbox mounted within the pod.

(U) Pod weight is governed by the above and by the selection of materials and coatings. The weight fraction as a percentage of the total foil system is always small. Pod weights as a function of material are shown in Figure II.B.5-15 relative to the configuration in Reference II.B.5-7.

5.5 STRUTS

(U) The struts carry the vertical loads from the foils and side loads and moments while the craft are in seas or are involved in uncoordinated maneuvers. They must also have adequate internal volume to house such internal components as drive shafts, ducting, etc.

(U) Retraction requirements, if any, the amount of effort required to initiate a given maneuver, the yaw angle to give a given turn rate with fixed struts fore and aft, and the directional stability considerations all have an impact on the choice of strut geometry.

5.5.1 Strut Section Selection

(U) The struts of a hydrofoil serve three primary functions. They support the lifting surfaces, provide directional stability, and house the actuation control linkage and the drive shafts in a propeller ship or the water duct in a waterjet ship. One would like the struts not to generate side force due to wave action while, at the same time, generate side force for directional stability. Clearly, you cannot have one without the other. The motion caused by the side forces generated in a seaway is dominantly roll and can to a great extent be attenuated by the automatic control system.

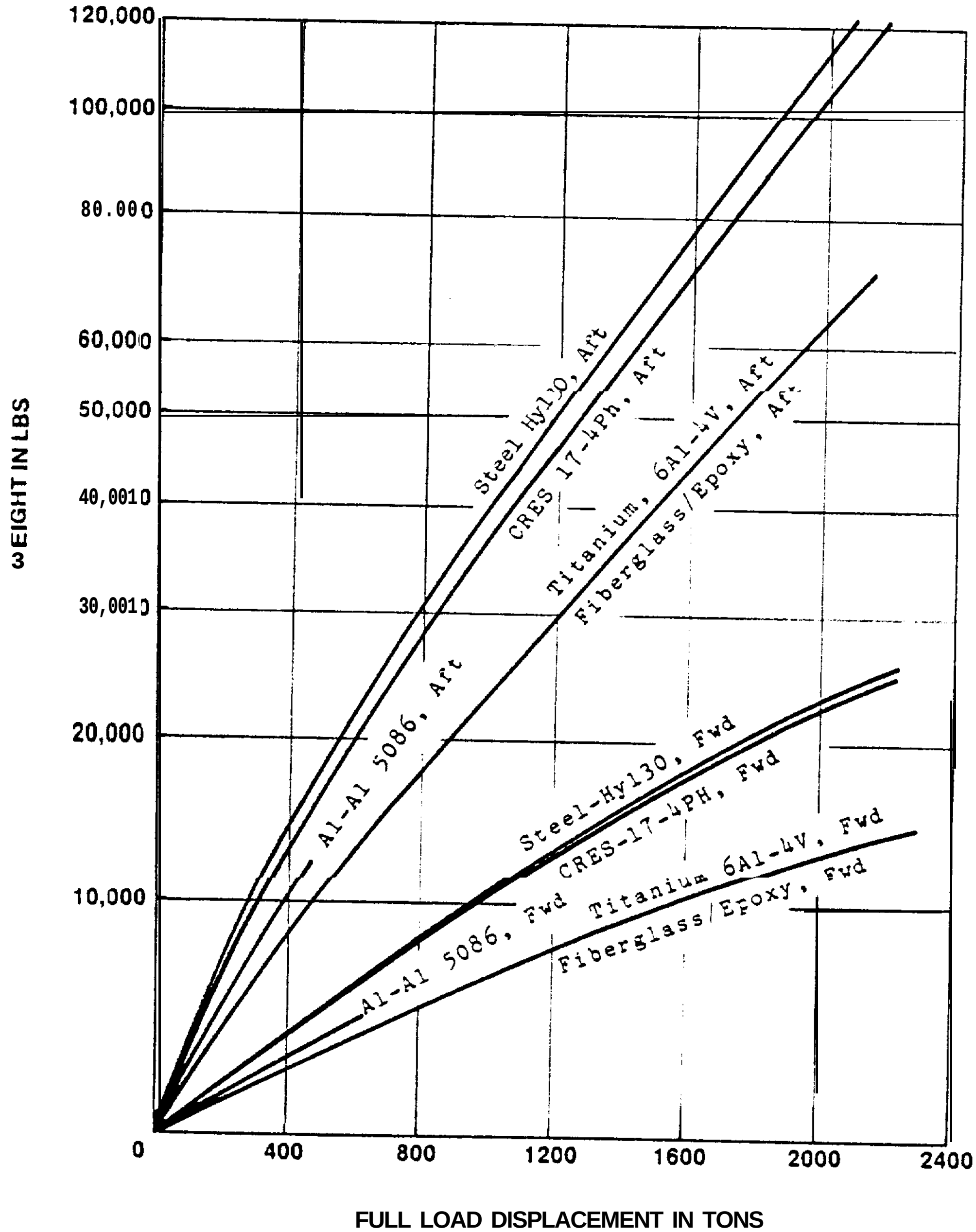
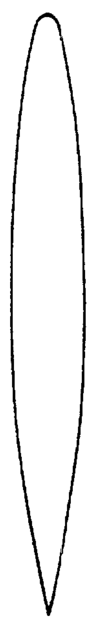


Figure II.B.5-15. POD WEIGHTS (PER SHIP SET)

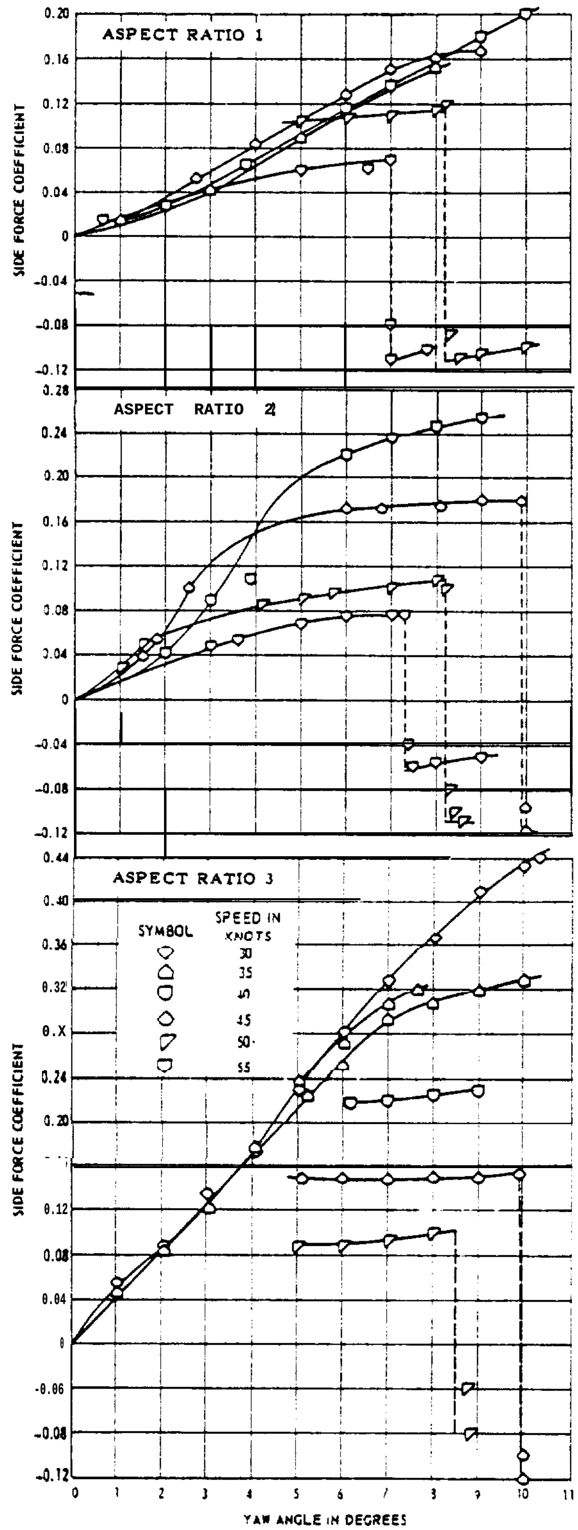
(U) As has been previously stated, the two major considerations in the design of the foil systems are hydrodynamic phenomena known as cavitation and ventilation. Cavitation occurs when the local static pressure is reduced to water vapor pressure; in other words, the fluid boils. Ventilation usually exists when an air path to a void caused by cavitation is opened to the surface and air rushes in to fill this void. Typical sources creating ventilation are foil tip vortices, cavitation near the air-water interface, and improper sealing of strut-internal structure carrying moving parts that translate control signals to flaps, rudders, foils, etc.

(U) Unpredictable ventilation could result in an abrupt change in side force causing an undesired turn and can result in the ship spinning into or out of a turn. Such an event would be rather unsettling for the crew. To illustrate the point, Figure II.B.5-16 depicts the variation of side force coefficient with yaw angle for a 16-series strut. The initial change in the side force slopes in Figure II.B.5-16 is caused by cavitation and the discontinuity is where the strut ventilates. Ventilation can be prevented by avoiding large side slip angles on the strut. This is the major reason for using a swivelable strut (forward on canard configurations and aft on airplane configurations) in conjunction with banked turns.

STRUT
SECTION



MODEL 2



– Side Force Coefficient versus Yaw Angle for Model 2

Figure II.B.5-16. SIDE FORCE COEFFICIENT VERSUS YAW ANGLE

(U) Good design practice requires the strut to be cavitation-free at the free surface at the ship design speed plus an incremental velocity for the design sea state. In other words, at the design speed the strut can see a certain yaw angle before cavitation and subsequent ventilation. Since strut sections must obviously be symmetrical, only two variables other than the type of section are left to control cavitation, and these are thickness to chord ratio and sweep. Sweep is limited by practical constraints, and thus the main control to avoid strut cavitation is only thickness/ chord ratio.

5.5.2 Strut Length Selection

(U) Strut length selection is based on the foreseen statistical wave height in the proposed worst area of operation anticipated for the vehicle, by the desirability to avoid broach up to and including the design sea state and the required ride quality. Usually it is desired that the foil or foils operate with a mean foil depth of at least one foil chord submergence. The length of the strut between the hinge point, if a retractable foil system is specified, or hull hard point with a fixed foil system and the keel line is a function of the hull geometry. A strut length between the keel and free surface equal to the significant wave height has been shown on existing ships to give satisfactory performance. However, the strut length can be adjusted to obtain a given ride quality, and, although simple equations can show trends, dynamic simulations determine the strut length more accurately. Variables which determine strut length include foil lift curve slopes, flap effectiveness, ocean spectra, foil loading, vehicle speed, broach frequency, and dynamic derivatives.

5.5.3 Structural Design and Manufacture

(U) Much of what has been said about foils in Section 5.3.4 applies to struts. Construction has typically been the spar and rib variety with either rolled or machiend skins. Leading edges and trailing edges are machined from solid material. Depending upon the material's reaction to salt water, coatings have either been necessary or not.

(U) The elements of strut structural design and manufacture are summarized in Table II.B.5-4 and are generally self-explanatory. The structural design load for the strut which occurs during rapid maneuvers or during slamming andbroaching in a seaway is normally set at the maximum hydrodynamic load which can be generated by the strut. The bending moment on the lowerportion of the strut then determines the strength and structure of the attachment point on the hull. If the foil or foils are not pin-jointed to the struts and are fixed, then an additional moment must be reacted by the struts. Sufficient stiffness must be maintained in the structure to avoid transmitting extraneous loads to gearboxes and rotating shafting.

(U) A typical view of a pair of forward struts is shown in Figure II.B.5-17, which is sectioned for a finite element

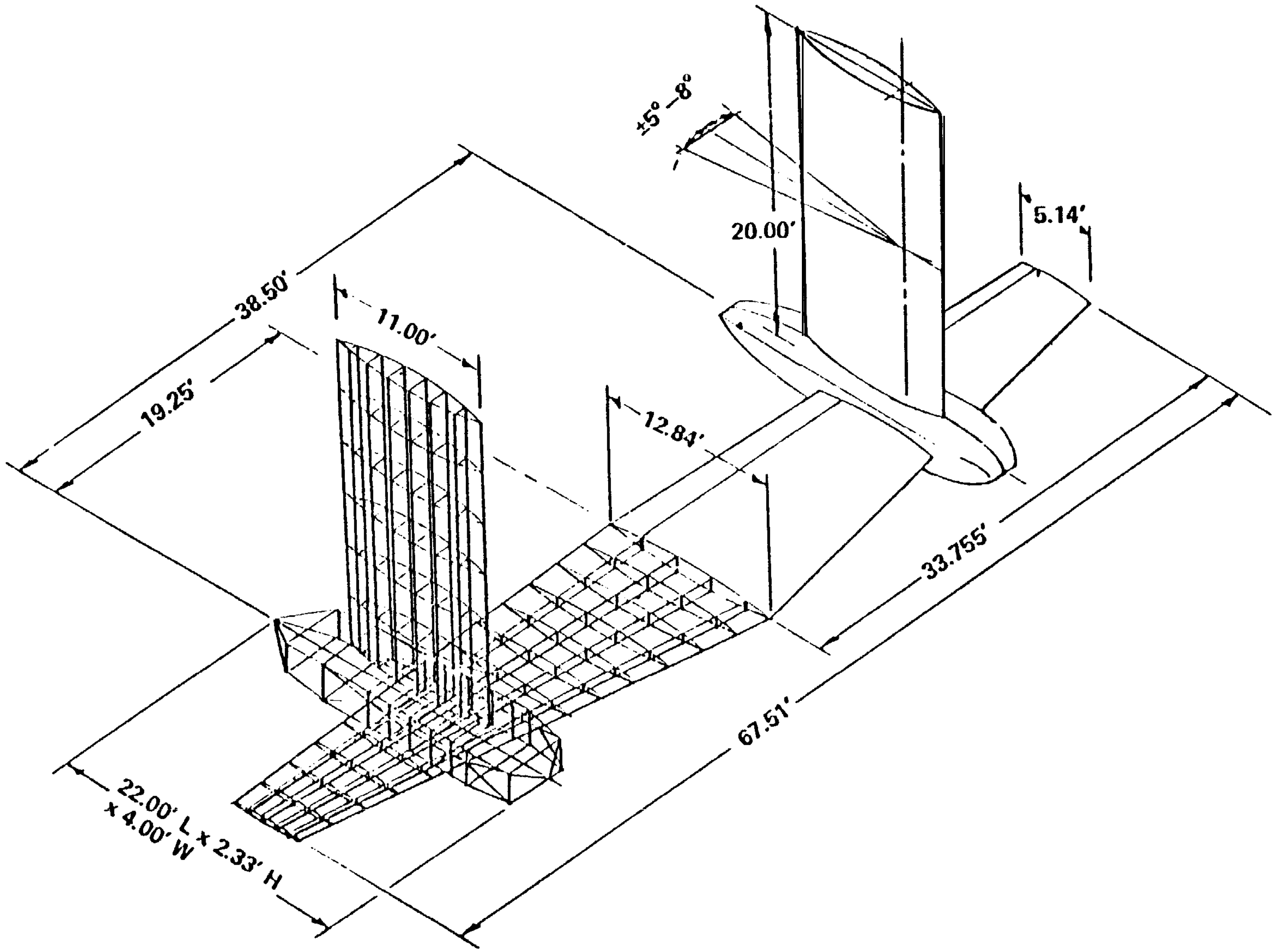


Figure II.B.5-17. STEERABLE FORWARD STRUTS (U)

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analysis. Omitted from the drawing are the hydraulic lines, the actuators and linkages for the flap and incidence mechanisms, and electrical harneesses. A rear strut assembly would show transmission shafting right angle drives and appropriate gearboxes.

(U) Structural weights for struts manufactured out of various materials are presented in Figure II.B.5-18, once again emphasizing the tremendous weight-saving potential of composites. Table II.B.5-5 summarizes the range of various parameters used in strut design to date. andidate materials for immediate and future strut construction are titanium, HY-130, and stainless steel.

5.6 BUOYANCY

(U) Buoyancy reduces the dynamic lift required to be carried by the foils at a given craft displacement or gross weight. The gross weight or displacement of the hydrofoil ship is that which would be registered by a crane holding the complete ship in free air at dockside.

(U) On small hydrofoil ships, buoyancy was of little or no concern. The magnitude of buoyancy from Reference II.B.5-2 is tabulated below for hydrofoil ships having a gross weight of 1,000 tons. Table II.B.5-6 shows how buoyancy reduces the lift and thus the required foil area about 10% for a l,OOO-ton hydrofoil.

Table II.B.5-5. SUMMARY OF STRUT CHARACTERISTICS STUDIED OR USED ON FUTURE OR EXISTING HYDROFOIL SHIPS

SUBJECT OF PARAMETER	RANGE OR TYPE	REMARKS
STRUT LEADING EDGE SWEEP	$0^{\circ} \rightarrow 15^{\circ}$	Zero sweep used on all hardware to date.
STRUT TAPER RATIO	0.7 → 1.0	Hardware has been tapered in thickness but with rectangular planform.
STRUT t/c AT FOIL CHORD PLANES	10 → 15 Percent	Design Studies and Hardware.
STRUT SECTIONS	NACA 16 Series (Symmetrical),	Design Studies and Hardware.
HULL KEEL TO SURFACE CLEARANCE	1 → 7 Meters	7 Meters represents a study figure 2,000-ton ship.
MATERIALS	17-4PH, 15-5PH, HY80 HY-130, Titanium, Composites, Aluminum	17 -4PH, HY-80, HY-130 & Aluminum used on hardware

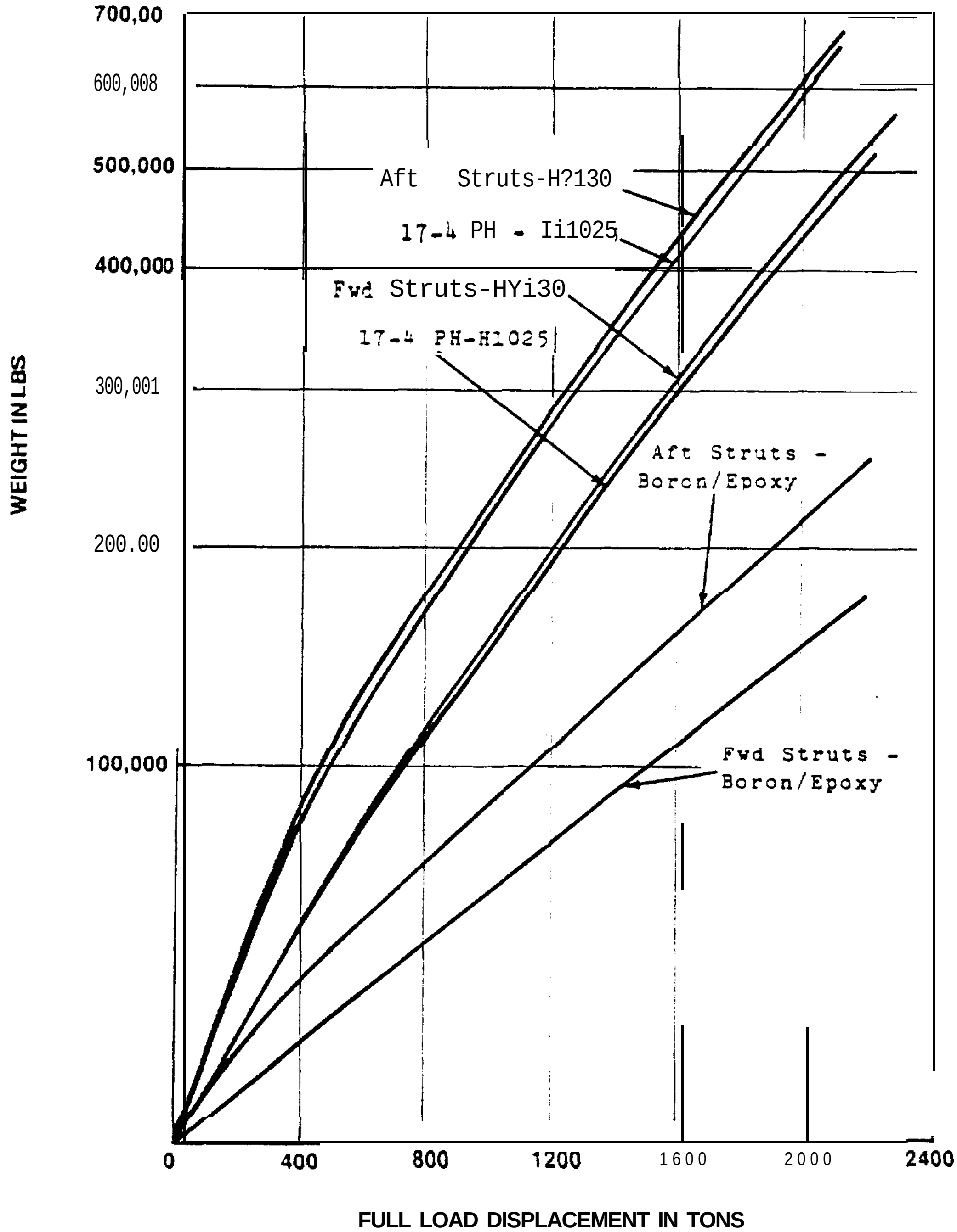

Figure II.B.5-18. STRUT WEIGHTS (PER SHIP SET)

Table II.B.5-6. LIFT REDUCTION BY BUOYANCY

1,000 TON HYDROFOIL

ASPECT RATIO	FOIL LOADING RATIO	DESIGN SPEED (kts)	RATIO OF BUOYANT LIFT TO GROSS WEIGHT %
6	1.56	50	9.9
6	1.10	50	12.1
9	1.56	40	10.8
9	1.00*	40	13.5

*Reference loading 908.4 lbs/ft^2

5.6.1 ' Total Lift Svstem Weights

(U) Total lift system weights for various operating vehicles and studies have been included in Figure II.B.5-19. It should be recognized that some scatter is inevitable because of varied design speeds and design philosophies. However, the trend is for an increasing foil system weight as a percentage of gross weight. While the foils increase in weight, the struts do not increase weight at the same rate as the foils as their length tends to remain about constant.

5.7 HY-130 TAIL STRUT CONSTRUCTION

(U) Already mention has been made of the U.S. PLAINVIEW (AGEH-1), which is the largest of the U.S. Navy's hydrofoil ships. In 1975 work commenced on the manufacture of a new larger tail strut from high yield steel (HY-130) for the PLAINVIEW. The new strut was completed in April 1976 and delivered to the Navy. The finished article has been built well within the manufacturing tolerances specified by the U.S. Navy and is the basis for construction of new larger hydrofoil system components of HY-130 for future ships.

(U) The strut with foil and pod attached is shown in Figure II.B.5-20. It was designed so that a minimum of machining was required on the completed weldment. The foil pivot fitting was completely machined before welding, leaving the boring of the steer- ing axis holes as the only remaining machining. All other machining was done before welding.

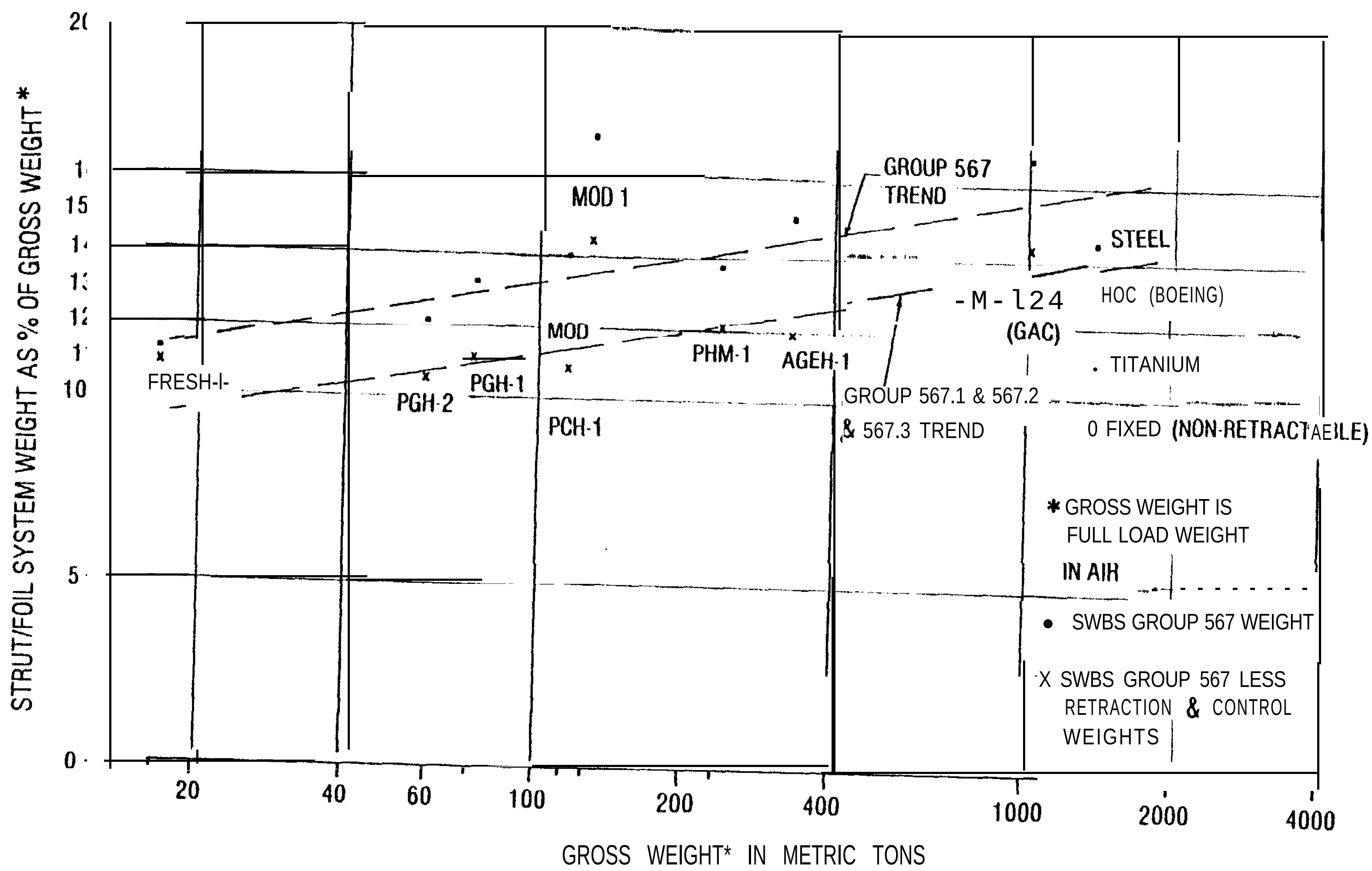

Figure II.B.5-19. FOIL SYSTEM WEIGHT AS PERCENT SHIP GROSS WEIGHT VERSUS SHIP GROSS WEIGHT

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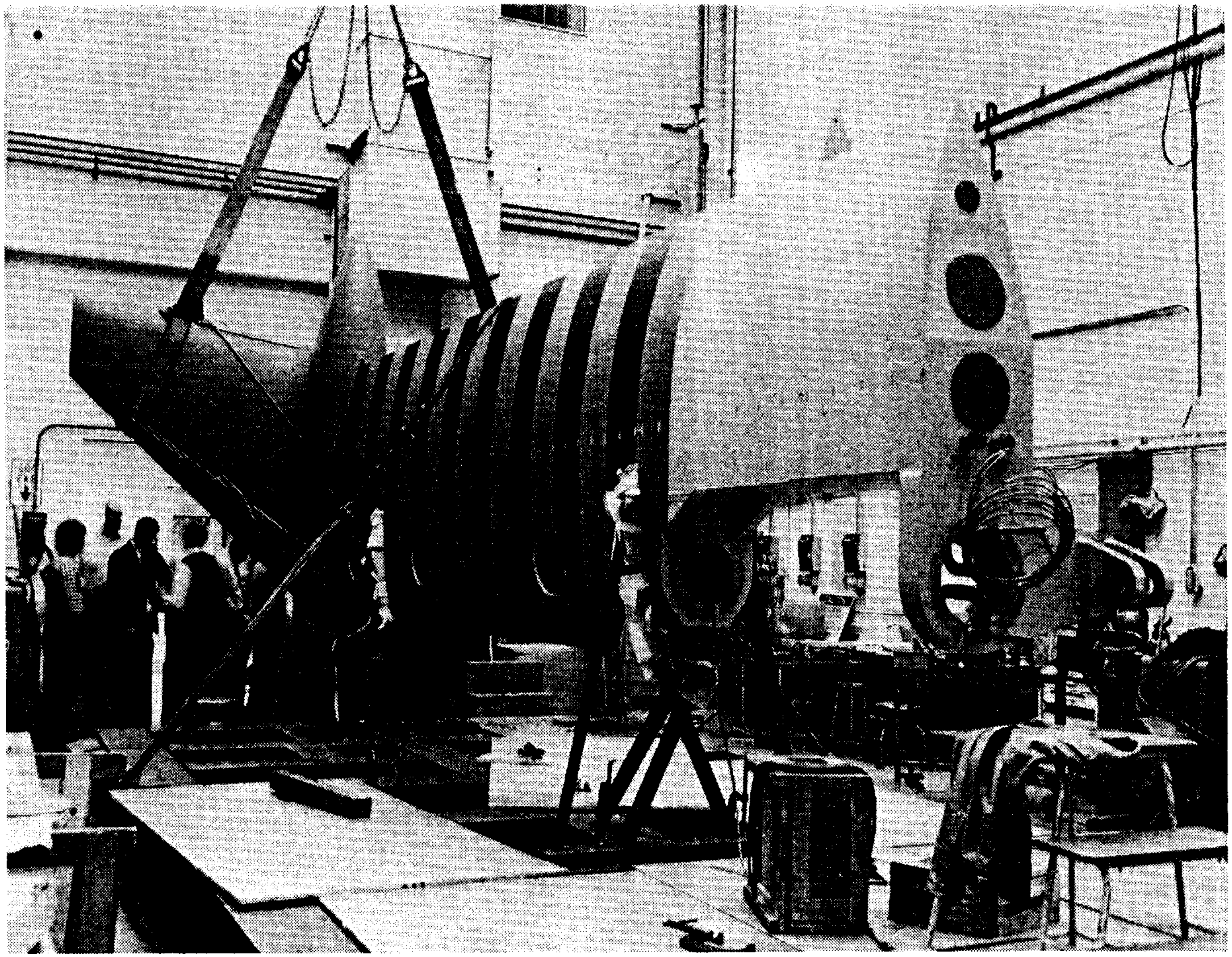

Figure II.B.5-20. AGEH-1 TAIL STRUT WITH FOIL AND POD

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(U) A strut assembly jig, Figure II.B.5-21, was used to properly locate the spars and ribs and other detailed parts prior to, and during, welding with a minimum of restraint. The assembly fixture with the spars and ribs located is illustrated in Figure II.B.5-22. The latter approach was adopted for two reasons:

a. The shrinkage forces developed during welding exceed the forces which could be developed by jig restraint. The ability to determine the dimensional conformance of the tail strut during assembly was vital to properly balance subsequent welding to arrive at a dimensionally acceptable strut.

b. Minimum restraint tooling is consistent with minimizing residual stress levels.

(U) As shown in Figure II.B.5-23, all welds in or to the strut structure were designed to permit fabrication by the Gas Metal Arc Welding Process and/or the Shielded Metal Welding Process. Four contour templates were used during weld operations so that compensatory weld sequencing could be applied to provide acceptable final contours. Warpage and twist were continuously checked by means of a series of plumb lines attached to the leading edge and also suspended above the trailing edge during the welding procedures.

(U) After the welding process, the strut was checked geometrically, and the final boring of the steering attachment fitting was done. The system was then tested for watertightness without internal coatings. Then internal coatings were applied, bearings and bushings installed, strut mounted on the yoke, incidence system

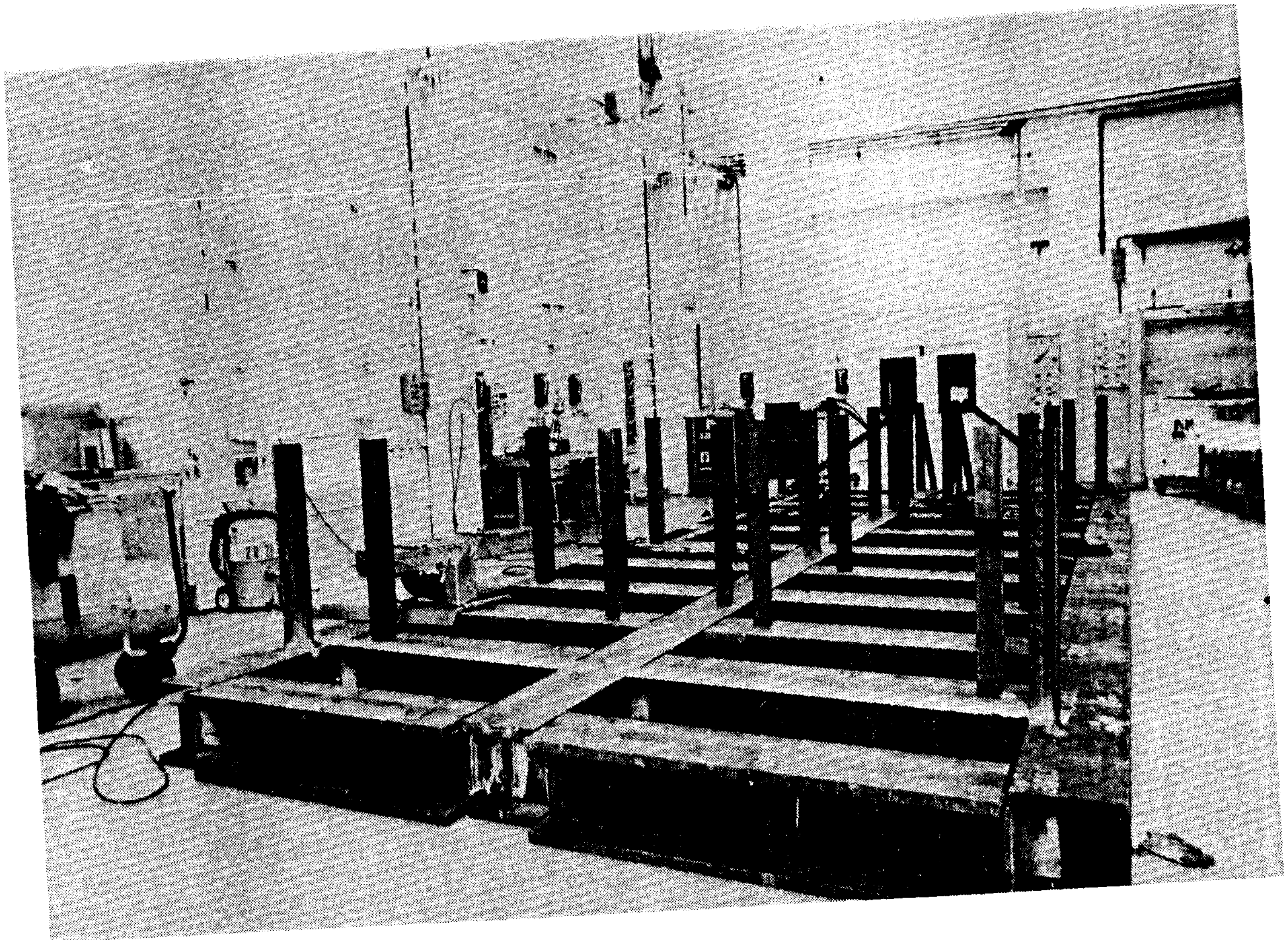

Figure II.B.5-21. AGEH-1 TAIL STRUT FABRICATION FACILITY

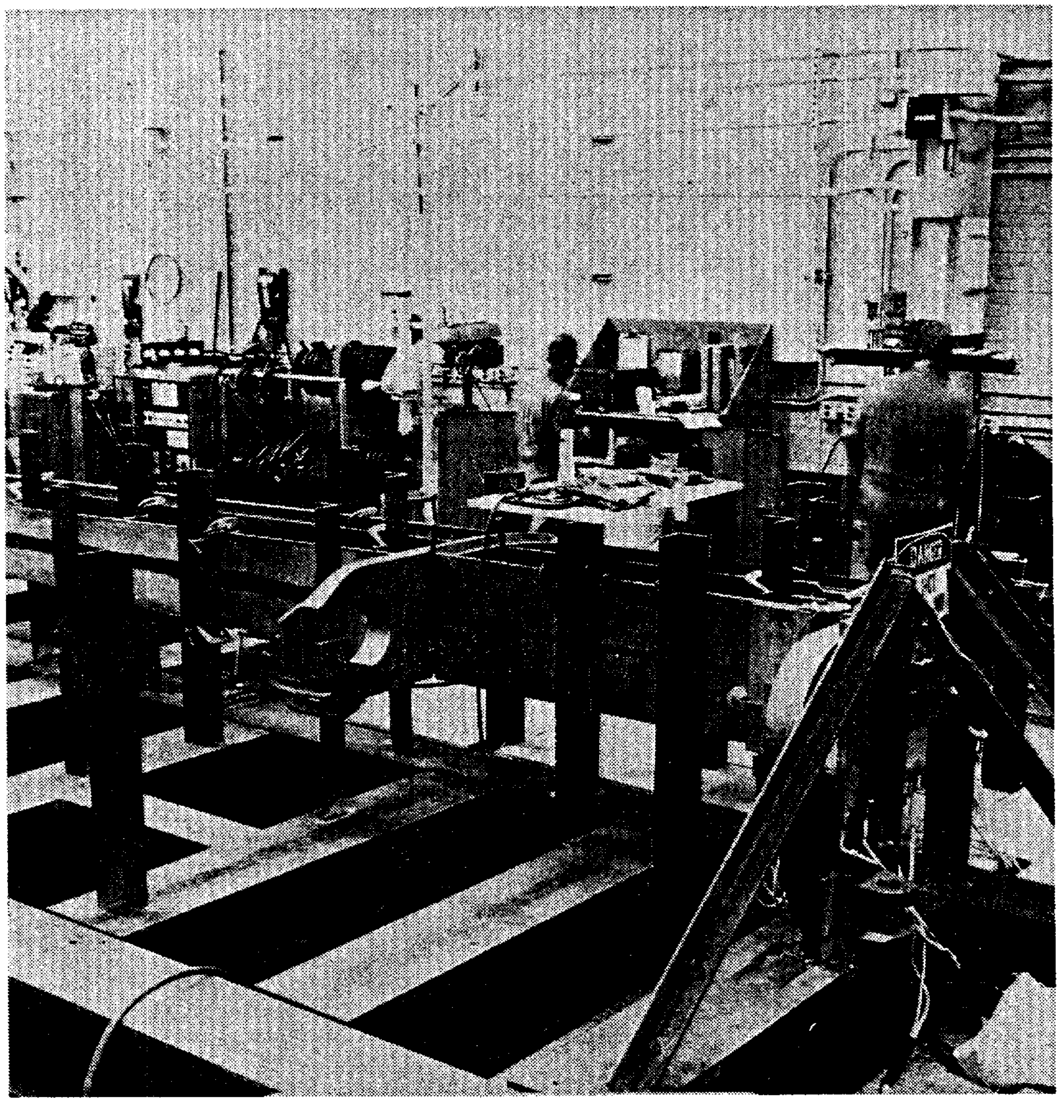

Figure II.B.5-22. TAIL STRUT SPAR AND UPPER RIB WELD ASSEMBLY

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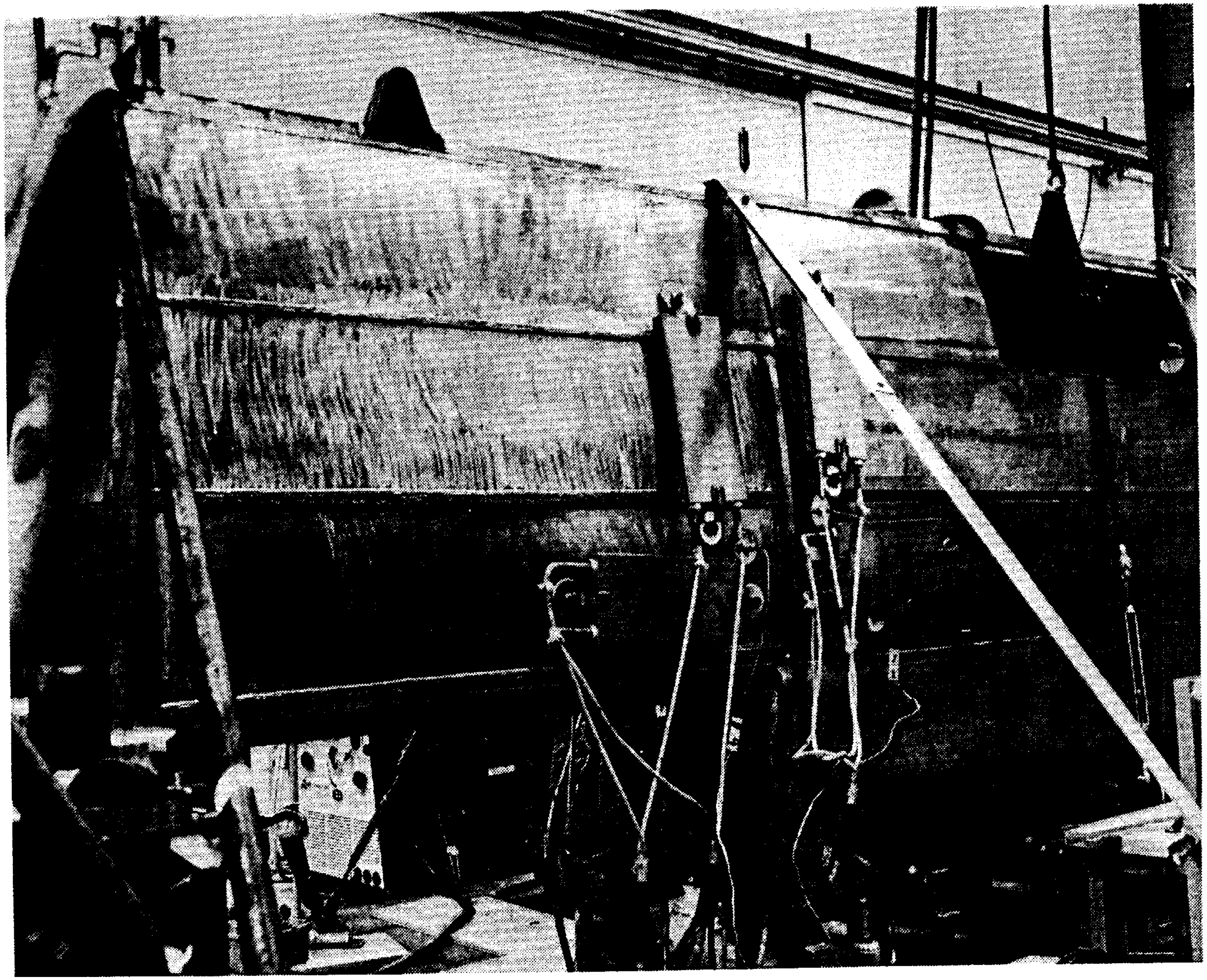

Figure II.B.5-23. AGEH-1 STRUT WELDING

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installed, incidence system and steering functionally tested, water tightness checked, and, finally, external coatings and markings applied (See Figure II.B.5-24).

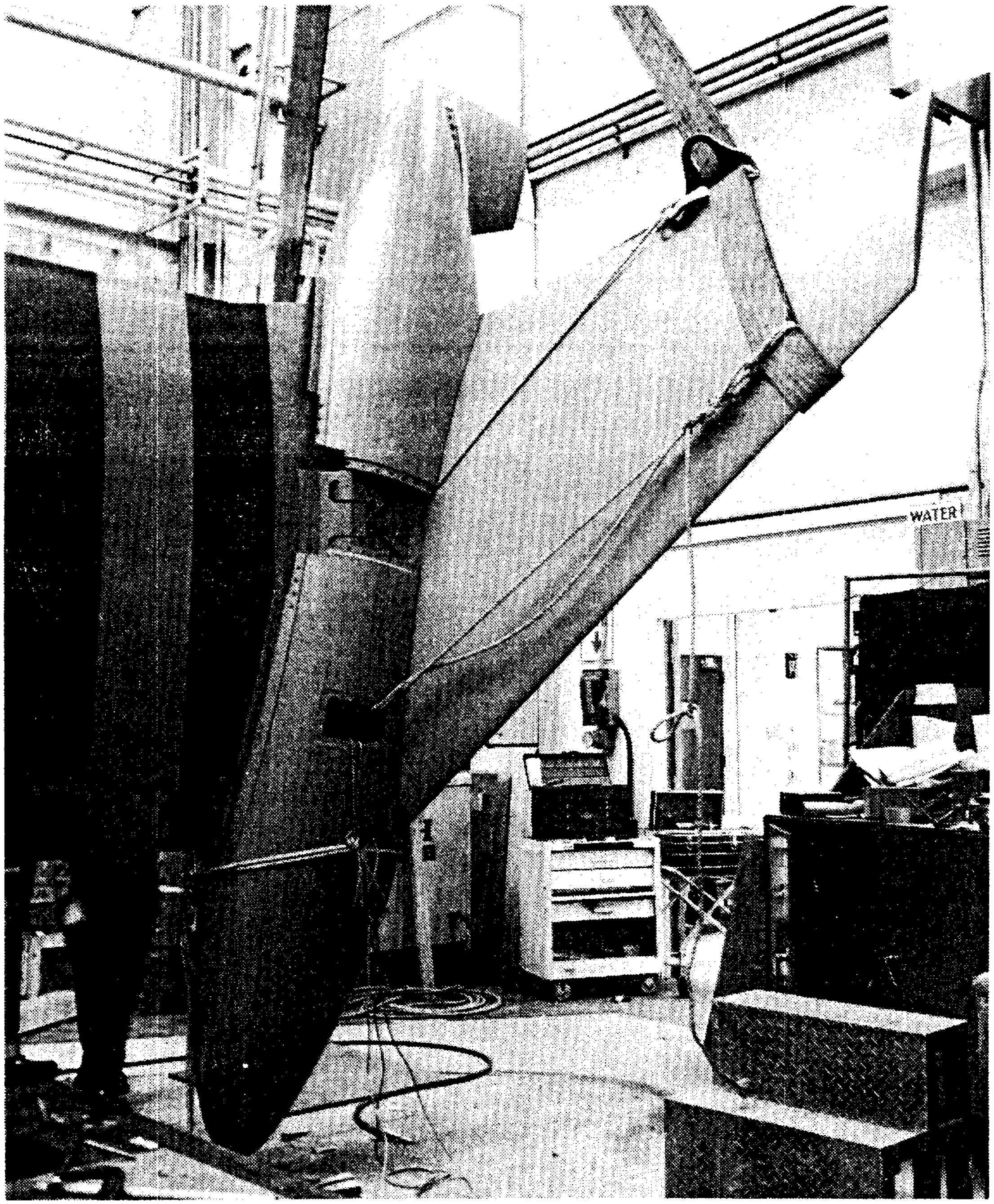

Figure II.B.5-24. AGEH-1 TAIL STRUT FINAL ASSEMBLY

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NOMENCLATURE

Symbol			Units
C_L	-	Lift Coefficient	-
C_D	-	Drag Coefficient	-
$\frac{W}{S}$, $\frac{W_F}{S}$	-	Dynamic Foil Loading	lbs/ft^2
V_K	-	Speed	knots
V_{KD}	-	Design Speed Foilborne	knots
V_{KTO}	-	Take-Off Speed	knots
V_{KMR}	-	Maximum Range Speed	knots
V_{KME}	-	Maximum Endurance Speed	knots
Ws	-	Structural Weight	lbs
AR	-	Aspect Ratio	-
λ	-	Taper Ratio (Tip Chord/Root Chord)	-
Λ	-	Quarter Chord Sweep	degrees
Y	-	Camber	percent chord
t/c	-	Thickness Chord Ratio	-
$\alpha_{ox\eta}$	-	Twist Relative to Some Datum	degrees
q_{∞}	-	Dynamic Pressure	lbs/ft^2
c	-	Chord	ft
R	-	Reynolds Number	-
CL_{max}	-	Maximum Lift Coefficient	-

NOMENCLATURE (Continued)

Symbol		Units
S	- Total Foil Area	ft^2
α	- Angle of Attack	degrees
$L/_D$	- Lift/drag Ratio	-
$C_{m_{ac}}$	- Pitching Moment Coefficient about Aerodynamic Chord	-

II. STATUS OF VEHICLE TECHNOLOGY

B. SUBSYSTEMSAND DESIGN AND CONSTRUCTION FEATURES

6. SPECIALIZED SYSTEMS

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LIST OF FIGURES

II.B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

6. SPECIALIZED SYSTEMS

6.1 INTRODUCTION

(U) The choice of fully submerged foils carries with it a commitment to an active, automatic control system. This is necessary to:

- Provide or augment stability in roll, pitch, and heave
- Provide maneuverability
- Control and optimize takeoff, landing, and turning maneuvers
- Provide safety and controlability in extreme conditions
- Counter wave disturbances to give good ride quality

The accomplishment of these objectives has resulted in a high order of maneuverability and seakeeping capability for relatively small size ships compared with conventional naval vessels.

6.2 CONTROL SYSTEM DESCRIPTION

(U) The control system is a conventional servo, or feedback control with elements shown in the block diagram in Figure II.B.6-1. The ship is the controlled element having height, attitude, angular velocities, and linear and angular accelerations as the controlled variables. Input commands may include the flying height, the pitch angle and the rudder angle, the yaw rate, or some other turn-related variable.

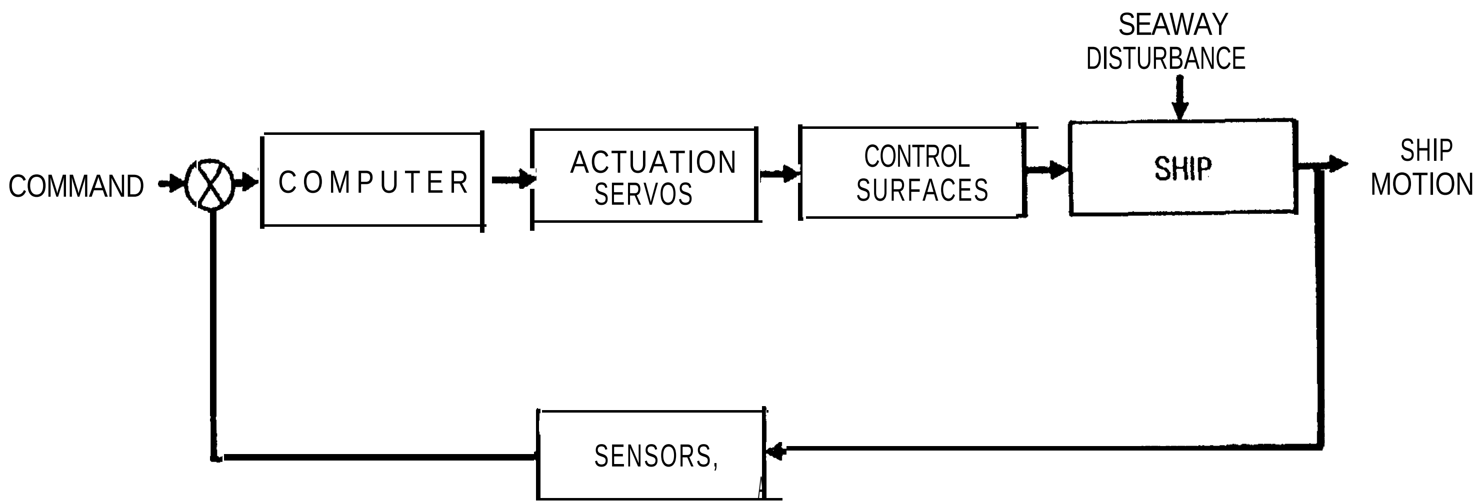

Figure II.B.6-1. HYDROFOIL SHIP CONTROL SYSTEM BLOCK DIAGRAM

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(U) Ship maneuvers are effected, and the motion of the ship is controlled by hydrodynamic forces developed on the control surfaces which are positioned by the actuators in response to commands generated in the computer. The overall feedback is supplied by sensors with output compared with the input commands to provide the necessary error signals for the computer. The computer, in turn, modifies the error signals and delivers appropriate inputs to the actuation servos. Finally, the ship is influenced by disturbances in the form of hydrodynamic forces imposed on the hull and on the struts and foils by wave action. Countering these disturbances is a principal task of the control system, which is more complex than the necessary task of providing foilborne stability. Hydrofoil ship control philosophy has evolved over a period of 20 years or more, is well covered in Reference II.B.6-1, and will not be reiterated here.* What will be addressed here is the state of the art in four key areas: system design, sensors, the computer, and the actuation system.

6.3 SYSTEM DESIGN

(U) Feedback control system theory and design techniques, both linear and nonlinear, are well developed and widely

*It should be noted that a Hydrofoil Ship Control and Dynamics Specification and criteria is presently being developed which will serve as a focal point to bring diverging, varying philosophies into a central focus. It will be published in January 1977 as a key section of the Design Criteria for Naval Hydrofoil Ships.

understood, as is the ability to develop accurate mathematical simulations of hydrofoils. These are used to develop the control system logic, signal shaping, and mixing to be done in the computer.

(U) There are many different control algorithms which will control and stabilize any given hydrofoil ship. Until about 1970, the control system *was* tuned to give the best ship performance by using analytical techniques and a six degree-of-freedom ship simulator to arrive at the proper feedback paths, shaping networks and gains. The development of optimal control. techniques not only helps converge on a solution in multivariable space, but establishes a combination of system gains which optimizes a predetermined multivariable performance index derived from the requirements of the ship, its environment and operator interfaces. Performance indices can be formulated which include a frequency-weighted combination of vertical and lateral acceleration that more carefully matches the human sensitivity to acceleration than the straight root-mean-square vertical acceleration so often used to assess ride quality.

6.4 SENSORS

(U) Most of the sensors employed in hydrofoil ship control systems are well-developed components of aircraft autopilot systems. These include a vertical axis gyro for measurement of the roll and pitch angles, rate gyros used to measure yaw rate, and linear vertical accelerometers. The distinctive sensor is that for ship height measurement. Most hydrofoil ships *to* date have used an acoustic height sensor by which height from the water surface is measured by the time of transit and return of a pulse of high frequency sound reflected off the water. Acoustic height sensors are, however, sensitive to extraneous noises such as the ship's own gunfire and missile launching. This has led to the replacement of the acoustic sensor on FLAGSTAFF with a radar altimeter developed for missiles and also used extensively on helicopters. A radar altimeter has been placed on HIGH POINT and thoroughly evaluated; this type of height sensor will be installed on PLAINVIEW as the primary height sensor. On the basis of the total experience to date, it would appear that a radar altimeter will replace the ultrasonic height sensor for most hydrofoil applications.

6.5 COMPUTER

(U) The control computers (the traditional black boxes) of existing hydrofoil ships have been of the analogue type based on advanced solid state technology which had been extensively developed for aircraft. These computers have achieved a high degree of reliability and there is no recorded computer failure in flight. Despite this success, it is likely that an analogue computer will be replaced by the rapid advancement of miniature digital computers on the next generation of hydrofoil ships. Following the lead of aircraft and missile control technology, future hydrofoil ships will almost certainly employ digital computers. To this end, developmental work has already been carried out for a Hydrofoil Universal Digital Autopilot (HUDAP), and a prototype has been successfully tested on HIGH POINT in both smooth and rough water. This prototype provides a highly reliable, standardized, digital computer with flexibility incorporated in software, so that adaptation to any ship is readily accomplished.

(U) The advantages of a digital autopilot are numerous. They include the Eollowing:

- High reliability, having potentially 10 times the mean time to failure of an analogue system because of the ease with which redundancy and multiple fault tolerance can be incorporated.
- Flexibility that allows changes to be made using software only; hardware remains fixed.
- Automatic self-testing which checks each function 10 times a second, automatically pinpoints a fault, and switches to the redundant circuit.
- Extra capacity to incorporate ancillary functions such as navigation, machinery monitoring, and fire control, thus providing the central processor with which to make the hydrofoil ship an integrated fighting ship and reduce man-loading requirements.

A detailed description of the HUDAP and its operation and performance on HIGH POINT is documented in References II.B.6-2 and II.B.6-3.

(U) During its present overhaul and modernization program, PLAINVIEW will have a digital autopilot installed as its primary control. Once installed on PLAINVIEW, the autopilot will be used to develop software for ancillary functions required on future hydrofoil ships such as navigation, collision avoidance, and simplifying man-machine interface. The digital autopilot will be accumulating at-sea operational testing in preparation for installation on future hydrofoil ships.

6.6 ACTUATION SYSTEMS

(U) The final element in the control system is the actuation system which positions the control surfaces. Because of the efficiency of energy transfer, low compressibility of the power transfer medium, and high power to weight ratio, hydraulic actuation devices are generally more attractive than pneumatic or electrical actuation systems. A range of readily available and qualified servo values, pumps, accumulators, filters, fittings and other hydraulic equipment is available from the aircraft industry, most of which need only minor modifications for hydrofoil application. However, there is an upper limit to the capacity of most of these elements which tends to create deficiencies in larger hydrofoil ships.

Although the U.S. Government has invested considerable effort to build and qualify large lightweight hydraulic pumps (400 to 500 horsepower), the results have not been encouraging. The largest qualified aircraft pumps are in the 150 to 200 horsepower range. For high power systems, therefore, it has been the practice to parallel a series of pumps rather than use large unqualified pumps. The AGEH-1 originally attempted to use a 450-horsepower pump (previously used on earth-moving machinery) although it was qualified for only intermittent duty at full power. It was hoped that a fully qualified pump of this capacity would be available as a replacement by 1970. Since this did not occur, the AGEH-1 hydraulic system was redesigned to use a cluster of fully qualified 160-horsepower pumps. The system now installed on the AGEH-1 resembles the type of systems used on the C5A, 747, and SST aircraft. The following principal features are incorporated in the system design:

- Utilization of strong lightweight steel tubing with welded connections maximized to reduce weight and reduce potential leakage and increase efficiency.
- Utilization of modulization, i.e., manifolding concept to centralize flexible fitting connections, filters, test fixture connections, etc. - to provide simplified and faster component replacement while minimizing leakage points.
- Utilization of proven aircraft type lightweight pumps to increase redundancy and ease pump replacement.
- Utilization of several independent systems with interconnecting power-transfer capability to increase reliablity and operational capability.
- System designed to utilize the new fire resistant synthetic hydrocarbon hydraulic fluid MIL-H-83282.

(U) Since the hydraulic system now installed on the AGEH-1 has more than enough power to actuate flaps on the HOC, it will serve as a forerunner of the future hydrofoil ship systems and give valuable at-sea experience.

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II. STATUS OF VEHICLE TECHNOLOGY

B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

7. EXTERNAL SUPPORT SYSTEMS

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II.B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

7. EXTERNAL SUPPORT

7.1 INTRODUCTION

(U) This section reviews hydrofoil ship external support experience.

(U) The scope of a general discussion of external support would include:

a. Support policy, planning, and administration

b. Management systems

c. Maintenance

d. Manning

e. Overhaul and modernization

f. Provisioning and supply

g. Repair and spare parts

h. Replenishment

1. Standardization

j. Training

k. Common support

1. Peculiar support

The scope of this review of hydrofoil ship external support experience will, however, be limited to c, e, i, k, and 1 above, as the remaining items are not specifically significant in hydrofoil ship experience.

7.1.1 Definitions

7.1.1.1 External Support

(U) External support may be defined as the capabilities and resources provided by the Navy to sustain the operational effectiveness of its forces.

7.1.1.2 Internal Support

(U) Internal support may be defined as the capabilities and resources available within a given ship, or class, to enable the latter to sustain a required level of operational effectiveness in conjunction with the external support otherwise provided.

7.1.1.3 Common Support

(U) Common support may be defined as the support required by a given ship, or class, in common with the support requirements of all other ships, or classes.

7.1.1.4 Peculiar Support

(U) Peculiar support may be defined as the support uniquely required by a given ship, or class, because of the nature of its operations, or of the features of its design.

7.1.2 Hydrofoil Ship External Support

(U) The external support requirements of hydrofoil ships may be summarized by illustrating common and peculiar support requirements.

7.1.2.1 Hydrofoil Ship Common Support

(U) Examples of hydrofoil ship common support requirements are:

a. Replenishment at Sea: Underway replenishment
Vertical replenishment

b. Provisions, stores, and supplies

c. Fuel

d. Manning and training

e. Mooring and towing

f. Overhaul and repair

7.1.2.2 Hydrofoil Ship Peculiar Support

(U) Hydrofoil ships bear only superficial similarities to conventional surface ships, and differ significantly in operation, performance, design, and construction. They are far more weight sensitive than conventional ships, have comparatively smaller crews, and when foilborne are automatically controlled. Substantial use is made of aircraft components and technology in mechanical systems. Therefore, their peculiar support requirements extend to the following:

a. Propulsion systems

b. Control systems

c. Auxiliary systems

d. Materials

e. Berthing and drydocking

f. Lift systems

7.1.3 Hvdrofoil Ship Svstems

(U) Based on 7.1.2.2 the following paragraphs illustrate features of hydrofoil ship systems.

7.1.3.1 Propulsion Systems

(U) Hydrofoil ship propulsion systems presently include dual propulsion plants, one for hullborne propulsion and one for foilborne propulsion. Gas turbines or diesel engines may be used for hullborne power. Foilborne power is drawn from gas turbine engines. Propulsive thrust, hullborne and foilborne, is obtained either from waterjet pumps or from right angle bevel gear power trains driving subcavitating or supercavitating propellers.

(U) Foilborne power conversion and transmission systems in hydrofoil ships differ from those on conventional surface ships in size, weight, configuration, and relative speed. Therefore, reduction gears, shafting, bevel gears, pumps, couplings, clutches, bearings, thrust meters, and torque meters differ from those in conventional ships and so necessitate peculiar support for overhaul, repair, spares, and training.

7.1.3.2 Control Systems

(U) Hydrofoil ships differ from conventional surface ships in the fact that, when foilborne, the ship is supported by hydrodynamic lift on the foils rather than by the force of buoyancy on the hull. Sea motion and ship response continuously influence the lift force, and the lift surfaces must be continuously moved to maintain the lift force. Therefore, hydrofoil ships use automatic control systems.

(U) The control systems for hydrofoil ships are therefore quite different from those in conventional surface ships. They consist of wave height sensors, ship motion sensors, a control program, a computer, and an electrical command system which operates the hydraulic system actuators to control the movements of the lift surfaces and directional control surfaces. The control systems are unique in hydrofoil ships and so necessitate a measure of peculiar support for overhaul, repair, spares, and training, although experience to date indicates support requirements for control systems, beyond those associated with drydocking, are minimal.

7.1.3.3 Auxiliary Systems

(U) Hydrofoil ship auxiliary systems, in general, provide the same services as are required on conventional surface ships. All are either electrically or hydraulically powered there being no steam plants aboard hydrofoil ships to date.

(U) The auxiliary systems of hydrofoil ships differ from the auxiliary systems of conventional surface ships because of the need for electrolytic compatibility of internal systems with the materials used in hydrofoil construction, because of space constraints, and because of weight sensitivity. Aircraft machinery and components therefore tend to be used. Occasionally, such components have to be modified to ensure electrolytic compatibility. Auxiliary systems components used in hydrofoil ships may, therefore, occasionally necessitate peculiar support for overhaul, repair, spares, and training.

7.1.3.4 Materials

(U) Materials used in hydrofoil ship construction are generally aluminum alloys for structure, components and fittings, and high yield steel or stainless steel in foil systems. Hydrofoil ships, therefore, are quite different from conventional surface ships in these regards. Details and features of construction and fabrication differ and so influence hydrofoil ship support requirements for overhaul, repair, and spares.

7.1.3.5 Berthing and Drydocking

(U) The foil systems of hydrofoil ships are extendable or retractable appendages which are quite different from the appendages of conventional surface ships. When extended the foil systems lie well below the keel; when extended, or retracted, the foil tips reach beyond the beam of the ship. When foils are laterally extendable or retractable, the ship may require a clear space of approximately twice its beam to extend or retract the foil system.

(U) Therefore, hydrofoil ships require greater water depth when maneuvering hullborne with foils down, and greater side clearance when maneuvering alongside another ship, or a pier, than may be apparent from the size of the hull. The implications of the foil systems on drydocking are discussed in Chapter V, Vulnerability and Survivability.

(U) With the foil system retracted, a hydrofoil ship may be subject to minor wind influences.

(U) These considerations affect the space allowed at moorings, when alongside a pier or other ship, and when a hydrofoil ship may be nested with other ships as alongside a tender.

(U) Peculiar support requirements of hydrofoil ships will involve:

a. Assuring adequate water depth and area in moorings

b. Provision of camels to stand hydrofoil ships clear of piers, quays, or other ships

c. Use of camels or other suitable measures when hydrofoil ships have fuel, provisions and stores, or ammunition barges alongside, or when they are being controlled by tugs

d. High keel blocking or cradles in drydock or special foil system cradles when hydrofoil ships are docked on their foils. (See Section V.2-1 for further discussion).

7.1.3.6 Lift Systems

(U) The lift surfaces of hydrofoil ships produce the lift and directional control forces which enable the ship to fly and to maneuver. The lift and directional control forces depend upon the hydrodynamic qualities of the lift surfaces. The hydrodynamic qualities of the lift surfaces depend upon the contour, fairness, smoothness, alignment, and adhesion of protective coatings. These qualities, in turn, are dependent upon the care and s'kill employed in fabrication, installation, maintenance, repair, and overhaul of the lift surfaces. The standards of workmanship and quality control which are required are much higher than for the skegs, bilge keels, rudders, or stabilizing fins of conventional surface ships.

(U) The lift systems of hydrofoil ships include:

- Foils and flaps
- Struts
- Pods
- Kingposts
- Pivots
- Control linkages
- Uplocks and downlocks
- Internal propulsion components such as bevel gear-boxes, shafting, bearings, seals, propellers, thrust, and torque meters
- Electrical, lubrication, and scavenge components
- Vibration monitoring sensors
- Installed sonar, underwater communications, fathometer, and speed sensors and transducers
- Fairings and fasteners
- Breakaway joints
- Replaceable segments

From the above, it is evident that the lift systems of hydrofoil ships are unique and so necessitate peculiar support for overhaul, repair, spares, and training.

7.2 CURRENT EXPERIENCE

(U) The existing U.S. Navy hydrofoil ships are PCH-1 AGEH-1, PGH-1, and PHM-1. PGH-2 was stricken 3 years ago as a result of grounding damage.

(U) The respective ships differ in size, configuration, performance, and composition of internal systems, components, and equipment, with little standardization or commonality among them.

(U) All of the ships are commonly supportable by existing naval facilities and logistic support echelons, outside their specific peculiar support requirements. When the ships were acquired, it was desired to minimize the effects of the latter by providing each with a measure of organic support capability in the form of mobile trailer vans. The vans were outfitted commensurate with anticipated requirements and were intended:

a. To facilitate the inspection, maintenance, and repair of auxiliary systems components

b. To enable the flushing and draining of hydraulic and lubrication fluids

c. To enable test, calibration, and repair of electrical and electronic equipment, particularly ship control sensors, autopilot components, ship instruments, and instrumentation

d. To store spares, repair parts, special tools, special equipment, and other tools and equipment not normally carried aboard ship

e. To store manuals, drawings, and records.

(U) In service the vans proved to be of limited value. Facilities were cramped and, more often than not, work required in support of the ships required more comprehensive facilities. As a result, the vans were increasingly used for storing components, equipment, and tools and to transport tools, equipment, spares, and repair parts when the ships operated away from home port or were in overhaul.

(U) PHM-1 differs from the other ships in that she is supported by an organic mobile logistics support force which, in time, may include a tender.

(U) PCH-1, PGH-1, and PHM-1 were acquired for operational service. AGEH-1 was acquired for ASW and high speed research and development. PCH-1 was assigned, with AGEH-1, to the David W. Taylor Naval Ship Research and Development Center (DTNSRDC), Hydrofoil Special Trials Unit (HYSTU), Bremerton, Washington. PGH-1 and PGH-2 were in operational service and operated in Viet Nam. PGH-2 subsequently operated in Europe. PGH-1, subsequent to operations off Viet Nam, has been operating out of San Diego, California, where she has participated in various tests, demonstrations, and exercises.

(U) PCH-1 and PGH-1 were turned over to the Coast Guard for evaluation in Coast Guard missions.

(U) PHM-1 is completing pre-delivery operational test and evaluation. The mobile logistics support force has been supporting her, and has implemented the DTNSRDC Advanced Ships Information System, Technical (ASSIST) program. PHM-1 experience with ASSIST is discussed in Section II.A.8, Reliability, Maintainability, and Availability.

(U) All of the ships experienced significant problems in their earlier years. Most of these problems occurred in secondary systems and components. Since each ship was, in fact, a prototype, and since the earliest of the ships, namely PCH-1 and AGEH-1, were new departures in naval ship design, construction, and performance, developmental problems were inevitable. In many cases, the effects of the problems, measured in man-hours and effort required for correction, and in ship down time, were disproportionate to the nature of the problems. This was because accessibility for inspection, maintenance, and repair, particularly of subsystems and components within the foil systems was limited, and often impossible without significant dismantling.

(U) None of the existing hydrofoil ships other than PGH-1 has as yet operated on a sustained basis through its design and performance boundaries. Operational and support doctrine based on realistic test and evaluation has not been cohesively defined. Such evaluations will be necessary in order to establish requirements and criteria for future hydrofoil ship design and operational use and support planning.

(U) More formal and disciplined logistics support planning, and greater attention to reliability and maintainability is required in future designs in order to draw benefit from past experience in enhancing ship availability and ensuring cost effective maintenance support. PHM-1 represents the first hydrofoil ship in which, through ASSIST, availability and support are being meaningfully evaluated.

7.3 MAINTENANCE

(U) A discussion of maintenance tends to be rather abstract, unless it is associated with some measure of operating effectiveness. Operating effectiveness cannot be measured until a system has been shaken down and brought up to a satisfactory operating standard. This is happening with PHM-1 at present, and it will pay dividends into the future. To a limited extent, it happened with PGH-1 and PGH-2 during their deployment to Viet Nam. However, neither PCH-1 nor AGEH-1 was ever shaken down, with the result that they have required excessive maintenance during their first 10 years of service. This excessive maintenance is attributable, in part, to the nature of their primary mission in the R&D community in that PCH-1 and AGEH-1 have undergone extensive modification throughout their existence.

7.3.1 Maintenance Philosophy

(U) On the basis of current experience, the following is offered:

a. The reliability and maintainability (R&M) of hydrofoil components and equipment must be determined compatible with operating duty cycles projected over planned operational periods and maintenance or overhaul cycles.

b. Critical components and equipment must be appropriately pretested and refined in shore test facilities and, if feasible, aboard seagoing test platforms, before they are installed on the craft. Critical components include:

- Automatic control system
- Hydraulic system
- Propulsion power train
- Foil system mechanisms
- Pumps and filters
- High pressure fluid system fittings
- High speed motors
- Firefighting system
- Steering system
- Navigation system
- Combat system sensors, data processing, fire control, and weapons systems

c. Commonality and interchangeability of components equipment and parts must be enhanced.

d. Ships must be designed and equipped with adequate maintenance and repair space and facilities aboard to accommodate workshops and storage of tools, equipment, and spares to enable ships to better maintain themselves.

e. Improved accessibility for inspection, maintenance, and repair must be provided to improve the ability of the crew to effect maintenance more readily.

f. Drawings and manuals must be current at the time of delivery of the ship and should be revised periodically.

g. Appropriate spares and repair parts must be provided, inventoried periodically, and replenished.

h. Oceangoing hydrofoil ships, intended for fleet operations, must be fleet supportable and not dependent upon special logistics support echelons.

i. Fluids circulated through propulsion and hydraulic machinery must be monitored daily, and sampled and analyzed when contamination is detected, in order to forewarn of possible wear.

j. Vibration monitoring equipment must be installed to forestall failure of critical propulsion machinery.

7.3.2 Hydrofoil Ship Maintenance Facilities

(U) The routine maintenance of hydrofoil ships will not require special facilities or capabilities beyond those which can be found in any naval, and most commercial, shipyards, although some measure of peculiar support in such cases as in Section 7.13 may be necessary. Special tools and equipment will normally be delivered with the ships. Camels and cradles for drydocking can readily be fabricated. Fluid decontamination equipment is readily available. Instrument and instrumentation test, calibration and repair equipment is readily available. Installation and alignment can be verified with available shipyard equipment. Future hydrofoil ships would benefit if foil systems were retractable and capable of repair, maintenance, and overhaul or replacement in the retracted position. Use of replacement strut or foil segments would also be beneficial. If the foil system was nonretractable or fixed then the possibility exists that special drydocking facilities would be required for the larger hydrofoil ships.

7.3.3 Hydrofoil Ship Maintenance Personnel Support

(U) In general, given suitable training, hydrofoil ships will not impose peculiar demands for special personnel support. Whereas PHM-1 obtains support from a mobile logistics support unit, future operation combatant hydrofoil ships could not be supported in the same way. Maintenance away from home port will depend upon the technical capabilities of the crew which, in turn, will depend upon adequate technical and operating training.

7.4 OVERHAUL AND MODERNIZATION

(U) Overhaul or modernization is a complex and costly undertaking which involves careful planning and coordination in the preparatory phase and sound management in the implementary phase.

(U) Factors which are of consequence, and which exercise external support to the fullest, include:

a. Identification of work requirements

b. Ship and systems inspection and survey

c. Engineering definition

d. Definition of ripout schedule

e. Definition of material and equipment lists

f. Definition of specifications

g. Work task scoping and cost estimating

h. Definition of procurement schedule

1. Definition of GFM, GFE schedule

j. Definition of cost profile and overhaul schedule

k. Definition and issue of bid package, and evaluation and selection of contractor

1. Award of contract

m. Overhaul management and contract administration

n. Supervision, inspection, and quality control

o. Change control

p. Checkout and testing

(U) On the basis of PCH-1 and AGEH-1 experience, strong, active, integrated participation by Supervisor of Shipbuilding and Repair (SUPSHIP) and Naval Supply functions is necessary from the outset. The definition and scoping of work must be thorough, in order to ensure that specifications, schedules, and cost estimates are complete; otherwise, substantial change action will result with inevitable cost increases and schedule delays. The performance of overhauls or modernization must be effected against cohesive and detailed planning which account for design, procurement, fabrication, installation, integration, and checkout and test, of both contractor and government phases of the work.

(U) Because hydrofoil ships are different in so many respects from conventional surface ships, appropriate controls, instructions, and procedures must be imposed to avoid harmful occurrences resulting from differences between hydrofoil,ships and conventional surface ships.

(U) Vigilant management, configuration control, inspection, and quality control must be effected throughout the undertaking, and status, progress, and problems must be monitored and resolved in a timely and effective manner. New subsystems and components must be properly inspected, integrated, and tested. Documentation such as specifications, drawings, procedures, manuals, and test agenda and memoranda must be consistent with the as-built ship.

7.5 STANDARDIZATION

(U) The existing hydrofoil ships differ from one another in configuration, design, purpose, size, capability, construction, and composition of subsystems, components, and equipment. Each was individually acquired and has little in common with the others. There is no standardization or interchangeability either among the four ships or between the hydrofoil ships and conventional naval surface ships. The extent of the differences among the hydrofoil ships and between hydrofoil ships and conventional surface ships, in general, is summarized by the following:

a. Hull Structure: aluminum alloy and varied use of welded stiffener-plating, and extruded stiffener-plating panels

b. Automatic foilborne control systems

c. Waterjet and right angle geared drive propulsion trains

d. Vertical, lateral radial, and fore and aft radial, foil system retraction

e. Canard or airplane foil systems configurations

f. HY or stainless steel materials and construction techniques used in foil systems

g. Variable use of aircraft components

(U) Standardization reduces the burden of external support because it contributes to fewer variations in the configurations, characteristics and types or models of components and equipment, enhances interchangeability, reduces the diversity of spares and repair parts, and mostly contributes to improved efficiency, training, availability, and cost benefits.

(U) Standardization between hydrofoil ships and conventional surface ships will be feasible only to a limited extent, principally in the areas of gas turbines, electronic systems, weapons systems, and, to some extent, outfit and furnishings.

(U) In the future, hydrofoil ships will be designed on the basis of common design criteria and standards and, in the interests of enhancing common support, will seek to utilize components and equipment used in naval aircraft.

7.6 COMMON SUPPORT

(U) Hydrofoil ship compatibility with respect to common support has been demonstrated in a number of ways. Table II.B.7-1 summarizes the history of such demonstrations, which are briefly described herein.

(U) The evolutions described hereafter were experimental in nature and were steps in the development and definition of external support systems requirements. External support systems* may be identified as follows:

*Refueling is often not broken out separately from UNREP, but vertical replenishments, (VERTREP and medical evacuations (MEDEVAC) are.

Table II.B.7-1 INSTANCES OF EXTERNAL SUPPORT PERFORMED FOR HYDROFOILS

DATE	SHIPS INVOLVED	TYPE OF OPERATION	LOCATION
5/67	HIGH POINT/Navy Tug	UNREP	Puget Sound, WA
11/69	TUCUMCARI/LST	UNREP	Viet Nam Deployment
11/69	TUCUMCARI/HELO	MEDEVAC	Viet Nam Deployment
12/69	FLAGSTAFF/HELO	MEDEVAC	Viet Nam Deployment
12/70	TUCUMCARI/AFS	UNREP	Viet Nam Deployment
12/70	TUCUMCARI & FLAGSTAFF/HELO	VERTREP	Viet Nam Deployment
12/70	TUCUMCARI & FLAGSTAFF/A0	UNREP	Viet Nam Deployment
1/70	HIGH POINT/HELO	MEDEVAC	Straits of Juan De Fuca
3/71	TUCUMCARI/LST	UNREP	European Deployment
3/71	HIGH POINT/DEG	UNREP	San Diego, CA (Fleet Exercise Admixture)
7/71	HIGH POINT/HELO	VERTREP	Straits of Juan De Fuca
7/72	PLAINVIEW/HELO	MEDEVAC	Straits of Juan De Fuca
8/74	FLAGSTAFF/DE	UNREP	San Diego, CA (Fleet Exercise Bell Cam)
8/74	HIGH POINT/DD	UNREP	San Diego, CA (Fleet Exercise Bell Cam)

Logistics

a. Underway Replenishment

- Replenishment at sea
- Ship stores and euqipment handling systems
- Cargo handling systems
- Vertical replenishment systems

b. Facilities on board the craft

Berthing

a. Mooring

b. Anchoring

c. All methods and machinery necessary for securing the craft when not underway

Special External Support Requirements

a. Compatibility between ship and shore power

b. Bumpers, fenders, camels, etc.

7.6.1 Underway Replenishments

(U) On May 11, 1967, PCH-1 conducted tests in Puget Sound to determine the best speed and stationing for underway replenishment. Using a Navy tug for the supply ship, it was concluded that such an operation could be accomplished. The UNREP speed was 8 knots and the alongside position was abeam of the delivery craft, Reference II.B.7-1.

(U) In November, 1969, PGH-2 and a LST conducted refueling exercises while proceeding out of DaNang harbor. Astern refueling of the hydrofoil ship was accomplished while traveling at 5 knots, Reference II.B.7-2.

(U) On 16 February 1970, a stores replenishment was conducted by PGH-1 and PGH-2 with AFS-1. The evaluation took place in sea state 1 with swells between 2 and 4 feet, at a speed of 10 knots. A modified "Regulus" rig was used for the transfer. A standard transfer bag containing 200 pounds was cycled five times between each PGH and AFS-1. A slight problem with stationkeeping was experienced during the replenishment, due to interference with the bow wake of the AFS-1. The officer-in-charge of PGH-1 noted that less bow wake interferences would have occurred if the transfer had taken place at AFS-1 Station 6 instead of Station 4. The officer-in-charge of PGH-2 also noted that distance corrections were required for stationkeeping instead of compass course corrections. Such correction was necessary because of the difficulty in making minor course corrections with the present markings on the gyro compass repeater, Reference II.B.7-3.

(U) PGH-1 and PGH-2 conducted alongside refueling at sea with AO 24 in February 1970. The craft were proceeding north of DaNang in sea state 1 at 8 knots. Both craft received a special close in rig with 2½ inch hose from station 6 of the AO. An increase of speed from 8 knots to 10 knots aided PGH-1 in stationkeeping.

(U) On 7 March 1971, PCH-1 during Fleet Exercise Admixture rendezvoused with DEG-3 to exercise refueling and replenishment, Reference II.B.7-4.

(U) A modified NATO astern refueling rig was designed and tested in Chesapeake Bay on 15 March 1971, using PGH-2 and LST-1178. After transferring a token amount of fuel, close in, an alongside rig was tested. Nine underway refuelings and replenishments were conducted with LST 1178 in sea states between 5 and 6. During UNREP operations in sea state 4 and above, the main deck was awash, a considerable hazard of crew safety, Reference II.B.7-5.

(U) During its European deployment, PGH-2 was refueled on 3 May 1971 by a Danish oiler at anchor 2 miles off the East Coast of Jutland in sea state 1.

(U) In August 1974, PGH-1 rendezvoused with DE-1065 during Fleet Exercise Bell Cam. PGH-1 was also taken under tow at speeds up to 8 knots thus demonstrating the feasibility of conducting an astern UNREP in this fashion, Reference 11.8.7-6.

(U) On 21 August 1974 PCH-1 and DD 826 rendezvoused off the coast of San Diego, California, as a part of Fleet Exercise Bell Cam. Proceeding at 12 knots, PGH-1 was alongside the destroyer for 30 minutes. The craft remained on turbine power with the auto pilot active in the flat turn mode.

(U) The helmsman encountered problems in maintaining station. Water flowing between the craft caused him to misjudge relative distance. This was corrected by placing a lookout on the deck and communicating between ships via sound power phones, Reference II.B.7-6.

7.6.2 Vertical Replenishment

(U) On 16 February 1970 a vertical replenishment was conducted at 10 knots by both PGH-1 and PGH-2 using CH-46 helicopters from AFS-1. Both PGHs received a bag of provisions from the end of the hoist cable from the CH-46. Neither craft experienced difficulties during the transfer. The altitude of the helicopter during the PGH-1 transfer was approximately 40 feet and varied from 50 to 60 feet during the PGH-2 transfer. Since PGH-1 had a collapsible antenna, her deck protrusions were not considered a hazard. On PGH-2, however, the non-collapsible whip antenna extending 55 feet above the waterline prevented the helicopter from hovering as in a normal VERTREP and was considered a hazard, Reference II.B.7-3.

(U) PCH-1 simulated refueling from a CH-46 helicopter in the Straits of Juan De Fuca in June and July of 1971. This was accomplished in sea state 3, which was simulated by injecting sinusoidal signals into the height channel of the ship's auto pilot. In the first event of the exercise, the helicopter was positioned 150' in altitude and slightly abaft the stern. The aircraft experienced no difficulty in maintaining position as the hydrofoil ship executed turn rates of 3 degrees per second at speeds of 35 to 40 knots. PCH-1 experienced no control problems as a result of helicopter noise or rotor downwash.

(U) For the second event, PCH-1 passed the free end of a 175-foot nylon line to the helo, simulating a fuel line transfer. It was determined that the ideal station for the helicopter was somewhat aft of the hydrofoil ship fantail. This allows the pilot an unobscured view of the ship. The actual transfer had to be accomplished while the ship was hullborne. However, once this was completed, PCH-1 went foilborne and maneuvered as it did in the previous event.

(U) A simulated higher sea state had no adverse effect on the operation, References II.B.7-7 and II.B.7-8.

7.6.3 Medical Evacuations

(U) In October and November 1969, PGH-2 conducted simulated medical evacuations hullborne in conjunction with UH-1, CH-46, and HH-3A helicopters. The non-collapsible antenna did not present a problem during the exercise. However, pilots stated that in sea states greater than 3, the rise and fall of the antenna would present a major hazard to helicopter operations, References II.B.7-3 and II.B.7-8.

(U) Simulated medical evacuations were conducted from PGH-1 hullborne during December 1969 with HH-3A and CH-46 helicopters. During the HH-3A MEDEVAC, both a stokes stretcher and paramedic were raised and lowered satisfactorily. The whip antenna of the PGH-1 was removed. A stokes stretcher, and personnel sling with dummy attached, were raised and lowered by the CH-46 in the evaluation with PGH-1, Reference II.B.7-3.

(U) On 4 January 1971, a simulated medical evacuation exercise was conducted by PCH-1 in the straits of Juan De Fuca between Port Angles and Port Wilson.

(U) A USCG helicopter rendezvoused with PCH-1 and assumed a position off the port quarter. The pilot reported that he could operate satisfactorily in this position. A medical evacuation was then simulated by lowering a "horse collar" to the deck of the ship. The helicopter pilot was able to maintain a position within 3 feet of the pilothouse for several miles. However, it was the pilot's opinion that in rough water he would probably have to assume a higher altitude, Reference II.B.7-9.

(U) On 18 July 1972, a simulated medical evacuation was conducted with AGEH-1 using a Navy helicopter. In this instance, a man was hoisted off the deck of the hydrofoil ship and into the helicopter.

7.6.4 Berthing

(U) Berthing and mooring has not proved to be a problem for any of the hydrofoil ships as long as a camel is made available. During voyages to the San Diego area, PCH-1 berthed without any particular difficulty, and this includes all intermediate stops along the way. This also can be said of PGH-1 and PGH-2 deployments to Viet Nam in 1969-70, as well as the 1971 European deployment of PGH-2.

7.7 PECULIAR SUPPORT

(U) To date no extensive experience has been acquired in sustained operations with conventional surface forces to evaluate the peculiar support implications of hydrofoil ships. Hydrofoil ships have participated in various exercises, but have generally done so on a daily basis operating out of a port, the latter, on occasion, other than home port. In such cases, they have supported themselves.

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II.B.7-2 Astern Refueling, LST and PGH; Results bnd Recommendations, Nov 69, B.O. Lane, USS Park County (LST-1077) LTR ser 581 DTD 20 Nov. ASDB No. 10-UO2327M

II.B.7-3 Memo, Project Officer U.S. Navy Research and Development Unit, Viet Nam to Deputy Commander, Operational Test and Evaluation Force, Pacific.

II.B.7-4 Memo, Officer in Charge, High Point (PCH-1) to Chief Observer, Sep 03-71, 6 Mar 1971.

II.B.7-5 Enclosure to NELC Confidential ltr J601/DDW:bc, ser 232-14.

II.B.7-6 Unpublished TN on Fleet Exercises, DTNSRDC Code 1152.

II.B.7-7 PHM UNREP/VERTREP Study, July 72, W.S. Severns, V.H. Salisbury, The Boeing Company.

II.B.7-8 HIGH POINT (PCH-1) Fueling VERTREP with CH-46 Helicopters: Final Report, Aug 71, H. Schmidt, NSRDC. ASDB No. UO1862M

II.B.7-9 Patrol Craft Hydrofoil HIGH POINT Summary and Logs for PCH-1 Simulated Medical Helicopter Evacuation, Sep 71, G.B. Roberts, The Boeing Company document number D2-133703-61. ASDB No. 10-UO1488M

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*References with an ASDB number are available from the DTNSRDC Advanced Ship Data Bank, DTNSRDC Code 1158.

II. STATUS OF VEHICLE TECHNOLOGY

B. SUBSYSTEMSAND DESIGN AND CONSTRUCTION FEATURES

8. MARGINS

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II.B. SUBSYSTEMS AND DESIGN AND CONSTRUCTION FEATURES

8. MARGINS

8.1 INTRODUCTION

(U) Margins may be described as engineering tolerances for the uncertainties of ship design development, performance prediction, and changes or modifications which will occur during a ship's life. The allocation of margins must be selected judiciously because of their effects upon ship size, performance, and cost.

(U) Margin policy as it pertains to U.S. Navy hydrofoil ships has varied from design to design and the establishment of a more uniform policy is currently underway and will be available in the near future as part of the USN Hydrofoil Design Criteria Volume.

8.2 MARGIN CATEGORIES

(U) Margins may be grouped under three categories:

- Design Margins
- Assurance Margins
- Future Growth Margins

8.3 DEFINITIONS

8.3.1 Design Margins

(U) Design margins are usually associated with weight, center of gravity, manning, space, area and/or volume, and service life, and may include accommodation margins which take the form of area margins associated with manning margins.

(U) Design margins tend to reduce as design development progresses and estimates and calculations refine. In some cases the term "tend to become absorbed" is used instead of the term "tend to reduce." The latter is preferred because it must be an objective in design to use margins only if necessary. Designs must be refined to prevent the passive description of margins, to avoid unnecessarily larger, higher powered and therefore more costly ships.

(U) Design margins are established for:

- Preliminary Design
- Contract Design
- Contract Modification
- Government Furnished Material
- Detail Design and Construction
- Service Life

8.3.2 Assurance Margins

(U) Assurance margins are intended to provide for the uncertainties of ship operation such as variable sea state, variable environmental factors, ship fouling, and damage, wear and deterioration of ship subsystems, components and equipment. The assurance margins are usually associated with system loads, power and capacity, and either reduce or become absorbed in the design as the latter progresses and refines. Assurance margins include:

- Endurance Power
- Sustained Speed Power
- Electrical Power

8.3.3 Future Growth Margins

(U) Future growth margins are intended to provide capacity to absorb the effects of future changes or modifications of a ship. Such margins are usually associated with weight, space, manning, center of gravity, electrical power and ship service systems capacity. They tend to remain fixed as design progresses. Future growth margins include:

- Space and weight reservations
- Electrical power reserve capacity, which may include either surplus installed electrical powers or reservations to prevent either additional, or higher capacity generations to be installed
- Electronic costing capacity
- Manning increases

a.4 MARGIN ALLOWANCES

8.4.1 Weight Margins

(U) In preliminary and contract design, the weight margin will be on the order of 3-7% of the lightship weight.

(U) The contract modification weight margin is intended to provide for the effects of anticipated contract changes during detail design and construction. The margin is established on the basis of the Navy's assessment of how much development may be involved in detail design and construction. It is a poor and extremely expensive policy, to carry development over into detail design.

(U) The GFM weight margin will be on the order of 1% of the lightship weight.

(U) The detail design and construction weight margin consists of two margins, namely, a design margin, which will be on the order of 3-5% of the Accepted Weight Estimate lightship, and a construction margin which will be on the order of 1% of the Accepted Weight Estimate.

(U) The service lift weight margin will be on the order of 5% of the full load displacement.

8.4.2 Center of Gravity Margins

(U) The center of gravity margins for hydrofoils are of two types, one pertaining to the vertical center of gravity and the other, more a constraint than a margin, pertaining to the longitudinal center of gravity.

(U) The basic vertical center of gravity margin is on the order of 1% of the KG, plus flat allowance to allow for inaccuracies associated with the inclining experiment. The longitudinal center of gravity margin is related to the foil lift overload margin discussed in Section 8.4.8.

(U) The service life KG margin will be on the order of 7-15 cms (3-6 inches).

8.4.3 Manning Margins

(U) No specific standard margins are known for manning. However, it would be prudent to allow 10% of the total initial manning estimates at least through the preliminary design phase.

8.4.4 Space Margins

(U) The space margin in preliminary design will be about 5% of the estimated areaand volume requirements, reducing to 0% on contract design.

8.4.5 Endurance and Sustained Speed Power Margins

(U) The endurance power margin will be on the order of 20% of design installed propulsion horsepower; the sustained speed power margin will be on the order of 25% of design installed propulsion horsepower.

8.4.6 Electrical Power Margin

(U) The electrical power margin will be on the order of 20% of the design electrical load of the ship service generators with one system inoperative.

8.4.7 Future Growth Margins

(U) The future growth margins will vary from ship to ship depending upon the complexity of the combat suite and cannot be generally qualified in any terms that would be meaningful.

8.4.8 Hydrofoil Peculiar Margins

(U) There *are* certain additional margins peculiar to hydrofoils which DTNSRDC Identifies as:

- Cavitation Margin. A margin of 20% of the cavitation free design lift is used at design speed in calm water to allow for the lift loss effects due to possible foil cavitation in rough water.

- Takeoff Margin. A margin of 20-25% of the cavitated calm water takeoff propulsion horsepower is allowed to ensure the adequacy of takeoff power in rough water. This has been reduced from an eariler margin of 40%, as a result of experience gained with the existing USN hydrofoils.

- Control System Margin. A 100% gain margin and 60° phase margin are designed into the automatic control system control loops.

- Foil Lift Overload Margin. An overall margin of about 10% on foil lift load is being considered for future hydrofoil ships to allow for future weight growth effects on foil loading.

These margins are tentative at present.

II. STATUS OF VEHICLE TECHNOLOGY

C. PERFORMANCE INTERDEPENDENCIES

SPEED, ENDURANCE RANGE, ENDURANCE PERIOD, AND PAYLOAD CARRYING ***CAPABILITY***

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II.C. TECHNOLOGY ASSESSMENT PERFORMANCE INTERDEPENDENCIES

Section 1

INTRODUCTION

(U) This section will summarize the performance inter-dependencies of subcavitating hydrofoil ships (less than 55 knots) in sizes from 200 to 3,000 tons, and supercavitating hydrofoil ships (greater than 55 knots) in sizes from 100 to 300 tons.

(U) Hydrofoil ship design is a complex process involving highly interrelated effects of diverse design factors. Because of the difficulty of calculating ship performance with these interdependencies taken into consideration, it has become standard practice to simplify the preliminary design process by varying certain design factors serially and determining ship performance with "other factors remaining constant."

(U) To permit calculation of more realistic hydrofoil ship designs during the preliminary design process, the U.S. Navy undertook the development of the Hydrofoil Analysis and Design Program (HANDE). Development of this program was begun by The Boeing Company under Navy Contract Number N00600-73-C-0450 and is continuing under Contract Number N00600-75-C-1107. The first phase of this program, the Initialization Module, has been delivered to the U.S. Navy and has been used satisfactorily by both DTNSRDC and NAVSEC. This portion of the program employs parametric methods and a digital data bank of existing hydrofoil ship information to determine quickly the gross hydrofoil ship characteristics required to meet the specified mission requirements.

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

(U) The Initialization Module of the HANDE program has been used to investigate performance interdependencies for hydrofoil ships. The parametrics which were determined provide a definition of these interdependencies and are described below. The approaches taken and assumptions made are also described.

(U) A description of HANDE is contained in References II.C.1-1 and II.C.1-2.

Section 2

RESULTS

(U) The performance parameters considered in this study are payload and foilborne range. Operational range would be appreciably greater than that shown if hullborne operation were considered. However, for purposes of illustrating performance interdependencies, a single parameter is more easily used. The numerical range of values is intended to include or exceed current areas of interest. Ship size variation from 200 to 3,000 tons surpasses ship sizes of immediate interest.

(U) Design variables investigated were those having the greatest effect on ship performance or being of general interest. Other design factors were fixed at values considered to be typical for each ship size. For example, Figure II.C.2-1 fixes the number of crew, in each of three categories, as a function of ship size.

(U) The length-to-beam ratio was varied from 5 for small ships to 7.5 for the largest. Figure II.C.2-2 illustrates the linear relationship between length-to-beam ratio and ship size.

2.1 SHIP SIZE

(U) The data generated were based on four baseline configurations which were similar in all major respects, but differed in size. These configurations had full load weights of 205, 1,062, 2,188, and 3,358 tons. These correspond to dynamic lifts of 200, 1,000, 2,000, and 3,000 tons, respectively. Dynamic lift

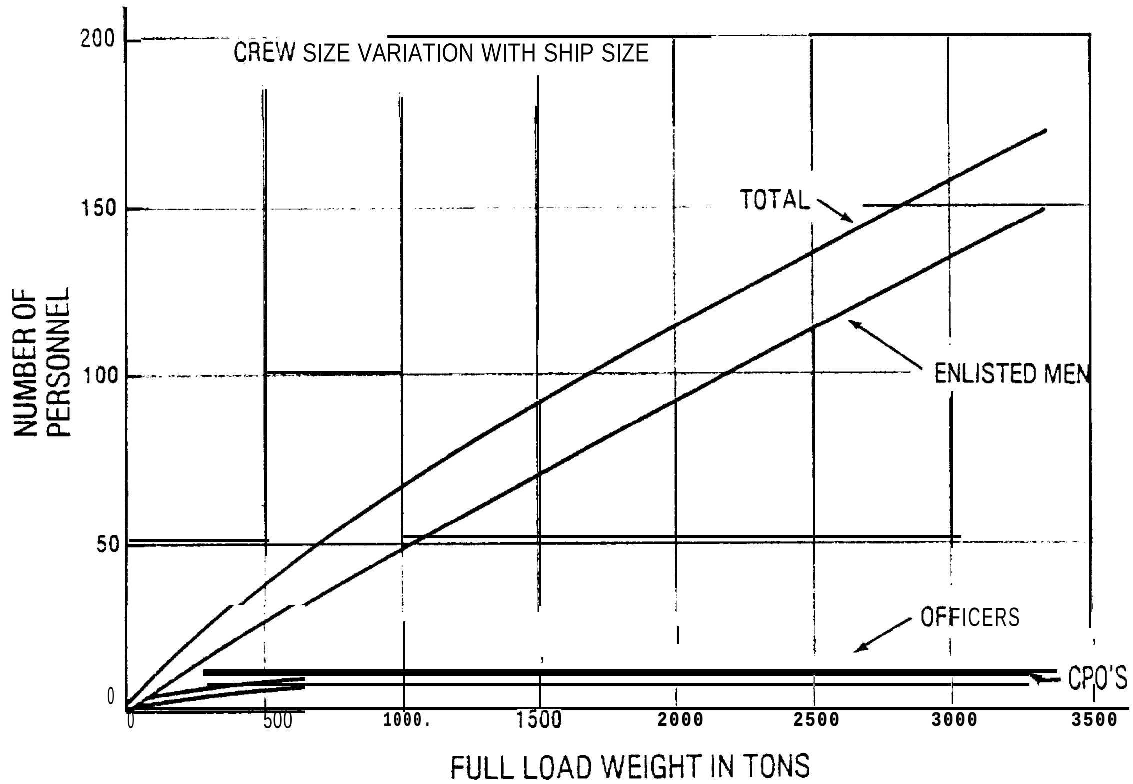

Figure II.C.2-1. CREW SIZE VARIATION WITH SHIP SIZE

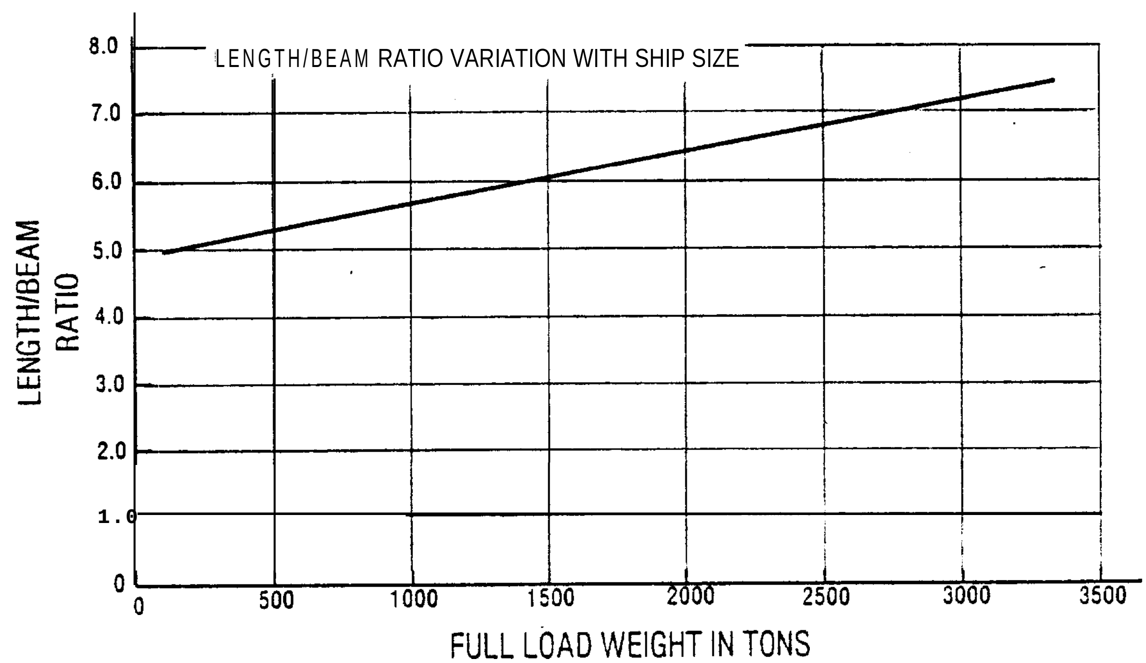

Figure II.C.2-2. LENGTH/BEAM RATIO VARIATION WITH SHI? SIZE is defined as the weight supported by the foil/strut system during foilborne operation; it is equal to the full load weight less foil/strut system buoyancy. The dynamic lift is a critical variable in hydrofoil ship design and is a primary parameter in the HANDE program.

(U) The relationship between full load weight and dynamic lift is shown in Figure II.C.2-3. In the parametric variations which follow, both full load weight and dynamic lift have been indicated for convenience. Since ship size has the greatest effect on performance, ship size is indicated for all other parameters.

2.2 LIFT/DRAG RATIO

(U) The performance available from a hydrofoil ship is directly proportional to the lift/drag ratio provided by the foil/strut system. Therefore, the performance of the four study configurations was calculated for a series of lift/drag ratios. The payload-range performance of the 200, 1,000, 2,000, and 3,000 ton ships is presented in Figures II.C.2-4 through II.C.2-7, respectively. The overall foil/strut system L/D was varied from 12 to 18 as indicated. The L/D values shown are averages based on utilization of half of the usable fuel weight. This definition applies to all L/D values.

(U) Engine size for each L/D line for each configuration was fixed at an appropriate level as described in a later section. Other parameters were fixed as shown in the figures or as stated in Section 3.

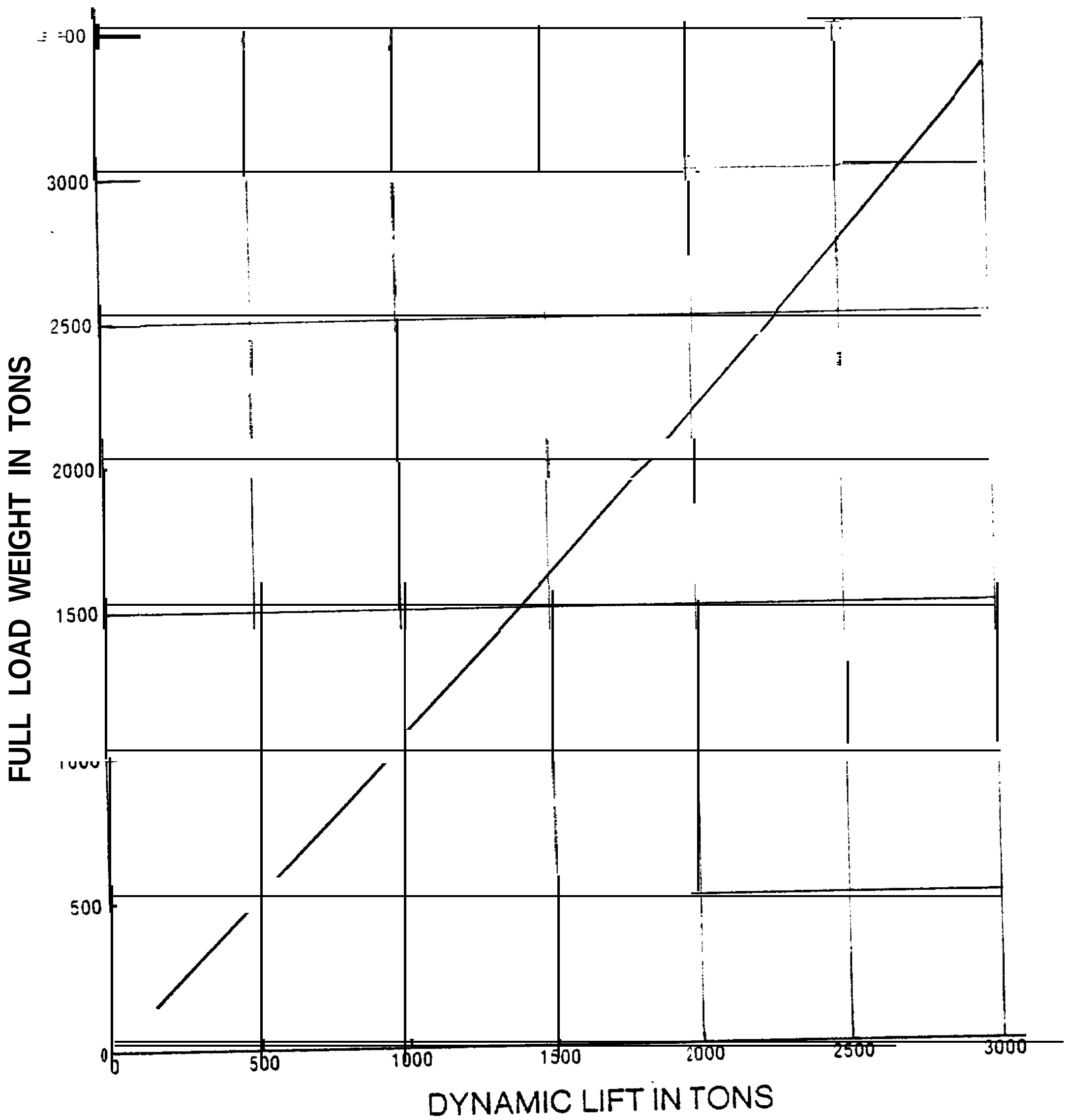

Figure II.C.2-3. HYDROFOIL SHIP FULL LOAD WEIGHT/DYNAMIC LIFT RELATIONSHIP

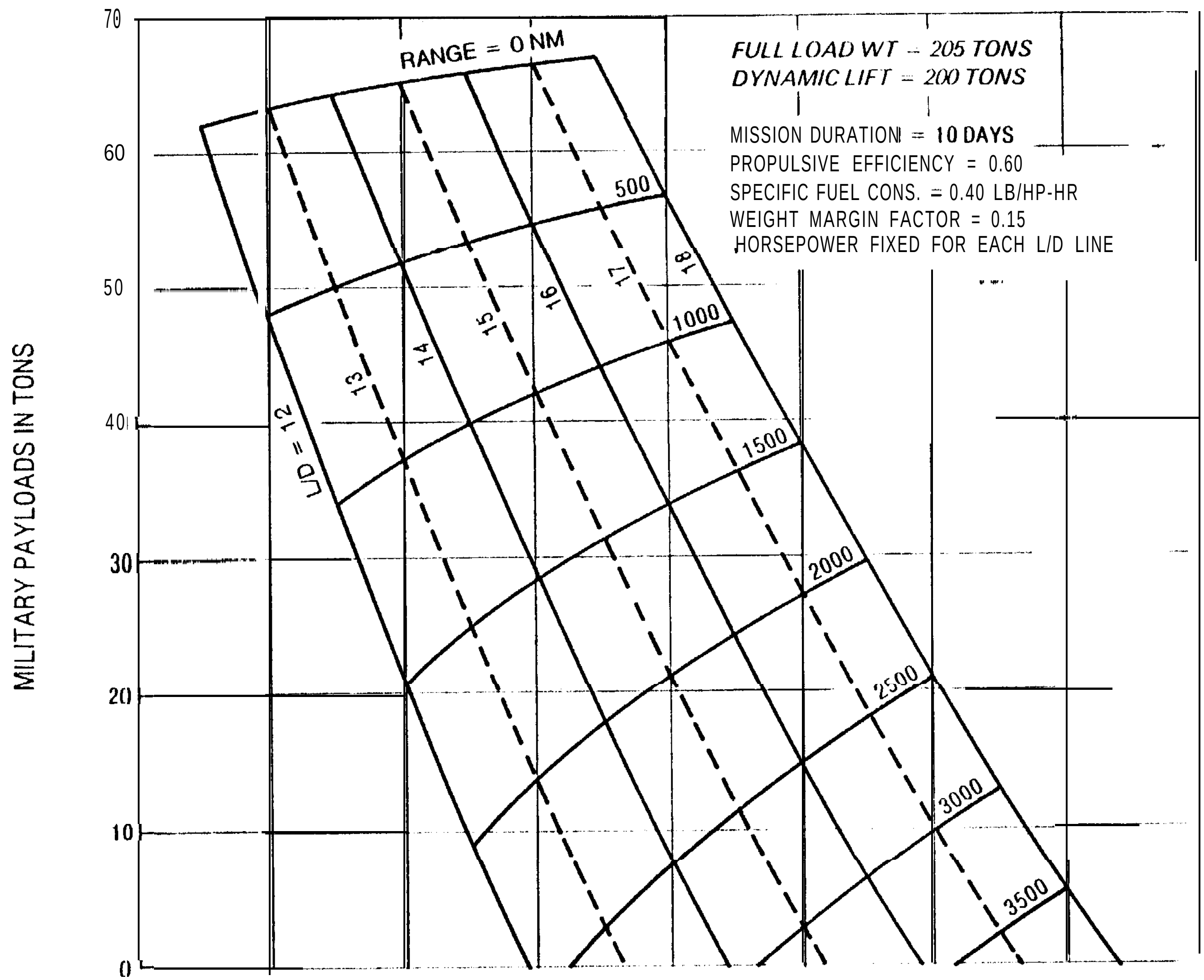

Figure II.C.2-4. L/D PERFORMANCE EFFECT (200-TON)

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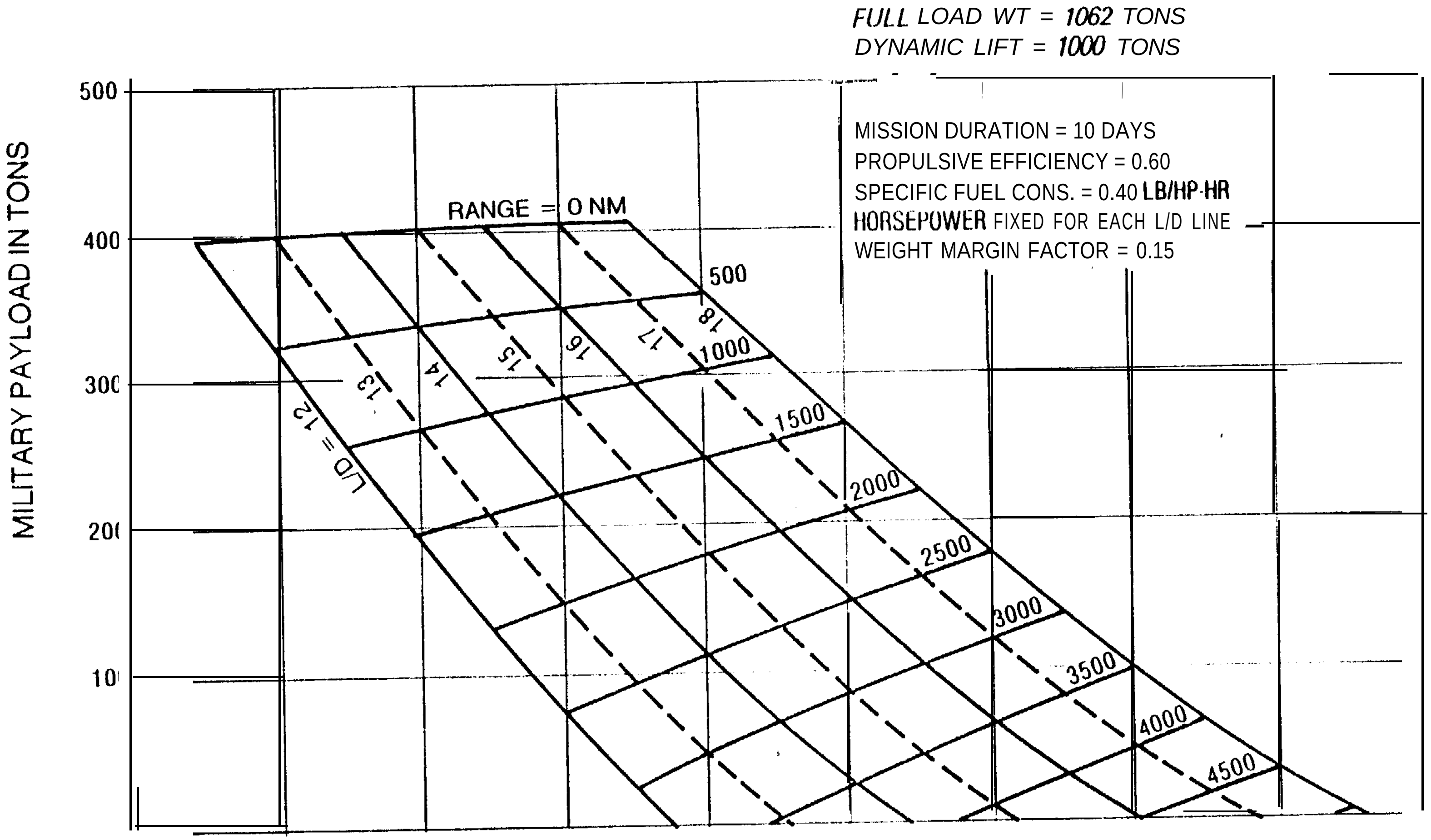

Figure II.C.2-5. L/D PERFORMANCE EFFECT (1,000-TON)

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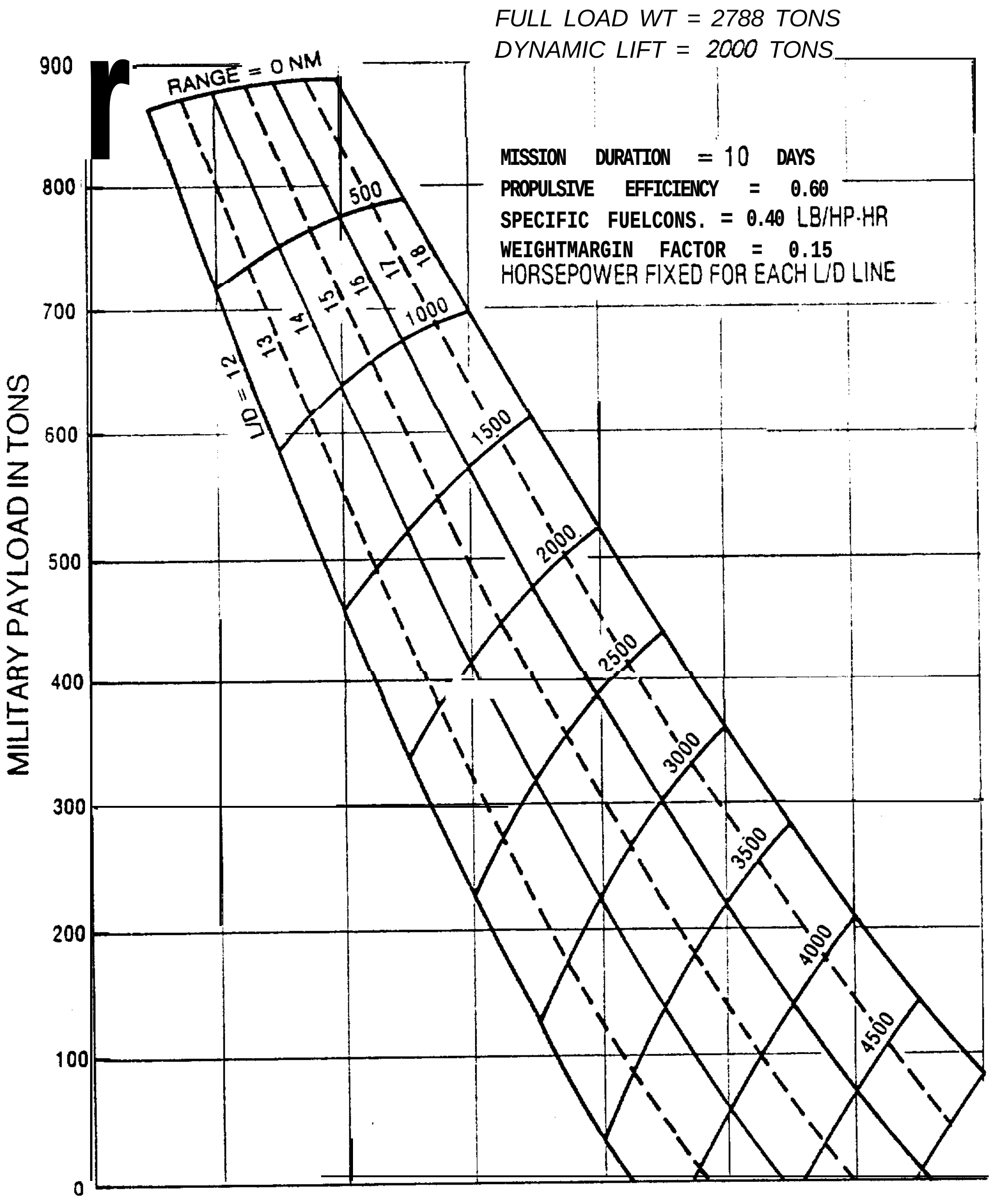

Figure II.C. 2-6. L/D PERFORMANCE EFFECT (2,000-Ton)

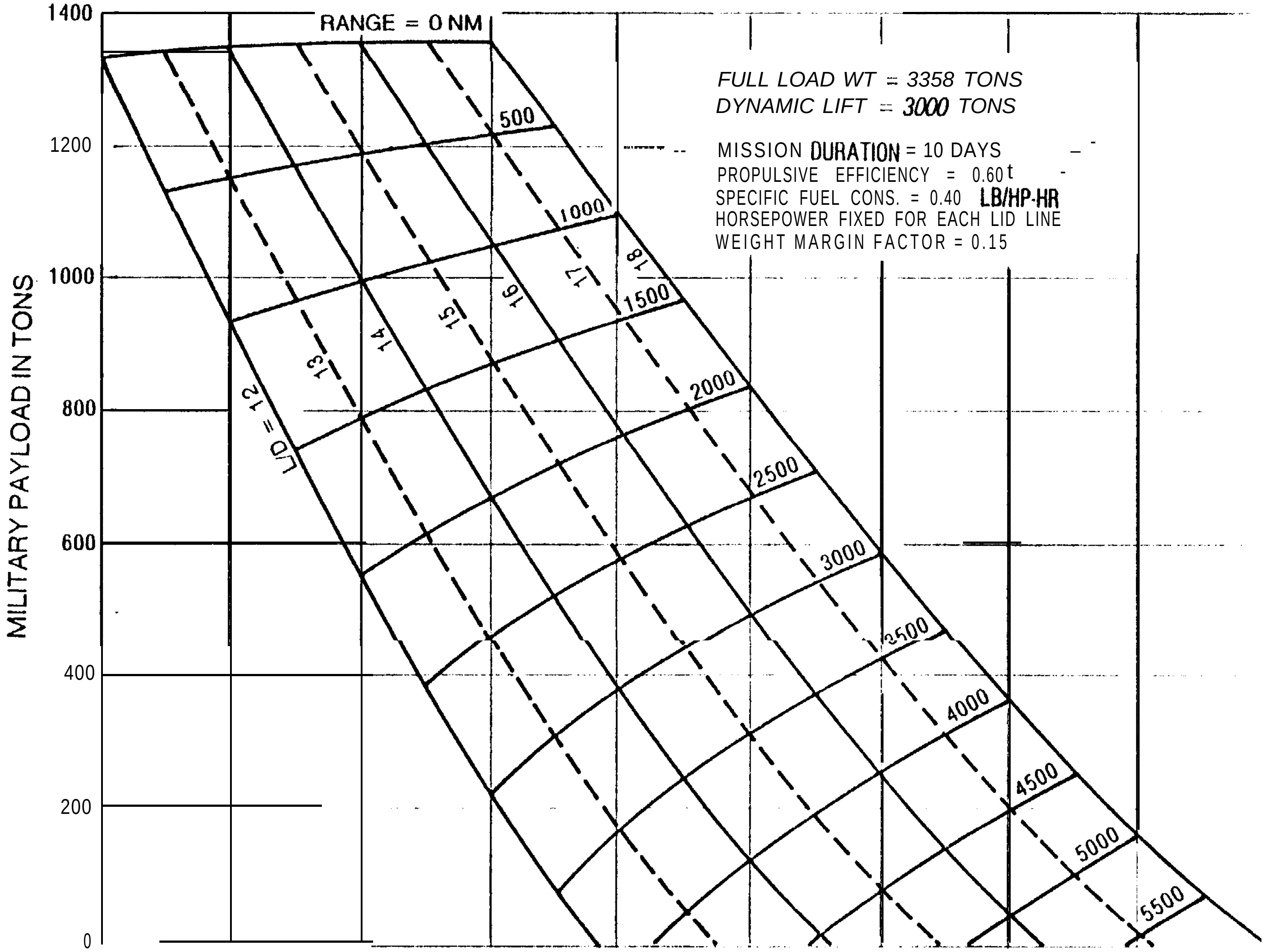

Figure II.C.2-7. L/D PERFORMANCE EFFECT (3,000-TON)

UNCLASSIFIED

(U) Figure II.C.2-8 is a composite of Figures II.C.2-4 through II.C.2-7 and permits interpolation of payload-range relationships for ships of other sizes. The performance improvement attainable through increasing ship size and L/D is clearly illustrated.

(U) Note that the L/D was set as an independent variable in this series; ship speed and foil loading were not specifically considered in these calculations. Thus, these data must be used with the recognition that the higher L/D values may be difficult or impossible to achieve in practice. Therefore, the effects of speed and foil loading on performance are independently determined.

2.3 FOILBORNE SPEED

(U) Foilborne speed is a major factor determining the foil system L/D. An option in the HANDE program permits the lift/drag ratio to be calculated based on speed, foil unit loading, and weight factors. This option is used to calculate performance at a series of speeds. The foil unit loading is held constant at 1,400 psf to determine the speed effect on performance.

(U) Figures II.C.2-9, II.C.2-10, and II.C.2-11 present payload-range performance for foilborne speeds of 40, 45, and 50 knots, respectively. The HANDE program calculated the average L/D, horsepower, and specific fuel consumption for these figures. Thus, the horsepower and L/D vary from point to point on these curves.

(U) Figure II.C.2-12 superimposes the speed-performance lines onto the basic data of Figure II.C.2-8. This permits the overall effect of ship speed to be seen more easily, since the effect

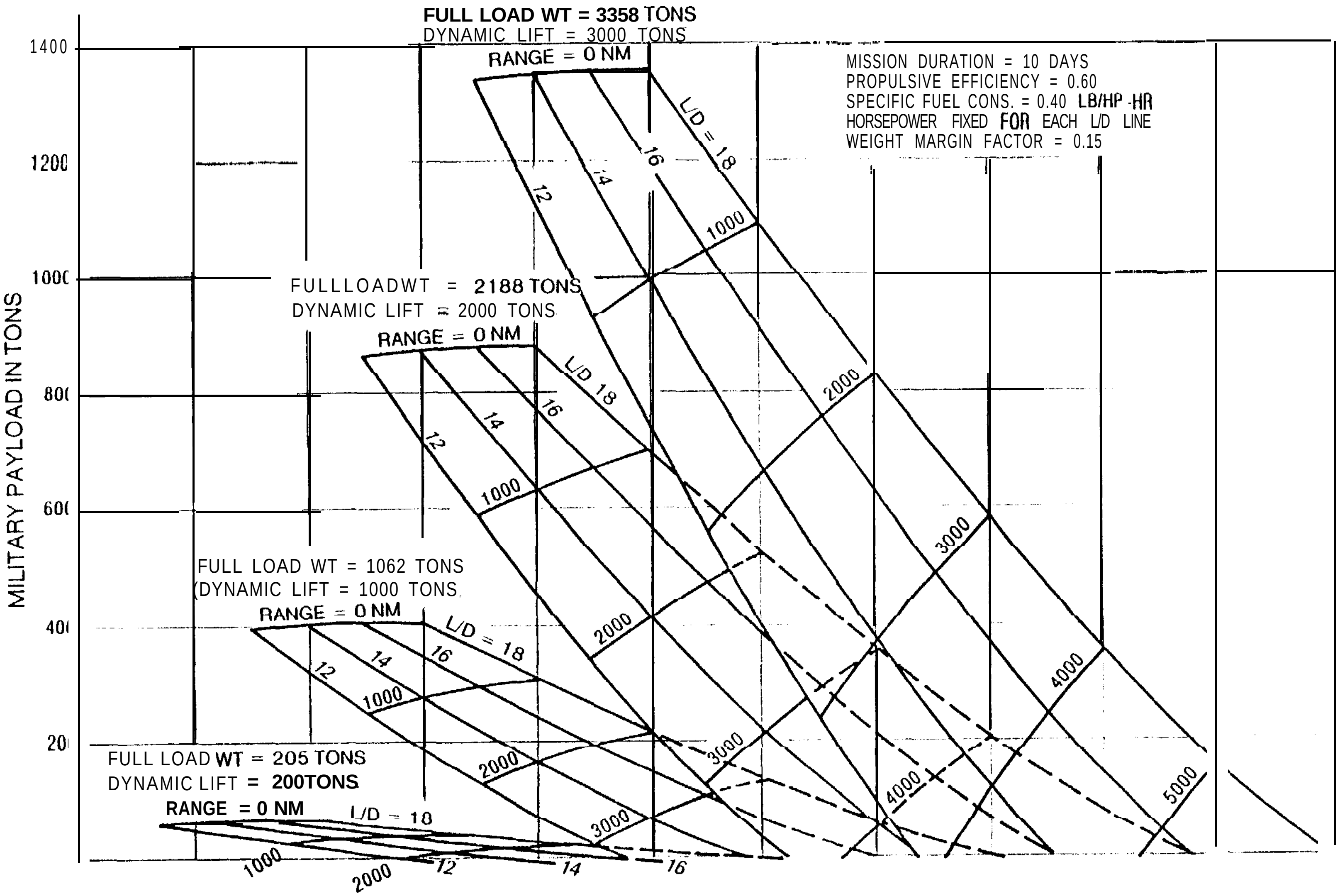

Figure II.C.2-8. COMPOSITE OF L/D PERFORMANCE EFFECT (for Figs II.C. 2-4 to II.C. 2-7)

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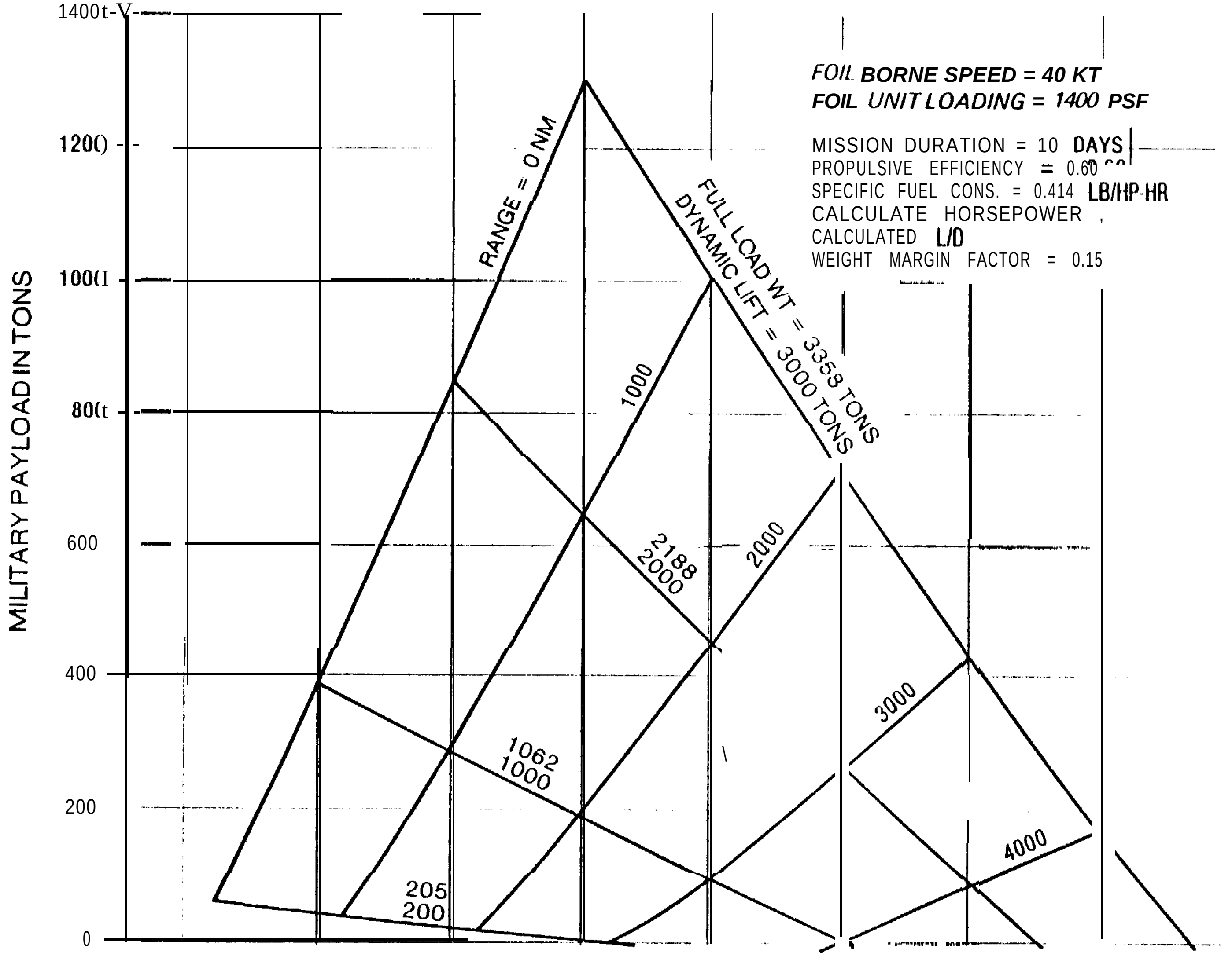

Figure II. C. 2-9. SPEED-PERFORMANCE EFFECT (40 KNOTS)

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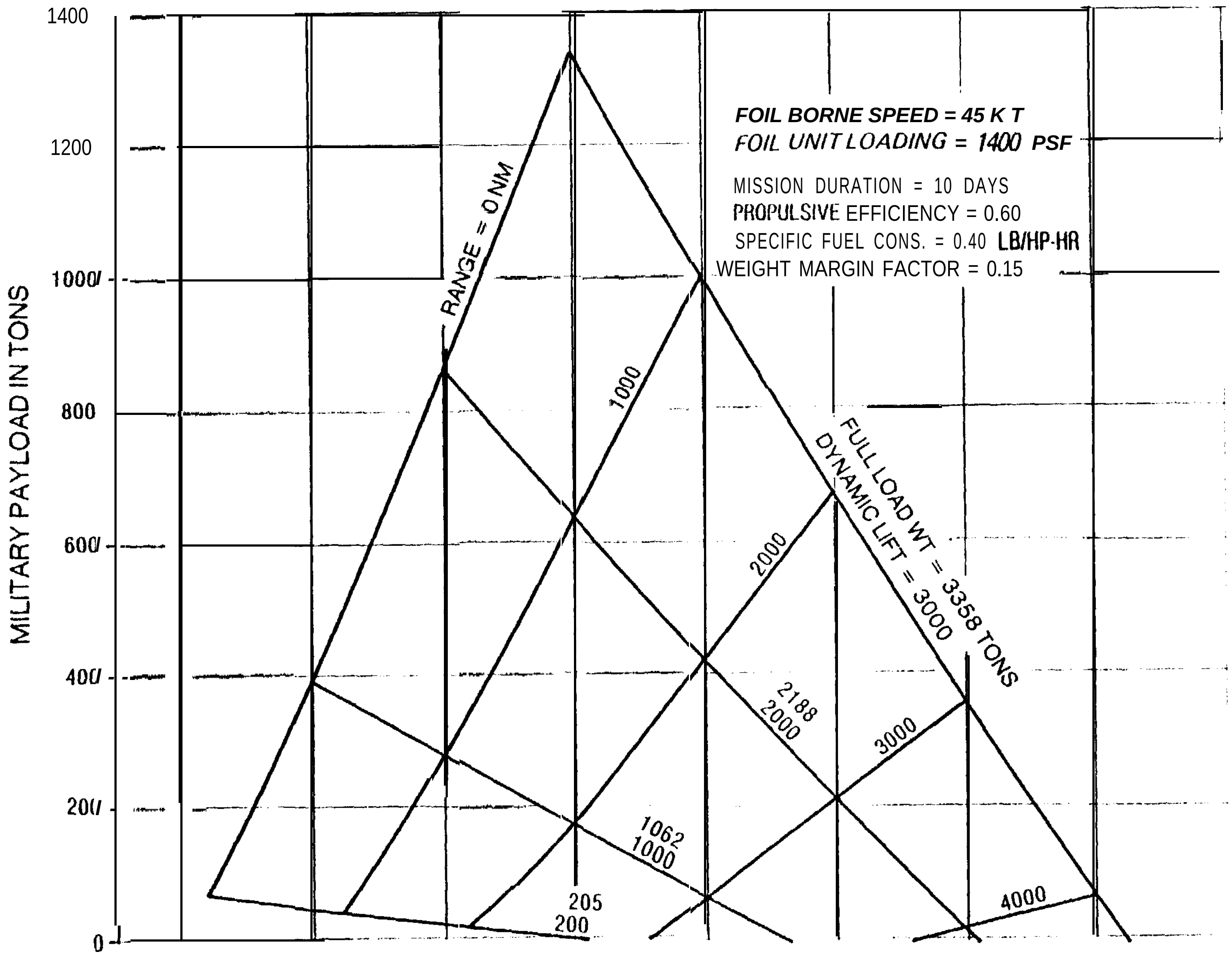

Figure II.C .2-10. SPEED-PERFORMANCE EFFECT (45 KNOTS)

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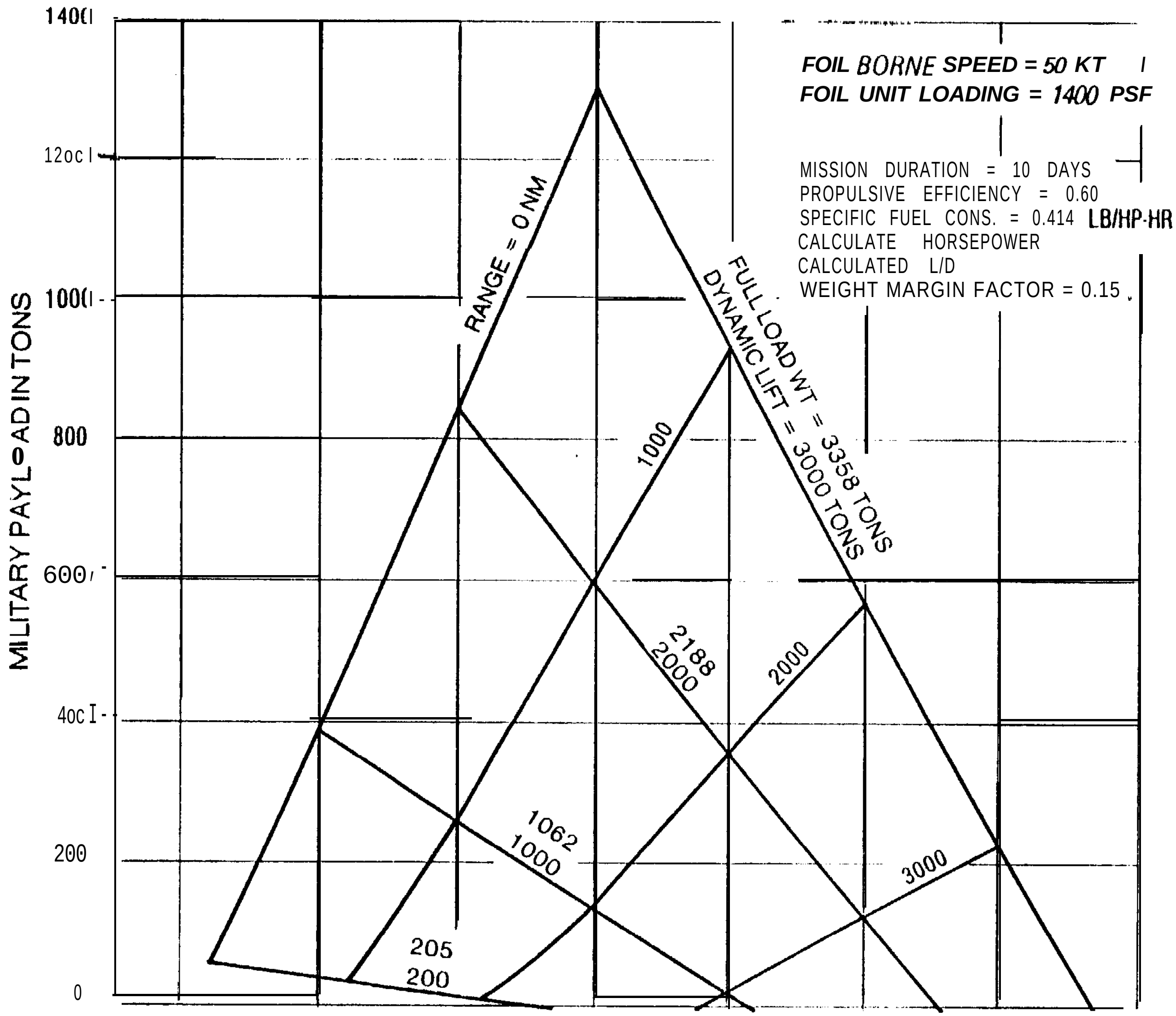

Figure II.C. 2-11. SPEED-PERFORMANCE EFFECT (50 KNOTS)

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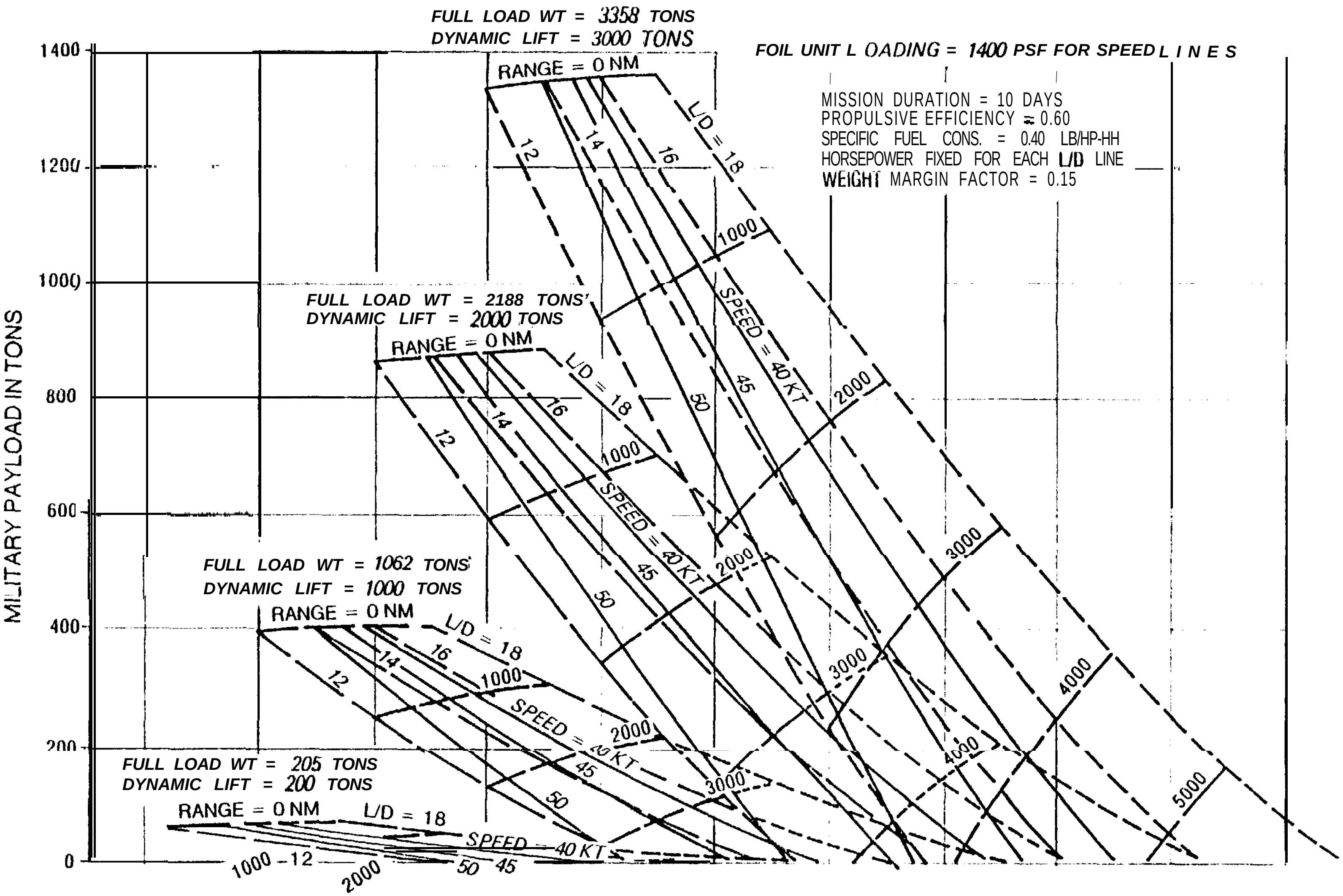

Figure II.C.2-12. SPEED-PERFORMANCE & L/D PERFORMANCE EFFECT COMPOSITE AT 1,400 PSF FOIL UNIT LOADING of increasing speed is to increase ship drag and, therefore, decrease the average L/D. Performance decreases as speed increases as shown by these figures.

2.4 FOIL UNIT LOADING

(U) A second determinant of the foil system lift/drag ratio is the foil unit loading. The effect of this factor on ship performance was calculated for foil unit loadings of 1,200 and 1,600 psf and is shown in Figures II.C.2-13 and II.C.2-14, respectively. A foil loading of 1,400 psf was shown in Figure II.C.2-10. These three loadings were calculated at a foilborne speed of 45 knots. These curves are based on assumptions noted in the figures.

(U) As with the speed data, the average L/D for this series was calculated by HANDE and varies from point to point on the curves. Therefore, the composite figure, Figure II.C.2-15 was developed to illustrate the effect of foil unit loading on performance and on the overall L/D. Lower foil loadings which result from larger foil systems have lower average L/D values and poorer performance. The optimum foil loading will vary with speed and must also take cavitation into account. The effects illustrated in these figures are typical of this type of parametric variation.

2.5 FOILBORNE HORSEPOWER

(U) The propulsive horsepower required is an important parameter in ship design. Figure II.C.2-16 presents the horsepower levels upon which the basic data of Figures II.C.2-4 through II.C.2-8

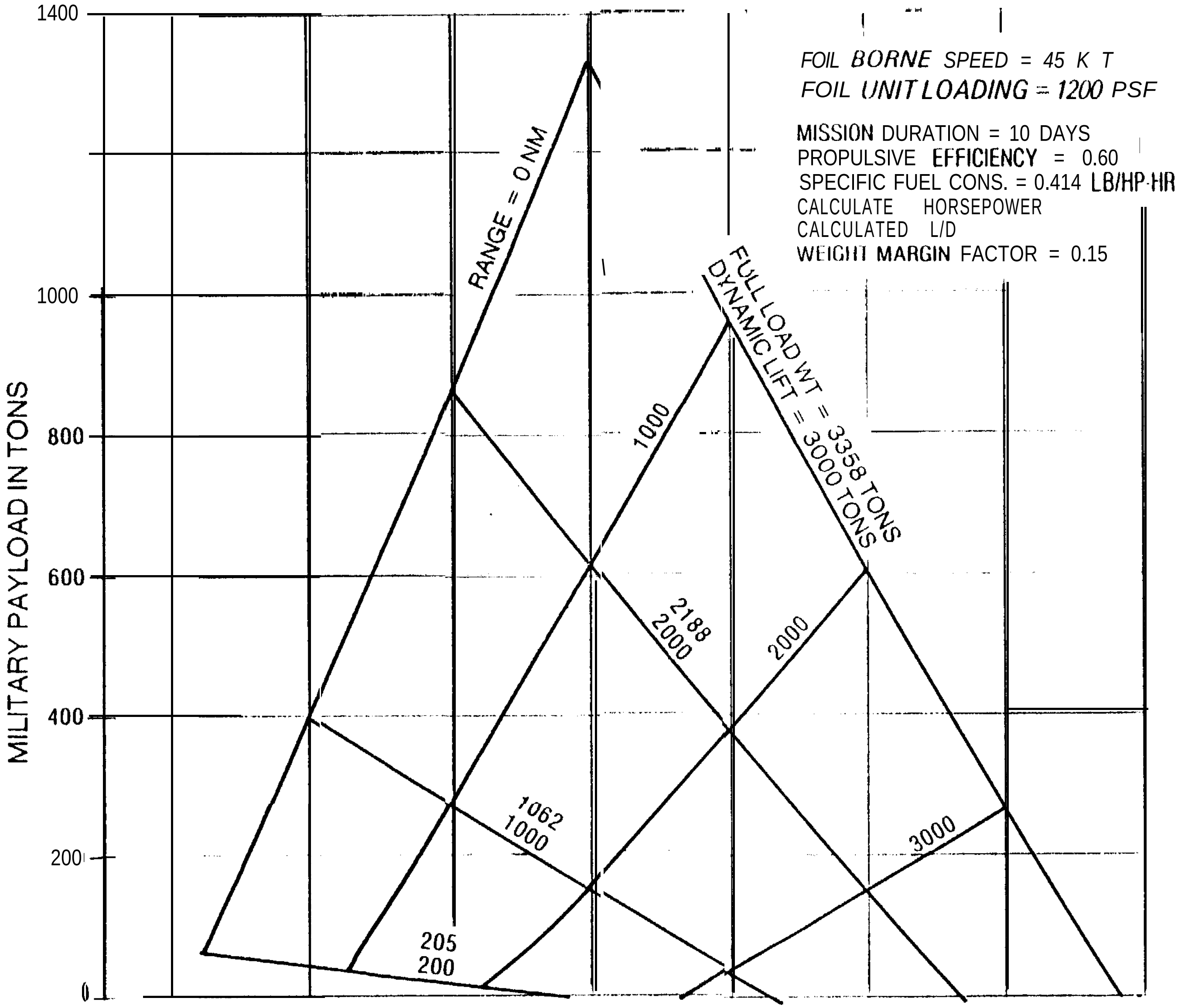

Figure II.C.2-13. FOIL UNIT LOADING-PERFORMANCE EFFECT (1200)

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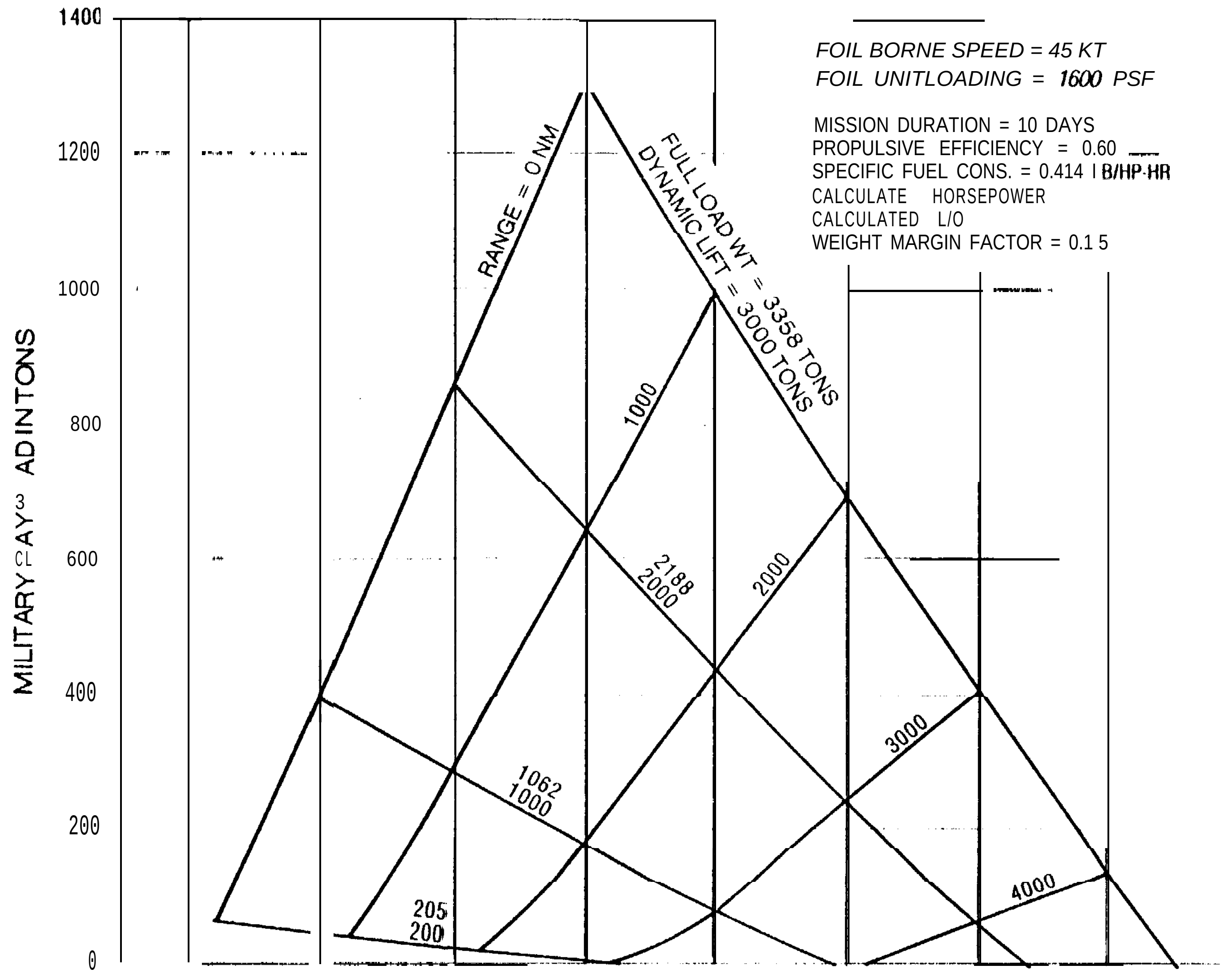

Figure II.C.2-14. FOIL UNIT LOADING-PERFORMANCE EFFECT (1600)

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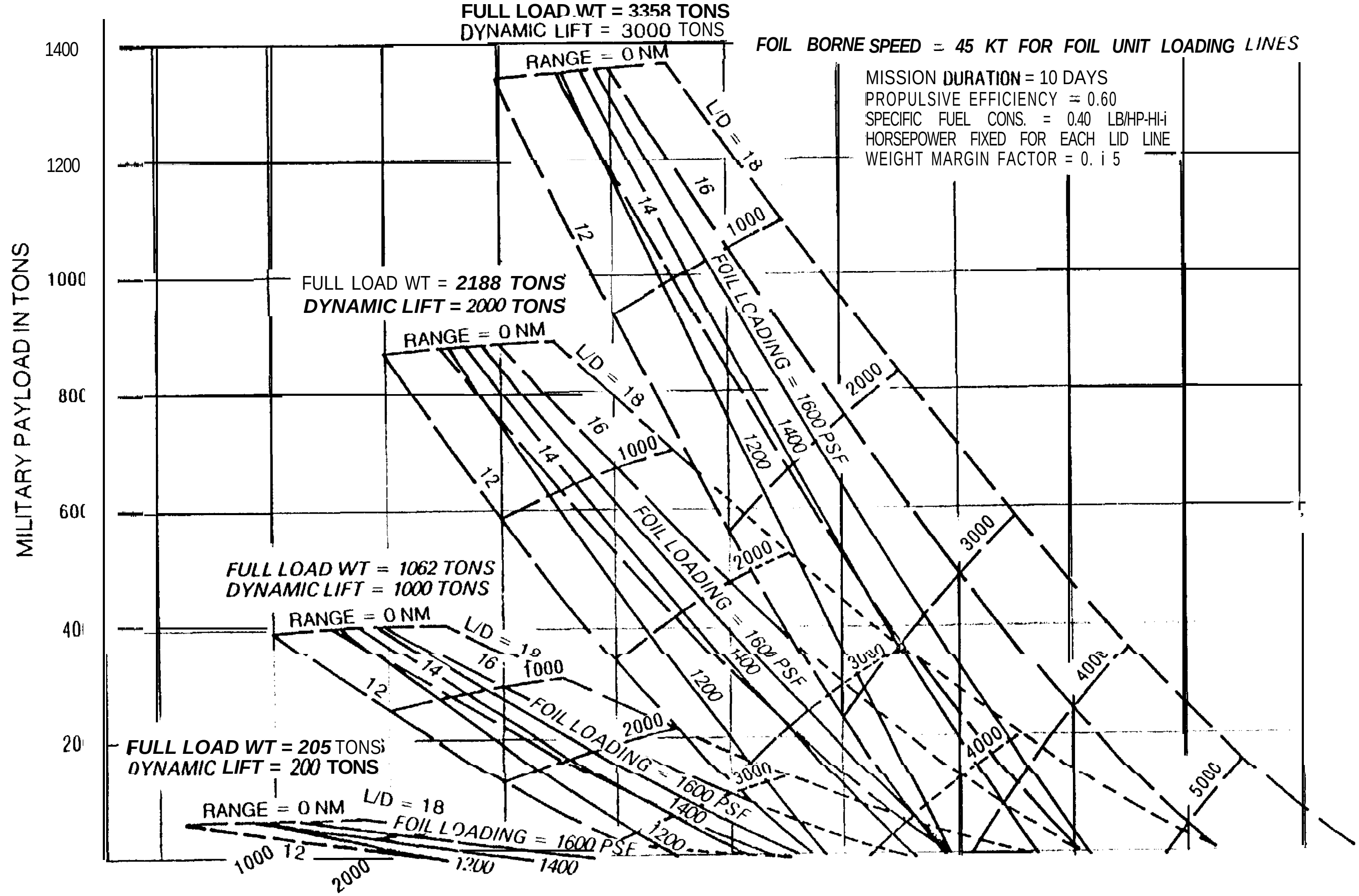

Figure II.C.2-15. FOIL UNIT LOADING AND L/D PERFORMANCE EFFECT COMPOSITE AT 45-KNOT FOILBORNE SPEED

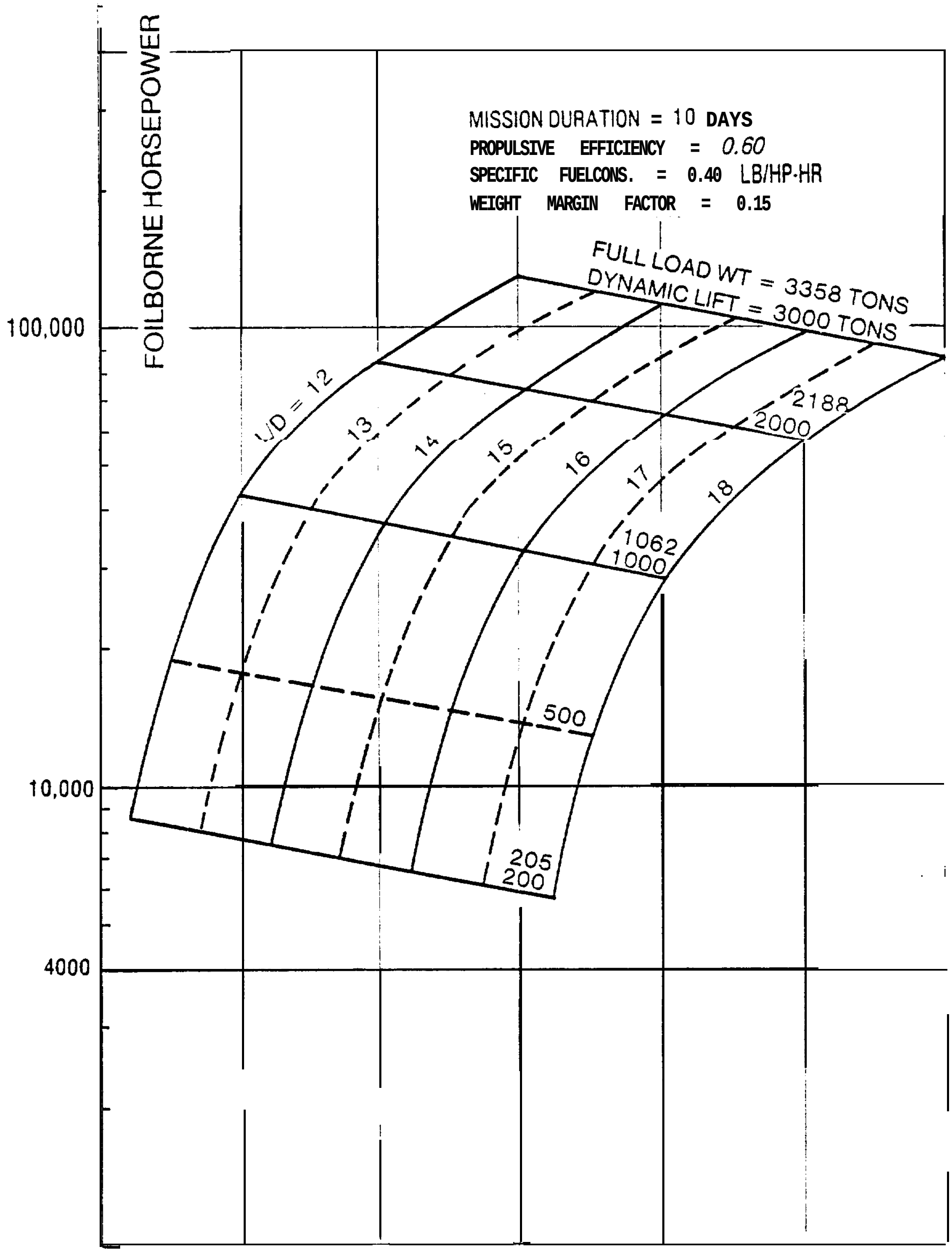

Figure II.C.2-16. MAXIMUM HORSEPOWER VS L/D were based. Engine size varied for each ship size and for each assumed average L/D. The data shown in these curves were calculated through use of an option of the HANDE program which permits the horsepower to be set by the designer. Figure II.C.2-17 redefines the data of Figure II.C.2-15 in terms of specific power, full load weight and lift/drag ratio.

(U) Most of the parametric variations of this study were made with the automatic engine sizing option of HANDE. In this option, the engine power is calculated at the point at which half of the usable fuel has been burned. This results in reduced engine weight and somewhat higher performance than would be obtained with the engine fixed at the maximum size. The effect of this option selection is generally relatively small and may be determined at any point by comparison between the various performance curves.

2.6 PROPULSIVE EFFICIENCY

(U) All of the preceding parametric variations were calculated using a propulsive efficiency of 0.60. The performance attainable from the study configurations with propulsive efficiencies of 0.55 and 0.70 are shown in Figures II.C.2-18 and II.C.2-19, respectively. These figures may be compared with Figure II.C.2-10 in which the propulsive efficiency is 0.60.

(U) The direct proportionality between range and propulsive efficiency, evident by comparing the above figures, is more clearly shown in Figure II.C.2-20. The ordinate gives the range

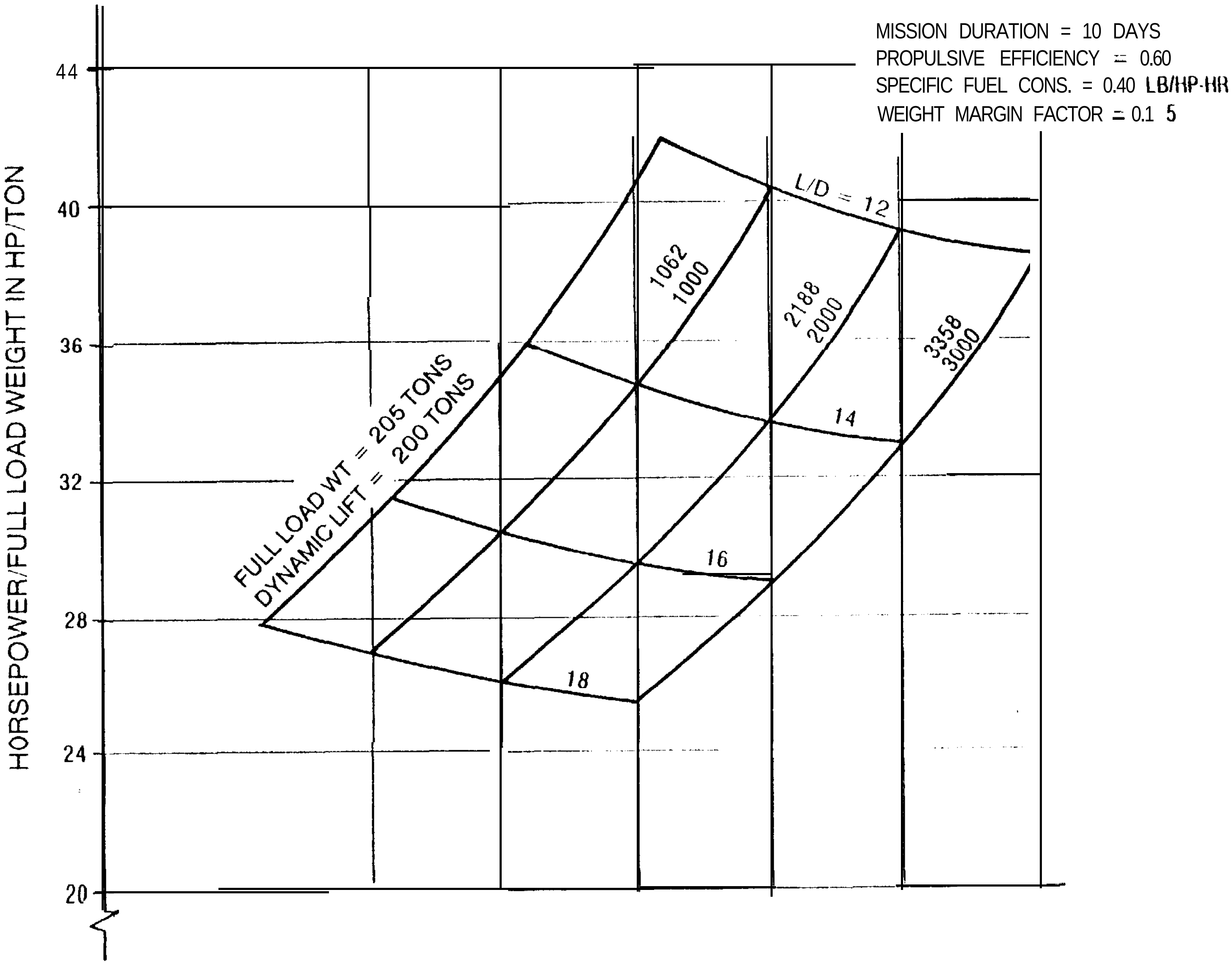

Figure II.C.2-17. L/D AND SHIP WEIGHT AS A FUNCTION OF FOILBORNE POWER/WEIGHT FRACTION

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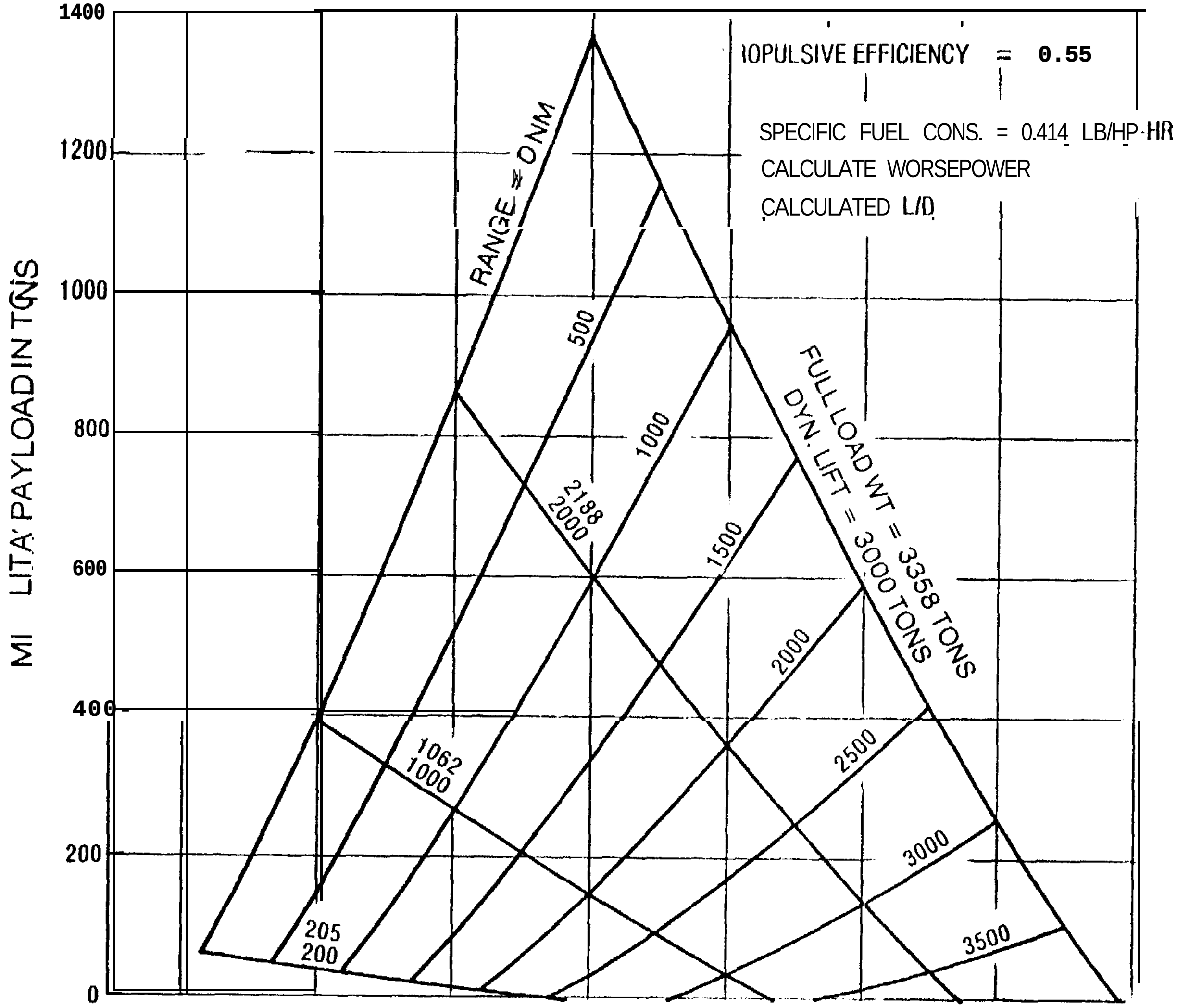

Figure II.C.2-18. PAYLOAD-PERFORMANCE FOR .55 FOILBORNE PROPULSIVE EFFICIENCY

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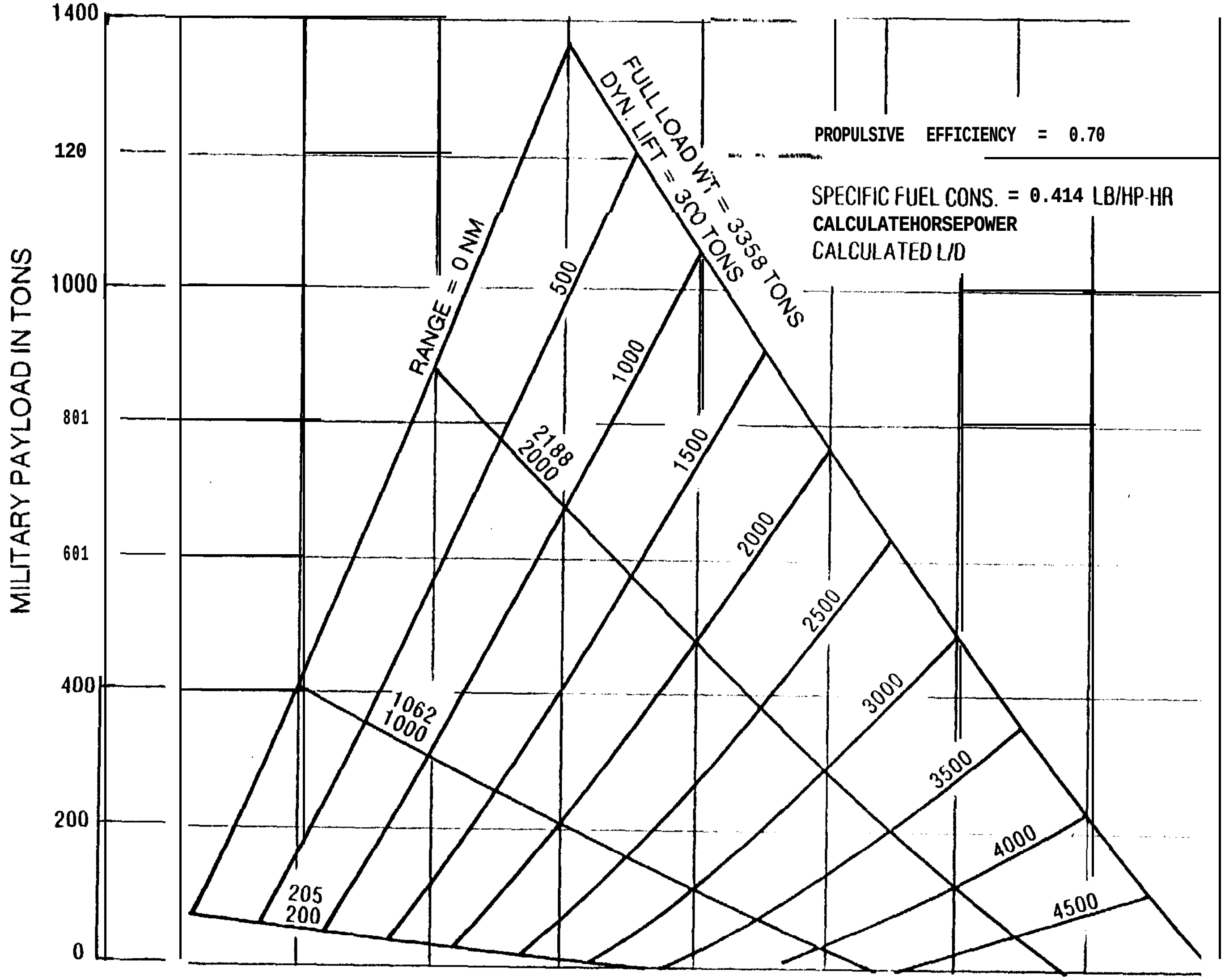

Figure II.C.2-19. PAYLOAD-PERFORMANCE FOR .70 FOILBORNE PROPULSIVE EFFICIENCY

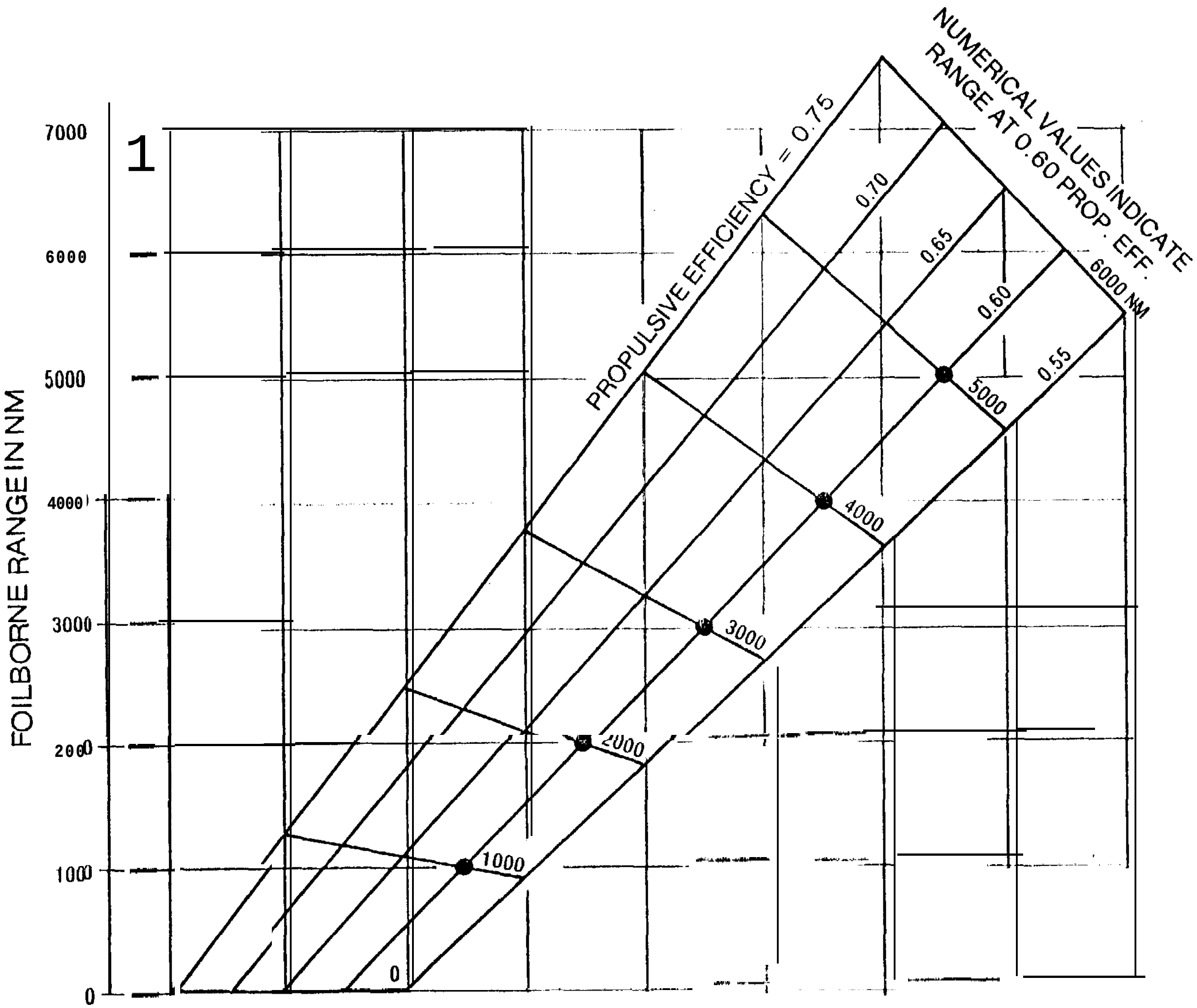

Figure II.C.2-20. FOILBORNE RANGE AT VARIOUS FOILBORNE PROPULSIVE EFFICIENCIES COMPARED WITH FOILBORNE RANGES AT .60 FOILBORNE PROPULSIVE EFFICIENCIES obtainable at the various propulsive efficiency values. The range on the curve is for a propulsive efficiency of 0.60. As an example of use, assume that a point having a range of 3,000 miles has been obtained from a previous figure in which propulsive efficiency is 0.60, and it is desired to determine the range obtainable with an efficiency of 0.65. The intersection of the 3,000 mile and .65 efficiency lines is located on the figure. The new range is then read off of the ordinate as 3,250 miles.

2.7 FUEL CONSUMPTION

(U) Tine range attainable from any ship is inversely proportional to the specific fuel consumption of the propulsion plant. This relationship is illustrated in Figure II.C.2-21 which is similar to Figure II.C.2-20 and is used in the same manner.

(U) The parametric data shown in Figures II.C.2-4 - II.C.2-8, II.C.2-12, II.C.2-15, II.C.2-22, II.C.2-23, and II.C.2-24 were calculated with specific fuel consumption given as 0.4 lbs/hp-hr indicated on the figures. The various parametric variations described in Figures II.C.2-9, -10, -11, -13, -14, -18, -19, -25, and -26 were inadvertently determined with the value calculated by the module. This is based on current turbine engines and is 0.414 lbs/hp-hr as indicated in these figures. This slight difference will result in a difference in range of only 3 percent and was not felt significant enough to redo these figures.

(U) Fuel consumption in terms of miles per ton of usable fuel is illustrated in Figure II.C.2-22. The same data are

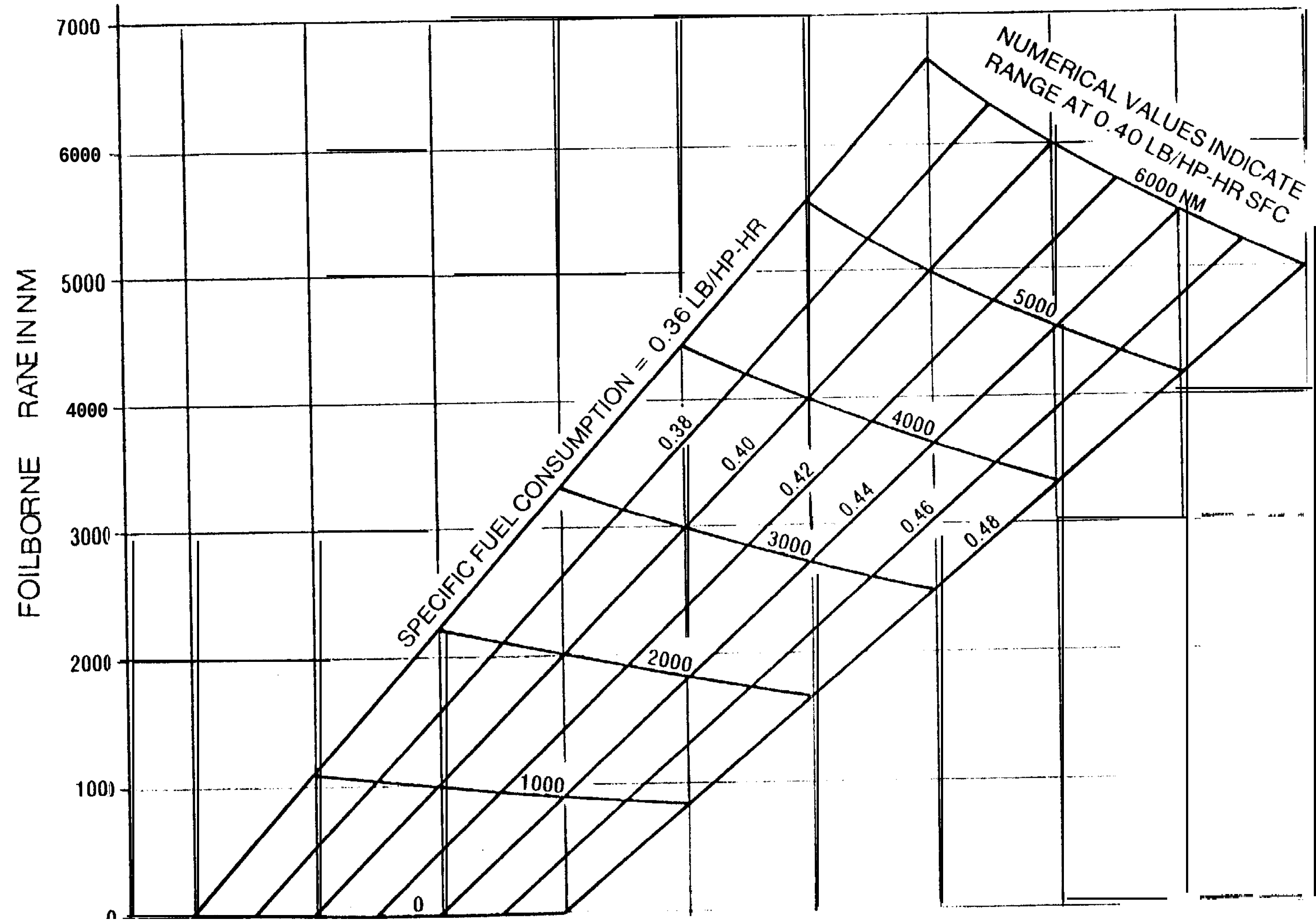

Figure II.C.2-21. FOILBORNE RANGE FOR VARIOUS SFC VALUES COMPARED WITH FOILBORNE RANGES AT .40 SFC

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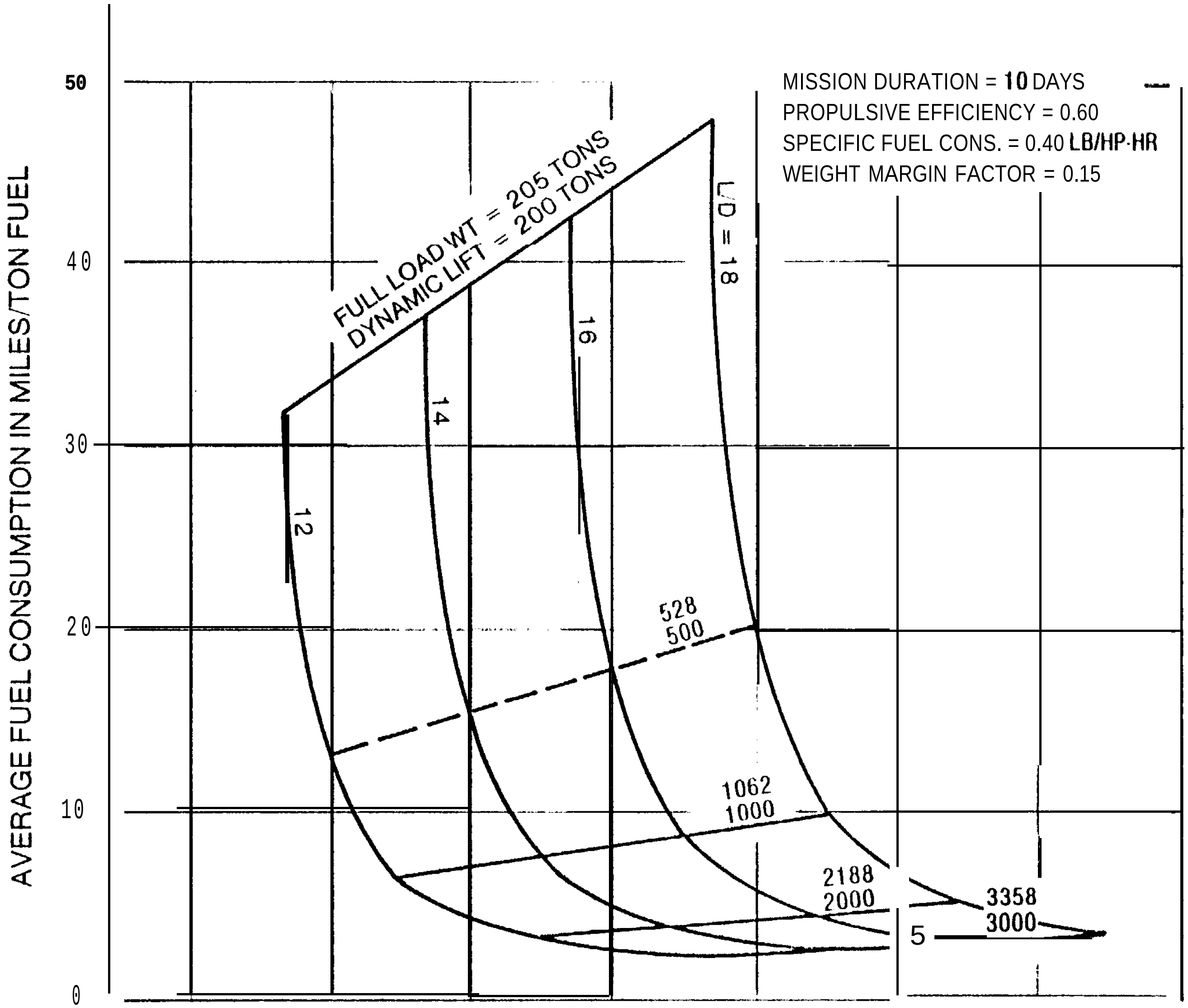

Figure II.C.2-22. FUEL CONSUMPTION FOR AVERAGE PAYLOAD WEIGHTS BY SHIP SIZE AND L/D

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shown in terms of ton-miles per ton of fuel in Figure II.C.2-23. These figures are for average payload weights for each ship weight and L/D.

2.8 FUEL WEIGHT

(U) A major performance trade may be made between the payload and fuel weight. This basic performance interdependency is illustrated throughout the preceding figures. The relationship between usable fuel weight and range for each of the study ships is shown in Figure II.C.2-24. The top of each curve is defined by the zero payload condition. This figure may be used with Figures II.C.2-4 through II.C.2-8 for determining fuel-payload relationships. This trade is not ton-for-ton because of the effects of the weight margin and the unusable fuel calculation.

(U) The usable fuel shown in Figure II.C.2-24 is not all available for propulsive purposes. It is assumed that 2-1/2 percent of the fuel is used for nonpropulsive purposes.

2.9 MISSION DURATION

(U) The two main effects of mission duration are manifested in the requirements for fuel for auxiliary hotel purposes and for crew provisions. As noted previously, 2-1/2 percent of the usable fuel load is considered to be used for hotel purposes. The HANDE Initialization Module does not calculate auxiliary fuel strictly on the basis of the given mission duration. Thus, the auxiliary

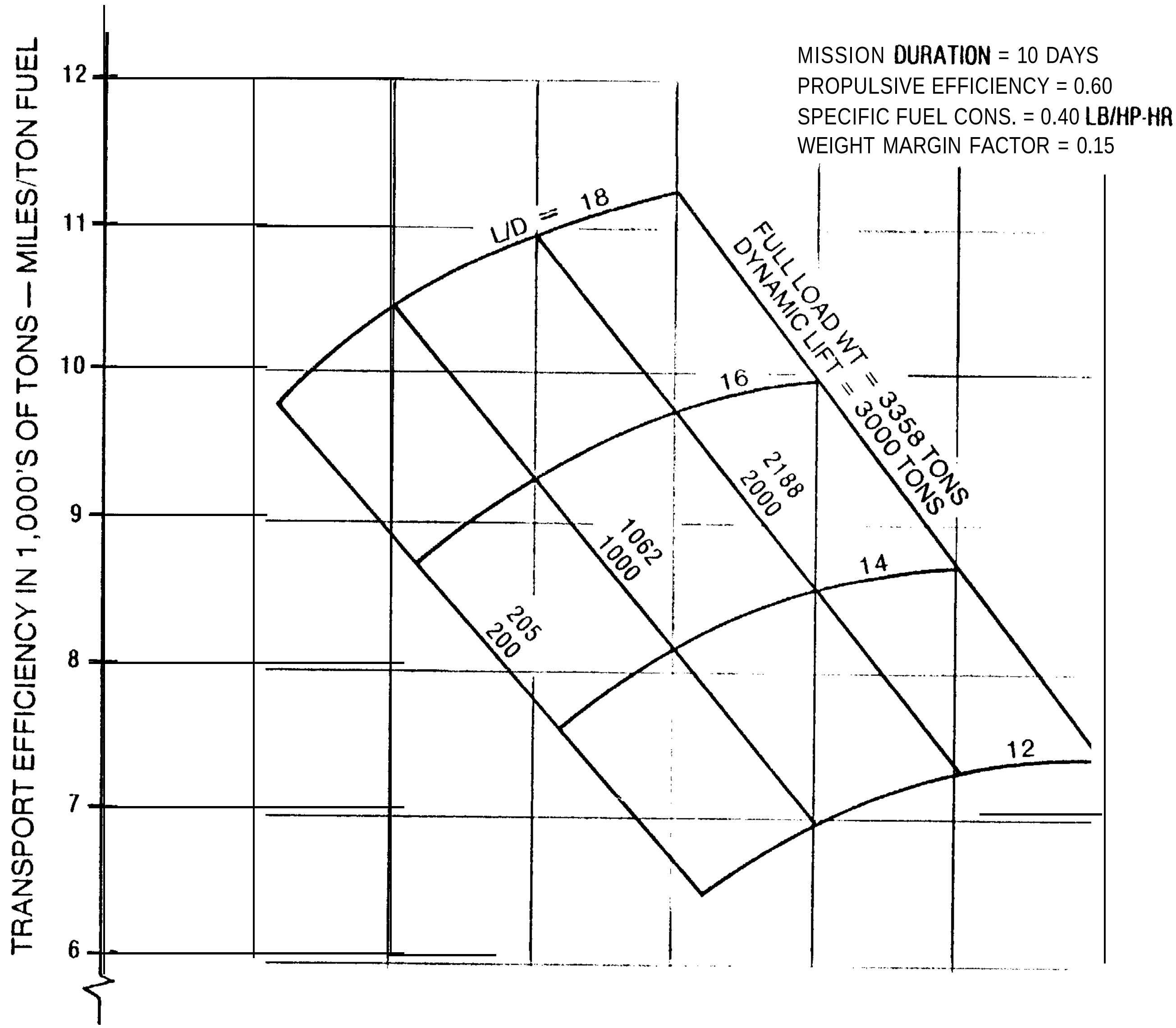

Figure II.C.2-23. TON-MILES PER TON OF FUEL BY SHIP SIZE AND L/D

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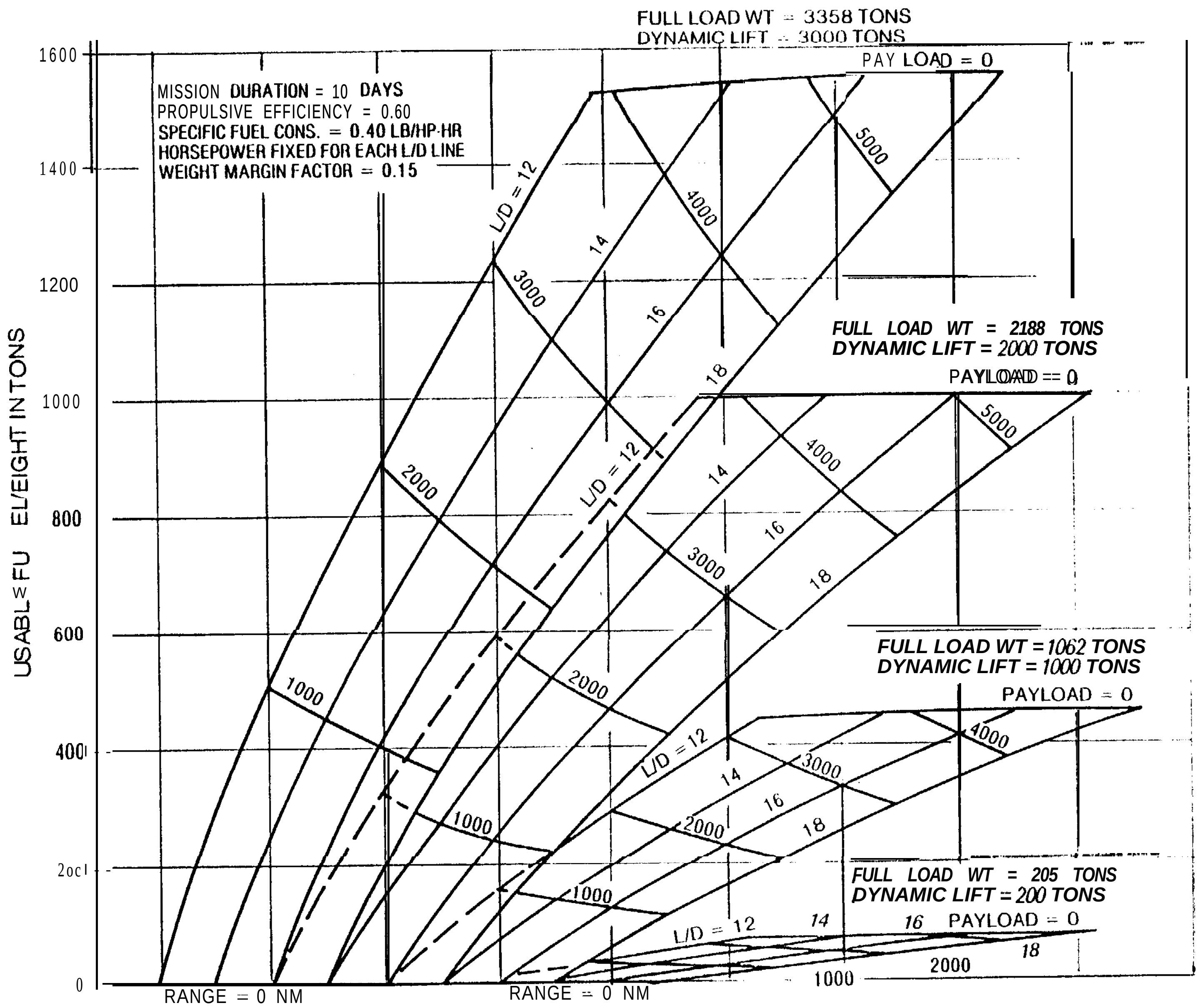

Figure II.C.2-24. USABLE PUEI, WEIGHT AND FOILBORNE RANGE FOR SELECTED SHIP SIZES fuel is taken into account automatically since the fuel load presumable varies with mission duration. However, the effect on performance of allowing differing amounts of fuel for hotel purposes may be determined from Figure II.C.2-24.

(U) The second weight component, crew provisions, is calculated on the basis of crew size, composition, and mission duration. Figure II.C.2-25 presents the payload-range performance for four ships with a specified mission duration of 30 days. Comparison of this figure with Figure II.C.2-10 in which a mission duration of 10 days was specified, reveals only a slight effect caused by the additional provisioning, This may be seen more easily in Figure II.C.2-26 which presents the effect of provisioning on the 2,000-ton configuration. The provision weight for the four configurations is presented in Table II.C.2-1.

Table II.C.2-1. CREW PROVISION WRIGHT

Ship Size, Tons	10 Days Tons	30 Days Tons
205	0.8	2.5
1,062	3.2	9.5
2,188	5.5	16.6
3,358	7.7	23.6

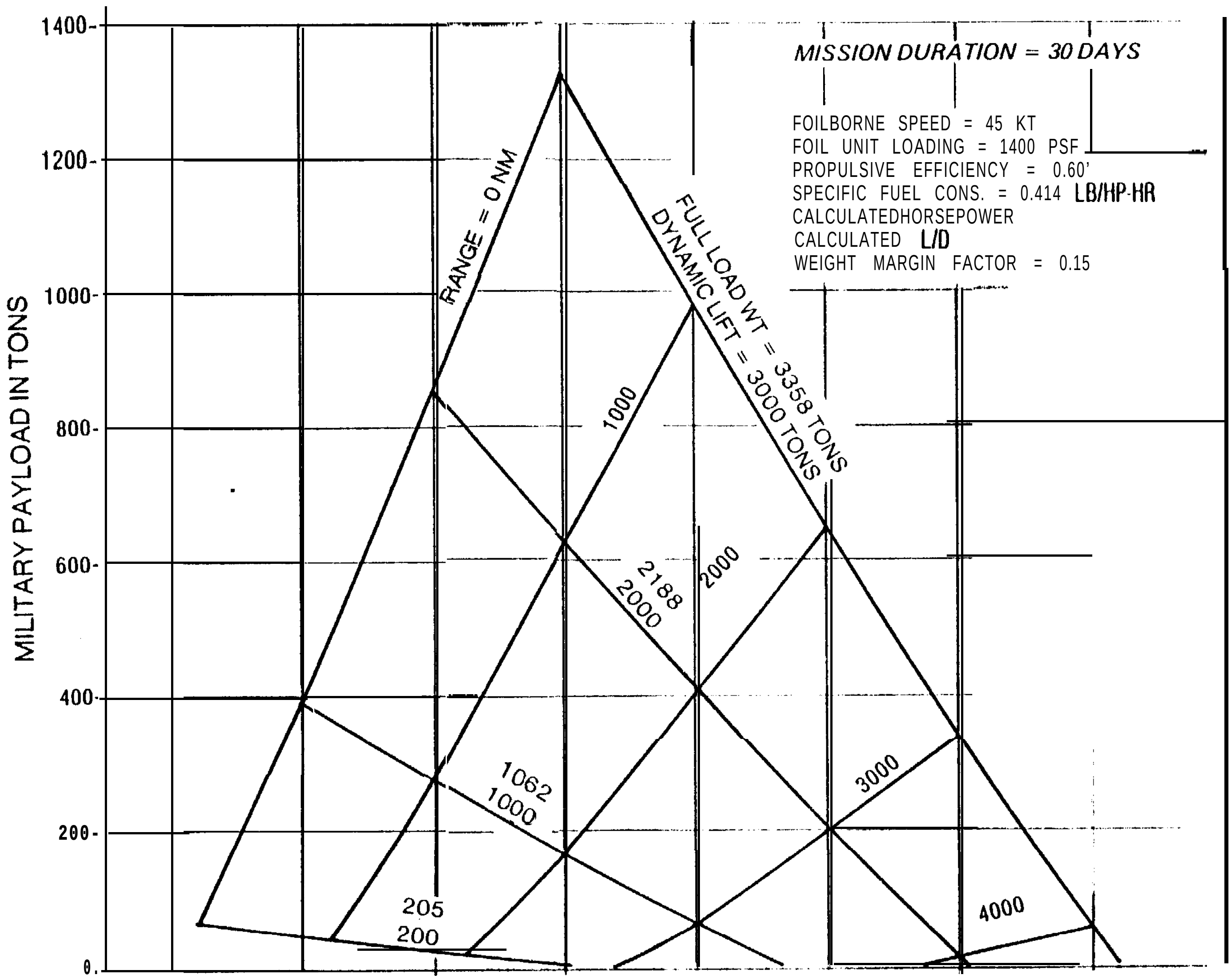

Figure II.C.2- 25. PAYLOAD-RANGE PERFORMANCE AT SPEED BY SHIP SIZE FOR 30-DAY MISSION

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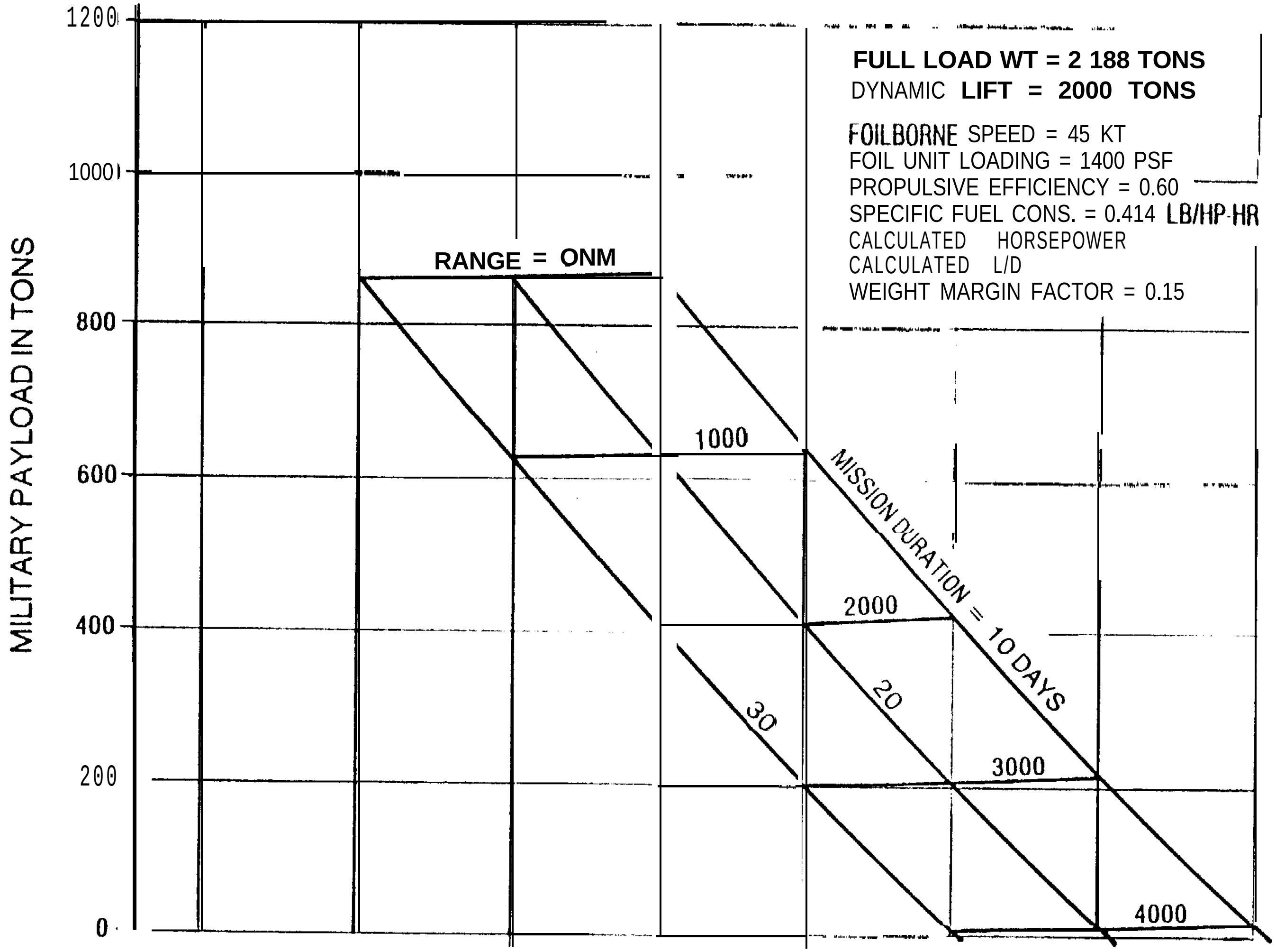

Figure II.C.2-26. PROVISIONINC EFFECT ON RANGE AND MILITARY PAYLOAD

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Section 3

APPROACH AND ASSUMPTIONS

(U) The Initialization Module of the HANDE program was used for calculating the parametric variations of this study. These calculations are based largely on empirical data. Modules of the synthesis section of HANDE were used to calculate hull offsets and to spot check some of the initialization results.

(U) Parametric variations were made about four ship configurations having fixed foilborne dynamic lifts of 200, 1,000, 2,000, and 3,000 tons. These configurations were based on parameter values as defined in following paragraphs.

(U) The payload of each ship configuration was varied and the resulting range and power requirements were determined. Major design variables were then perturbed in sequence to determine individual effects on performance. Various options available in the Initialization Module were used to obtain desired results.

(U) The assumptions made are described below.

3.1 MILITARY PAYLOAD

(U) The military payload is defined as the sum of the 400 and 700 groups of the SWBS plus ammunition. (Section II.D identifies SWBS groups in the figures showing selected specific designs.) However, HANDE excludes the 420 and 430 subgroups from military payload and includes them as part of the lightship weight. Therefore, the entire 400 group was set to zero and the command and surveillance portion of the payload was included in the 700 group, Armament. The effect of this is to reduce lightship weight slightly from that which would be obtained if the fixed portion of payload were divided between the two groups. Thus, the definition of payload results in a range increase of about 2 percent over the standard HANDE range.

(U) The division of the military payload between fixed items and ammunition was taken to be 60 percent fixed, 40 percent expendable as indicated by some local data. The fixed payload items are subject to the weight margin factor; the ammunition is not.

(U) Military payload was the primary independent variable.

3.2 WEIGHT MARGIN FACTOR

(U) The weight margin factor was fixed at 15 percent. Spot checks indicate that a reduction of this margin to 10 percent would increase the range by about 9 to 10 percent.

3.3 NUMBER OF CREW

(U) The number of crew was varied with ship size in accordance with empirical relationships based on data on hand for various hydrofoil ship designs and a patrol frigate, The total number of personnel on board was found to be given by:

$$\text{Total personnel} = 0.25\ (\text{Dynamic lift})^{.817}$$

The number of enlisted men was calculated as:

$$\text{Enlisted men} = .060\ (\text{Dynamic lift})^{.977}$$

(U) The difference between these equations represents the number of officers plus CPOs. Sixty percent of this difference is assumed to be officers. The results of these calculations are given in Figure II.C.2-1.

3.4 HULL CONFIGURATION

(U) The hull offsets for the four configurations are based on PHM hull lines. These basic lines are scaled and warped to meet the ship requirements. The length-to-beam ratio is varied from 5 for smaller ships to 7.5-8 for the larger ships. The linear variation of length-to-beam ratio used is shown in Figure II.C.2-2. As a result of this variation, it was also necessary to vary displacement-length ratio to maintain a constant ship density. Displacement-length ratios were determined by successive approximations. The Hull Geometry Module of the synthesis section of HANDE was used to recalculate the hull offsets to conform to the new length-to-beam and displacement-length ratios. Table II.C.3-1 presents the major configuration parameters. Length-to-depth ratio remained constant at 8.6. The effect of scaling shipsize at a constant displacement-length ratio and constant length-to-beam ratio was checked and appeared to be negligible.

(U) Arrangements were not considered.

Table II.C.3-1. SHIP CONFIGURATION PARAMETERS

Full Load wt. - Tons	Length Ft.	Beam Ft	Disp-Length Ratio*-Ton/Ft^3	Ship Density Lb/Ft^3	Deck House-Total Ship Volume Ratio
205	116	23	130	14.8	.182
1,062	208	36	117	14.7	.183
2,188	274	41	106	15.0	.181
3,358	330	44	93	14.5	.183

* Defined as $\Delta_{FL}/(.01\ L_{PP})^3$

3.5 DECKHOUSE CONFIGURATION

(U) Since deckhouse volume does not scale directly with hull size, iteration through the hull Geometry Module was required to achieve comparable volume ratios for each ship configuration. The ratios of deck house volume to total ship volume used are shown in Table II.C.3-1. The ratio of deckhouse volume to total ship volume for all configurations is slightly over 18 percent.

3.6 FOIL/STRUT CONFIGURATION

(U) The foil/strut configurations for the ships are scaled from PHM foils and struts. An inverted "T" foil forward is assumed to carry one-third of the dynamic lift; the inverted "Pi" foil aft carries two-thirds. A foil unit loading of 1,400 psf was assumed for both foils. No effort was made to match foil/strut configuration with ship size. The foil/strut system buoyancy is determined from an empirical relationship based on ship dynamic lift.

3.7 PROPULSION SYSTEM CONFIGURATION

(U) The foilborne and hullborne propulsion systems are each assumed to be powered by two gas turbine engines. Each turbine drives its own propeller.

(U) The Initialization Module calculates the horsepower required for foilborne operation on the basis of the average lift/drag ratio. This tends to understate the horsepower. Therefore, the basic curves were run with given power levels which were determined iteratively to satisfy the greatest horsepower requirement. For some of the parametric variations, the average power level was used.

(U) Takeoff performance is not considered. It is assumed that the intermittent power rating of the engine required for cruise will meet the takeoff requirement.

3.8 MISCELLANEOUS

(U) Hullborne speed was fixed at 18 knots.

(U) A gas turbine power plant was assumed for the 400 Hz electrical plant. Use of a diesel would result in a range degradation on the order of 8 percent for the larger ships. For the smallest ships the effect may be as high as 20 percent.

(U) Two and one-half percent of the usable fuel is assumed to be consumed for hotel purposes.

3.9 SUMMARY OF RESULTS

(U) By using Figures II.C.2-8, II.C.2-12, II.C.2-15, II.C.2-17, II.C.2-20, II.C.2-24, and II.C.2-26, it is possible to make reasonable estimates of the major interdependent variables of a hydrofoil ship.

Section 4

SUPERCAVITATING HYDROFOIL SHIPS

(U) This section will summarize parametric studies on high speed (60 to 90 knot) hydrofoil ships in the 100- to 300-ton size range. The basis for these studies was Reference II.C.4-1 and the results of the NAVMAT direct laboratory-funded program to develop a lift system for high speed hydrofoil ships which is summarized in Reference II.C.4-2. The foil-lift-to-drag ratios and propulsive coefficients used in Reference II.C.4-1 were optimistic and represent the best that could be achieved with highly polished, thin foils and propeller blades. To be more conservative and realistic the propulsive power of Reference II.C.4-1 has been increased 20 percent to reflect propulsive coefficients that have been achieved in tests.

(U) The lift-to-drag ratios used in Reference II.C.4-1 represent the optimum which could be achieved after considerable development. To give the reader a better idea of the demonstrated state-of-the-art, the performance using the TAP-2 foil system which was developed and tested in Reference II.C.4-2, is shown on all graphical data presented herein.

(U) Finally, the performance of a 245-ton, 70-knot derivative of the PHM is presented.

4.1 SHIPS STUDIED

(U) Table II.C.4-1 lists the principle characteristics of the family of ships considered. Figures II.C.4-1, II.C.4-2, and

Table II.C.4-1. CHARACTERISTICS SHEET FOR VARYING DISPLACEMENTS AND SPEEDS

	100 TONS 80 KNOTS	200 TONS 60 KNOTS	200 TONS 70 KNOTS	200 TONS 80 KNOTS	200 TONS 90 KNOTS	300 TONS 80 KNOTS
PRINCIPLE DIMENSIONS						
LOA (FT)	100	135	135	135	135	150
LBP (FT)	9[illegible]	1[illegible]	120	120	12[illegible]	135
BOA (HULL) (FT)	24	19.5	29.5	29.5	29.5	33.0
HULL DEPTH (MIDSHIP) (FT)	12	14.5	14.5	14.5	14.5	16.1
DRAFT (FT) FOILS UP	4.75	5.75	5.75	5.75	5.75	6.67
FOILS DOWN	18.36	22.89	22.33	22.24	22.37	25.23
FLYING	7.85	12.05	11.10	10.73	10.65	12.80
FOIL						
NUMBER	3	3	3	3	3	3
AREA (FT^2)	34.2	121.2	89.1	68.3	53.8	102.7
ASPECT RATIO (AR)	3.59*	[illegible]	3.35	3.59	3.68	3.59
DESIGN C_L	.12	.12	.12	.12	.12	.12
FLAP AREA (FT^2)	17.1	60.6	44.6	34.15	26.9	51.4
SPAN (FT)	11.1	21.7	17.30	15.62	14.10	18.85
FOIL LOADING (PSF)	2185	1230	1680	2185	2770	2185
STRUTS						
LENGTH (FT)	16.86	19.39	19.33	18.74	18.37	20.56
CHORD (FT) HULL	6.97	10.76	8.70	8.23	10.67	10.88
FOIL	3.14	5.66	4.28	3.98	5.04	5.45
THICKNESS TO CHORD RATIO	.14	.13	.14	.15	.11	.14
AFTER PODS						
LENGTH (FT)	9.2	8.36	9.39	12.29	15.55	14.3
MAX DIAMETER (FT)	1.91	2.55	2.33	2.55	2.750	2.97
BASE DIAMETER (FT)	1.35	1.80	1.65	1.8	1.95	2.1

	100 TONS 80 KNOTS	200 TONS 60 KNOTS	200 TONS 70 KNOTS	200 TONS 80KNOTS	200 TONS 90 KNOTS	300 TONS 80 KNOTS
MACHINERY						
INSTALLED POWER	13,000	15,000	20,000	25,000	35,000	35,000
HULLBORNE CRUISE HP	400 @ [illegible] KTO	800 @ 11.6 KTO	800 @ 11.6 KTO	800 @ 11.6 KTO	800 @ 11.6 KTO	1200@ [illegible] KTO
TRANSMISSION SYSTEM	Z-Drive Ratio 5:1	Z-Drive Ratio 5:1	Z-Drive Ratio 5:1	Z-Drive Ratio 5:1	Z-Drive Ratio 5:1	Z-Drive Ratio 5:1
PROPULSION						
NO. OF PROPELLERS	2	2	2	2	2	2
PROPELLER DIAMETER (FT)	4.5	6.0	5.5	6.0	6.5	7.0
BAR	.35	.35	.35	.35	.35	.35
NO. OF BLADES	4	4	4	4	4	4
DESIGN RPM	1,200	800	1,000	800	1,000	800
HUB DIAMETER (FT)	1.35	1.80	1.65	1.80	1.95	2.10

WEIGHT SUMMARY	100 TONS 80 KNOTS		200 TONS 60 KNOTS		200 TONS 70 KNOTS		200 TONS 80 KNOTS		200 TONS 90 KNOTS		300 TONS 80 KNOTS	
SWBS GROUP	LONG TONS	*%	LONG TONS	%	LONG TONS	%	LONG TONS	%	LONG TONS	%	LONG TONS	%
100 HULL STRUCTURE	22.4	22.4	36.5	18.25	38.7	19.85	41.1	20.55	43.2	21.6	60.5	20.2
200 PROPULSION	14.7	14.7	18.3	9.15	21.7	10.85	25.4	12.7	34.4	17.2	37.1	12.4
300 ELECTRIC PLANT	2.[illegible]	2.[illegible]	4.8	2.4	4.8	2.4	4.8	2.4	4.8	2.4	6.8	2.26
400 COMMAND & SURVEILLANCE	0.8	0.8	1.8	0.9	1.8	0.9	1.8	0.9	1.8	0.9	2.3	0.77
500 AUX-MACHINERY	6.1	6.1	11.7	5.85	11.7	5.85	11.7	5.85	11.7	5.85	17.0	5.66
567 LIFT SYSTEMS	10.8	10.8	29.2	14.6	27.7	13.85	23.8	11.9	22.7	11.35	36.8	12.25
600 OUTFIT & FURNISHINGS	5.1	5.1	9.7	4.85	9.7	4.85	9.7	4.85	9.7	4.85	14.4	4.8
MARGIN	3.1	3.1	5.6	2.8	5.8	2.9	5.9	2.95	6.4	3.2	8.7	2.9
LIGHT SHIP	65.[illegible]	65.[illegible]	117.6	58.8	121.9	60.95	124.2	62.1	134.7	67.35	183.6	61.0
CREW & SUPPLIES	2.6	2.6	2.6	1.3	2.6	1.3	2.6	1.3	2.6	1.3	2.6	.87
PAYLOAD & FUEL	32.[illegible]	32.[illegible]	79.8	39.9	75.5	37.75	73.2	36.6	62.7	31.35	113.8	37.8
LOAD CONDITION DISPL'MT.	100	100	200	100	200	100	200	100	200	100	300	100

* % OF LOAD CONDITION DISPL'MT.

HYDRONAUTICS, INC

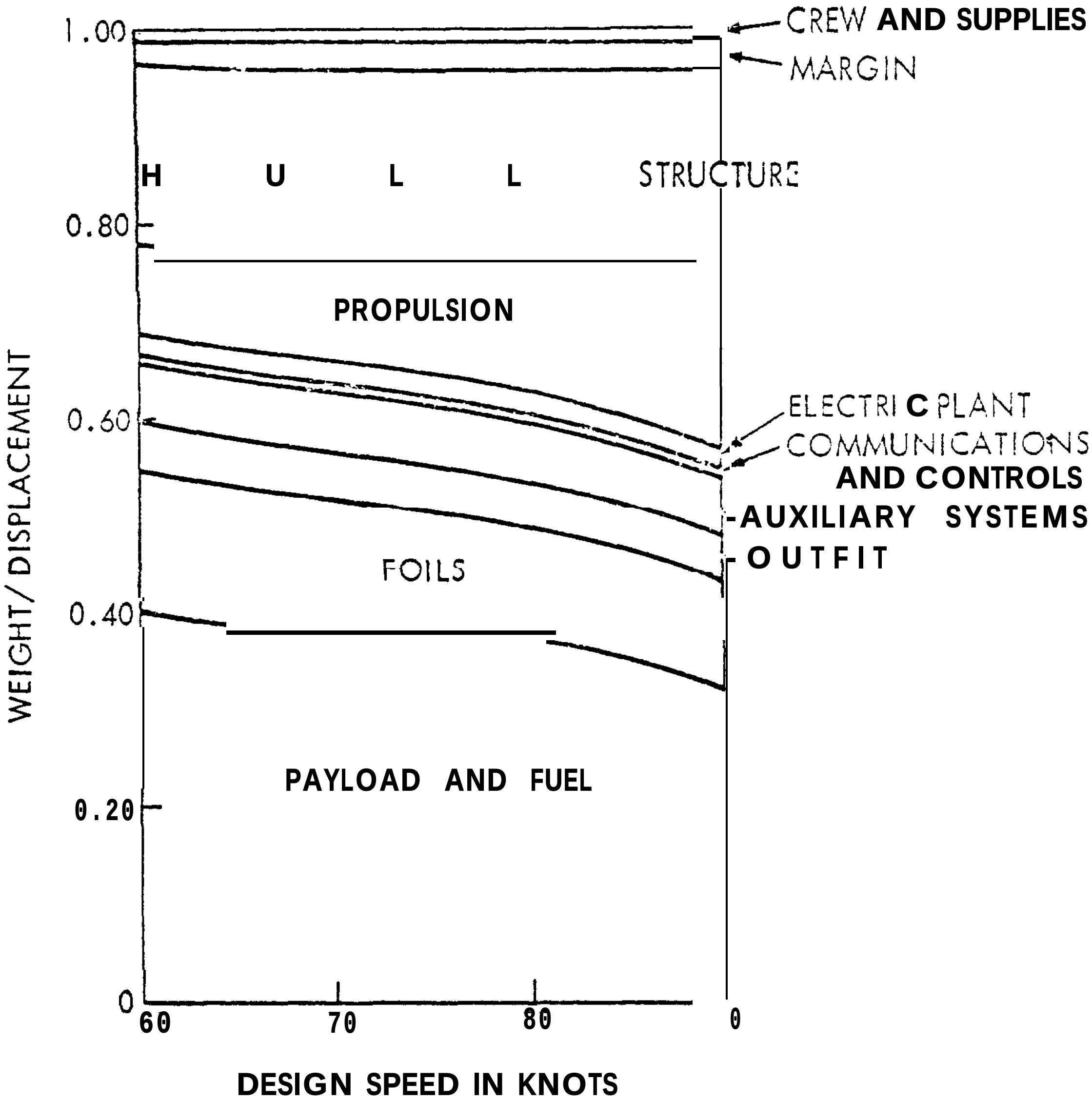

Figure II.C.4-1 WEIGHT DISTRIBUTION FOR 100-TON DFH

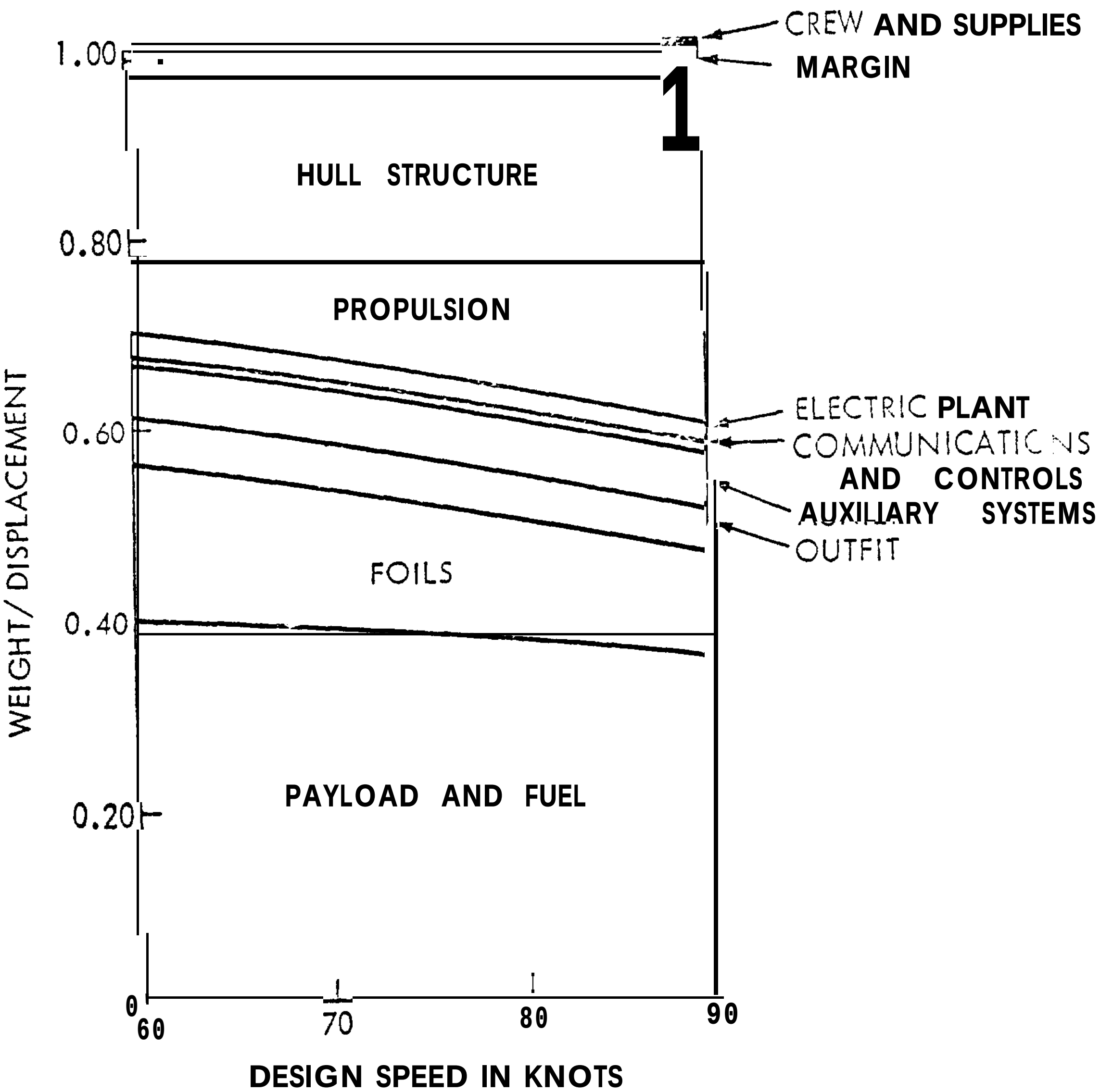

Figure II.C.4-2. WEIGHT DISTRIBUTION FOR 200-TON DFH

II.C.4-3 graphically summarize the weight data of the family of ships studied. Figure II.C.4-4 shows the outboard profile, plan-view, and rear view of the 200-ton, 80-kn ship.

4.2 RESULTS OF STUDIES

(U) The overall craft lift-to-drag ratio for difference design speeds and displacements based on Reference II.C.4-1 is shown in Figure II.C.4-5. The overall lift-to-drag ratio for a 200-ton ship using a TAR-2 foil system with 3-ft diameter propulsion pods mounted 3 ft below the rear foils is shown to demonstrate what has been achieved to date.

(U) Figure II.C.4-6 shows the design speed power requirements in calm water for different speeds and displacements, based on Reference II.C.4-1 with the power increased by 20 percent to reflect a propulsive coefficient of 0.6 at design speed. The power for a 200-ton ship using a TAR-2 foil system is again shown for reference.

(U) Figure II.C.4-7, using the data from Figure II.C.4-6, shows the range of full load weight of a 200-ton ship with a 20-ton payload at different design speeds for different sea states. Figure II.C.4-8 shows the range versus full load weight for various size ships at 80 knots with a payload fraction of 10 percent. All ranges are based on conservative engine fuel economics as shown in Table II.C.4-2. If fuel burnoff is taken into account, the ranges would be increased.

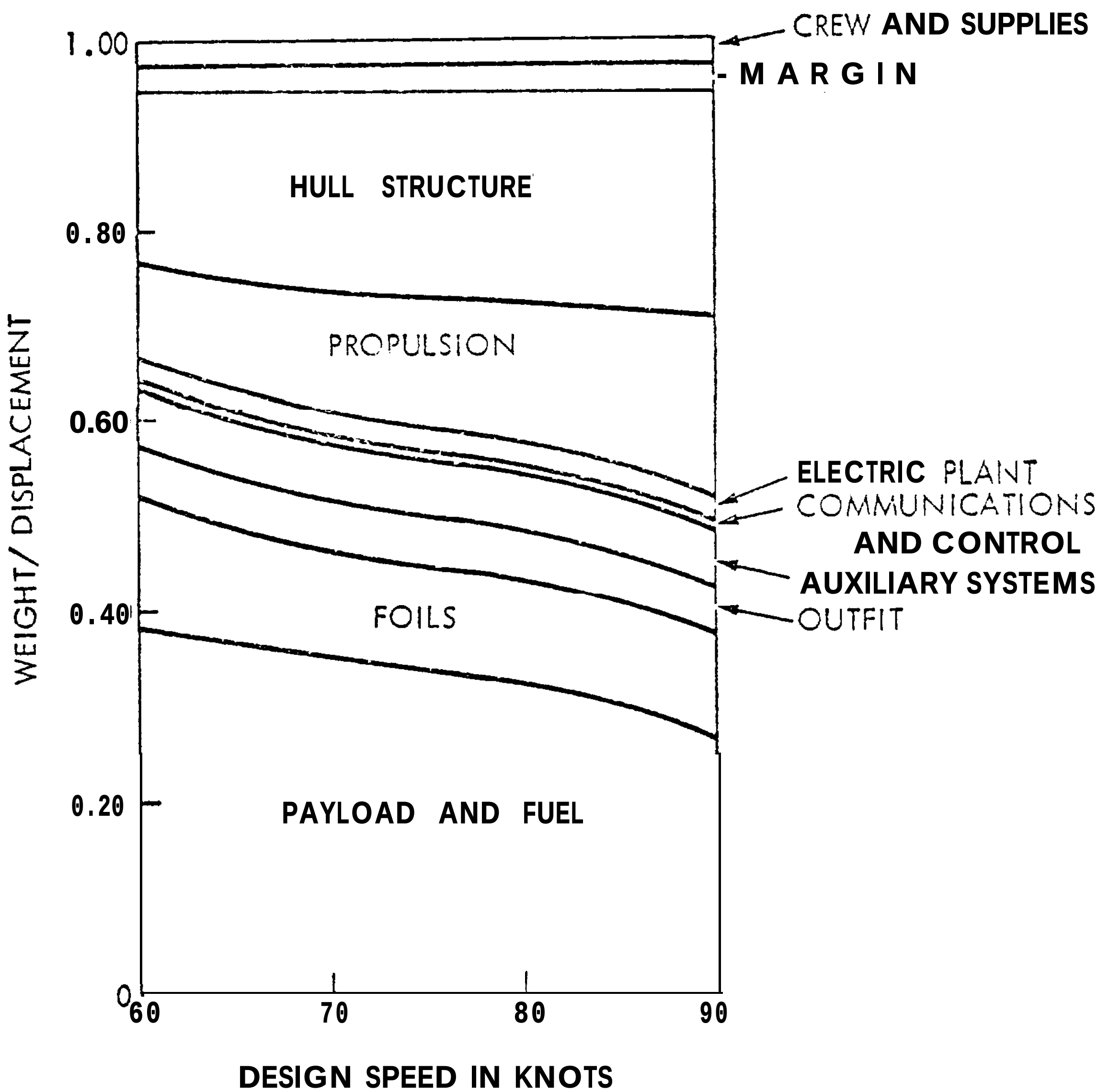

Figure II.C.4-3. WEIGHT DISTRIBUTION FOR 300-TON DFH

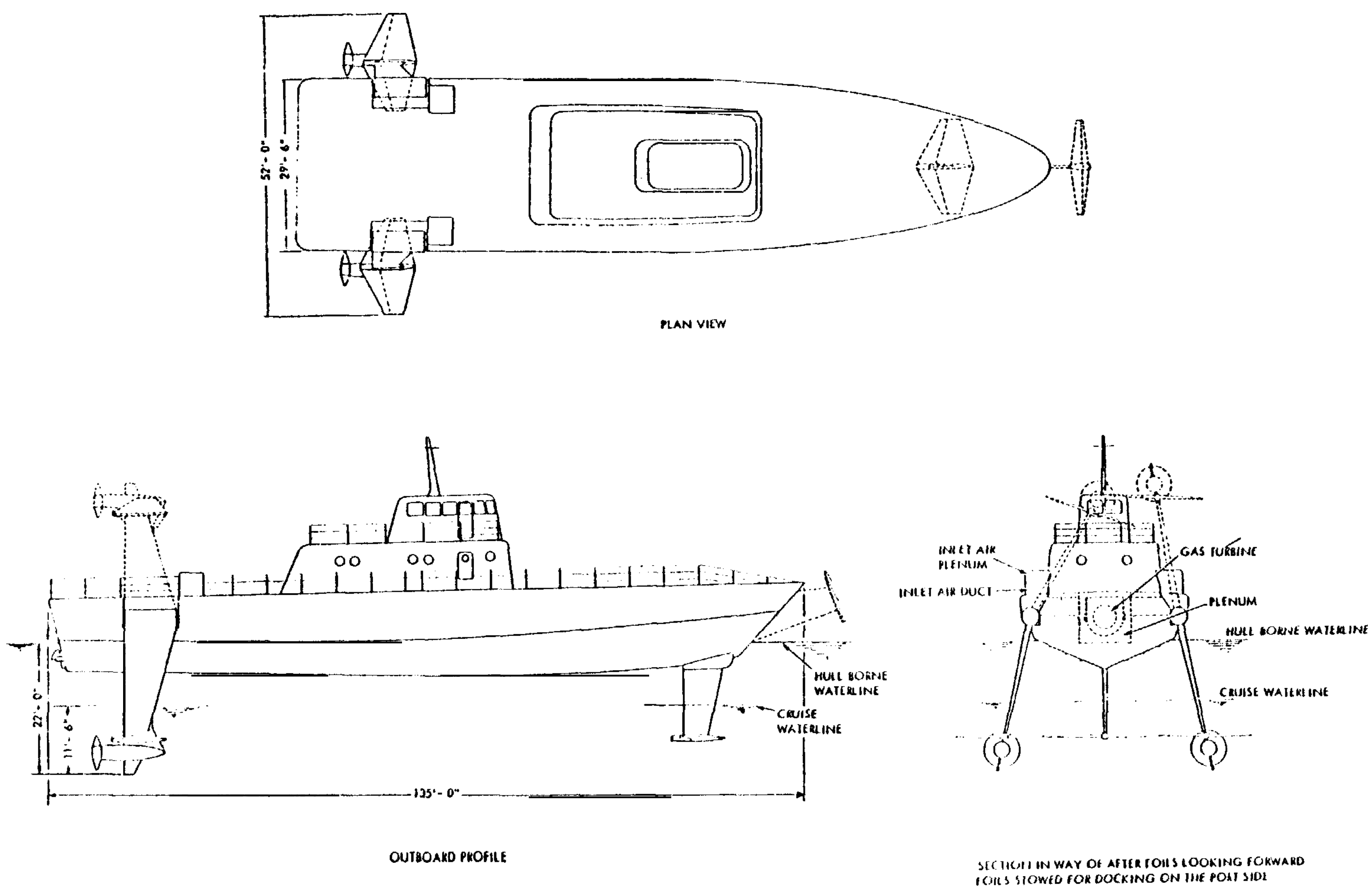

Figure II.C.4-4. DFH ARRANGEMENT DRAWING

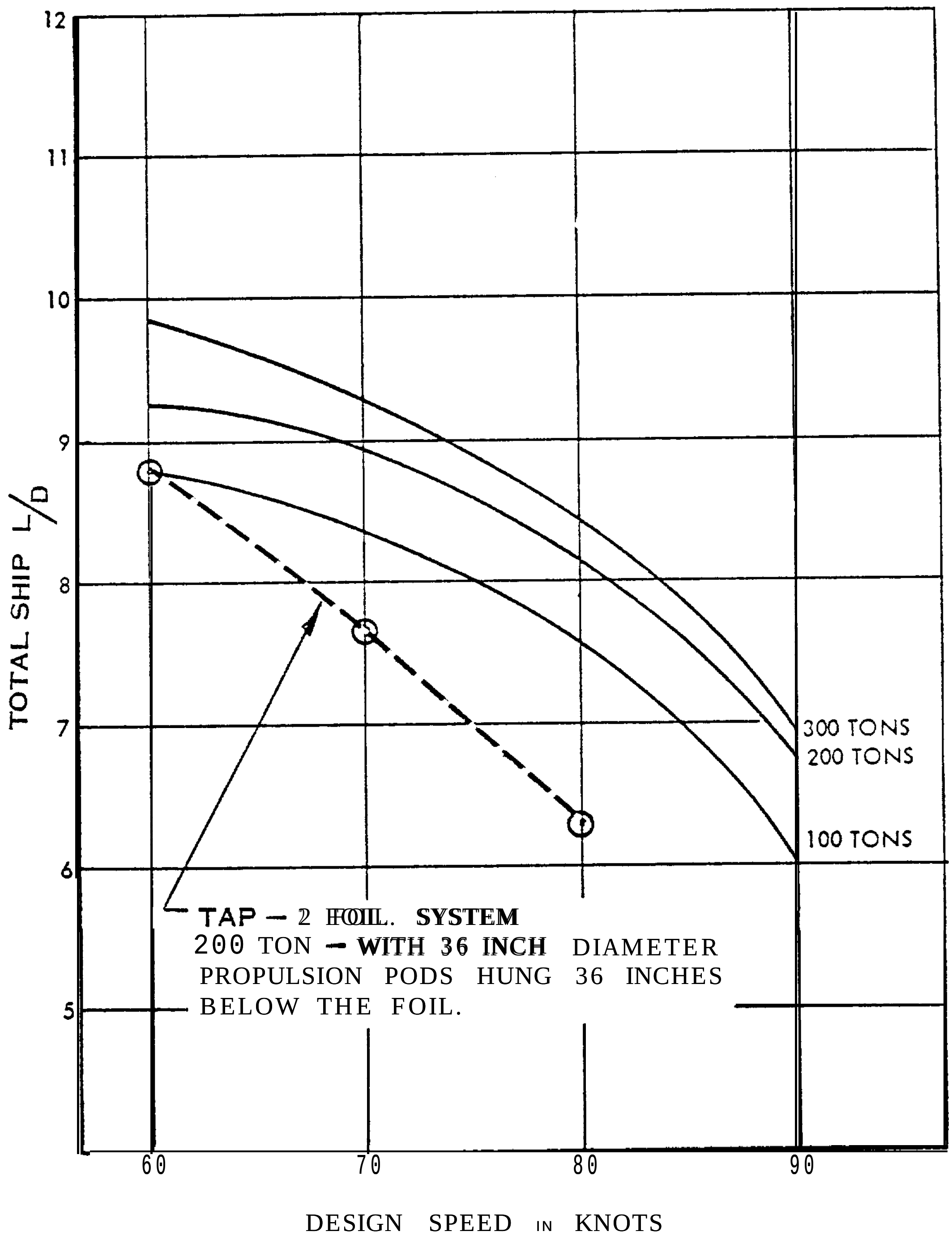

Figure II.C.4-5. CRUISE LIFT-DRAG RATIO VERSUS DESIGN SPEED AND DISPLACEMENT

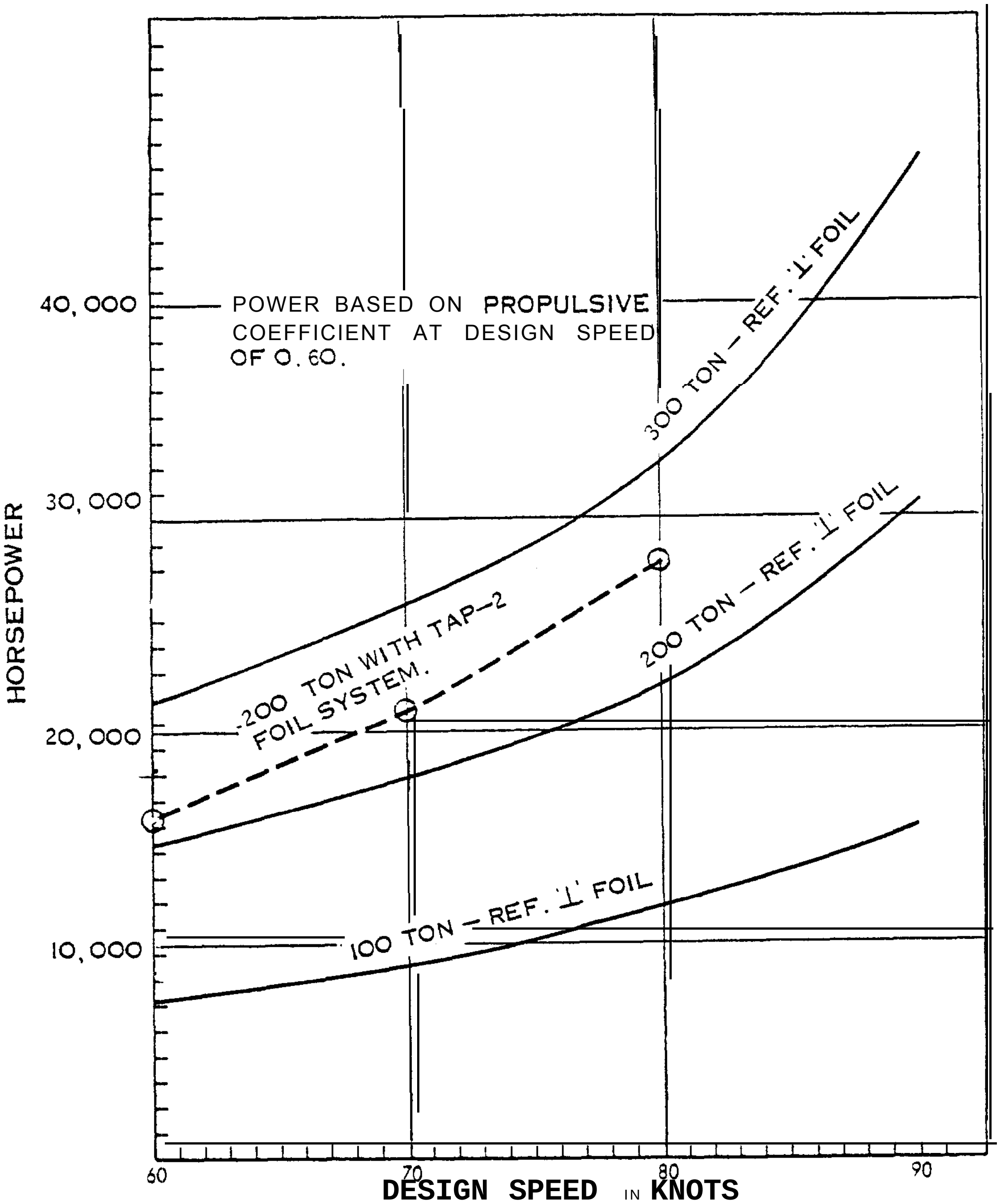

Figure II.C.4-6. HORSEPOWEX VERSUS DESIGN SPEED

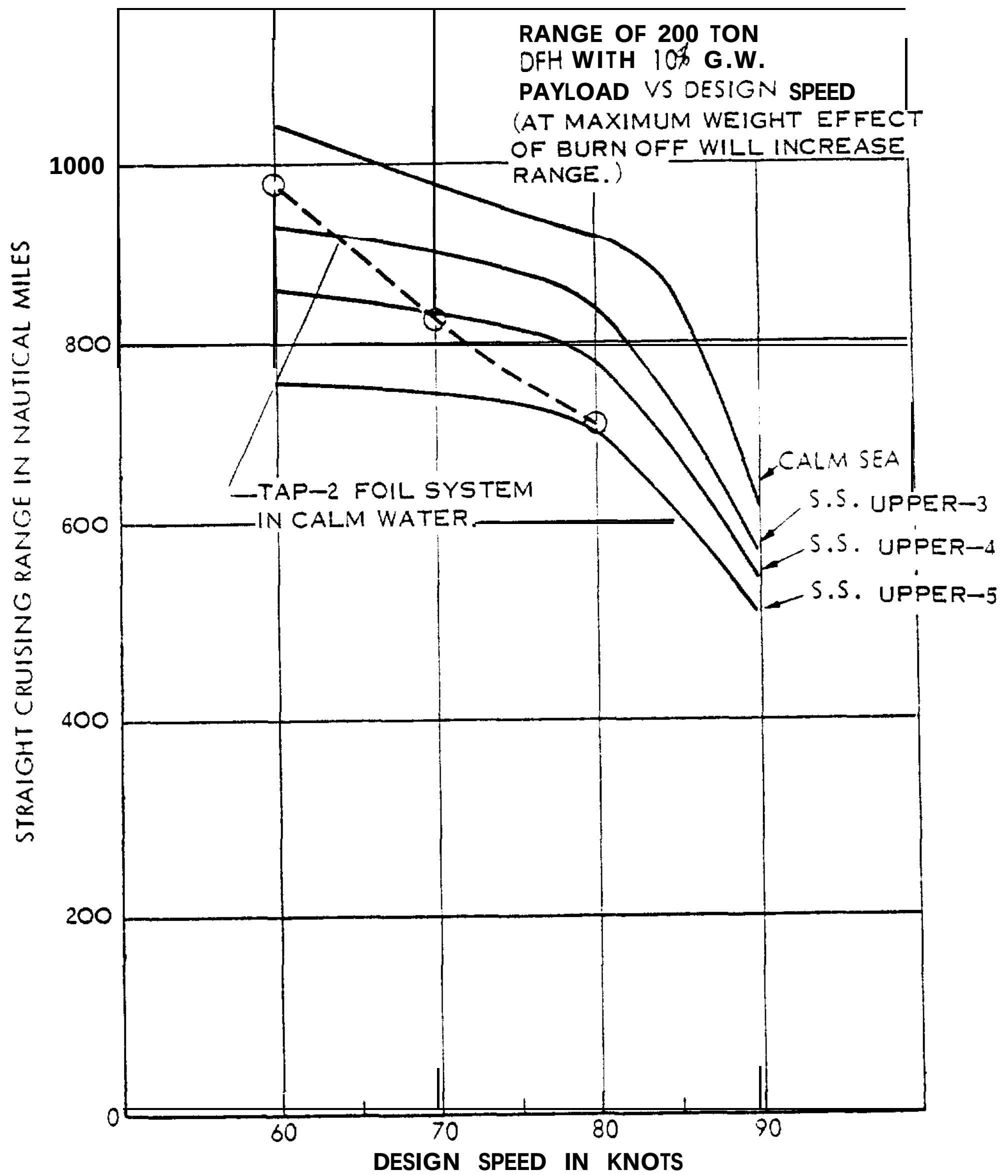

Figure II.C.4-7. RANGE WITH A 10 PERCENT PAYLOAD VERSUS DESIGN SPEED AND SEA STATE

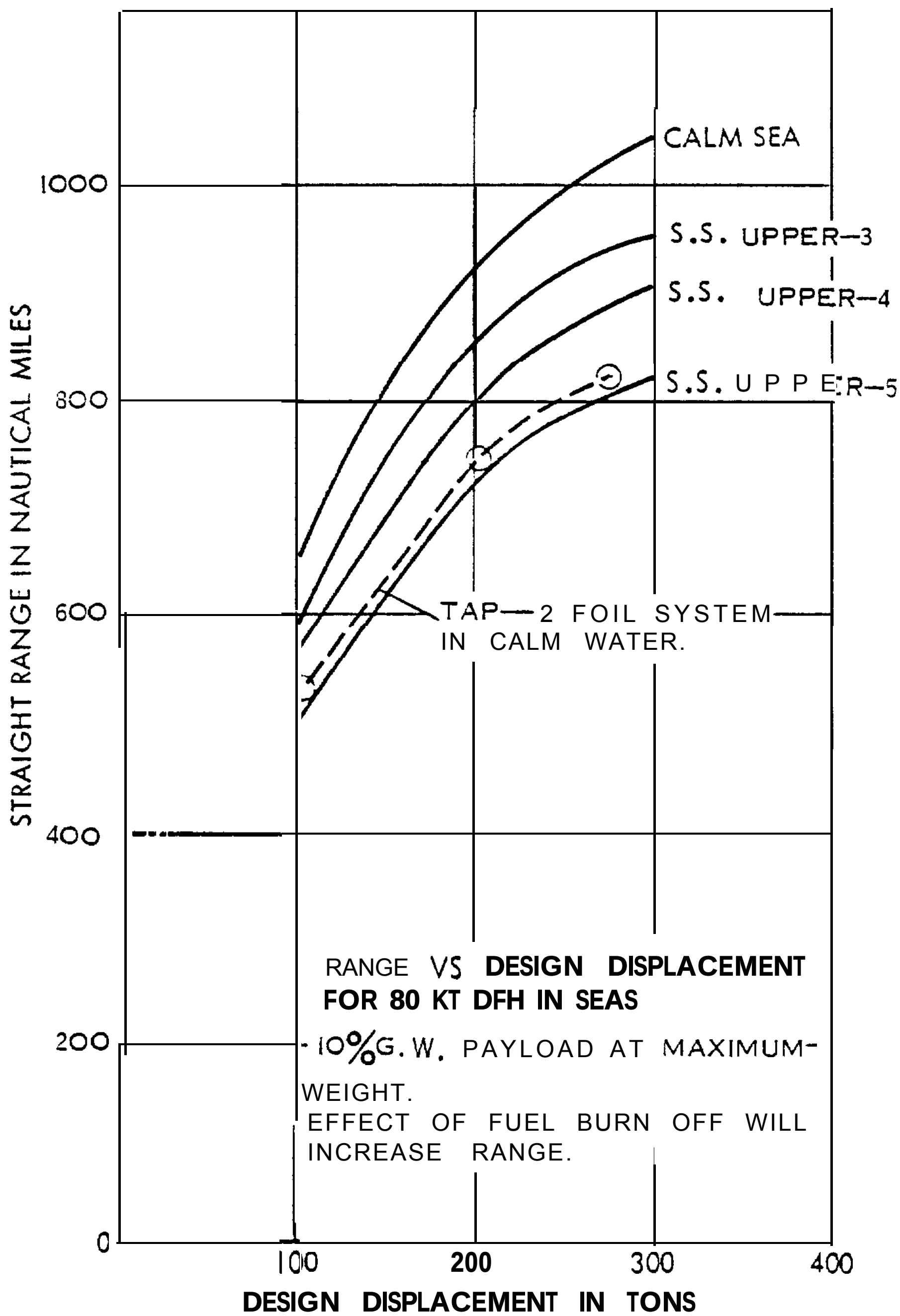

Figure II.C.4-8. RANGE WITH A 10 PERCENT PAYLOAD VERSUS DISPLACEMENT AND SEA STATE

Table II.C.4-2. TYPICAL SPECIFIC FUEL CONSUMPTION RELATED TO CRUISE POWER

POWER	SFC
5,000 hp	0.52 lbs/hp-hr
10,000 hp	0.52 lbs/hp-hr
15,000 hp	0.52 lbs/hp-hr
20,000 hp	0.47 lbs/hp-hr
30,000 hp	0.44 lbs/hp-hr
40,000 hp	0.44 lbs/hp-hr

(U) In Figure II.C.4-9, sensitivity of range to changes in pertinent parameters is given so that data can be corrected for variations in input parameters.

(U) Finally the above data were used to determine the performance of a propeller driven 245-ton derivative of the PKM in which the foil system is replaced with a supercavitating foil design as per Reference II.C.4-1 and with a TAP-2 foil design as per Reference II.C.4-2. The fuel tankage capacity of the ship was increased by 12 tons to a total of 64 tons and the weapon system weight was set at 24 tons.

(U) The speed-power relationship of a high speed PHM derivative is shown in Figure II.C.4-10. This figure demonstrates the high efficiency of the TAP-2 foil at speeds below 50 knots compared to a supercavitating foil.

(U) The range of these derivative PHMs (based on the M-2500 engine fuel consumption) as a function of speed and payload is shown in Figure II.C.4-11.

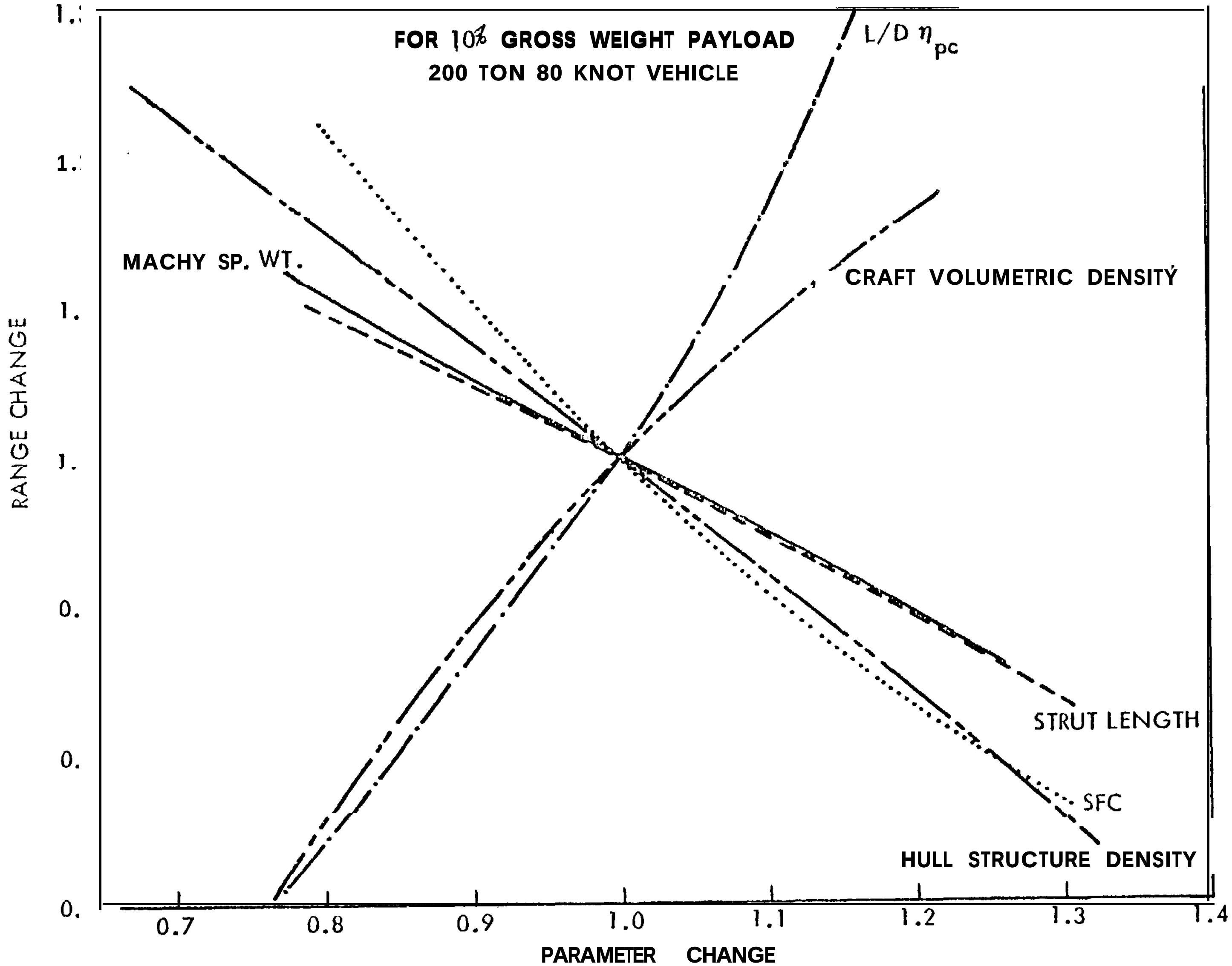

Figure II.C.4-9. PERCENT CHANGE IN RANCE VERSUS CHANGE IN PARAMETER

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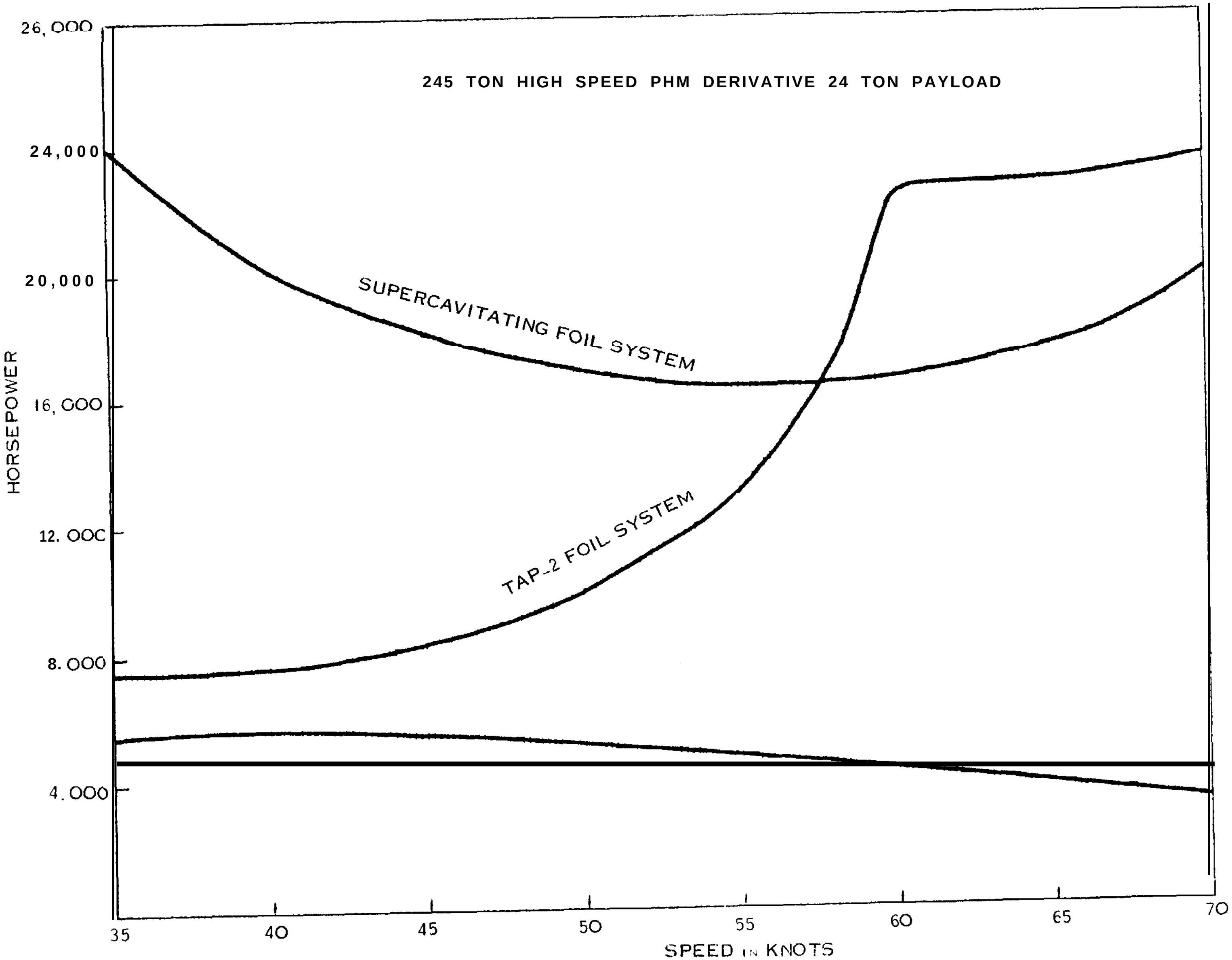

Figure II.C.4-10. 245-TON HIGH SPEED PHM DERIVATIVE, 24-TON PAYLOAD

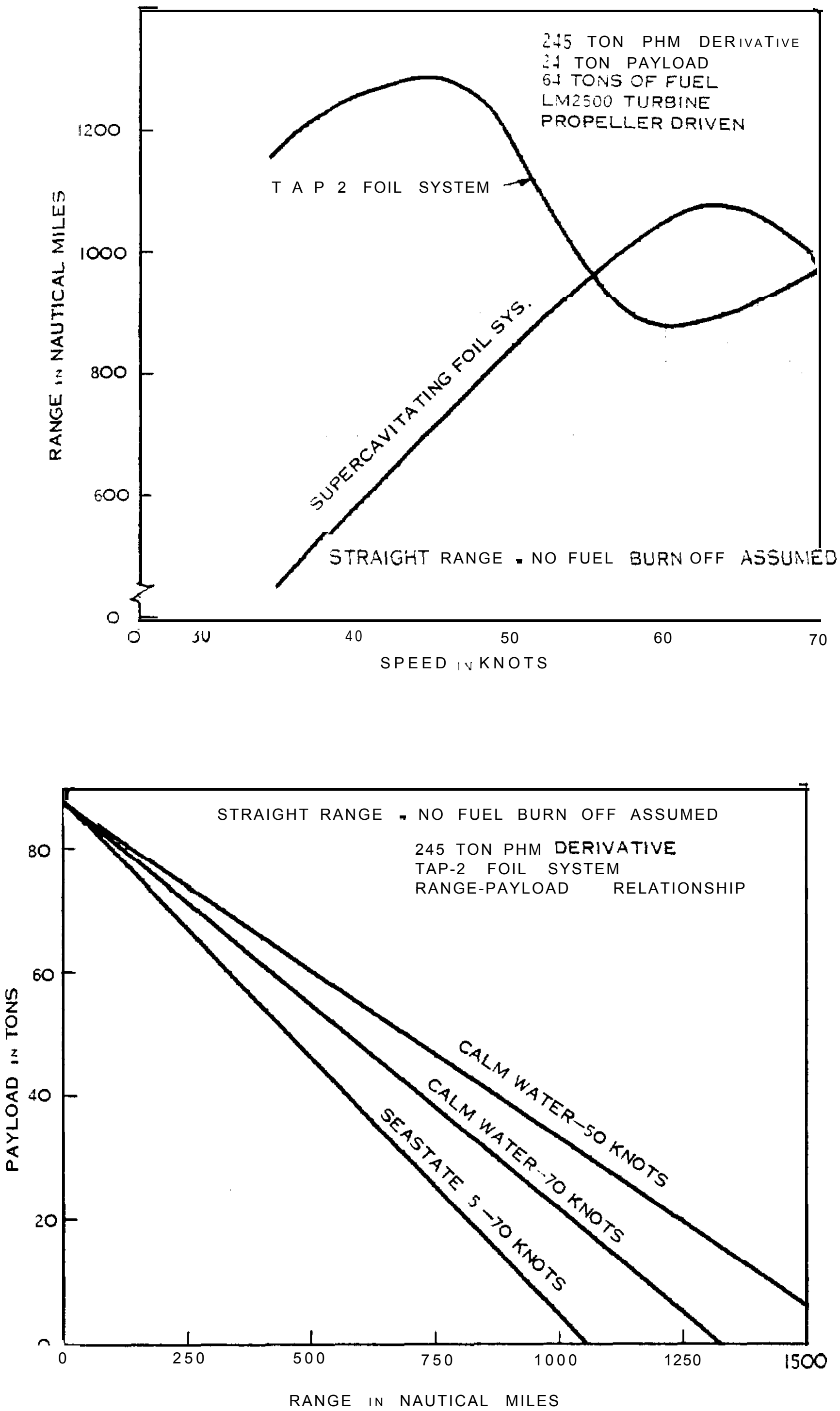

Figure II.C.4-11. RANGE OF DERIVATIVE PHMs AS A FUNCTION OF SPEED AND PAYLOAD

REFERENCES

II.C.1-1 "Hydrofoil Analysis and Design Program (HANDE)," A.J. Brennan, J.D. Burroughs, and W.C. Hurt, The Boeing Company Document Number D221-51302-1, AD-A005 487, 1974,

II.C.1-2 "Hydrofoil Analysis and Design Program (HANDE)," A.J. Brennan, J.D. Burroughs, and W.C. Hurt, The Boeing Company Document Number D321-51303-1, AD-A005 488, 1974.

II.C.4-1 "A Parametric Analysis of Fast Hydrofoil Configurations," Eugene Miller, Jr., Ronald Altmann, Gary Paquette and Horton Lain. Hydronautics, Incorporated Technical Report 7224-1, November 1972.

II.C.4-2 "A Summary Report of Major Studies under the Program 'High Speed Hydrofoil Struts and Foils"' by Raymond Wermter and Young T. Shen. DTNSRDC Rpt 4779, December 1975.

II. STATUS OF VEHICLE TECHNOLOGY

D. SPECIFIC DESIGNS

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II. STATUS OF VEHICLE TECHNOLOGY

D. SPECIFIC DESIGNS

1.1 INTRODUCTION

(U) The specific designs presented herein are those hydrofoil ships which have been built and operated and designs based on conceptual studies conducted by both the U.S. Navy and indusrry.

(U) The design data are presented in a manner and accuracy so as to provide a quick, general, and broad comparison of each specific design. If a detailed or in-depth analysis is required, data should be obtained from the references listed in this section, and from Chapters II and III of this document.

1.2 SPECIFIC DESIGNS

(U) The specific designs are computed beginning with the operational hydrofoil ships and concluding with the designs provided by The Boeing Company and Grumman Aerospace Corp. For each hydrofoil ship, subsystem and predicted performance characteristics are presented. The foil geometry is also given for those hydrofoil ships which have been built and tested.

NOTE: To determine the Security Classification of data, see the following Security instructions:

1. PHM-1 - NAVSEA INST 5510.658 dated 12 Mar 1973
2. Others - NAVSEA INST 5510.49A dated 13 Dec 1973

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SPECIFIC DESIGNS SHIP CHARACTERISTICS

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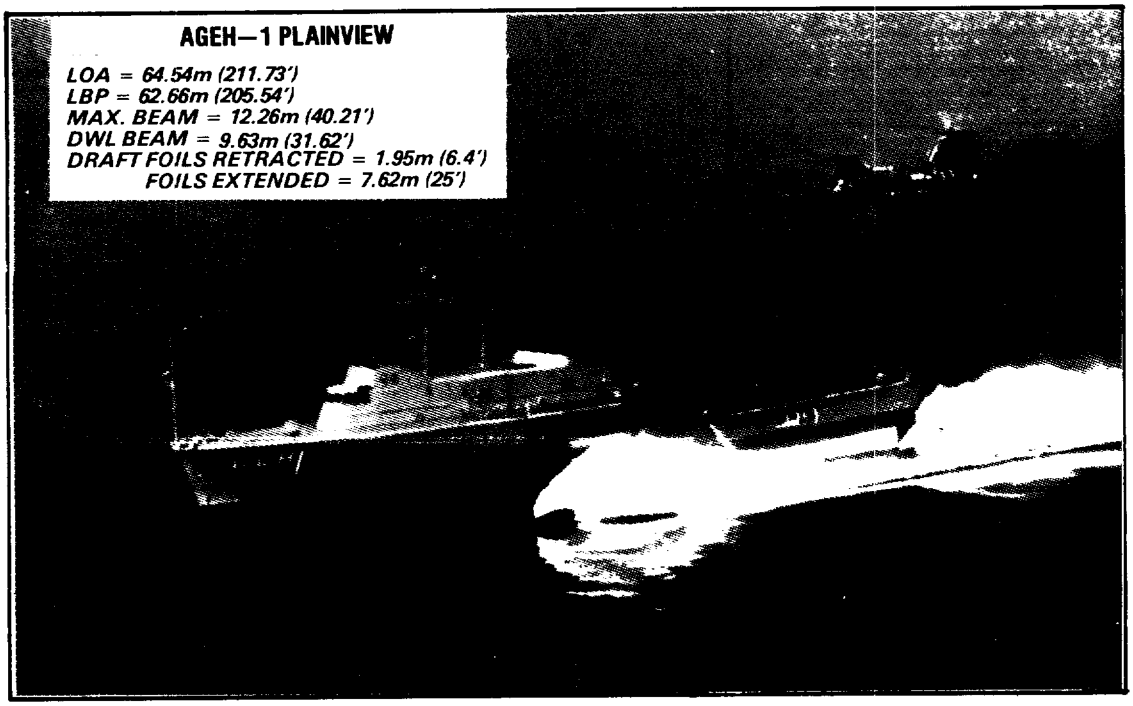


SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY	METRIC TONS	% F.L
SWBS 100 HULL STRUCTURE	92.17	26.53
200 PROPULSION SYSTEMS	43.06	13.25
300 ELECTRIC PLANT	9.35	2.66
(1) 400 COMMAND & SURVEILLANCE	14.63	4.50
500 AUXILIARY SYSTEMS	18.13	5.56
567 LIFT SYSTEMS	46.42	14.69
600 OUTFIT 6 FURNISHINGS	10.97	3.36
(1) 700 WEAPONS SYSTEMS	2.13	.66
M10 CONTRACTOR CONTROLLED	—	—
M21-M23 CONTRACT DESIGN, MOD, & GFM	—	—
MARGINS	—	—
DELIVERED LIGHTSHIP	239.48	73.66
NORMAL LOADS:		
(2) F10 SHIPS FORCE	2.44	.75
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	.41	.13
(1) F21 SHIP AMMUNITION	1.93	.59
(2) F30 STORES	.91	.28
(2) F40 SHIP FUEL	79.15	24.34
(2) F50 POTABLE WATER	.61	.19
OTHER (MISC) LIQUIDS	.20	.06
(2) F60 CARGO (IF ANY)	—	—
DELIVERED FULL LOAD DISPLACEMENT	325.14	100
M24 FUTURE GROWTH MARGIN	16.56	—
MAXIMUM DISPLACEMENT	341.70	
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	— 21.24	—6.53
FB DYNAMIC LIFT (F.L.)	303.90	93.47
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700 LOADS F20)	5.45	1.68
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)	83.32	25.63
USEFUL PAYLOAD (1 & 2)	88.77	27.31

100 HULL

VOLUME

Hullgirder ____ 2314.6m³ (81,740ft³)

Superstructure ____ 362 2m³ (12 790ft³)

Total ____ 2676.8m³ (94,530ft³)

AREAS (Hull & Superstructure)

Shell Plating ____ 933.02m² (10,040ft²)

Deck ____ 1388.19m² (14,938ft²)

Bulkheads ____ 445 97m² (4,799ft²)

MATERIAL ____ 5456-H311 & H321 Alum.

METHOD OF CONSTRUCTION ____ Welded

HULL GIRDER STRUCTURE DENSITY ____ 1.85

SUPERSTRUCTURE DENSITY ____ 91

TOTAL HULL STRUCTURE DENSITY ____ 1.72

HULL IMPACT DESIGN PRESSURE ____ 310 KN/m² (45psi)

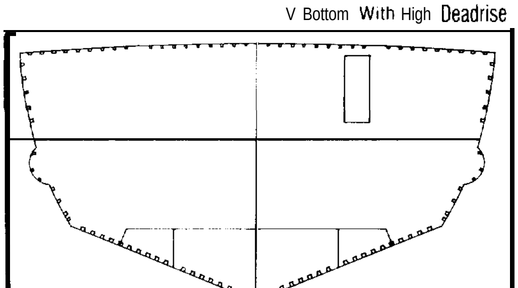
FRAME SPACING ____ .91m (3' 0")

NO. OF STRUCTURAL BULKHEADS ____ 13

DAMAGE ZONE CRITERIA ____ Two Compartments

(Floodable Length)

HULL FORM DESCRIPTION ____ Hard Chine, Fine Forward, Large Bow, Beamy Amidships, V Bottom With High Deadrise



TYPICAL FRAME SECTION

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SUBSYSTEM CHARACTERISTICS (CONT.)

200 PROPULSION

FB GAS TURBINE (Type & Number) **GE-LM1500** (2)

HB ENGINE (Type & Number) ______ Diesel (2)

FB TURBINE SHP

Max. Cont.- **14,194.60mph (14,000shp) @** 5000rpm

Max. **Inter'm.**_ **17,743.25mph (17,500shp) @** 5500rpm

TYPE **TRANSMISSION**_____ **'Z** Drive' 2 Shaft, Bevel Gears

PROPULSOR **TYPE**____ 3 Blade Supercavitating Fixed Pitch Propeller

NO. OF PROPULSORS ______ **(2)**

TYPE FUEL ______ Diesel Oil or JP-5

300 ELECTRIC RANT

TOTAL POWER ______ 250KVA

60 Hz SYS

VOLTAGES **USED**_______ **450-3ϕ**

400 COMMAND & SURVEILLANCE

TYPE OF NAV SYS ______ **N/A**

TYPE OF SURVEILLANCE SYS ____ Surface Search Radar

TYPE OF **F/C** SYS ______ None

500 AUXILIARY SYSTEM

ND. & TYPE OF RUDDER -- Steerable Strut (Aft)

TYPE OF ACS ______ Analog

NO. & TYPE OF HEIGHT SENSORS______ **(4)** Sonic

567 LIFT SYSTEM

CONFIGURATION ______ Airplane

% OF WEIGHT **DIST'B.** __FWD = **90%,** AFT = 10%

ASPECT RATIO ______ **3.0**

RETRACTABLE FOIL SYS.

SPAN ______ **FWD-7.92m** (26.0')

AFT - 4.08m (13.4')

FOIL LOADING ______ AFT **47.93KN/m²** (1001 psf)

FWD 64.88KN/m² (1355psf)

, TYPE CONTROL ______ Incidence

LID ______ 1 0 . 3 **@ 45KTs**

600 OUTFITTING & FURNISHINGS

NO. & TYPE COMPARTMENTS ____ (7) Watertight

AREA PER MAN **Officer**___ **11.96m²** (1 2 8 . 7 **ft²)**

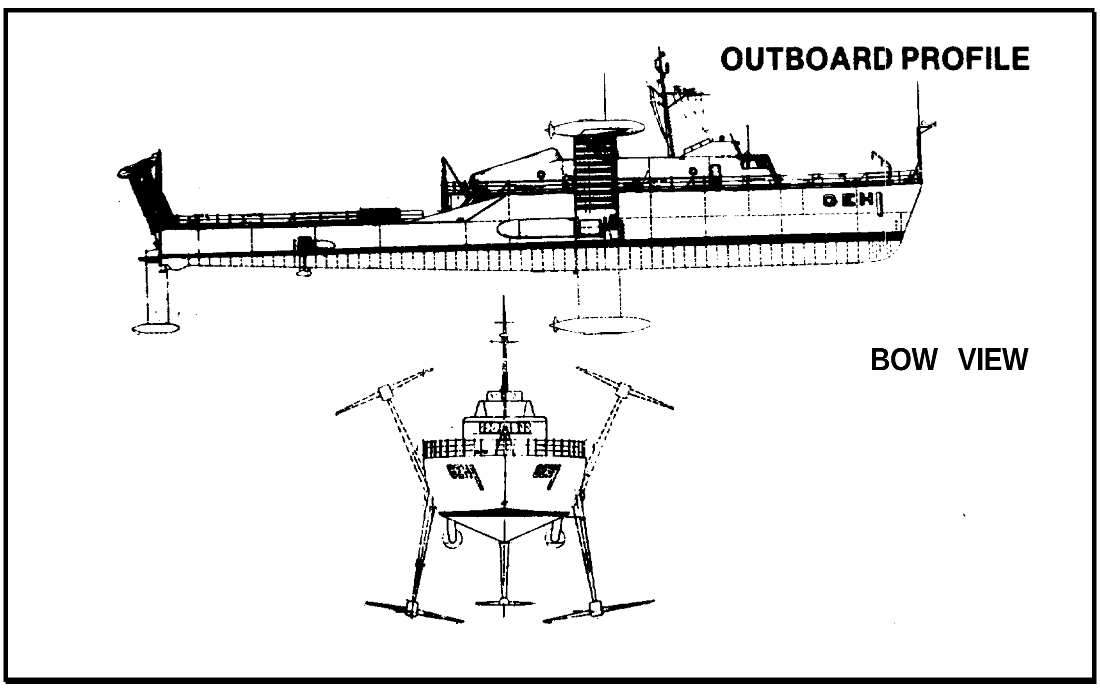
Enlisted ___ **3.49m²** (37.6 **ft²)**

MANNING ______ Officer ______ **4**

Enlisted ______ **16**

700 WEAPONS

TYPE & NO. OF WEAPONS **(4)** MK44 Torpedoes



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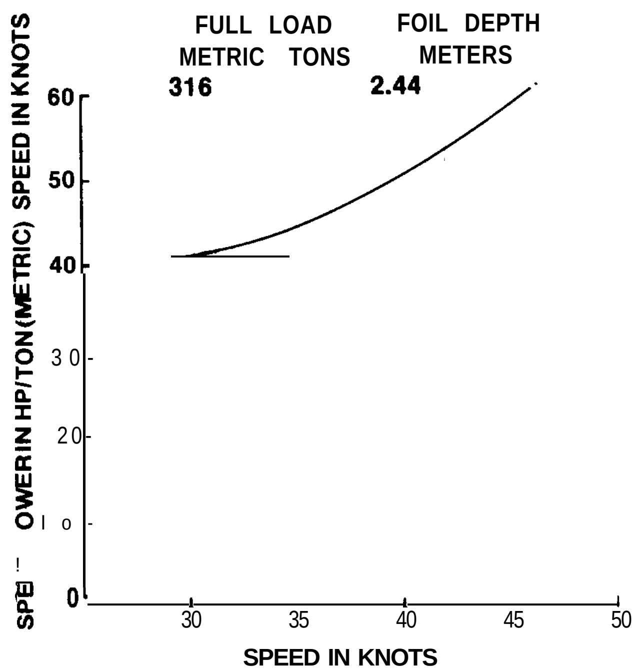
PREDICTED PERFORMANCE CHARACTERISTICS



RETRACTION & EXTENSION TIME ____ 3 min.

OPERATIONAL RESPONSE TIME ____ 10 min

TURNING RATES
(Rough & Calm Water) ____ 6 °/sec
MINIMUM TURNING DIAMETER ____ 197m
(646.333

SPEED
Max. ____ 50 + kts
Cruise ____ 48kts
Min. ____ 37kts

DESIGN SEASTATE ____ 5

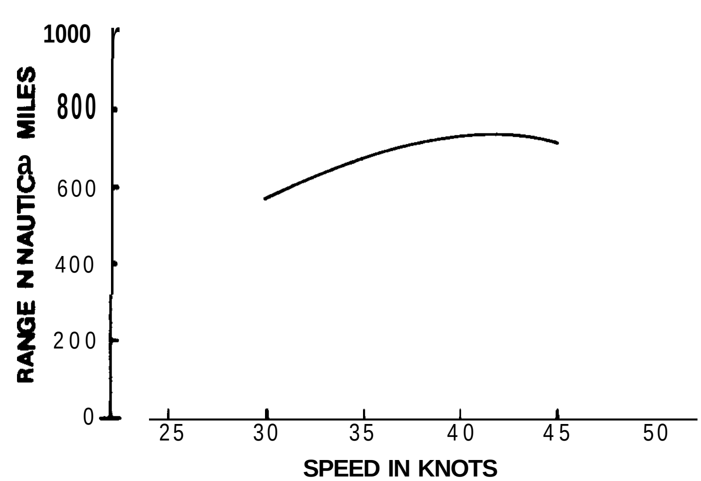
SHIP MOTION @ PILOT HOUSE
(Significant Wave Height 2.1m)
Pitch ____ .06°
Roll ____ .5°
Vert. Accel. ____ .036g
Lat. Accel. ____ .04g

RANGE ____ 500NM Foilborne

GENERAL
Designer ____ Grumman
Builder ____ Lockeed
Delivered ____ 1969

MISSION APPLICABILITY
Operations ____ kesearch & Development
Warfare Capability ____ Single, SUW
(Demonstration Only)

AGEH-1
RANGE AND ENDURANCE
FOILBORNE PERFORMANCE
FUEL WEIGHT 316 MT



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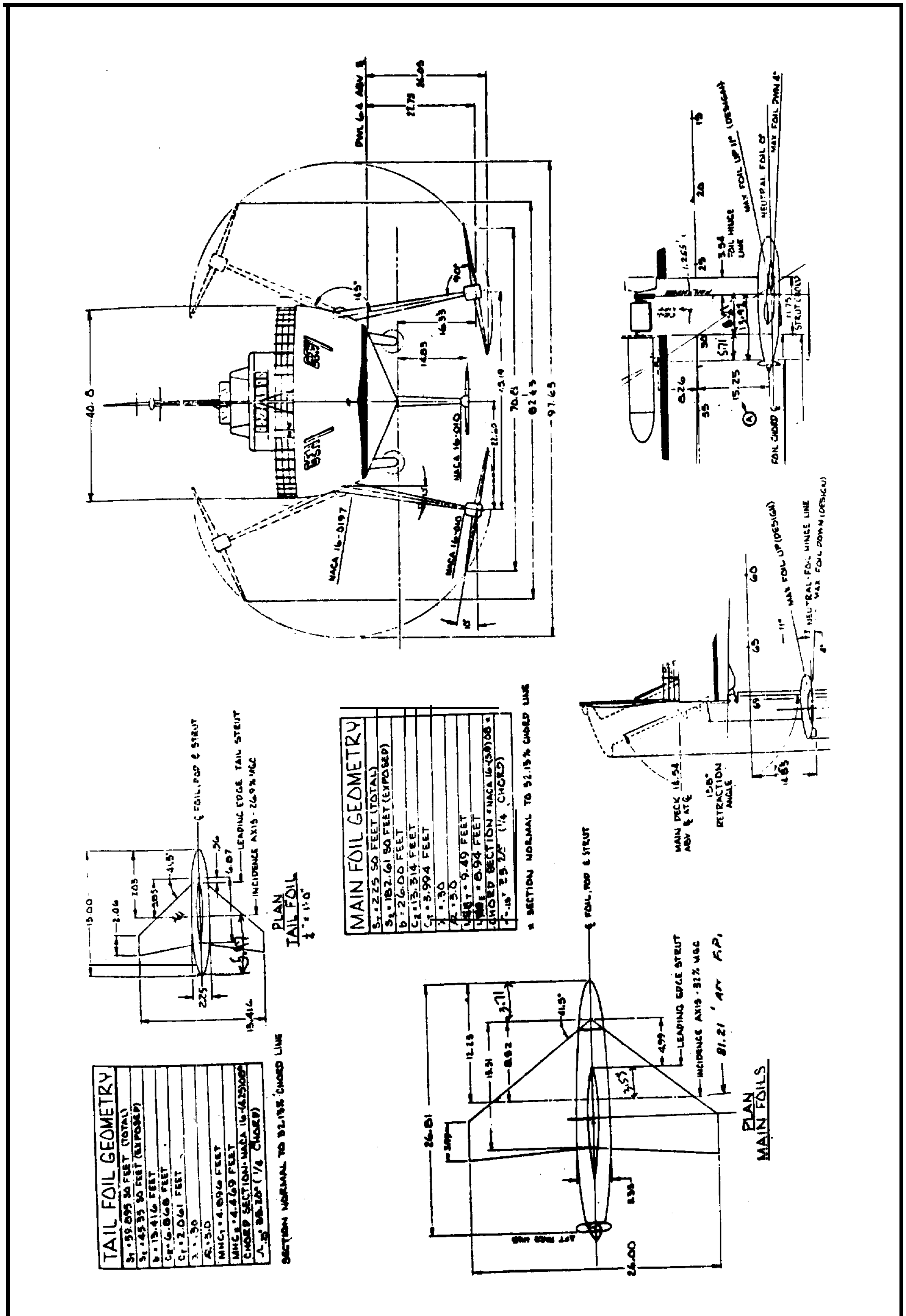
AGEH-1 FOIL GEOMETRY



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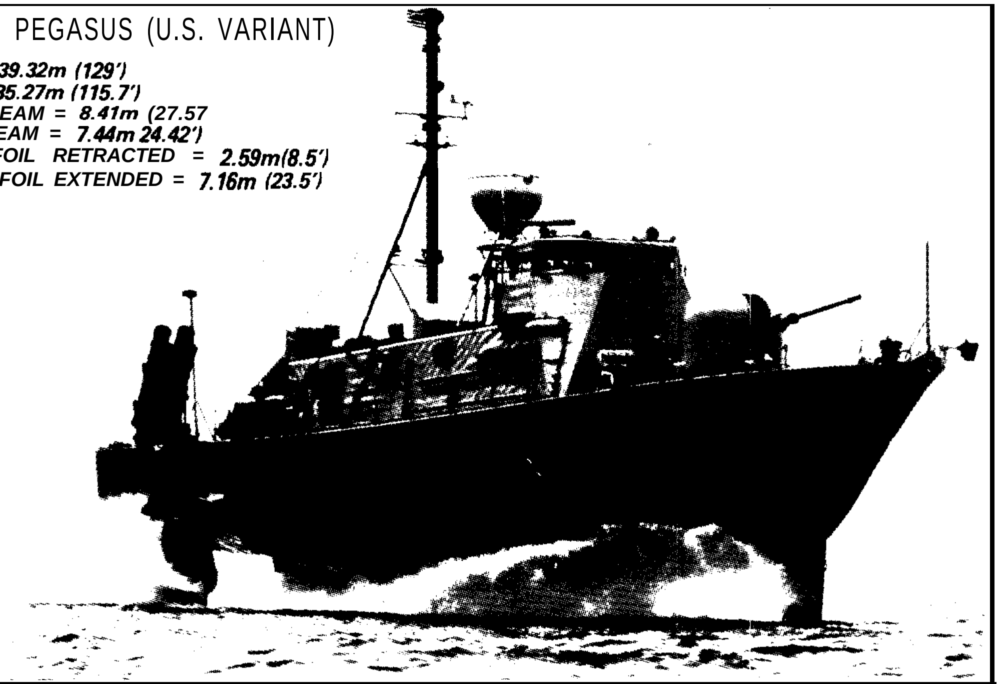
PHM-1 PEGASUS (U.S. VARIANT)

LOA = 39.32m (129')
LBP = 35.27m (115.7')
MAX. BEAM = 8.41m (27.57
DWL BEAM = 7.44m 24.42')
DRAFTFOIL RETRACTED = 2.59m(8.5')
DRAFT FOIL EXTENDED = 7.16m (23.5')



SUBSYSTEM CHARACTERISTICS

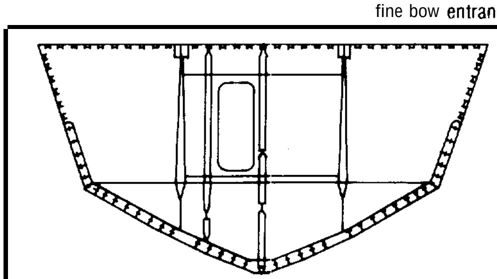
WEIGHT SUMMARY	*METRIC TONS*	*% F. L.*
WBS 100 HULL STRUCTURE	45.91	19.53
200 PROPULSION SYSTEMS	33.61	14.30
300 ELECTRIC PLANT	8.44	3.59
(1) 400 COMMAND & SURVEILLANCE	10.53	4.48
500 AUXILIARY SYSTEMS	13.60	5.79
567 LIFT SYSTEMS	32.00	13.62
600 OUTFIT & FURNISHINGS	16.34	6.95
(1) 700 WEAPONS SYSTEMS	9.31	3.96
M10 CONTRACTOR CONTROLLED	–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM	–	–
MARGINS	2.12	.90
DELIVERED LIGHTSHIP	171.84	73.12
NORMAL LOADS:		
(2) F10 SHIPS FORCE	2.76	1.17
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	.41	.18
(1) F21 SHIP AMMUNITION	13.40	5.70
(2) F30 STORES	.73	.31
(2) F40 SHIP FUEL	41.10	17.49
(2) F50 POTABLE WATER	1.00	.43
OTHER (MISC) LIQUIDS	.10	.04
(2) F60 CARGO (IF ANY)	–	–
DELIVERED FULL LOAD DISPLACEMENT	229.03	197.46
M24 FUTURE GROWTH MARGIN	5.96	2.54
MAXIMUM DISPLACEMENT	234.99	100
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	– 4.79	–2.04
FB DYNAMIC LIFT (F.L.)	230.20	97.96
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700 LOADS F20)	29.46	12.54
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)	45.67	19.43
USEFUL PAYLOAD (1 & 2)	75.13	31.97

100 HULL

VOLUME
- Hullgirder ____________ 804m³ (28,393ft³)
- Superstructure ____________ 211.8m³ (7,480ft³)
- Total ____________ 101 5.8m³ (35,873)

AREAS (Hull & Superstructure)
- Shell Plating ____________ 468.23m² (5,040ft²)
- Deck ____________ 459.87m² (4.950ft²)
- Bulkheads ____________ 176.52m² (1 .900ft²)

MATERIAL ____________ 5456-H111 & H117 Aluminum
METHOD OF CONSTRUCTION ____________ Welded
HULL GIRDER STRUCTURE DENSITY ____________ 2.24
SUPERSTRUCTURE DENSITY ____________ 1.23
TOTAL HULL STRUCTURE DENSITY ____________ 2.03
HULL IMPACT DESIGN PRESSURE ____________ 72.78 Kn/m² (1,520psf)
FRAME SPACING ____________ .42m tol m
NO. OF STRUCTURAL BULKHEADS ____________ 12
DAMAGE ZONE CRITERIA ____________ Two Compartments (Floodable Length)
HULL FORM DESCRIPTION ______ Single chine, constant deadrise, fine bow entranc



TYPICAL FRAME SECTION

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SUBSYSTEM CHARACTERISTICS (CONT.)

200 PROPULSION

FB GAS TURBINE (Type & Number) ______ GE, LM2500 • (1)

HB ENGINE (Type & Number) ______ MTU Diesel • (2)

FB TURBINE SHP
- • Max. Cont. ______ 16,215.30 mph (15,993 shp)
- Max. Inter'm ______ 16,215.30 mph (15,993 shp)

TYPE TRANSMISSION __ N/A (integral Part of Water Jet)

PROPULSOR TYPE -- 2 Stage Axial Flow Pump

NO. OF PROPULSORS ______ (1)

TYPE FUEL ______ Diesel Oil & JP-5

300 ELECTRIC PLANT

TOTAL POWER ______ 500KVA

400 Hz SYS

VOLTAGES USED ______ 450 • 3ϕ

400 COMMAND & SURVEILLANCE

TYPE OF NAV SYS -- Radar, Radio Reciever, Depth Measuring, Gyrocompass With Speed & Dead Reckoning Equip.

TYPE OF SURVEILLANCE SYS ______ Surface Search Radar & IFF

TYPE OF F/C SYS ______ MK 94 Or MK92 (Gun & Missile)

• Water Jet Max RPM Limits Turbine HP @16,215

500 AUXILIARY SYSTEM

NO. & TYPE OF RUDDER -- FWD Steerable Strut

TYPE OF ACS ______ Analog

NO. & TYPE OF HEIGHT SENSORS ______ (2) Sonic & Radar

567 LIFT SYSTEM

CONFIGURATION ______ Canard

% OF WEIGHT DIST'B. AFT • 65.4% FWD • 34.6%

ASPECT RATIO ______ 7.5

RETRACTABLE FOIL SYS.

SPAN ______ AFT • 14.51 m (47.59')
FWD • 8.50m (27.88')

TYPE CONTROL ______ Flaps FWD & AFT Foils

L/D ______ 10.7 @ 45KTs

600 OUTFITTING & FURNISHINGS

NO. & TYPE COMPARTMENTS ______ 26 Water Tight

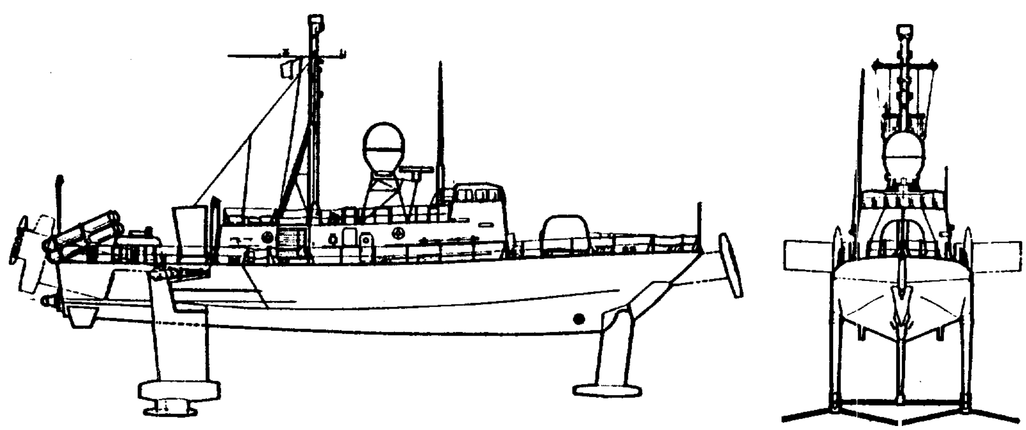
AREA PER MAN ______ Officer- 4.18m² (45ft²)
Enlisted- 2.69m² (29ft²)

MANNING ______ Officer ______ 5
Enlisted ______ 16

700 WEAPONS

TYPE & NO. OF WEAPONS (1) OTO-Melara 76mm/62 Cal C30/II Compact Gun
(8) Harpoon Missiles

OUTBOARD PROFILE



BOW VIEW

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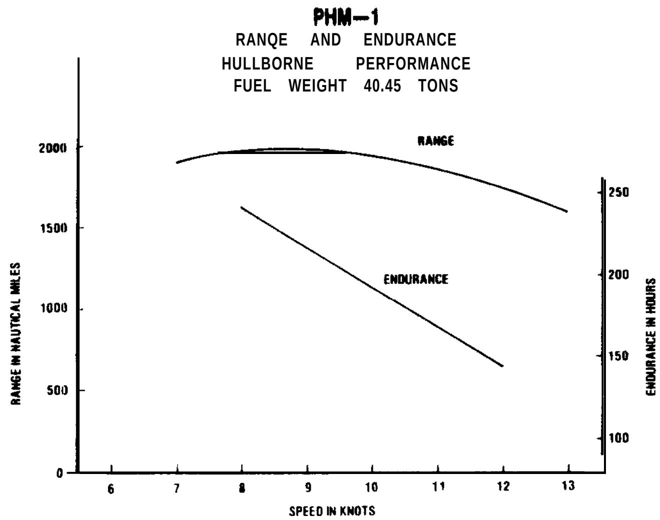
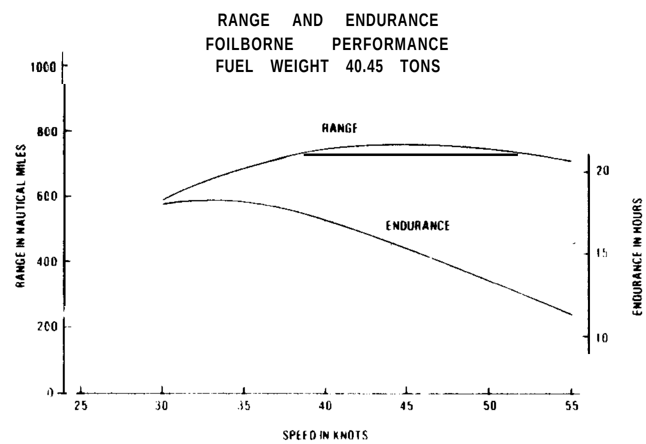
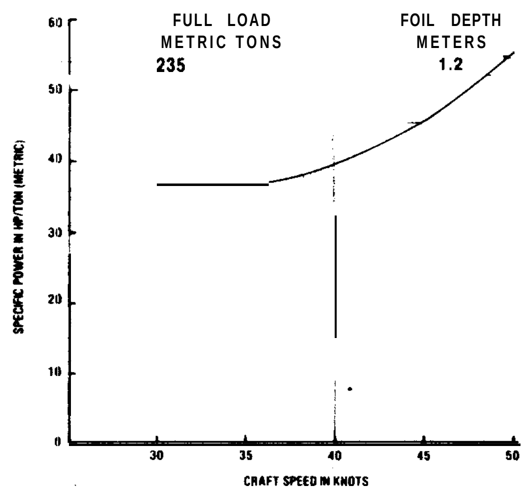
PREDICTED PERFORMANCE CHARACTERISTICS







RETRACTION & EXTENSION TIME — 3 Minutes

OPERATIONAL RESPONSE TIME — 5 Minutes

TURNING RATES
(Rough a **Calm Water)** ________ 8 °/sec
MIN. TURNING DIAMETER — 236m (774.28')

SPEED
- **Max.** ________ 51 kts
- **Cruise** ________ 45 kts
- Min. ________ 33 kts

DESIGN SEASTATE ________ 5

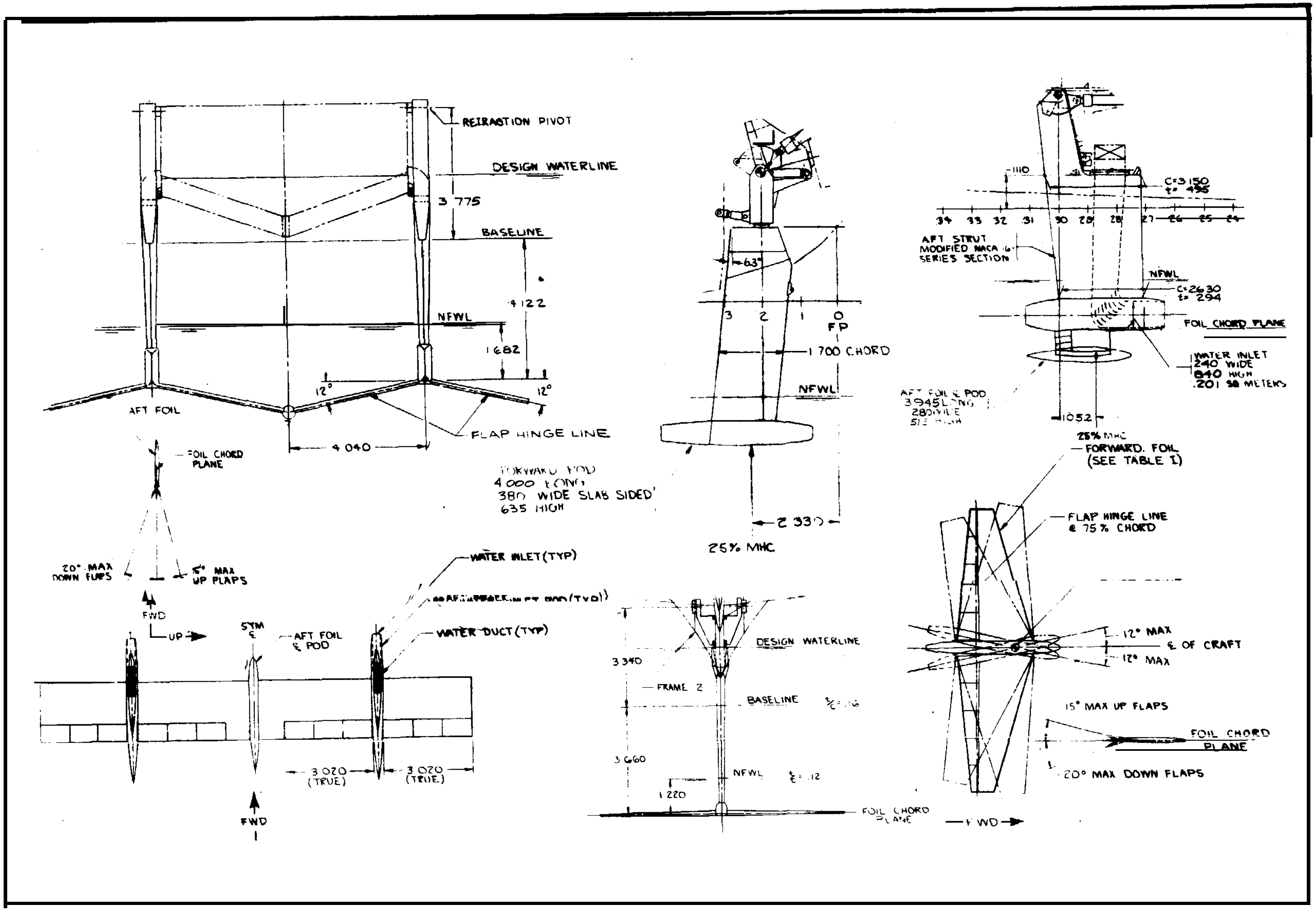
SHIP MOTION @ pilot house
(SIGNIFICANT WAVE HEIGHT - 2.5m)
- **Pitch** ________ .49°
- **Roll** ________ .37°
- **Vert. Accel.** ________ .054g
- **Lat. Accel.** ________ .028g

RANGE
- **Foilborne** ________ 700nm
- **Hullborne** ________ 11 00nm

GENERAL
- **Designer** ________ Boeing
- **Builder** ________ Boeing
- **Delivered** __ (Estimated,Summer of 1976)

MISSION APPLICABILITY
- **Operations** ________ Onshore Patrol
- **Warfare Capability** ____ Single-SUW & SPW

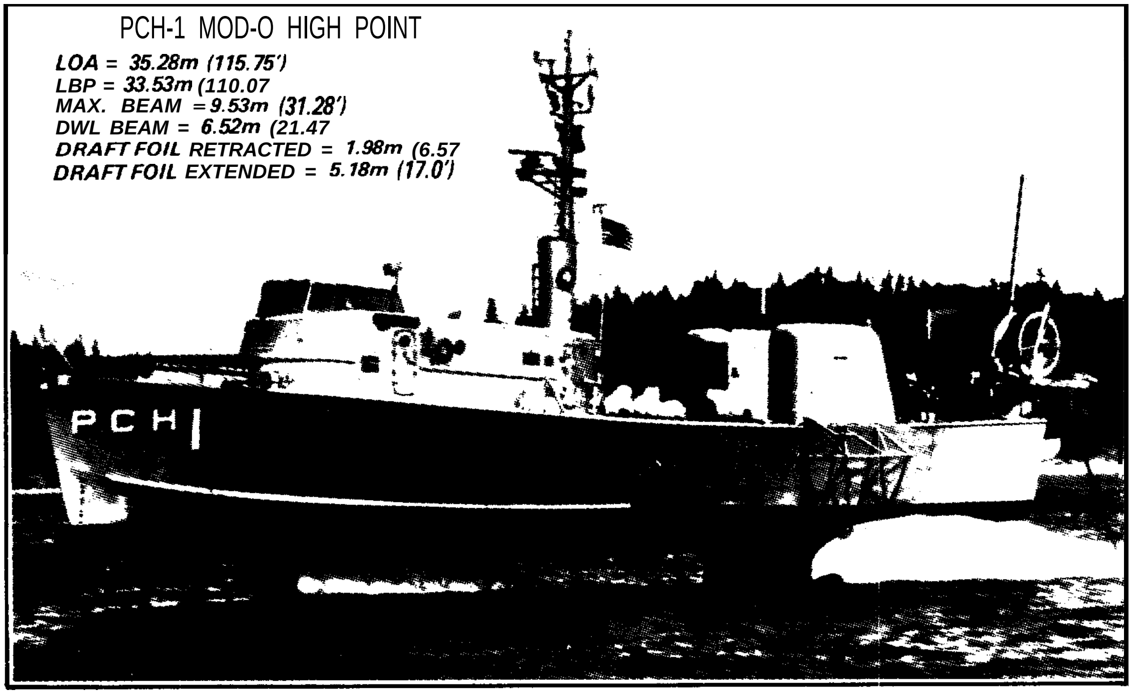
UNCLASSIFIED
[redacted]



PHM—1 FOIL GEOMETRY

SPECIFIC DESIGNS SHIP CHARACTERISTICS

UNCLASSIFIED



SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY			METRIC TONS	% F.L
SWBS	100	HULL STRUCTURE	30.09	26.31
	200	PROPULSION SYSTEMS	16.81	14.13
	300	ELECTRIC PLANT	4.61	4.10
	(1) 400	COMMAND & SURVEILLANCE	a.37	7.34
	500	AUXILIARY SYSTEMS	5.41	4.74
	567	LIFT SYSTEMS	15.70	13.76
	600	OUTFIT & FURNISHINGS	5.86	5.14
	(1) 700	WEAPONS SYSTEMS	1.68	1.47
M10 CONTRACTOR CONTROLLED			—	—
M21-M23 CONTRACT DESIGN, MOD, & GFM			—	—
MARGINS			—	—
DELIVERED LIGHTSHIP			88.58	77.63
NORMAL LOADS:				
(2) F10 SHIPS FORCE			1.52	1.34
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS			—	—
(1) F21 SHIP AMMUNITION			1.43	1.26
(2) F30 STORES			.66	.58
(2) F40 SHIP FUEL			21.18	18.57
(2) F50 POTABLE WATER			.66	.58
OTHER (MISC) LIQUIDS			.06	.05
(2) F60 CARGO (IF ANY)			—	—
DELIVERED FULL LOAD DISPLACEMENT			114.10	100
M24 FUTURE GROWTH MARGIN			—	—
MAXIMUM DISPLACEMENT			114.10	
GROUP 567 BUOYANCY				
NORMAL FOILBORNE			— 3.25	—2.85
TO DYNAMIC LIFT (F.L			110.85	97.16
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700 LOADS F20			10.35	9.07
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)			24.08	21.11
USEFUL PAYLOAD (1 & 2)			34.43	30.18

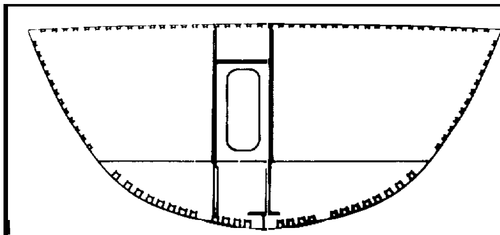
100 HULL

VOLUME

Hullgirder	730m³ (25,780ft³)
Superstructure	1 1 9 9M³ (4,235ft³)
Total	849.9M³ (30,01 5ft³)

AREAS (Hull & Superstructure)

Shell Plating	397 74m² (4.280 ft²)
Deck	415 68m² (4,473 ft²)
Bulkheads	116 35m² (l .252 ft²)
MATERIAL	5456-H311 & 6061 T6 Alum
METHOD OF CONSTRUCTION	Welded
HULL GIRDER STRUCTURE DENSITY	2 12
SUPERSTRUCTURE DENSITY	1 15
TOTAL HULL STRUCTURE DENSITY	1 98
HULL IMPACT DESIGN PRESSURE.	71 82 KN/m² (1,500psf)
FRAME SPACING	43m To 1 52m (3 92' To 5 0')
NO OF STRUCTURAL BULKHEADS	28
DAMAGE ZONE CRITERIA (Floodable Length)	One Compartment
HULL FORM DESCRIPTION	Round Bilge Bottom Constant Deadrise Fine Bow



TYPICAL FRAME SECTION

UNCLASSIFIED

SUBSYSTEM CHARACTERISTICS (Cont.)

200 PROPULSION

FB GAS TURBINE (Type & Number) ______ Bristol Siddeley Proteus • (2)

HB ENGINE (Type & Number) ______ Diesel 1

FB TURBINE SHP

Mas. Cont. __ 3,1 43.09 mph (3,100 shp) @ 5000 rpm

Max. Inter'm._ 3,954.21 mph (3,900 shp) @ 5300 rpm

TYPE TRANSMISSION ____ 'Z Drive' 2 shah, bevel gears

PROPULSOR TYPE ______ 3-Blade subcavitating fixed pitch propellers

NO. OF PROPULSDRS ______ *(4)*

TYPE FUEL ______ Diesel oil & JP-5

300 ELECTRIC PLANT

TOTAL POWER ______ 106 25KVA

60 Hz SYS

VOLTAGES USED ______ 440-3φ

400 **COMMAND &** SURVEILLANCE

TYPE OF NAV SYS ______ Visual with Loran & Radar

TYPE OF SURVEILLANCE SYS ____ Surface Search Radar, IFF, Variable Depth Sonar AN(SQS–33(XN-1)

TYPE OF F/C SYS ______ None

500 AUXILIARY SYSTEM

NO. & TYPE OF RUDDER ____ (2) Flap, Trailing Edge Fwd Strut Above & Below Foil

TYPE OF ACS ______ Analog

NO. & TYPE OF HEIGHT SENSORS ______ (2) Sonic

567 LIFT SYSTEM

CONFIGURATION ______ Canard

% OF WEIGHT DIST'B. ____ Aft-69.8%, Fwd . 30.2%

Aspect Ratio ______ -6.6 (Aft) & 6.1 (Fwd)

RETRACTABLE FOIL SYS. (WET)

SPAN ______ Aft 9.60m (31.5') Fwd · 6.1m (20.0')

TYPE CONTROL ______ Flaps

L/D ______ 12.9 @ 46Kts

600 OUTFITTING & FURNISHINGS

NO, & TYPE COMPARTMENTS -- ______ 14 Watertight

AREA PER MAN ______ Officer – 7.06m² (76ft²)
Enlisted – 3.34m² (36ft²)

MANNING ______ OFFICER ______ 1

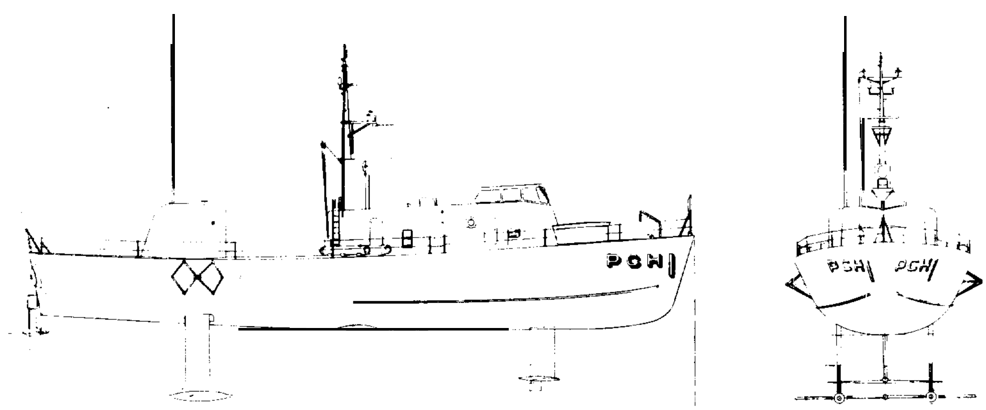
EM. ______ 12

700 WEAPONS

TYPE & NO. OF WEAPONS .(1) 50 Cal Machine Gun With Fixed Tripod Mount

(4) – MK44 Torpedoes

(1) 40 mm Gun Added For Trials After Delivery To The Navy



OUTBOARD PROFILE **BOW VIEW**

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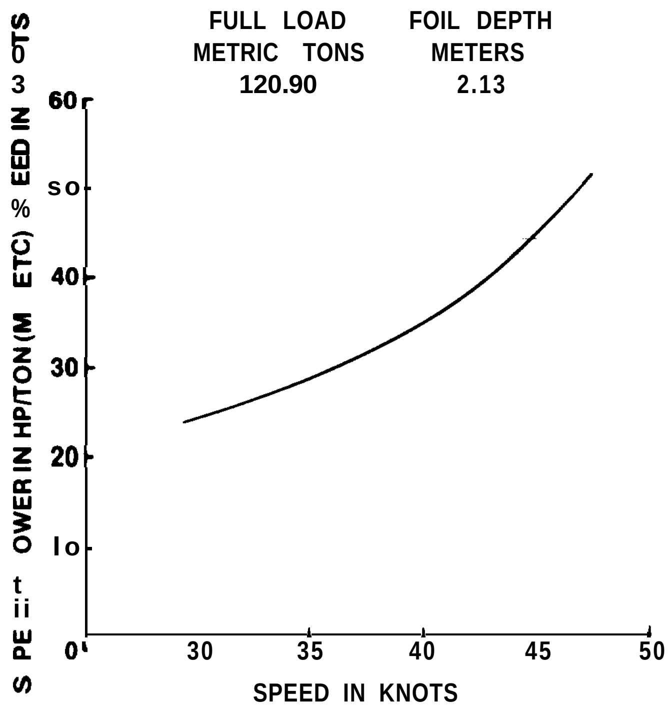
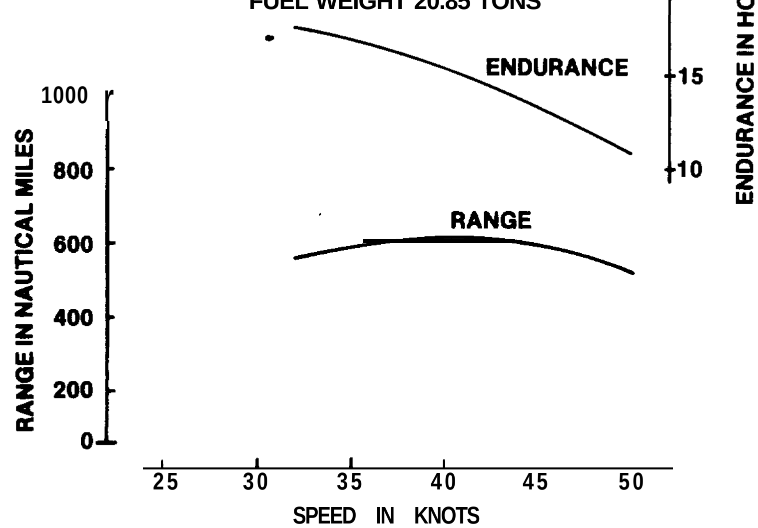
PREDICTED PERFORMANCE CHARACTERISTICS



PCH-1 MOD-O

RANGE AND ENDURANCE
FOILBORNE PERFORMANCE
FUEL WEIGHT 20.85 TONS



RETRACTION &
EXTENSION TIME ________ (AFT) 5.1 minutes
(FWD) 2.5 minutes

OPERATIONAL RESPONSE **TIME** __ 6 minutes

TURNING RATES
(Rough & Calm Water) ____________ 7 °/sec
MIN. TURNING **DIAMETER** ________ 169.16m
(554.99')

SPEED
Max. ________________________ 46 kts
Cruise ________________ 42 kts
Min. ________________________ 30 kts

DESIGN SEASTATE ________________ 5

SNIP **MOTION @ PILOT** HOUSE
(SIGNIFICANT WAVE HEIGHT = **1.8m)**
Pitch ________________________ .6°
Roll ________________________ .7°
Vert. Accel. ____________________ .14g
Lat. Accel. ____________________ .045g

RANGE ________________ 500 NM Foilborne

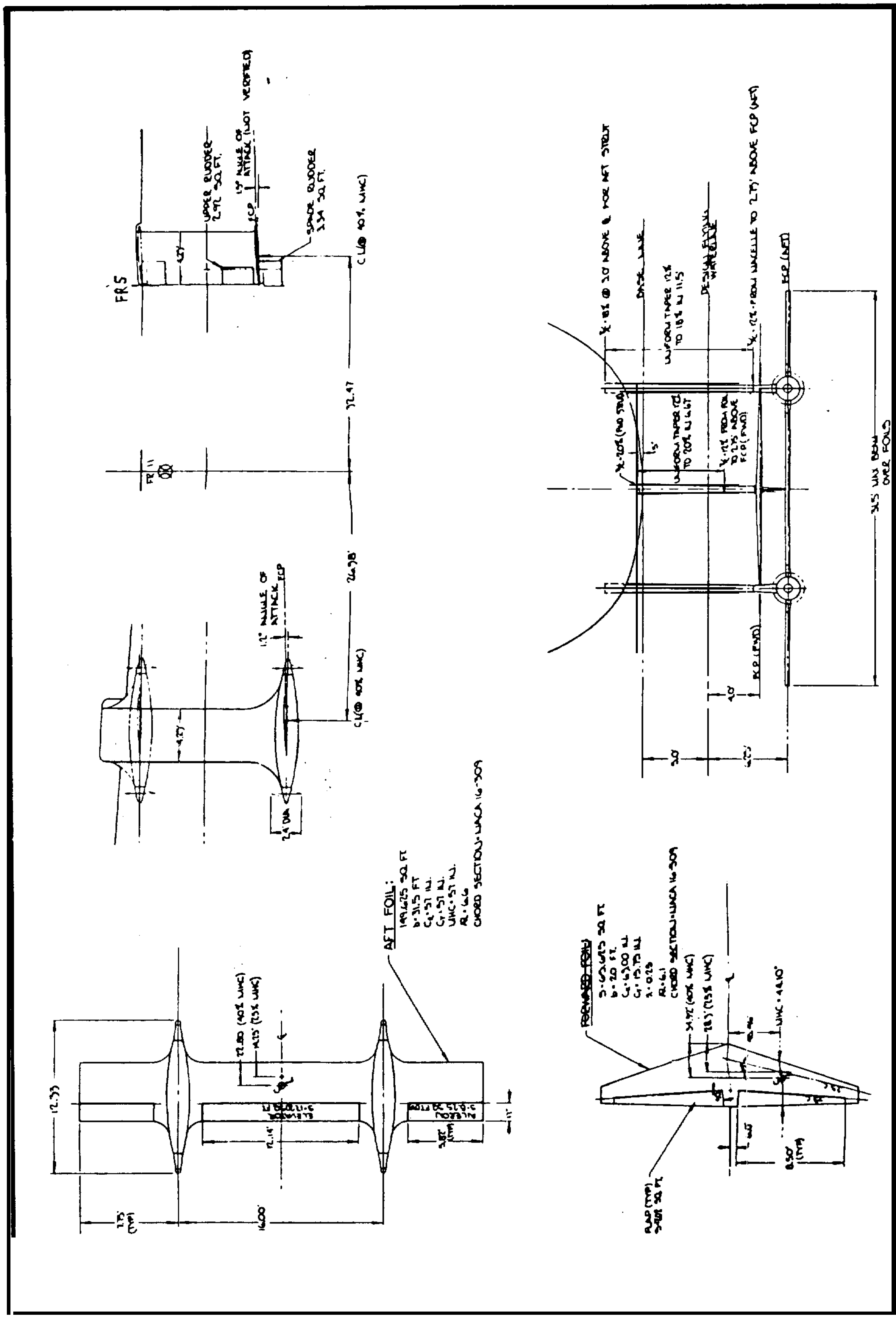
GENERAL
Designer ____________________ Navsec
Buillder ______________________ Boeing
Delivered ____________________ 1963

MISSION APPLICABILITY
Operations __ Off Shore Patrol (R & D)
Warfare **Capability** Single ASW
(Demonstration Only)

UNCLASSIFIED

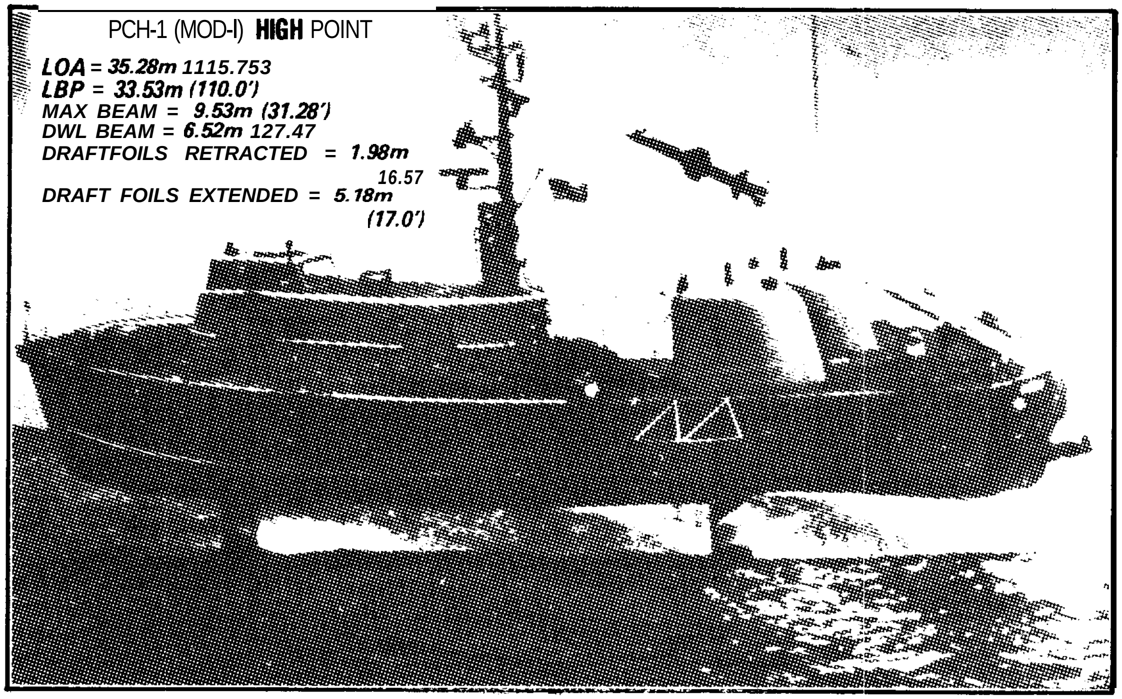
[redacted]L

PCH—1 (MOD—O) FOIL GEOMETRY



SPECIFIC DESIGNS SHIP CHARACTERISTICS

UNCLASSIFIED



SUBSYSTEM CHARACTERISTICS

WEIGHTSUMMARY		METRIC TONS	%F L
SWBS	100 HULL STRUCTURE	33.12	26.30
	200 PROPULSION SYSTEMS	18.34	14.30
	300 ELECTRIC PLANT	6.19	4.83
	(1) 400 COMMAND & SURVEILLANCE	2.74	2.14
	500 AUXILIARY SYSTEMS	8.12	6.33
	567 LIFT SYSTEMS	22.07	17.21
	600 OUTFIT & FURNISHINGS	9.25	7.21
	(1) 700 WEAPONS SYSTEMS	1.41	1.10
M10 CONTRACTOR CONTROLLED		–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM		–	–
MARGINS		–	–
DELIVERED LIGHTSHIP		101.84	79.42
NORMAL LOADS			
	(2) F10 SHIPS FORCE	3.22	2.51
	(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	–	–
	(1) F21 SHIP AMMUNITION	.30	.24
	(2) F30 STORES	.66	.52
	(2) F40 SHIP FUEL	20.25	15.79
	(2) F50 POTABLE WATER	.75	.59
	OTHER (MISC) LIQUIDS	.34	.26
	(2) F60 CARGO (IF ANY)	.86	.67
DELIVERED FULL LOAD DISPLACEMENT		128.23	100
M24 FUTURE GROWTH MARGIN		–	–
MAXIMUM DISPLACEMENT		128.23	
GROUP 567 BUOYANCY			
	NORMAL FOILBORNE	– 4.35	–3.39
	FB DYNAMIC LIFT (F.L.)	123.88	96.61
MILITARY PAYLOAD (1) INCLUDES SWBS 442, 499 & 700 LOADS F20		3.31	2.58
VARIABLE PAYLOAD (2) INCLUDES LOADS F10, F30, F40, F50 AND F60		26.08	20.34
USEFUL PAYLOAD (1 & 2)		29.39	22.92

100 HULL

VOLUME

- Hullgirder ______ 730m³ (25,780ft³)
- Superstructure ______ 11.9 9m³ (4235ft³)
- Total ______ 849 9m³ (30,015ft³)

AREAS (Hull & Superstructure)

- Shell Plating ______ 397 63m² (4,280ft²)
- Deck ______ 41 5.56m² (4,473ft²)
- Bulkheads ______ 116 31 m² (1,252112)

MATERIAL ______ 5456-H311 & 6061 -T6 Alum

METHOD OF CONSTRUCTION ______ Welded

HULL GIRDER STRUCTURE DENSITY ______ 2.12

SUPERSTRUCTURE DENSITY ______ 1.15

TOTAL HULL STRUCTURE DENSITY ______ -1.98

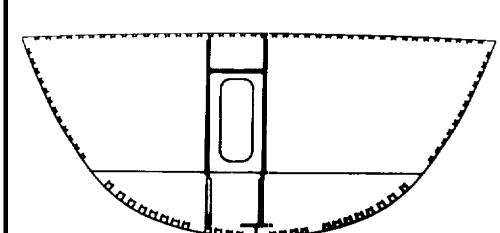
HULL IMPACT DESIGN PRESSURE ______ 71 82KN/m² (1,500PSF)

FRAME SPACING ______ 43m to 1 52m (3.92'10 5.03

NO. OF STRUCTURAL BULKHEADS ______ '28

DAMAGE ZONE CRITERIA ______ One Compartment (Floodable Length)

HULL FORM DESCRIPTION - - Round Bilge Bottom, Constant Deadrise, Fine Bow



TYPICAL FRAME SECTION

UNCLASSIFIED

SUBSYSTEM CHARACTERISTICS (CONT.)

200 PROPULSION

FB GAS TURBINE (Type & Number) ____ RR Proteus PT-1 273 (2)

HB ENGINE (Type & Number) ____ Diesel (1)

FB TURBINE SHP

Mas. Cont. ____ 3143.09MPH (31 OOSHP) @ 4200 RPM

Max. Inter'm.__ 3852.82MHP (3800S'hp) @ 4200RPM

TYPE TRANSMISSION ____ 'Z Drive' 2 Shaft Bevel Gears

PROPULSOR TYPE-____ 5 Blade Subcavitating Fixed Pitch Propeller

NO. OF PROPULSORS ____ (4)

TYPE FUEL ____ Diesel Oil & JP-5

300 **ELECTRIC** PLANT

TOTAL POWER ____ 175KVA

60 Hz SYS

VOLTAGES USED____ 440-3ϕ

400 COMMAND & **SURVEILLANCE**

TYPE OF NAV SYS ____ Visual With Loran & Radar

TYPE OF SURVEILLANCE SYS Surface Search Radar & IFF

TYPE OF F/C SYS ____ None

500 AUXILIARY SYSTEM

NO. & TYPE OF RUDDER ____ Steerable FWD Strut

TYPE OF ACS ____ Analog & Digital (Demonstratio)

NO. & TYPE OF HEIGHT SENSORS ____ 2 (Sonic & Radar)

567 **LIFT** SYSTEM

CONFIGURATION ____ Canard

% OF WEIGHT DIST'B. ____ AFT 65.5% FWD 34.5%

RETRACTABLE FOIL SYS. (WET)

SPAN ____ AFT - 9.6m (31.5') FWD - 6.1m (20.0')

ASPECT RATIO ____ FWD 6.1 AFT · 7.6

TYPECONTROL ____ Flaps

Foil Loading ____ AFT - 4'9.6 KN/M² (1035psf) FWD 60.3 KN/M² (1260psf)

L/D ____ 13.3 @ 45kts

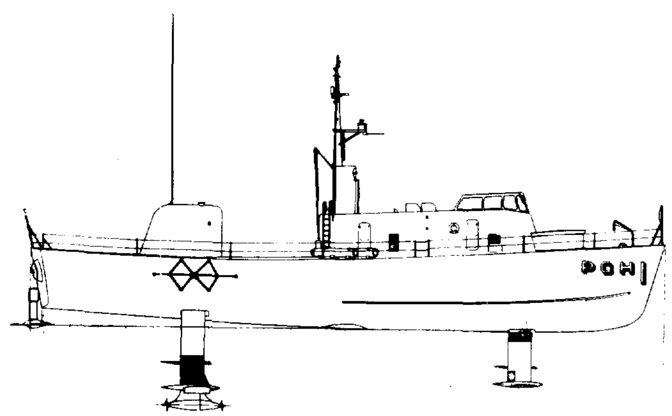
600 OUTFITTING & FURNISHINGS

NO. & TYPE COMPARTMENTS ____ 14 Watertight

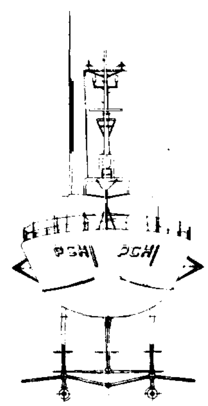
AREA PER MAN ____ Officer - 7.06m² (76ft²) Enlisted - 3.34m² (36ft²)

700 WEAPONS

TYPE & NO. OF WEAPONS ____ (4) MK 44 Torpedoes



OUTBOARD PROFILE



BOW VIEW

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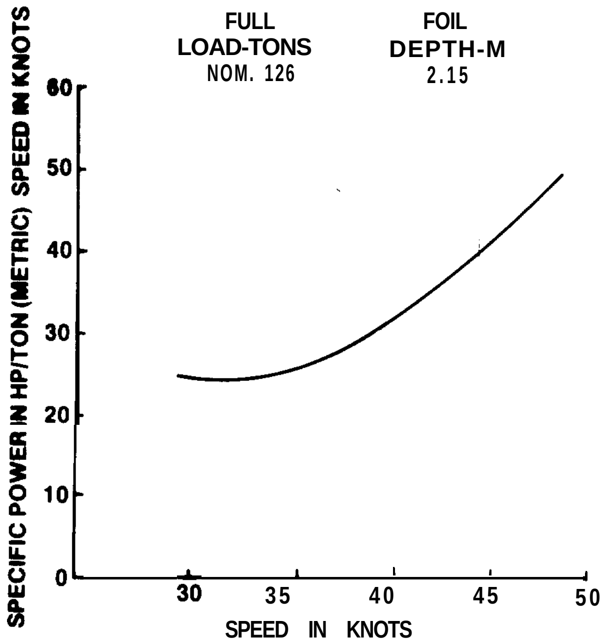
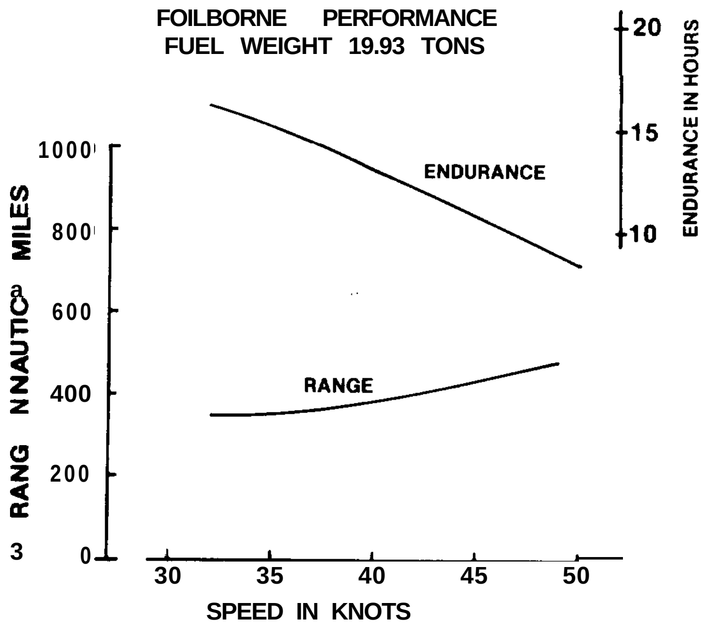
PREDICTED PERFORMANCE CHARACTERISTICS



PCH-1 MOD-I
RANGE AND ENDURANCE
FOILBORNE PERFORMANCE
FUEL WEIGHT 19.93 TONS



RETRACTION &
EXTENSION TIME ___ AFT 5. minutes
FWD 2.5 minutes

OPERATIONAL RESPONSE TIME ___ 6 minutes

TURNING RATES
(Rough & Calm Water) ___ 7°/sec
MIN. **TURNING DIAMETER** ___ 169.16m
(554.99')

SPEED
Max. ___ 52 kts
Cruise ___ 42 kts
Min. ___ 30 kts

DESIGN SEASTATE ___ 5

SHIP **MOTION @** PILOT **HOUSE**
(Significant Wave Height—2.5m)
Pitch ___ 38°
Roll ___ .63°
Vert. Accel. ___ .079g
Lat. Accel. ___ .037g

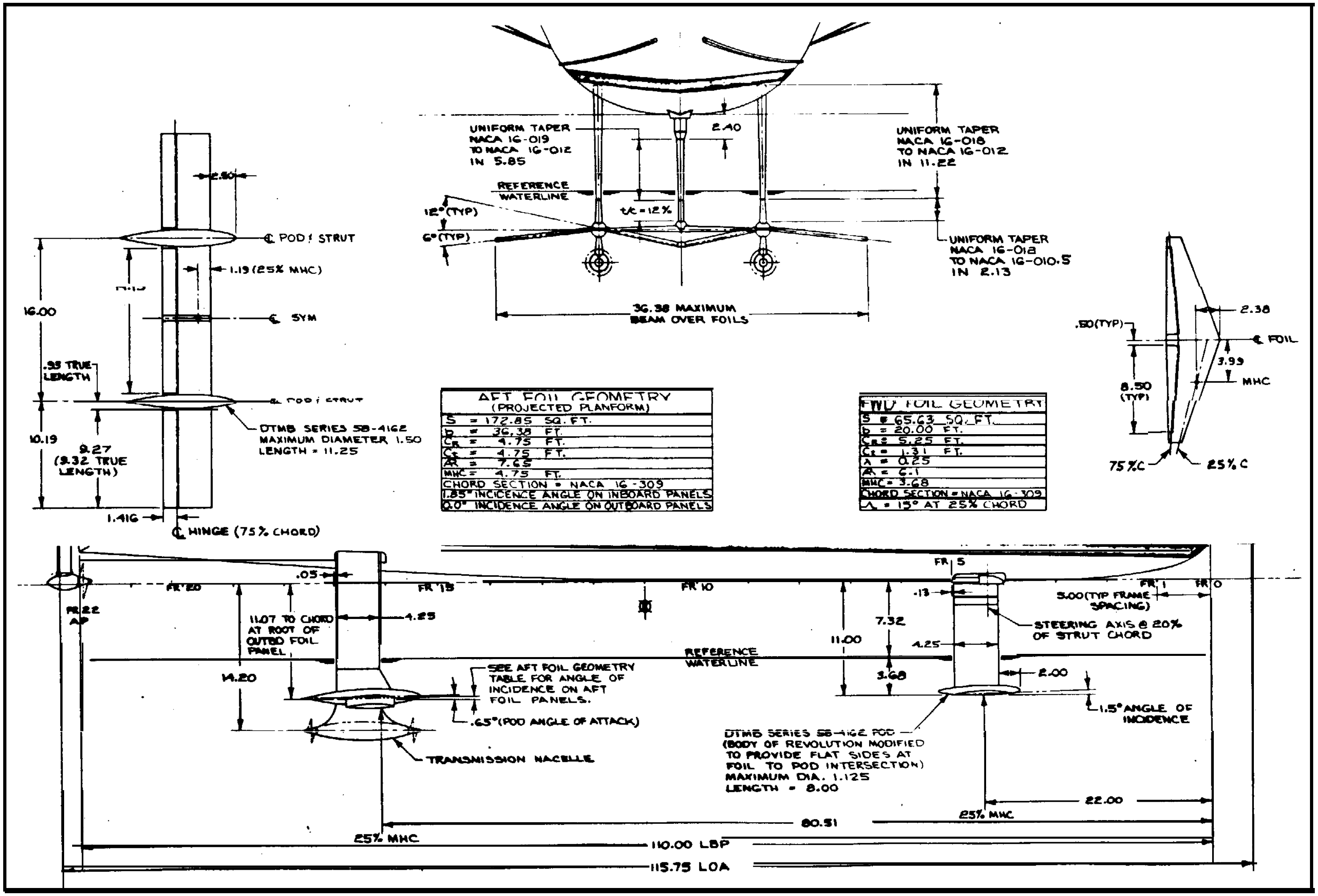
RANGE ___ 500 NM Foilborne

GENERAL
Designer ___ Navsec
Builder ___ Boeing
Delivered (MOD-I) ___ 1973

MISSION **APPLICABILITY**
Operations ___ Research & Development

UNCLASSIFIED
[redacted]L

PCH-1 (MOD-1) FOIL GEOMETRY



AFT FOIL GEOMETRY (PROJECTED PLANFORM)
S = 172.85 SQ. FT.
b = 36.38 FT.
C_R = 4.75 FT.
C_T = 4.75 FT.
AR = 7.65
MHC = 4.75 FT.
CHORD SECTION = NACA 16-309
1.85° INCIDENCE ANGLE ON INBOARD PANELS
0.0° INCIDENCE ANGLE ON OUTBOARD PANELS

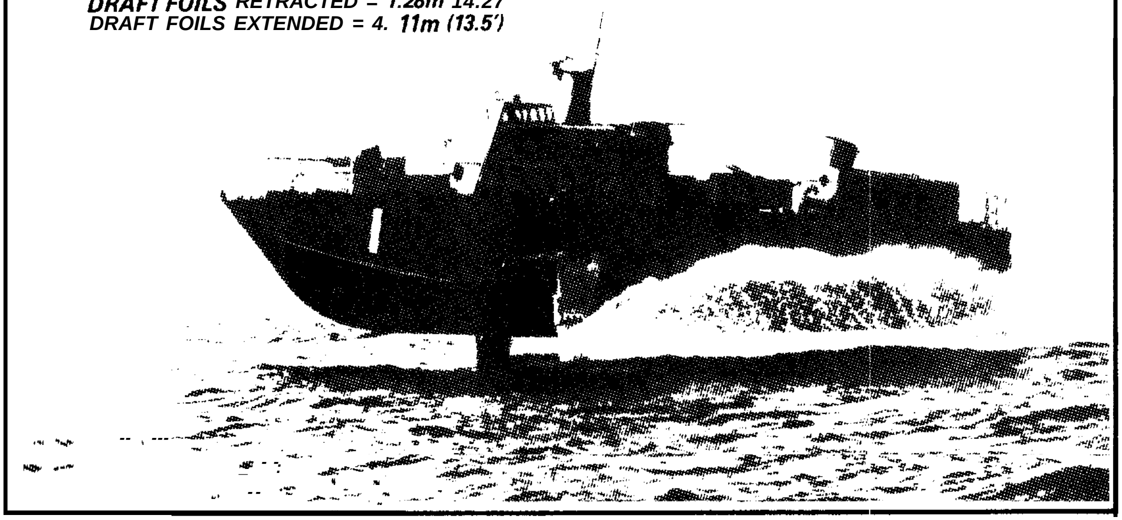
FWD FOIL GEOMETRY
S = 65.63 SQ. FT.
b = 20.00 FT.
C_R = 5.25 FT.
C_T = 1.31 FT.
λ = 0.25
AR = 6.1
MHC = 3.68
CHORD SECTION = NACA 16-309
Λ = 15° AT 25% CHORD

SPECIFIC DESIGNS SHIP CHARACTERISICS

UNCLASSIFIED

PGH-1 FLAGSTAFF

LOA = 22.25m (73')
LBP = 20.32m 166.677
MAX BEAM = 6.54m (21.47')
DWL BEAM =
DRAFT FOILS RETRACTED = 1.28m 14.27
DRAFT FOILS EXTENDED = 4. 11m (13.5')



SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY			METRIC TONS	% F.L.
SWBS	100	HULL STRUCTURE	18.39	26.38
	200	PROPULSION SYSTEMS	9.45	13.56
	300	ELECTRIC PLANT	3.56	5.10
	(1) 400	COMMAND & SURVEILLANCE	1.73	2.48
	500	AUXILIARY SYSTEMS	4.95	7.10
	567	LIFT SYSTEMS	9.11	13.16
	600	OUTFIT & FURNISHINGS	4.17	5.96
	(1) 700	WEAPONS SYSTEMS	2.64	3.19
M10 CONTRACTOR CONTROLLED			–	–
M21-M23 CONTRACT DESIGN, MOD, & GFM			–	–
MARGINS			2.03	2.92
DELIVERED LIGHTSHIP			66.09	80.47
NORMAL LOADS:				
(2) F10 SHIPS FORCE			1.42	2.04
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS			.20	.29
(1) F21 SHIP AMMUNITION			2.24	3.21
(2) F30 STORES			.30	.44
(2) F40 SHIP FUEL			9.14	13.12
(2) F50 POTABLE WATER			.30	.44
OTHER (MISC) LIQUIDS			–	–
(2) F60 CARGO (IF ANY)			–	–
DELIVERED FULL LOAD DISPLACEMENT			69.70	100
M24 FUTURE GROWTH MARGIN			3.45	–
MAXIMUM DISPLACEMENT			73.15	
GROUP 567 BUOYANCY				
NORMAL FOILBORNE			– .61	– .88
FB DYNAMIC LIFT (F.L.)			69.09	99.12
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700, LOADS F20)			5.80	8.32
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)			11.18	16.04
USEFUL PAYLOAD (1 & 2)			16.98	24.36

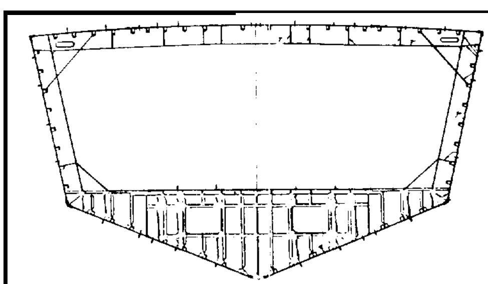
100 HULL

VOLUME

Hullgirder 294 5m³ (1 0,400ft³)
Superstructure 40 3m³ (1,424ft³)
Total 334 8m³ (11 ,824ft³)

AREAS (Hull & Superstructure)
Shell Plating 21 8.8m² (2,355ft²)
Deck 130.1 m² (1,400ft²)
Bulkheads 121 .6m² (1,309ft²)

MATERIAL 5456-H311, H321, & H343 Alum
METHOD OF CONSTRUCTION Welded
HULL GIRDER STRUCTURE DENSITY 2.84
SUPERSTRUCTURE DENSITY 2.17
TOTAL HULL STRUCTURE DENSITY 2 76
HULL IMPACT DESIGN PRESSURE 206.8 KN/M² (30 psi)
FRAME SPACING .28m To .69m (11 "To 27")
NO OF STRUCTURAL BULKHEADS 8
DAMAGE ZONE CRITERIA Two Compartments (Floodable Length)
HULL FORM DESCRIPTION -- Flush Deck, Reverse Sheer Hard Chine, Constant Deadrise



TYPICAL FRAME SECTION

UNCLASSIFIED

SUBSYSTEM CHARACTERISTICS (CONT.)

200 PROPULSION

FB GAS TURBINE (Type & Number) RR Tyne MK 621110 (1)

HB ENGINE (Type & Number) ____ Diesel (1)

FB TURBINE SHP

- Max. Cont. __ 3497.9 mhp (3,450 shp) @ 14.500 rpm
- Max. Inter'm. _ 3497.9 mph (3,450 shp) @ 14,500 rpm

TYPE TRANSMISSION __ 'Z Drive' Single Shaft Bevel Gears

PROPULSOR TYPE ___ 3 Blade Supercavitating, Variable Pitch Propeller

NO. OF PROPULSORS ____ (1)

TYPE FUEL ____ Diesel Oil & JP-5

300 **ELECTRIC** PLANT

TOTAL POWER ____ 125KVA

60 Hz SYS

VOLTAGES USED-- ____ 120-3ϕ

400 COMMAND & SURVEILLANCE

TYPE OF NAV SYS ____ Integrated Automatic Dead Reckoning System

TYPE OF SURVEILLANCE SYS ____ Surface Search Radar

TYPE OF F/C SYS ____ None

• NOTE-FLATRATED

500 **AUXILIARY** SYSTEM

NO. & TYPE OF RUDDER ____ Steerable Aft Strut

TYPE OF ACS ____ Analog

NO. & TYPE OF HEIGHT SENSORS ____ (2) Sonic

567 LIFT SYSTEM

CONFIGURATION. ____ Airplane

% OF WEIGHT DIST'B. __ (AFT) 30% (FWD) — 70%

RETRACTABLE FOIL SYS.

SPAN __ (AFT) — 4.23m (13.9') (FWD) — 4.23m (13.9')

AR ____ 5.5

TYPE CONTROL ____ Incidence

Foil Loading ____ AFT - 59.8KN/M² (1248 psf)

FWD. 64.9 KN/M² (1356psf)

600 OUTFITTING & **FURNISHINGS**

NO. &TYPE COMPARTMENTS ____ (4) Water Tight

AREA PER MAN ____ Officer — 5.3m² (57ft²)

Enlisted- 1 .1 m² (11 .3ft²)

MANNING ____ OFFICER ____ 1

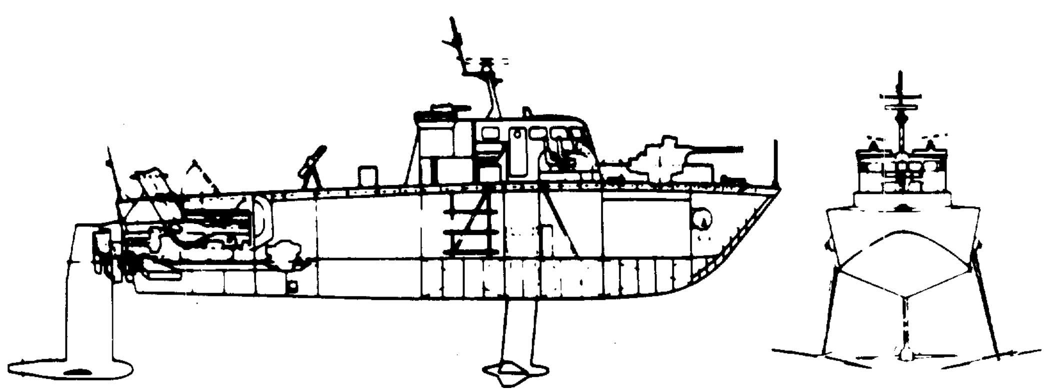
ENLISTED ____ 12

700 WEAPONS

TYPE & NO. OF WEAPONS __ (1) 40 mm MK3 Mod-O Gun

(2) Twin 50 Cal Mg MK 56 Mod-O

(1) Single 81 mm MK2 Mod-O Tripod Mounted Mortar



OUTBOARD PROFILE **BOW VIEW**

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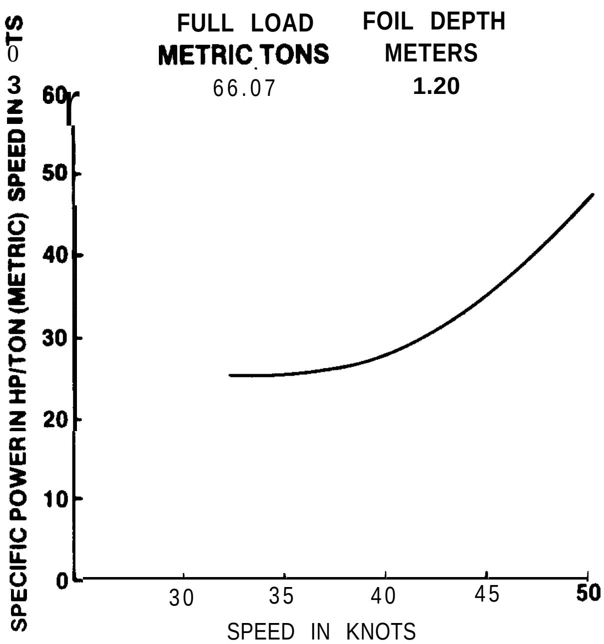
PREDICTED PERFORMANCE CHARACTERISTICS



RETRACTION & EXTENSION TIME ___ 1 Minutes

OPERATIONAL RESPONSE TIME ___ 5 Minutes

TURNING RATES

(Rough & Calm Water) ___ 8.5 °/sec

MIN. TURNING DIAMETER ___ 213m (699')

SPE:EO

- MAX. ___ 52 kts
- Cruise ___ 48 kts
- Min. ___ 35 kts

DESIGN SEASTATE ___ 4

SHIP MOTION

- pitch ___
- Roll ___
- Vert. Accel. ___
- Lat. Accel. ___

DATA NOT AVAILABLE

RANGE ___ 500NM Foilborne
1300NM Hullborne

GENERAL

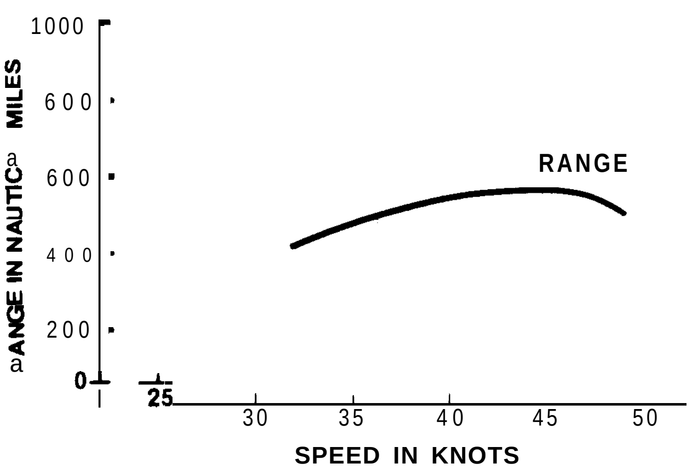
- Designer ___ Grumman
- Builder ___ Grumman
- Delivered ___ 1966

MISSION APPLICABILITY

- Operations ___ Off Shore Patrol
- Warfare Capability ___ Single SUW

PGH-1

RANGE AND ENDURANCE
FOILBORNE PERFORMANCE
FULL LOAD 66.7 TONS



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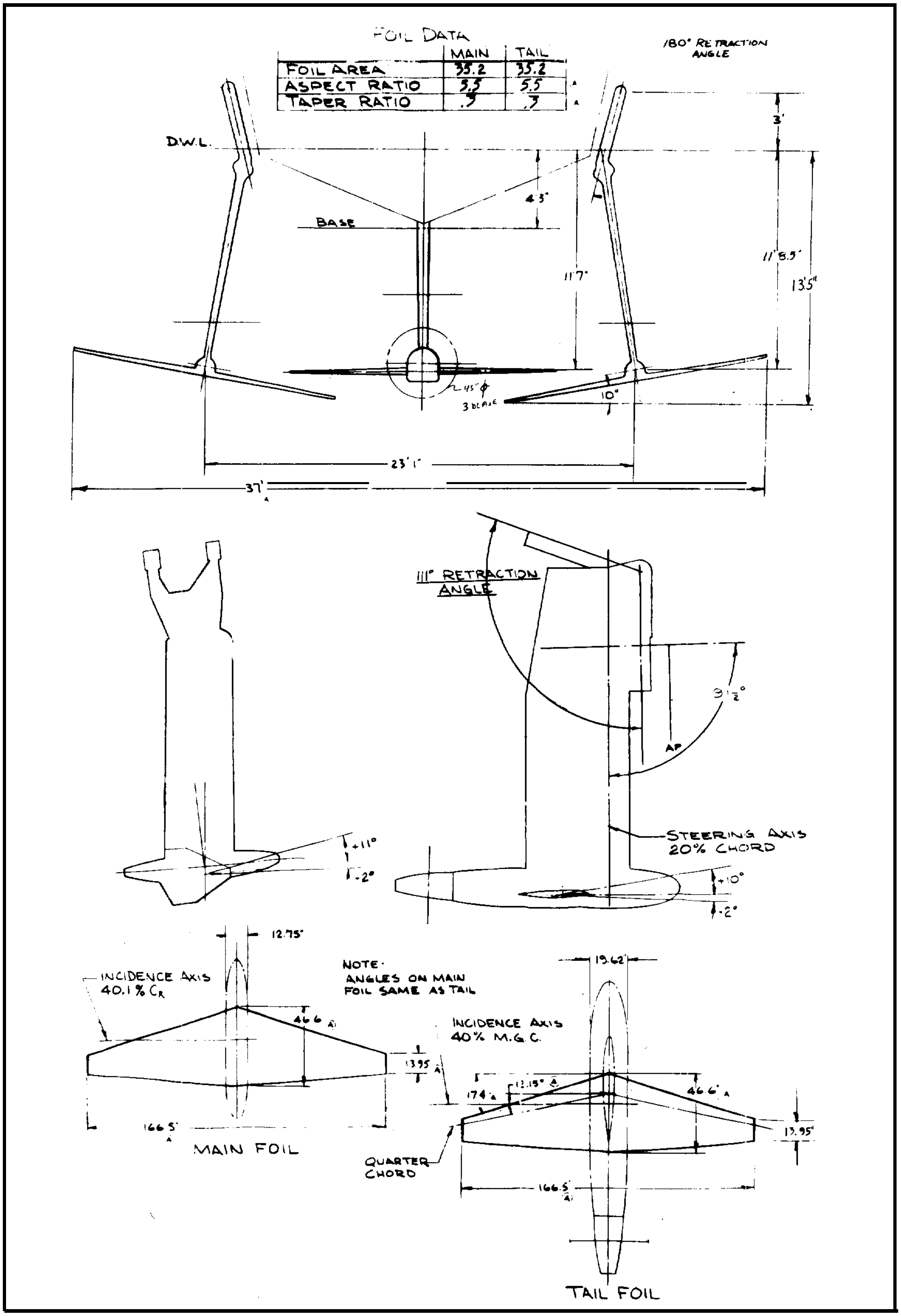
PGH-1 FOIL GEOMETRY

UNCLASSIFIED



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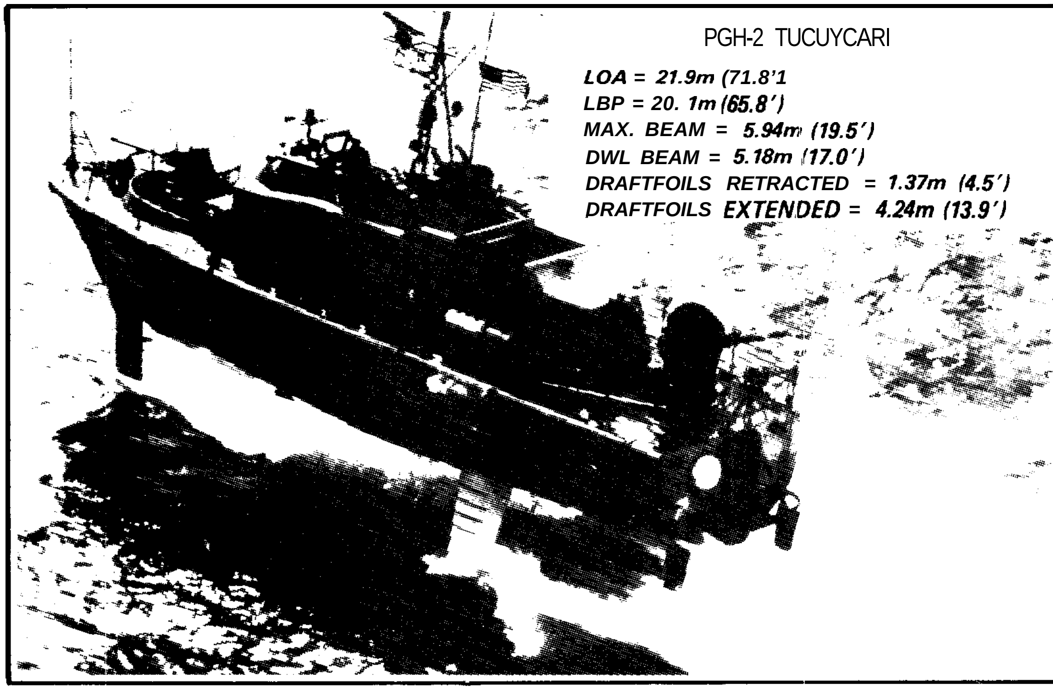


SUBSYSTEM CHARACTERISTICIS

WEIGHTSUMMARY		METRIC TONS	%F L
SWBS	100 HULL STRUCTURE	12.92	21.98
	200 PROPULSION SYSTEMS	7.06	12.10
	300 ELECTRIC PLANT	3.06	5.24
	(1) 400 COMMAND & SURVEILLANCE	1.15	1.97
	500 AUXILIARY SYSTEMS	3.11	5.33
	567 LIFT SYSTEMS	7.04	12.07
	600 OUTFIT & FURNISHINGS	2.97	5.09
	(1) 700 WEAPONS SYSTEMS	2.70	4.63
M10 CONTRACTOR CONTROLLED		—	—
M21-M23 CONTRACT DESIGN, MOD, & GFM		—	—
MARGINS		2.39	4.09
DELIVERED LIGHTSHIP		42.30	72.50
NORMAL LOADS			
	(2) F10 SHIPS FORCE	1.43	2.46
	(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	—	—
	(1) F21 SHIP AMMUNITION	2.33	3.99
	(2) F30 STORES	.49	.84
	(2) F40 SHIP FUEL	11.17	19.14
	(2) F50 POTABLE WATER	.57	.98
	OTHER (MISC) LIQUIDS	.06	.10
	(2) F60 CARGO (IF ANY)	—	—
DELIVERED FULL LOAD DISPLACEMENT		58.34	100
M24 FUTURE GROWTH MARGIN		—	—
MAXIMUM DISPLACEMENT		58.34	
GROUP 567 BUOYANCY			
	NORMAL FOILBORNE	— .51	— .87
	FB DYNAMIC LIFT (F L)	57.83	99.13
MILITARY PAYLOAD (1) INCLUDES SWBS 442 499 & 700 LOADS F20		5.50	9.43
VARIABLE PAYLOAD (2) INCLUDES LOADS F10 F30 F40 F50 AND F60		13.72	23.52
USEFUL PAYLOAD (1 & 2)		19.22	32.95

100 HULL

VOLUME
- Hullgirder ____ 238m³ (8,406ft³)
- Superstructure ____ 68 2m³ (2 40/ li
- Total ____ 306 2m³ (10 81 ill ,

AREAS (Hull & Superstructure)
- Shell Plating ____ 222 9m² (2,400ft²)
- Deck ____ 176 5m² (1 ,900ft²)
- Bulkheads ____ 121 6m² (1 .309ft²)

MATERIAL 5456 H311, H321, H322 & H323 Alum

METHOD OF CONSTRUCTION ____ Welded

HULLGIRDER STRUCTURE DENSITY ____ 2 33

SUPERSTRUCTURE DENSITY 88

TOTAL HULL STRUCTURE DENSITY ____ 2 01

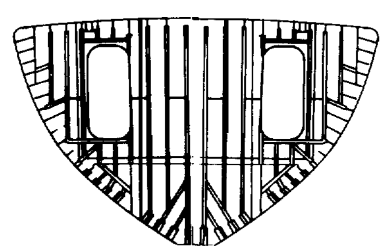
HULL IMPACT DESIGN PRESSURE ____ 310 3 To 7589 KN/M² (6,480 To 15,850 psl)

FRAME SPACING ____ 55m To 91 m (1 8' To 3 0')

NO OF STRUCTURAL BULKHEADS ____ 5

DAMAGE ZONE CRITERIA ____ Two Compartments (Floodable Length)

HULL FORM DESCRIPTION ____ Round Bildge W/Transom Stern Constant Deadrise, Raked Stem Profile Fine Bow Entrance



TYPICAL FRAME SECTION

UNCLASSIFIED

SUBSYSTEM CHARACTERISTICS (CONT.)

200 **PROPULSION**
FB GAS TURBINE (Type & Number) ______ RR-Proteus 15m/530 (1)
HB ENGINE (Type & Number) ______ Diesel (1)
FB TURBINE SHP
Max. Cont ______ 3244 mhp (3,200shp) @ 11,350 rpm
Max. Inter'm ______ 3852mhp (3,800shp) @ 11,700 rpm
TYPE TRANSMISSION ______ NIA
PROPULSOR TYPE ______ Byron Jackson Double Volute Double Suction, Centrifugal Pump (Water Jet)
NO. OF PROPULSOR ______ (1)
TYPE FUEL ______ Diesel Oil & JP-5

300 ELECTRIC PLANT
TOTAL POWER ______ 125 KVA
60 Hz SYS
VOLTAGES USED ______ 450-3ϕ

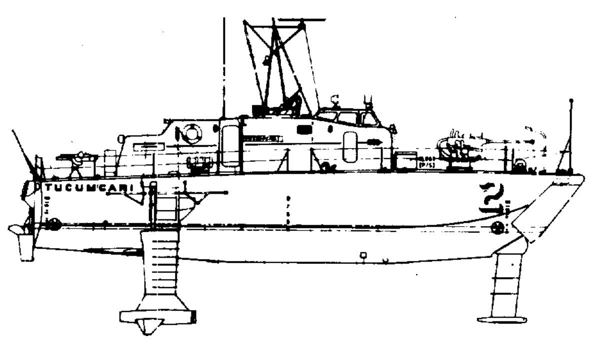
400 COMMAND &SURVEILLANCE
TYPE OF NAV SYS ______ Integrated Automatic Dead Reckoning
TYPE OF SURVEILLANCE SYS ______ Surface Search Radar
TYPE OF F/C SYS ______ None

500 AUXILIARY SYSTEM
NO. & TYPE OF RUDDER ______ Steerable FWD Strut
TYPE OF ACS ______ Analog
NO. & TYPE OF HEIGHT SENSORS ______ (2) Sonic

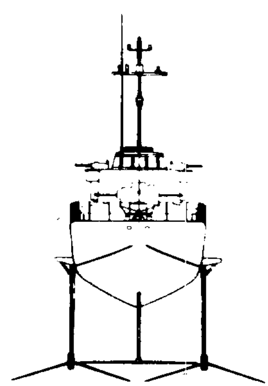
567 LIFT SYSTEM
CONFIGURATION ______ Canard
% OF WEIGHT DIST ______ (AFT) 69% (FWD) 31%
RETRACTABLE FOIL SYS.
SPAN ______ (AFT) 5.2m (16.9') (FWD) 4.9m (16.2')
ASPECT RATIO ______ 7.3
TYPE CONTROL ______ Flap (FWD & AFT Foils)
FOIL LOADING ______ (AFT) 54.3kn/m² (1135psf)
(FWD) 56.7 kn/m² (1185psf)
L/D ______ 12.4 @ 48kts

600 OUTFITTING & FURNISHINGS
NO. & TYPE COMPARTMENTS ______ (4) Watertight
AREA PER MAN ______ Officer - 3.62m² (39ft²)
Enlisted ______ 1.63m² (17.53
MANNING ______ OFFICER ______ 1
EM ______ 12

700 WEAPONS
TYPE & NO OF WEAPONS- (1) 40mm MK3 Mod-0 Gun
(2) Twin 50 cal mg MK56 Mod-0
(1) Single 81 mm MK2 Mod-0 Tripod Mount Mortar



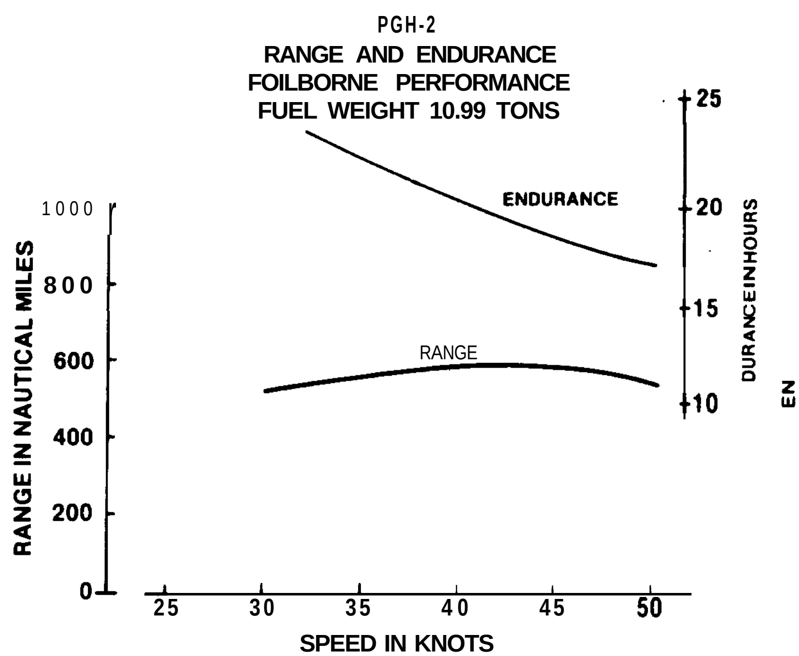
OUTBOARD PROFILE



BOW VIEW

PREDICTED PERFORMANCE CHARACTERISTICS

UNCLASSIFIED



RETRACTION & EXTENSION TIME __ .67 min.

OPERATIONAL RESPONSE TIME __ 8 minutes

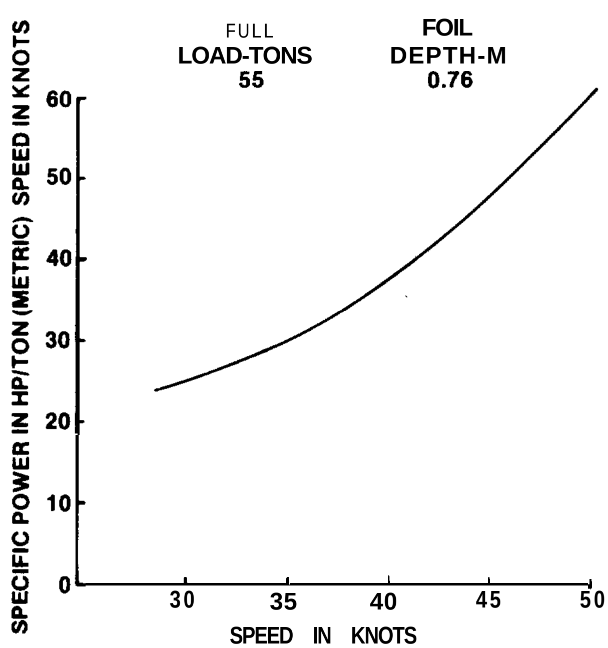
TURNING RATES
(Rough & Calm Water) __________ 12 °/sec
MIN. TURNING DIAMETER ____ 97.8m (320.8')

SPEED
- Max. __________ 50 kts
- Cruise __________ 42.5 kts
- Min. __________ 27 kts

OESIGN SEASTATE __________ 4

SNIP MOTION @ PILOT HOUSE
(Significant Wave length 1.21m)
- Pitch __________ .25°
- Roll __________ .5°
- Vert. Accel. __________ .07g
- Lat. Accel. __________ .04g

RANGE __________ 540NM Foilborne

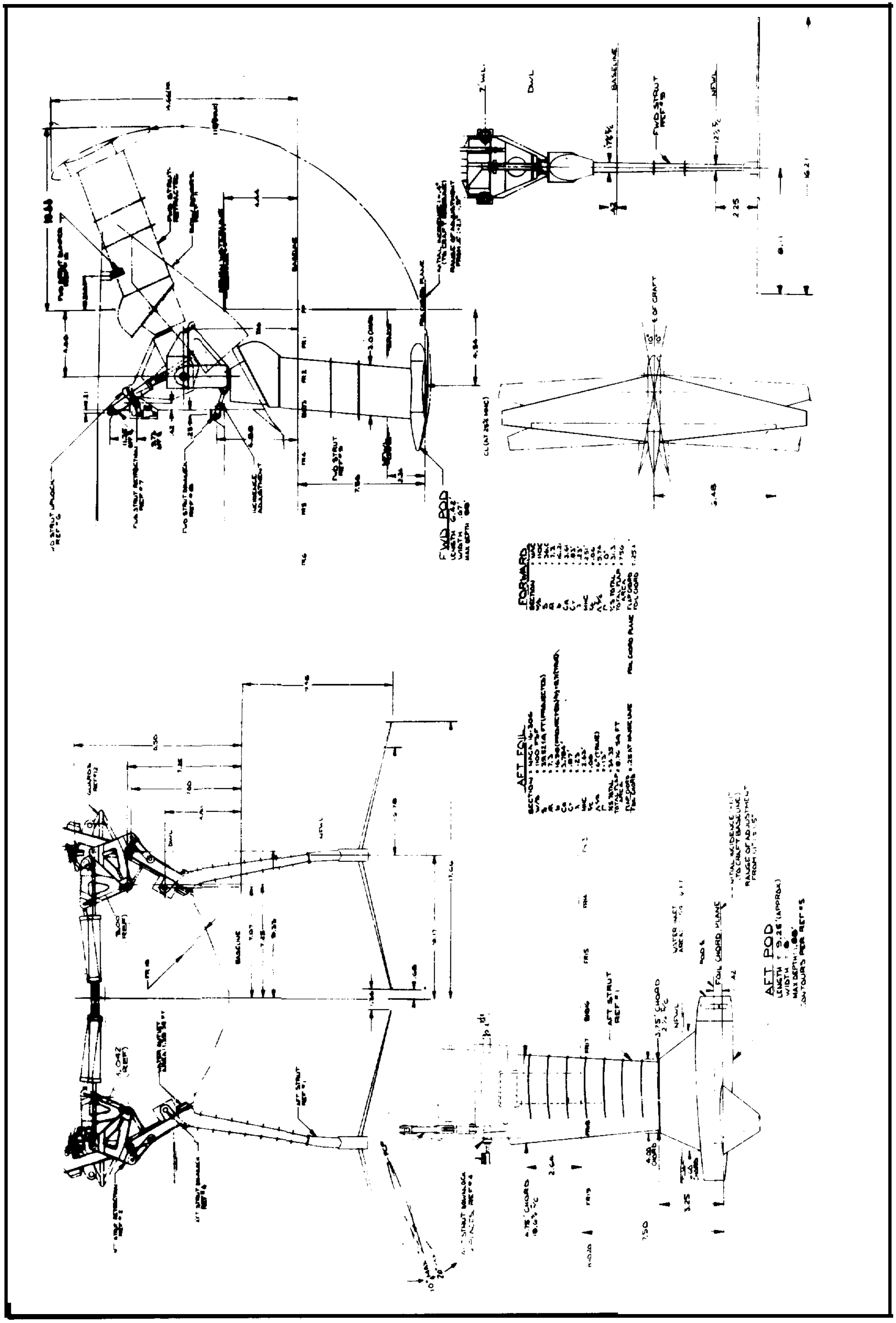


GENERAL
- DESIGNER __________ Boeing
- BUILDER __________ Boeing
- Delivered __________ 1968

MISSION APPLICABILITY
- Operations __________ Off Shore Patrol
- Mission Capability __________ Single SUW

UNCLASSIFIED

PGH-2 FOIL GEOMETRY

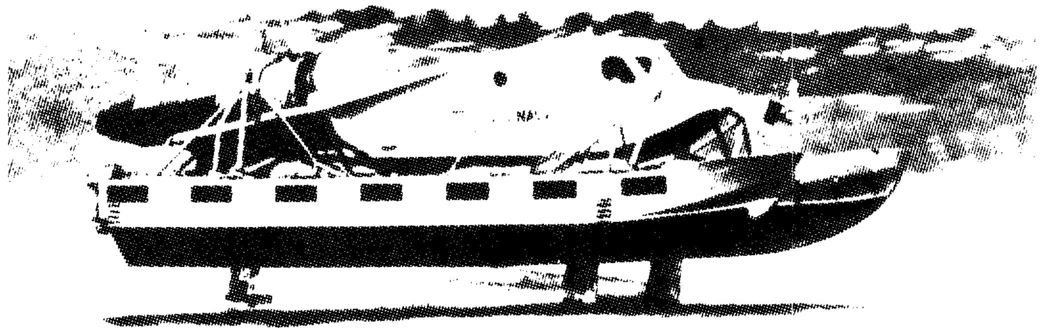


SPECIFIC DESIGNS SHIP CHARACTERISTICS

UNCLASSIFIED

(HTC) FRESH-I

LOA = 17.4m 157.27
LBP = 14.4m 147.33
MAX. BEAM = 6.9m (22.5')
DWL BEAM = 6.9m (22.5')
DRAFT FOILS EXTENDED = 5. 1m (16.7')

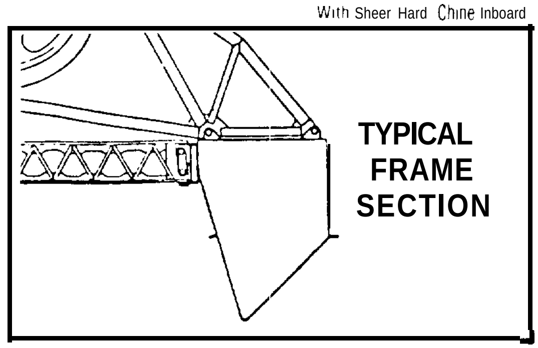


SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY			METRIC TONS	% F L.
SWBS	100	HULL STRUCTURE	6 26	3626
	200	PROPULSION SYSTEMS	2.95	18.01
	300	ELECTRIC PLANT	.35	2.11
	(1) 400	COMMAND & SURVEILLANCE	.05	.31
	500	AUXILIARY SYSTEMS	.55	3.35
	567	LIFT SYSTEMS	1.64	11.24
	600	OUTFIT & FURNISHINGS	.41	2.48
	(1) 700	WEAPONS SYSTEMS		
M10 CONTRACTOR CONTROLLED			-	-
M21-M23 CONTRACT DESIGN, MOD, & GFM			-	-
MARGINS			-	-
DELIVERED LIGHTSHIP			12.41	75.84
NORMAL LOADS:				
(2) F10 SHIPS FORCE			.23	1.43
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS			-	-
(1) F21 SHIP AMMUNITION			-	-
(2) F30 STORES			.01	.06
(2) F40 SHIP FUEL			3.14	19.19
(2) F50 POTABLE WATER			.16	.99
OTHER (MISC) LIQUIDS			.07	.43
(2) F60 CARGO (IF ANY)			.34	2.05
DELIVERED FULL LOAD DISPLACEMENT			16.36	100
M24 FUTURE GROWTH MARGIN			-	-
MAXIMUM DISPLACEMENT			16.36	
GROUP 567 BUOYANCY				
NORMAL FOILBORNE			— .05	— .31
FB DYNAMIC LIFT (F.L.)			16.31	99.69
MILITARY PAYLOAD (1) INCLUDES SWBS 442 499 & 700 LOADS F20				
VARIABLE PAYLOAD (2) INCLUDES LOADS F10 F30 F40 F50 AND F60			3.94	24.10
USEFUL PAYLOAD (1 & 2)			3.94	24.10

100 HULL
VOLUME
Hullgirder ____ 7 3 51m (2 596ft
Superstructure ____ 22.43m³ (792ft³)
Total ____ 95.71m³ (3,380ft³)
AREAS (Hull & Superstructure)
Shell Plating 131.55m² (1,416ft²)
Deck ____ 35.12m² (378ft²)
Bulkheads ____ 10.03m² (108ft²)
MATERIAL ____ 5456 & 2014 16 A lm
METHOD OF CONSTRUCTION ____ Welded & Riveted
HULL GIRDER STRUCTURE DENSITY ____ 2 7 :
SUPERSTRUCTURE DENSITY ____ 2 57
TOTAL HULLSTRUCTURE DENSITY ____ 2 73
HULL IMPACT DESIGN PRESSURE ____ Unknown

FRAME SPACING ____ 76m (2 5')
NO OF STRUCTURAL BULKHEADS ____ 6 Per Hull
DAMAGE ZONE CRITERIA ____ FR 3 FR 19 Each Hull
(Floodable Length)
HULL FORM DESCRIPTION ____ Catamaran V Bottom
With Sheer Hard Chine Inboard



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200 **PROPULSION**
FB GAS TURBINE (Type & Number) P W Turbo-Fan YTF-33-P. (1)
HB ENGINE (Type & Number) ________ 75HP Outboard (2)
• FB TURBINE SHP (ESTIMATED)
Max. Cont. - 2331.9 MHP (2,300 shp) @ 9600 rpm
Max. Inter'm. ___ 2534.7 mhp (2,500 shp) @ 9900 rpm
TYPE TRANSMISSION ________ None
PROPULSOR TYPE ________ None

NO. OF PROPULSORS ________ NIA
TYPE FUEL ________ JP-5

300 ELECTRIC PLANT
TOTAL POWER ________ 30KVA DC - 1.9KW DC
400 Hz SY S
VOLTAGES USED-- ________ 1201200 3φ

400 COMMAND & **SURVEILLANCE**
TYPE OF NAV SYS ____ Magnetic Compass, Gyrocompass, Pitot-Electric Log & Speed Indicator
TYPE OF SURVEILLANCE SY S ________ None
TYPE OF F/C SYS ________ None
* NOTE 18.000 LBS OF THRUST @ 9900 RPM (MEASURED)

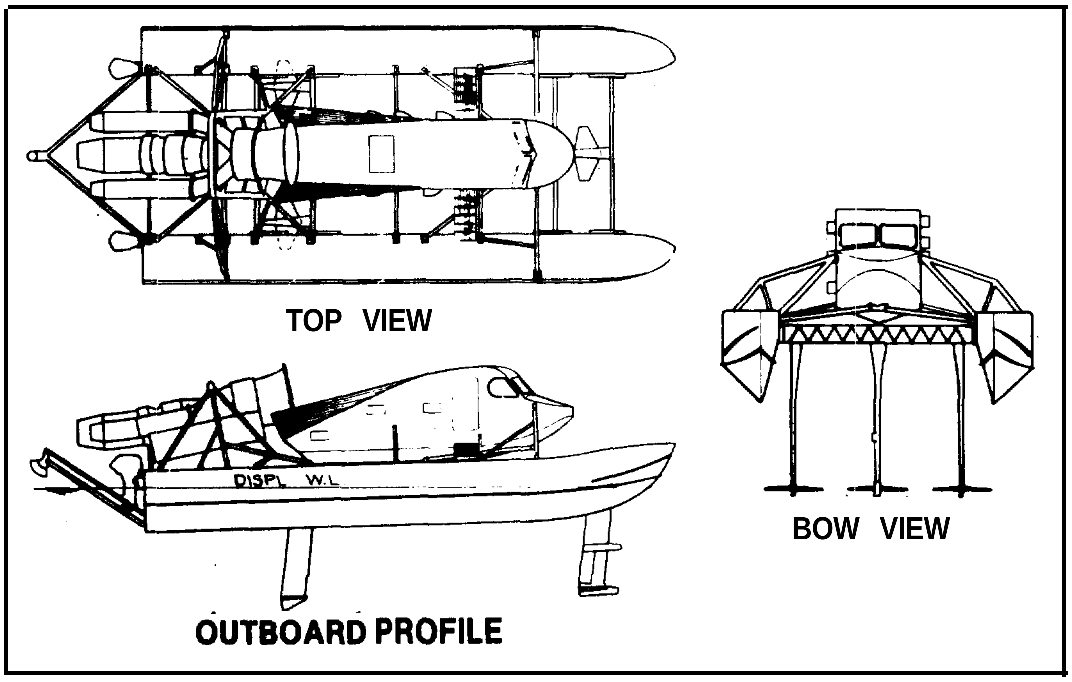
500 **AUXILIARY** SYSTEM
NO. & TYPE OF RUDDER ___ (1) FWD Strut Trailing Edge
TYPE OF ACS ________ Analog
NO. & TYPE OF HEIGHT SENSORS ________ (1) Sonic

567 **LIFT** SYSTEM
CONFIGURATION ________ Canard or Airplane
% OF WEIGHT DIST'B. ________ 33% Each

FIXED
SPAN ________ AFT 1.4m (4.7') FWD 1.4m (4.7')
ASPECT RATIO ________ 3.0
TYPE CONTROL ________ Flaps FWD & AFT Foils
LID ________ 3.3
FOIL LOADING ________ (AFT) 95.8 KN/m^2 (2000 psf)
(FWD) 95.8 KN/m^2 (2000 psf)

600 **OUTFITTING &** FURNISHINGS
NO. & TYPE COMPARTMENTS __ 4 Per Hull, Water Tight & Pilot House
MANNING ________ Officer / Enlisted } 3 Man Test Crew

700 WEAPONS
TYPE & NO. OF WEAPONS ________ None



TOP VIEW

BOW VIEW

OUTBOARD PROFILE

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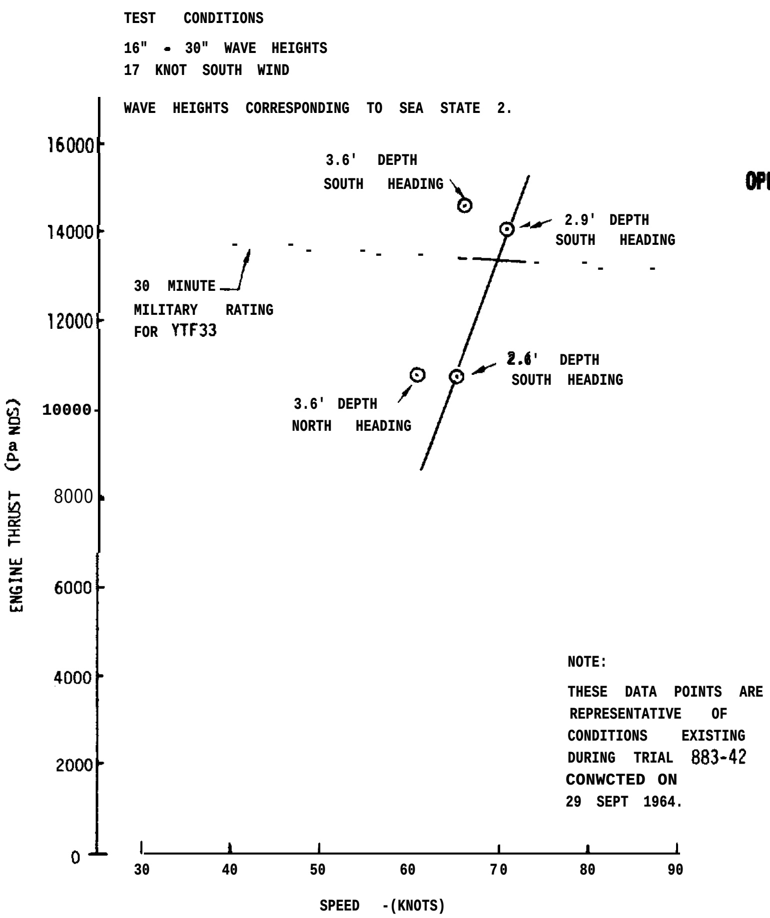
PREDICTED PERFORMANCE CHARACTERISTICS



RETRACTION & EXTENSION TIME ___ N/A

OPERATIONAL RESPONSE **TIME** ________ N/A

TURNING RATES
(Rough & Calm Water) ____________ 4 °/sec
MI. **TURNING** MAMETEA ____ 749m (2,457')

SPEED
LX. ________________________ a2 kts
Cruise ________________________ N/A
Min. ________________________ 47 kts

DESIGN SEASTATE ______________ N/A

SHIP MOTION
Pitch
Roll
Vert. Accell
Lat. Accel.
} NO MEASUREMENTS MADE

RANGE ________________________ N/A

GENERAL
Designer ________________ Boeing
Builder ________________ Boeing
Delivered ________________ 1963

MISSION APPLICABILITY
Operations _____ Research & Development (Test Platform)

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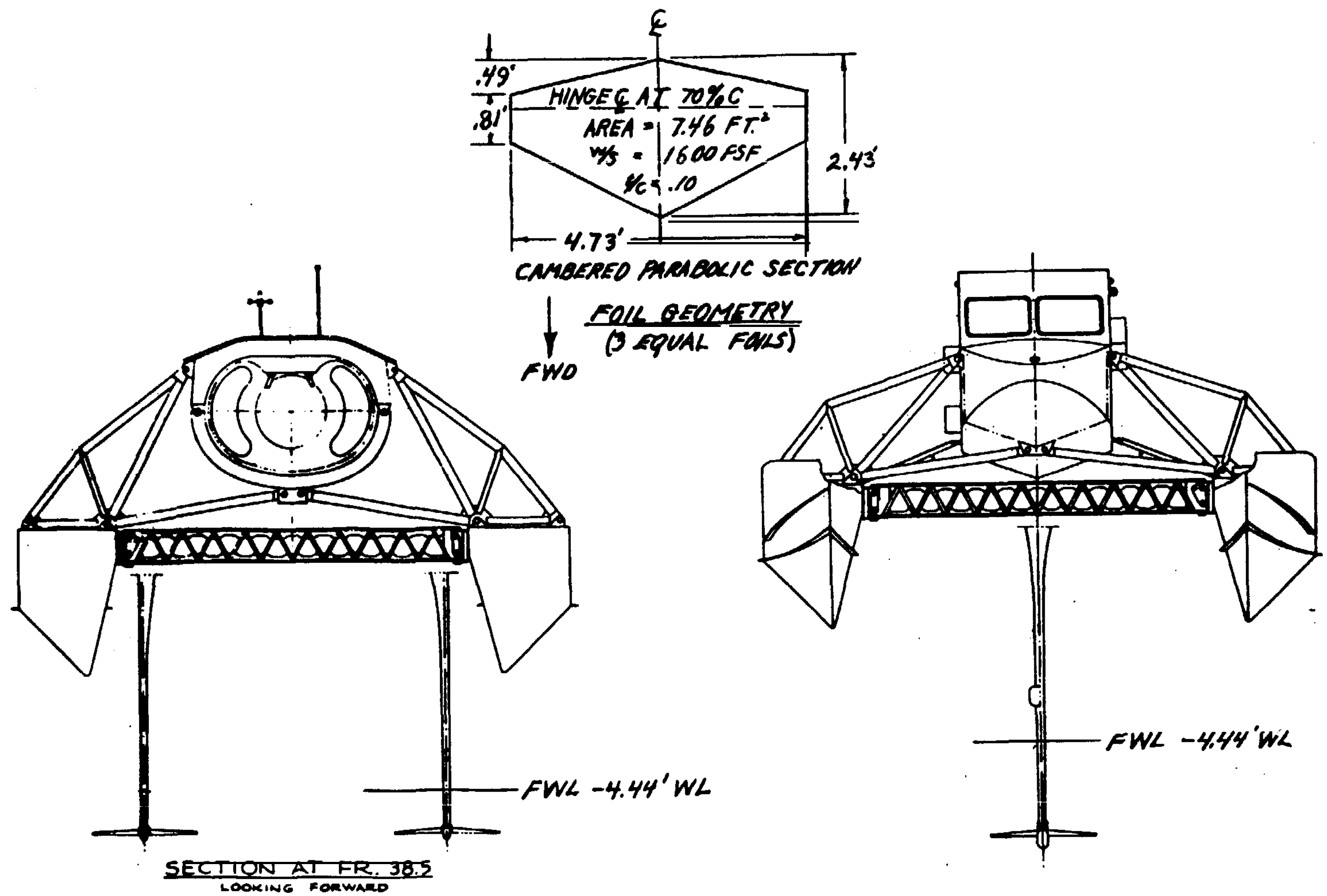
[redacted]

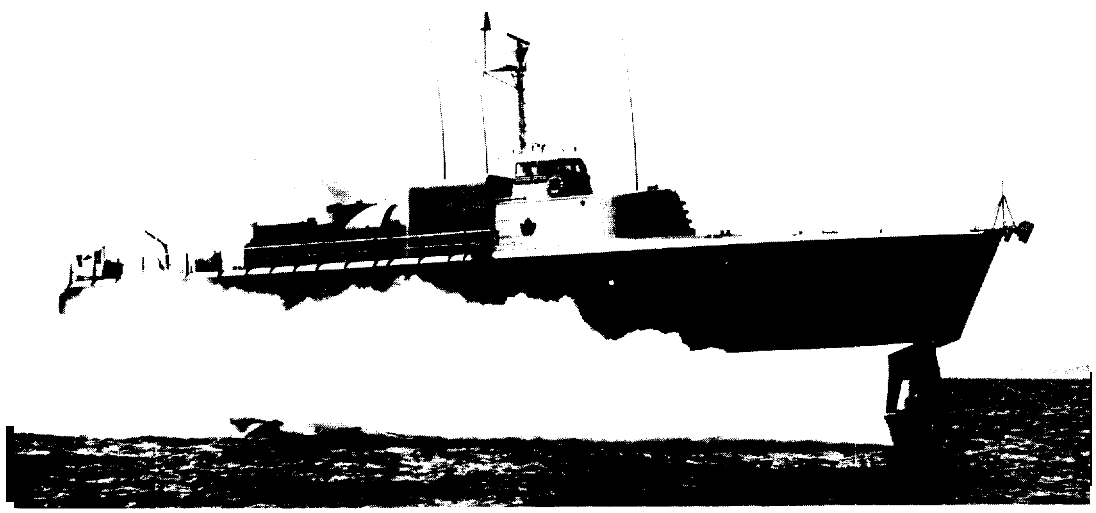
(HTC) FRESH-1 FOIL GEOMETRY



SPECIFIC DESIGNS SHIP CHARACTERISTICS

FHE-400HMSBARSD'OR

LOA = 45.95m (150.8')
LBP = 44.65m (146.5')
MAX. BEAM = 6.55m 121.57
DWL BEAM = 5.67m (18.9')
DRAFT FOILS EXTENDED = 7.16m (23.5')



SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY			METRIC TONS	% F.L.
SWBS	100	HULL STRUCTURE	35.81	16.62
	200	PROPULSION SYSTEMS	34.61	16.06
	300	ELECTRIC PLANT	1.47	.68
	(1) 400	COMMAND & SURVEILLANCE	18.88	8.76
	500	AUXILIARY SYSTEMS	12.79	5.94
	567	LIFT SYSTEMS	42.45	19.70
	600	OUTFIT & FURNISHINGS	10.56	4.90
	(1) 700	WEAPONS SYSTEMS	3.27	1.52
M10 CONTRACTOR CONTROLLED			—	—
M21-M23 CONTRACT DESIGN, MOD, & GFM			—	—
MARGINS			−1.15	−.53
DELIVERED LIGHTSHIP			158.69	73.66
NORMAL LOADS				
(2) F10 SHIPS FORCE			2.35	1.09
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS			—	—
(1) F21 SHIP AMMUNITION			2.77	1.29
(2) F30 STORES			2.58	1.20
(2) F40 SHIP FUEL			43.51	20.19
(2) F50 POTABLE WATER			1.30	.60
OTHER (MISC) LIQUIDS			4.25	1.97
(2) F60 CARGO (IF ANY)			—	—
DELIVERED FULL LOAD DISPLACEMENT			215.45	100
M24 FUTURE GROWTH MARGIN			—	—
MAXIMUM DISPLACEMENT			215.45	
GROUP 567 BUOYANCY				
NORMAL FOILBORNE			— DNA	— —
FB DYNAMIC LIFT (F.L.)			DNA	—
MILITARY PAYLOAD (1) INCLUDES SWBS 447 499 & 700, LOADS F20			22.42	10.41
VARIABLE PAYLOAD (2) INCLUDES LOADS F10, F30, F40, F50, AND F60			53.99	25.06
USEFUL PAYLOAD (1 & 2)			76.41	35.47

100 HULL

VOLUME

- Hullgirder ______ 779.9m³ (27,540ft³)
- Superstructure ______ 101.2m³ (3,575ft³)
- Total ______ 881.1m³ (31,115ft³)

AREAS (Hull & Superstructure)

- Shell Plating ______ 469.6m² (5,055ft²)
- Deck ______ 427.8m² (4,605ft²)
- Bulkheads ______ 92.4m² (995ft²)

MATERIAL ______ (Alcan D54S) 5083 Alum.

METHOD OF CONSTRUCTION ______ Welded

HULL GIRDER STRUCTURE DENSITY ______ 2.87

SUPERSTRUCTURE DENSITY ______ 1.34

TOTAL HULL STRUCTURE DENSITY ______ 2.97

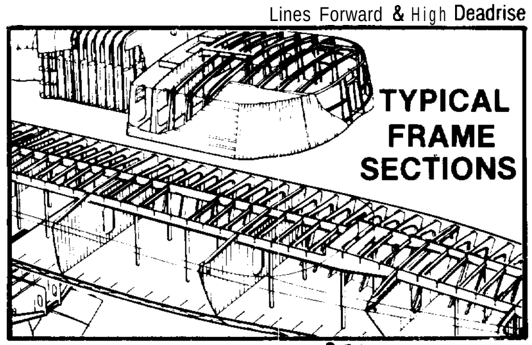
HULL IMPACT DESIGN PRESSURE ______ 84.1 Kn/m² (12.2PSI @ DWL)

FRAME SPACING ______ .76m (2.53

NO. OF STRUCTURAL BULKHEAD- ______ 7

DAMAGE ZONE CRITERIA ______ DATA NOT AVAILABLE

HULL FORM DESCRIPTION -Slender Hull With Extremely Fine. Lines Forward & High Deadrise



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SUBSYSTEM CHARACTERISTICS (CONT.)

200 **PROPULSION**
FB GAS TURBINE (Type & Number) ____ P & W FT4A-2 (1)

HB ENGINE (Type & Number) - 16YJCM Diesel(l)
FB TURBINE SHP
Max. Cont. ____ 20278 mhp (20,000 shp)
Max. Inter'rn. ____ 25348 rnhp (25,000 shp)
TYPE TRANSMISSION ____ 'Z Drive', With Twin Down Shafts In Each Strut
PROPULSDR TYPE ____ Sup&cavitating, Fixed Pitch Propeller
NO. OF PROPULSORS ____ (2)
TYPE FUEL ____ JP-5

300 ELECTRIC PLANT
TOTAL POWEI ____ 220 KVA
60 Hz & 400 Hz SYS
VOLTAGES USED ____ 115-30

400 **COMMAND & SURVEILLANCE**
TYPE OF NAV SYS ____ Gyrocompass With Readouts, Depth Sounder, Radar
TYPE OF SURVEILLANCE SYS ____ None
TYPE OF F/C SYS ____ No Data Available (Computer System Designed, Never Fitted)

500 AUXILIARY SYSTEM
TYPE OF STEERING ____ FWD Foil 'All Moving'.

TYPE OF ACS ____ (Stabilization Only)
ND. & TYPE OF HEIGHT SENSORS ____ None

567 LIFT SYSTEM
CONFIGURATION ____ Surfacing-Piercing
% OF WEIGHT DIST'B. -- AFT 90% FWD 10%

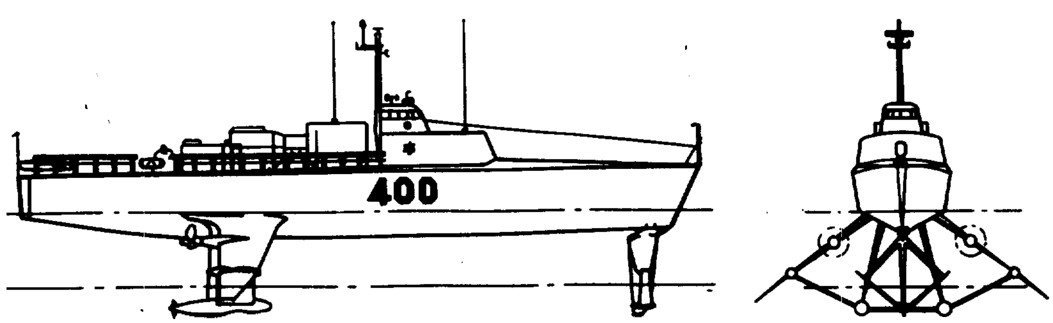
FIXED FOIL SYS.
SPAN ____ AFT 20.1m (66') FWD 6.4m (21')
TYPECONTROL ____ Incidence
LID ____ 6.5 @ 50kts

600 **OUTFITTING & FURNISHINGS**

MANNING ____ Officers,- ____ (4)
NCO'S ____ (4)
EM ____ (12)

AREA PER MAN ____ Officer ____ } DATA NOT AVAIL.
Enlisted ____ }

700 **WEAPONS**
TYPE & NO OF WEAPONS __ (12) MK44/46 Torpedoes



OUTBOARD VIEW **BOW VIEW**

UNCLASSIFIED [redacted]

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PREDICTED PERFORMANCE CHARACTERISTICS

TURNING RATES
(Rough & Calm Water) ____________ 4.8°/Sec @ 40 KTS
MIN. TURNING DIAMETER ____________ 457.2m (1500')

SPEED
MAX. ____________ 60 KTS
CRUISE ____________ 50 KTS
MIN. ____________ 30 KTS

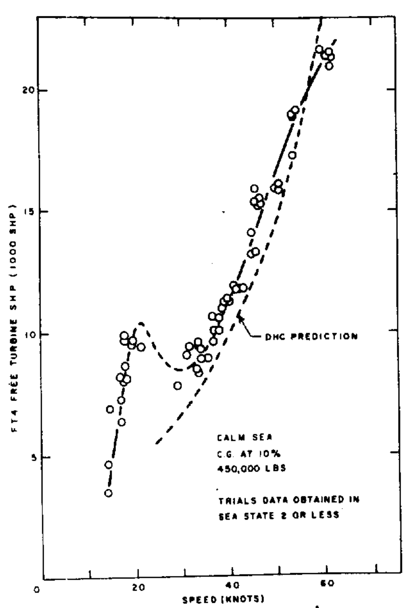
SHIP MOTION
FOILBORNE SEASTATE 5
PITCH ____________ 2.4"
ROLL ____________ 4.6"
VERT. ACCEL. ____________ .46g (STERN)
LAT. ACCEL. ____________ .21 g (OPNS RM)

RANGE
FOILBORNE ____________ DATA NOT AVAILABLE
HULLBORNE - - 3500NM @ 10.8 KTS

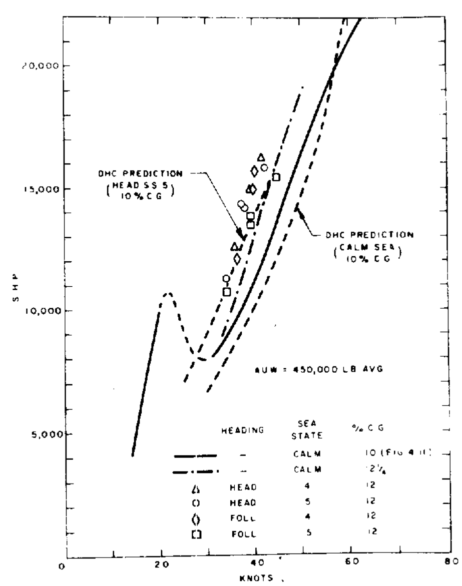
GENERAL
DESIGNER ____________ DeHavelland Aircraft of Canada
BUILDER ____________ DeHavilland Aircraft of Canada
DELIVERED ____________ 1967

MISSION APPLICABILITY
OPERATIONS ____________ Offshore Patrol
CAPABILITY ____________ Single - ASW

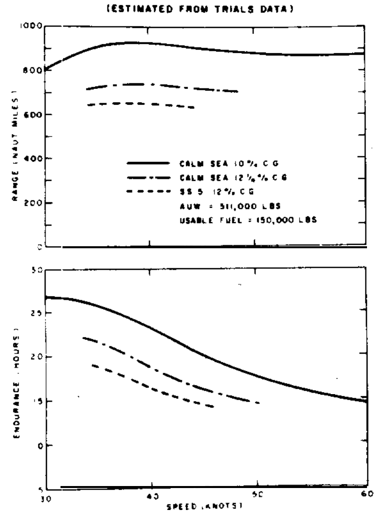
FT4 FREE TURBINE SHP vs SPEED



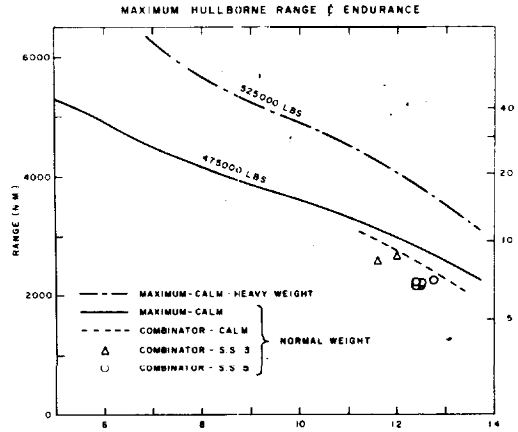
FOILBORNE PROPULSION SHP vs SPEED



RANGE & ENDURANCE
(ESTIMATED FROM TRIALS DATA)



MAXIMUM HULLBORNE RANGE & ENDURANCE



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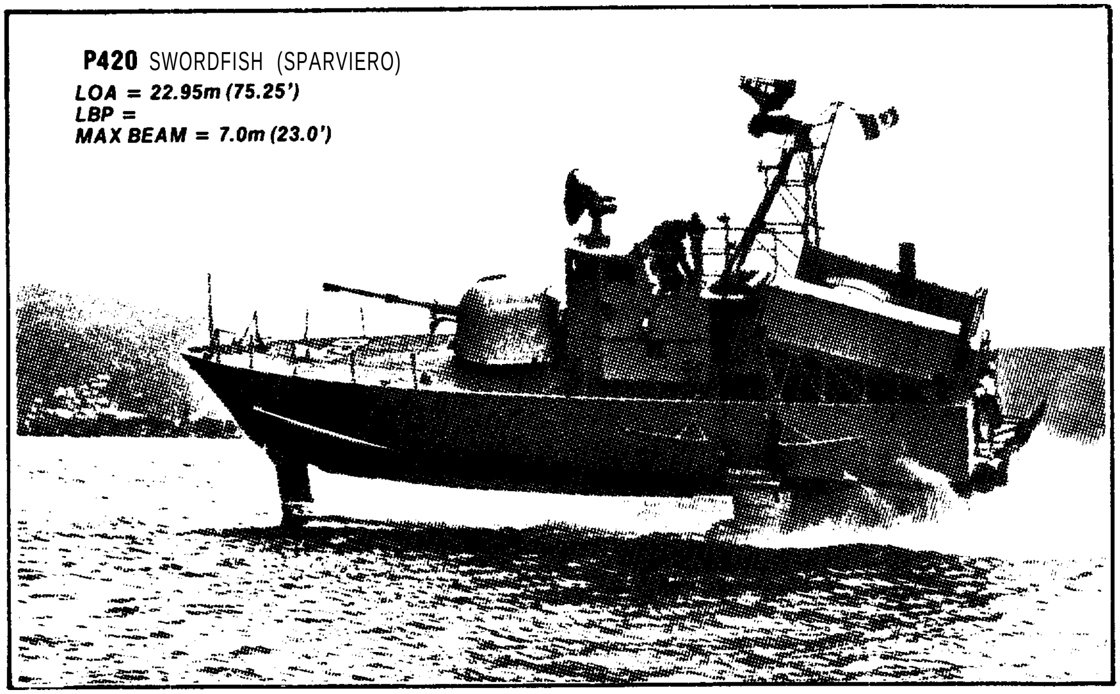
P420 SWORDFISH (SPARVIERO)

LOA = 22.95m (75.25')
LBP =
MAX BEAM = 7.0m (23.0')



SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY	METRIC TONS	% F.L.
SWBS 100 HULL STRUCTURE	15.28	24.09
200 PROPULSION SYSTEMS	8.07	12.72
300 ELECTRIC PLANT	1.78	2.81
(1) 400 COMMAND & SURVEILLANCE	4.76	7.50
500 AUXILIARY SYSTEMS	10.15	16.00
567 LIFT SYSTEMS	DATA NOT AVAIL.	
600 OUTFIT & FURNISHINGS	1.84	2.90
(1) 700 WEAPONS SYSTEMS	8.64	13.62
M10 CONTRACTOR CONTROLLED	.38	.60
M21-M23 CONTRACT DESIGN, MOD. & GFM	★ 1.73	2.73
MARGINS ★ GFM (GR. 700) IS 1.72 MT OVERWEIGHT	1.35	2.13
DELIVERED LIGHTSHIP	51.06	80.49
NORMAL LOADS:		
(2) F10 SHIPS FORCE	1.00	1.58
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	.06	.09
(1) F21 SHIP AMMUNITION	2.88	4.54
(2) F30 STORES	.20	.32
(2) F40 SHIP FUEL	7.88	12.42
(2) F50 POTABLE WATER	.30	.47
OTHER (MISC) LIQUIDS	.05	.08
(2) F60 CARGO (IF ANY)		
DELIVERED FULL LOAD DISPLACEMENT	63.44	100
M24 FUTURE GROWTH MARGIN	2.90	
MAXIMUM DISPLACEMENT	66.35	
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	— .70	– 1.10
FB DYNAMIC LIFT (F.L.)	62.74	98.90
MILITARY PAYLOAD (1) INCLUDES SWBS [illegible] 499 & 700 AND F20	16.35	25.77
VARIABLE PAYLOAD (2) INCL. LOADS F10, F30, F40, F50 AND F60	9.43	14.86
USEFUL PAYLOAD (1 & 2)	25.78	40.64

100 HULL

AREAS (Hull & Superstructure)

- Shell Plating ______ 237.8m²
- Deck ______ 128.2m²
- Bulkheads ______ 64.1 m²

MATERIAL ______ Alum 5083

METHOD OF CONSTRUCTION -Welded Alum Hull & Deckhouse

HULL GIRDER STRUCTURE DENSITY ______ 23.42 Kg/m³

SUPERSTRUCTURE DENSITY ______ 14.03 Kg/m³

TOTAL HULL STRUCTURE DENSITY ______ 41.49 Kg/m³

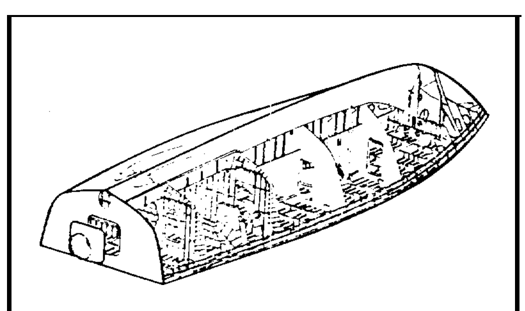
HULL IMPACT DESIGN PRESSURE ______ 7713 Kg/m²

FRAME SPACING ______ 91.4 cm

NO. OF STRUCTURAL BULKHEADS ______ 5 Watertight

DAMAGE ZONE CRITERIA ______ 2 Compartment Flooding (Floodable Length)

HULL FORM DESCRIPTION ______ Round Bottomed Motor Boat With High Deadrise



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SUBSYSTEM CHARACTERISTICS (CONT.)

200 PROPULSION

FB GAS TURBINE (TYPE & NO.) ________ Rolls Royce Marine Proteus (1) 15M/553

HB ENGINE (TYPE & NO.) ________ GM 6V53 (1)

FB TURBINE SHP

MAX. CONT. 3214.1 mhp (3170 shp) @ 26°C

MAX. INTER'M. __ 4015.1 mhp (3960 shp) @ 26°C
4562.5 mhp (4500 shp) @ 15°C

TYPE TRANSMISSION ________ N/A

PROPULSOR TYPE ________ Byron Jackson Double Volute, Double Suction, Centrifugal Pump (Waterjet)

NO OF PROPULSORS ________ (2)

TYPE FUEL ________ Diesel No. 2

300 ELECTRIC PLANT

TOTAL KVA ________ 150 KVA

60HZ & 400HZ SYS

VOLTAGES USED ________ 208V 3Φ 400 Hz
30 VDC 400 Hz

400 COMMAND & SURVEILLANCE

TYPE OF NAV SYS ________ Bendix Dr Sys, Chesapeake EM Log & Brown Gyro Compass

TYPE Of SURVEILLANCE SYS ________ NAV Radar SMA Mod 3RM 7-250

TYPE OF F/C SYS F/C Radar (Missiles)-SMA Mod 3RM 7-250
F/C Radar (Cannon) Selenia Mod Orion 1 OX
F/C Console: San Giorgio NA 10 Mod 1 With Integrated Dalmo Victor Lowlight Level TV (Camera Integrated in Gun Control Antenna)

500 AUX-SYS

NO. & TYPE OF RUBBER ________ F/B One Swivelled FWO Strut
H/B One Schottel-Werft SRP-100 Outdrive 360°

TYPE OF ACS (Analog) Boemg Model 2556600

NO. & TYPE OF HEIGHT SENSORS 2 Boemg Ultrasonic Model 300

567 LIFT SYS

CONFIGURATION ________ Canard

% OF WEIGHT DIST'B ____ FWD .. 35% AFT 65%

RETRACTABLE FOIL SYS.

SPAN ________ 4 94M

ASPECT RATIO ________ 73

TYPE CONTROL ____ Trailing Edge Flap With Auto Pitch Trim

L/D ________ 11.5

600 OUTFITTING & FURNISHINGS

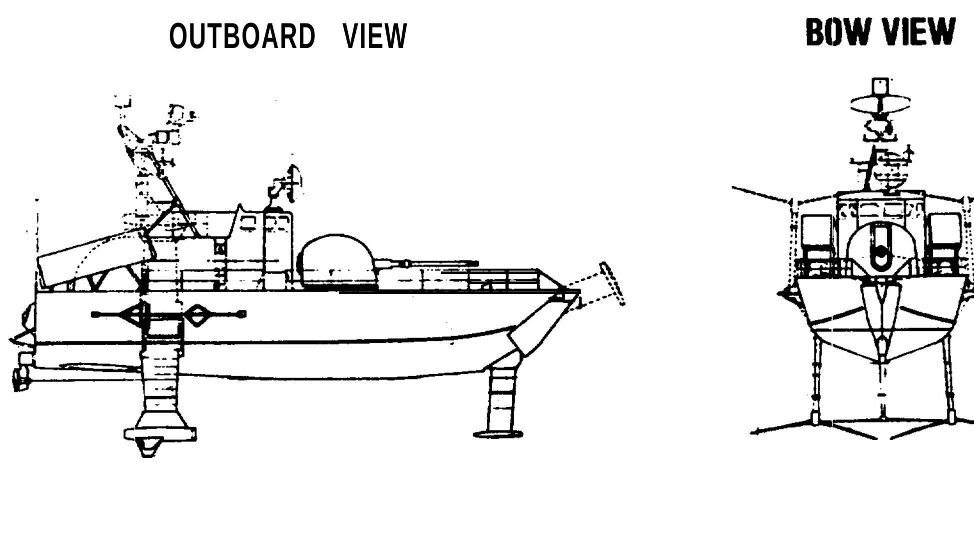
NO & TYPE COMPARTMENTS ____ 10 Compartments

MANNING ____ OFFICER ________ 1
EM ________ 12

AREA PER MAN ____ OFFICER ________ 2.6M²
ENLISTED ________ 1.6M²

700 WEAPONS

TYPE & NO OF WEAPONS ________ (1)-OTO Melara Compact 76162 Cannon
(2)-Otomat Anti-Ship Missiles



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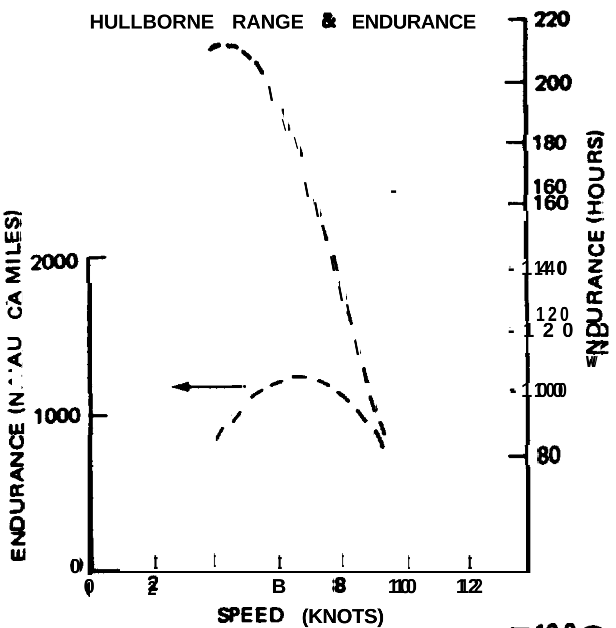
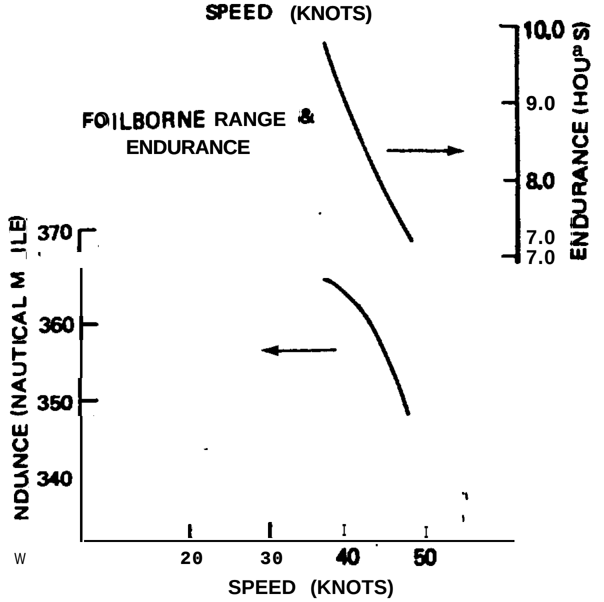
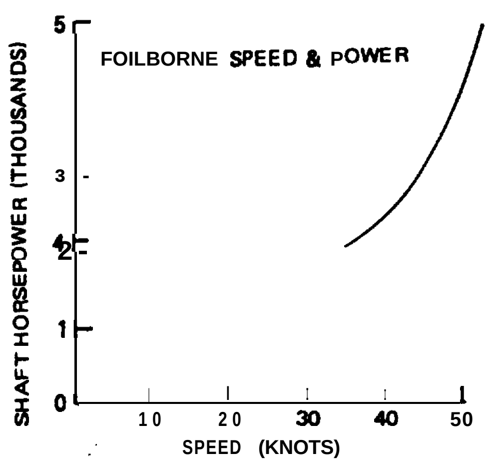
PREDICTED PERFORMANCE CHARACTERISTICS







RETRACTION & EXTENSION TIME ____________ 1.0 min.

OPERATIONAL RESPONSE TIME ______________ 5.0 MIN.

(Dead Ship to FIB @ 35K)

TURNING RATES ______________ -Calm 10 °/SEC

(Rough & Calm Water) Rough 7 °/SEC

MIN. TURNING DIAMETER ____________ 125M @ 40 KTS

SPEED

Max. ____________________________ 52.7

Cruise __________________________ 43

Min. ____________________________ 33

DESIGN SEASTATE ______________________ 4

SHIP MOTION

Pitch ____________________________ 0.8°

Roll _____________________________ 0.6°

Vert. Accel. ___________________ 0.1g**

Lat. Accel. ____________________ 0.05g

GENERAL

DESIGNER ____________________ Boeing-Alinavi

BUILDER _____________________ Boeing-Alinavi

Delivered ____________________ 1974

MISSION APPLICABILITY

OPERATIONS ________________ Offshore Patrol

WARFARE CAPABILITY ______________ Single, SUW

- MAX. RMS VALUE AT WORST S/S 4 HEADINGS IN AT 54.77 MTONS
- * AT STEERING STATION

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SPECIFIC DESIGNS SHIP CHARACTERISTICS

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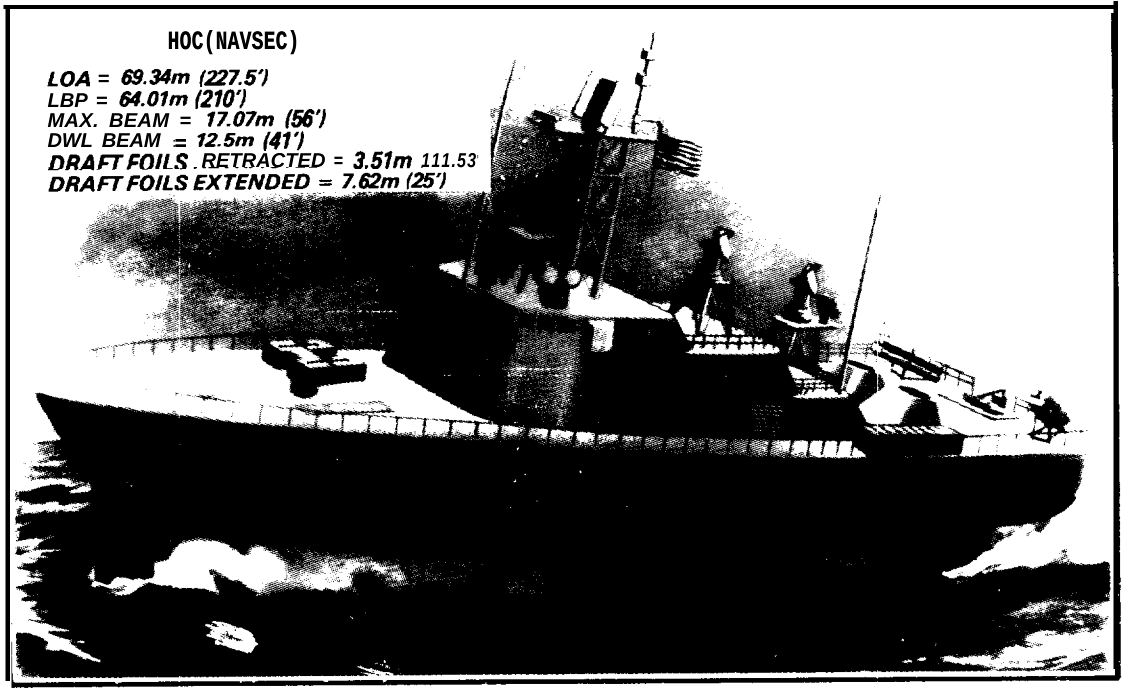


SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY		METRIC TONS	%F.L.
SWBS	100 HULL STRUCTURE	228.61	17.61
	200 PROPULSION SYSTEMS	60.96	4.69
	300 ELECTRIC PLANT	40.64	3.13
	(1) 400 COMMAND & SURVEILLANCE	80.37	6.19
	500 AUXILIARY SYSTEMS	238.77	18.39
	567 LIFT SYSTEMS (NOT INCLUDED IN STUDY)	DNA	
	600 OUTFIT & FURNISHINGS	44.71	3.44
	(1) 700 WEAPONS SYSTEMS	26.93	2.07
M10 CONTRACTOR CONTROLLED		–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM		–	–
MARGINS		108.11	8.33
DELIVERED LIGHTSHIP		829.09	63.85
NORMAL LOADS.			
	(2) F10 SHIPS FORCE	10.16	.78
	(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS		
	(1) F21 SHIP AMMUNITION	21.24	1.64
	(2) F30 STORES	16.26	1.25
	(2) F40 SHIP FUEL	406.52	31.31
	(2) F50 POTABLE WATER	14.22	1.10
	OTHER (MISC) LIQUIDS	1.02	.08
	(2) F60 CARGO (IF ANY)	-	-
DELIVERED FULL LOAD DISPLACEMENT		1298.51	100
M24 FUTURE GROWTH MARGIN		–	
MAXIMUM DISPLACEMENT		1298.51	
GROUP 567 BUOYANCY			
	NORMAL FOILBORNE	- 79.25	-6.10
	FB DYNAMIC LIFT (F.L.)	1219.26	193.90
MILITARY PAYLOAD (1) INCLUDES SWBS 442 499 & 700 LOADS F20		128.54	9.90
VARIABLE PAYLOAD (2) INCLUDES LOADS F10 F30 F40 F50 AND F60		448.18	34.51
USEFUL PAYLOAD (1 & 2)		576.72	44.41

• NOTE SWBS GROUP 400 WAS USED TO DETERMINE MILITARY PAYLOAD IN THIS STUDY

100 HULL

AREAS (Hull & Superstructure)
- Shell Plating
- Deck
- Bulkheads

} NOT INCLUDED IN STUDY

MATERIAL ____ 5456 Alum

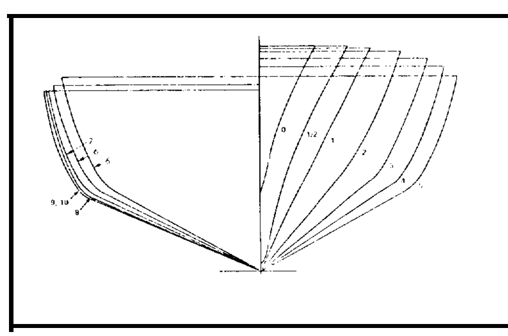
METHOD OF CONSTRUCTION ____ Welded

HULL GIRDER STRUCTURE DENSITY
SUPERSTRUCTURE DENSITY
TOTAL HULL STRUCTURE DENSITY
HULL IMPACT DESIGN PRESSURE
FRAME SPACING
NO OF BULKHEADS

} NOT INCLUDED IN STUDY

DAMAGE ZONE CRITERIA ____ Two Compartment (Floodable Length)

HULL FORM DESCRIPTION ____ Series 65 Model 5164 Hard Chine, Deep V



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SUBSYSTEM CHARACTERISTICS (CONT.,)

200 PROPULSION

- **FB** GAS TURBINE (TYPE & NO.) ________ GE **LM2500** (2)
- **HB** ENGINE (TYPE & NO.) ________ AVCO TF-35 (2)
- FB TURBINE SHP
  - MAX. CONT. ________ **50695 mhp (50,000 shp)**
  - MAX. **INTER'M.** ________ **NOT** INCLUDED IN STUDY
- TYPE TRANSMISSION ________ **'Z** Drive'
- PROPULSOR TYPE ____ **Supercavitating** Fixed Pitch Propeller (DESCRIPTION)
- NO. OF PROPULSORS ________ 2
- TYPE FUEL ________ Diesel Oil & JP-5

300 ELECTRIC PLANT

- TOTAL KVA ________ **200**
- **60HZ & 400HZ SYS**
- VOLTAGES USED ________ **440-30**

400 COMMAND & SURVEILLANCE

- TYPE OF NAV SYS ________ NOT INCLUDED IN STUDY
- TYPE **OF** SURVEILLANCE SYS . SPS-49, SPS-55 Radar, JPTDS (Varient) SADTOS, **ARRAPS, &** HAS
- **TYPE OF** F/C SYS ____ **MK92** Mod-2, MK113, & **MK116/114**

500 AUX-SYS

- NO. & TYPE OF RUDDER ________ Steerable Struts
- TYPE OF ACS ________ Digital
- NO. & TYPE OF HEIGHT SENSORS ________ Radar (2)

567 **LIFT SYS**

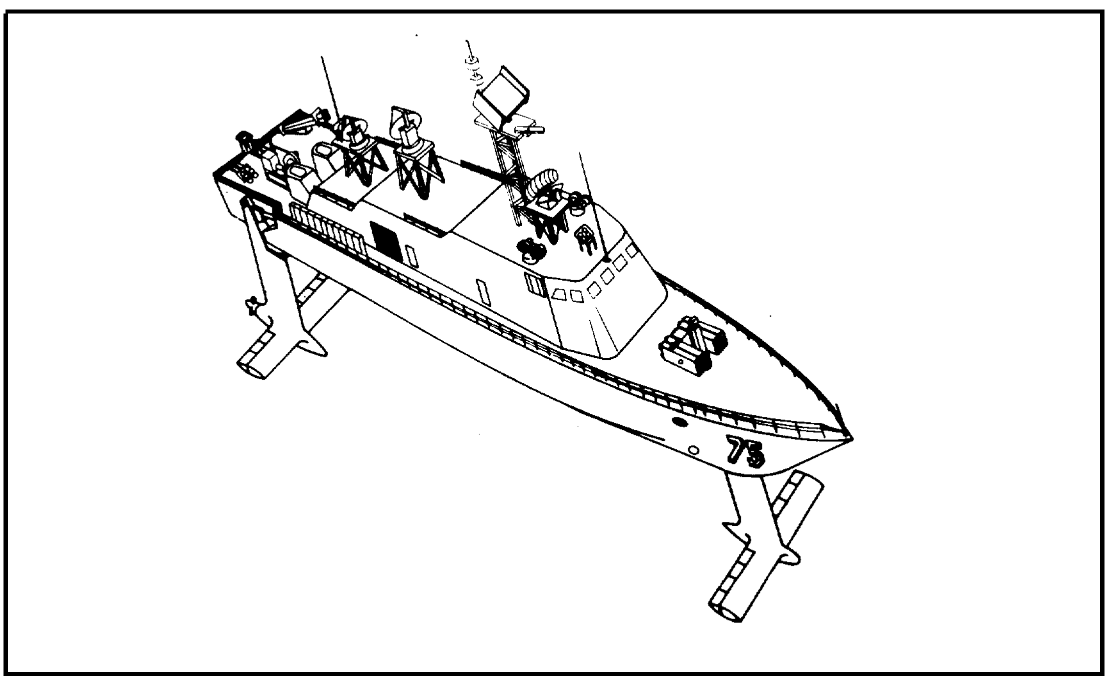
- CONFIGURATION ________ Inverted **π** AFT & T FWD
- % OF WEIGHT **DIST'B.** ________ (AFT) 67% (FWD) 33%
- RETRACTABLE **or** FIXED ASREO'D
- SPAN (AFT) **29.3m** (96.14') _(FWD) **16.37m** (53.7')
- ASPECT RATIO - (AFT) __ 6 __ **(FWD)** __ 5 __
- TYPECONTROL ________ **Flaps**
- **L/D** ________ NOT INCLUDED IN STUDY
- FOIL LOADING ________ FWD -- 57.46 **KN/m²(1 200psf)**
  AFT -- 57.46 **KN/m²(1200psf)**

600 OUTFITTING & FURNISHINGS

- NO. & TYPE COMPARTMENTS __ **NOT** INCLUDED IN STUDY
- MANNING ________ **OFFICER** ____ / **NCO** ____ / **EM** ____ } 86 TOTAL
- AREA PER MAN ________ OFFICER **7.43m (80ft²)**
  ENLISTED -- **3.59m (38.6ft²)**

700 WEAPONS

- TYPE & NO. OF WEAPONS ____ **SM—1** (MR), Harpoon & Tarpoon **Missiles,** Vertical Launchers MK 46 Torpedoes



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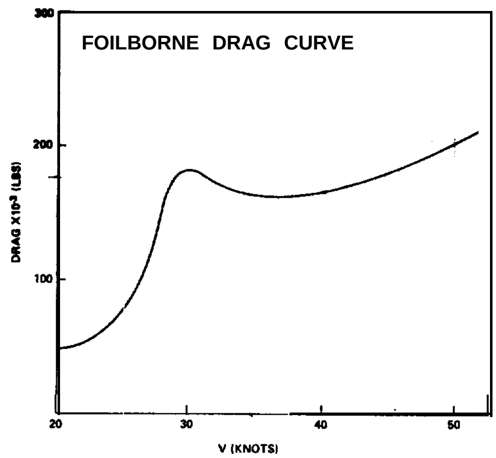
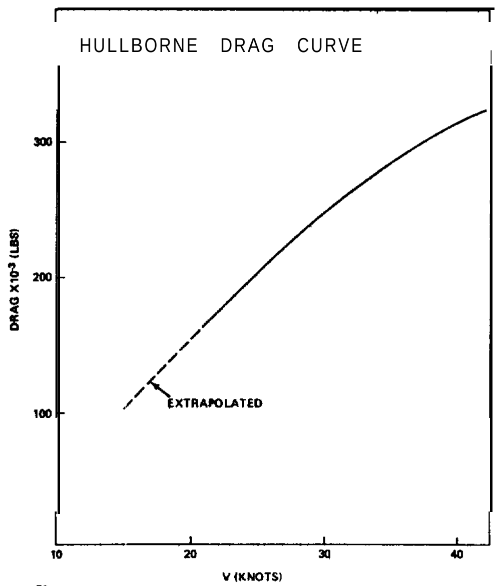
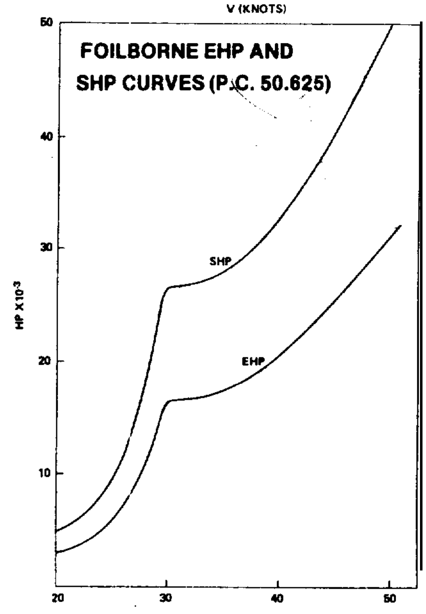
PREDICTED PERFORMANCE CHARACTERISTICS







RETRACTION & EXTENSION TIME ______ NOT INCLUDED IN STUDY

OPERATIONAL **RESPONSE** TIME ________ NOT INCLUDED IN STUDY

TURNING **RATES**
(Rough & Calm Water) ________ NOT INCLUDED IN STUDY

MIN. TURNING **DIAMETER** NOT INCLUDED IN STUDY

SPEED

MAX. ______________________ 45 t KTS

CRUISE ______________________ 45 KTS

MIN. __________ NOT INCLUDED IN STUDY

DESIGN **SEASTATE** __________________ 6

SHIP MOTION

PITCH ________
ROLL ________
VERT. ACCEL. ____
LAT. ACCEL. ____
} NOT INCLUDED IN STUDY

RANGE

FOILBORNE ____________________ 2600 NM

HULLBORNE ______ 3600 NM @ 10 KTS

GENERAL

STUDY CDNWCTED **BY** __________ NAVSEC (1975)

MISSION APPLICABILITY

OPERATIONS -- Open Ocean Combatant

CAPABILITY ________ Multiple ASW, SUW & AAW

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SPECIFIC DESIGNS SHIP CHARACTERISTICS

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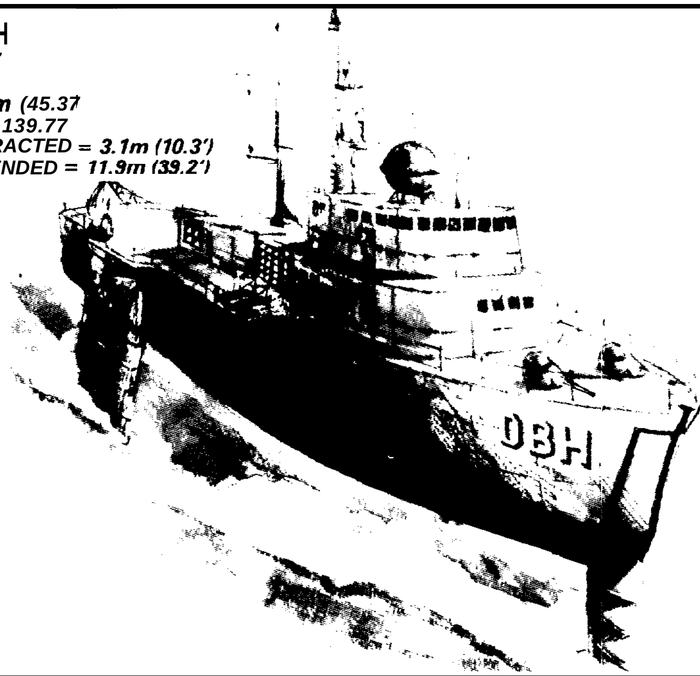
DBH

LOA = 52.8m 1173.27
LBP = –
MAX. BEAM = 13.8m (45.37
D WL BEAM = 12.1m 139.77
DRAFTFOILS RETRACTED = 3.1m (10.3')
DRAFTFOILS EXTENDED = 11.9m (39.2')



SUBSYSTEM CHARACTERISTICS

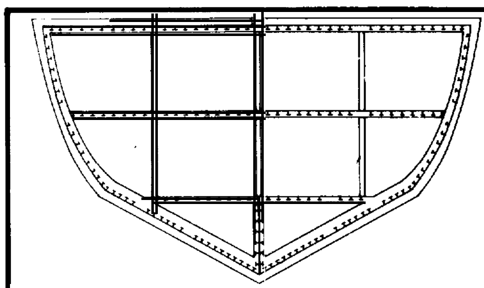
WEIGHTSUMMARY		METRIC TONS	% F.L.
SWBS	100 HULL STRUCTURE	106.66	13.56
	200 PROPULSION SYSTEMS	69.60	8.86
	300 ELECTRIC PLANT	12.90	1.64
	(1) 400 COMMAND & SURVEILLANCE	24.93	3.18
	500 AUXILIARY SYSTEMS	30.49	3.88
	567 LIFT SYSTEMS	120.70	15.36
	600 OUTFIT & FURNISHINGS	28.55	3.63
	(1) 700 WEAPONS SYSTEMS	43.79	5.57
M10 CONTRACTOR CONTROLLED		32.02	4.16
M21-M23 CONTRACT DESIGN, MOD, & GFM		8.74	1.11
MARGINS		41.56	5.29
DELIVERED LIGHTSHIP		479.27	61.01
NORMAL LOADS:			
	(2) F10 SHIPS FORCE	5.18	.66
	(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	–	–
	(1) F21 SHIP AMMUNITION	21.03	2.68
	(2) F30 STORES	5.79	.74
	(2) F40 SHIP FUEL	270.17	34.39
	(2) F50 POTABLE WATER	4.17	.53
	OTHER (MISC) LIQUIDS	–	–
	(2) F60 CARGO (IF ANY)	–	–
DELIVERED FULL LOAD DISPLACEMENT		785.61	100
M24 FUTURE GROWTH MARGIN		–	–
MAXIMUM DISPLACEMENT		785.61	
GROUP 567 BUOYANCY			
	NORMAL FOILBORNE	– 59.85	– 7.62
	FB DYNAMIC LIFT (F.L.)	717.33	91.31
MILITARY PAYLOAD	(1 INCLUDES SWBS 442 499 & 700 LOADS F20	88.14	11.22
VARIABLE PAYLOAD	(2 INCLUDES LOADS F10 F30 F40 F50 AND F60)	285.31	36.32
USEFUL PAYLOAD (1 & 2)		373.45	47.54

100 HULL

AREAS (Hull & Superstructure)
- Shell Plating } Not Included In Study
- Deck
- Bulkheads

MATERIAL -5456 H116 &H117 Alum
METHOD OF CONSTRUCTION Welded
HULL GIRDER STRUCTURE DENSITY } Not Included In Study
SUPERSTRUCTURE DENSITY
TOTAL HULL STRUCTURE DENSITY
HULL IMPACT DESIGN PRESSURE 64.64 KN/m² (1,350PSF)

FRAME SPACING .91m (3.0')
NO. OF BULKHEADS -- a
DAMAGE ZONE CRITERIA Two Compartment
(Floodable Length)
HULL FORM DESCRIPTION Hard Chine Planmg Hull Based On DTNSRDC Series 65 Model 5184



TYPICAL FRAME SECTION

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PREDICTED PERFORMANCE CHARACTERISTICS

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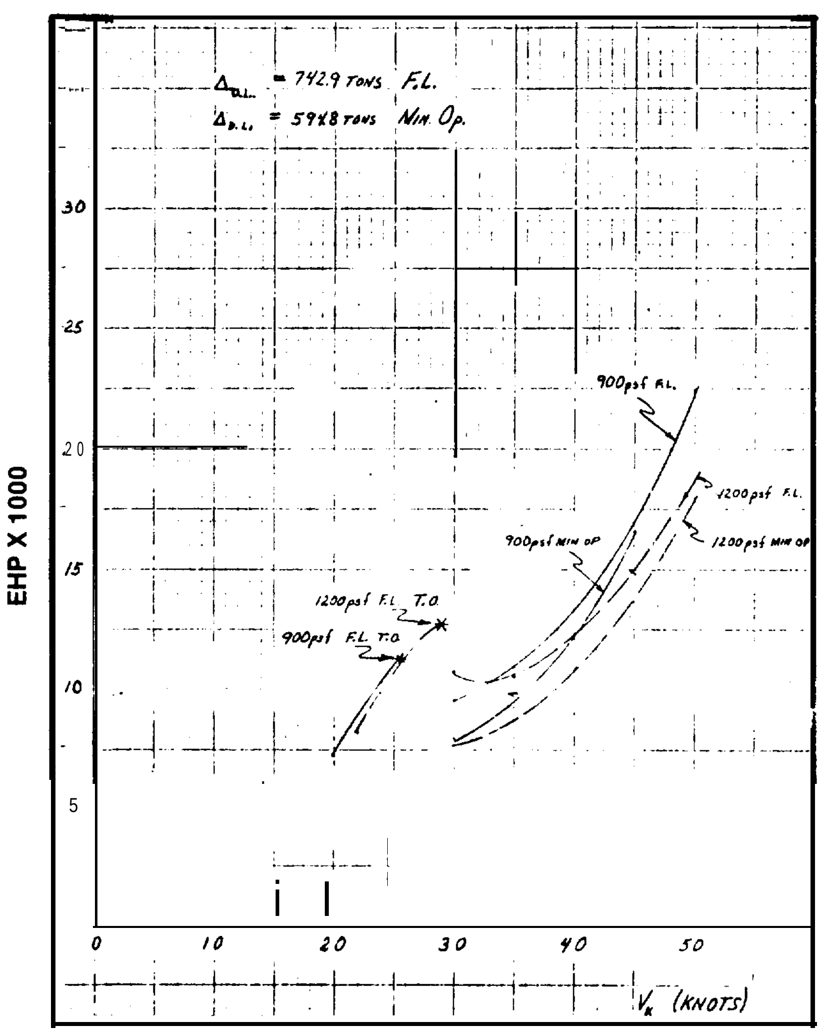
EHP vs SPEED



RETRACTION & EXTENSION TIME — Not Included In Study

OPERATIONAL RESPONSE **TIME** — Not Included In Study

TURNING RATES

(Rough & Calm Water) — Not Included In Study

MIN. TURNING DIAMETER — Not Included In Study

SPEED

Max.- ____ **50** KTS

Cruise ____ 45 KTS

Min. ____ 35 KTS

DESIGN SEASTATE ____ 6

SHIP MOTION

Pitch — NOT INCLUDED IN STUDY

Roll — NOT INCLUDED IN STUDY

Vert. Accel. — NOT INCLUDED IN STUDY

Lat. Accel. — NOT INCLUDED IN STUDY

RANGE

Foilborne ____ 2600 nm @ 35 kts

Hullborne ____ 3800 nm @ 10 kts

GENERAL

Study **Conducted** by ____ NAVSEC (1973)

MISSION APPLICABILITY

Operations ____ Open Ocean

Capability ____ Multiple ASW, AAW, & EW

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SUBSYSTEM CHARACTERISTICS (CONT.)

200 PROPULSION

FB GAS TURBINE (TYPE & NO.) ____ GE LM2500 (2)
HB ENGINE (TYPE & NO.) ____ AVCO TF-35 (2)
FB TURBINE SHP
MAX. CONT. ____ 48160mhp (47,500 shp)
MAX. INTER'M. ____

TYPE TRANSMISSION ____ 'Z Drive' Bevel Gears Double Shaft
PROPULSOR TYPE ____ Supercavitating Fixed Pitch Propellers (DESCRIPTION)
NO. OF PROPULSORS ____ (2)
TYPE FUEL ____ Diesel Oil & JP-5

300 ELECTRIC PLANT

TOTAL KVA ____ 300 & 600
60HZ & 400HZ SYS
VOLTAGES USED ____ 450-30

400 COMMAND 8 SURVEILLANCE

TYPE OF NAV SYS _ Omega, NAVSAT Plotter & Gyrocompass
TYPE OF SURVEILLANCE SYS AN/SPS-58, AN/SPS-55 Radar AN/SPA Display
TYPE OF F/C SYS ____ MK-92 with UYK-7 Computer

500 AUX-SYS

NO. & TYPE OF RUDDER ____ Steerable Strut
TYPE OF ACS ____ Analog
NO & TYPE OF HEIGHT SENSORS ____ (2) Sonic

567 LIFT SYS

CONFIGURATION ____ Canard
% OF WEIGHT DIST'B. ____ (AFT) 67% (FWD) 33%
RETRACTABLE FIXED
SPAN ____ (AFT) ____ 27.01m (88.63 ____ (FWD) ____ 14.02m (463
AR ____ (AFT) ____ 5 (FWD) ____ 8
TYPE CONTROL ____ Flaps
L/D ____ .1 68 @ 50 kts
FOIL LOADING ____ FWD 43.09 KN/m^2 (900 PSF)
AFT 57.46 KN/m^2 (1200 PSF)

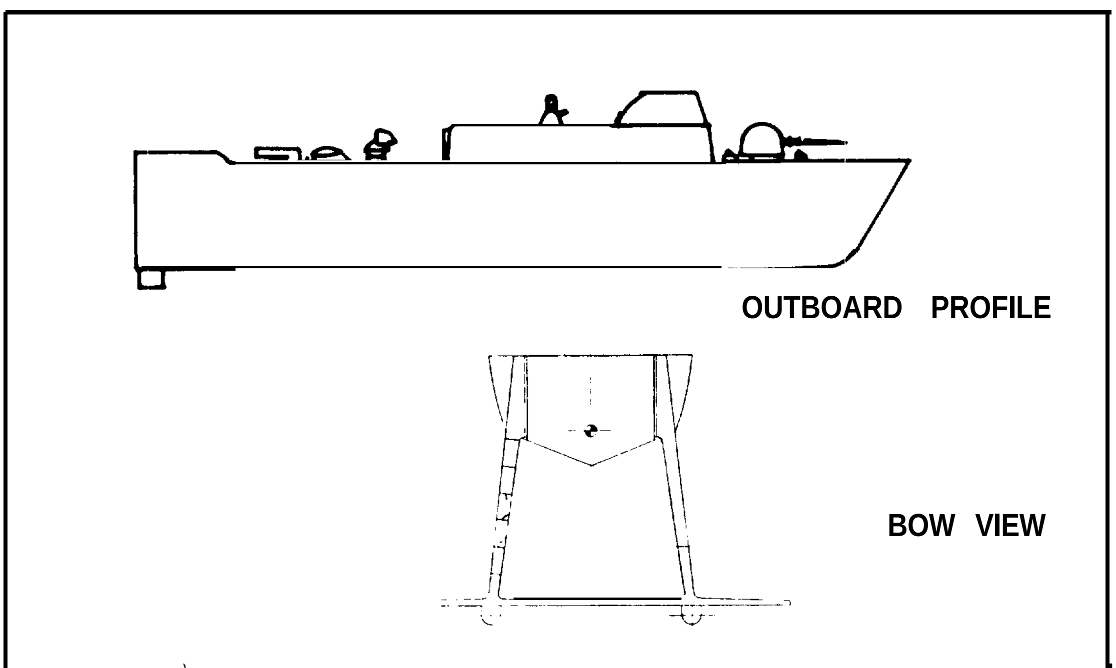
600 OUTFITTING & FURNISHINGS

NO. & TYPE COMPARTMENTS ____ (8) Watertight
MANNING ____ OFFICER ____ 5
NCO ____ 5
E M - - ____ 3 6

AREA PER MAN ____ OFFICER ____ $7.25m^2$ ($78ft^2$)
ENLISTED ____ $3.90m^2$ ($42ft^2$)

700 WEAPONS

TYPE & NO. OF WEAPONS ____ (1) 76mm Oto Malera Gun
(2) 20mm (CIWS) Gun or Twin 30/35mm Guns
Harpoon & Sea Sparrow Missiles
MK 48 Torpedoes



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SPECIFIC DESIGNS SHIP CHARACTERISTICS

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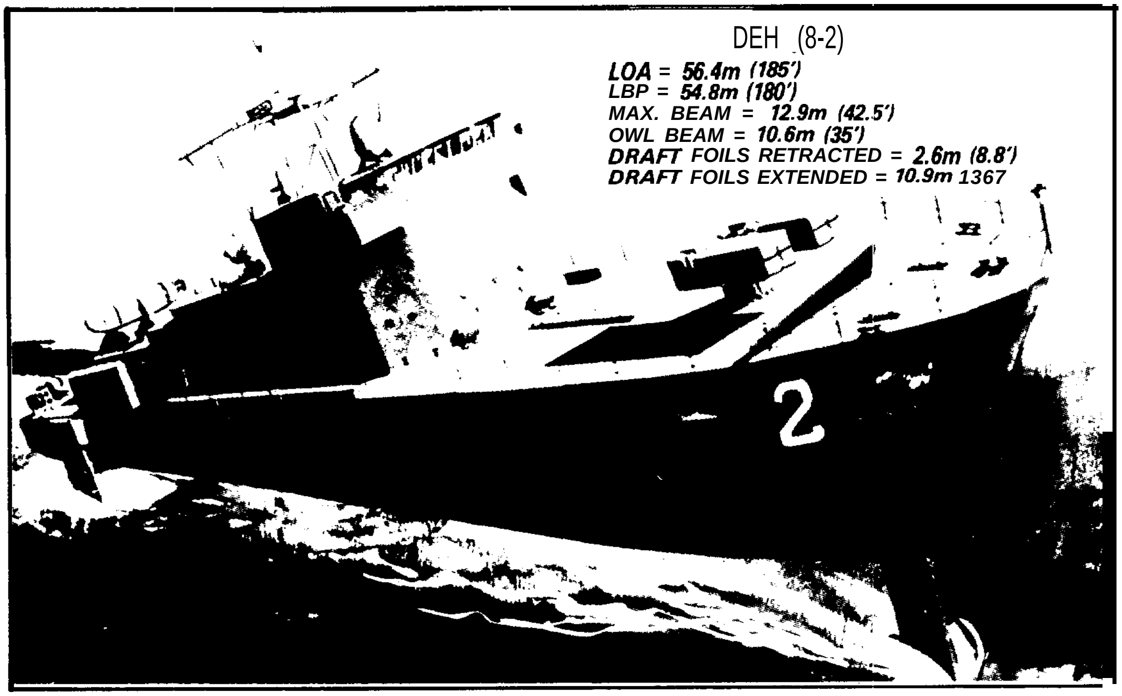


SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY			METRIC TONS	% F.L.
SWBS	100	HULL STRUCTURE	150.04	14.09
	200	PROPULSION SYSTEMS	59.44	5.58
	300	ELECTRIC PLANT	29.43	2.76
	(1) 400	COMMAND & SURVEILLANCE	54.74	5.14
	500	AUXILIARY SYSTEMS	197.14	18.51
	567	LIFT SYSTEMS (NOT INCLUDED IN STUDY)	DNA	–
	600	OUTFIT & FURNISHINGS	35.35	3.32
	(1) 700	WEAPONS SYSTEMS	23.02	2.16
M10 CONTRACTOR CONTROLLED			–	–
M21-M23 CONTRACT DESIGN, MOD, & GFM			–	–
MARGINS			82.37	7.73
DELIVERED LIGHTSHIP			631.51	59.29
NORMAL LOADS:				
		(2) F10 SHIPS FORCE	6.96	.65
		(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	6.11	.57
		(1) F21 SHIP AMMUNITION	35.39	3.32
		(2) F30 STORES	6.50	.61
		(2) F40 SHIP FUEL	371.06	34.84
		(2) F50 POTABLE WATER	6.80	.64
		OTHER (MISC) LIQUIDS	.74	.07
		(2) F60 CARGO (IF ANY)	–	–
DELIVERED FULL LOAD DISPLACEMENT			1065.07	100
M24 FUTURE GROWTH MARGIN			–	–
MAXIMUM DISPLACEMENT			1065.07	
GROUP 567 BUOYANCY				
		NORMAL FOILBORNE	– 63.56	–5.97
		FB DYNAMIC LIFT (F.L.)	1001.51	94.03
MILITARY PAYLOAD (1) INCLUDES SWBS 442, 499 & 700, LOADS F20			*119.26	11.20
VARIABLE PAYLOAD (2) INCLUDES LOADS F10, F30, F40, F50, AND F60)			392.06	36.81
USEFUL PAYLOAD (1 & 2)			511.32	48.01

* NOTE: TOTAL SWBS GROUP 400 WAS USED TO DETERMINE MILITARY PAYLOAD IN THIS STUDY

100 HULL

VOLUME
- Hullgirder
- Superstructure
- Total

} NOT INCLUDED IN STUDY

AREAS (Hull & Superstructure)
- Shell Plating
- Deck
- Bulkheads

} NOT INCLUDED IN STUDY

MATERIAL — 5456 Alum.

METHOD OF CONSTRUCTION — Welded

HULL GIRDER STRUCTURE DENSITY
SUPERSTRUCTURE DENSITY
TOTAL HULL STRUCTURE DENSITY
HULL IMPACT DESIGN PRESSURE
FRAME SPACING
NO OF BULKHEADS

} NOT INCLUDED IN STUDY

DAMAGE ZONE CRITERIA (Floodable Length) — 2 Compartment

HULL FORM DESCRIPTION — Series 63 Model 4780 Round Bottom

DATA NOT AVAILABLE

UNCLASSIFIED

SUBSYSTEM CHARACTERISTICS (CONT.)

200 **PROPULSION**

FB GAS TURBINE (TYPE & NO.) ____ GE LM2500 (2)

HB ENGINE (TYPE & NO.) ____ AVCO TF-35

FB TURBINE SHP

MAX. CONT. ____ 45625 mhp (45,000 shp)

MAX. INTER'M. ____ 50695 mhp (50,000 shp)

TYPE TRANSMISSION ____ 'Z Drive'

PROPULSDR TYPE ____ Supercavitating Fixed Pitch Propeller

NO. OF PROPULSORS ____ 2

TYPE FUEL ____ Diesel Oil & JP-5

300 ELECTRIC PLANT

TOTAL KVA ____ 900

60HZ & 400HZ SYS

VOLTAGES USED ____ 440-30

400 COMMAND& SURVEILLANCE

TYPE OF NAV SYS ____ NOT INCLUDED IN STUDY

TYPE OF SURVEILLANCE SYS ____ SPS-49 & SPS-55 Radars JPTDS (Variant) SADTOS, ARRAPS & HAS Towed Sonars

TYPE OF F/C SYS MK92 Mod-2 MK113 & MK116/114

500 NIX-SYS

NO. & TYPE OF RUOOER ____ Steerable Struts

TYPE OF ACS ____ Digital

NO. & TYPE OF HEIGHT SENSORS ____ Sonic or Radar

567 LIFT SYS

CONFIGURATION ____ Inverted π FWD & AFT

% OF WEIGHT OIST'B. ____ AFT 67% FWD 33%

RETRACTABLE FIXED

SPAN ____ -(AFT). 29.3m (96.14') ____ (FWD) 16.37m (53.7')

ASPECT RATIO (AFT) ____ 6 (FWD) 5

TYPE CONTROL ____ Flaps

LID ____ NOT INCLUDED IN STUDY

600 OUTFITTING & FURNISHINGS

NO & TYPE COMPARTMENTS NOT DETERMINED

MANNING ____ Officer ____ 7

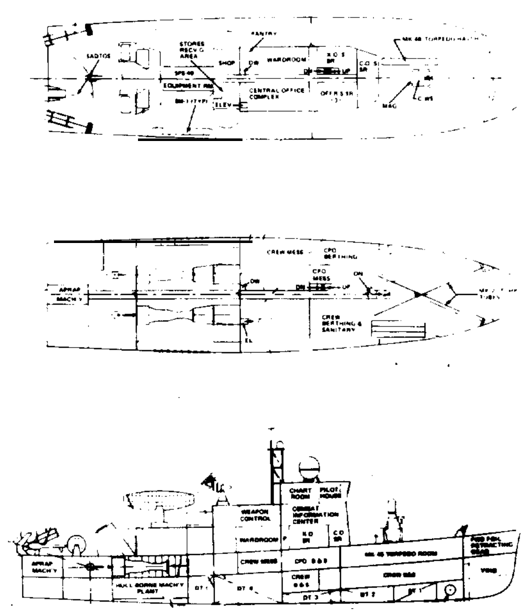
Enlisted ____ 76

AREA PER MAN ____ OFFICER 7.43m² (80ft²)

ENLISTED. ____ 3.59m² (38.6ft²)

700 WEAPONS

TYPE & NO. OF WEAPONS ____ SM-1 (MR), Harpoon Missiles (Vertical launchers), MK48 Torpedoes



MAIN DECK

SECOND DECK

INBOARD PROFILE

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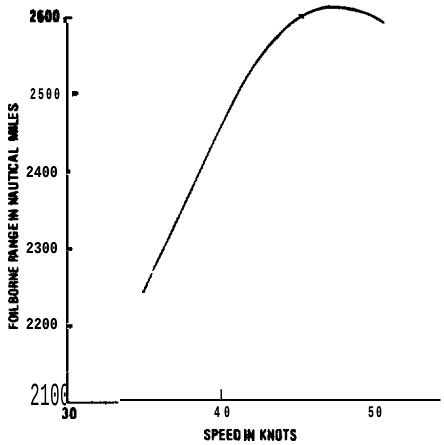
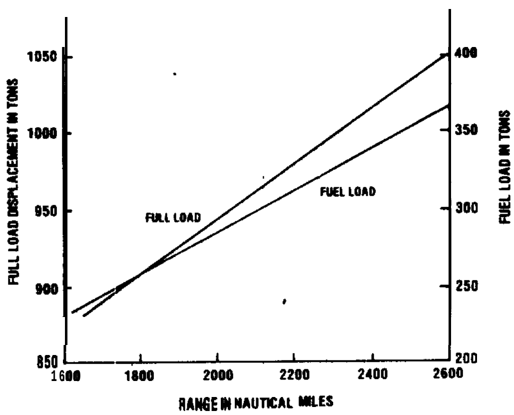
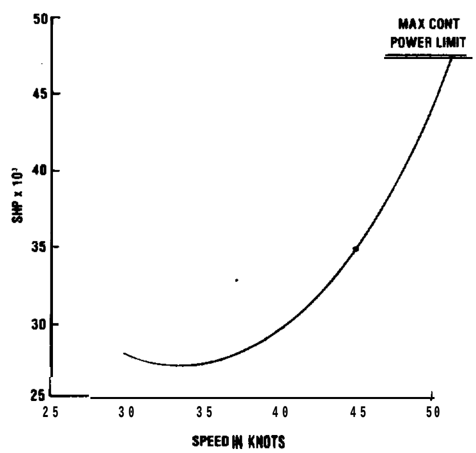
PREDICTED PERFORMANCE CHARACTERISTICS

UNCLASS



FOILBORNE RANGE
VS SPEED





FOILBORNE SPEED POWER

RETRACTION & EXTENSION TIME ______ } NOT INCLUDED IN STUDY
OPERATIONAL RESPONSE **TIME** ______ }

TURNING RATES
(Rough & Calm **Water)** ______ } NOT INCLUDED IN STUDY
MN. **TURNING** DIAMETER ______ }

SPEED
- **Max.** ______
- **Cruise** ______ 45 kts
- **Min.** ______

DESIGN SEASTATE ______

SHIP MOTION
- Pitch ______ }
- **Roll** ______ } NOT INCLUDED IN STUDY
- **Vert.** Accel. ______ }
- **Lat.** Aced. ______ }

RANGE
- **Foilborne** ______ 2600 nm
- **Hullborne** ______ 3600 nm @ 10 kts

GENERAL
- Study Conductod by ______ NAVSEC (1975)

MISSION APPLICABILITY
- **Operations** ______ Open Ocean Escort
- **Multiple** Mission ______ ASW, SUW, AAW

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SPECIFIC DESIGNS SHIP CHARACTERISTICS

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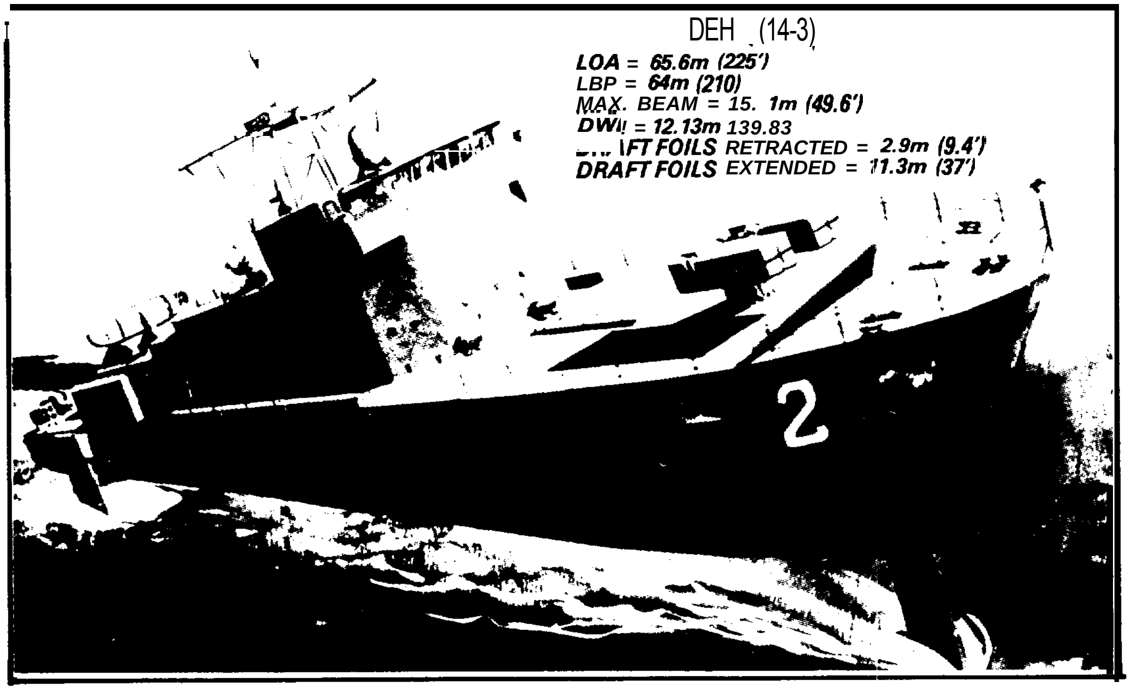

SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY	METRIC TONS	%F L.
SWBS 100 HULL STRUCTURE	213.00	15.99
200 PROPULSION SYSTEMS	59.44	4.46
300 ELECTRIC PLANT	37.63	2.83
(1) 400 COMMAND & SURVEILLANCE	63.90	4.80
500 AUXILIARY SYSTEMS	259.06	19.45
567 LIFT SYSTEMS (NOT INCLUDED IN STUDY)	DNA	–
600 OUTFIT & FURNISHINGS	57.46	4.31
(1) 700 WEAPONS SYSTEMS	25.59	1.92
M10 CONTRACTOR CONTROLLED	–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM	–	–
MARGINS	107.42	8.06
DELIVERED LIGHTSHIP	823.54	61.83
NORMAL LOADS		
(2) F10 SHIPS FORCE	15.23	1.14
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	10.27	.77
(1) F21 SHIP AMMUNITION	54.57	4.10
(2) F30 STORES	7.46	.56
(2) F40 SHIP FUEL	406.42	30.51
(2) F50 POTABLE WATER	14.73	1.11
OTHER (MISC) LIQUIDS	.74	.06
(2) F60 CARGO (IF ANY)	–	–
DELIVERED FULL LOAD DISPLACEMENT	1332.96	100
M24 FUTURE GROWTH MARGIN	–	–
MAXIMUM DISPLACEMENT	1332.96	
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	– 89.74	–6.75
FB DYNAMIC LIFT (F.L.)	1243.22	93.33
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700 LOADS F20)	154.33	11.58
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)	444.58	33.35
USEFUL PAYLOAD (1 & 2)	598.91	44.93

NOTE TOTAL SWBS GR 400 WAS USED TO DETERMINE MILITARY PAYLOAD IN THIS STUDY

100 HULL

VOLUME
- Hullgirder — DATA NOT AVAILABLE
- Superstructure — DATA NOT AVAILABLE
- Total — DATA NOT AVAILABLE

AREAS (Hull & Superstructure)
- Shell Plating — NOT INCLUDED IN STUDY
- Deck — NOT INCLUDED IN STUDY
- Bulkheads — NOT INCLUDED IN STUDY

MATERIAL — 5456 Alum.
METHOD OF CONSTRUCTION — Welded
HULL GIRDER STRUCTURE DENSITY — NOT INCLUDED IN STUDY
SUPERSTRUCTURE DENSITY — NOT INCLUDED IN STUDY
TOTAL HULL STRUCTURE DENSITY — NOT INCLUDED IN STUDY
HULL IMPACT DESIGN PRESSURE — NOT INCLUDED IN STUDY
FRAME SPACING — NOT INCLUDED IN STUDY
NO OF BULKHEADS — NOT INCLUDED IN STUDY
DAMAGE ZONE CRITERIA (Floodable Length) — Two Compartment
HULL FORM DESCRIPTION — Series 63 Model 4780 Round Bottom

DATA NOT AVAILABLE

UNCLASSIFIED

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SUBSYSTEM CHARACTERISTICS (CONT.)

200 PROPULSION

- FB GAS TURBINE (TYPE & NO.) ________ GE LM2500 (2)
- HB ENGINE (TYPE & NO.) ________ AVCO TF-35 (2)
- FB TURBINE SHP
  - MAX. CONT..- ________ 50695 mhp (50,000)
  - MAX. INTER'M. ________
- TYPE TRANSMISSION ________ 'Z' Drive
- PROPULSORTYPE ________ Supercavitating Fixed Pitch Propeller
- NO. OF PROPULSORS ________ (2)
- TYPE FUEL ________ Diesel Oil & JP-5

300 **ELECTRIC** PLANT

- TOTAL KVA ________ 1200
- 60HZ & 400HZ SYS
- VOLTAGESUSED ________ 440-30

400 **COMMAND & SURVEILLANCE**

- TYPE OF NAV SY S ________ NOT INCLUDED IN STUDY
- TYPE OF SURVEILLANCE SYS ________ SPS-52 & SPS-55 Radar and JPTOS (Variant)
- TYPE OF F/C SYS ________ NATO Sea Sparrow & Augmented Sea Phoenix FCS (2) MK113 & MK116/114

500 **AUX-SYS** ,

- NO. & TYPE OF RUDDER ________ Steerable Struts
- TYPE OF ACS ________ Digital
- NO & TYPE OF HEIGHT SENSORS ________ Radar or Sonic

567 **LIFT SYS**

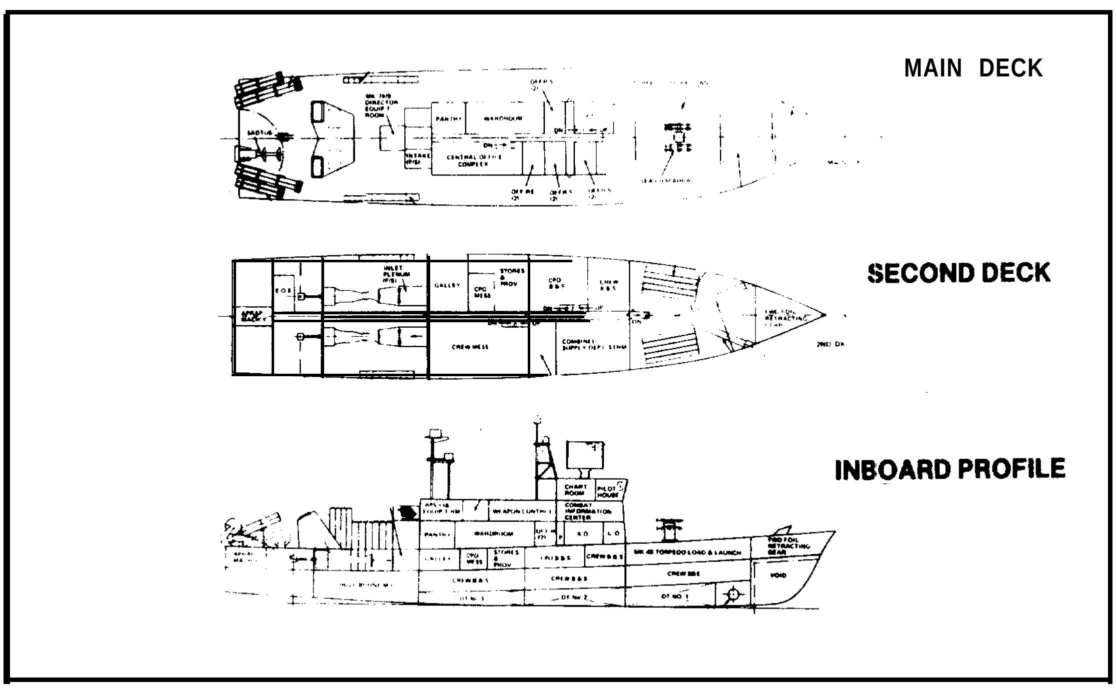
- CONFIGURATION ________ Inverted T FWD 6 AFT
- % OF WEIGHT DIST'B. ________ (AFT) 67% (FWD) 33%
- RETRACTABLE
- SPAN ________ (AFT) 33.5m (109.9') (FWD) -18.73 (61.53
- ASPECT RATIO ________ (AFT) ________ 8 (FWD) ________ 5
- TYPE CONTROL ________ Flap
- LID ________ NOT INCLUDED IN STUDY

600 **OUTFITTING & FURNISHINGS**

- NO. & TYPE COMPARTMENTS ________ NOT INCLUDED IN STUDY
- MANNING ________ OFFICER ________ 7
  - EM ________ 16
- AREA PER MAN ________ OFFICER ________ 6.0m² (65ft²)
  - ENLISTED ________ 3.5m² (38ft²)

700 WEAPONS

- TYPE & NO. OF WEAPONS ________ Sea Phoenix, Sea Sparrow. Sea Chaparral, Harpoon Missiles Vertical Launched MK48 Torpedoes



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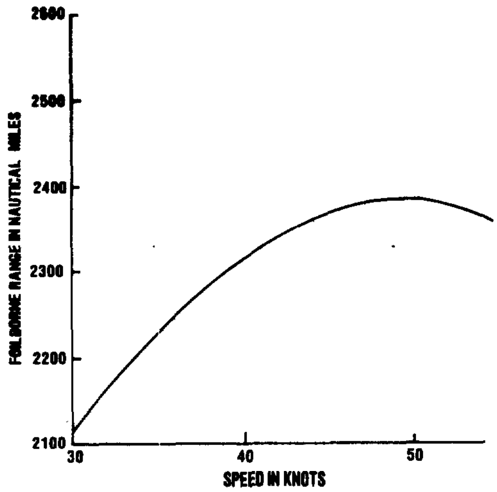
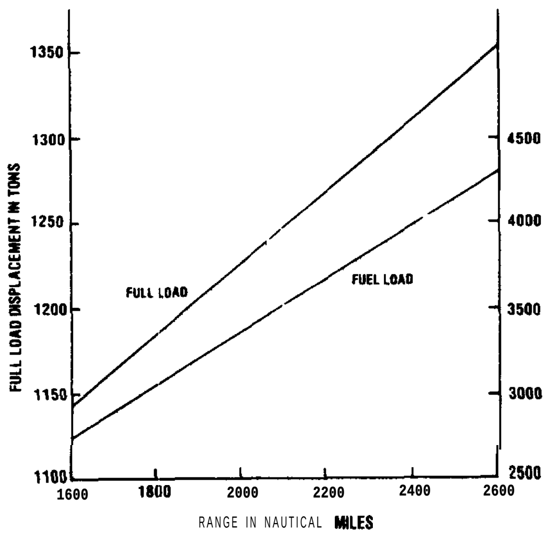
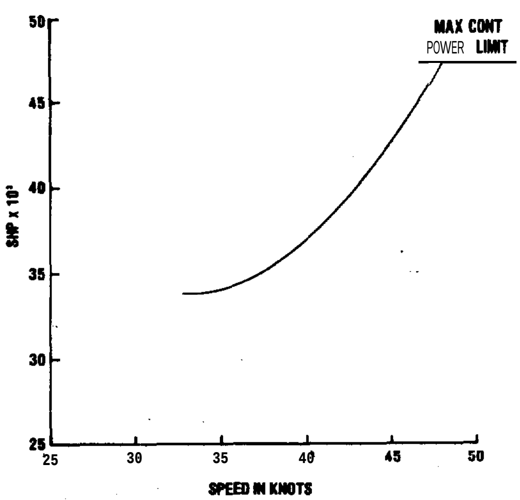


FOILBORNE RANGE
VS SPEED





FOILBORNE SPEED POWER

RETRACTION & EXTENSION TIME
OPERATIONAL RESPONSE TIME
TURNING RATES (Rough & Calm **Water**)
MIN. TURNING DIAMETER
} NOT INCLUDED IN STUDY

SPEED
- **Cruise** ______ 45 kts

DESIGN SEASTATE ______ 6

SHIP MOTION
- Pitch ______
- **Roll** ______
- **Vert. Accel.** ______
- Lat. **Accel.** ______

} NOT INCLUDED IN STUDY

RANGE
- **Foilborne** ______ 2600nm @ 10 kts
- **Hullborne** ______ 3600nm @ 10 kts

GENERAL
- **Study Conducted By** ______ NAVSEC (1975)

MISSION APPLICABILITY
- **Operations** ______ Deep Ocean Escort

MULTIPLE MISSION CAPABILITY ______ SUW & AAW

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SPECIFIC DESIGNS SHIP CHARACTERISTICS

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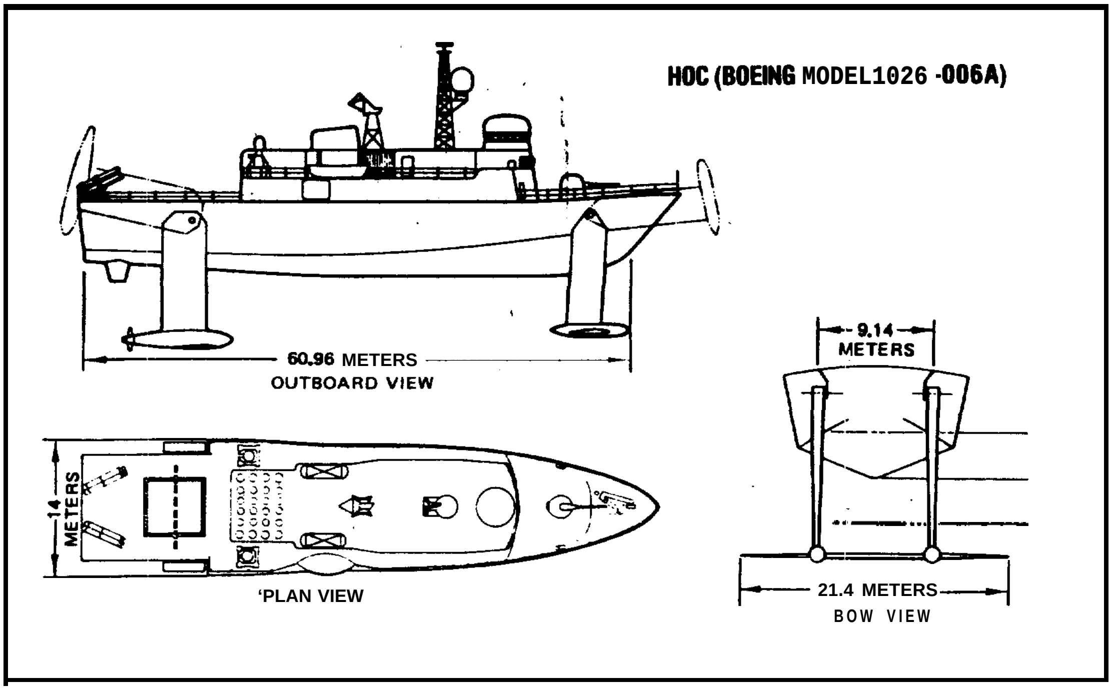
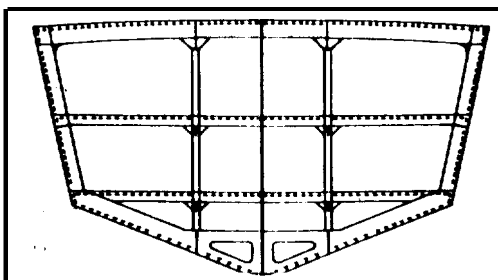


SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY			METRIC TONS	% F.L.
SWBS	100	HULL STRUCTURE	238.77	17.05
	200	PROPULSION SYSTEMS	91.44	6.53
	300	ELECTRIC PLANT	50.80	3.63
	(1) 400	COMMAND & SURVEILLANCE	80.27	5.73
	500	AUXILIARY SYSTEMS	81.29	5.81
	567	LIFT SYSTEMS	191.01	13.64
	600	OUTFIT & FURNISHINGS	64.01	4.57
	(1) 700	WEAPONS SYSTEMS	27.43	1.96
M10 CONTRACTOR CONTROLLED			—	—
M21-M23 CONTRACT DESIGN, MOD, & GFM			—	—
MARGINS			90.43	6.46
DELIVERED LIGHTSHIP			915.45	65.38
NORMAL LOADS:				
(2) F10 SHIPS FORCE			8.13	.58
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS			21.34	1.52
(1) F21 SHIP AMMUNITION			—	—
(2) F30 STORES			13.21	.94
(2) F40 SHIP FUEL			427.76	30.55
(2) F50 POTABLE WATER			10.16	.73
OTHER (MISC) LIQUIDS			4.06	.29
(2) F60 CARGO (IF ANY)			—	—
DELIVERED FULL LOAD DISPLACEMENT			1400.11	100
M24 FUTURE GROWTH MARGIN			—	—
MAXIMUM DISPLACEMENT			1400.11	
GROUP 567 BUOYANCY				
NORMAL FOIL BORNE			– 149.36	-10.67
FB DYNAMIC LIFT (F L)			1250.75	99.33
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700 LOADS F20			115.83	8.27
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)			463.32	33.09
USEFUL PAYLOAD (1 & 2)			579.15	41.36

100 HULL

AREAS (Hull & Superstructure)	
Shell Plating	NOT PROVIDED
Deck	NOT PROVIDED
Bulkheads	NOT PROVIDED
MATERIAL	Alum 5458
METHOD OF CONSTRUCTION	Welded
HULL GIRDER STRUCTURE DENSITY	46.5 Kg/M^3
SUPERSTRUCTURE DENSITY	18.9 Kg/M^3
TOTAL HULL STRUCTURE DENSITY	40.1 Kg/M^3
HULL IMPACT DESIGN PRESSURE	5.27 Kg/CM^2
FRAME SPACING	1.524 M
NO. OF STRUCTURAL BULKHEADS	8
DAMAGE ZONE CRITERIA (Floodable Length)	2 Compartment
HULL FORM DESCRIPTION	PHM Derivative



TYPICAL FRAME SECTION

UNCLASSIFIED

SUBSYSTEM CHARACTERISTICS (CONT.)

200 **PROPULSION**
- F B GAS TURBINE (TYPE & NO.) — (2) LM2500
- HB ENGINE (TYPE & NO.) — (2) GTPF990
- FB TURBINE SHP
  - MAX CONT.
  - MAX INTER'M. — Growth to 70,000 HP
- TYPE TRANSMISSION — Dual Downshaft 'Z'
- PROPULSOR TYPE — Supercavitatinp
- NO OFPROPULSORS — (2)
- TYPE FUEL — JP-5 or Diesel

300 ELECTRIC PLANT
- TOTAL KVA — 1200 KVA
- 60HZ & 400HZ SYS
- VOLTAGES USED — 440/220/110

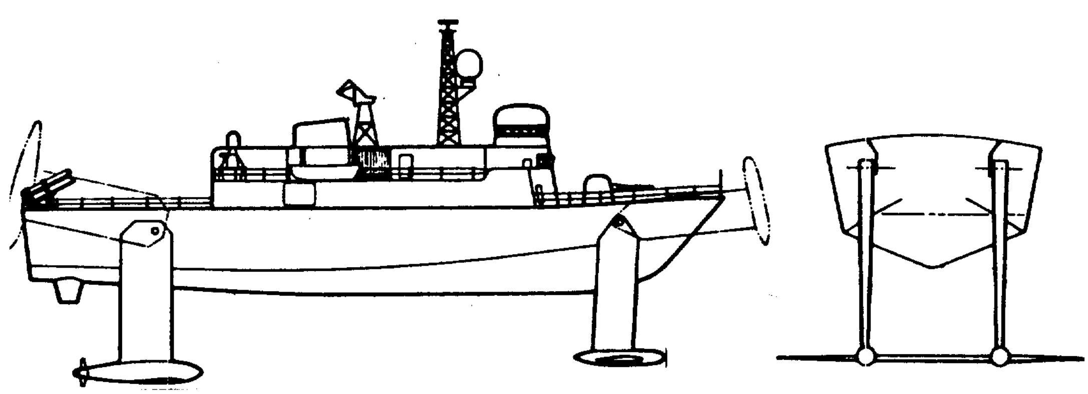
400 COMMAND & SURVEILLANCE
- TYPE OF NAV SYS
- TYPE OF SURVEILLANCE SYS — NOT DETERMINED
- TYPE OF F/C SYS

500 AUX-SYS
- NO. & TYPE OF RUDDER — (2) Spade
- TYPE OF ACS — Digital
- NO. & TYPE OF HEIGHT SENSORS — (2) (Radar or Acoustic)

567 LIFT SY S
- CONFIGURATION — Inverted FWD & AFT
- % OF WEIGHT DIST'B — 35% FWD 65% AFT
- RETRACTABLE
- SPAN (AFT). 100' (FWD) 73'
- ASPECT RATIO — 6.4
- TYPE CONTROL — Detached Flap
- L I D — Max Effective F/B = 17.3

600 OUTFITTING & FURNISHINGS
- NO & TYPE COMPARTMENTS — T.B.D.
- MANNING — OFFICER / NCO / EM — Standard for Type
- AREA PER MAN — OFFICER / ENLISTED — Standard for Type

700 WEAPONS
- TYPE & NO. OF WEAPONS — (16) Vert. Launch SAM
  - (8) ASW Torpedoes
  - (1) G.P. Rapid Fire (76mm) Gun
  - (8) Anti-Ship Missiles (Potential Growth)



OUTBOARD VIEW **BOW VIEW**

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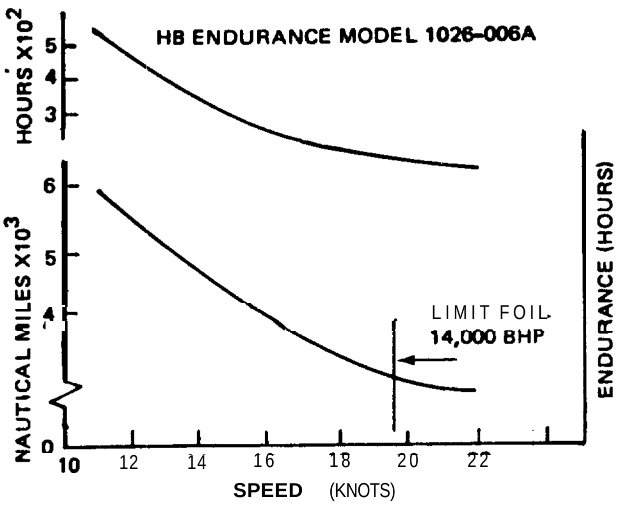
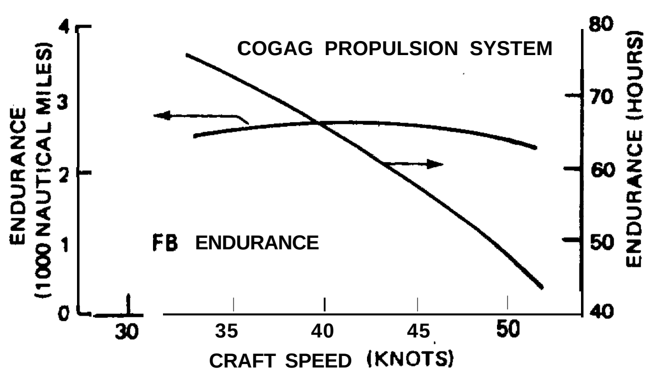
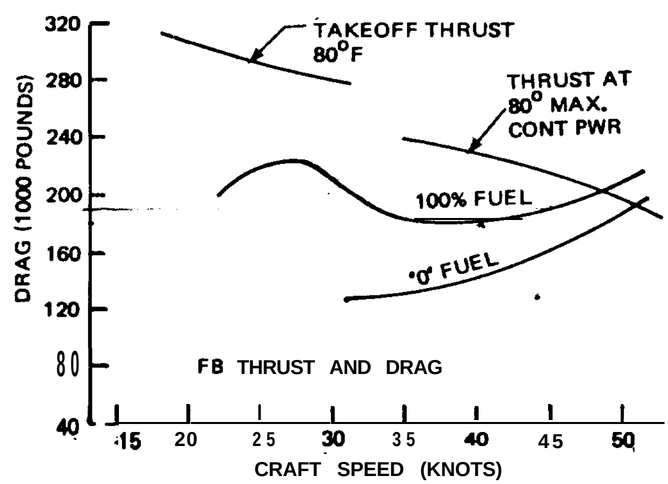
PREDICTED PERFORMANCE CHARACTERISTICS







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RETRACTION & EXTENSION TIME __________ 5 Minutes

OPERATIONAL RESPONSE **TIME** __________ 7 Minutes

TURNING GATES __________ 5 °/Second

(Rough & Calm Water)

MIN. TURNING **DIAMETER** __________ 493 Meters

SPEED

- MAX. __________ 50K
- CRUISE __________ 42 K
- MIN. __________ 1 K

DESIGN SEASTATE __________ $H^{1/3}$ = 20'

SHIP **MOTION** __________ FOILBORNE AVG.

- **PITCH** __________ .68°
- **ROLL** __________ 7°
- VERT. ACCEL. __________ 1 g
- LAT. ACCEL. __________ N.D.

GENERAL

- **STUDY** CONDUCTED **BY** __________ Boeing (1975)

MISSION APPLICABILITY

- **OPERATIONS** __________ Open Ocean Combatant

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SPECIFIC DESIGNS SHIP CHARACTERISTICS

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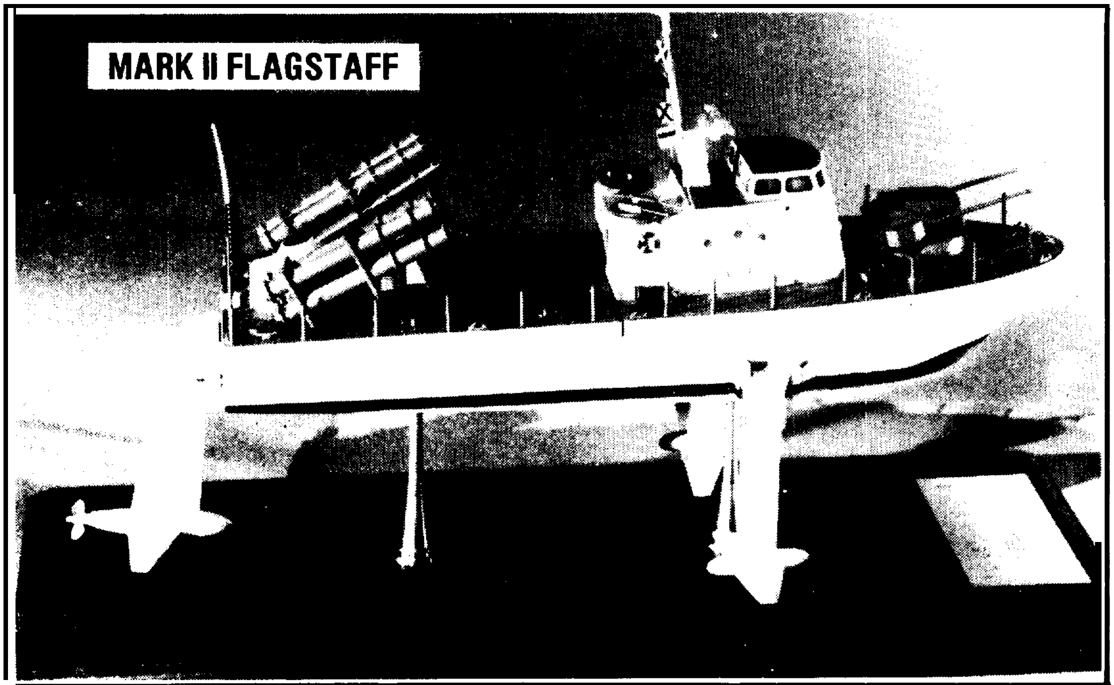
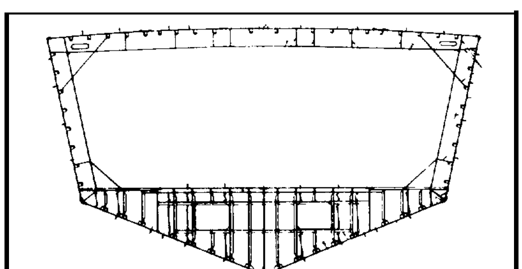


SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY			METRIC TONS	%F.L.
SWBS	100	HULL STRUCTURE	17.47	20.55
	200	PROPULSION SYSTEMS	10.25	12.06
	300	ELECTRIC PLANT	3.45	4.06
	(1) 400	COMMAND & SURVEILLANCE	5.95	7.00
	500	AUXILIARY SYSTEMS	5.41	6.36
	567	LIFT SYSTEMS	9.30	10.94
	600	OUTFIT & FURNISHINGS	3.76	4.42
	(1) 700	WEAPONS SYSTEMS	9.31	10.95
M10 CONTRACTOR CONTROLLED			–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM MARGINS			2.18 2.18	2.56
DELIVERED LIGHTSHIP			67.08	78.92
NORMAL LOADS:				
	(2) F10 SHIPS FORCE		1.25	1.47
	(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS		–	–
	(1) F21 SHIP AMMUNITION		–	–
	(2) F30 STORES		.29	.34
	(2) F40 SHIP FUEL		16.10	18.94
	(2) F50 POTABLE WATER		.28	.33
	OTHER (MISC) LIQUIDS		–	–
	(2) F60 CARGO (IF ANY)		–	–
DELIVERED FULL LOAD DISPLACEMENT			85.00	loo
M24 FUTURE GROWTH MARGIN			–	–
MAXIMUM DISPLACEMENT			85.00	
GROUP 567 BUOYANCY				
	NORMAL FOILBORNE		– DNA	–
	FB DYNAMIC LIFT (F.L.)		DNA	
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700 LOADS F20			15.7	18.5
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)			17.9	21.00
USEFUL PAYLOAD (1 & 2)			33.6	39.5

100 HULL

AREAS (HULL & SUPER-STRUCTURE)	SHELL. PLATING	218.8 M^2
	DECK	130.1 M^2
	BULKHEADS	121.6 M^2
MATERIAL		6086 AL. ALLOY
METHOD OF CONSTRUCTION		WELDED
HULL GIRDER STRUCTURE DENSITY		44.9 KG/M^3
SUPERSTRUCTURE DENSITY		34.8 KG/M^3
TOTAL HULL STRUCTURE DENSITY		44.2 KG/M^3
HULL IMPACT DESIGN PRESSURE		1.8 KG/CM^2
FRAME SPACING		0.7 M
NO. OF BULKHEADS		7
DAMAGE ZONE CRITERIA (FLOODABLE LENGTH)		2 COMPARTMENT
HULL FORM DESCRIPTION		MOTORBOAT HULL HARD CHINE



TYPICAL HULL SECTION

UNCLASSIFIED

SUBSYSTEM CHARACTERISTICS (CONT.)

200 PROPULSION

FB GAS TURBINE (TYPE & NUMBER)	1-501KF
HB ENGINE (TYPE &NUMBER)	2-6V-53N
FB TURBINE SHP	
MAX. CONT.	3850 HP
MAX. INTER'M.	4700 HP
TYPE TRANSMISSION	Z DRIVE
PROPULSOR TYPE	CONTROLLABLE PITCH SUPER CAVITATING
NO. OF PROPULSORS	ONE
TYPE FUEL	JP-5

300 ELECTRIC PLANT

TOTAL KVA	100 - KW
60 HZ	
VOLTAGES USED	220/440 3Ø

400 COMMAND & SURVEILLANCE

TYPE OF NAV SYS	CUSTOMER OPTION
TYPE OF SURVEILLANCE SYS	
TYPE OF F/C SYS.	

600 AUXSYS

NO. & TYPE OF RUDDER	1 – AFT STRUT F.B. WATER JET H.B.
TYPE OF ACS	ANALOG
NO. & TYPE OF HEIGHT SENSORS	1 TRT-AHV-7

567 LIFT SYS

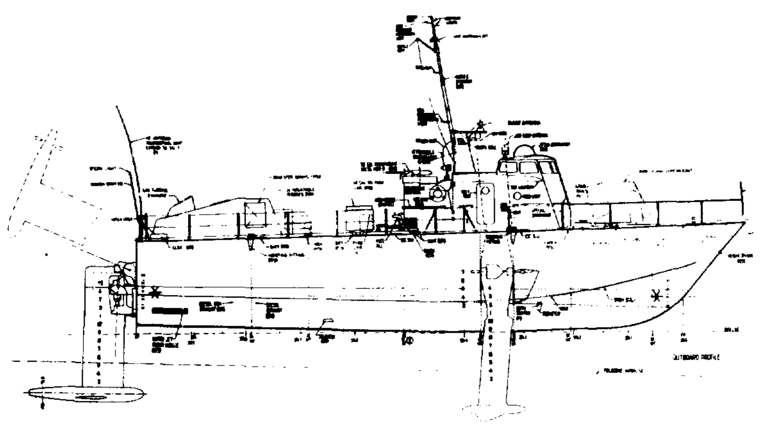
CONFIGURATION	CONVENTIONAL
% OF WEIGHT DIST'B.	70/30
RETRACTABLE OR FIXED	RETRACTABLE
SPAN	5.2 M EA – 3 FOILS
A.R.	5.5
TYPE CONTROL	STEERABLE AFT STRUT
L/D	12.5

600 OUTFITTING & FURNISHINGS

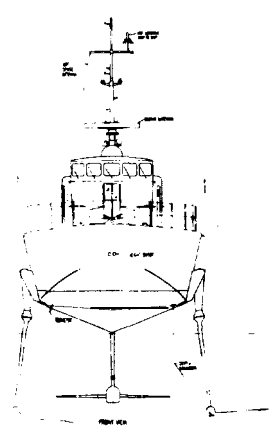
NO. & TYPE COMPARTMENTS	6
AREA PER MAJ. (OFFICER & ENLISTED)	NOT DETERMINED

700 WEAPONS

TYPE & NO. OF WEAPONS	1 – TWIN 30 MM GUN MOUNT 2 – 50 CAL TWIN MOUNT MOUNT MK 56 4.6 MISSILE (REPRESENTATIVE)

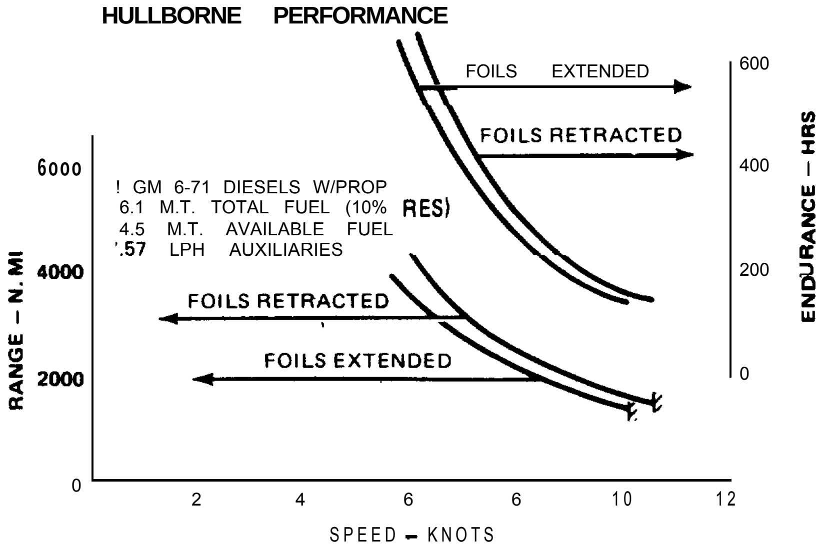


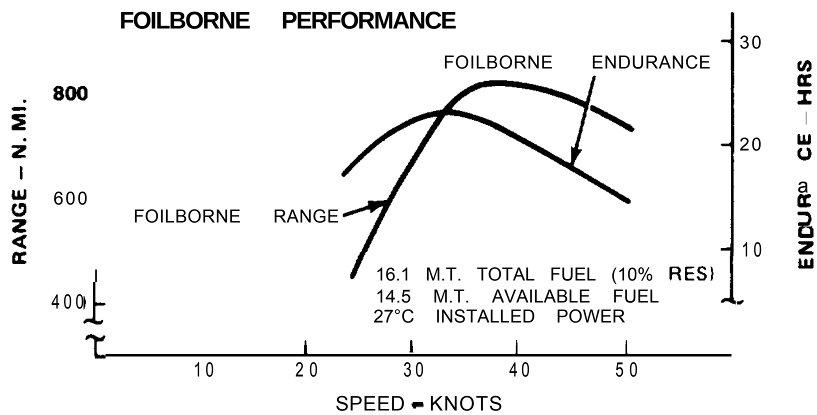
OUTBOARD VIEW



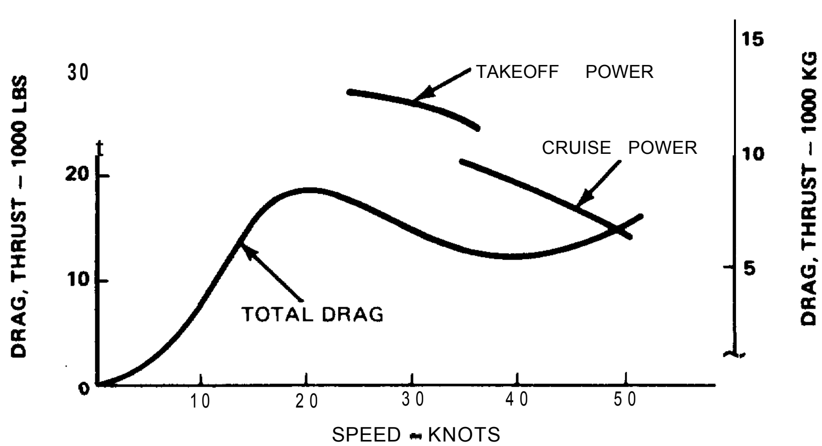
BOW VIEW

PREDICTED PERFORMANCE CHARACTERISTICS





DESIGN SEA STATE • 5
GENERAL:
DESIGNED BY GRUMMAN FOR ANTICIPATED SALES TO FREE WORLD NAVIES • 1975
USING PGH • 1 AS A BASELINE MISSION APPLICATION
OFFSHORE PATROL SUN



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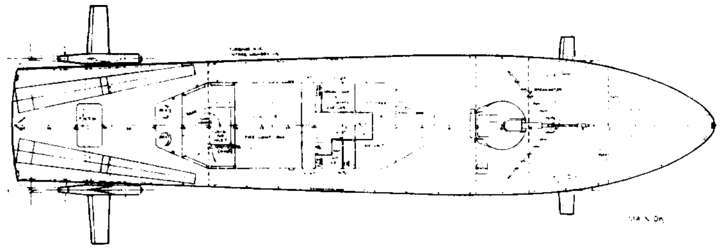
SPECIFIC DESIGNS SHIP CHARACTERISTICS

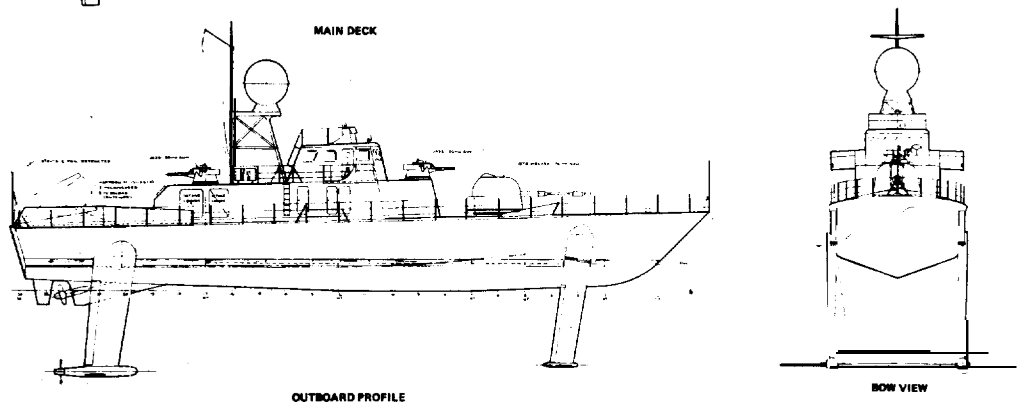
UNCLASSIFIED

GRUMMAN DESIGN M122C

Grumman Design M122C was one of a series of designs developed during CY 1971 in anticipation of the announced intended US Navy RFP for the subsequent PHM program.

The corporated funded, 174 metric ton, design is presented here to illustrate the performance advantages of propeller driven craft over the present waterjet propelled PHM design.



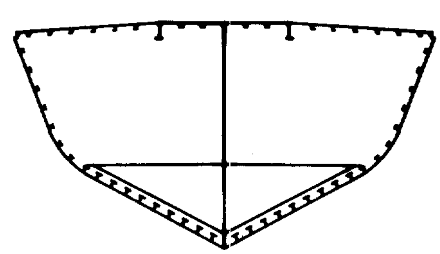


SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY			METRIC TONS	% F.L.
SWBS	100	HULL STRUCTURE	34.5	19.83
	200	PROPULSION SYSTEMS	13.7	7.87
	300	ELECTRIC PLANT	5.8	3.33
	(1) 400	COMMAND & SURVEILLANCE	4.9	2.82
	500	AUXILIARY SYSTEMS	11.5	6.61
	567	LIFT SYSTEMS	23.1	13.28
	600	OUTFIT & FURNISHINGS	7.4	4.25
	(1) 700	WEAPONS SYSTEMS	9.0	5.17
M10 CONTRACTOR CONTROLLED			–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM			–	–
MARGINS			5.0	2.11
DELIVERED LIGHTSHIP			114.9	66.03
NORMAL LOADS:				
(2) F10 SHIPS FORCE			2.8	1.61
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS			3.5	2.01
(1) F21 SHIP AMMUNITION			–	–
(2) F30 STORES			.7	.40
(2) F40 SHIP FUEL			44.9	25.80
(2) F50 POTABLE WATER			.4	.23
OTHER (MISC) LIQUIDS			6.8	3.91
(2) F60 CARGO (IF ANY)			–	–
DELIVERED FULL LOAD DISPLACEMENT			174.0	100
M24 FUTURE GROWTH MARGIN			–	–
MAXIMUM DISPLACEMENT			174.0	
GROUP 567 BUOYANCY				
NORMAL FOILBORNE			5.9	–
FB DYNAMIC LIFT (F.L.)			168.1	
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700 LOADS F20			22.4	12.87
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)			55.1	32.01
USEFUL PAYLOAD (1 & 2)			18.1	44.89

100 HULL

AREAS (HULL & SUPER-STRUCTURE)	SHELL PLATING	444.5 M^2
	DECK	364.6 M^2
	BULKHEADS	149.9 M^2
MATERIAL		ALUM. ALLOY
METHOD OF CONSTRUCTION		WELDED
HULL GIRDER STRUCTURE DENSITY		39.7 KG/M^3
SUPERSTRUCTURE DENSITY		19.9 KG/M^3
TOTAL HULL STRUCTURE DENSITY		35.6 KG/M^3 (AVG)
HULL IMPACT DESIGN PRESSURE		4.1 KG/CM^2
FRAME SPACING		1.5 M
NO. OF BULKHEADS		9
DAMAGE ZONE CRITERIA (FLOODABLE LENGTH)		2
HULL FORM DESCRIPTION		MOTORBOAT HULL ROUNDED CHINE



TYPICAL BULKHEAD

UNCLASSIFIED

SUBSYSTEM CHARACTERISTICS (CONT.)

200 PROPULSION

FB GASTURBINE (TYPE & NUMBER)	2-RM2B
HB ENGINE (TYPE & NUMBER)	1 TF14
FB TURBINE SHP MAX. CONT.	3650 HP X 2
TYPE TRANSMISSION	
PROPULSOR TYPE (DESCRIPTION)	2-PROPELLER F.S. I-PROPELLER H.B.
NO. OF PROPULSORS	3 PROFELLERS
TYPE FUEL	JP-5

300 ELECTRIC PLANT

TOTAL KVA	TSD
60 H_Z SYS	-'
VOLTAGES USED	440V 3Ø 115V 3Ø 24V DC

400 COMMAND&SURVEILLANCE

TYPE OF NAV SYS	NOT SELECTED
TYPE OF SURVEILLANCE SYS	
TYPE OF FIC SYS.	

SOOAUXIYS

NO. & TYPE OF RUDDER	4FLAPS
TYPE OF ACS	DIGITAL
NO. & TYPE OF HEIGHT SENSORS	RADAR

567 LIFT SYS

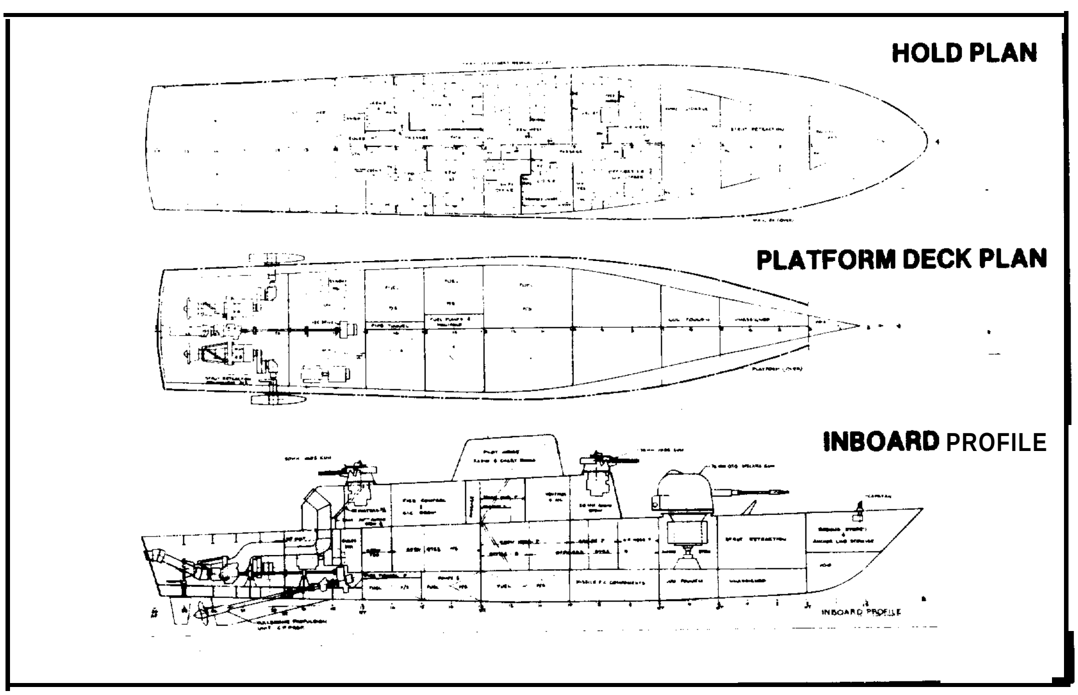
CONFIGURATION	INVERTED π TANDEM F/A
% OF WEIGHT DIST'B.	40/60
RETRACTABLE OR FIXED	RETRACTABLE
SPAN	13.4 M-AFT, 7.0 M FWD
A.R.	10.26 A, 4.96 F
TYPE CONTROL	FLAPS
LID	16.2

600 OUTFITTING & FURNISHINGS

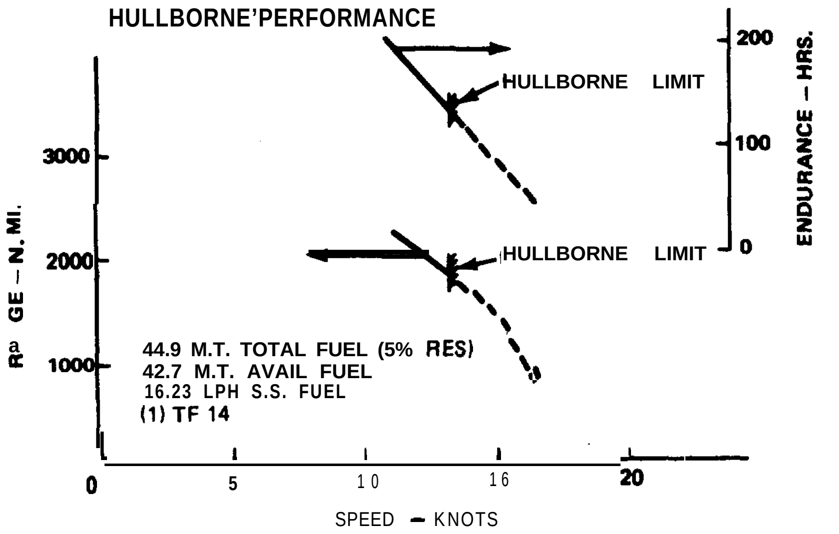
NO. & TYPE COMPARTMENTS	STANDARD FOR TYPE
AREA PER MAJ. (OFFICER & ENLISTED)	STANDARD FOR TYPE

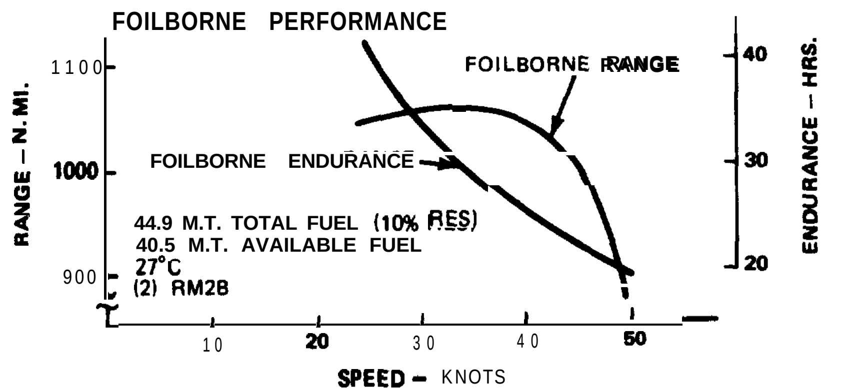
700 WEAPONS

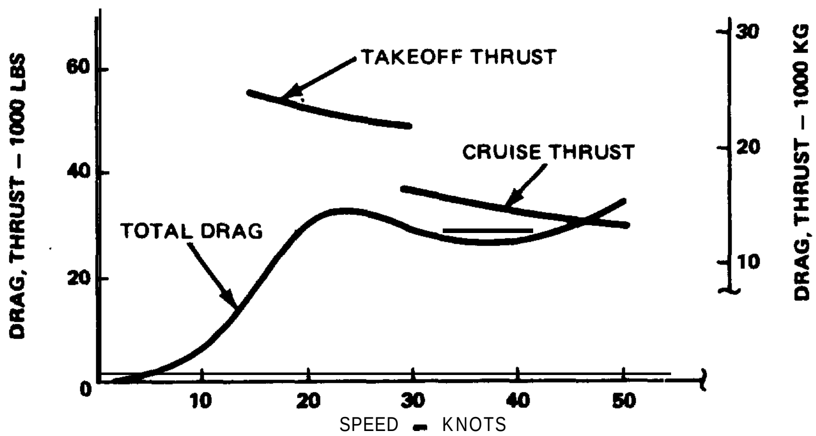
TYPE & NO. OF WEAPONS	NOT SELECTED



PREDICTED PERFORMANCE CHARACTERISTICS







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SPECIFIC DESIGNS SHIP CHARACTERISTICS

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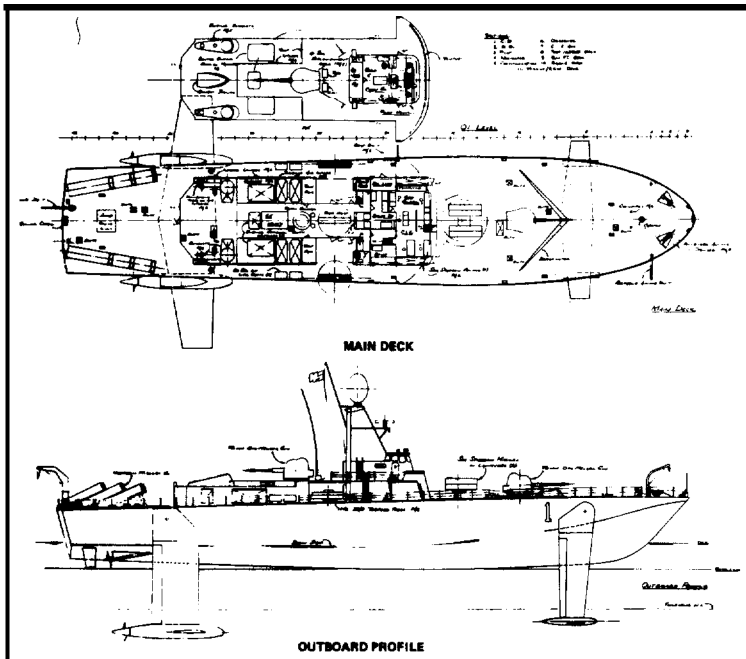
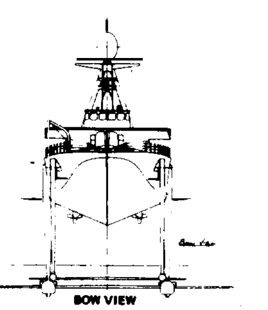


GRUMMAN DESIGN MI 24C

Grumman Design M124C was a twin GE LM 2500 gas turbine powered, propeller driven hydrofoil ship developed in CY 1972 for assessment of the large hydrofoil concept. The intended mission was to demonstrate and evaluate large hydrofoil ship performance and weapon system capabilities. The resulting general arrangements stressed a high degree of flexibility for ordnance and surveillance component location in keeping with the mission concept.

This corporate funded design has subsequently served as a baseline for technology developments, principally in lift system hydrodynamic and structural design, and propulsion system analysis.

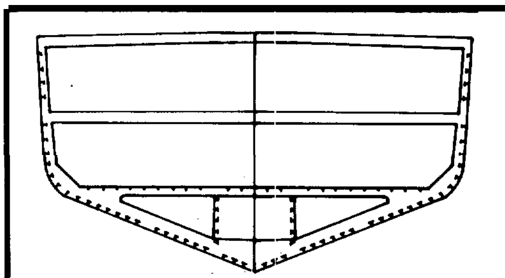


SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY			METRIC TONS	% F.L.
SWBS	100	HULL STRUCTURE	187.2	18.46
	200	PROPULSION SYSTEMS	56.4	5.55
	300	ELECTRIC PLANT	32.9	3.24
	(1) 400	COMMAND & SURVEILLANCE	19.5	1.92
	500	AUXILIARY SYSTEMS	42.50	4.18
	567	LIFT SYSTEMS	173.2	17.05
	600	OUTFIT & FURNISHINGS	27.6	2.72
	(1) 700	WEAPONS SYSTEMS	25.7	2.53
M10 CONTRACTOR CONTROLLED			–	–
M21-M22 CONTRACT DESIGN, MOD, & GFM				
MARGINS			55.5	3.00
DELIVERED LIGHTSHIP			575.5	55.55
NORMAL LOADS:				
(2) F 10 SHIPS			5.2	.61
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS			–	–
(1) F21 SHIP AMMUNITION			11.5	1.12
(2) F30 STORES			2.6	.25
(2) F40 SHIP FUEL			406.3	40.00
(2) F50 POTABLE WATER			4.4	.43
OTHER (MISC) LIQUIDS			2.3	.23
(2) F60 CARGO (IF ANY)			–	–
DELIVERED FULL LOAD DISPLACEMENT			1015.8	100
M24 FUTURE GROWTH MARGIN			–	–
MAXIMUM DISPLACEMENT			1015.8	
GROUP 567 BUOYANCY				
NORMAL FOILBORNE			– 99.1	–9.76
FB DYNAMIC LIFT (F.L.)			815.7	90.24
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700 LOADS F20			55.2	6.5
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)			421.5	41.53
USEFUL PAYLOAD (1 & 2)			488.1	48.1

100 HULL

AREAS (HULL & SUPER-STRUCTURE)	SHELL PLATING	1921.9 M^2
	DECK	2787.0 M^2
	BULKHEADS	542.6 M^2
MATERIAL	5086 H116 ALUM. ALLOY	
METHOD OF CONSTRUCTION	WELDED	
HULL GIRDER STRUCTURE DENSITY	30.1 KG/M^3	
SUPERSTRUCTURE DENSITY	17.5 KG/M^3	
TOTAL HULL STRUCTURE DENSITY	27.2 KG/M^3	
HULL IMPACT DESIGN PRESSURE	3.2 KG/CM' FWD (AVG) 1.6 KG/CM' AFT (AVG)	
FRAME SPACING	1.6 M	
NO. OF BULKHEADS	8	
DAMAGE ZONE CRITERIA (FLOODABLE LENGTH)	2 & 3 COMPARTMENT	
HULL FORM DESCRIPTION	MOTORBOAT HULL ROUNDED CHINE	



TYPICAL BULKHEAD

UNCLASSIFIED

SUBSYSTEM CHARACTERISTICS (CONT.)

UNCLASSIFIED

200 PROPULSION

FB GAS TURBINE (TYPE & NUMBER)	2-LM2500
HB ENGINE (TYPE & NUMEBR)	2-TF40
FB TURBINE SHP MAX. CONT.	19,800 HP
MAX: INTER'M.	24,800 HP
TYPE TRANSMISSION	BEVEL GEARS CROSS SHIP, DOWN STRUTS TO PODS, BEVEL GEARS IN PODS TO PLANETARY GEARS, TO PROPELLER
PROPULSOR TYPE (DESCRIPTION)	VARIABLE PITCH SUPER CAVITATING
NO. OF PROPULSORS	2
TYPE FUEL	P-B OR DIESEL

300 ELECTRIC PLANT

TOTAL KVA	600-900 KVA (TBD)
60 H_Z OR 400 H_Z SYS	
VOLTAGES USED	440/220/1 10

400 COMMAND &SURVEILLANCE

TYPE OF NAV SYS	(VARIOUS OPTIONS AS WEAPON TEST CRAFT)
TYPE OF SURVEILLANCE SYS	
TYPE OF F/C SYS.	

500 AUXSYS

NO. & TYPE OF RUDDER	4 FLAPS (F.B.) 2 SPADE (H.B.)
TYPE OF ACB	DIGITAL
NO. & TYPE OF HEIGHT SENSORS	RADAR

SUBSYSTEM CHARACTERISTICS (CONT'D)

567 LIFT SYS

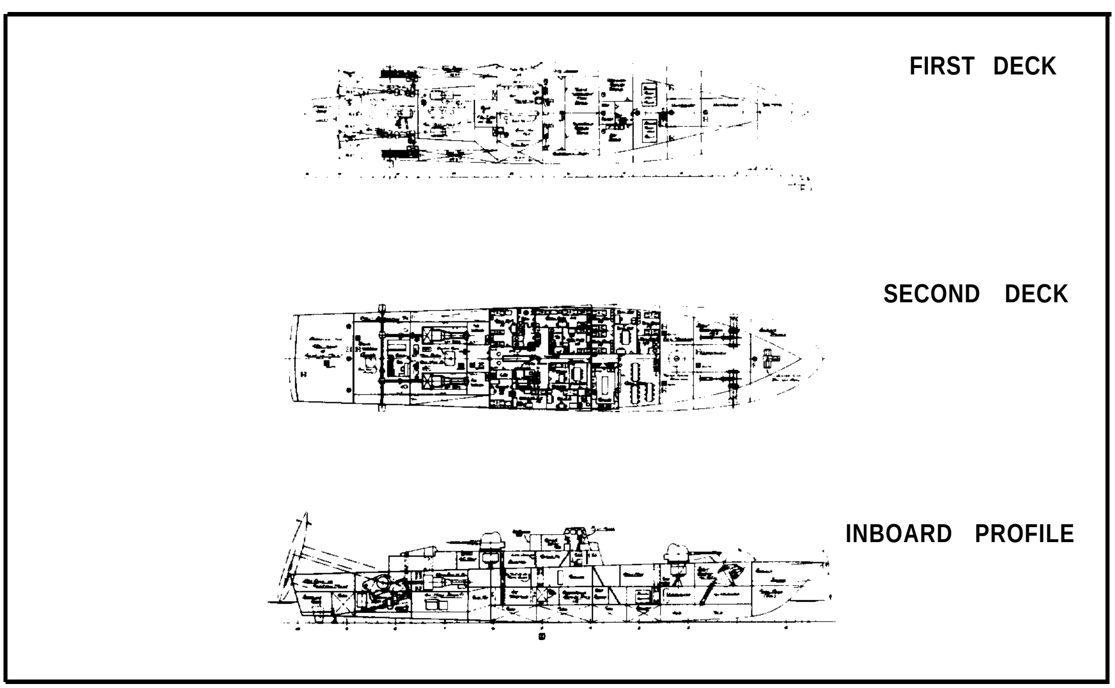
CONFIGURATION	INVERTED π TANDEM F/A
% OF WEIGHT DIST'B.	40/60
RETRACTABLE OR FIXED	RETRACTABLE
SPAN	27.4 M AFT, 29.2 M FWD
A.R.	6.0
TYPE CONTROL	FLAPS.
LID	15.91

600 OUTFITTING & FURNISHINGS

NO. &TYPE COMPARTMENTS	AS REQUIRED
AREA PER MAJ. (OFFICER & ENLISTED)	6.4 M^2

700 WEAPONS

TYPE & NO. OF WEAPONS	(VARIOUS OPTIONS AS WEAPONS TEST CRAFT1



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PREDICTED PERFORMANCE CHARACTERISTICS

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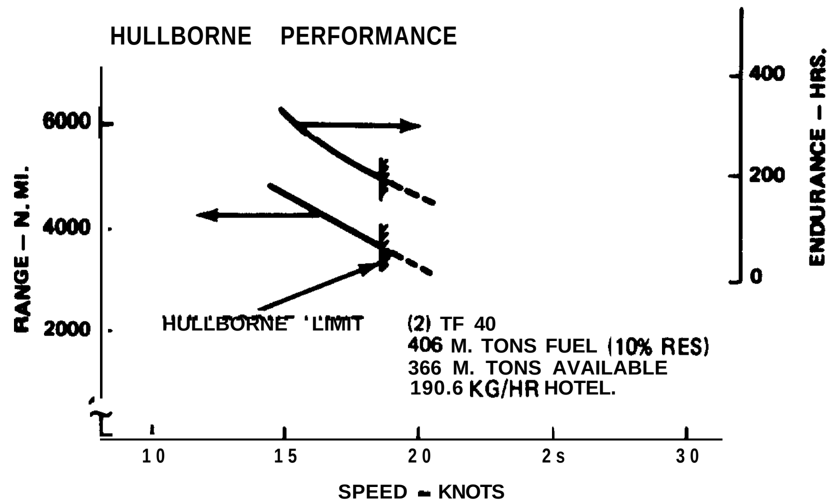

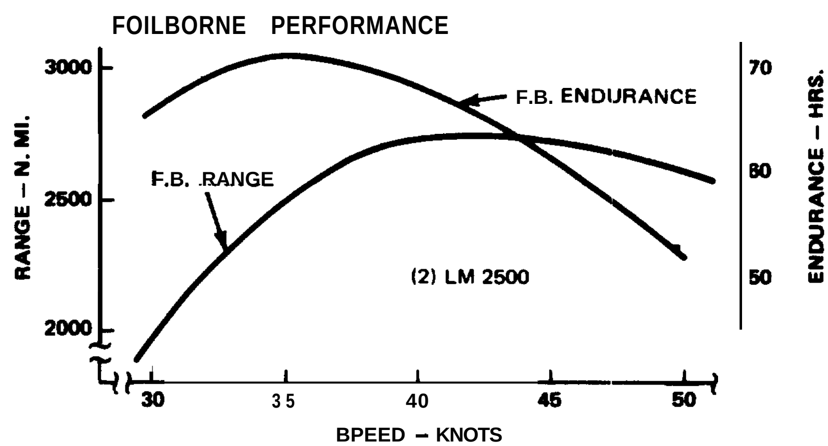

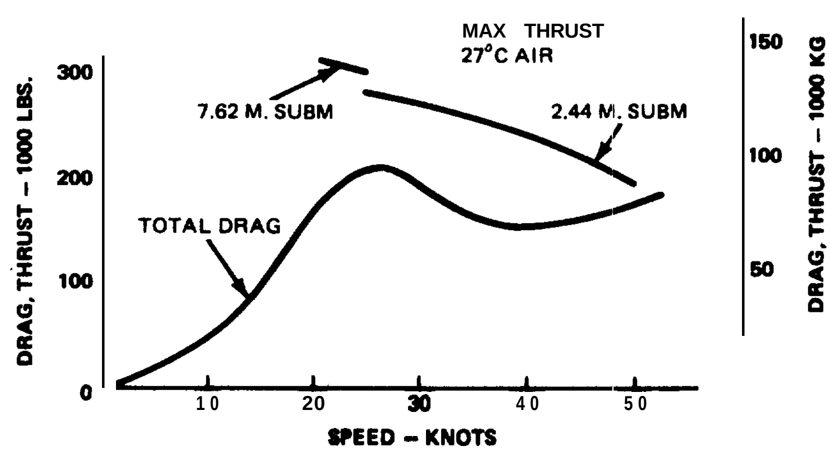

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SPECIFIC DESIGNS SHIP CHARACTERISTICS

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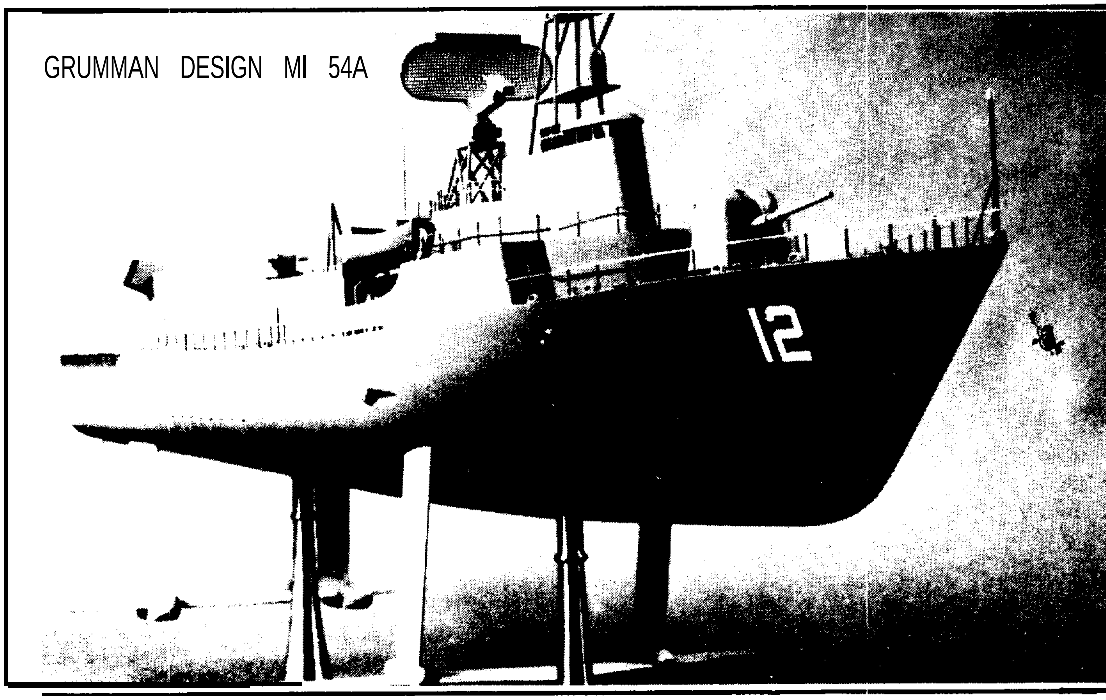

SUBSYSTEM CHARACTERISTICS

WEIGHT SUMMARY	METRIC TONS	% F.L.
SWBS 100 HULL STRUCTURE	251.2	16.90
200 PROPULSION SYSTEMS	81.4	6.12
300 ELECTRIC PLANT	46.5	3.50
(1) 400 COMMAND & SURVEILLANCE	31.7	2.38
500 AUXILIARY SYSTEMS	67.8	5.10
567 LIFT SYSTEMS	129.5	9.74
600 OUTFIT & FURNISHINGS	46.7	3.51
(1) 700 WEAPONS SYSTEMS	30.1	2.26
M10 CONTRACTOR CONTROLLED	—	—
M21-M23 CONTRACT DESIGN, MOD. & GFM	104.2	7.84
MARGINS	104.2	—
DELIVERED LIGHTSHIP	789.1	59.36
NORMAL LOADS:		
(2) F10 SHIPS FORCE	10.1	.76
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	—	—
(1) F21 SHIP AMMUNITION	67.7	5.09
(2) F30 STORES	17.6	1.32
(2) F40 SHIP FUEL	431.7	31.72
(2) F50 POTABLE WATER	13.0	.98
OTHER (MISC) LIQUIDS	—	—
(2) F60 CARGO (IF ANY)	—	—
DELIVERED FULL LOAD DISPLACEMENT	1329.4	100
M24 FUTURE GROWTH MARGIN	—	—
MAXIMUM DISPLACEMENT	1329.4	
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	— 67.3	—
FB DYNAMIC LIFT (F.L.)	1262.1	
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700 LOADS F20)	138.7	10.4
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)	472.6	35.20
USEFUL PAYLOAD (1 & 2)	611.3	45.6

100 HULL

AREAS (HULL & SUPER-STRUCTURE)	SHELL PLATING	1941.7 M^2
	DECK	3037.9 M^2
	BULKHEADS	867.7 M^2
MATERIAL		5456 AL. ALLOY
METHOD OF CONSTRUCTION		WELDED
HULL GIRDER STRUCTURE DENSITY		28.5 KG/M^3
SUPERSTRUCTURE DENSITY		13.1 KG/M'
TOTAL HULL STRUCTURE DENSITY		25 3 KG/M^3
HULL IMPACT DESIGN PRESSURE		3.5 KG/CM'
FRAME SPACING		.91 M
NO. OF BULKHEADS		13
DAMAGE ZONE CRITERIA (FLOODABLE LENGTH)		3 COMPARTMENT
HULL FORM DESCRIPTION		MOTORBOAT HULL ROUNDED CHINE

DATA
NOT
AVAILABLE

UNCLASSIFIED

SUBSYSTEM CHARACTERISTICS (CONT.)

200 PROPULSION

FE GAS TURBINE (TYPE & NUMBER)	2-LM 2500
HB ENGINE (TYPE & NUMBER)	SAME (+ LM 500 OPTION)
FB TURBINE SHP	
MAX. CONT.	24,336 HP
MAX. INTER'M	27,000 HP
TYPE TRANSMISSION	BEVEL GEARS CROSS SHIP, DOWN STRUTS TO PODS, BEVEL GRS IN PODS TO PLANETARY GRS TO PROPELLER
PROPULSOR TYPE (DESCRIPTION)	VARIABLE PITCH SUPER CAV!TATING
NO. OF PROPULSORS	TWO
TYPE FUEL	JP 5 OR DIESEL

300 ELECTRIC PLANT

TOTAL KVA	1080KVA
60 H_Z OR 400 H_Z SYS	
VOLTAGES USED	440/220/1 10

400 COMMAND6 SURVEILLANCE

TYPE OF NAV SYS	TBD
TYPE OF SURVEILLANCE SYS	TBD
TYPE OF F/C SYS.	TBD

500 AUX-SYS

NO. & TYPE OF RUDDER	4 FLAPS (F.B.) 2 SPADE (H.B.)
TYPE OF ACS	DIGITAL
NO. & TYPE OF HEIGHT SENSORS	RADAR

567 LIFT SYS

CONFIGURATION	INVERTED π TANDEM F/A
% OF WEIGHT DIST'B.	50/50
RETRACTABLE OR FIXED	FIXED
SPAN	20.3 M FWD & AFT
A R.	7.4
TYPE CONTROL	FLAPS
L/D	14.92

600 OUTFITTING & FURNISHINGS

NO. & TYPE COMPARTMENTS	AS REQUIRED
AREA PER MAJ. (OFFICERS ENLISTED)	6.0 m^2 (PRELIMINARY1

700 WEAPONS

TYPE & NO. OF WEAPONS	(REPRESENTATIVE1 32 STANDARD MISSILES 10 MK 48 TORPEDOES 1 OTO MELARA 76 MM GUN MOUNT 2 EMERLEC 30 MM TWIN GUN MOUNT

DATA
NOT
AVAILABLE

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PREDICTED PERFORMANCE CHARACTERISTICS

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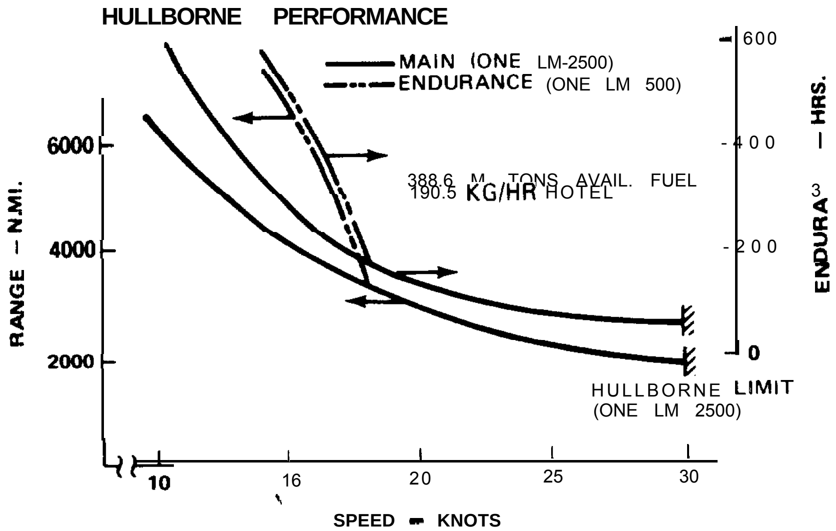

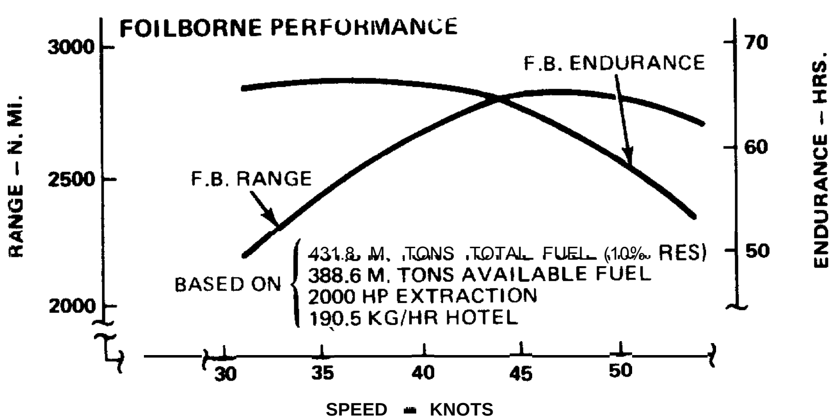

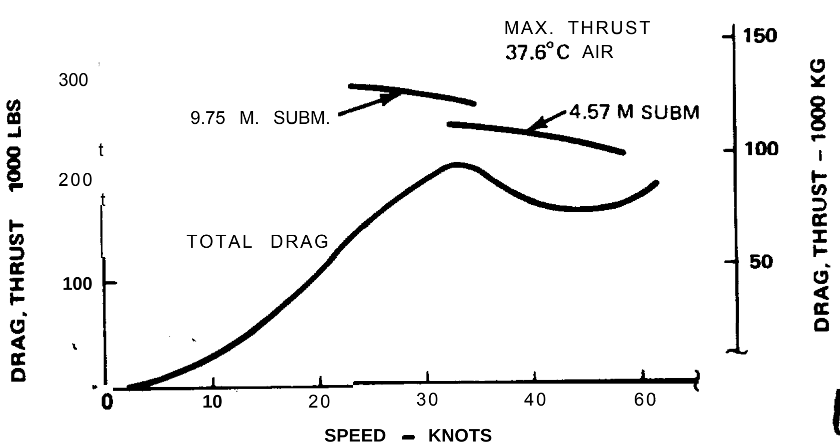

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SPECIFIC DESIGNS SHIP CHARACTERISTICS

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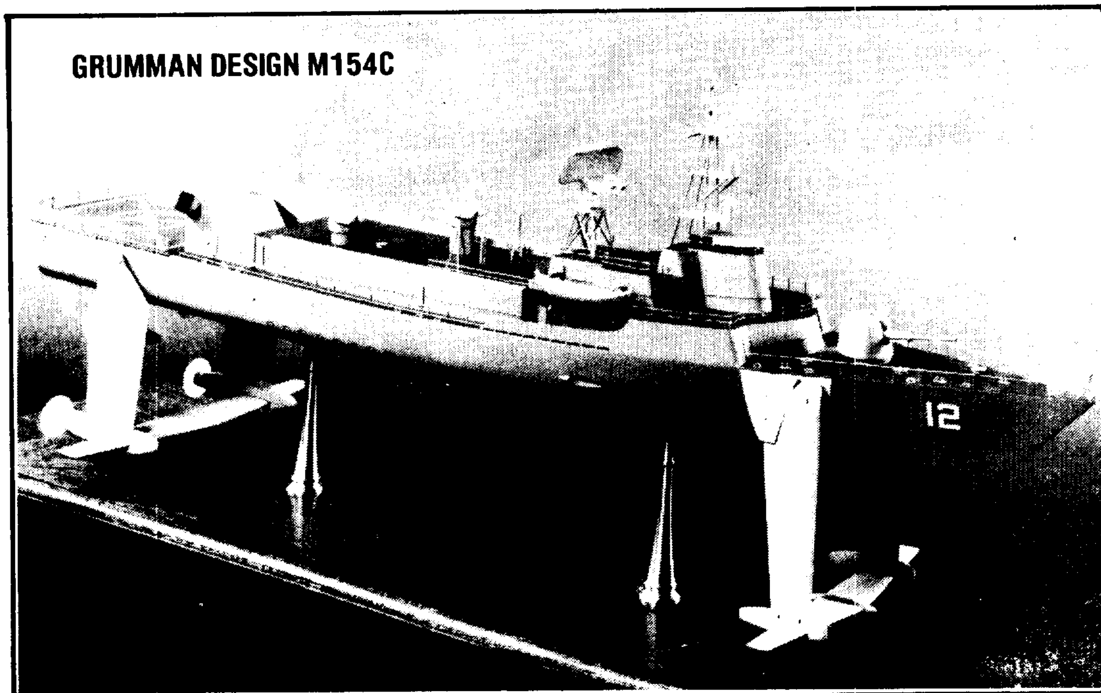

SUBSYSTEM CHARACTERISTICS

WEIGHTSUMMARY			METRIC TONS	% F. L.
SWBS	100	HULL STRUCTURE	251.2	15.45
	200	PROPULSION SYSTEMS	99.1	6.10
	300	ELECTRIC PLANT	46.5	2.86
	(1) 400	COMMAND & SURVEILLANCE	31.7	1.95
	500	AUXILIARY SYSTEMS	67.80	4.17
	567	LIFT SYSTEMS	271.1	16.68
	600	OUTFIT & FURNISHINGS	46.7	2.87
	(1) 700	WEAPONS SYSTEMS	30.1	1.85
M10 CONTRACTOR CONTROLLED			—	—
M21-M23 CONTRACT DESIGN, MOD, & GFM			126.7	—
MARGINS			126.7	1.10
DELIVERED LIGHTSHIP			10.1	.62
NORMAL LOADS			—	—
(2) F10 SHIPS FORCE			67.7	4.16 .62
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS				
(1) F21 SHIP AMMUNITION			67.7	4.16
(2) F30 STORES			17.8	1.10
(2) F40 SHIP FUEL			431.7	26.56
(2) F50 POTABLE WATER			13.0	.80
OTHER (MISC) LIQUIDS			—	—
(2) F60 CARGO (IF ANY)			114.3	7.03
DELIVERED FULL LO.40 DISPLACEMENT			1625.5	100
M24 FUTURE GROWTH MARGIN			—	—
MAXIMUM DISPLACEMENT			1625.5	
GROUP 567 BUOYANCY				
NORMAL FOIL BORNE			— 79.1	—4.87
FB DYNAMIC LIFT (F.L.)			1546.4	95.13
MILITARY PAYLOAD (1 INCLUDES SWBS 442 499 & 700 LOADS F20			138.7	8.5
VARIABLE PAYLOAD (2 INCLUDES LOADS F10 F30 F40 F50 AND F60)			472.6	21.5
USEFUL PAYLOAD (1 & 2)			611.3	30.0

100 HULL

AREAS (HULL & SUPER-STRUCTURE)	SHELL PLATING	1941.7 M^2
	DECK	3047.9 M^2
	BULKHEADS	867.7 M^2
MATERIAL		5456 ALUM ALLOY
METHOD OF CONSTRUCTION		WELDED
HULL GIRDER STRUCTURE DENSITY		28.5 KG/M^3
SUPERSTRUCTURE DENSITY		13.1 KG/M^3
TOTAL HULL STRUCTURE DENSITY		25.3 KG/M'
HULL IMPACT DESIGN PRESSURE		3.5 KG/CM' (AVG)
FRAME SPACING		.91 M
NO. OF BULKHEADS		13
DAMAGE ZONE CRITERIA (FLOODABLE LENGTH)		3 COMPARTMENT
HULL FORM DESCRIPTION		MOTORBOATHULL ROUNDED CHINE

DATA
NOT
PROVIDED

UNCLASSIFIED

ZOO PROPULSION

FB GAS TURBINE (TYPE & NUMBER)	2-LM 2500
HB ENGINE (TYPE & NUMBER)	SAME + OPTIONS
FB TURBINE SHP	
MAX. CONT.	24,336 H.P.
MAX. INTER'M.	26,500 H.P.
TYPE TRANSMISSION	BEVEL GEARS CROSS SHIP, DOWN STRUTS TO PODS, BEVEL GRS IN PODS TO PLANETARY GRS TO PROPELLER
PROPULSOR TYPE (DESCRIPTION)	VARIABLE PITCH SUPER CAVITATING
NO. OF PROPULSORS	FOUR
TYPE FUEL	JP-5 OR DIESEL

300 ELECTRIC PLANT

TOTAL KVA	1060 KVA
60 H_Z OR 400 H_Z SYS	
VOLTAGES USED	440/220/110

400 COMMAND & SURVEILLANCE

TYPE OF NAV SYS	TBO
TYPE OF SURVEILLANCE SYS	TBD
TYPE OF F/C SYS.	TBD

500 AUXSYS

NO. & TYPE OF RUDDER	4 FLAPS (F.B.) 2 SPADE (H.B.)
TYPE OF ACS	DIGITAL
NO. & TYPE OF HEIGHT SENSORS	RADAR

557 LIFT SYS

CONFIGURATION	INVERTED π TANDEM F/A
% OF WEIGHT DIST'B.	40/60
RETRACTABLE OR FIXED	RETRACTABLE
SPAN	27.5 M AFT, 22.5 M FWD
A.R.	7.4
TYPE CONTROL	FLAPS
LID	17.4

600 OUTFITTING & FURNISHINGS

NO. & TYPE COMPARTMENTS	AS REQUIRED
AREA PER MAJ. (OFFICER & ENLISTED)	6.0 M^2 (PRELIMINARY)

700 WEAPONS

TYPE & NO. OF WEAPONS	32 STANDARDMISSILES 10 MK 46 TORPEDOES 1 OTO MELARA 76 MM GUN MOUNT 2 EMERLEC 30 MM TWIN GUN MOUNT

DATA
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PROVIDED

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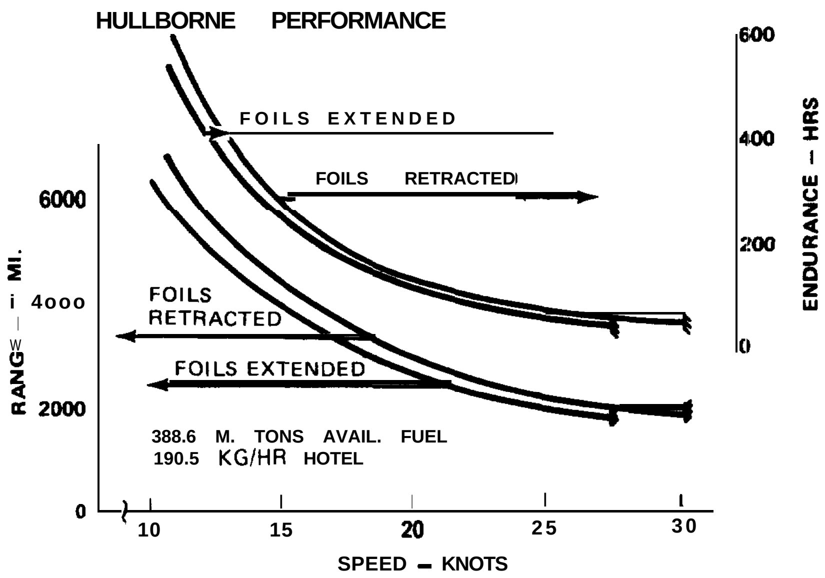
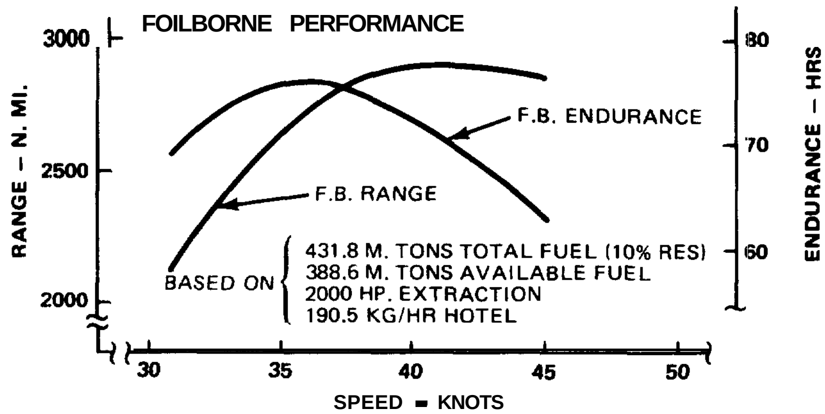
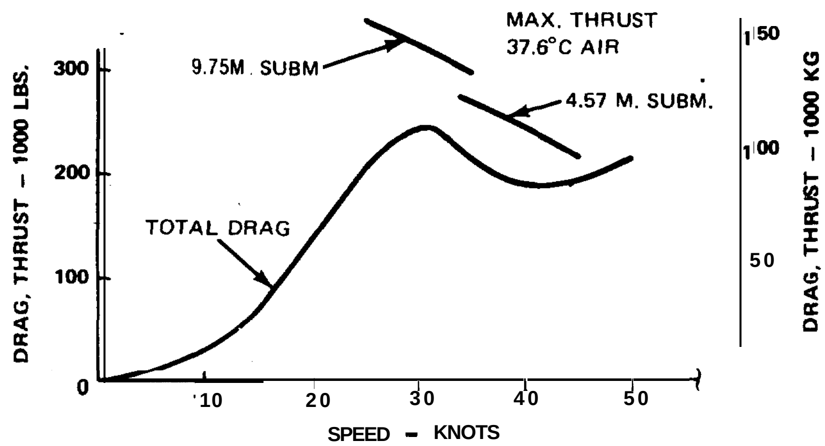
PREDICTED PERFORMANCE CHARACTERISTICS







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"HOC Hydrofoil Ocean Combatant Concept Design Baseline Report," NAVSEC Report No. 6114-75-20, April 4, 1975.

"Deepwater Escort Hydrofoil (DEH) Study-An Analysis of Mission, Combat Systems and Ship Concept Design," NAVSHIPS, 1973.

"750 Ton Developmental Big Hydrofoil (DBH) Feasibility Study (U)," Naval Ship Engineering Center, TN-6114-73-3, 10-C00395, February, 1973.

III. STATUS OF PERFORMANCE DATA

(SUMMARY OF EXPERIMENTAL RESULTS)

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III. STATUS OF PERFORMANCE DATA (SUMMARY OF EXPERIMENTAL RESULTS)

Section 1

INTRODUCTION

(U) Full scale performance trials are the final verification of a ship design. They are the final validation of performance prediction techniques and the design process which combines the various disciplines and subsystems into art integrated operating ship.

(U) The advanced hydrofoil program has recorded, analyzed, and assembled an extensive data base of full scale data on hydrofoil ships. The data has been derived from tests of five hydrofoils, the PGH-1, PGH-2, PCH-1 (Mod 0 and Mod 1), the AGEH-1, and the PHM-1. Most have been thoroughly tested both in calm water and seaways to beyond their design sea states. This full scale performance, with few exceptions, has agreed closely with predictions. Where predictions are not in agreement, the discrepancies are generally understood. The excellent agreement of full scale and predicted performance achieved to date gives the Navy the background and confidence to design and build future hydrofoil ships which will perform as predicted.

(U) This section will summarize in tabular and graphical form the most pertinent performance data from the wealth of data available. For additional data, the reader is directed to the relevant documents ordered by type of data and ship in Tables 111.1-l through 111.1-7 and listed in Reference 111.1-l.

(U) The ships considered herein were designed and built over a period of years, and to different requirements. Engineering judgment must be exercised in projecting the performance of future designs from information presented. For instance, the newer second generation marine gas turbines (LM 2500 and FT-9, etc.) have a specific fuel consumption up to 33 percent less than the first generation turbines such as the ROLLS-ROYCE PROTEUS. In addition, larger hydrofoil ships operate at higher Reynolds numbers, a lower ratio of the strut wetted area to gross weight, and a higher fuel fraction, all of which improve their efficiency and range. The data in this section are grouped into the following categories:

Speed-Power

- Drag and L/D versus speed
- Propulsive efficiency
- Transport efficiency
- Power and/or power/weight versus speed
- Rough water power

Endurance-Range

- Fuel flow
- Specific range
- Fuel flow/gross weight versus speed
- Endurance versus speed
- Range versus speed

Table III. 1-1. PERFORMANCE DATA OVERVIEW - SPEED - POWER

VEHICLE	NOMINAL WEIGHT (METRIC TONS)	ANALYSIS 4	MODEL TEST	FULL SCALE 4 TEST	4. NUMBER OF RELEVANT DOCUMENTS
HOC / DEH I	1000 TO 1600	●	◒		10
DBH	750 TO 1000	●	◒		3
AGEH-I	325.14	●	●	●	38
PHM-I	235.0	●	●	●	14
FHE-400 (3.)	215.50	●	●	●	11
PCH-MOD-0	114.10	●	●	●	[illegible]
PCH-MOD-I	28.23	●	●	●	16
PGH-I	69.70	●	●	●	16
PGH-2	58.34	●	●	●	32
SWORDFISH	(1.) 63.4	●	●	●	3
FRESH-I	(2.) 16.36	●	●	●	8

NOTES:
1. Essentially same as Tucumcari (PCH-2)
2. Supercavitating Foil Sys.
3. Surface Piercing Foil Sys.
4. See - SDD Data Bank Hydrofoil Document Listing "PERFORMANCE" DB/NO. 10-U07662

○ PAPER STUDY

◒ PERFORMANCE UNCERTAINTIES EXIST, OR NOT FULLY TESTED

● PERFORMANCE VALIDATION COMPLETE.

Table III.1-2. PERFORMANCE DATA OVERVIEW - RANGE - ENDURANCE

VEHICLE	NOMINAL WEIGHT (METRIC TONS)	ANALYSIS [6]	MODEL TEST	FULL SCALE TEST	0 4. NUMBER OF RELEVANT DOCUMENTS
HOC/DEH	1000 TO 1600	0			9
DBH	750 TO 1000	●			3
AGEH-I	325.14	0	0	0	8
PHM-I	235.0	0	●	0	9
FHE-400	[3] 0 215.50	●	□	●	6
PCH-MOD-O	114.10	0	0	0	6
PCH-MOD-I	128.23	0	●	0	4
PGH-I	69.70	0	0	0	7
PGH-2	58.34	0	0	0	11
SWORDFISH	(1.) 63.4	●	0	0	3
FRESH-I	[2] 0 16.36	0	0	0	1

NOTES:
1. Essentially same as Tucumcari (PGH-2)
2. Supercavitating Foil Sys.
3. Surface Piercing Foil Sys.
4. See - SDD Data Bank Hydrofoil Document listing "PERFORMANCE" DB/NO. 10-U07662

○ PAPER STUDY

◒ PERFORMANCE UNCERTAINTIES EXIST, OR NOT FULLY TESTED

● PERFORMANCE VALIDATION COMPLETE.

Table 11X.1-3. PERFORMANCE DATA OVERVIEW - MANEUVERABILITY

VEHICLE	NOMINAL WEIGHT (METRIC TONS)	ANALYSIS	MODEL TEST	FULL SCALE TEST	(4) NUMBER OF RELEVANT DOCUMENTS
HOC I DEH	1000 TO 1600	⊖			1
DBH	750 TO 1000	⊖			2
AGEH-I	325.14	♋	●	●	31
PHM-I	235.0	●	●	♋	20
FHE-400 (3.)	215.50	●	♋	●	6
PCH-MOD-0	114.10	●	●	a	51
PCH-MOD-1	128.23	a	●	●	[illegible]
PGH-I	69.70	●	●	●	10
PGH-2	58.34	a	a	3	21
SWORDFISH (1.)	63.4	●	♋	●	[illegible]
FRESH-I (2.)	16.36	●	a	a	4

NOTES:
1. Essentially same as Tucumcari (PCH-2)
2. Supercavitating Foil Sys;
3. Surface Piercing Foil Svs.
4. See SDD Data Bank Hydrofoil Document listing "PERFORMANCE" DB/NO. 10-U07662

○ PAPER STUDY

⊖ PERFORMANCE UNCERTAINTIES EXIST, OR NOT FULLY TESTED

● PERFORMANCE VALIDATION COMPLETE.

Table III.1-4. PERFORMANCE DATA OVERVIEW - STABILITY

VEHICLE	NOMINAL WEIGHT (METRIC TONS)	ANALYSIS[4]	MODEL TEST	FULL SCALE TEST	4. NUMBER OF RELEVANT DOCUMENTS
HOC[I] DEH	1000 TO 1600				
DBH	750 TO 1000				
AGEH-I	325.14	●	●	●	24
PHM-I	'235.0	6	●	●	3
FHE400 (3.)	215, SO	●	●	●	8
PCH-MOD-CI	114.10	●	●	●	28
PCH-MOD-I	128.23	●	●	●	4
PGH-I	69.70	[illegible]	[illegible]	●	8
PGH-2	58.34	●	●	●	11
SWORDFISH (1.)	63.4				
FRESH-I (2.)	16.36	●	●	●	[illegible]

1. Essentially same as Tucumcari (PGH-2)
2. Supercavitating Foil Sys.
3. 'surface Piercing Foil Sys.
4. See ■ SDD Data Bank Hydrofoil Document listing "PERFORMANCE" DB/NO. 10-U07662

○ PAPER STUDY

◒ PERFORMANCE UNCERTAINTIES EXIST, OR NOT FULLY TESTED

● PERFORMANCE VALIDATION COMPLETE.

Table III. 1-5. PERFORMANCE DATA OVERVIEW - SEAKEEPING/SEAKINDLINESS

VEHICLE	NOMINAL WEIGHT (METRIC TONS)	ANALYSIS	MODEL TEST	FULL SCALE TEST	(4) NUMBER OF RELEVANT DOCUMENTS
HOC DEH	1000 TO 1600	⊖	⊖		3
DBH	750 TO 1000	⊖	⊖		2
AGEH-I	325.14	●	●	○	34
PHM-I	235.0	●	●	●	7
FHE-400 (3)	215.50				16
PCH-MOD-0	114.10	●	●	●	45
PCH-MOD-i	128.23	●	●	a	15
PGH4	69.70	●	●	●	12
PGH-2	58.34	●	●	●	22
SWORD-FISH (1)	63.4	●	●	●	3
FRESH-i (2)	16.36	●	●	●	5

NOTES:
1. Essentially same as Tucumcari (PGH-2)
2. Supercavitatinq Foil Sys.
3. Surface Piercing Foil Sys.
4. See - SDD Data Bank Hydrofoil Document listing "PERFORMANCE" DB/NO. 10-U07662

○ PAPER STUDY

⊖ PERFORMANCE UNCERTAINTIES EXIST, OR NOT FULLY TESTED

● PERFORMANCE VALIDATION COMPLETE.

Table 11X.1-6. PERFORMANCE DATA OVERVIEW - INTERNAL ENVIRONMENT

VEHICLE	NOMINAL WEIGHT (METRIC TONS)	ANALYSIS	MODEL TEST	FULL SCALE TEST	(4.) NUMBER OF RELEVANT DOCUMENTS
HOC I DEH	1000 TO 1600				
DBH	750 TO 1000				
AGEH-I	325.14	0		0	10
PHM-I	235.0	●	●	●	
FHE-400	3. 0 215.50				
CH-MOD-0	114.10	0	0	0	7
PCH-MOD-I	128.23			0	2
PGH-I	69.70	0	0	0	11
PGH-2	58.34	0		0	12
SWORDFISH	(1.) 63.4				
FRESH-f	(2.) 16.36				

NOTES:
1. Essentially same as Tucumcari (PGH-2)
2. Supercavitating Foil Sys.
3. Surface Piercing Foil Sys.
4. See - SDD Data Bank Hydrofoil Document listing "PERFORMANCE" DB/NC. 10-U07662

○ PAPERSTUDY

⊖ PERFORMANCE UNCERTAINTIES EXIST, OR NOT FULLYTESTED

● PERFORMANCE VALIDATIONCOMPLETE.

Table III.1-7. PERFORMANCE DATA OVERVIEW - PAYLOAD CAPABILITIES

VEHICLE	NOMINAL WEIGHT (METRIC TONS]	ANALYSIS	MODEL TEST	FULL SCALE TEST	4.1 NUMBER OF RELEVANT DOCUMENTS
HOC I DEH	1000 TO 1600	●			18
DBH	750 TO 1000	a			1
AGEH-i	325.14	●		●	4
PHM-I	235.0	a		a	3
FHE-400	(2) 215.50				
PCH-MOD-0	114.10	●	●	●	3
PCH-MOD-I	128.23	●	●	●	5
PGH-I	69.70	●	●	◒	4
PGH-2	58.34	◒	●	●	4
SWORDFISH	(1.) 63; 4	●		a	1
FRESH-I	(3) 16.36			●	1

NOTES:
1. Essentially same as Tucumcari (PGH-2)
2. Supercavitating Foil Sys;
3. Surface Piercing Foil Sys.
4. See - SDD Data Bank Hydrofoil Document Listing "PERFORMANCE" DB/NO. 10-U07662

○ PAPER STUDY

◒ PERFORMANCE UNCERTAINTIES EXIST, OR NOT FULLY TESTED

● PERFORMANCE VALIDATION COMPLETE.

Maneuverability

- Turning rate versus speed
- Turning diameter versus speed
- Turn rate versus rudder angle
- Foilborne tactical maneuver capability

Stability

- Step responses

Ride Quality

- Motion in sea state with varying wave direction
- RMS g's vertical accelerations as a function of significant wave height
- RMS g's lateral accelerations as a function of significant wave height
- Standard deviation pitch angles as a function of significant wave height
- Standard deviation roll angles as a function of significant wave height
- RMS g's vertical accelerations as a function of encounter frequency
- RMS g's lateral accelerations as a function of encounter frequency

Internal Environment

- Noise and vibration levels - general statements

Payload Capabilities

- Military payload as a function of gross weight
- Useful load fraction as a function of gross weight
- Payload as a function of endurance
- Payload as a function of range

Section 2

SUBCAVITATING HYDROFOIL SHIPS

2.1 FOILBORNE PERFORMANCE

2.1.1 Soeed-Power

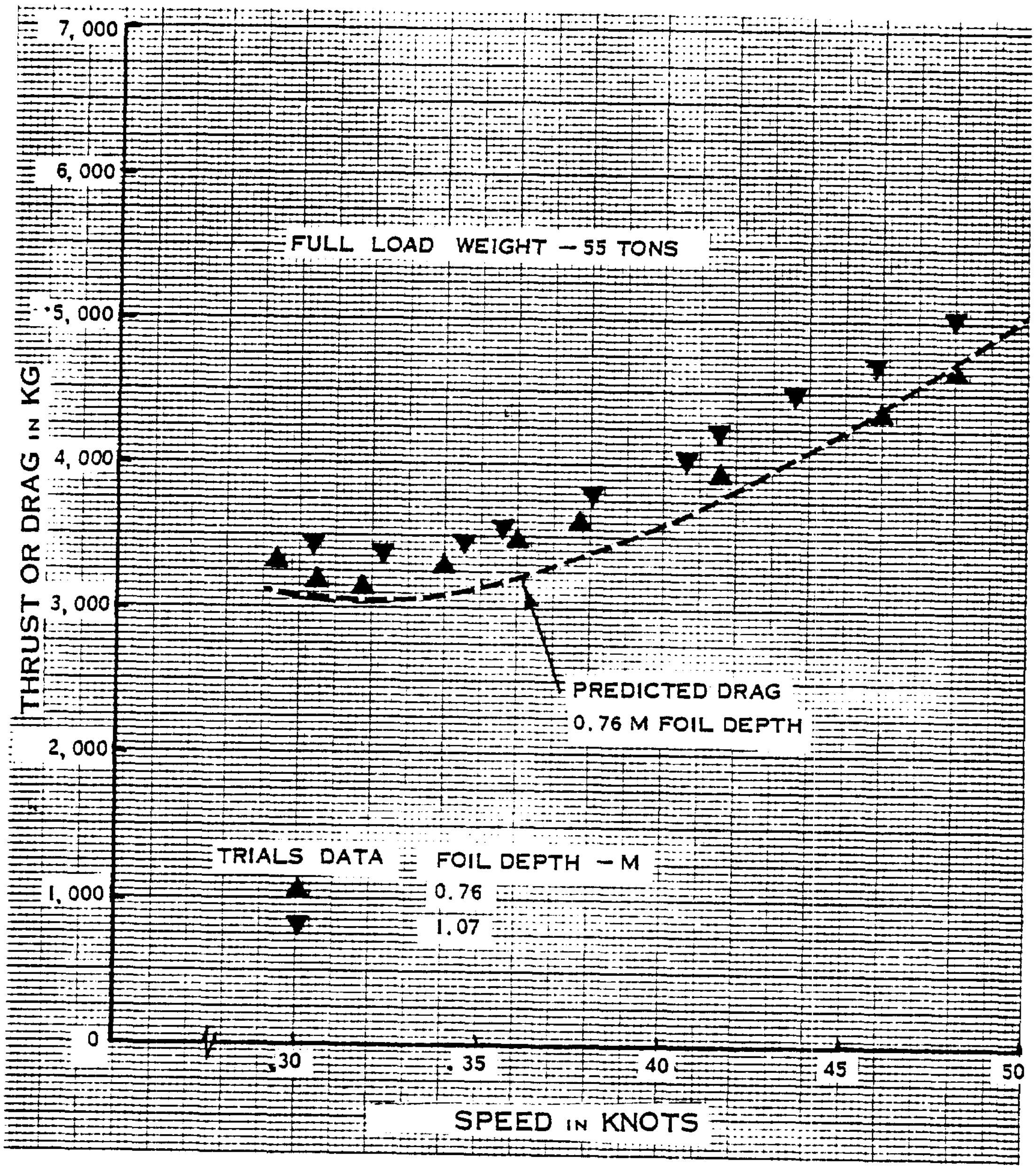
(U) Power can be divided into two parts; first, mission power comprising hotel loads, navigation, and weapon systems requirements, and second, propulsion power including power required to control the ships. For the purposes of this section, total power is the propulsion power plus any control power. Power required is a function of the ship speed, ship drag, and propulsive coefficient, and, therefore, at a given speed, is a measure of the hydrodynamic propulsive efficiencies.

2.1.1.1 Drag

(U) Predicted drag and drag obtained from trials data are shown in Figures 111.2-l through 111.2-5 for PGH-2, PCH-1 (Mod-l), AGEH-1, and PHM-1. Appropriate references are numbered on the figures.

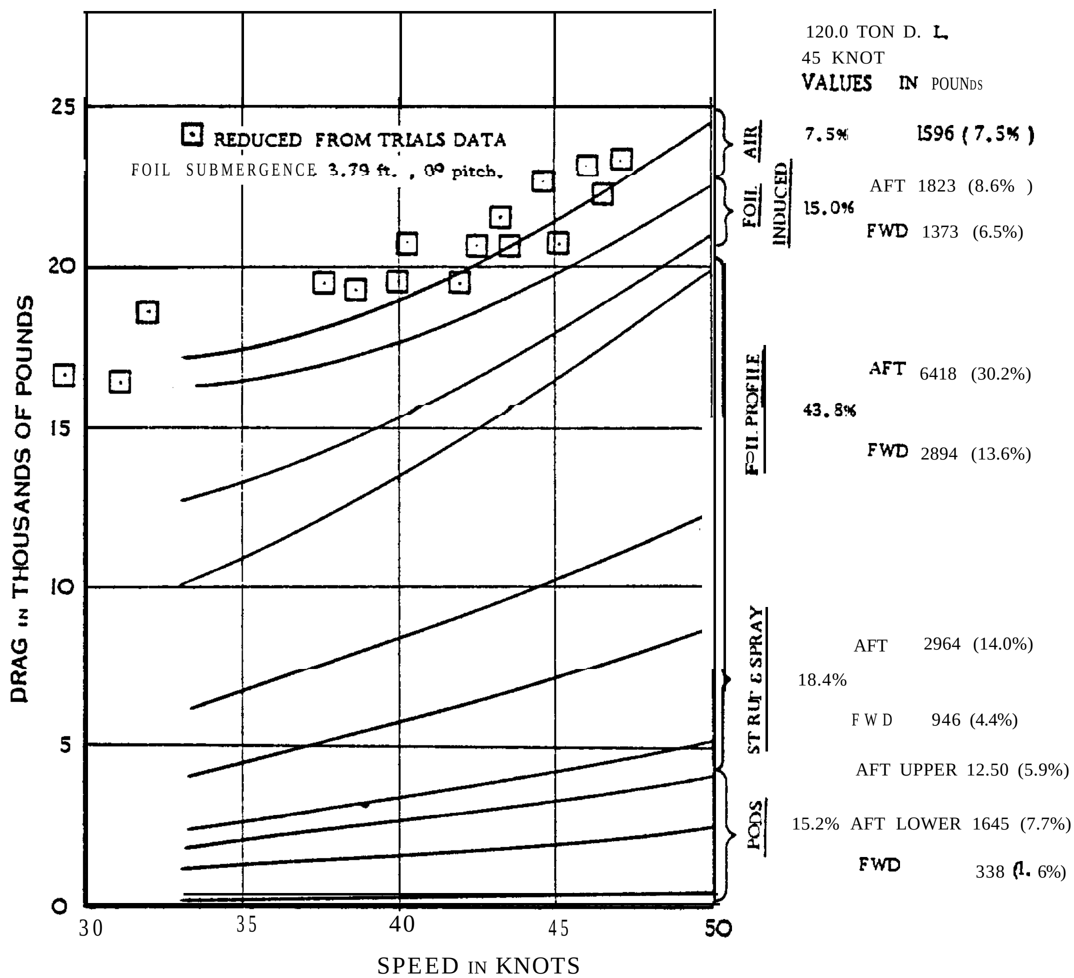
(U) Agreement is good with the exception of the PHM-1. The reasons for the discrepancy with the PHM-1 are well understood.

(U) The major cause of the higher than predicted drag, as explained in Reference 111.2-l is attributable to the cavitation at all foilborne speeds on the foils (particularly the rear center span) of the PHM. This cavitation is a direct result of the large deviations of the as-built foil contours from the design contours. Based on the accuracy of drag prediction on other hydrofoil ships



Reference III.2-2

Figure III.2-1. PGK-2 FOILBORNE DRAG



Reference III.2-3

Figure III.2-2. PCH-1, MOD 1 FOILBORNE AND DRAG BUILD-UP

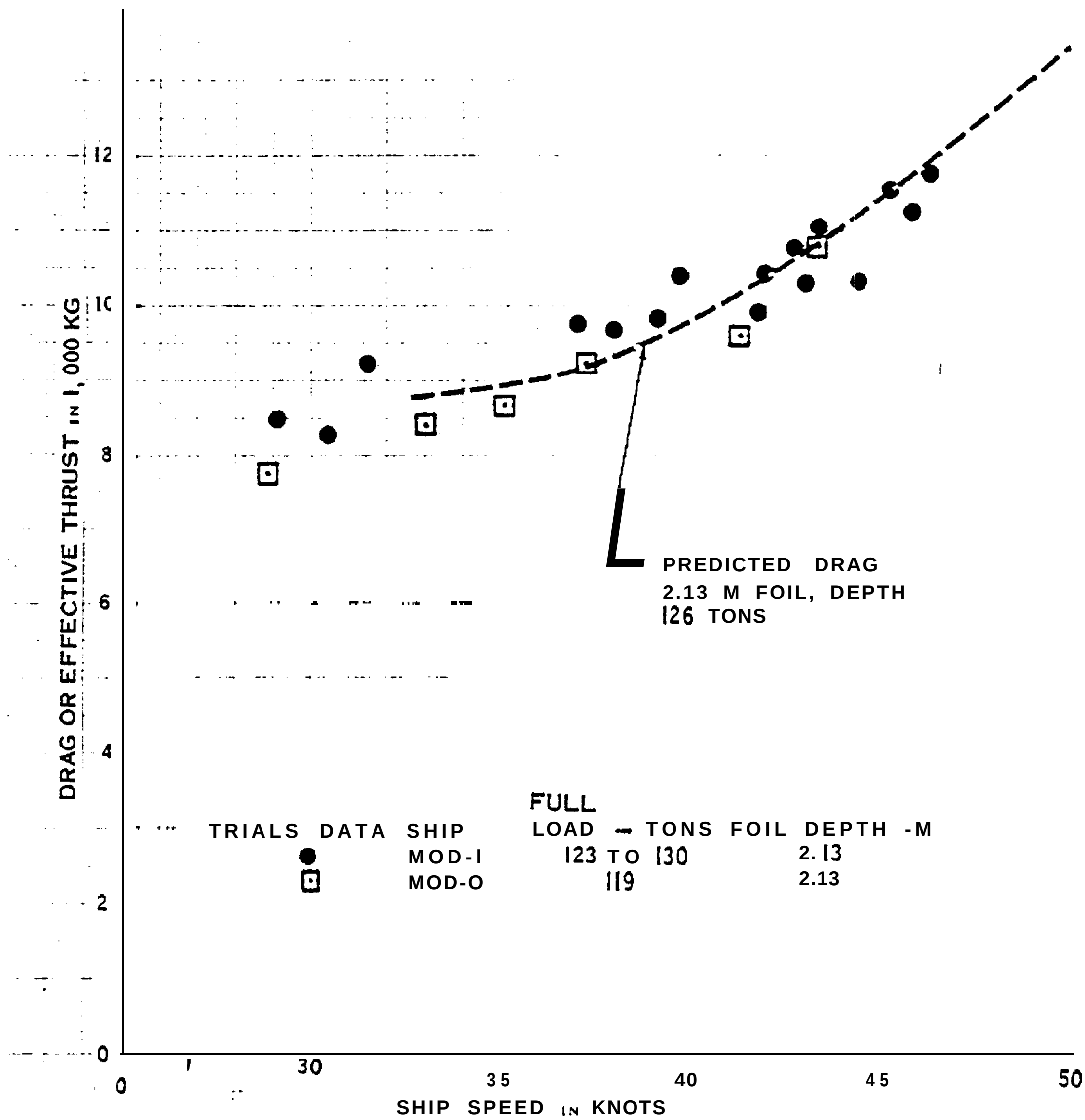


Figure III.2-3. PCH-1 FOILBORNE DUG

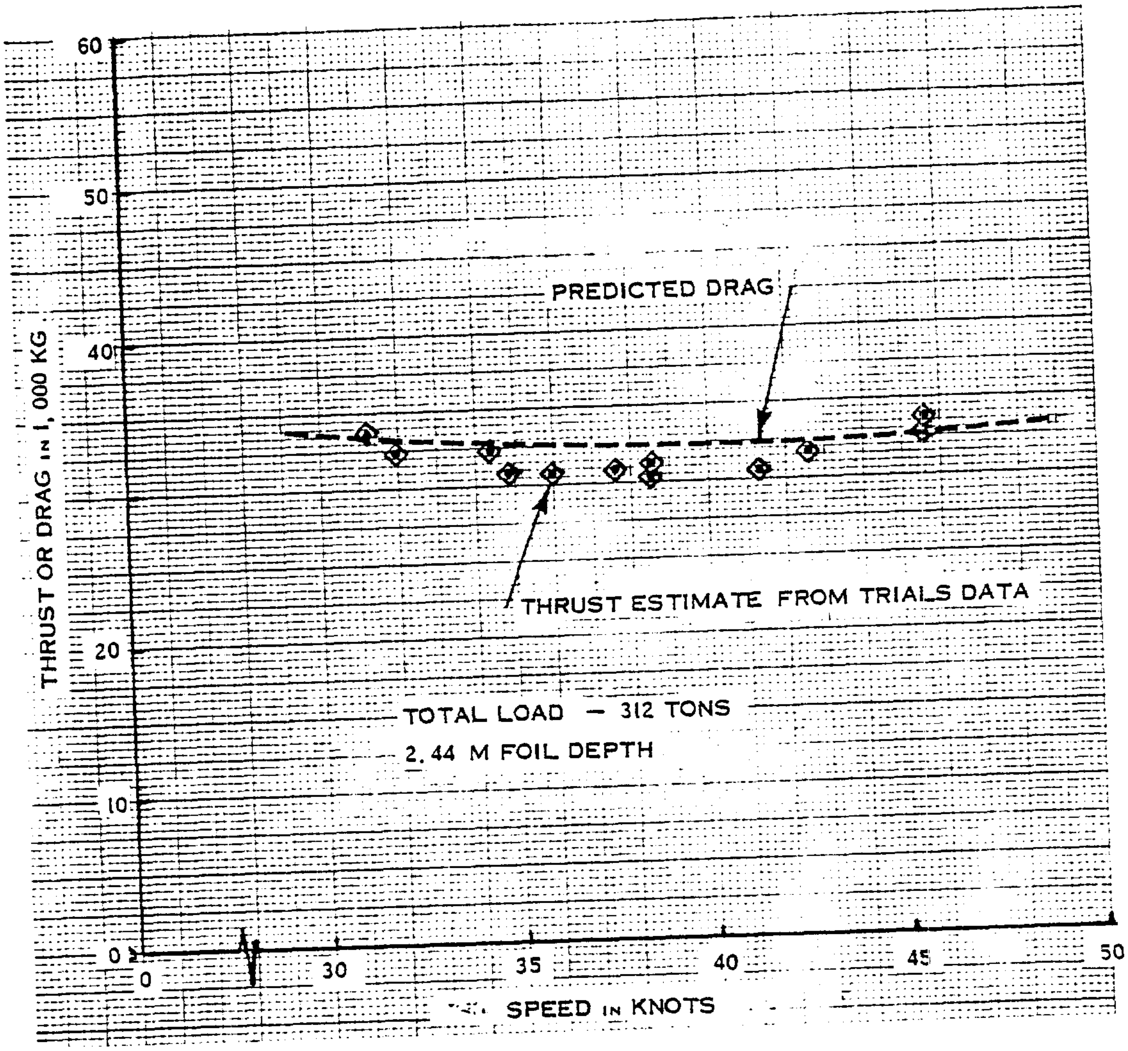


Figure III.2-4. AGEH-1 FOILBORNE DRAG

Reference 11X.2-4

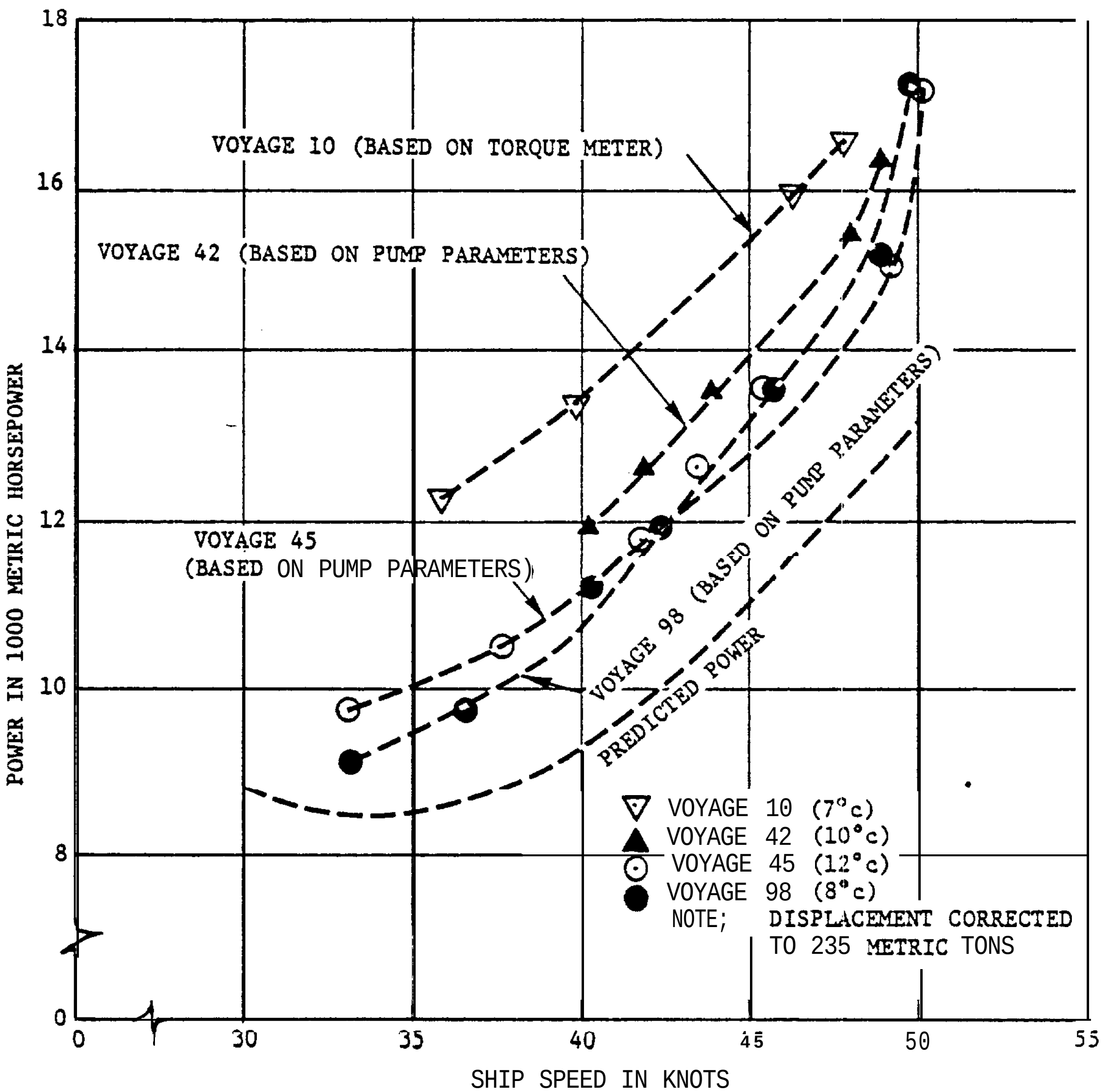


Figure 111.2-Z. PHM-1 MEASURED AND PREDICTED DRAG AS A FUNCTION OF SPEED (U)

built to date, the PHM, with proper foil contours, will also meet its predicted drag. Table III.2-1 lists the recommended contour tolerances which, if adhered to, will make the PHM free of cavitation throughout its operating speed regime. These tolerances are reasonable and achievable as all previous Navy hydrofoil ships have been built to equal or smaller tolerances.

2.1.1.2 Lift/Drag Hydrodynamic and Overall Lift to Drag Ratio

(U) Hydrodynamic L/D as a function of full load weight (long tons) is presented in Figure III.2-6, which shows the benefits of increased size. The hydrodynamic L/D is distinguished from the overall L/D in that the former is based on the hydrodynamic lift while the latter is based on the buoyant and hydrodynamic lift. Therefore, overall L/Ds tend to be larger than hydrodynamic L/Ds. This disparity exhibits an increase with size.

(U) Overall lift/drag ratio is shown for existing ships in Figure 111.2-7. The differences in Figure 111.2-7 are attributed to both varying design requirements and design philosophies. The hydrodynamic efficiencies of larger ships generally are better than those of existing ships because:

- They operate at higher Reynolds numbers
- The ratio of the strut wetted area as a function of gross weight tends to decrease with an increase in gross weight

Variation of foil L/D as a function of foil Reynolds numbers for a nominal loading of 1,000 lbs/ft^2 is shown in Figure III.2-8 for

Table III.2-1. RECOMMENDED TOLERANCES FOR STRUTS AND FOILS FOR PHM

AFT CENTER SPAN-LOWER SURFACE

L.E. to 15% chord	X/C = .0016
15% chord to T.E.	X/C = .0032
Waviness	ΔX/ΔS = .030

AFT CENTER SPAN - UPPER SURFACE

L.E. to 152 chord	X/C = .0008
15% chord to T.E.	X/C = .0016
Waviness	ΔX/ΔS = .015

AFT TIPS AND FORWARD FOIL - LOWER SURFACE;

Pod to 80% Span

L.E. to 15% chord	X/C = .0016
15% chord to T.E.	X/C = .0032
Waviness	ΔX/ΔS = .030

80% Span to Tip

L.E. to 15% chord	X/C = .0019
15% chord to T.E.	X/C = .0038
Waviness	ΔX/ΔS = .030

AFT TIP AND FORWARD FOIL - UPPER SURFACE

Pod to 80% Span

L.E. to 15% chord	X/C = .0008
15% chord to T.E.	X/C = .0016
Waviness	ΔX/ΔS = .015

80% Span to Tip

L.E. to 15% chord	X/C = .0010
15% chord to T.E.	X/C = .0020
Waviness	ΔX/ΔS = .015

STRUTS

From Pod to 3 Meters above Pod

L.E. to 15% chord	X/C = .0008
15% chord to T.E.	X/X = .0016
Waviness	ΔX/ΔS = .015

STRUT - FOIL SURFACE FINISH

L.E. to 15% chord	< 2 μm rms
15% chord to T.E.	< 4 μm rms

STRUT-FOIL TWIST TOLERANCES

When looking spanwise, the angle between any two chord lines shall deviate from the design twist by less than 0.4 degrees and the rate of change of twist shall deviate from the design twist rate by less than 0.3 degrees per meter.

PODS

Nose to 25% chord	X/C = .0008
25% chord to Tail	X/C = .0016
Waviness	ΔX/ΔS = .020

Pod Finish:

Pod Finish

Nose to 25% chord	< 2 μm rms
25% chord to tail	< 4 μm rms

DEFINITIONS

L.E	Leading edge
T.E	Trailing edge
C	Chord
X	Deviation from the design contour which is defined as the normal distance from the design contour to the actual contour when superimposed.
S	Distance measured along the design contour
Δ	Change in
Waviness	ΔX/ΔS. Note waviness applies in both spanwise and chordwise direction.

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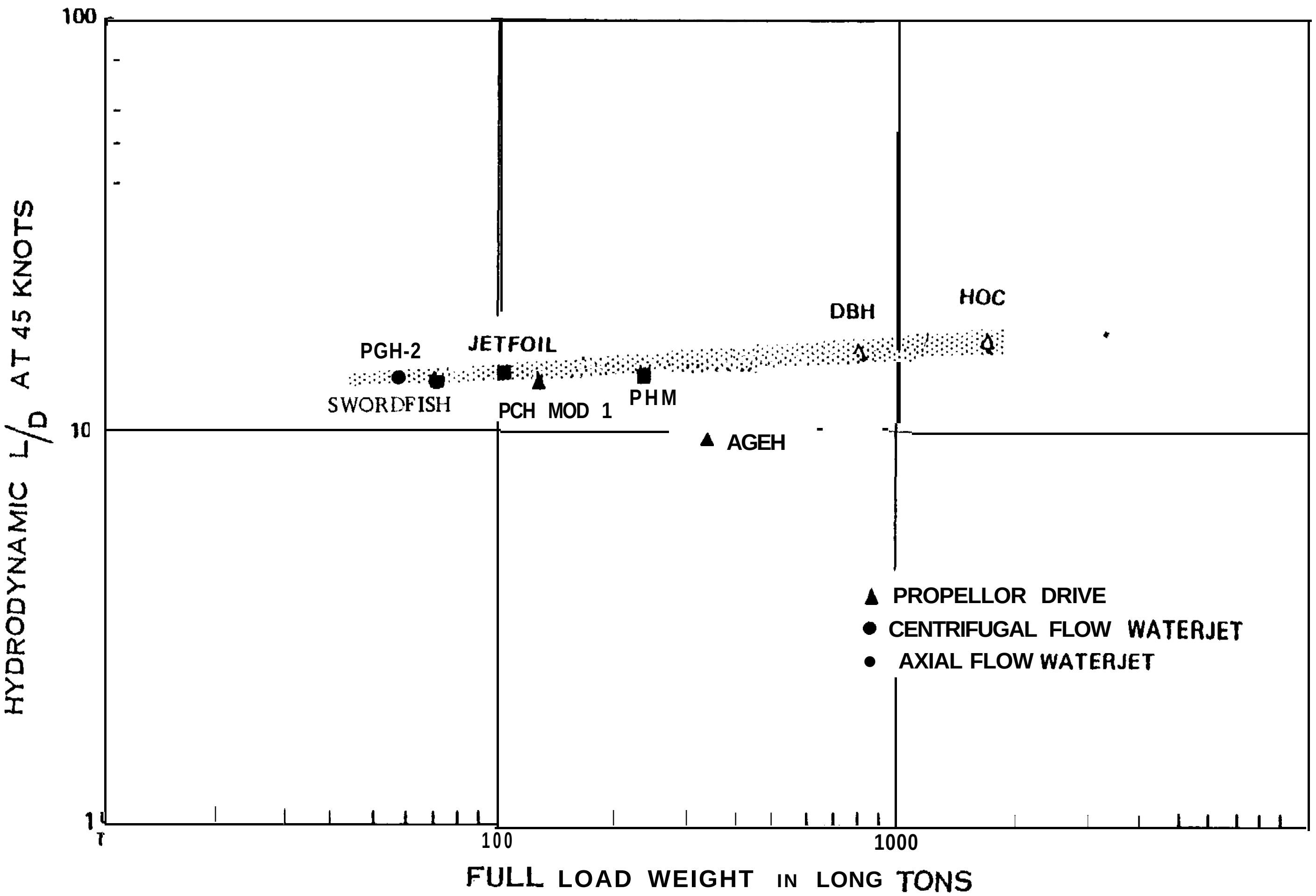

Reference III.2-5

Figure 111.2-6. INTRINSIC CHARACTERISTICS-SHIP SIZE BENEFIT (U)

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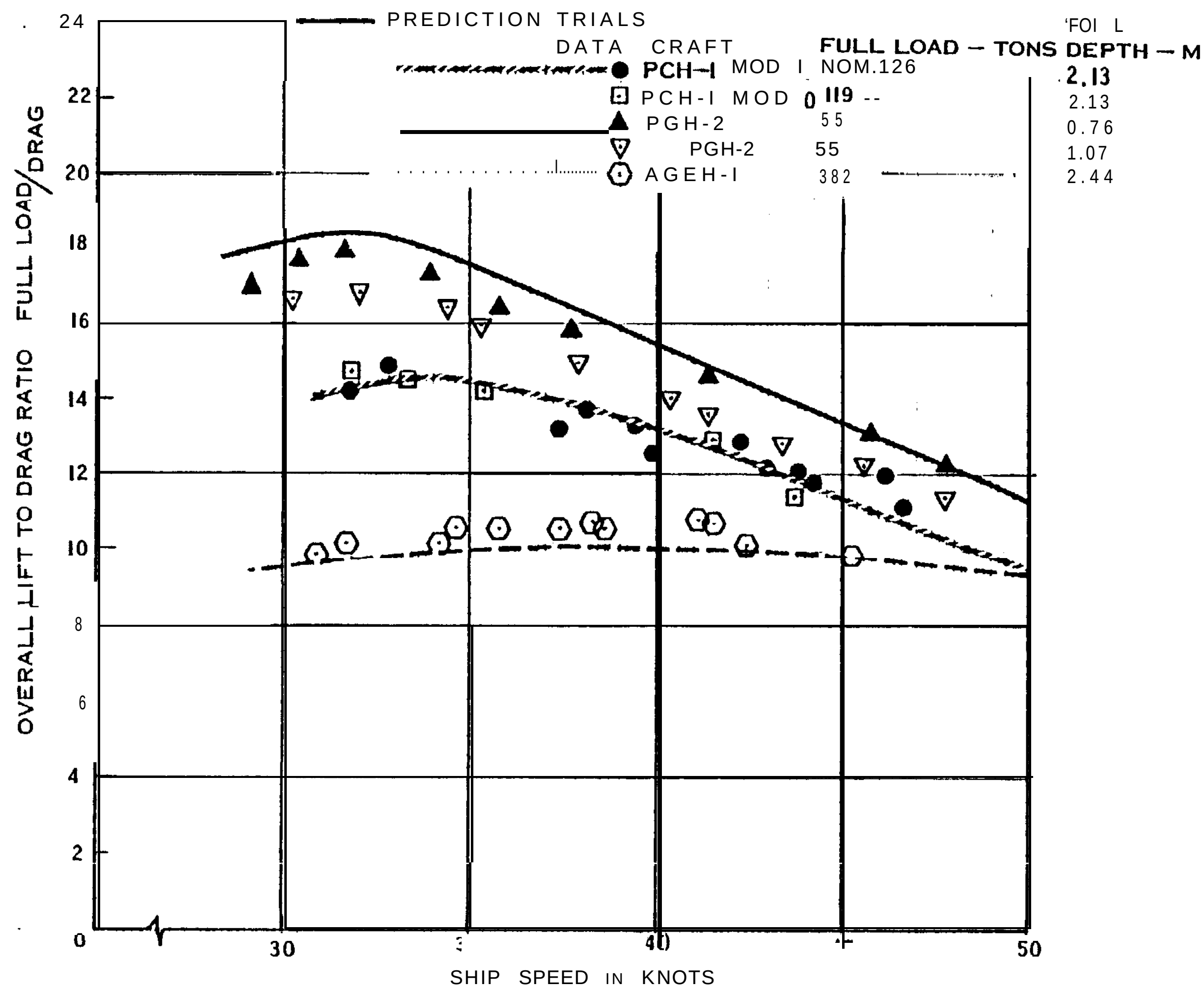

Figure III.2-7. OVERALL LIFT-TO-DRAG RATIO AS A FUNCTION OF SPEED

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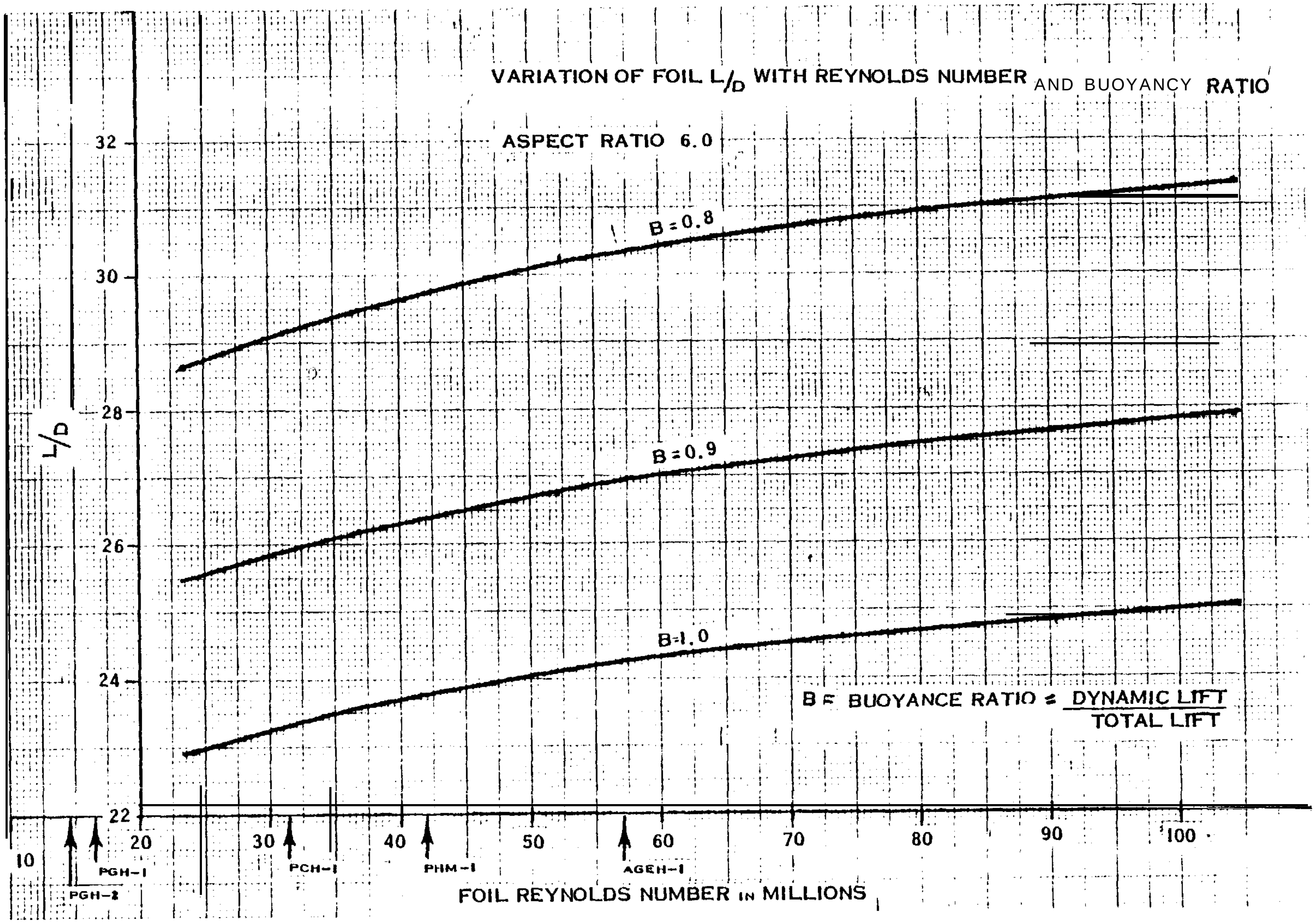


Reference III.2-5

Figure III.2-8. VARIATION OF FOIL L/D WITH REYNOLDS NUMBER AND BUOYANCY RATIO

UNCLASSIFIED

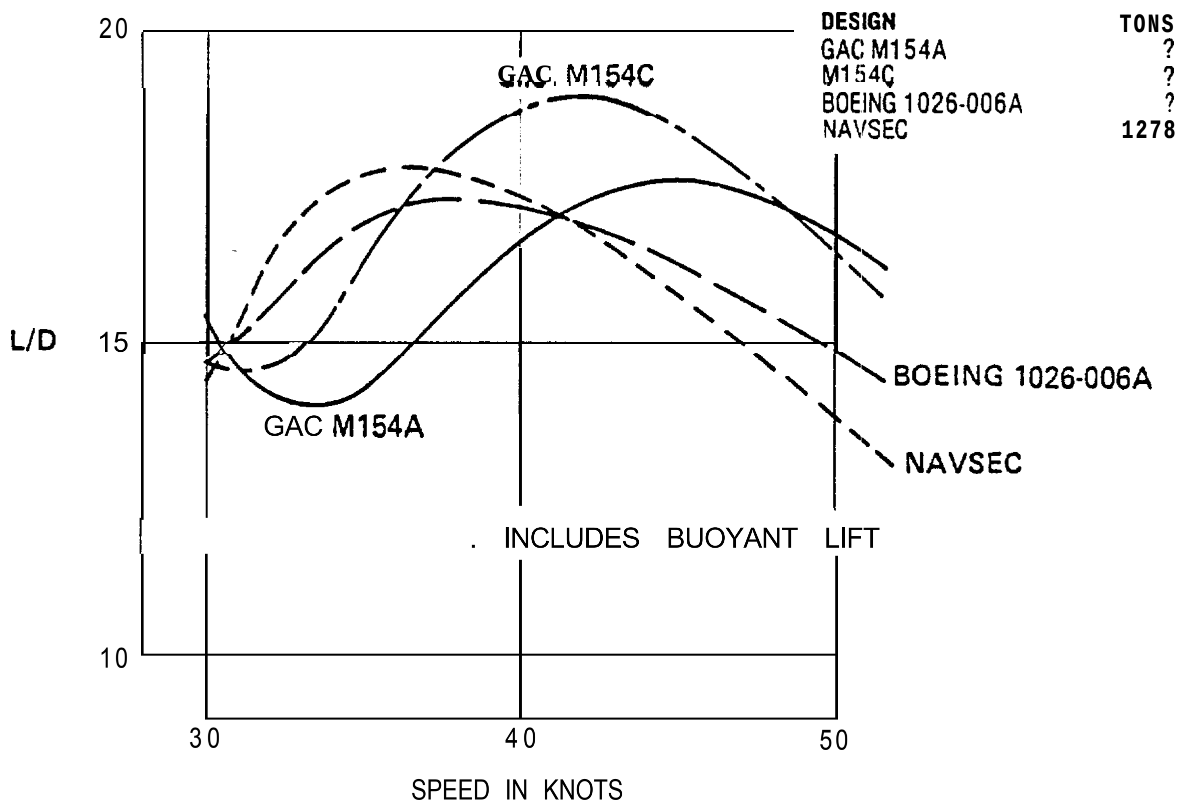
various buoyancy ratios (B). Hydrofoil ships grossing upwards of 1,000 tons will have a buoyancy ratio of around 0.85 to 0.90. It should be noted that the L/D improvement is reflected throughout the foil system. Typical L/Ds for four large hydrofoil designs are presented in Figure III.2-9. The differences in L/D for these four designs is directly related to the speed at which the foil system was optimized.

2.1.1.3 Propulsive Coefficient

(U) Propulsive coefficient for existing and future hydrofoil ships is given in Figures III.2-10 to 111.2-12. No appreciable improvements over existing values are anticipated in the near future.

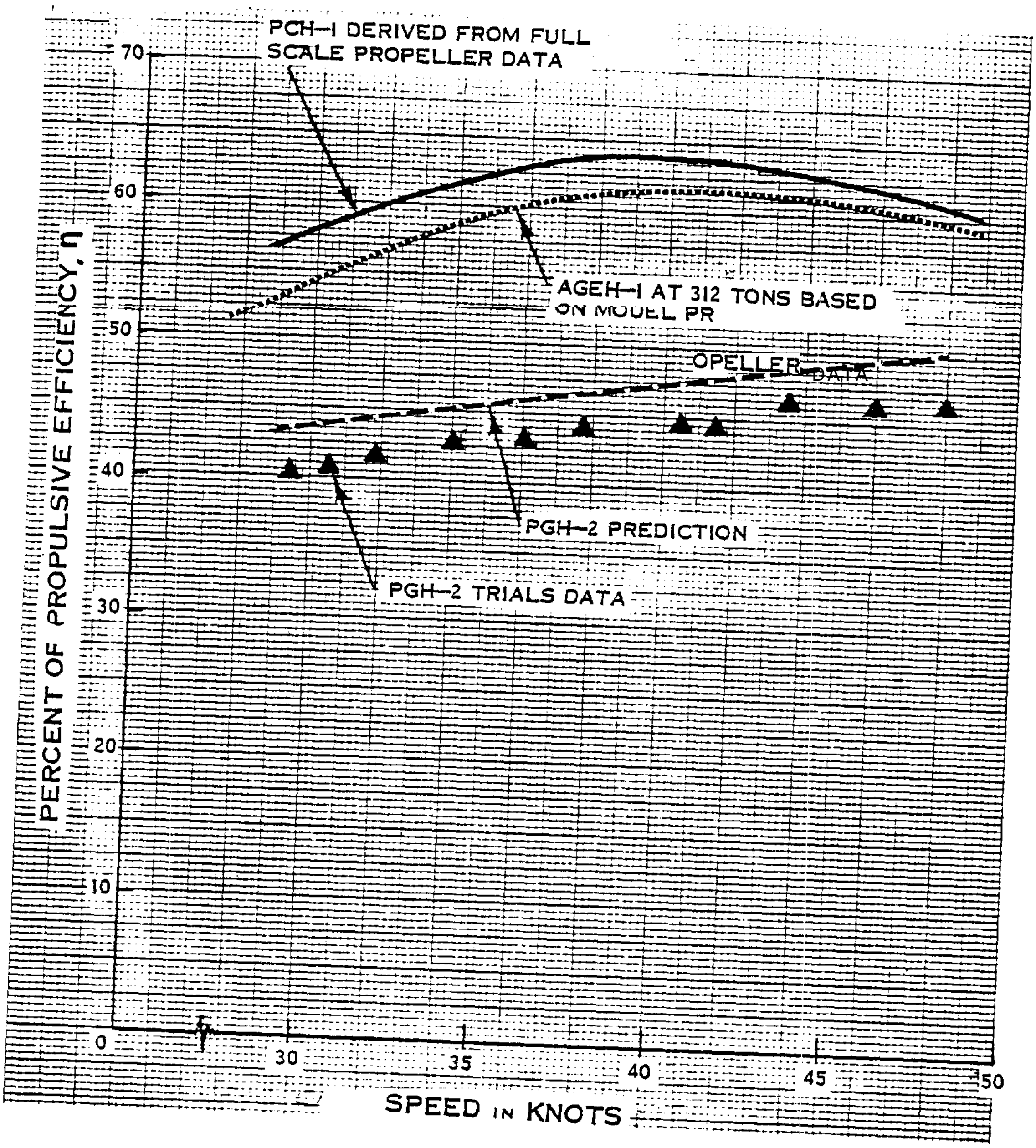
2.1.1.4 Transport Efficiency (η L/D or $\frac{WV}{P}$).

(U) This is an expression which measures the efficiency of a vehicle neglecting, among other things, its payload capabilities and the response of the vehicle to its environment. Nevertheless it is used for vehicle comparison and is presented here with the reservations previously noted in Figures 111.2-13 and 111.2-14. The scatter in the data reflects the choice of propulsor configurations as well as mission requirements. Figure III.2-15 projects the transport efficiency for three large hydrofoil ship designs, and reflects the improvement in lift-to-drag ratio inherent in large hydrofoil ships.



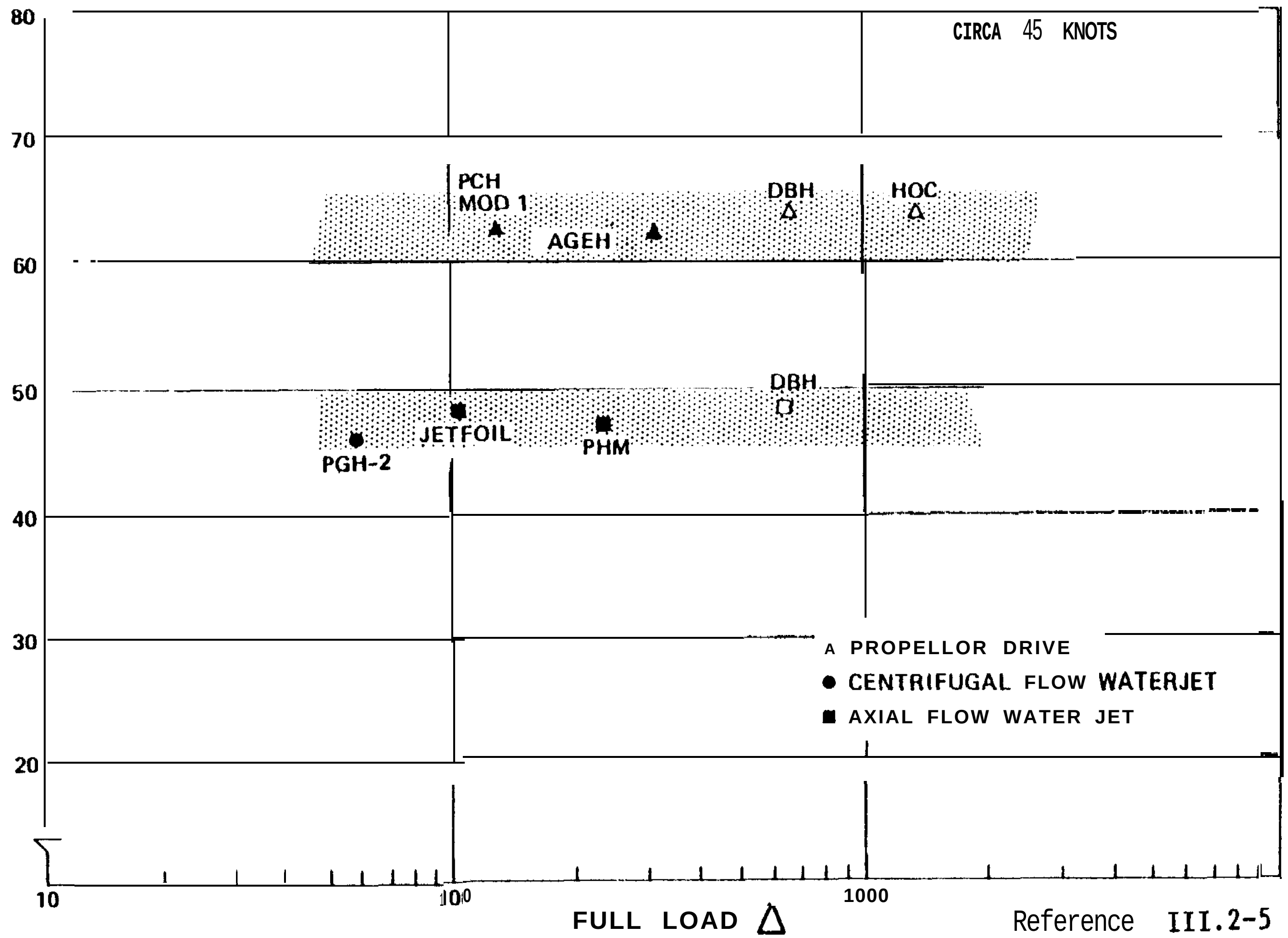
Reference 111.2-s

Figure 111.2-g. PREDICTED OVERALL LIFT/DRAG RATIO FOR LARGE HYDROFOIL SHIPS (U)



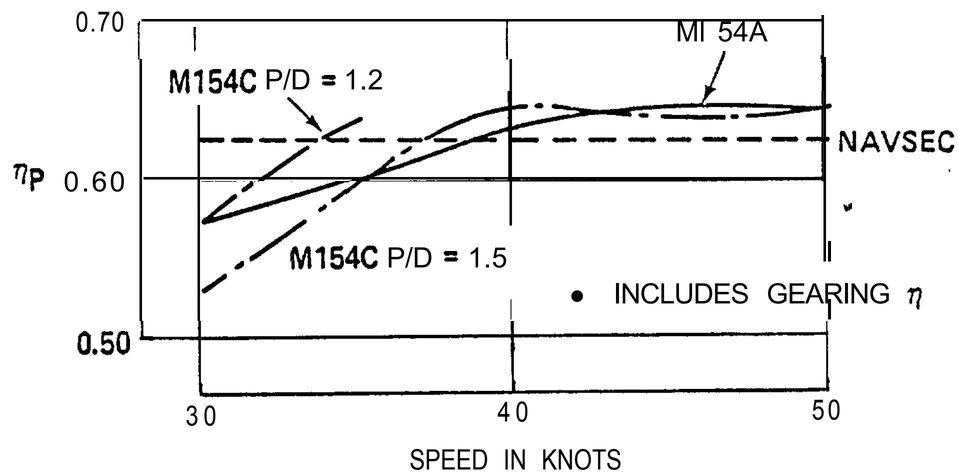
References 111.2-2, 111.2-6, III.2-7, 111.2-a

Figure III.2-10. PROPULSIVE COEFFICIENT VERSUS SPEED FOR VARIOUS HYDROFOIL SHIPS



Reference III.2-5

Figure III.2-11. INTRINSIC CHARACTERISTICS - PROPULSIVE COEFFICIENT (U)



Reference III.2-5

Figure 111.2-12. PROPULSIVE COEFFICIENT FOR LARGE HYDROFOIL DESIGN STUDIES (U)

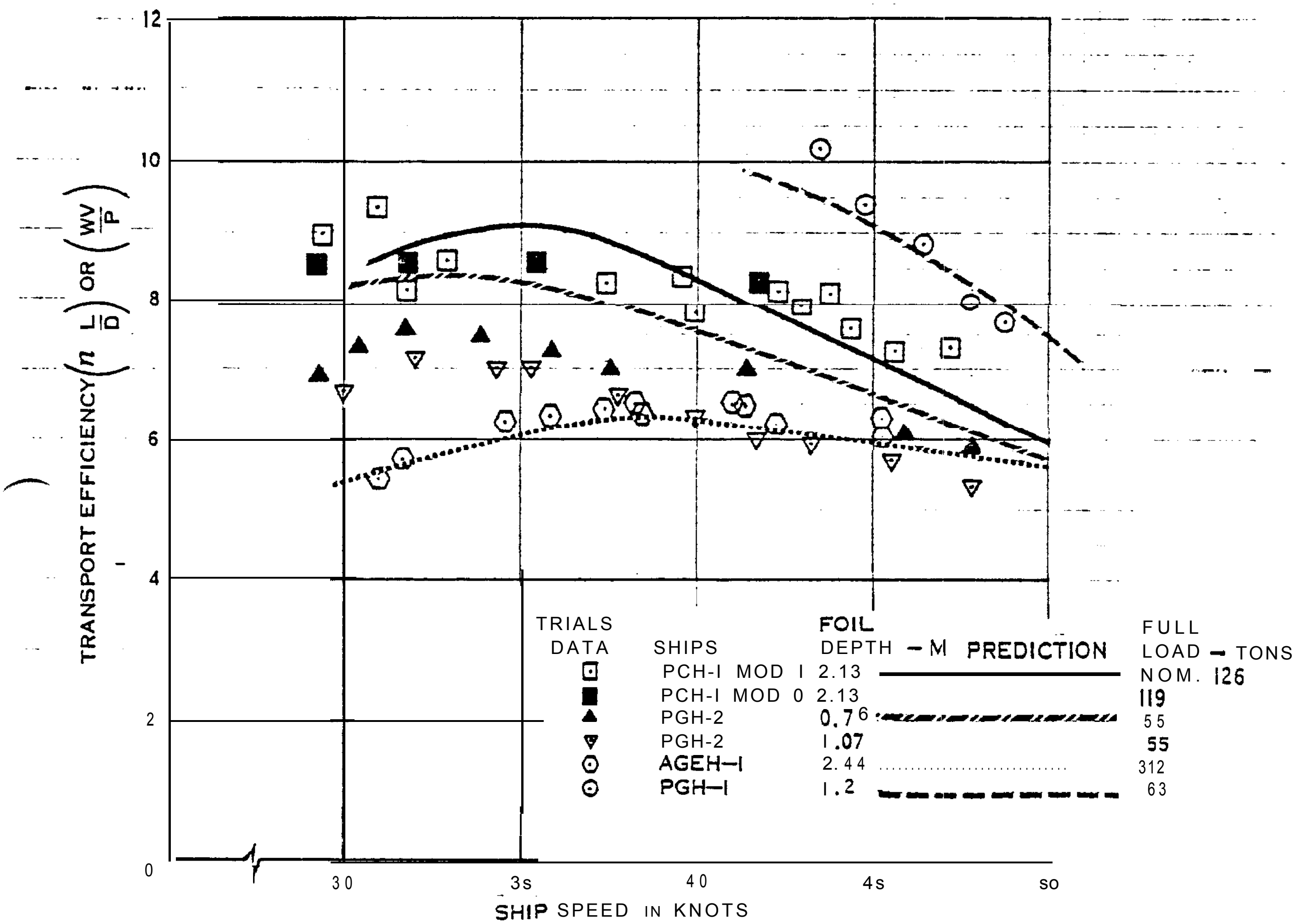
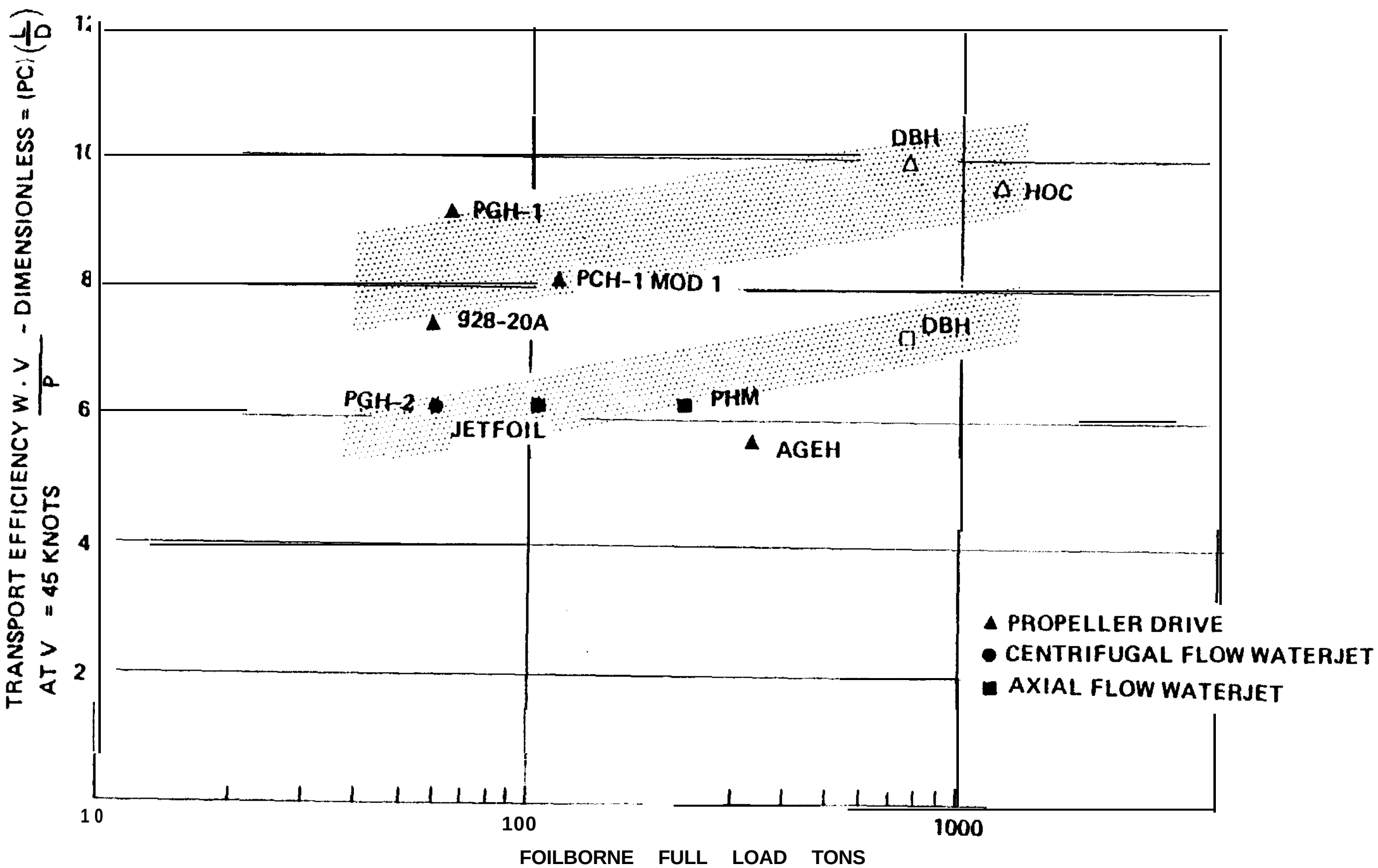


Figure III.2-13. TRANSPORT EFFICIENCY FOR EXISTING U.S NAVY HYDROFOIL SHIPS



Reference 111.2-5

Figure 111.2-14. INTRINSIC CHARACTERISTICS-TRANSPORT EFFICIENCY

[redacted]

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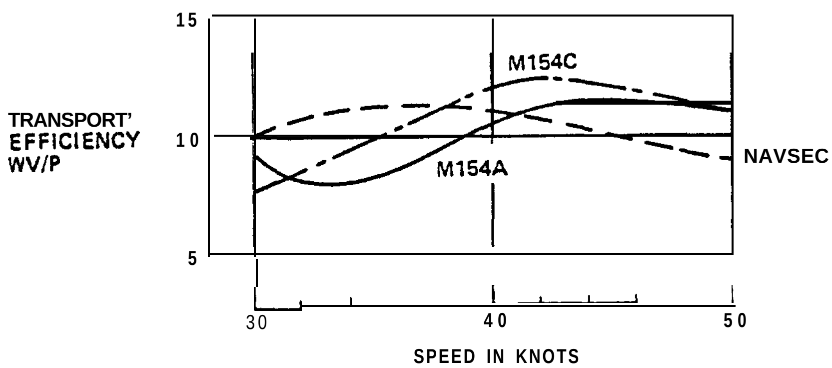

Reference III.2-5

Figure 111.2-15. TRANSPORT EFFICIENCY FOR LARGE HYDROFOIL SHIPS (U)

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2.1.1.5 Calm and Rough Water Speed-Power

(U) Speed-power curves for operational hydrofoil ships and studies are shown in Figures 111.2-16 through 111.2-22. Figure III.2-20 shows that all the predictions are close to the actual test results with the exception of the TUCUMCARI and PRM-1. While TUCUMCARI met its design speed requirements, the actual waterjet propulsive coefficient fell short of the predicted value. The same is true of the PHM-1, where the propulsive coefficient equalled 0.470 at design speed compared with a predicted value of 0.495 (Reference 111.2-9). Also, the drag problem which was discussed earlier, combined with the deficiency in propulsive coefficient, aggravated the discrepancy between the predicted and measured power levels (Figure III.2-19).

(U) Rough water power versus speed is shown in Figure III.2-21 from Reference III.2-10 for both the HIGH POINT and TUCUMCARI. (Note that the TUCUMCARI was operating beyond its design Sea State 4.)

(U) Specific power for three large hydrofoil designs is presented in Figure 111.2-22. The differences between the vehicles are due to different design approaches and speeds at which the foil designs were optimized. Trending of specific power with size is shown in Figure 111.2-23, which again reflects the higher lift-to-drag ratio inherent in larger hydrofoil ships.

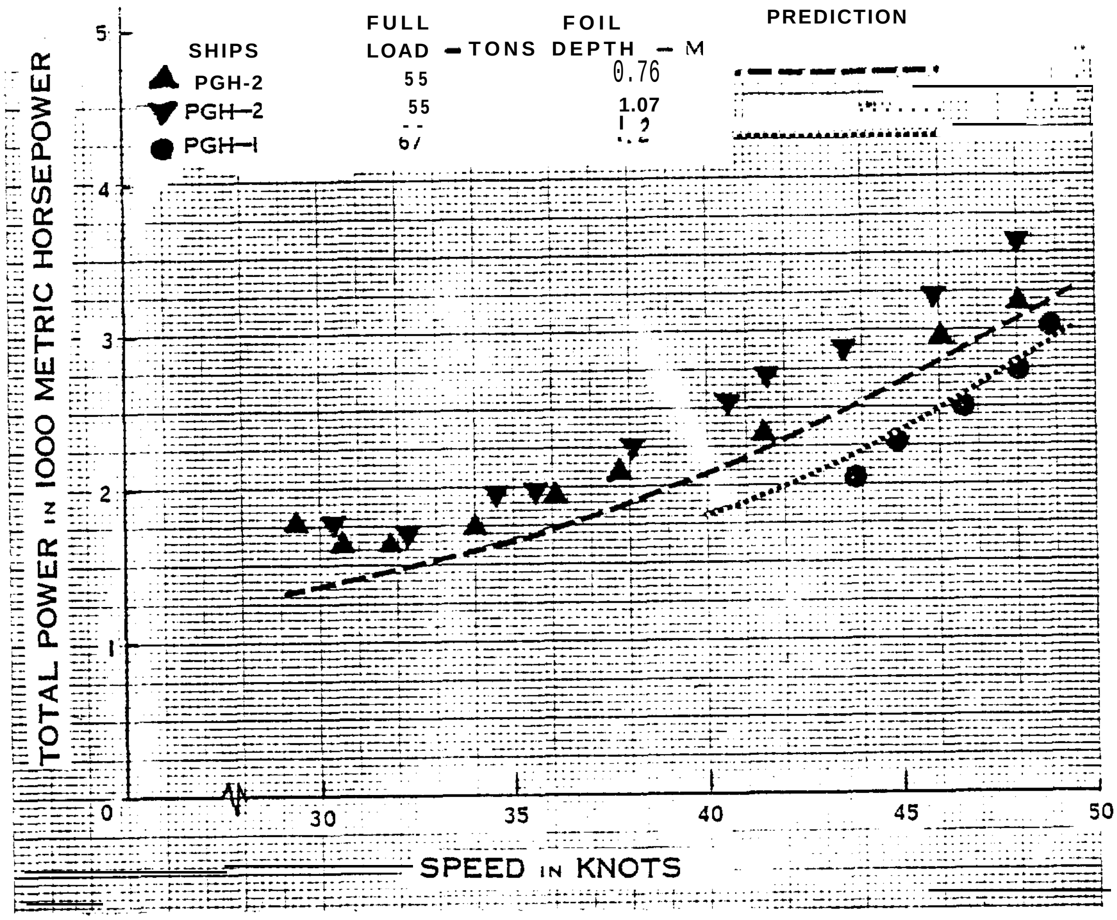


Figure III.2-16. PGH-1&2 FOILBORNE SPEED-POWER

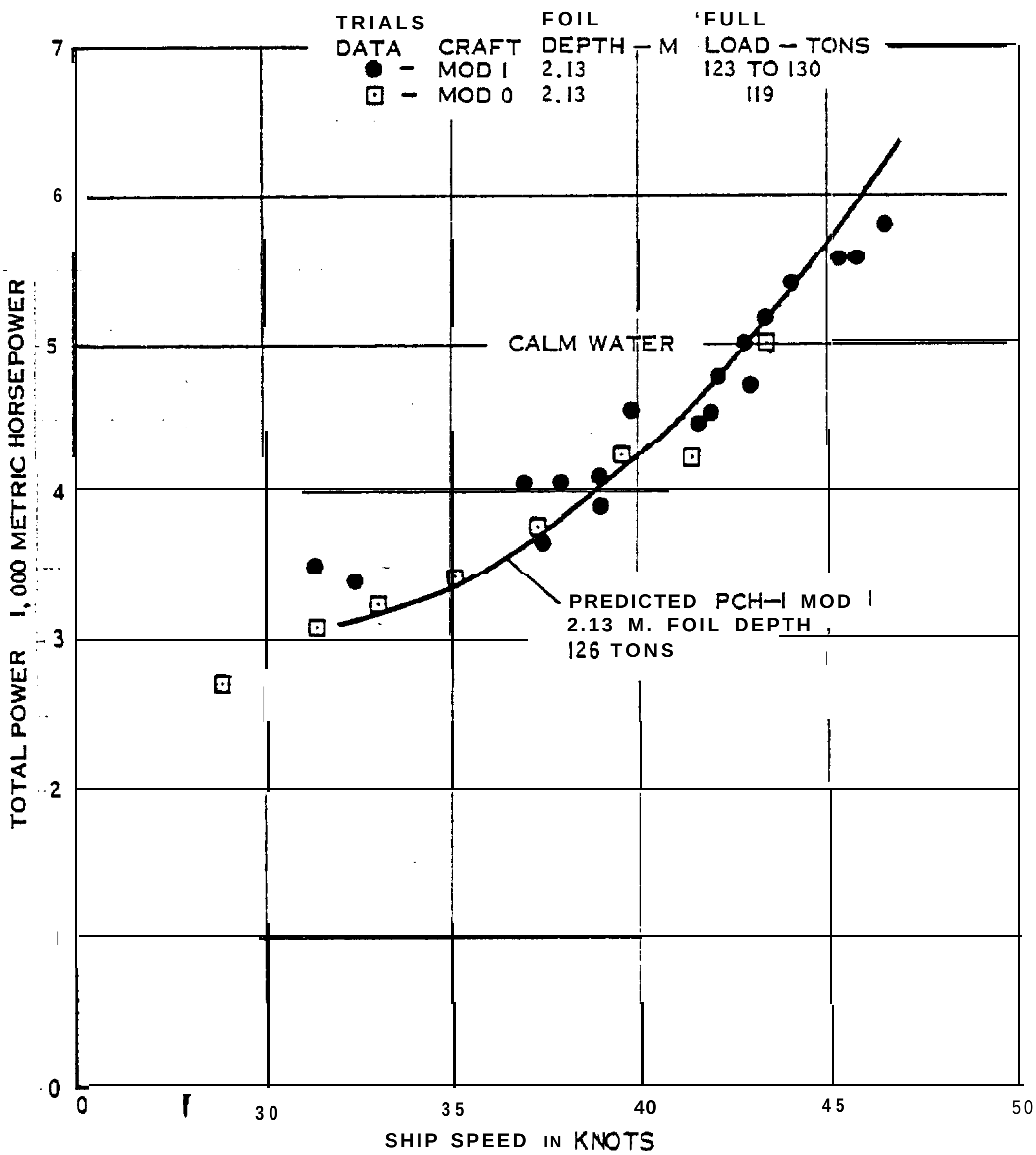


Figure III.2-17. PCH-1 FOILBORNE SPEED-POWER

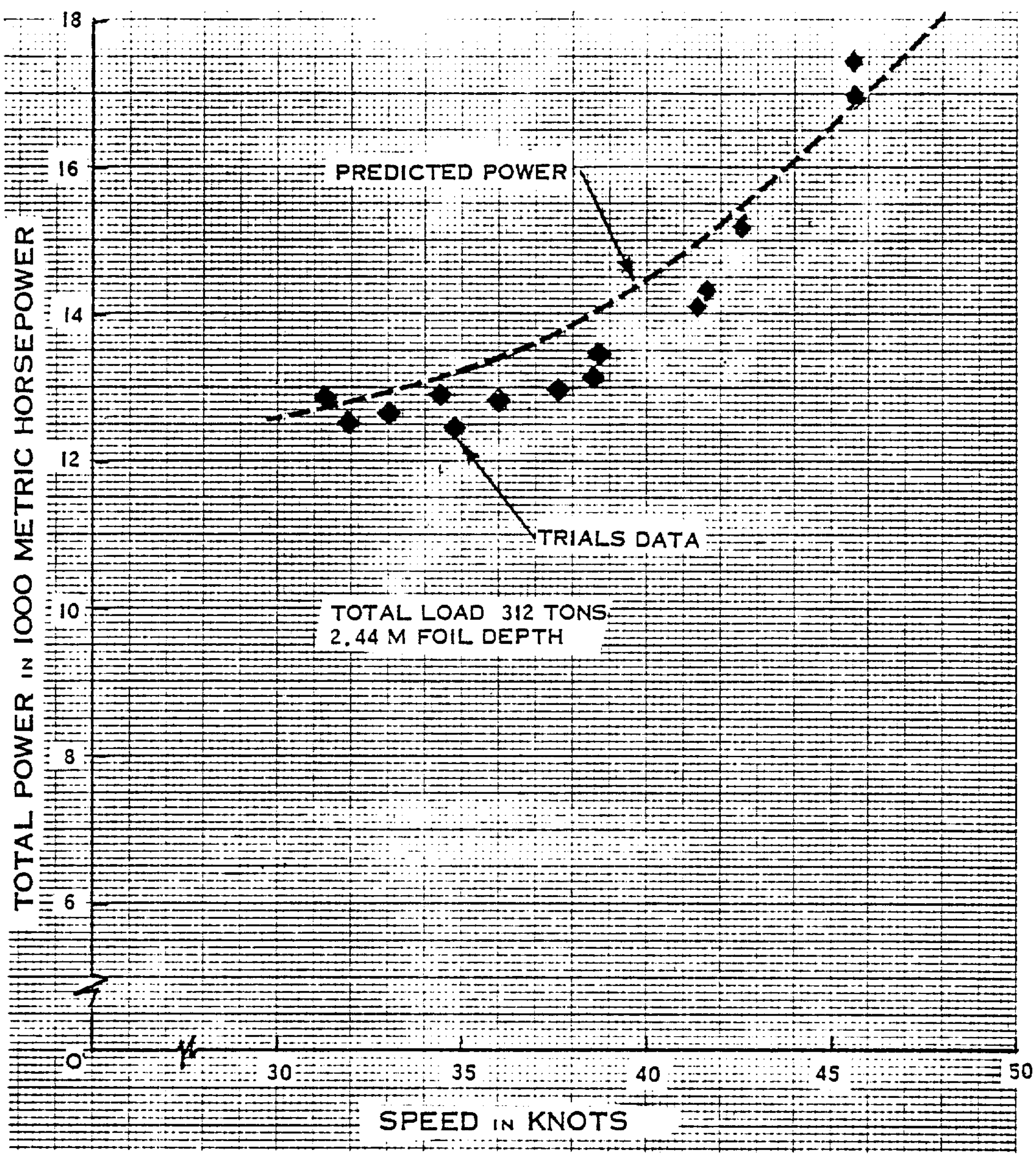


Figure III.2-18. AGEH-1 FOILBORNE SPEED-POWER

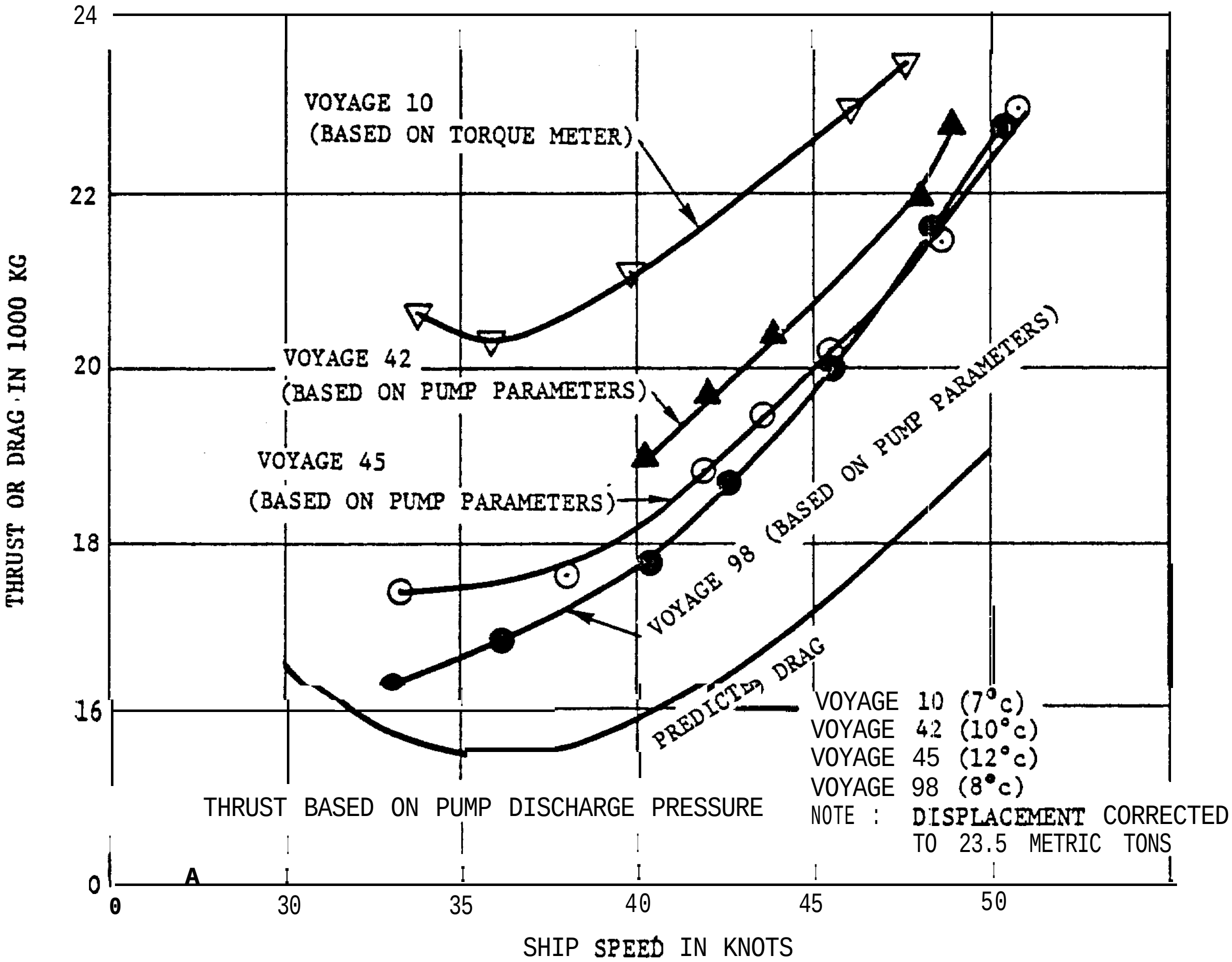


Figure III.2-19. PHM-1 MEASURED AND PREDICTED DRAG AND POW-ERAS A FUNCTION OF SPEED (U)

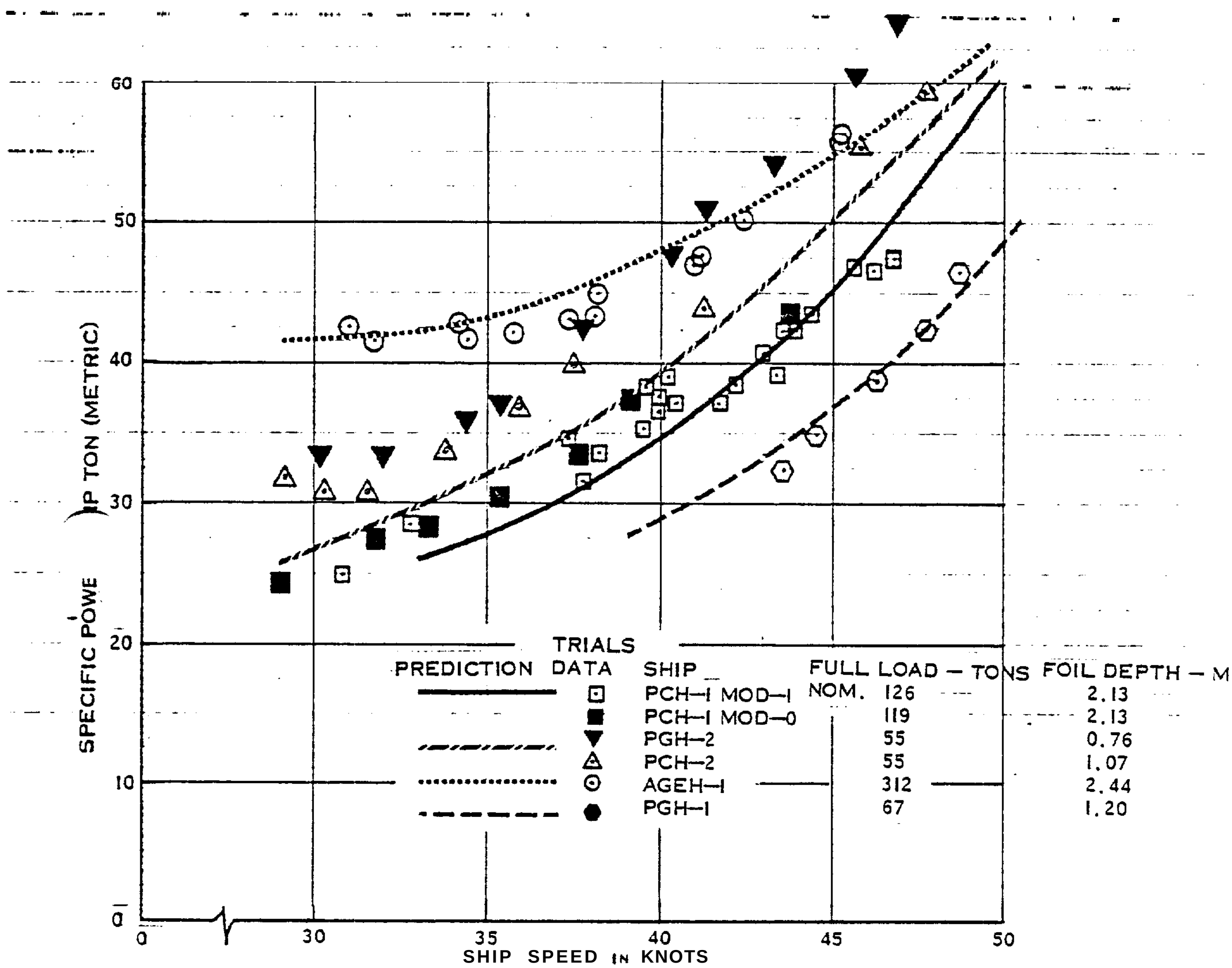
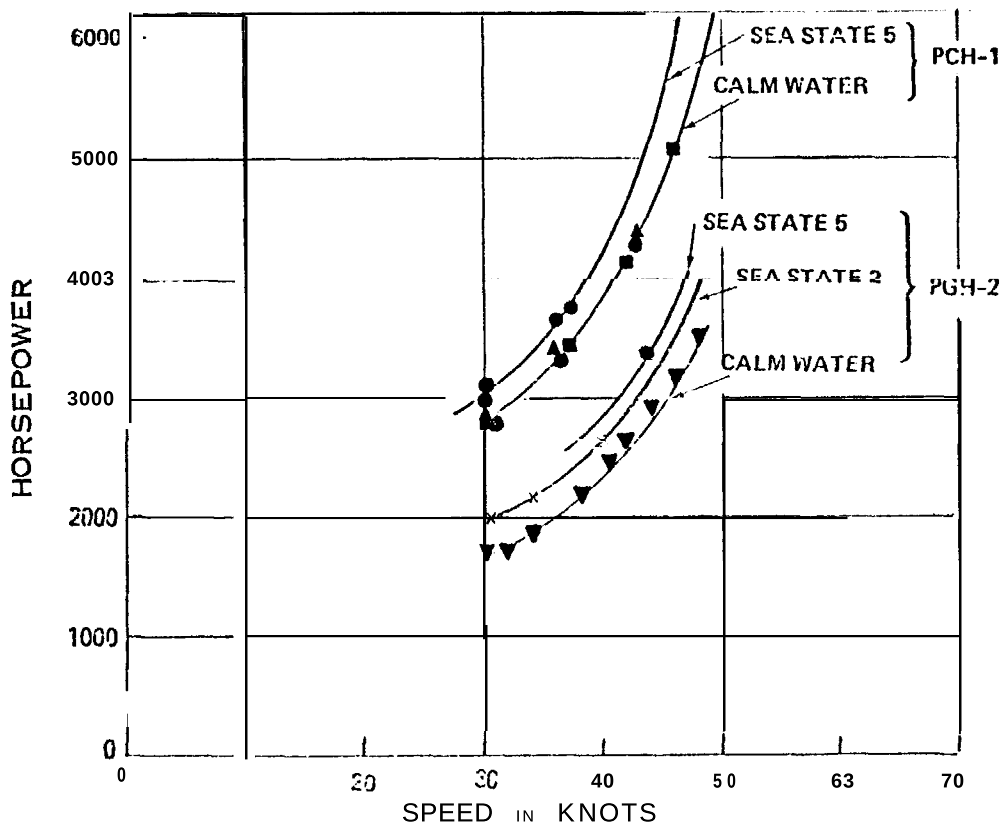


Figure 1X.2-20. FOILBORNE SPECIFIC POWER COMPARISON



Reference III.2-5

Figure 111.2-21. HYDROFOIL SHIPS CALM/ROUGH WATER COMPARISON

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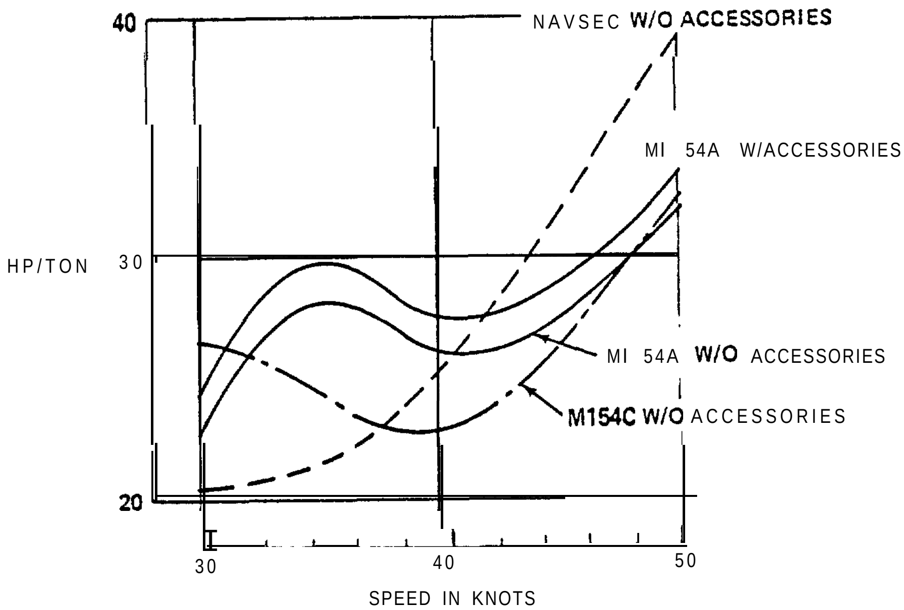
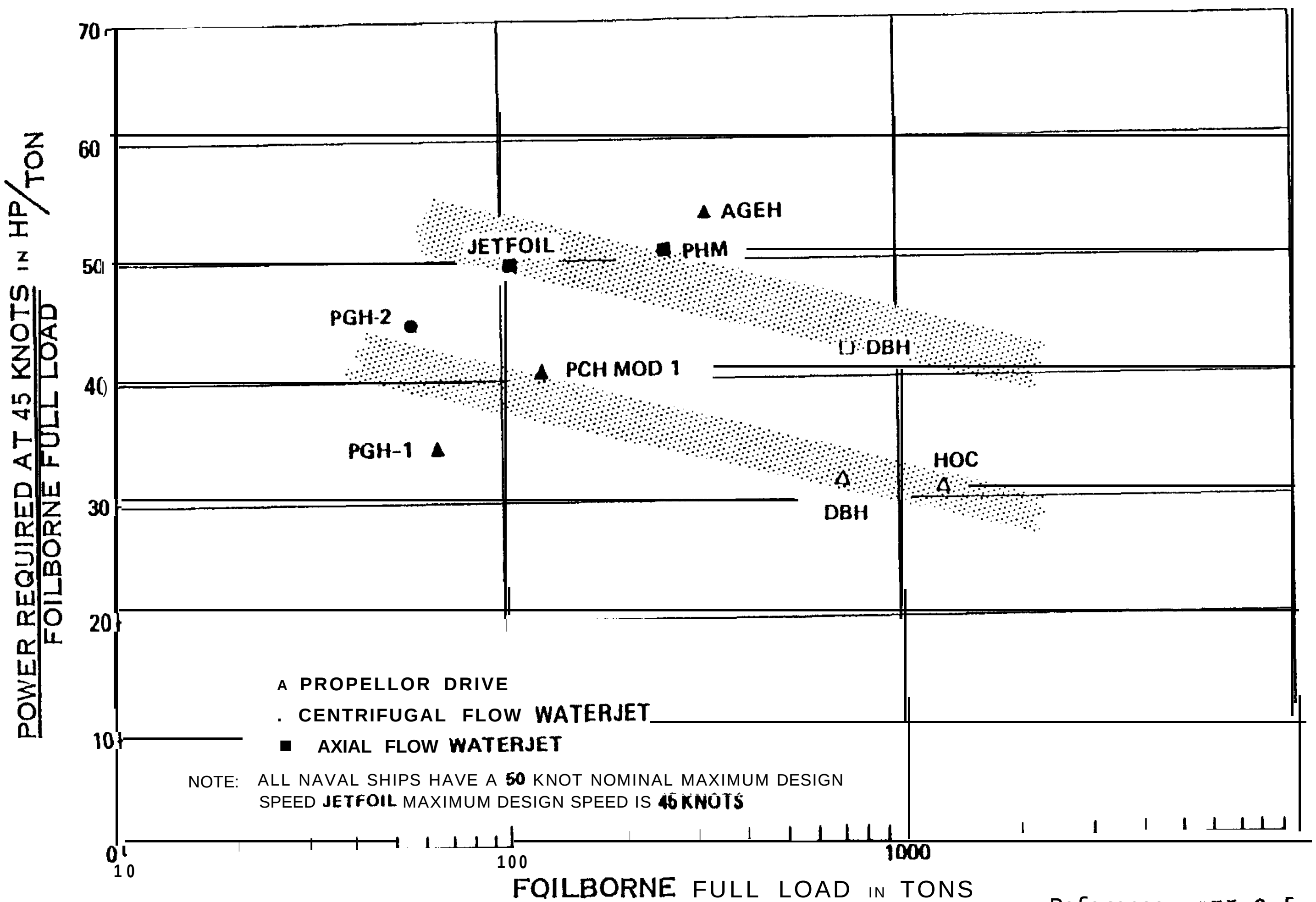


Figure X1.2-22. SPECIFIC HORSEPOWER FOR LARGE HYDROFOIL SHIPS (U)



Reference III.2-5

Figure III.2-23. INTRINSIC CHARACTERISTICS - CRUISE POWER (U)

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2.1.2 Range and Endurance

(U) Endurance and range for a given ship depends on the vehicle fuel flow, speed, and amount of fuel carried. Range and endurance are two separate parameters and the maximization of one does not necessarily maximize the other. The fuel flow rate for PHM-1 is plotted in Figure 111.2-24 and for other hydrofoil ships in Figure III.2-25.

(U) The ratio of fuel flow to gross weight or displacement is given in Figure 111.2-26. This shows rather distinctly the improvement in engine specific fuel consumption by comparing TUCUMCARI with PHM-1, although the L/Ds of the two vehicles are only slightly different.

(U) Specific range, or nautical miles per ton of fuel, is presented in Figures 111.2-27 and 111.2-28. Endurance and Range are shown in Figures III.2-29 through III.2-33. Ship weights and tankage were obtained from Reference 111.2-11 and are identified in Tables 111.2-2 and 111.2-3.

2.1.3 Maneuverability

(U) Hydrofoil maneuverability can be expressed in terms similar to those used by the aircraft world. The craft essentially has three degrees of freedom but one, rotation about the lateral axis, is inherently limited. Freedom in pitch, then, is relatively small and this is applicable to any hydrofoil design. Turning performance, takeoff and landing performance are dealt with separately.

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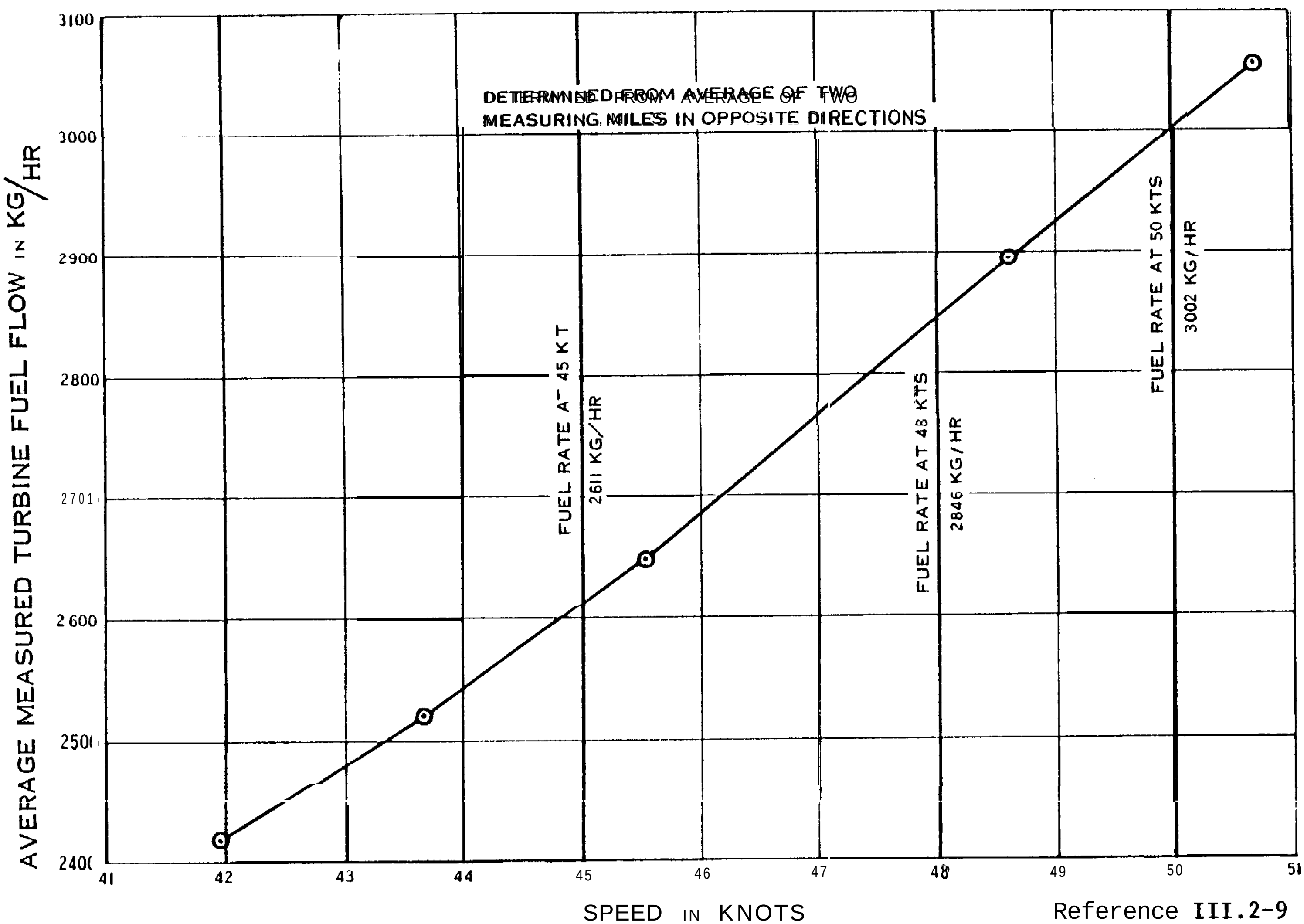

Figure III.2-24. **PHM** FUEL FLOW FOILBORNE ENGINE AS A FUNCTION OF SHIP SPEED **(U)**

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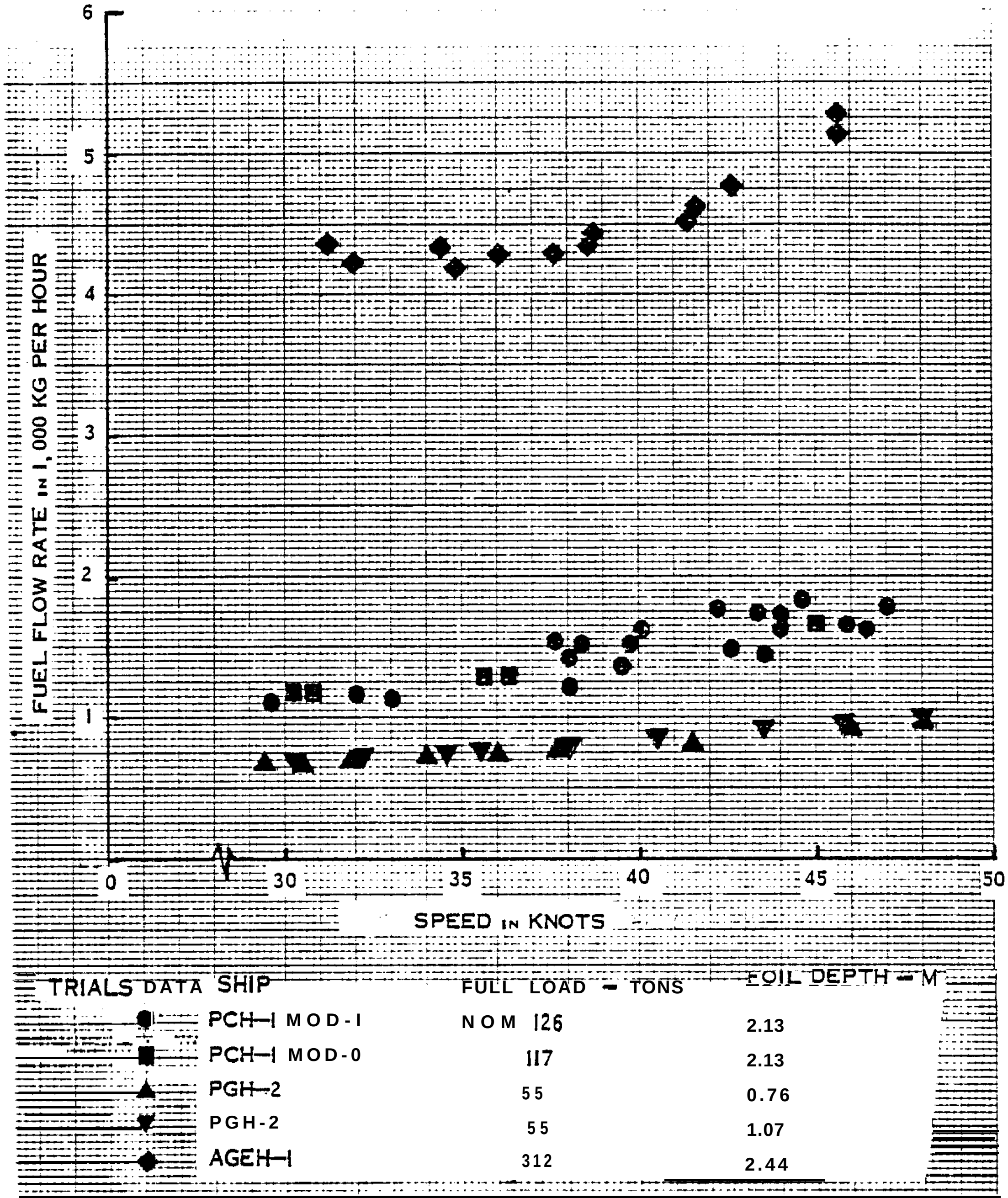

Figure X1.2-25. FOILBORNE FUEL USAGE

UNCLASSIFIED [redacted]

References 111.2-16, III.2-9, 111.2-12, 111.2-13, III.2-14

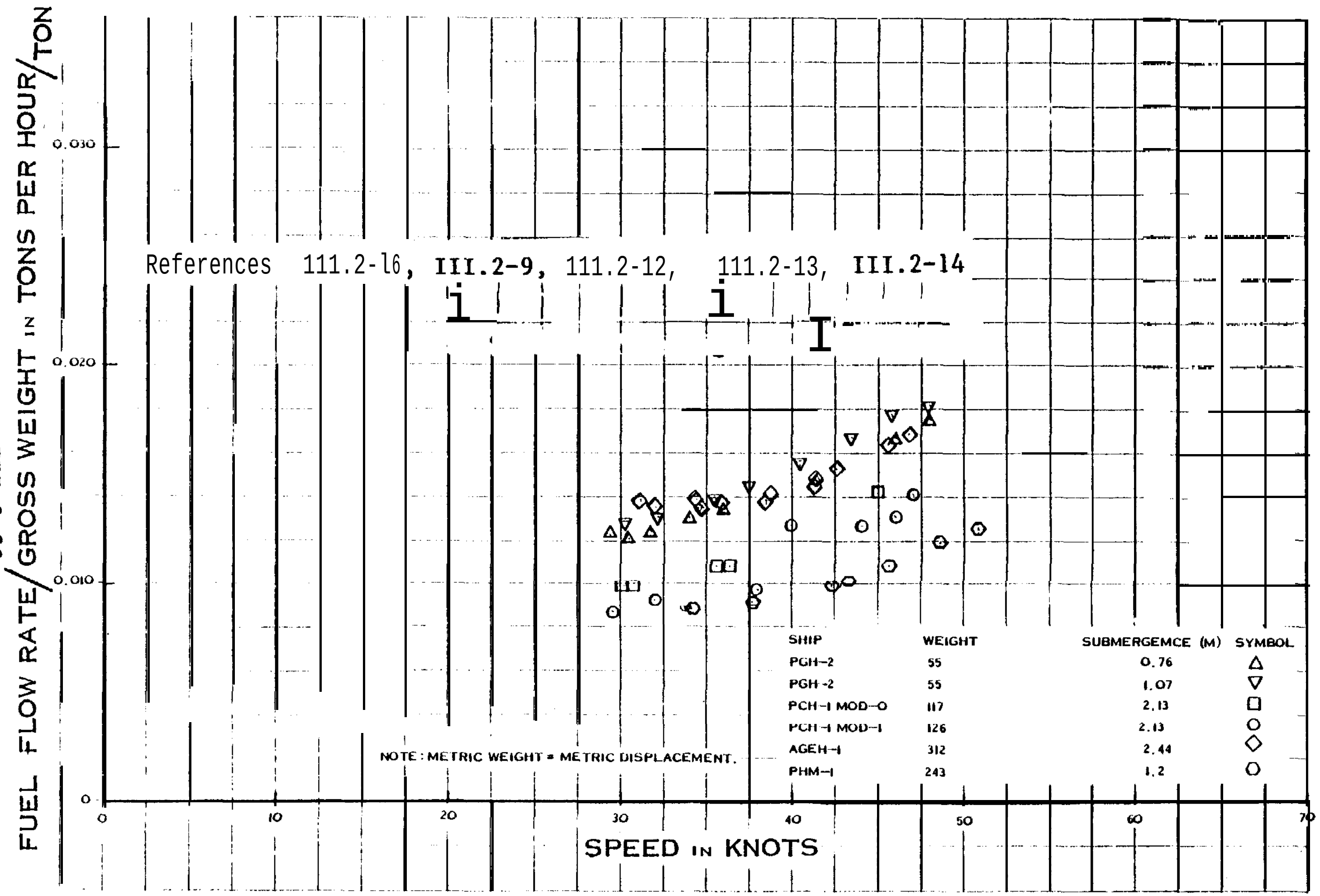

Figure 111.2-26. RATIO OF FUEL FLOW TO METRIC WEIGHT VERSUS SPEED

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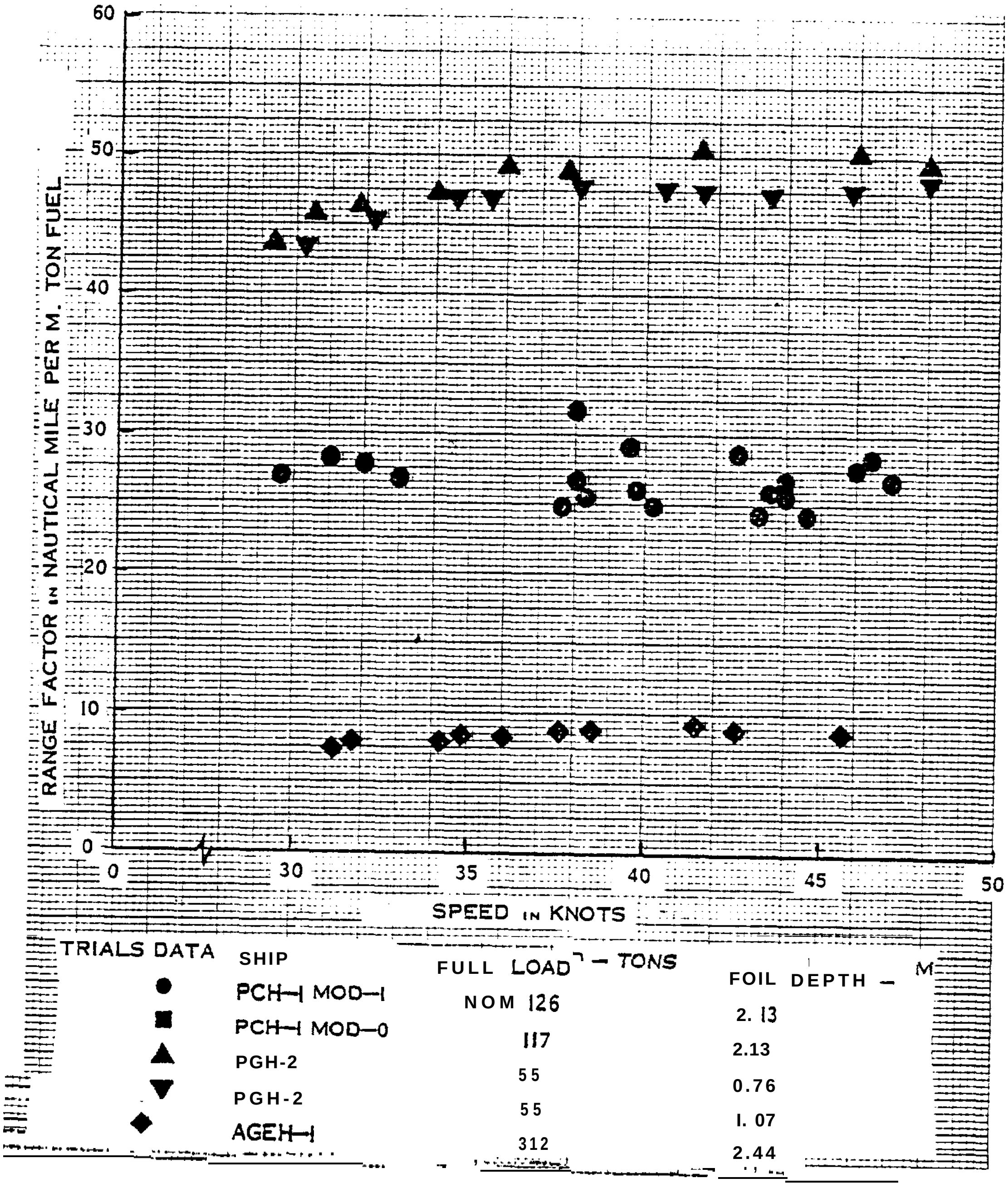
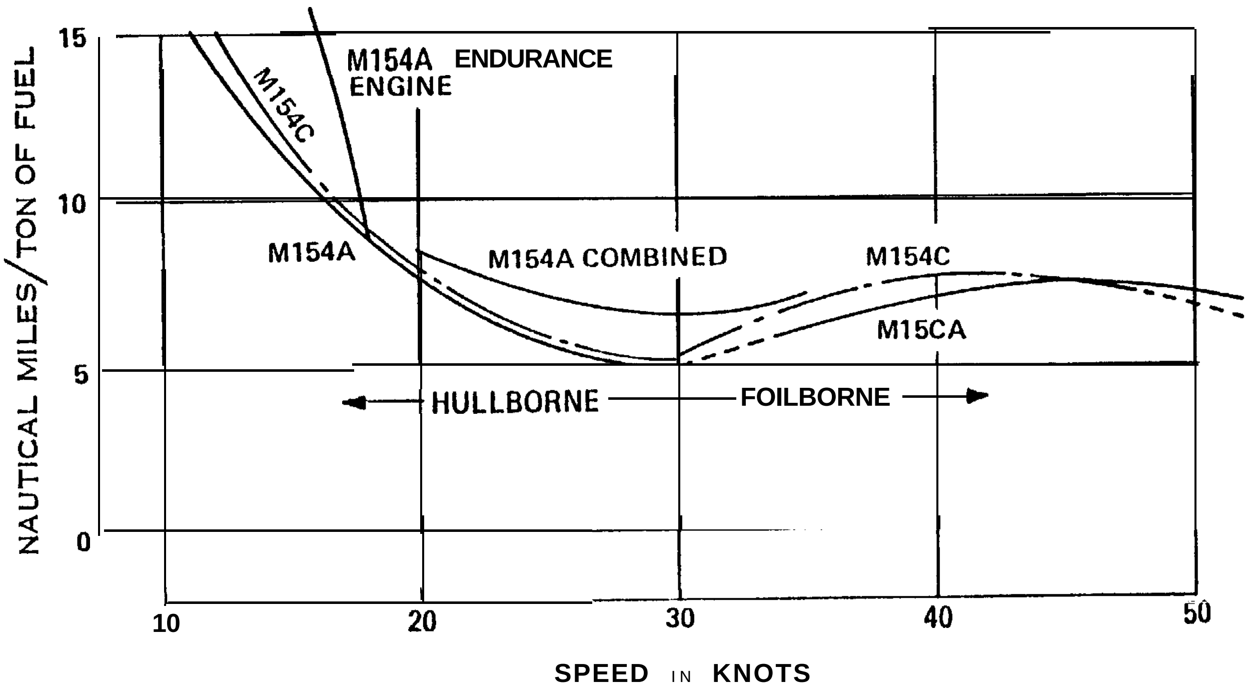


Figure III.2-27. FOILBORNE RANGE FACTOR

[redacted]



Reference III.2-5

Figure III.2-28. FUEL CONSUMPTION - HOC DESIGN (U)

[redacted]

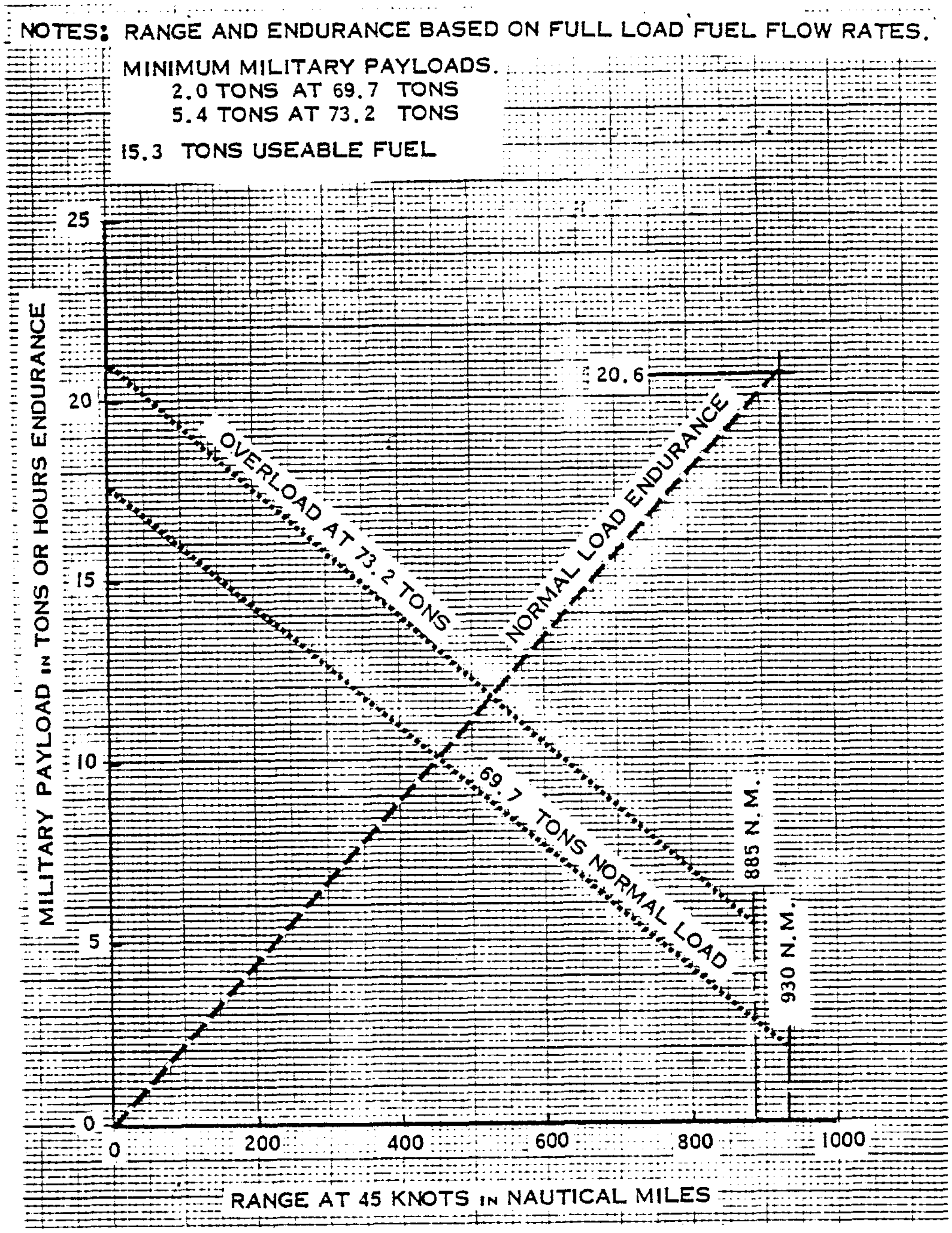


Figure III. 2-29. PGH-1 FOILBORNE RANGE

NOTES RANGE AND ENDURANCE BASED ON FULL LOAD FUEL FLOW RATES.
MINIMUM MILITARY PAYLOAD 2.9 TONS.
16.8 TONS USEABLE FUEL:

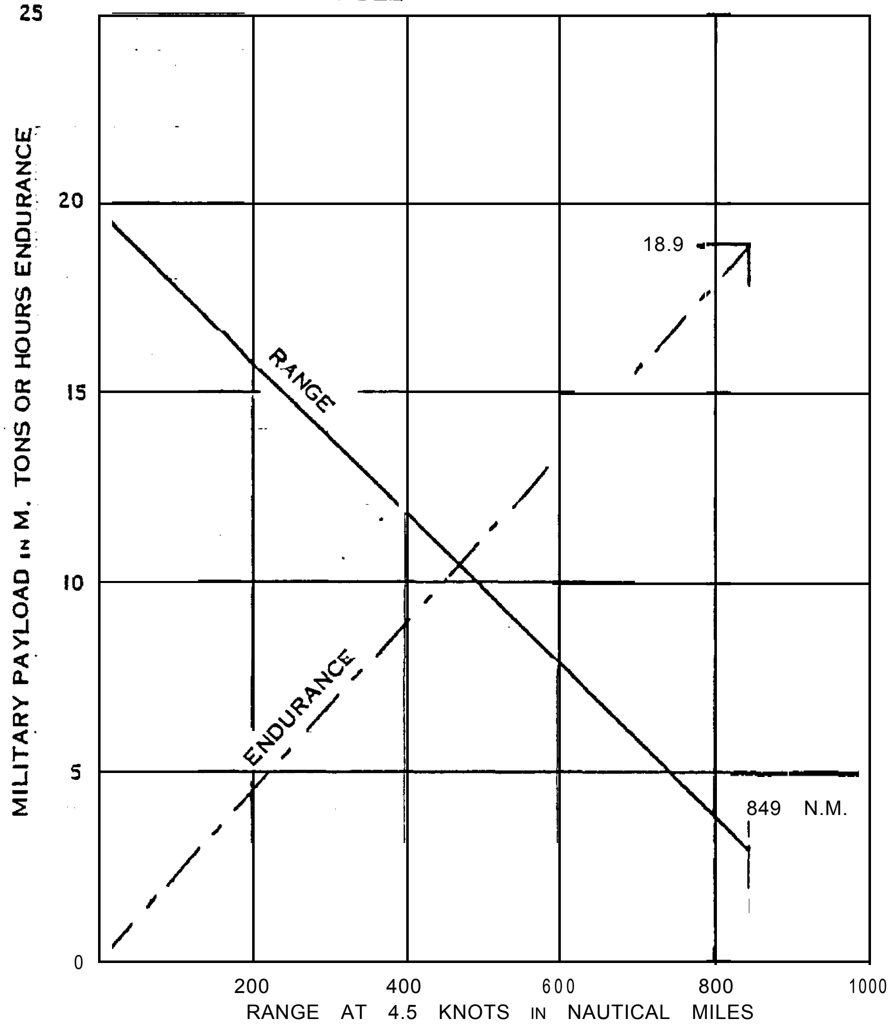


Figure X1.2-30. PGR-2 FOILBORNE RANGE

NOTES RANGEANDENDURANCE BASED ON FULL LOAD FUELFLOWRATES
MINIMUM MILITARY PAYLOAD .08 TONS
23.3 TONS USEABLE FUEL

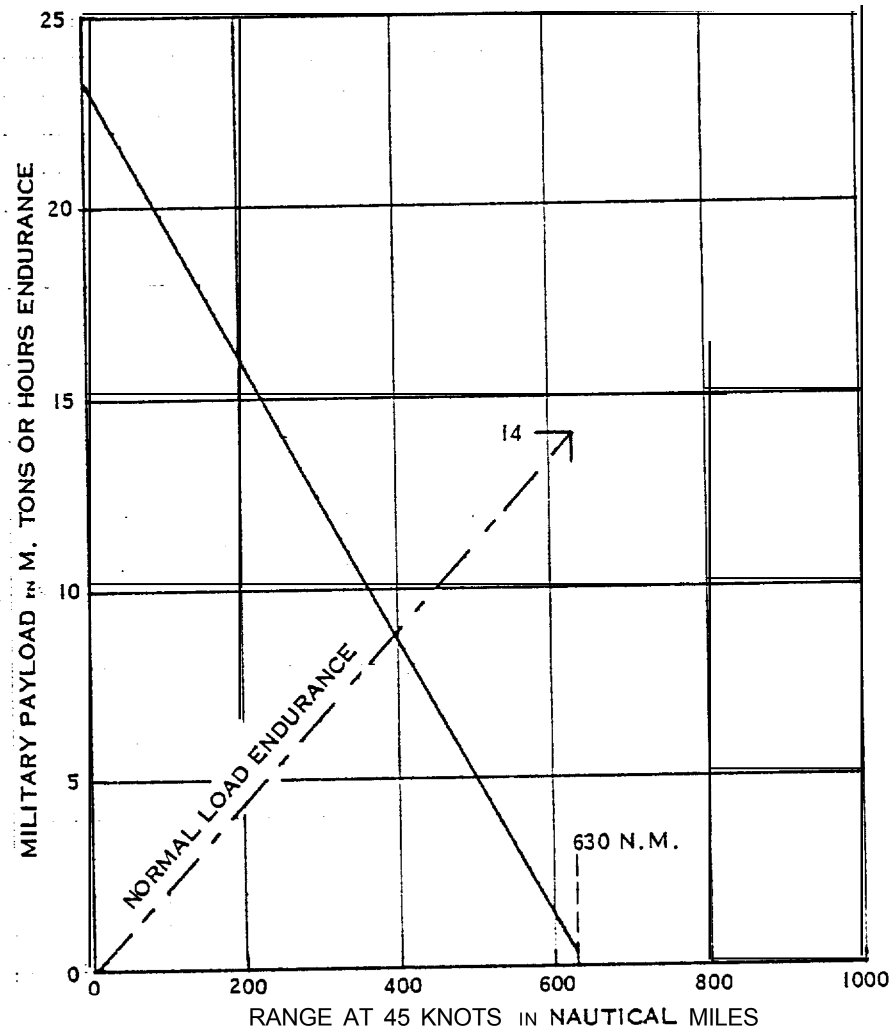


Figure III.2-31. PCH-1 FOILBORNE RANGE (MOD 1)

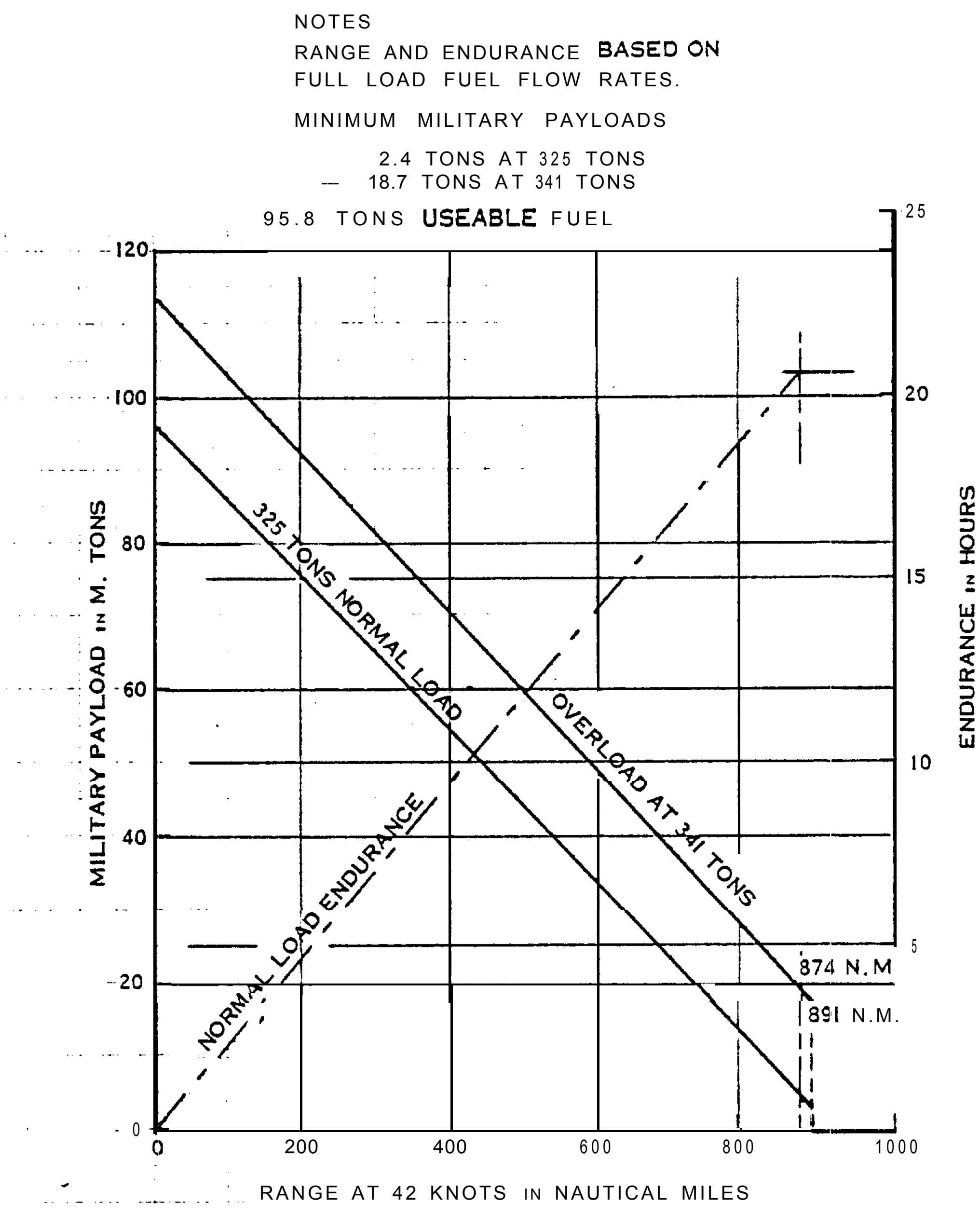


Figure III.2-32. AGEH-1 FOILBORNE RANGE

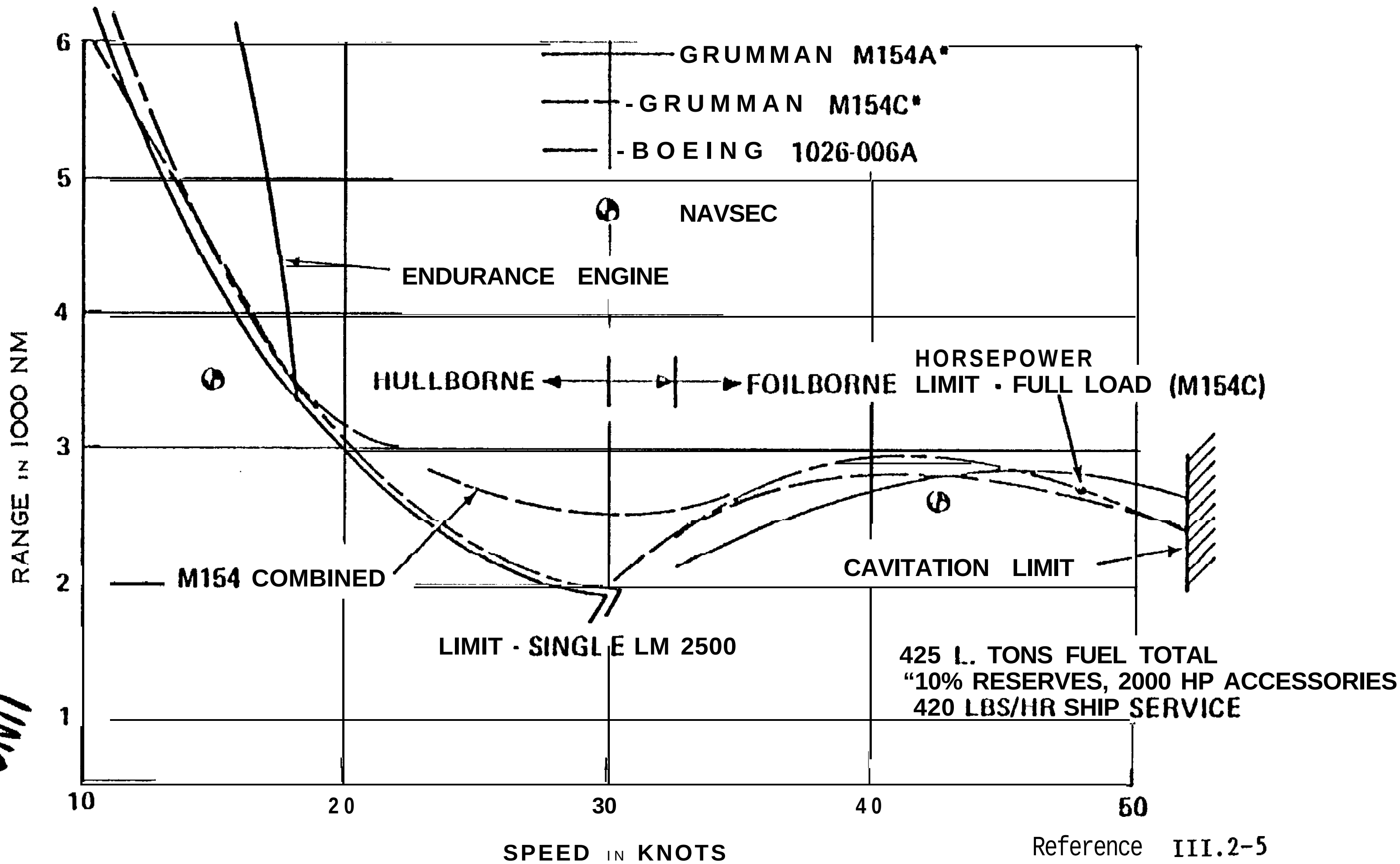


Figure 111.2-33. RANGES - HOC DESIGNS (U)

Table X11.2-2. WEIGHT SUMMARY FOR AGEH-1, PHM-1, AND PCH-I (MOD 0)

AGEH-I

WEIGHT SUMMARY	METRIC TONS	% F.L.
SWBS 100 HULL STRUCTURE	92.77	28.53
200 PROPULSION SYSTEMS	43.08	13.25
300 ELECTRIC PLANT	9.35	2.88
(1) 400 COMMAND & SURVEILLANCE	14.63	4.50
500 AUXILIARY SYSTEMS	18.13	5.58
567 LIFT SYSTEMS	48.42	14.89
600 OUTFIT & FURNISHINGS	10.97	3.38
(1) 700 WEAPONS SYSTEMS	2.13	.66
M10 CONTRACTOR CONTROLLED	–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM	–	–
MARGINS	–	–
DELIVERED LIGHTSHIP	239.48	73.66
NORMAL LOADS:		
(2) F10 SHIPS FORCE	2.44	.75
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	.41	.13
(1) F21 SHIP AMMUNITION	1.93	.59
(2) F30 STORES	.91	.28
(2) F40 SHIP FUEL	79.15	24.34
(2) F50 POTABLE WATER	.61	.19
OTHER (MISC) LIQUIDS	.20	.06
(2) F60 CARGO (IF ANY)	–	–
DELIVERED FULL LOAD DISPLACEMENT	325.14	100
M24 FUTURE GROWTH MARGIN	16.56	–
MAXIMUM DISPLACEMENT	341.70	
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	–21.24	–6.53
F8 DYNAMIC LIFT (F.L.)	303.90	93.47
MILITARY PAYLOAD (1) INCLUDES SWBS 442, 499 & 700, LOADS F20	5.45	1.68
VARIABLE PAYLOAD (2) INCLUDES LOADS F10, F30, F40, F50, AND F60	83.32	25.63
USEFUL PAYLOAD (1 & 2)	88.77	27.31

PHM-I

WEIGHT SUMMARY	METRIC TONS	% F.L.
SWBS 100 HULL STRUCTURE	45.91	19.53
200 PROPULSION SYSTEMS	33.61	14.30
300 ELECTRIC PLANT	8.44	3.59
(1) 400 COMMAND & SURVEILLANCE	10.53	4.48
500 AUXILIARY SYSTEMS	13.60	5.79
567 LIFT SYSTEMS	32.00	13.62
600 OUTFIT & FURNISHINGS	16.34	6.95
(1) 700 WEAPONS SYSTEMS	9.31	3.96
M10 CONTRACTOR CONTROLLED	–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM	–	–
MARGINS	2.12	.90
DELIVERED LIGHTSHIP	171.84	73.12
NORMAL LOADS:		
(2) F10 SHIPS FORCE	2.76	1.17
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	.41	.18
(1) F21 SHIP AMMUNITION	13.40	5.70
(2) F30 STORES	.73	.31
(2) F40 SHIP FUEL	41.10	17.49
(2) F50 POTABLE WATER	1.00	.43
OTHER (MISC) LIQUIDS	.10	.04
(2) F60 CARGO (IF ANY)	–	–
DELIVERED FULL LOAD DISPLACEMENT	229.03	97.46
M24 FUTURE GROWTH MARGIN	5.96	2.54
MAXIMUM DISPLACEMENT	234.99	100
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	–4.79	–2.04
F8 DYNAMIC LIFT (F.L.)	230.20	97.96
MILITARY PAYLOAD (1) INCLUDES SWBS 442, 499 & 700, LOADS F20	29.46	12.54
VARIABLE PAYLOAD (2) INCLUDES LOADS F10, F30, F40, F50, AND F60	45.67	19.43
USEFUL PAYLOAD (1 & 2)	75.13	31.97

PCH-I (MOD 0)

WEIGHT SUMMARY	METRIC TONS	% F.L.
SWBS 100 HULL STRUCTURE	30.09	26.37
200 PROPULSION SYSTEMS	16.81	14.73
300 ELECTRIC PLANT	4.67	4.10
(1) 400 COMMAND & SURVEILLANCE	8.37	7.34
500 AUXILIARY SYSTEMS	5.41	4.74
567 LIFT SYSTEMS	15.70	13.76
600 OUTFIT & FURNISHINGS	5.86	5.14
(1) 700 WEAPONS SYSTEMS	1.68	1.47
M10 CONTRACTOR CONTROLLED	–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM	–	–
MARGINS	–	–
DELIVERED LIGHTSHIP	88.58	77.63
NORMAL LOADS:		
(2) F10 SHIPS FORCE	1.52	1.34
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	–	–
(1) F21 SHIP AMMUNITION	1.43	1.26
(2) F30 STORES	.66	.58
(2) F40 SHIP FUEL	21.18	18.57
(2) F50 POTABLE WATER	.66	.58
OTHER (MISC) LIQUIDS	.06	.05
(2) F60 CARGO (IF ANY)	–	–
DELIVERED FULL LOAD DISPLACEMENT	114.10	100
M24 FUTURE GROWTH MARGIN	–	–
MAXIMUM DISPLACEMENT	114.10	
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	–3.25	–2.85
F8 DYNAMIC LIFT (F.L.)	110.85	97.16
MILITARY PAYLOAD (1) INCLUDES SWBS 442, 499 & 700, LOADS F20	10.35	9.07
VARIABLE PAYLOAD (2) INCLUDES LOADS F10, F30, F40, F50, AND F60	24.08	21.11
USEFUL PAYLOAD (1 & 2)	34.43	30.18

Table 111.2-3. WEIGHT SUMMARY FOR PCH-1 (MOD 1), PGH-1, and PGH-2

PCH-I (MOD I)

WEIGHT SUMMARY	METRIC TONS	%F.L.
SWBS 100 HULL STRUCTURE	33.72	26.30
200 PROPULSION SYSTEMS	18.34	14.30
300 ELECTRIC PLANT	6.19	4.83
(1) 400 COMMAND & SURVEILLANCE	2.74	2.14
500 AUXILIARY SYSTEMS	8.12	6.33
567 LIFT SYSTEMS	22.07	17.21
600 OUTFIT & FURNISHINGS	9.25	7.21
(1) 700 WEAPONS SYSTEMS	1.41	1.10
M10 CONTRACTOR CONTROLLED	–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM	–	–
MARGINS	–	–
DELIVERED LIGHTSHIP	101.84	79.42
NORMAL LOADS:		
(2) F10 SHIPS FORCE	3.22	2.51
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	–	–
(1) F21 SHIP AMMUNITION	.30	.24
(2) F30 STORES	.66	.52
(2) F40 SHIP FUEL	20.25	15.79
(2) F50 POTABLE WATER	.75	.59
OTHER (MISC) LIQUIDS	.34	.26
(2) F60 CARGO (IF ANY)	.86	.67
DELIVERED FULL LOAD DISPLACEMENT	128.23	100
M24 FUTURE GROWTH MARGIN	–	–
MAXIMUM DISPLACEMENT	128.23	
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	–4.35	–3.39
FB DYNAMIC LIFT (F.L.)	123.88	96.61
MILITARY PAYLOAD	3.31	2.58
VARIABLE PAYLOAD	26.08	20.34
USEFUL PAYLOAD (1 & 2)	29.39	22.92

PGH-I

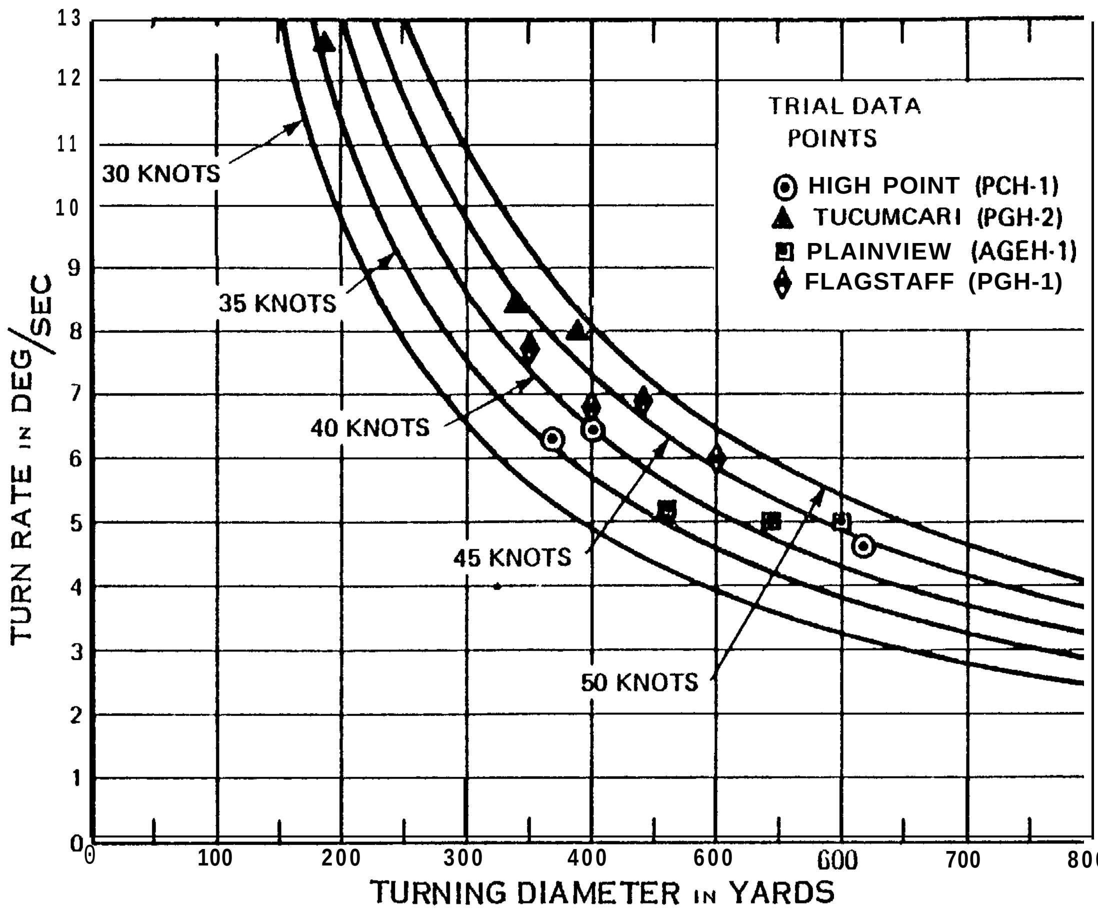
WEIGHT SUMMARY	METRIC TONS	%F.L.
SWBS 100 HULL STRUCTURE	18.39	26.38
200 PROPULSION SYSTEMS	9.45	13.56
300 ELECTRIC PLANT	3.56	5.10
(1) 400 COMMAND & SURVEILLANCE	1.73	2.48
500 AUXILIARY SYSTEMS	4.95	7.10
567 LIFT SYSTEMS	9.17	13.16
600 OUTFIT & FURNISHINGS	4.17	5.98
(1) 700 WEAPONS SYSTEMS	2.64	3.79
M10 CONTRACTOR CONTROLLED	–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM	–	–
MARGINS	2.03	2.92
DELIVERED LIGHTSHIP	56.09	80.47
NORMAL LOADS:		
(2) F10 SHIPS FORCE	1.42	2.04
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	.20	.29
(1) F21 SHIP AMMUNITION	2.24	3.21
(2) F30 STORES	.30	.44
(2) F40 SHIP FUEL	9.14	13.12
(2) F50 POTABLE WATER	.30	.44
OTHER (MISC) LIQUIDS	–	–
(2) F60 CARGO (IF ANY)	–	–
DELIVERED FULL LOAD DISPLACEMENT	69.70	100
M24 FUTURE GROWTH MARGIN	3.45	–
MAXIMUM DISPLACEMENT	73.15	
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	– .61	– .88
FB DYNAMIC LIFT (F.L.)	69.09	99.12
MILITARY PAYLOAD	5.80	8.32
VARIABLE PAYLOAD	11.18	16.04
USEFUL PAYLOAD (1 & 2)	16.98	24.36

PGH-2

WEIGHT SUMMARY	METRIC TONS	%F.L.
SWBS 100 HULL STRUCTURE	12.82	21.98
200 PROPULSION SYSTEMS	7.06	12.10
300 ELECTRIC PLANT	3.06	5.24
(1) 400 COMMAND & SURVEILLANCE	1.15	1.97
500 AUXILIARY SYSTEMS	3.11	5.33
567 LIFT SYSTEMS	7.04	12.07
600 OUTFIT & FURNISHINGS	2.97	5.09
(1) 700 WEAPONS SYSTEMS	2.70	4.63
M10 CONTRACTOR CONTROLLED	–	–
M21-M23 CONTRACT DESIGN, MOD. & GFM	–	–
MARGINS	2.39	4.09
DELIVERED LIGHTSHIP	42.30	72.50
NORMAL LOADS:		
(2) F10 SHIPS FORCE	1.43	2.46
(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	–	–
(1) F21 SHIP AMMUNITION	2.33	3.99
(2) F30 STORES	.49	.84
(2) F40 SHIP FUEL	11.17	19.14
(2) F50 POTABLE WATER	.57	.98
OTHER (MISC) LIQUIDS	.06	.10
(2) F60 CARGO (IF ANY)	–	–
DELIVERED FULL LOAD DISPLACEMENT	58.34	100
M24 FUTURE GROWTH MARGIN	–	–
MAXIMUM DISPLACEMENT	58.34	
GROUP 567 BUOYANCY		
NORMAL FOILBORNE	– .51	– .87
FB DYNAMIC LIFT (F.L.)	57.83	99.13
MILITARY PAYLOAD	5.50	9.43
VARIABLE PAYLOAD	13.72	23.52
USEFUL PAYLOAD (1 & 2)	19.22	32.95

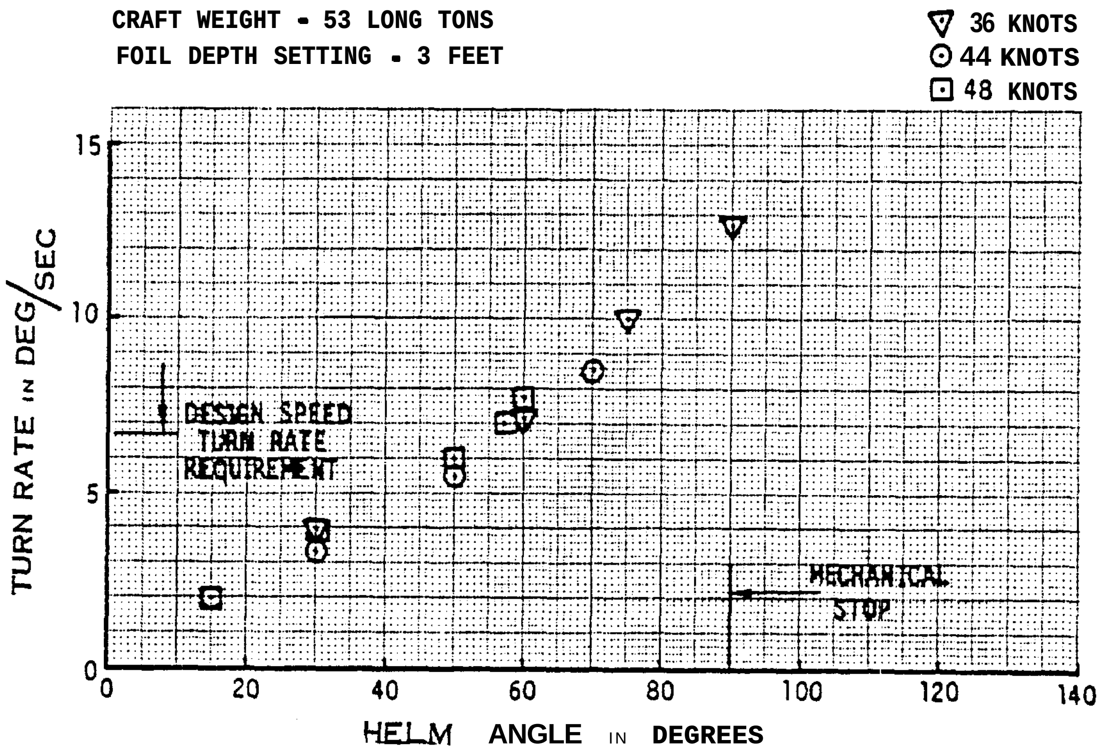
2.1.3.1 Turning Performance

(U) Hydrofoil ships can either make flat turns or partially to fully coordinated turns. A fully coordinated turn is one in which the component of the lift vector balances exactly the centrifugal force imparted by the turning maneuver. Depending on the design philosophy of the manufacturer or design agency the ship may or may not have flat turn capability. PCH-1, PGH-1, and AGEH-1 have flat turn capability; PHM-1 and PGH-2 do not. PGH-2 and PHM-1 are designed for fully coordinated turns at approximately 40 kn. Above 40 kn the turns are over-coordinated and under 40 kn slightly under-coordinated. FLAGSTAFF experience has shown that the difference in flat turn and coordinated turn radii and rates is small. But this does not necessarily apply to larger ships. Figure 111.2-34 shows the turn rate versus radius for various craft from data gathered from References 111.2-15, 111.2-16, and 111.2-17. The points exemplifying AGEH's rates should be observed with caution since the craft has not yet been tested to its limits because of structural limitations of the aft strut which has been replaced with a new, stronger strut in the present overhaul. However, as a general trend, turning rates can be expected to decrease slightly with ship size. TUCUMCARI, the smallest of the operational military hydrofoil ships, is shown to have the highest turning rate. TUCUMCARI and HIGH POINT turning characteristics are given in Figures 111.2-35 through 111.2-40. The above curves not only show the excellent maneuvering performance



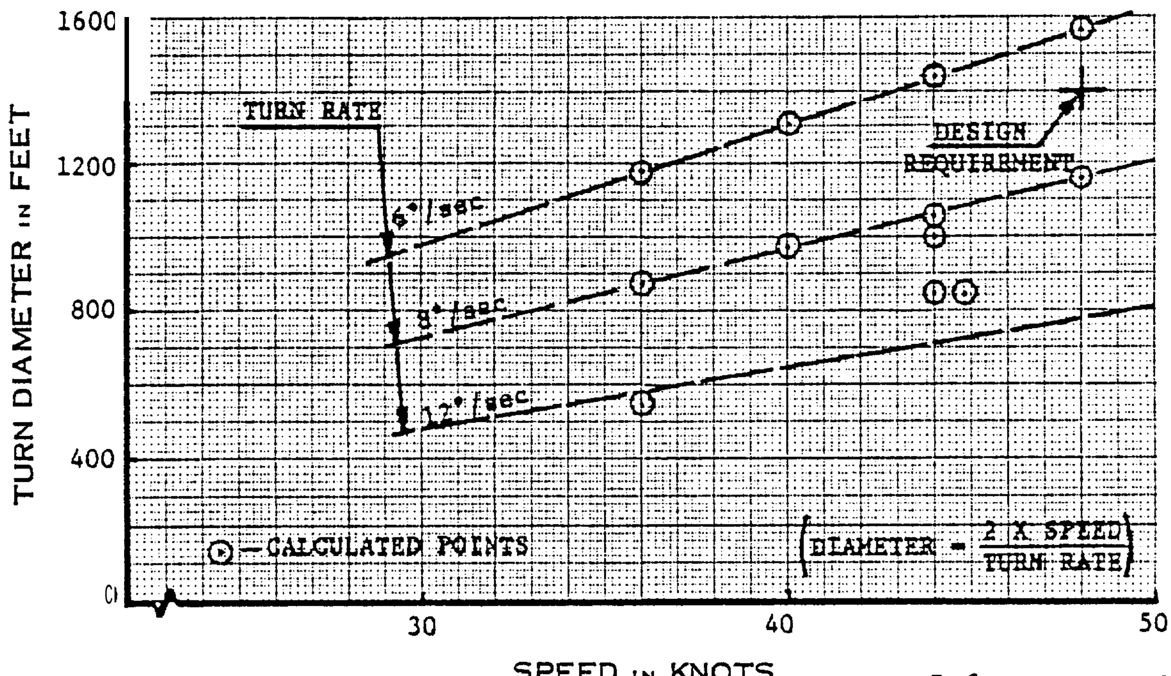
Reference III.2-18

Figure 111.2-34. TURNING RATE VERSUS RADIUS (U)



Reference III.2-6

Figure III. 2-35. TUCUMCARI PGH-2 HELM CHARACTERISTICS



Reference III.2-6

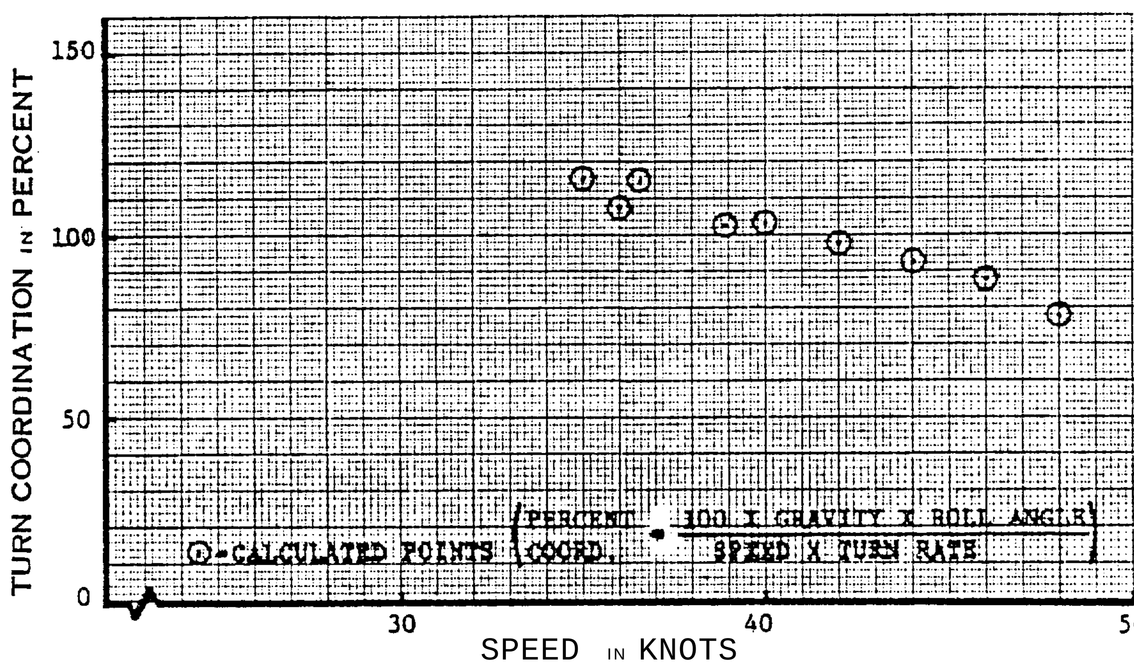
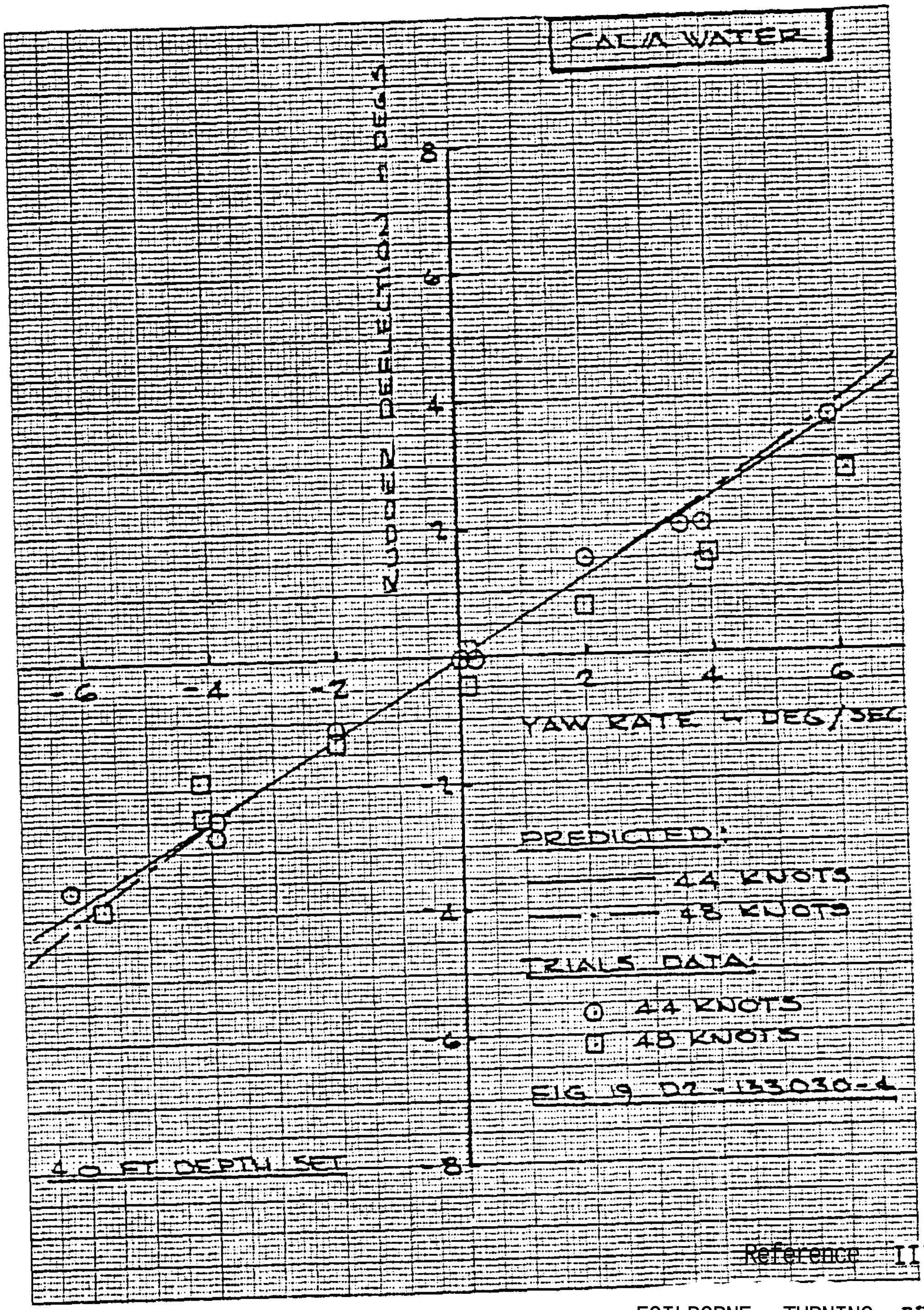
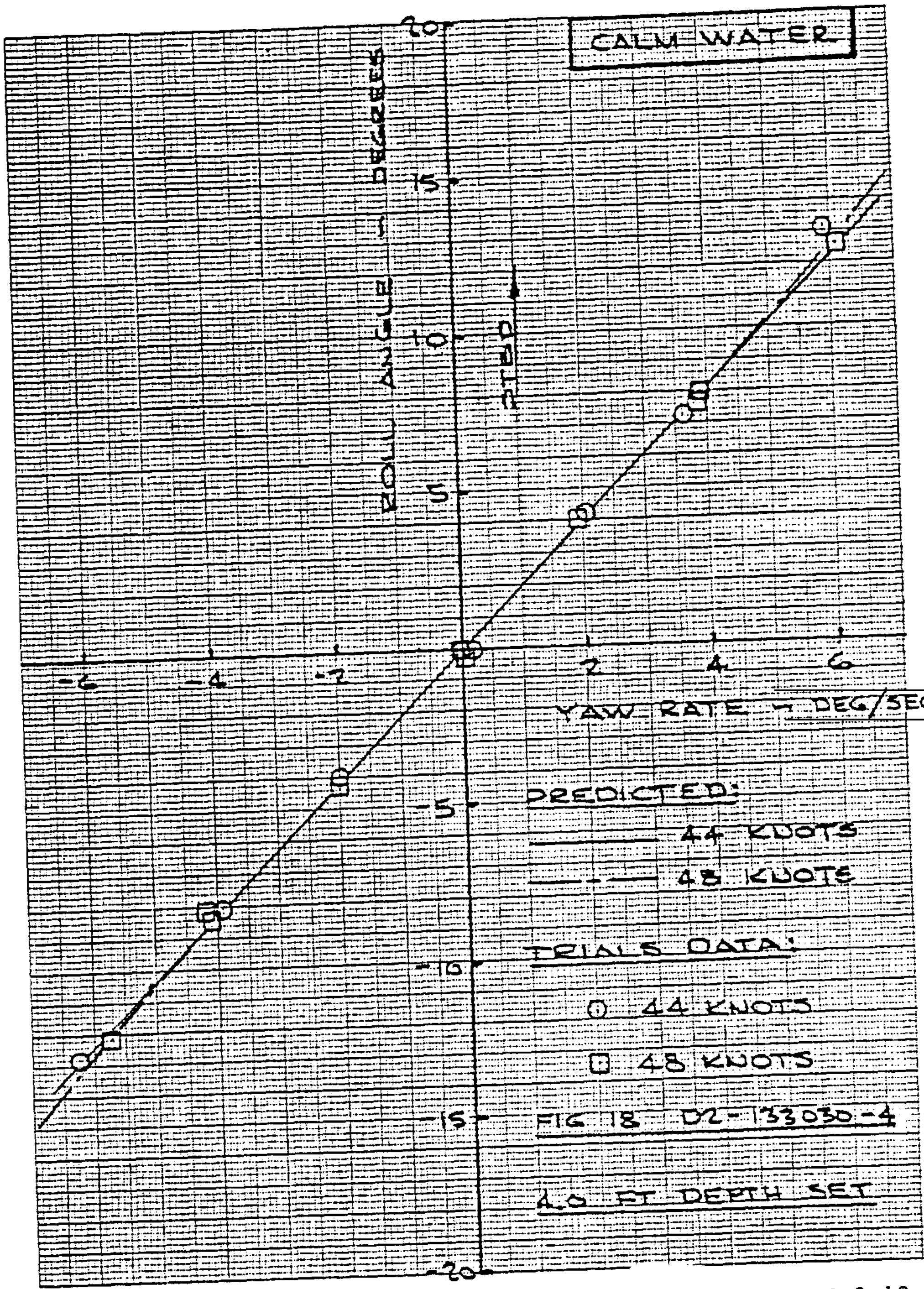


Figure X1.2-36 TUCUMCARI PGH-2 TACTICAL DIAMETER



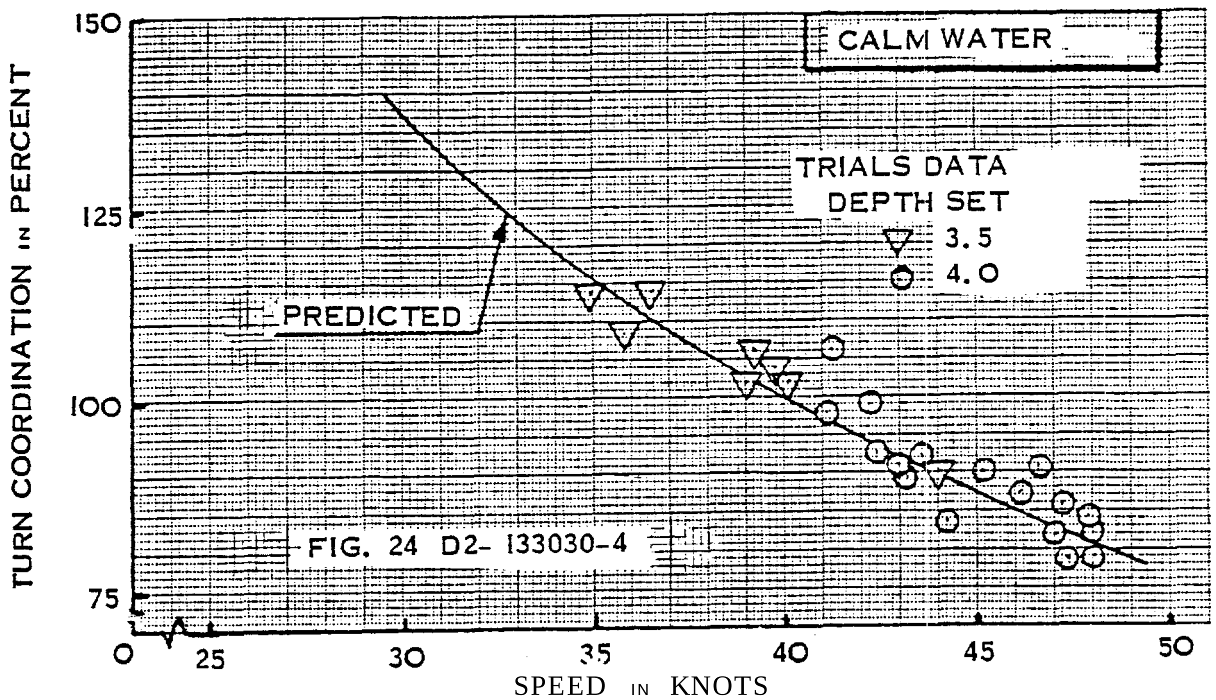
Reference III.2-19

Figure 11X.2-37 TUCUMCARI PGH-2 FOILBORNE TURNING RUDDER DEFLECTXON WITH YAW RATE



Reference III.2-19

Figure III.2-38 TUCUMCARI PGH-2 FOILBORNE TURNING ROLL ANGLE WITH YAW RATE



Reference X11.2-19

Figure III.2-39. TUCUMCARI PGH-2 FOILBORNE TURNING TURN COORDINATION

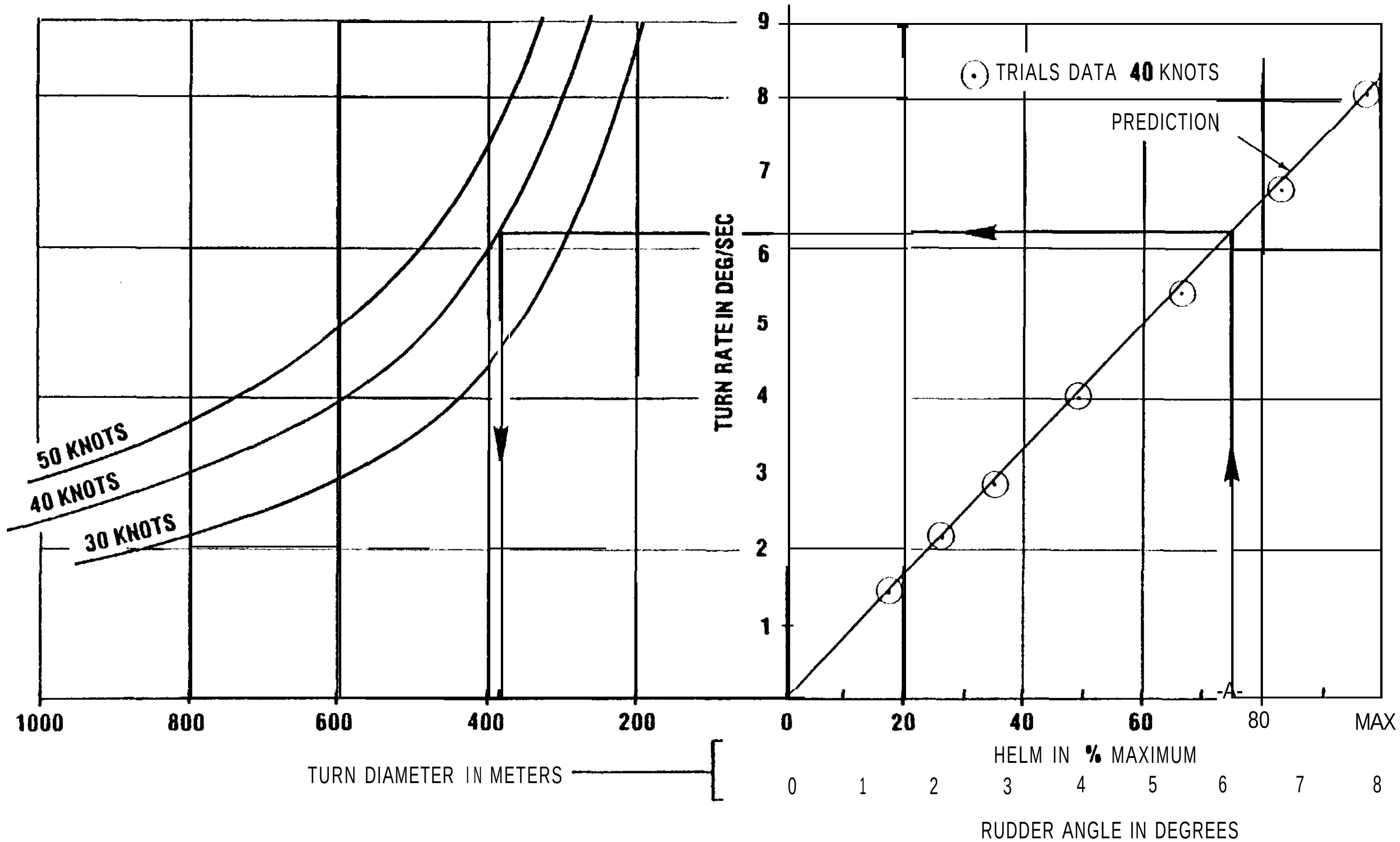


Figure 111.2-40. PCH-1 MOD 1 TURNING PERFORMANCE TRIALS 4-4-75

of hydrofoil ships, but also show the good agreement between predicted and full scale measurements. Foilborne tactical maneuvering capability for PHM-1, presented in Figure 111.2-41, shows how little the transfer and advance vary from the turn radius. Rough water turning capability is almost as high as calm water turning capability. Figure III.2-42 shows standard deviation in turn rate as a function of significant wave height shows the ability of a hydrofoil to maintain its ordered course in a seaway.

2.1.3.2 Takeoff Performance

(U) Table 111.2-4 tabulates the takeoff performance for four ships. For a hydrofoil ship, takeoff distance means the distance from a point at which the craft has zero speed to the point where the keel leaves the free surface. The time taken depends upon the ratio of the power available to that required. In the case of TUCUMCARI the hullborne propulsion unit can be used to give an extra takeoff assist at high ambient temperatures.

2.1.3.3 Landing Performance

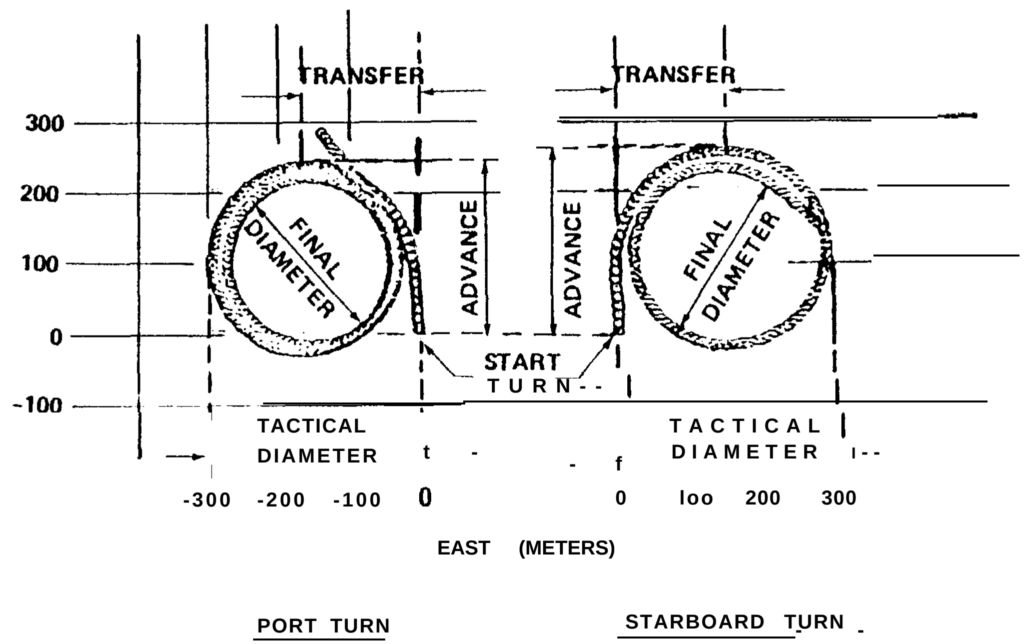
(U) There are two distinctive ways of landing the hydrofoil ship when foilborne. The first is to pull back the power and allow the hull to sink back in the water in its own time **just** as the power is pulled back on an airplane over the runway threshhold as it lands. The second is somewhat more dramatic. It involves a foil down/flaps up command to all foils by reducing the height command and pulling back on the power. This sequence of events causes

[redacted]

PHM-1 PEGASUS

TURN RATE REQUIREMENT ≥ 8.0 DEGRFFS/SECOND

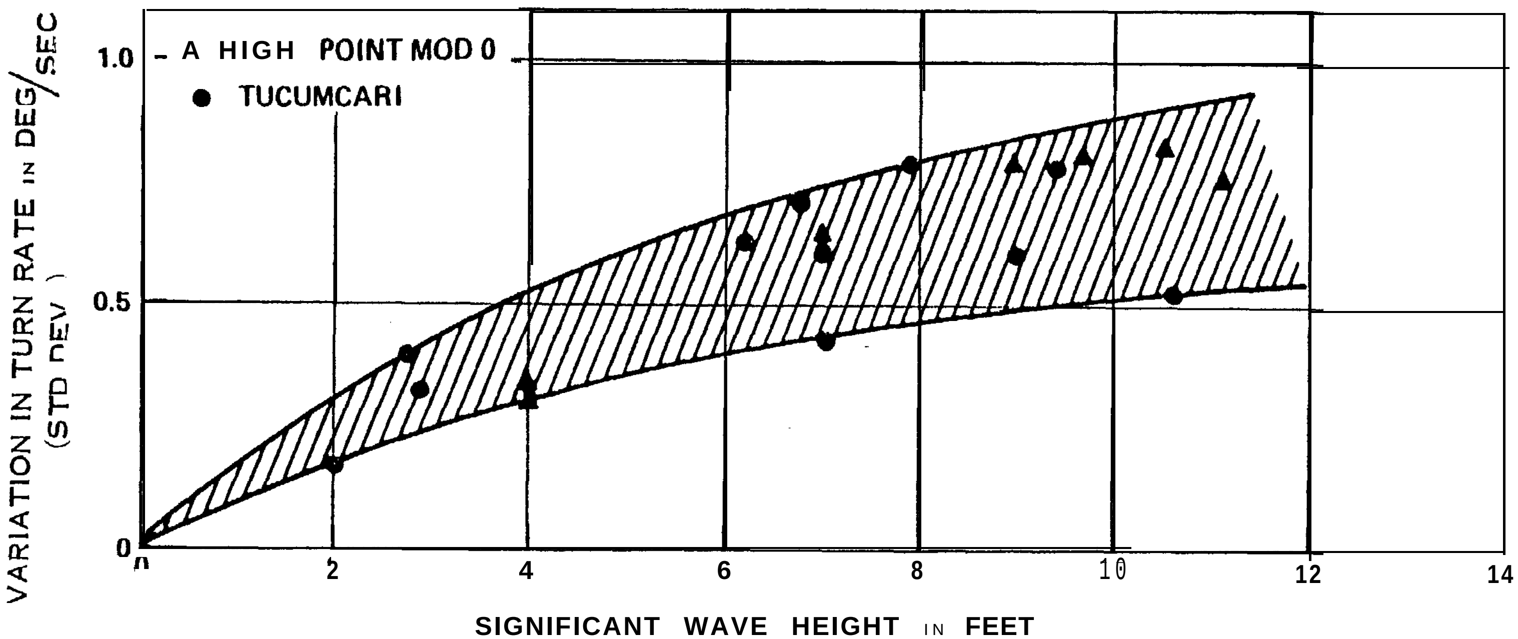
TURN RATE	8.69 DEG/SEC	8.33 DEG/SEC
INITIAL SHIP SPEED	49 KNOTS	48 KNOTS



Reference X11.2-5

Figure 111.2-41. FOILBORNE TACTICAL MANEUVER CAPABILITY (U)

[redacted]



Reference III. 2-5

Figure 111.2-42. MEASURED ROUGH WATER VARIATION IN TURNING CAPABILITY - HYDROFOIL SHIPS

)

Table III.2-4. CALM WATER TAKEOFF PERFORMANCE

SHIP	GROSS WRIGHT (TONS)	MAXIMUM TOTAL HORSEPOWER	TIME (SEC)	SPRED (KNOTS)	DISTANCE (METERS)	REF.
TUCUMCARI (PGH-2)	--	--	30-32	19-21	180-200	1
HIGH POINT (PCH-1)	--	--	30-35	22-26	210-250	1
FLAGSTAFF (PGH-1)	--	--	22-50	24-27	120-800	2

Table III.2-5. DECELERATION CAPABILITY-TWO MODES

SHIP	INITIAL SPEED (KNOTS)	FINAL SPEED (KNOTS)	TIME (SEC)	DISTANCE (METERS)	TYPEOFSTOP
TUCUMCARI (PGH-2)	45	11	30-35	450-550	CONVENTIONAL
HIGH POINT (PCH-1)	35	11	25-30	300-370	CONVENTIONAL
TUCUMCARI (PGH-2)	45	< 2	12-16	150-310	CRASH
HIGH POINT (PCH-1)	35	< 2	50-90	370-490	CRASH
FLAGSTAFF (PCH-1)	50	< 2	5-15	80-150	CRASH

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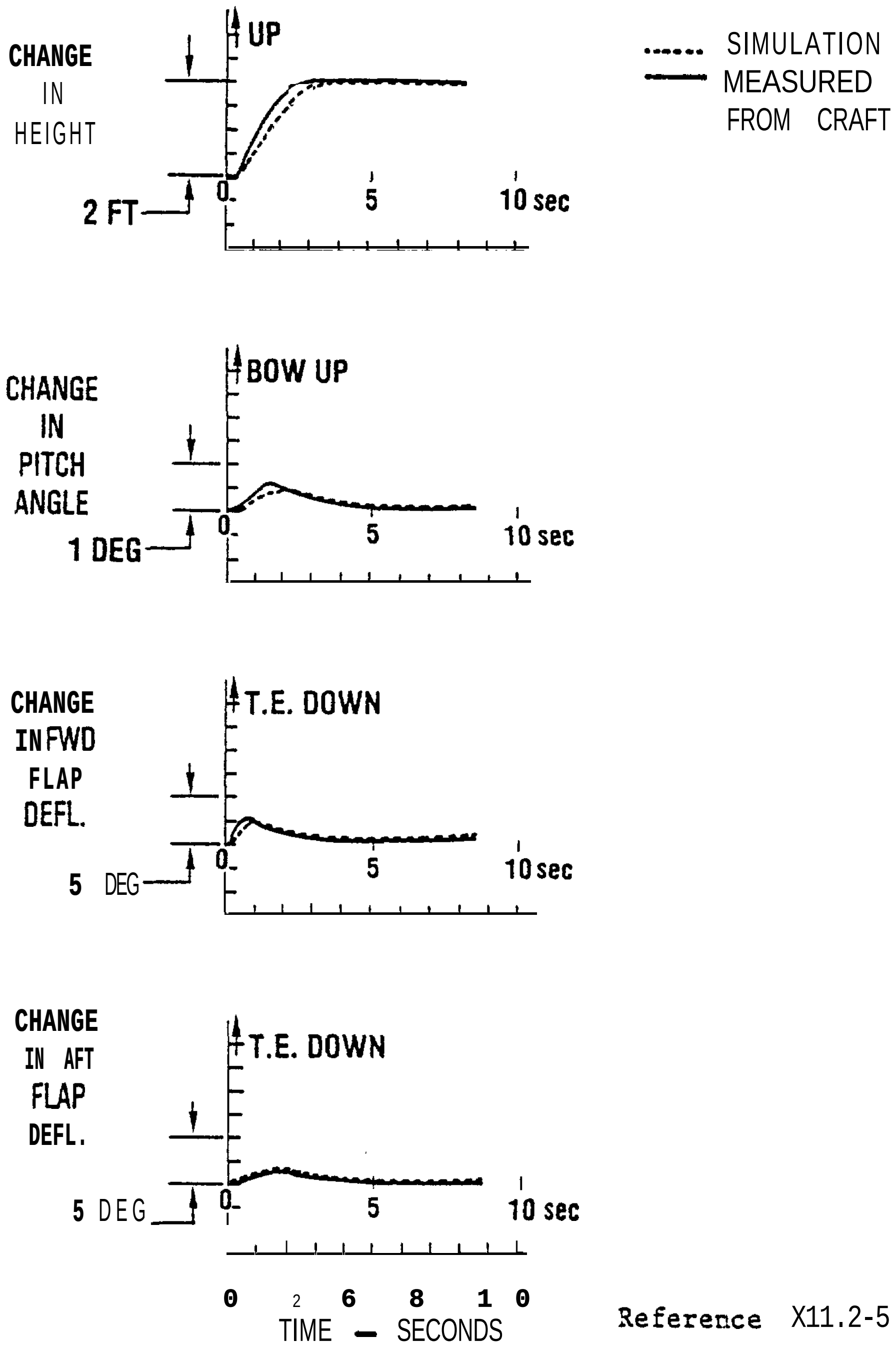
an abrupt termination of forward velocity and is referred to as a "crash stop." Typical times for both methods are illustrated in Table III.2-5. This is not detrimental to the hull structure since the loads induced by this maneuver are well within the design.

2.1.4 Stability

(U) By necessity, submerged foil system hydrofoil ships are equipped with automatic control systems. Provided that the hydrodynamic controls are not saturated by any combination of control system demands, a stability level in all axes can be prescribed, ensuring the best ride quality without sacrificing the overall hydrodynamic and, to some extent, propulsive efficiencies of the vehicle. Because each ship built to date has had different automatic control systems with varying characteristics, there is no basis for meaningful comparison except in the ride quality area which is addressed in Section III.2.2.4. A discussion of hydrofoil automatic control systems and stability and ride quality issues is contained in Directional Stability/Maneuverability/Control (II.A.2) and in Specialized Systems (II.B.6).

(U) Dynamic response of a controlled hydrofoil ship is measured by the ship's response to step input commands. Data are available for the HIGH POINT, PCH-1 (Mod O), and the AGEH-1, PLAINVIEW. Figure 111.2-43 from Reference 111.2-10 shows the simulated and measured pitch, heave, and control surface responses to step height command for the HIGH POINT. As can be seen, there is good agreement with the simulation.



Reference X11.2-5

Figure III.2-43. PCH-1, HIGH POINT PITCH/HEAVE RESPONSE TO STEP HEIGHT COMMAND

(U) Figure 1X.2-44 compares pitch step responses of the AGEH-1 from simulation data and from trials data for a 0.9 degree pitch-up command. Figure III.2-45 shows similar data for a pitch-down command. The figures show good agreement between the step responses predicted by the simulation and those from trials. Figure III.2-46 compares aft foil response from simulation data and from trials data for a 0.9 degree pitch-up command. Figure 111.2-47 shows similar data for a pitch-down command. Figures 111.2-46 and 111.2-47 show the agreement between the dynamic characteristics predicted by the simulation and those from trials. Although the agreement is adequate, it is not as close as other response data. These small discrepancies can be attributed to the fact that the dynamic model of the downwash of the forward foil on the aft was not included in the simulation. Figure III.2-48 compares the height response from simulation data and from trials data for a height step command from 5 ft to 3 ft. Figure X11.2-49 shows similar data for a step command from 3 ft to 5 ft. The figures show good correlation in the dynamic characteristics of the simulation and trials data.

(U) Figures III.2-44 through 111.2-49 are taken from AGEH-1 trials and simulation data published in Reference 111.2-20.

2.1.5 Ride Quality

(U) An indication of ride quality can be obtained from visual observations of time histories including mean values, peak values, and average frequencies. Craft motions in rough water

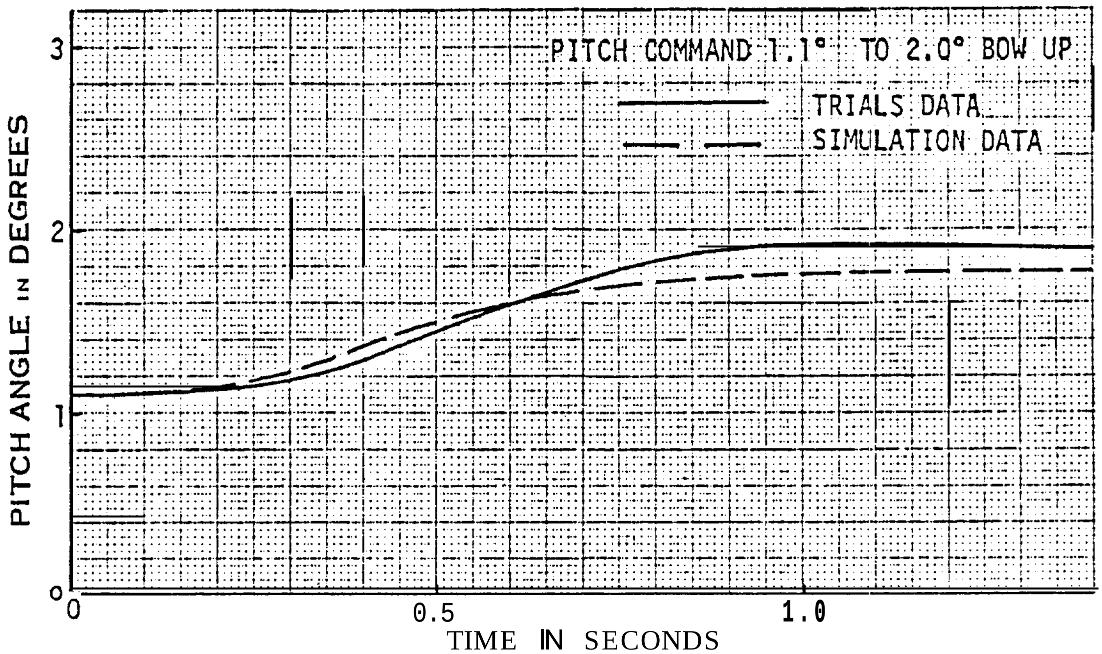


Figure X1.2-44. COMPARISON OF SIMULATION AND TRIALS PITCH STEP RESPONSE (Pitching Up) AGEH-1

Reference 111.2-20

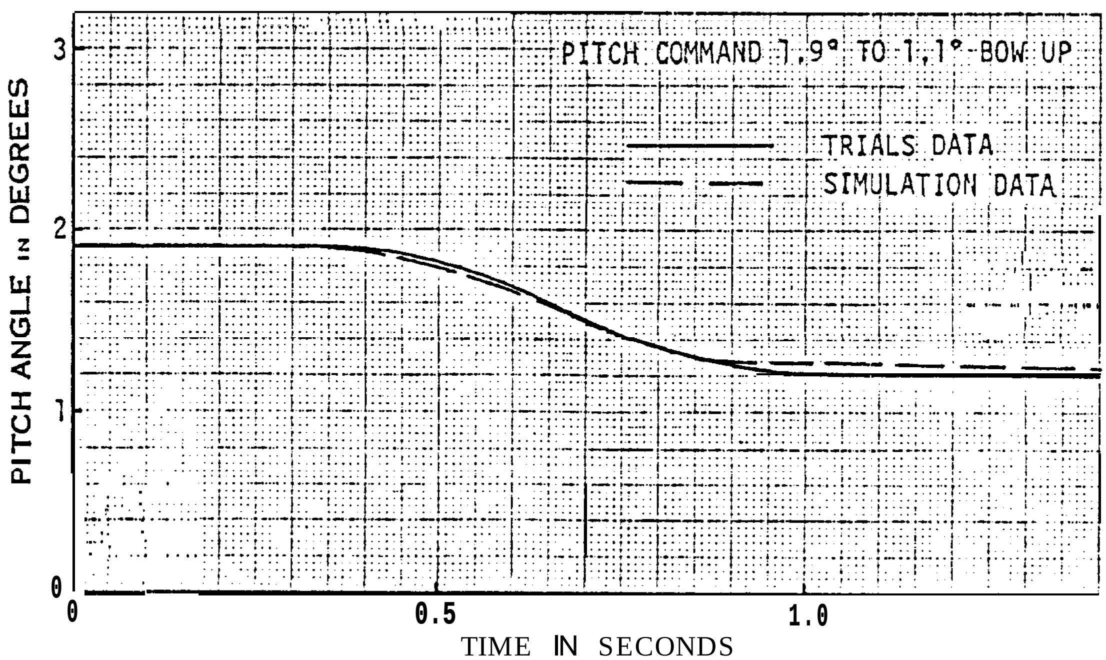


Figure 111.2-45. COMPARISON OF SIMULATION AND TRIAL PITCH STEP RESPONSE (Pitching Down) AGEH-l

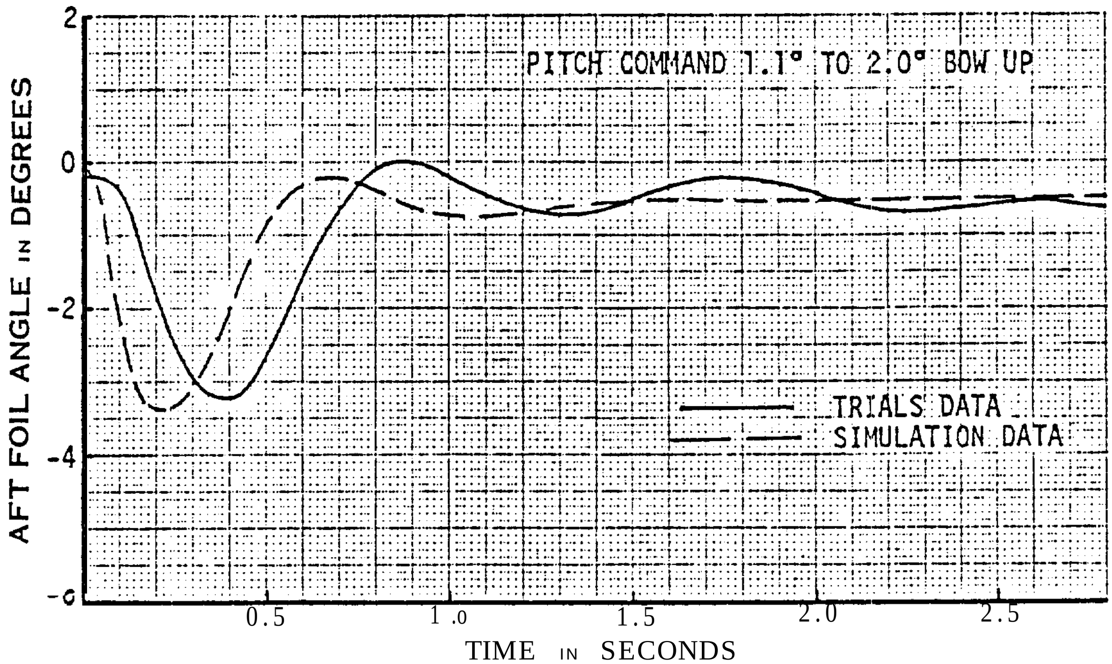


Figure x11.2-46. COMPARISON OF SIMULATION AND TRIALS AFT FOIL RESPONSE (Pitching Up) AGEH-1

Reference III.2-20

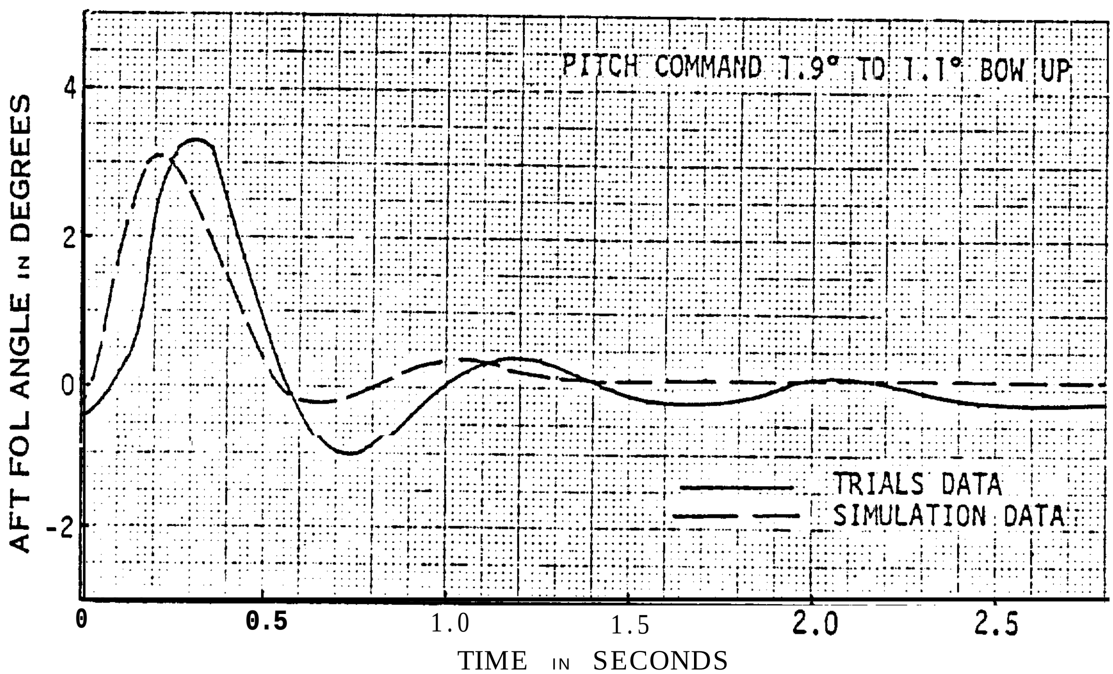


Figure III.2-47. COMPARISON OF SIMULATION AND TRIALS AFT FOIL RESPONSE (Pitching Down) AGEH-I

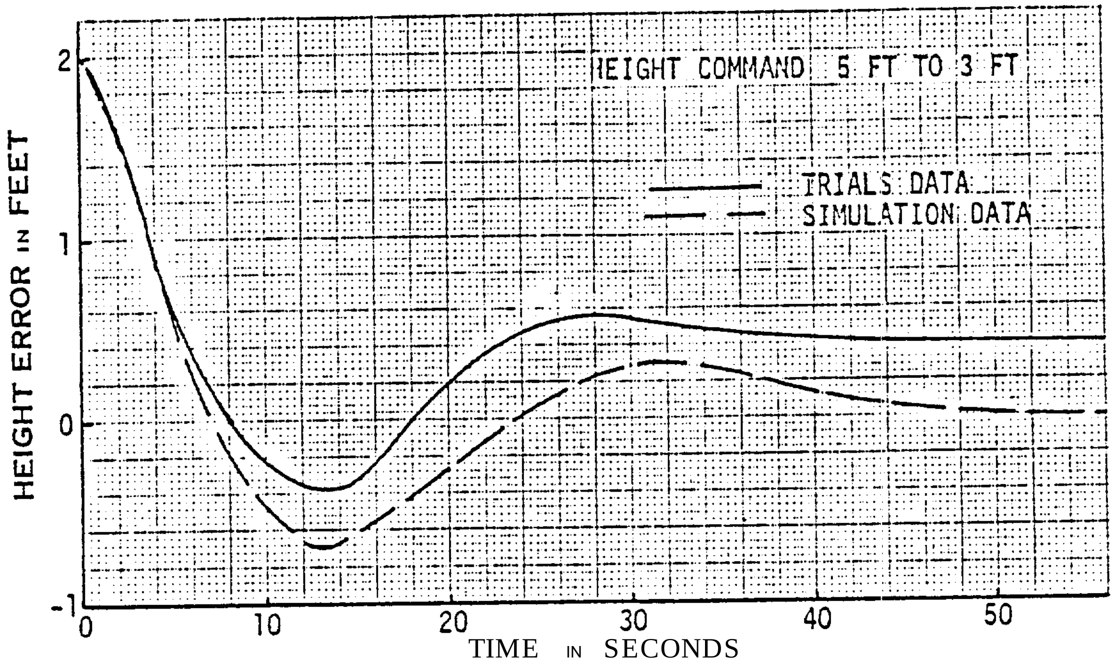


Figure X1.2-48. COMPARISON OF SIMULATION AND TRIAL HEIGHT STEP RESPONSE (Decreasing Height) AGEH-1

Reference 111.2-5

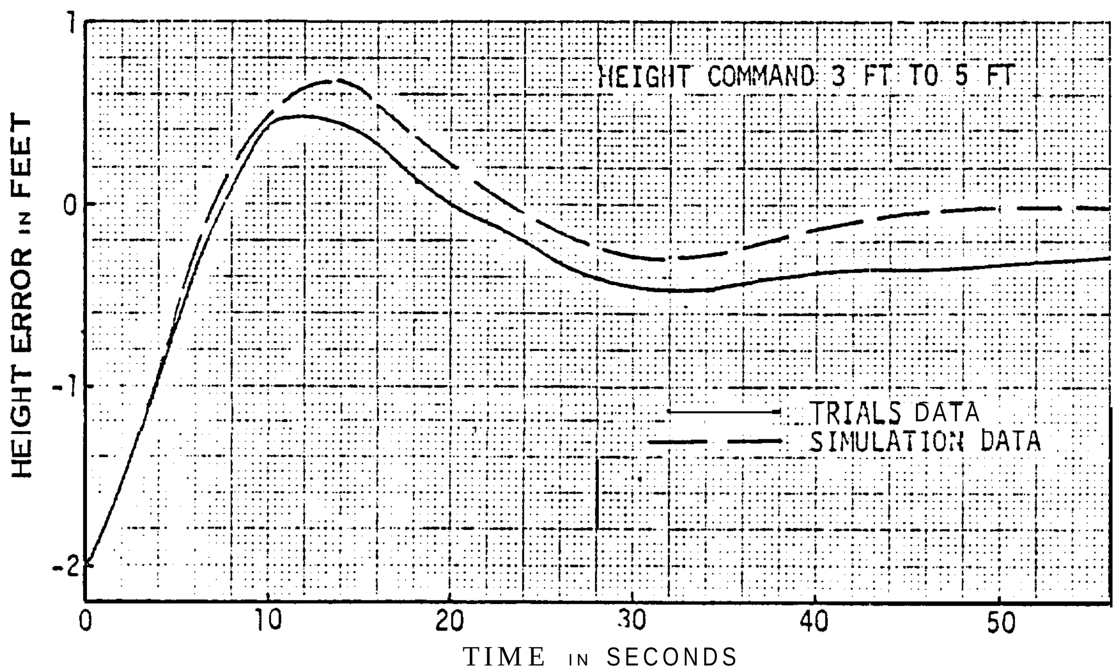
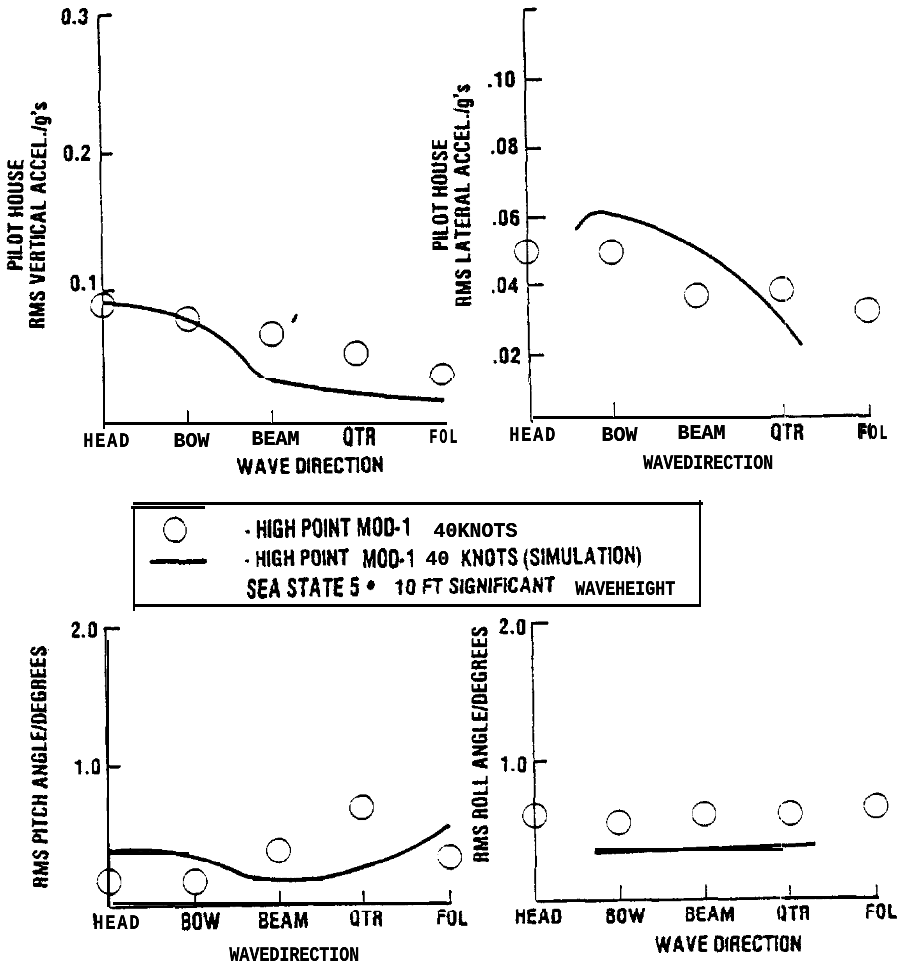


Figure 111.2-49. COMPARISON OF SIMULATION AND TRIAL HEIGHT STEP RESPONSE (Increasing Height) AGEH-1

are, of course, of a random nature. Therefore, for detailed engineering comparisons of ride qualities of hydrofoil craft, statistical data reduction processes on recorded time histories are used. Commonly employed forms of reduced statistical data consist of mean values, standard deviations, spectral densities, and probability distributions. Standard deviation values are universally accepted as a representative statistical measure of random varying parameters and can be thought of as a measurement of the dynamic or fluctuating component of a random varying process. The static or time invariant component is the mean (or time-average) value. Thus, standard deviations are determined from time histories of recorded data by either analog, digital, or manual data reduction techniques.

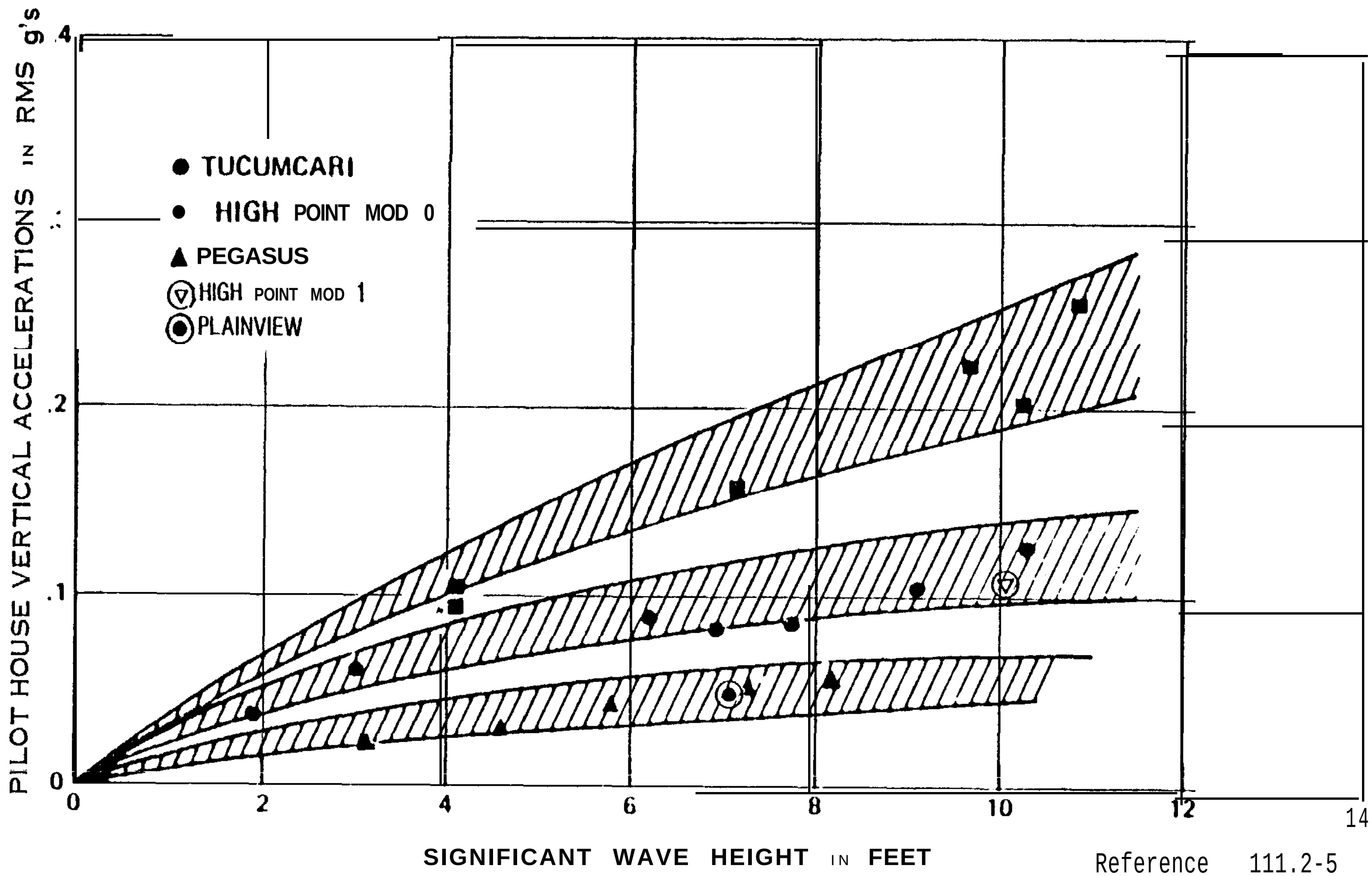
(U) A useful and significant comparison between the riding quality of hydrofoil ships operating in rough water can be made in terms of standard deviations of vertical and lateral accelerations as a function of craft encounter frequency. The measuring station position relative to the center of gravity and the significant wave height and heading should be indicated.

(U) Typical motions of HIGH POINT in Sea State 5 are shown in Figure x11.2-50 compared with the simulation. Agreement is good particularly if one considers the expanded scales used. Comparisons of measured foilborne, vertical, and lateral accelerations and roll and pitch motions of various hydrofoil ships are given in Figures III.2-51 through 111.2-54. The significance of



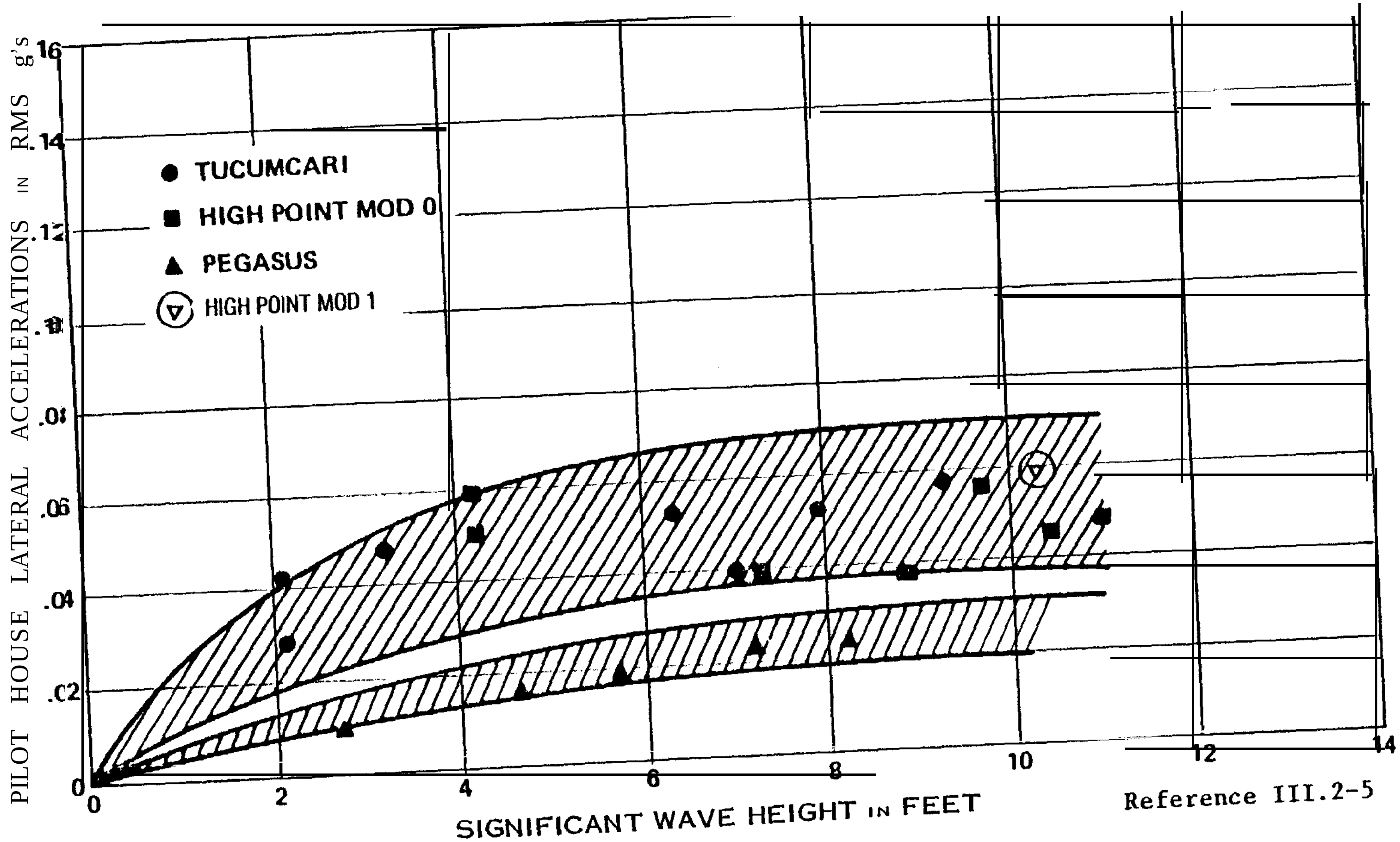
Reference 1X1.2-5

Figure 111.2-50. PCH-1, (MOD 1) MOTION IN SEA STATE 5



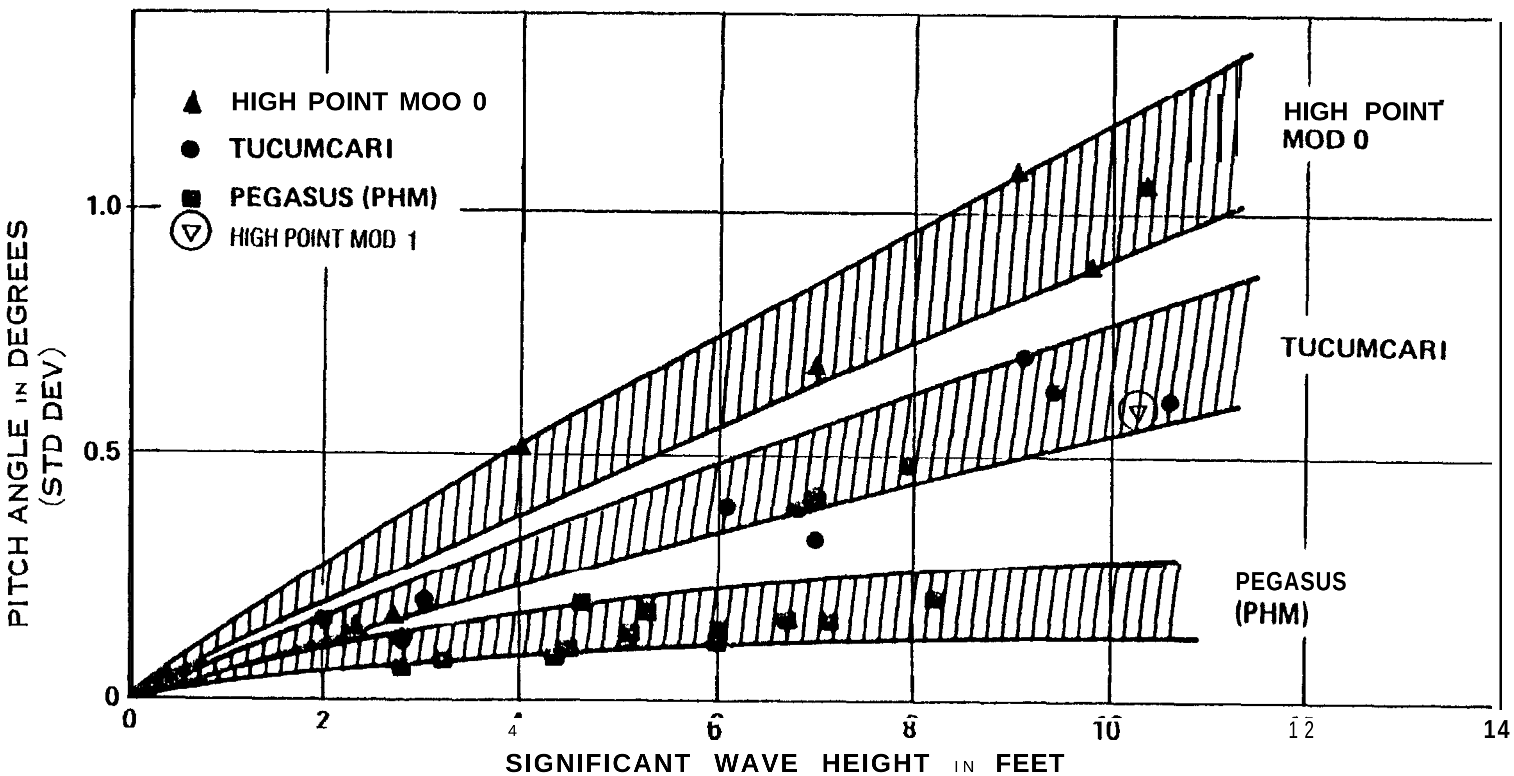
Reference 111.2-5

Figure 111.2-51. FOILBORNE MEASURED VERTICAL ACCELERATIONS



Reference III.2-5

Figure III.2-52. FOILBORNE MEASURED LATERAL ACCELERATIONS



Reference III.2-5

Figure 111.2-53. FOILBORNE MEASURED ROUGH WATER PITCH ACCELERATIONS

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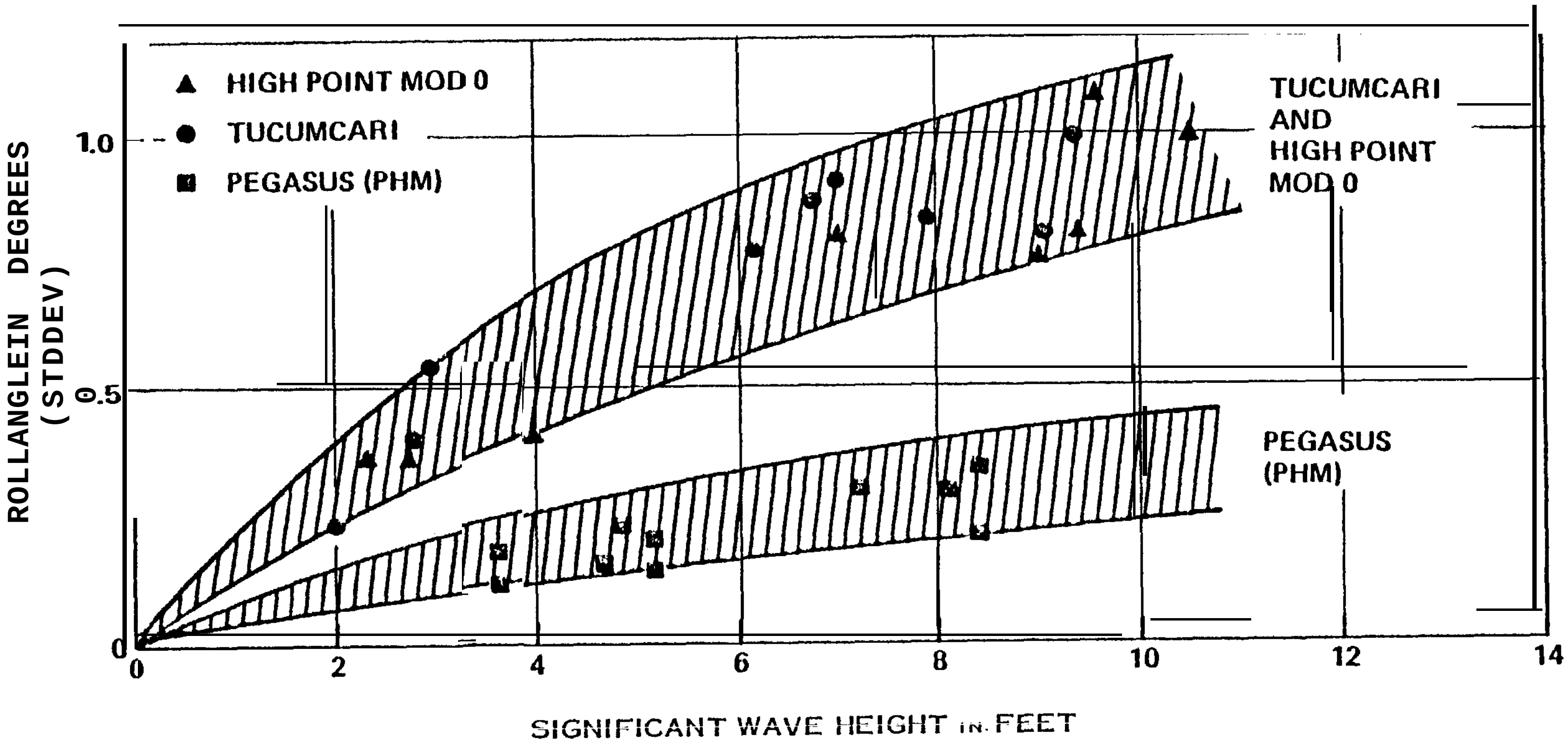

Figure III.2-54 ROLL MOTIONS FOR VARIOUS HYDROFOILS

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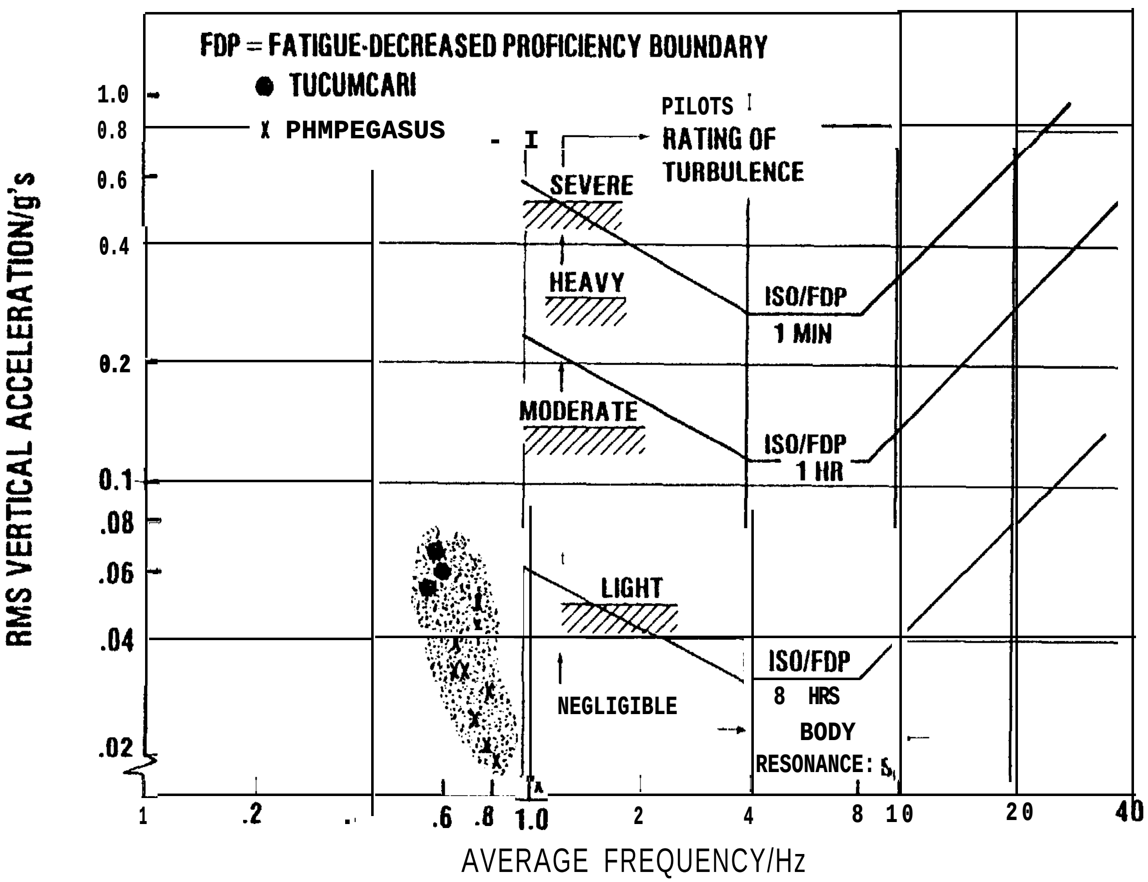
these figures is that they show that as time and control technology have progressed and as size increases, motions become smaller.

(U) Root mean square vertical and lateral accelerations are presented as a function of encounter frequency and compared with the International Organization for Standardization Fatigue Decreased Proficiency Boundaries, Reference 111.2-21, in Figures 111.2-55 and 111.2-56.

2.1.6 Internal Environment

(U) The internal environment of hydrofoil ships, notably PCH-1, PGH-1, PCH-2, AGEH-1, and currently PHM-1, has been observed and measured over several thousand hours of operation. Crew environment is favorable in all respects and Navy habitability standards are complied with in all cases. Foilborne and hullborne ride quality in design sea state are far superior to conventional ships, even those equipped with stabilizers.

(U) Noise levels of approximately 70dB have been achieved in manned spaces of existing hydrofoil ships. Temperatures and humidity are controlled by normal ship heating and air conditioning practices. Vibration levels vary from ship to ship and with respect to the proximity of rotating machinery within a given ship. In general, the vibration level of hydrofoil ships attributed to the main propulsion system is low due to the use of gas turbines on the prime movers. Ships employing waterjet propulsion have demonstrated the lowest propulsion system vibration level.



Reference III.2-5

Figure III.2-55. RMS VERTICAL ACCELERATIONS VERSUS AVERAGE ENCOUNTER FREQUENCY

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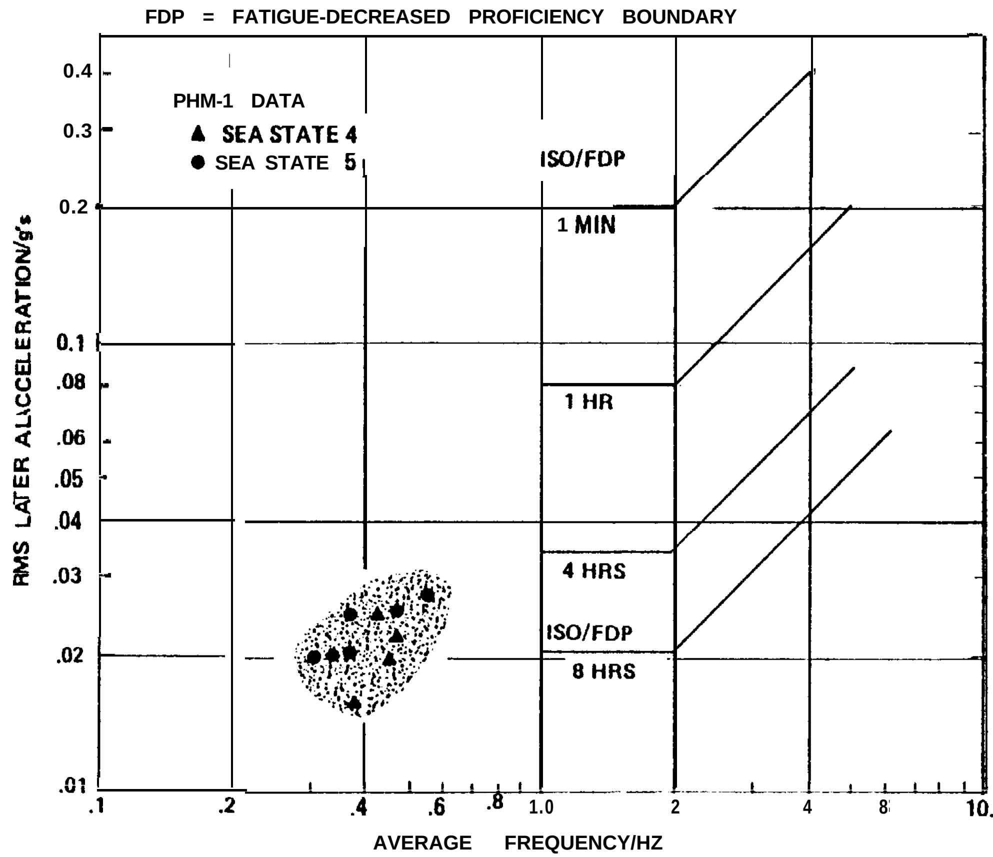
III.2-68



Reference III.2-5

Figure 111.2-56. RMS LATERAL ACCELERATIONS VERSUS AVERAGE ENCOUNTER FREQUENCY

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(U) All normal foilborne functions are designed to be accomplished from within the superstructure or below decks because of the high relative wind velocity topside.

(U) Preliminary foilborne vibration trials have been conducted on PLAINVIEW (AGEH-1) to evaluate the vibration characteristics of foilborne craft and to provide data for future tests on the craft. According to Reference III.2-22 the level of hull vibration appears to be satisfactory. The PLAINVIEW should not experience loss of machinery or personnel effectiveness or any limitations in its operations due to hull vibrations under conditions similar to those of the trial

2.1.7 Payload Capabilities

(U) Both military payload and useful load are considered in this section. Military payload is defined as the summation of SWBS groups 400 and 700, Loads F20 and F21 (see Reference III.2-9)*. The useful load is a combination of the military payload and the variable payload, Loads F10, F30, F40, F50, and F60. Designed military payload and useful load fraction as a function of gross weight are presented in Figures 111.2-57 and 111.2-58, respectively. Information for these latter figures is contained in Tables 111.2-2, 111.2-3, and 111.2-6.

*This definition is also used for II.D. Specific Designs; it varies slightly from ANVCE WP-002 Definition of Terms, 2 April 1976.

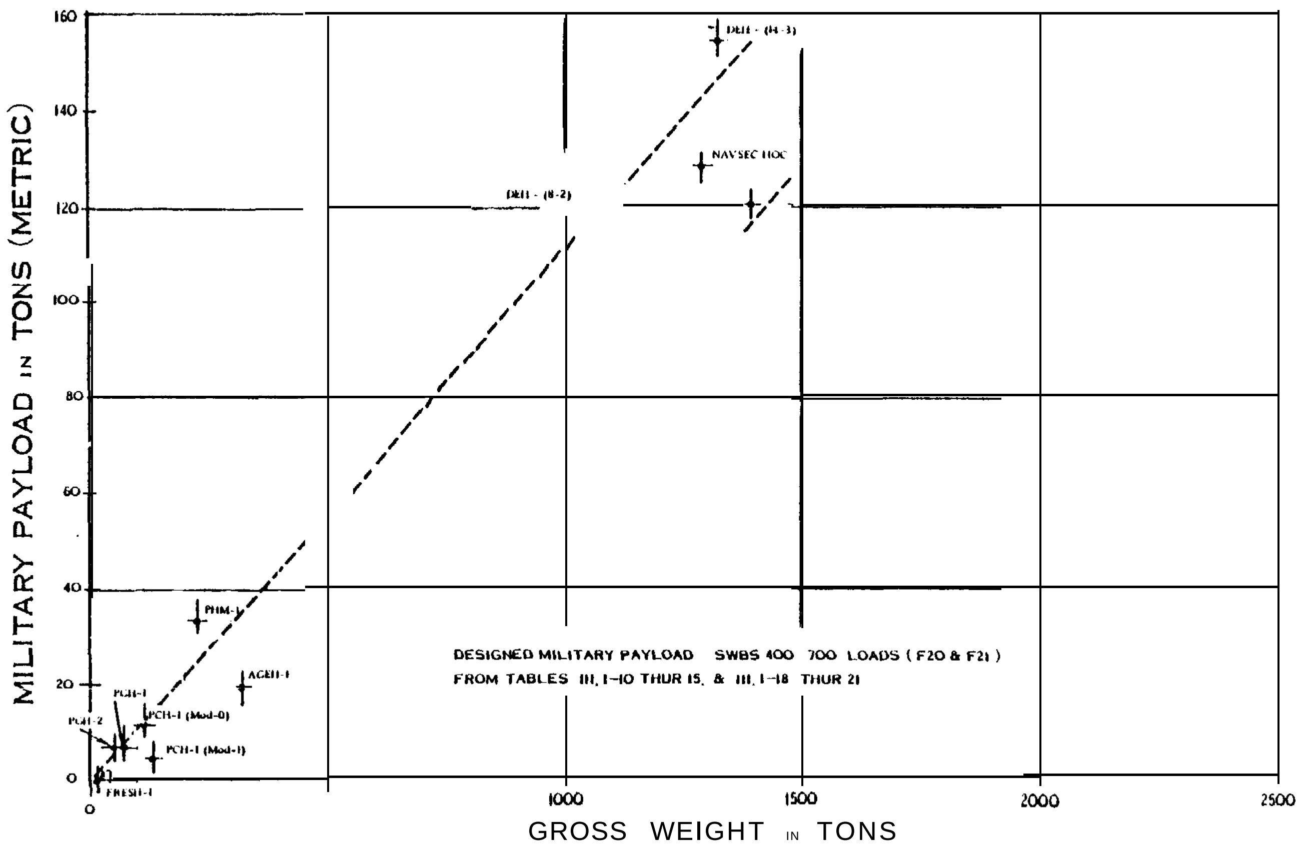

Figure III.2-57. MILITARY PAYLOAD VERSUS GROSS WEIGHT

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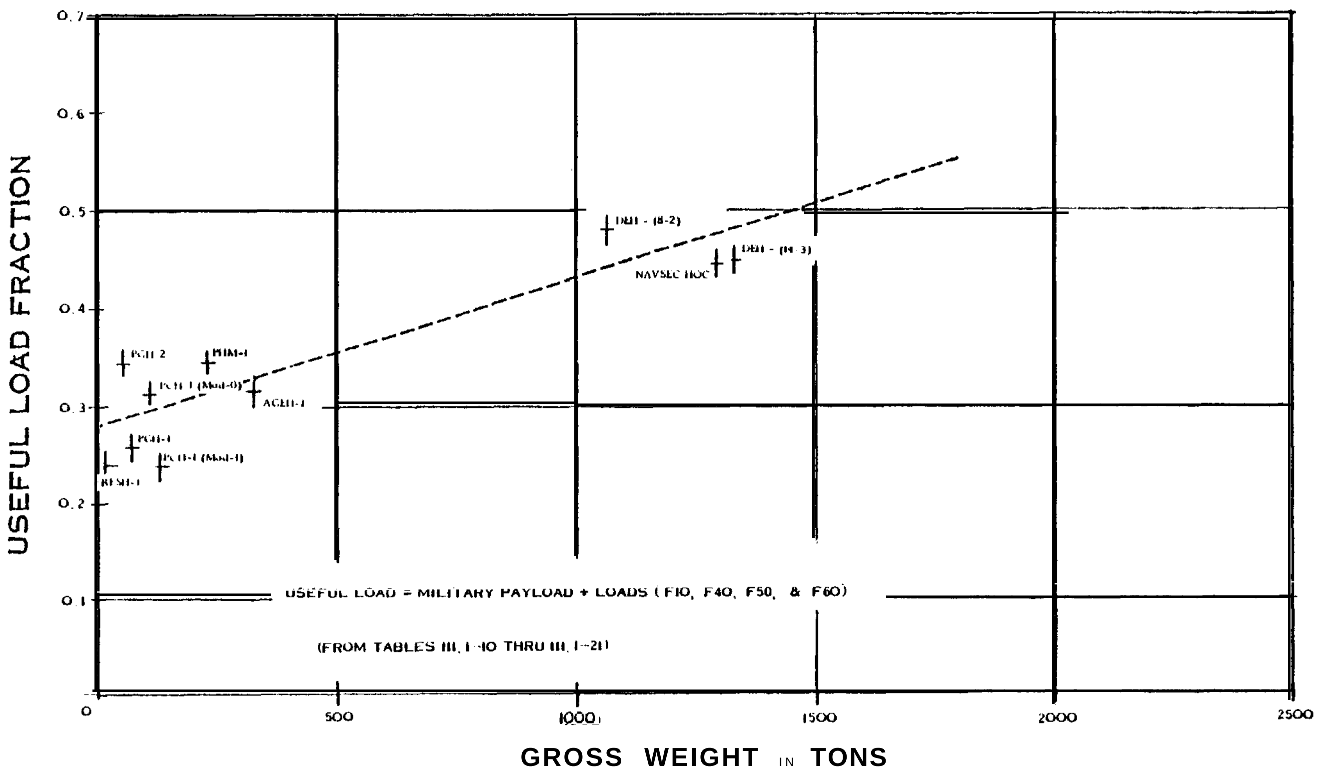

Figure 111.2-58. USEFUL LOAD FRACTION VERSUS GROSS WEIGHT

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Table III.2-6. WEIGHT SUMMARY FOR FRESH-l, HOC, DEH (8-2), AND DEH (14-3)

FRESH-I

WEIGHT SUMMARY			METRIC TONS	% F.L.
SWBS	100	HULL STRUCTURE	6.26	38.28
	200	PROPULSION SYSTEMS	2.95	18.03
	300	ELECTRIC PLANT	.35	2.11
	(1) 400	COMMAND & SURVEILLANCE	.05	.31
	500	AUXILIARY SYSTEMS	.55	3.36
	567	LIFT SYSTEMS	1.84	11.24
	600	OUTFIT & FURNISHINGS	.41	2.48
	(1) 700	WEAPONS SYSTEMS	—	—
M10 CONTRACTOR CONTROLLED			—	—
M21-M23 CONTRACT DESIGN, MOD, & GFM			—	—
MARGINS			—	—
DELIVERED LIGHTSHIP			12.41	75.84
NORMAL LOADS:				
		(2) F10 SHIPS FORCE	.23	1.43
		(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	—	—
		(1) F21 SHIP AMMUNITION	—	—
		(2) F30 STORES	.01	.06
		(2) F40 SHIP FUEL	3.14	19.19
		(2) F50 POTABLE WATER	.16	.99
		OTHER (MISC) LIQUIDS	.07	.43
		(2) F60 CARGO (IF ANY)	.34	2.08
DELIVERED FULL LOAD DISPLACEMENT			16.36	100
M24 FUTURE GROWTH MARGIN			—	—
MAXIMUM DISPLACEMENT			16.36	
GROUP 567 BUOYANCY				
NORMAL FOILBORNE			—.05	—.31
F8 DYNAMIC LIFT (F.L.)			16.31	99.69
MILITARY PAYLOAD (1) INCLUDES SWBS 442 499 & 700 LOADS F20			—	—
VARIABLE PAYLOAD (2) INCLUDES LOADS F10 F30 F40 F50 AND F60			3.94	24.10
USEFUL PAYLOAD (1 & 2)			3.94	24.10

HOC

WEIGHT SUMMARY			METRIC TONS	% F.L.
SWBS	100	HULL STRUCTURE	228.61	17.61
	200	PROPULSION SYSTEMS	60.96	4.69
	300	ELECTRIC PLANT	40.64	3.13
	(1) 400	COMMAND & SURVEILLANCE	80.37	6.19
	500	AUXILIARY SYSTEMS	238.77	18.39
	567	LIFT SYSTEMS (NOT INCLUDED IN STUDY)	DNA	
	600	OUTFIT & FURNISHINGS	44.71	3.44
	(1) 700	WEAPONS SYSTEMS	26.93	2.07
M10 CONTRACTOR CONTROLLED			—	—
M21-M23 CONTRACT DESIGN, MOD, & GFM			—	—
MARGINS			108.11	8.33
DELIVERED LIGHTSHIP			829.09	63.85
NORMAL LOADS:				
		(2) F10 SHIPS FORCE	10.16	.78
		(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	* —	—
		(1) F21 SHIP AMMUNITION	21.24	1.64
		(2) F30 STORES	16.26	1.25
		(2) F40 SHIP FUEL	406.52	31.31
		(2) F50 POTABLE WATER	14.22	1.10
		OTHER (MISC) LIQUIDS	1.02	.08
		(2) F60 CARGO (IF ANY)	—	—
DELIVERED FULL LOAD DISPLACEMENT			1298.51	100
M24 FUTURE GROWTH MARGIN			—	—
MAXIMUM DISPLACEMENT			1298.51	
GROUP 567 BUOYANCY				
NORMAL FOILBORNE			— 79.25	—6.10
F8 DYNAMIC LIFT (F.L.)			1219.26	93.90
MILITARY PAYLOAD (1) INCLUDES SWBS 442 499 & 700 LOADS F20			128.54	9.90
VARIABLE PAYLOAD (2) INCLUDES LOADS F10 F30 F40 F50 AND F60			448.18	34.51
USEFUL PAYLOAD (1 & 2)			576.72	44.41

* NOTE: TOTAL SWBS GROUP 400 WAS USED TO DETERMINE MILITARY PAYLOAD IN THIS STUDY

DEH (8-2)

WEIGHT SUMMARY			METRIC TONS	% F.L.
SWBS	100	HULL STRUCTURE	150.04	14.09
	200	PROPULSION SYSTEMS	59.44	5.58
	300	ELECTRIC PLANT	29.43	2.76
	(1) 400	COMMAND & SURVEILLANCE	54.74	5.14
	500	AUXILIARY SYSTEMS	197.14	18.51
	567	LIFT SYSTEMS (NOT INCLUDED IN STUDY)	DNA	—
	600	OUTFIT & FURNISHINGS	35.35	3.32
	(1) 700	WEAPONS SYSTEMS	23.02	2.16
M10 CONTRACTOR CONTROLLED			—	—
M21-M23 CONTRACT DESIGN, MOD, & GFM			—	—
MARGINS			82.37	7.73
DELIVERED LIGHTSHIP			631.51	59.29
NORMAL LOADS:				
		(2) F10 SHIPS FORCE	6.96	.65
		(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	6.11	.57
		(1) F21 SHIP AMMUNITION	35.39	3.32
		(2) F30 STORES	6.50	.61
		(2) F40 SHIP FUEL	371.06	34.84
		(2) F50 POTABLE WATER	6.80	.64
		OTHER (MISC) LIQUIDS	.74	.07
		(2) F60 CARGO (IF ANY)	—	—
DELIVERED FULL LOAD DISPLACEMENT			1065.07	100
M24 FUTURE GROWTH MARGIN			—	—
MAXIMUM DISPLACEMENT			1065.07	
GROUP 567 BUOYANCY				
NORMAL FOILBORNE			— 63.56	—5.97
F8 DYNAMIC LIFT (F.L.)			1001.51	94.03
MILITARY PAYLOAD (1) INCLUDES SWBS 442 499 & 700 LOADS F20			*119.26	11.20
VARIABLE PAYLOAD (2) INCLUDES LOADS F10 F30 F40 F50 AND F60			392.06	36.81
USEFUL PAYLOAD (1 & 2)			511.32	48.01

NOTE TOTAL SWBS GROUP 400 WAS USED TO DETERMINE MILITARY PAYLOAD IN THIS STUDY

DEH (14-3)

WEIGHT SUMMARY			METRIC TONS	% F.L.
SWBS	100	HULL STRUCTURE	213.08	15.99
	200	PROPULSION SYSTEMS	58.44	4.48
	300	ELECTRIC PLANT	37.63	2.83
	(1) 400	COMMAND & SURVEILLANCE	63.96	4.80
	500	AUXILIARY SYSTEMS	259.06	19.45
	567	LIFT SYSTEMS (NOT INCLUDED IN STUDY)	DNA	—
	600	OUTFIT & FURNISHINGS	57.46	4.31
	(1) 700	WEAPONS SYSTEMS	25.66	1.92
M10 CONTRACTOR CONTROLLED			—	—
M21-M23 CONTRACT DESIGN, MOD, & GFM			—	—
MARGINS			107.42	8.06
DELIVERED LIGHTSHIP			825.54	61.93
NORMAL LOADS:				
		(2) F10 SHIPS FORCE	15.23	1.14
		(1) F20 ORDNANCE AND ORDNANCE DELIVERY SYSTEMS	10.27	.77
		(1) F21 SHIP AMMUNITION	54.57	4.10
		(2) F30 STORES	7.46	.56
		(2) F40 SHIP FUEL	406.42	30.51
		(2) F50 POTABLE WATER	14.73	1.11
		OTHER (MISC) LIQUIDS	.74	.06
		(2) F60 CARGO (IF ANY)	—	—
DELIVERED FULL LOAD DISPLACEMENT			1332.96	100
M24 FUTURE GROWTH MARGIN			—	—
MAXIMUM DISPLACEMENT			1332.96	
GROUP 567 BUOYANCY				
NORMAL FOILBORNE			— 89.74	—6.75
F8 DYNAMIC LIFT (F.L.)			1243.22	93.33
MILITARY PAYLOAD (1) INCLUDES SWBS 442 499 & 700 LOADS F20			*154.33	11.58
VARIABLE PAYLOAD (2) INCLUDES LOADS F10 F30 F40 F50 AND F60			444.58	33.35
USEFUL PAYLOAD (1 & 2)			598.91	44.93

NOTE TOTAL SWBS GR 400 WAS USED TO DETERMINE MILITARY PAYLOAD IN THIS STUDY

2.2 HULLBORNE PERFORMANCE

(U) The hullborne performance requirements of a hydrofoil have not been emphasized on the ships built to date. Therefore the hullborne performance of present hydrofoil ships is not as thoroughly characterized as their foilborne performance. Since envisioned missions of larger and faster hydrofoil ships require higher hullborne speeds and more extensive operation in the hullborne mode, increased emphasis is planned to obtain more hullborne performance data. The AGEH will be the major test vehicle for this effort. (The PCH is not a good vehicle for hullborne investigations as its foils cannot be retracted out of the water.)

(U) In the hullborne mode, hydrofoil ships differ from conventional displacement ships in two ways. First, with the foils extended, a hullborne hydrofoil ship's motions are considerably less than a conventional ship of the same displacement due to the damping effect of the struts and foils. Second, at higher hullborne speeds, over 12 kn, additional stability in rough water is achieved by activating the automatic control system. Hullborne speed-power, range, and endurance, maneuvering, and motion data on existing hydrofoil ships are presented in this Section.

2.2.1 Hullborne Speed-Power

(U) Hullborne power required for a given forward speed is developed from the known, or estimated, hull drag and propeller efficiency. Estimated and model test drag versus speed for the AGEH-1 PLAINVIEW is presented in Figure III.%-59. The estimated array for

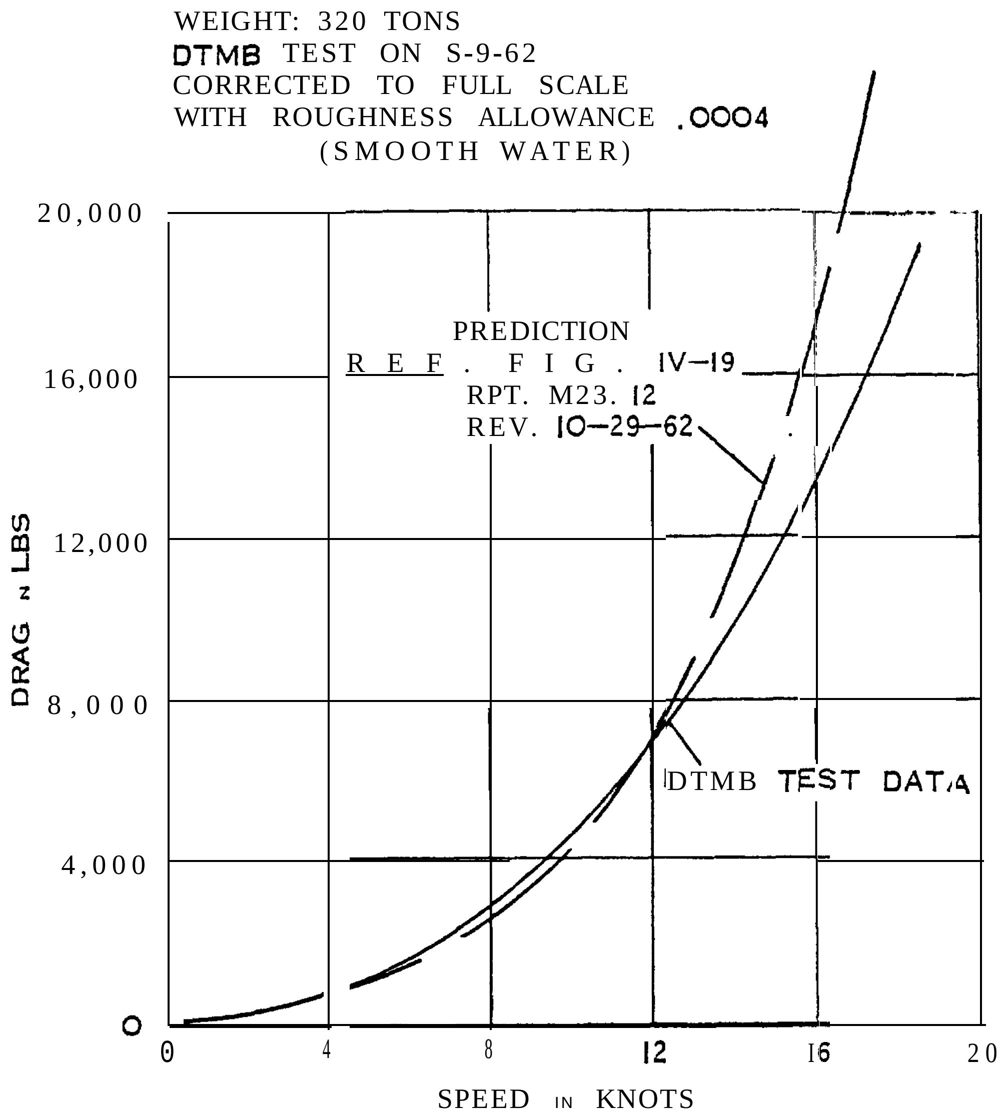

Figure III.2-59. AGEH HULL DRAG VERSUS SPEED (U)

PCH-1 FLAGSTAFF (from References X11.2-23 and III.2-24) is presented in Figure 111.2-60. PHM drag versus speed is given for both foils extended and foils retracted in Figure 111.2-61.

(U) Ship speed as a function of main propulsion pump rpm is given in Figure 111.2-62 for the PHM-1 *as* determined from trials data (Reference III.2-25). With foils up, the main propulsor absorbs full power, attaining a maximum ship speed of about 15 knots. The pump inlet pressure becomes extremely low in this condition, tending to create pump cavitation. In order to avoid pump cavitation damage, power turbine rpm normally is limited to about 60 percent of the maximum when foils are retracted. With foils down, any ship speed can be obtained up to foilborne maximum, depending on how high the hull is allowed to rise. Holding the hull in the water by using the foilborne control flaps, ship speed is approximately 25 knots at full power.

(U) Trials data for FLAGSTAFF PGH-1 showing speed as a function of hullborne power plant engine rpm are given in Figure 111.2-63 (Reference III.2-24).

2.2.2 Hullborne Range and Endurance

(U) For PGH-1 hullborne powerplant fuel consumption versus engine speed, endurance versus engine speed, and hullborne range versus hullborne speed are shown in Figures 111.2-63 through 111.2-66 with foils and struts retracted, or as otherwise indicated.

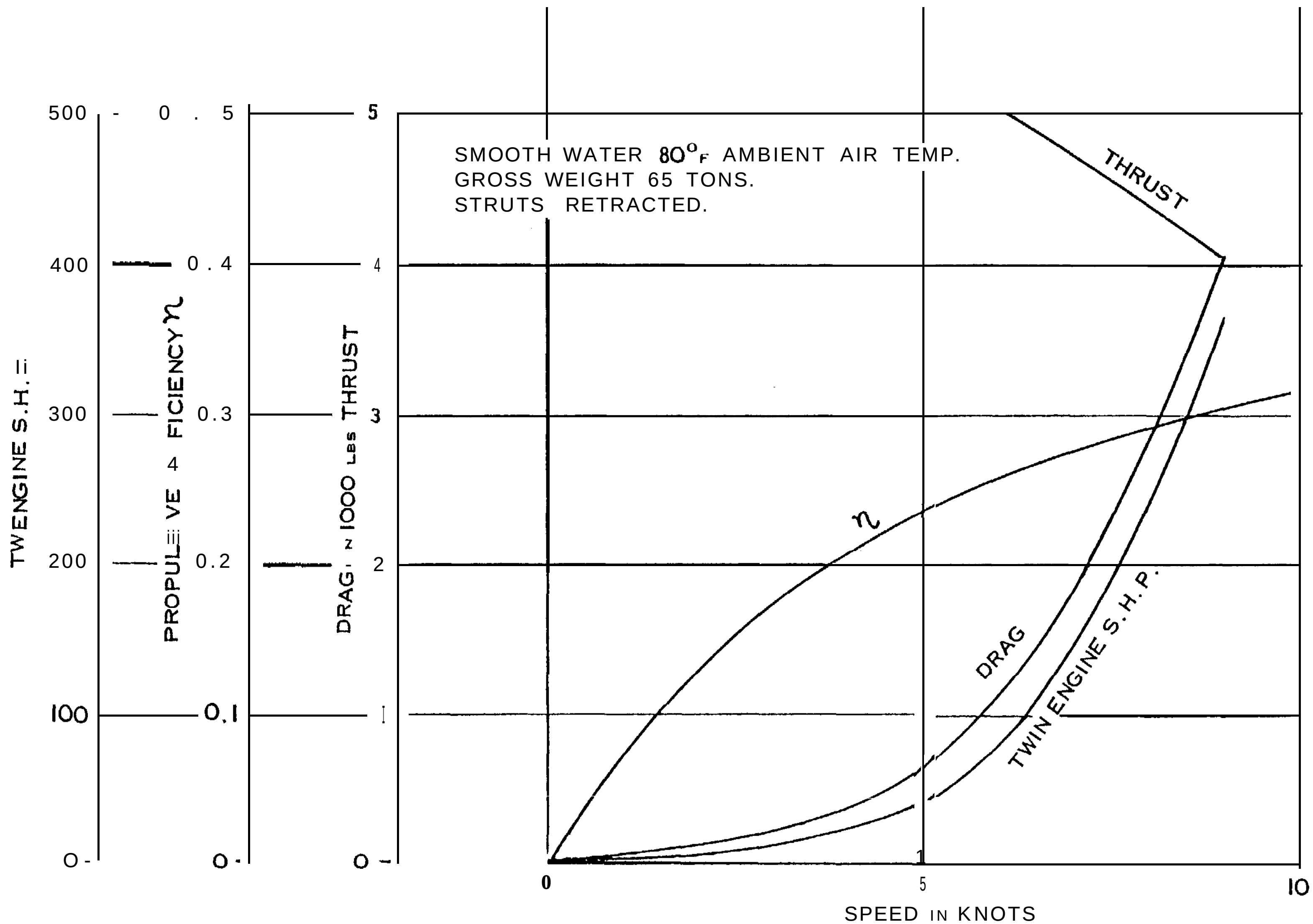

Figure III.2-60. FLAGSTAFF PGH-1 HULLBORNE PERFORMANCE

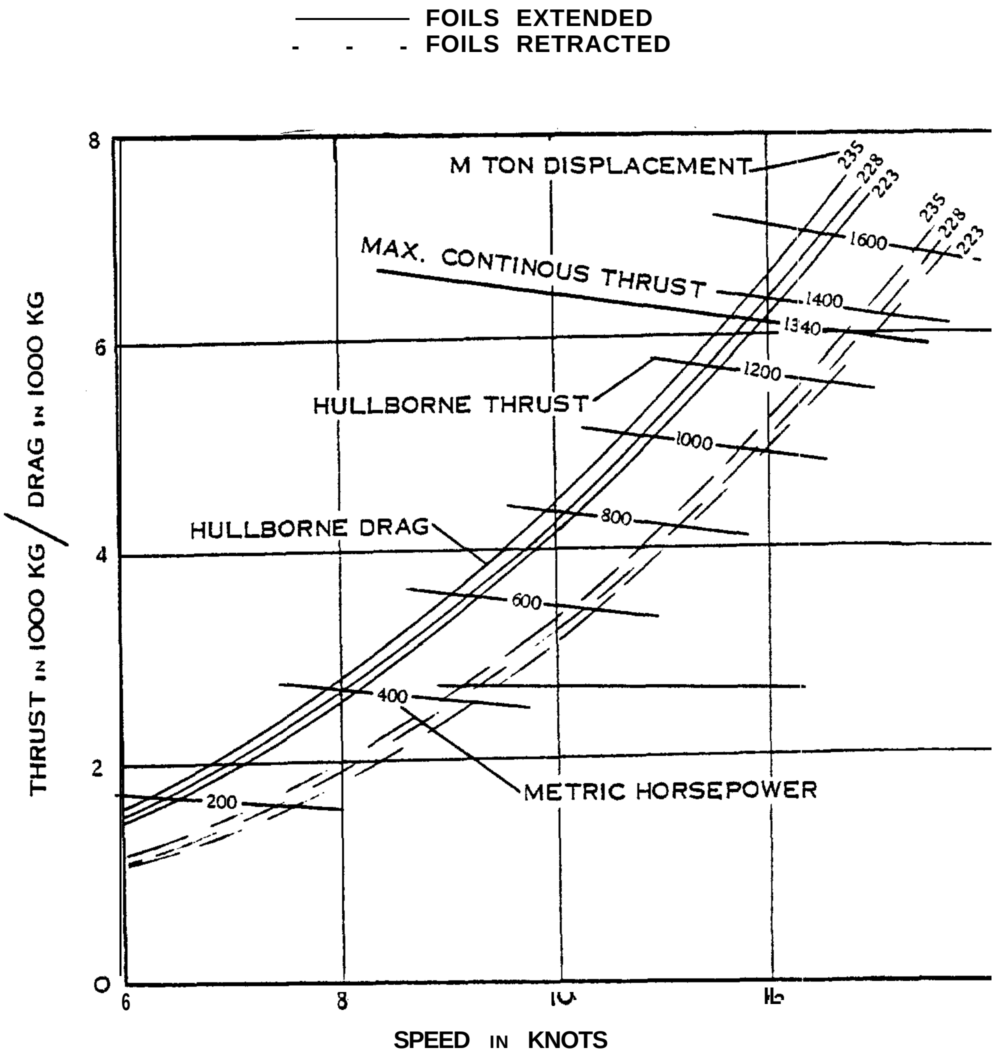

Figure 1X1.2-61. PHM-1 PEGASUS HULLBORNE THRUST A.-ND DRAG

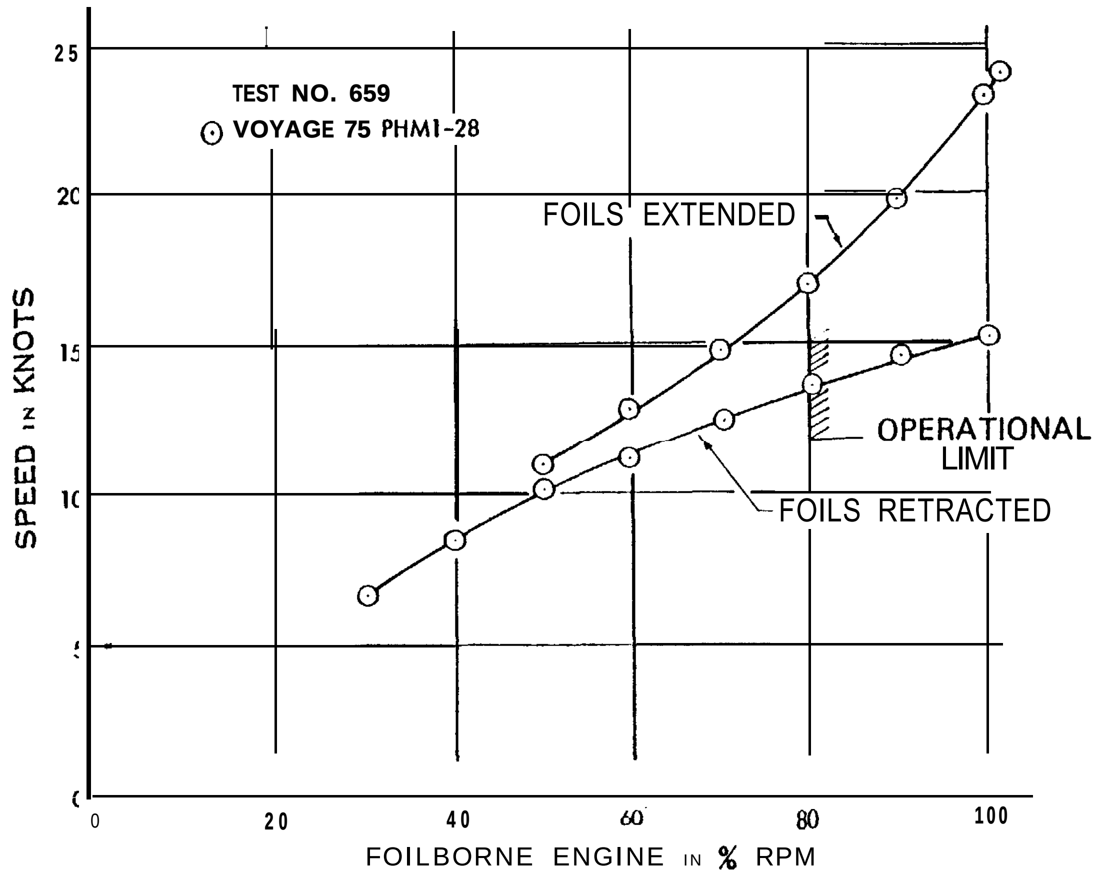

Figure 111.2-62. PHM-1 HULLBORNE SPEED - FOILBORNE PROPULSION

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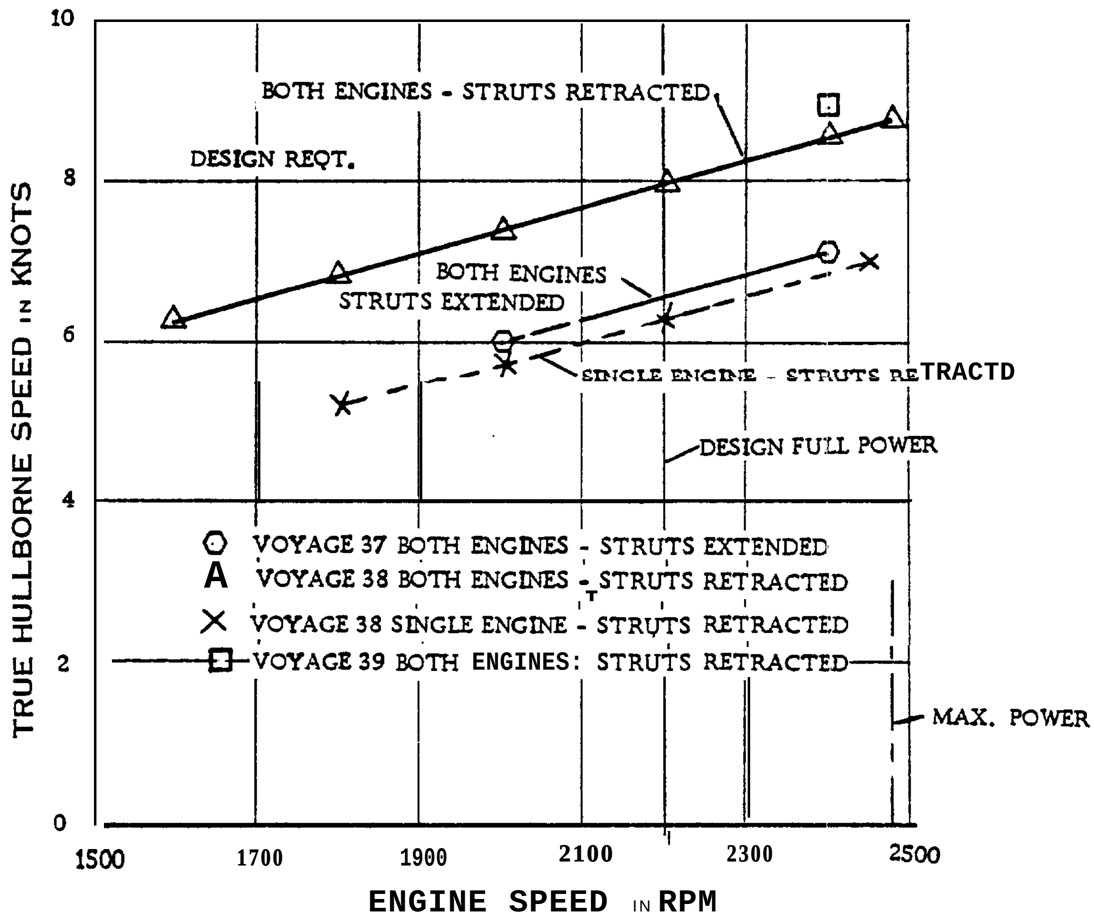

Figure 111.243. PGH-1 HULLBORNE SPEED VERSUS ENGINE RPM FOR VARIOUS OPERATING MODES, MEASURED OVER INNER RANGE (U)

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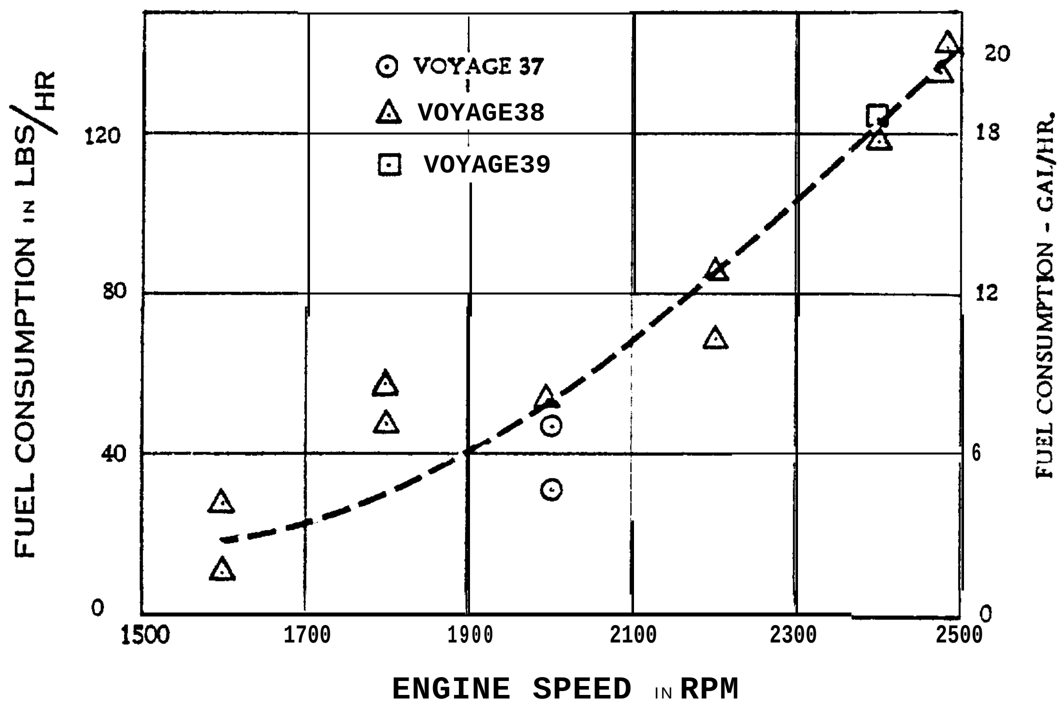

Figure III.2-64. PGH-1 HULLBORNE FUEL CONSUMPTION, STRUTS RETRACTED (U)

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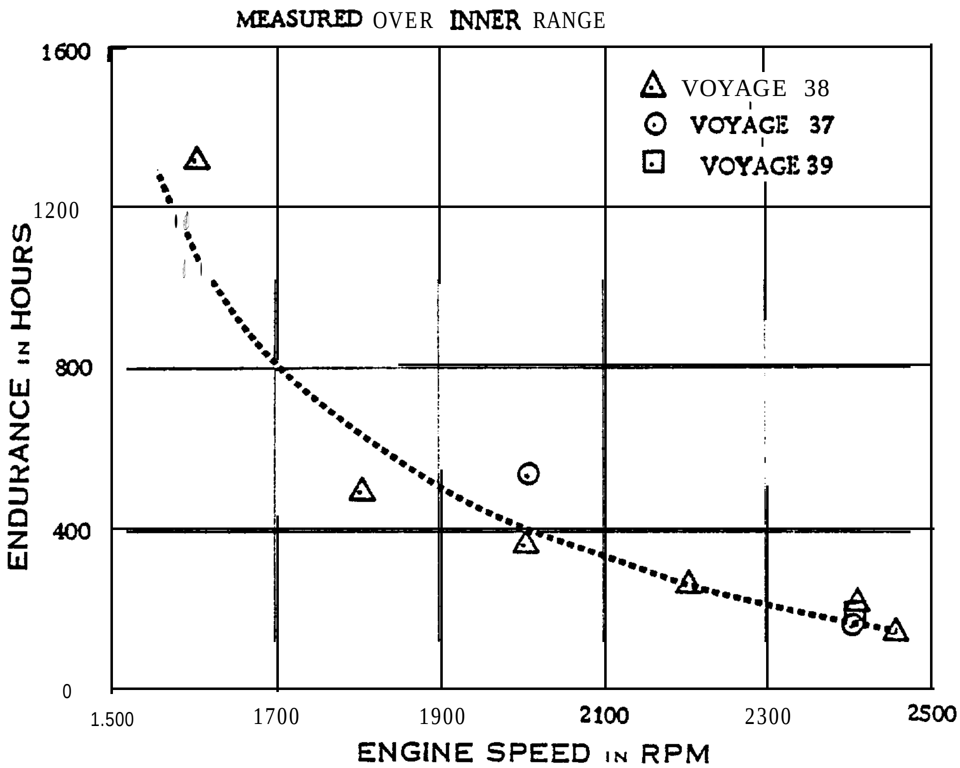

Figure 111.2-65. PGH-1 HULLBORNE ENDURANCE VERSUS ENGINE RPM, BOTH ENGINES IN CALM WATER, STRUTS RETRACTED (U)

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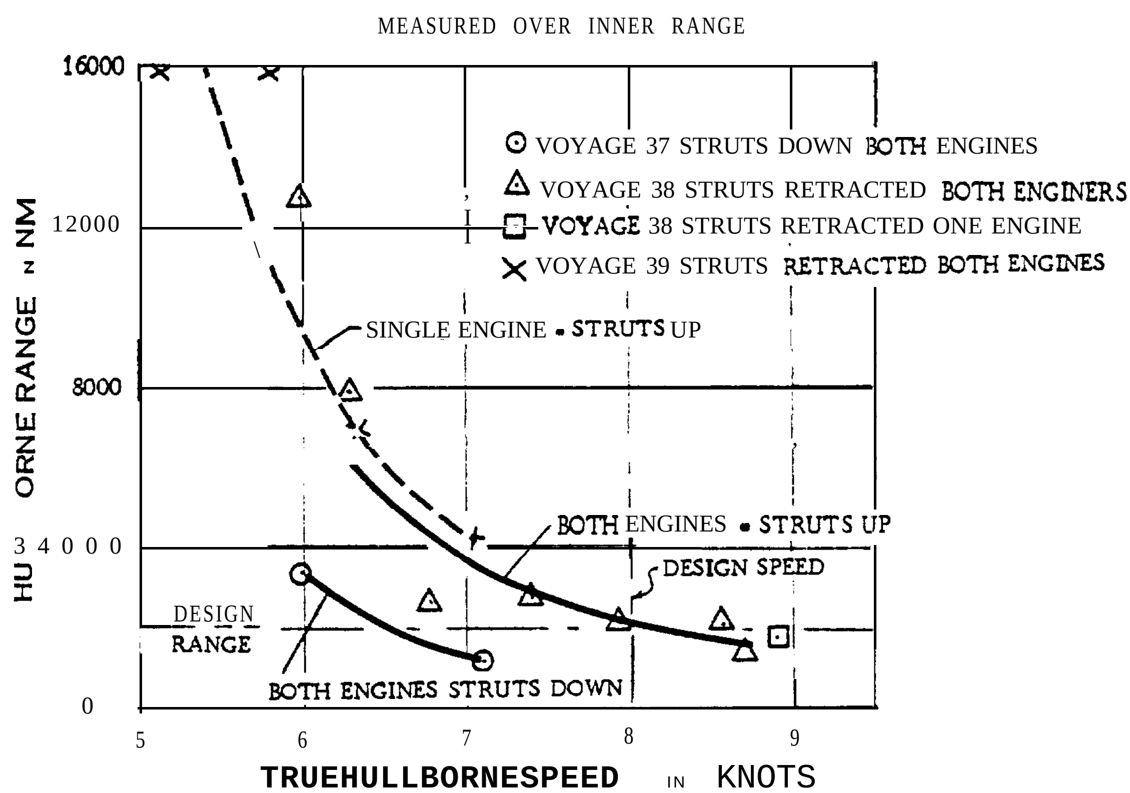

Figure X1.2-66. PGH-1 HULLBORNE RANGE FOR VARIOUS OPERATING MODES (U)

(U) The hullborne range for the AGEH-1 PLAINVIEW based on 60 tons of usable fuel and a gross weight of 320 tons is stated as 6,550 NM at 12 kn.

2.2.3 Hullborne Maneuverability

(U) Figure 111.2-67 shows PHM-1 turn rate roll angle, port and starboard flap deflection as a function of helm input for the flat turn mode of operation. Turn rates up to 1.8 degrees per second to the right and 1.0 degrees per second to the left were performed. Turn rate capability increased as ship speed increased. Ship roll angle was less than 2.0 degrees and the aft flaps did not exceed 8 degrees deflection for maximum helm turn, indicating that adequate roll control was maintained while maneuvering in this mode. PHM-1 hullborne turn diameters are shown in Figure 111.2-68.

2.2.4 Hullborne Ride Quality

(U) The ride quality of a hullborne hydrofoil ship is superior to a conventional ship of the same displacement due to the damping effect of the strut foil system, as can be seen from the data presented in this section. The motion attenuation from the foil system is of such a magnitude, that preliminary studies by the Canadians indicate that in seas above Sea State 3, the total drag of a hydrofoil ship is less with the foils extended than with the foils retracted. More test data on the PHM and AGEH are needed to verify the above. In this section the ride quality of three ships the PHM-1, the AGEH-1, and PCH-1 is addressed.

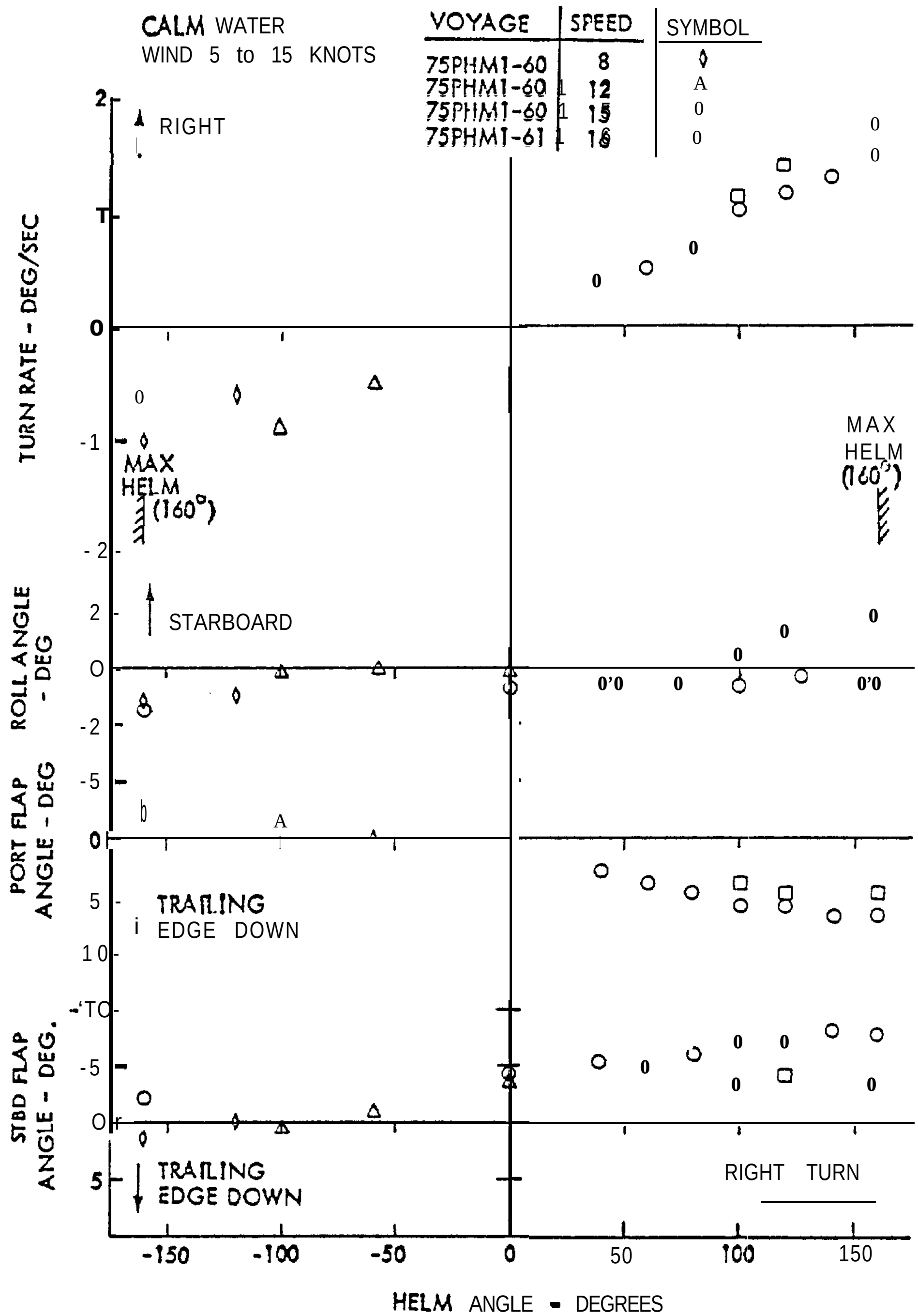

Figure X1.2-67. PHM-1 HULLBORNE MANEUVERING, STRUTS DOWN, FLAT MODE (U)

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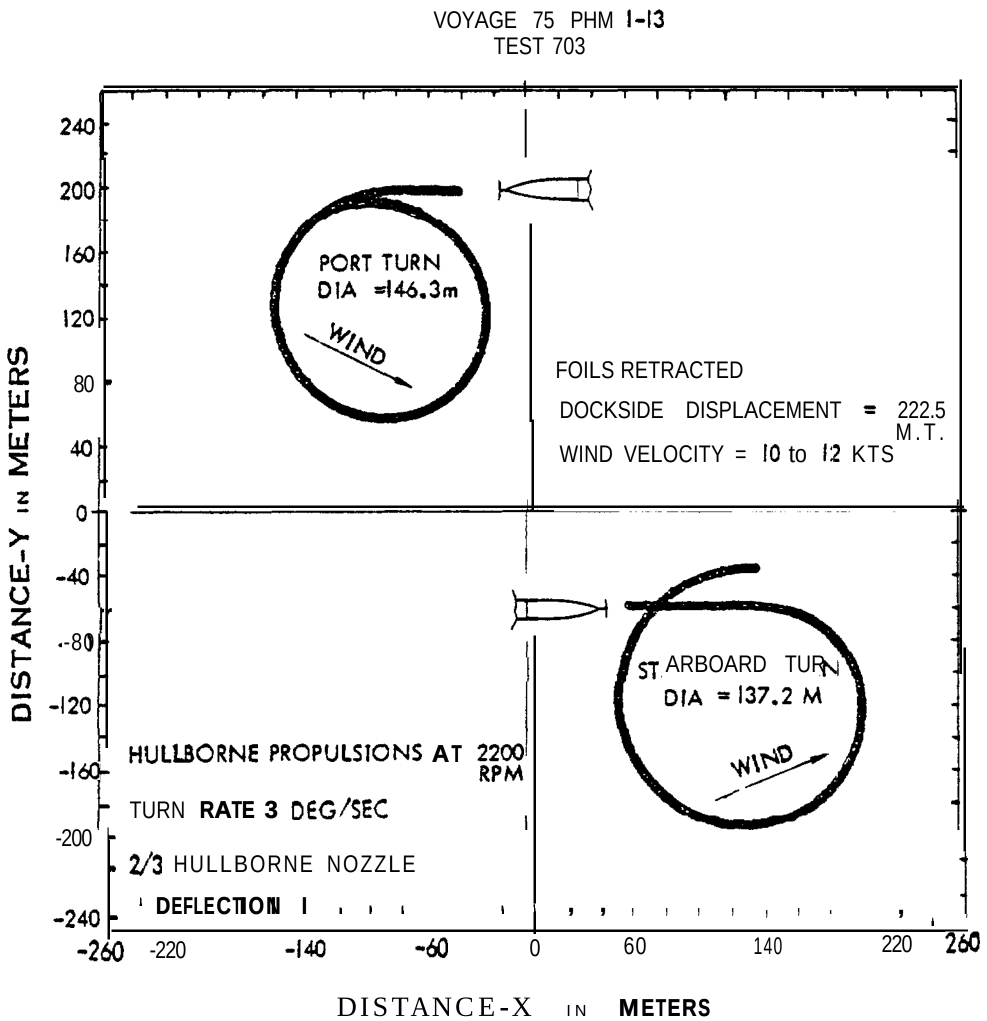

Figure 111.2-68. PEM-1 HULLBORNE TURN DIAMETER (U)

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2.2.4.1 PHM-1 Angular Motions

(U) Measured RMS pitch and roll angles for hullborne operation are compared with approximate foilborne levels in Figure 111.2-69. Angular motions were significantly greater during hullborne operation. Hullborne roll motions were an order of magnitude greater than foilborne. Hullborne RMS roll angles with the foils up were in excess of 2 degrees in the relatively mild sea state. Considerable roll damping is provided with struts down, however at these low hullborne speeds the ACS did not appear to further reduce rolling motions. Hullborne pitching motion was independent of ship operating mode. Pitch tended to reduce as hullborne speed increased.

2.2.4.2 PHM-1 Ship Motion

(U) No hullborne ship motion requirements are specified for PHM but a limited amount of hullborne rough water data were gathered at relatively low hullborne speeds, between 2 and 8 knots. Significant wave height was estimated to be between 1.5 and 2.0 meters, with significant wave period between 6 and 9 seconds. Data were obtained for three operating modes: foils down, Automatic Control System (ACS) on; foils down, ACS off; and foils up. Most data was for head sea operation. Pilothouse RMS acceleration as a function of ship speed is presented in Figure III.2-70 for the three hullborne operation modes. Approximate foilborne levels for the same sea conditions are indicated in the figure.. At these low hullborne speeds wave encounter frequencies are significantly less

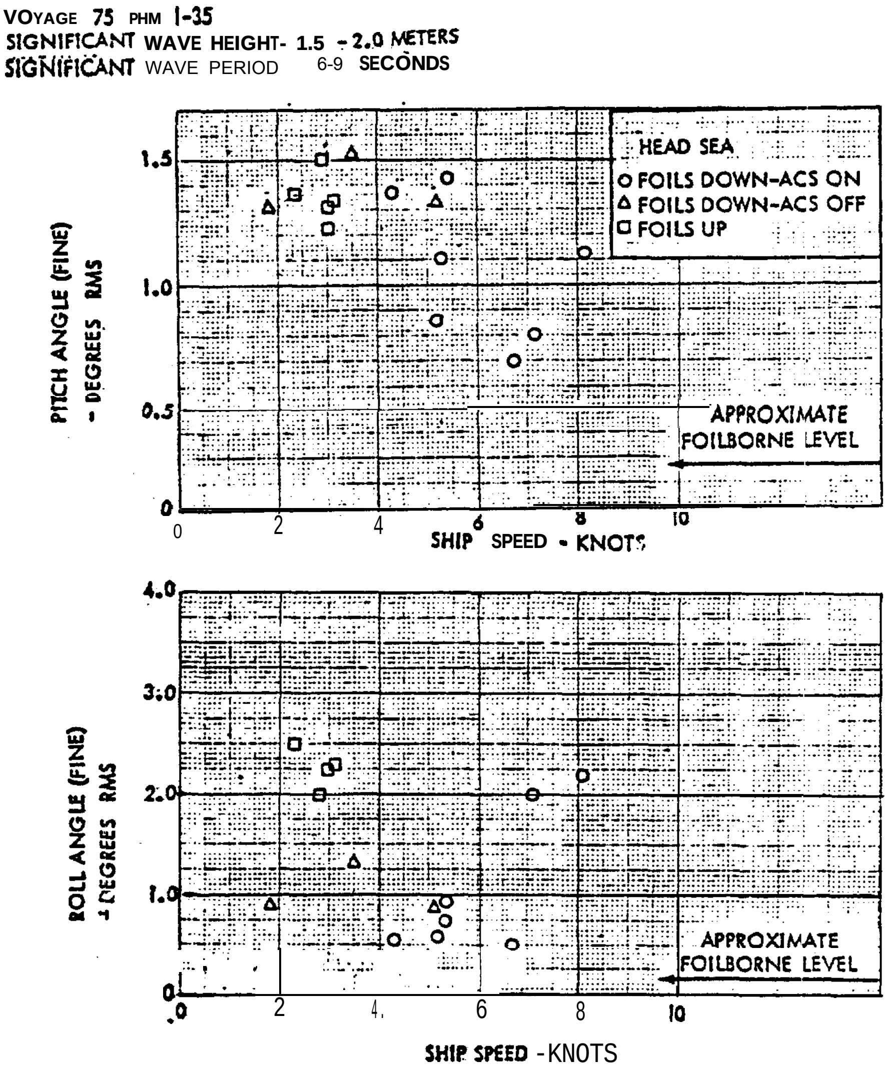

Figure III.2-69. PHM-1 HULLBORNE SHIP ANGULAR MOTION

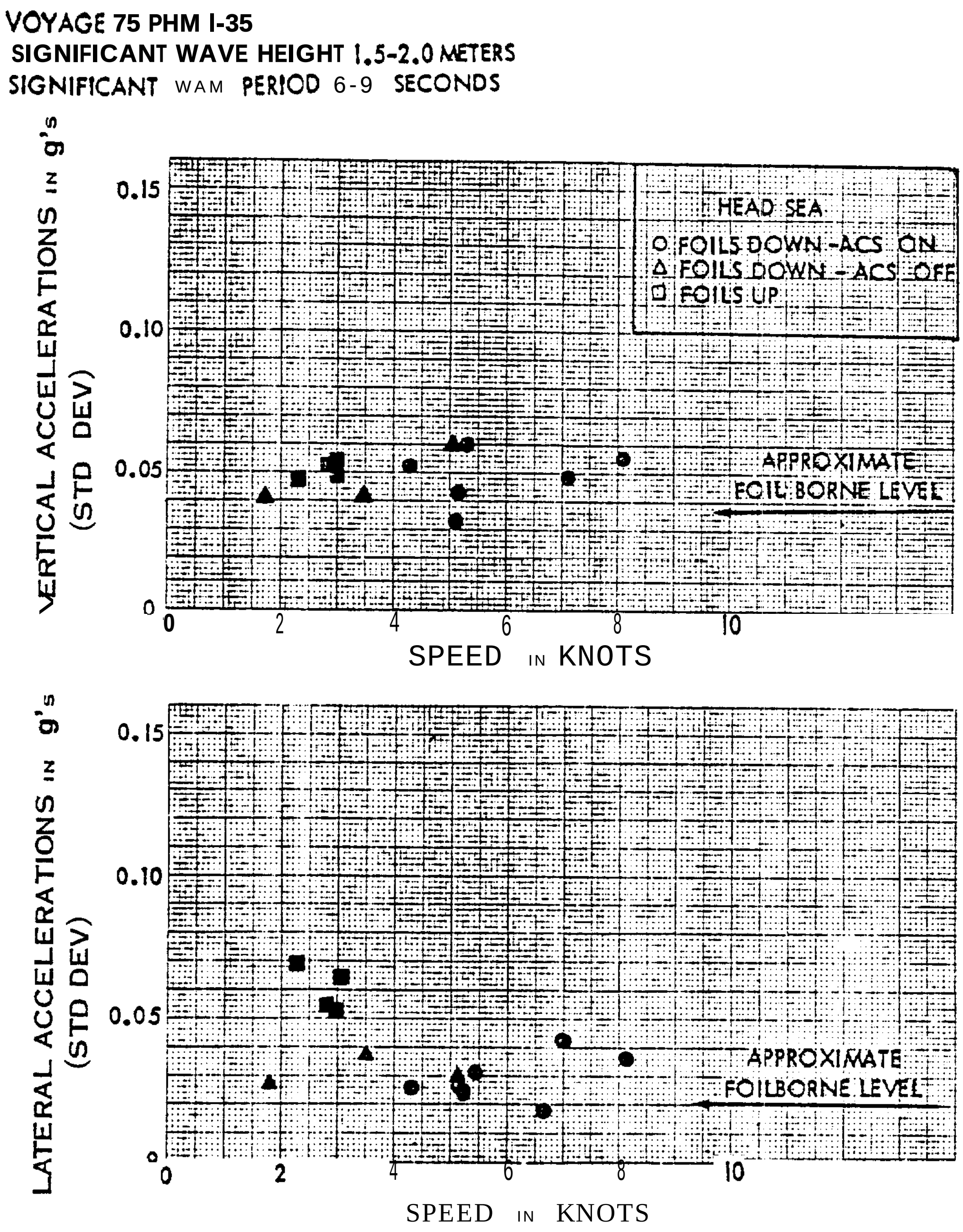

Figure 111.2-70. PHM-1 HULLBORNE SHIP ACCELERATIONS

than foilborne operation by a factor of about five. Pilothouse accelerations were nevertheless higher for hullborne operation than for foilborne, especially in the lateral direction. Pilothouse lateral accelerations were markedly more severe with foils retracted, due to increased roll motion. Lateral accelerations were independent of the ACS mode, with the foils extended. Hullborne vertical accelerations were not a strong function of operating mode, but tended to be lower with the ACS active.

2.2.4.3 PCH-1 Mod 0

(U) Hullborne motions are shown for both foils extended and retracted Figure 111.2-71. When the foils are retracted on the PCH-1 Mod 0 they still remain partially immersed and therefore continue to provide roll and pitch damping in heavy seas.

2.2.4.4 AGEH-1

(U) For Sea State 7, average vertical accelerations, average roll amplitudes, and average lateral accelerations are given from data, in Figures 111.2-72, 111.2-73, and 111.2-74 respectively as a function of ship heading in a heave-to condition.

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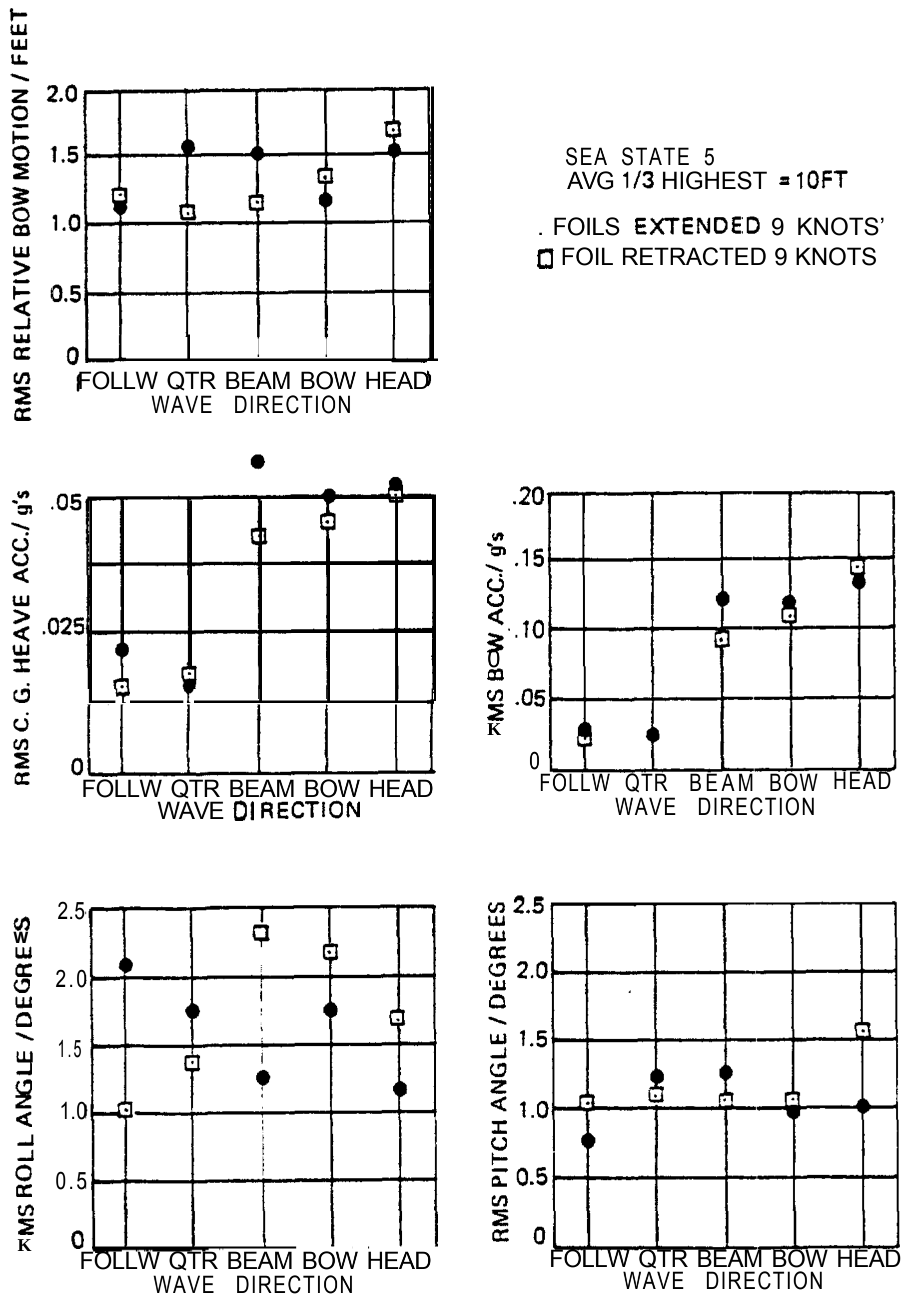

Figure III.2-71. HULLBORNE MOTIONS OF HIGH. POINT MOD 1 (U)

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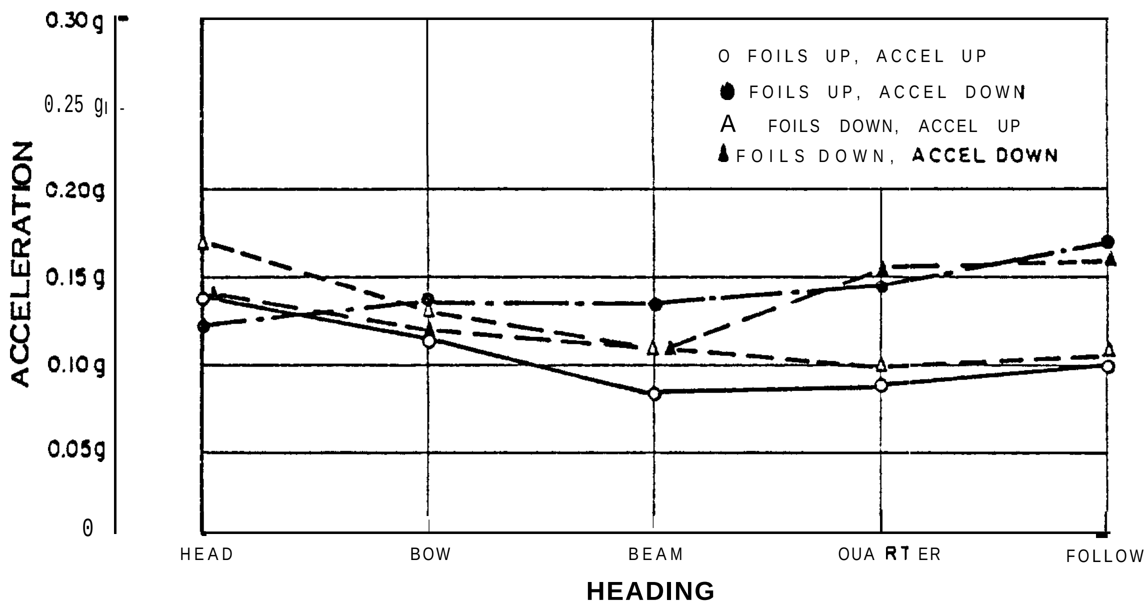

Figure 111.2-72. AGEH-1 AVERAGE VERTICAL ACCELERATION IN SEA STATE 7

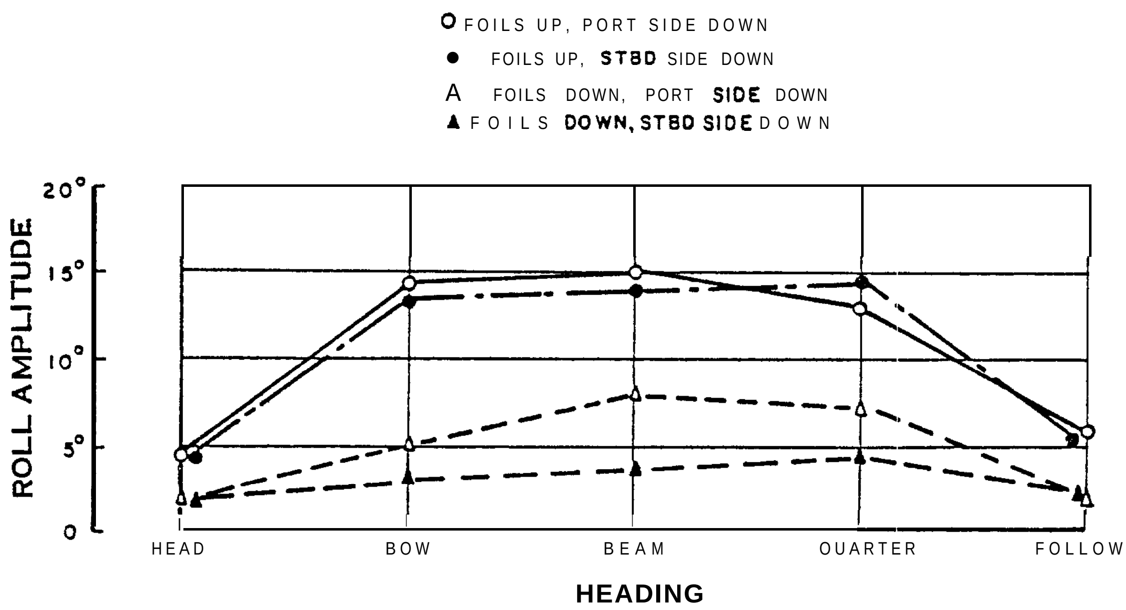

Figure 111.2-73. AGEH-1 AVERAGE ROLL AMPLITUDE IN SEA STATE 7

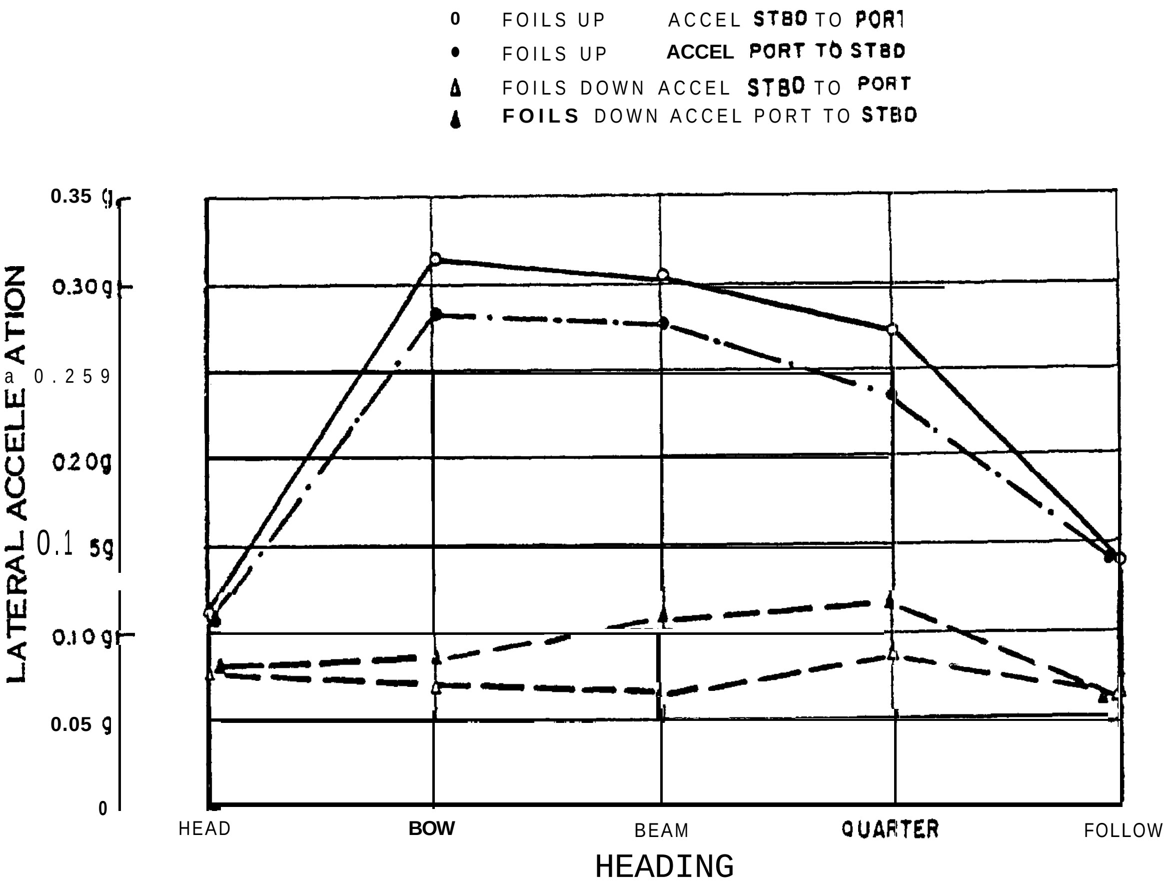

Figure 1X.2-74. AGEH-1 AVERAGE LATERAL ACCELERATION IN SEA STATE 7

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IV. COMBAT SYSTEM AND VEHICLE COMPATIBILITY

PAYLOADIVEHICLE COMPATIBILITY FEATURES
LIST OF COMPATIBLE SENSORS AND WEAPONS

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IV. COMBAT SYSTEM AND VEHICLE COMPATIBILITY

SECTION 1

INTRODUCTION

(U) This chapter of the State-of-the-Art Summary provides an assessment of mission equipment compatibility and interfaces with hydrofoil ships. The chapter includes all command and surveillance equipment covered by Group 4 and all armament covered by Group 7 of the Ship Work Breakdown Structure (SWBS). The chapter is organized according to SWBS Sub-Groups 410 through 490 and 710 through 790.

(U) There are a few compatibility factors which are of special importance to the technical and operational interfaces between elements of combat systems and hydrofoil ships.

(U) Because hydrofoil ships are capable of high speeds and have a high degree of maneuverability, high data acquisition rates and good gyro-stabilizer elements are required for the combat systems. Also in mixed mode conditions (foilborne and hullborne) which are essentially two different design environments, dual sensors (water depth and speed log) are necessary. Thus combat systems/equipment should be carefully chosen/(developed) to assure compatibility with hydrofoil ships and to synergize the total system.

1.1 <u>WEIGHT AND SIZE</u>

(U) Weight and size of installed equipment is of critical importance to the design of the combat system for a high-performance ship like the hydrofoil ship. Weight considerations have made aircraft type control and surveillance equipment very attractive for hydrofoil application where function and performance can be obtained without compromise. In general, the military avionics equipment tested was not mil-spec qualified for shipboard environments. For hydrofoil ships with fleet operational requirements some modification may be necessary for certain of the avionics-based components.

1.2 WIND

(U) High speeds and high sea states associated with hydrofoil operations result in relative wind conditions for hydrofoil ships which need not be considered for conventional displacement ships. Design criteria for hydrofoil ships can include a requirement for 100 kn relative wind, since operation at 50 kn into a 50-kn headwind is not unrealistic. This requirement has impact on equipment installed externally, especially equipment with large surface area, such as search radar antennas, which must be articulated or rotated. This wind factor is also an important consideration for missile launching and any manned operation on deck while foilborne.

1.3 INSHORE NAVIGATION AND COLLISION AVOIDANCE

(U) The high speeds and great maneuverability of hydrofoil ships can only be used if special consideration is given to the problem of providing the conning officer with accurate real time data on navigational landmarks and potential collision hazards. This requires high data rate sensors, real time data processing, and integrated displays similar to aircraft systems and generally not found on conventional surface ships.

1.4 FOIL INTERFERENCE

(U) Due to the relatively large area swept by the submerged foils, special consideration is required for torpedo and mine launching systems. Launchers must be directed and provide initial launch velocities that assure that the weapons will not impinge on the foil system.

1.5 UNDERWATER SENSORS

(U) Due to the small surface area wetted during foilborne operations, certain underwater Antisubmarine Warfare (ASW) sensors require special design and consideration.

SECTION 2

COMMAND AND CONTROL SYSTEMS (SWBS GROUP 410)

2.1 HYDROFOIL SHIP AND COMMAND AND CONTROL INTERFACES

2.1.1 Operational and Performance Interfaces

(U) The hydrofoil ship as a platform imposes no special compatibility constraints on the command and control equipment. Representative systems elements such as the data processing equipment and digital data communications have been tested in small warships. For example, the UNIVAC 1830 computer with associated peripherals and auxiliaries and the Collins USC-27 Link 11 equipment have been installed in the S 143 Fast Patrol Boat (FPB) of the Federal Republic of Germany.

2.1.2 Technical and Physical Interfaces

(U) Although the standard command and control equipments can be used in hydrofoil ships, the smoother ride and more benign vibration environment existing in the hydrofoil ship compared with conventional warships of equivalent size may permit relaxation of shock and vibration requirements for equipments and thus open the way for application of avionics packaging standards. This measure or the direct adoption of avionics equipment is seen as a potential weight-saving option.

2.2 COMMAND AND CONTROL SYSTEMS COMPATIBLE: WITH HYDROFOIL SHIPS

2.2.1 Experimental and Patrol Hydrofoil Ships

(U) The level of sophistication needed in the command and control system is based on the ship's mission and the concept of operations. Hydrofoil ships developed as experimental platforms in the technology programs (PCH-1 and AGEH-1), or as feasibility demonstrations or prototypes (PHM-1, PGH-1, and PGH-2), require only rudimentary command and control. PHM-1 command and control relies on proven analog techniques commonly used in small warships. cost of automated digital displays, data processing, and links for the leadships did not appear justified by program considerations. Where tactical employment requires high data handling capacity and fast reaction times, use of more extensive automation is foreseen. The PHM command and control system consists of two AN/SPA-25B radar repeaters, a Weapon Assignment Unit (WAU), a radar distribution switchboard, and a tactical plot. This equipment weighs 885 lb and takes 43 sq ft of design space. Also part of the command and decision station is the Identification Friend Foe (IFF) decoder unit AN/UPA-59.

2.2.2 Large Hydrofoil Ships

(C) The equipment required for command and control in large ocean escort multimission hydrofoil ships will be derivative of equipment now evolving for large warships. A variant of the Junior Participating Tactical Data System (JPTDS) has been studied for use on future hydrofoil ships (Reference IV.2-1). Central to the operation of JPTDS is a third generation microminiaturized digital computer designated AN/UYK-7. The system utilizes multipurpose Plan Position Indicator (PPI) display consoles to provide operators display of search radar video, display of alphanumeric characters and tactical symbology generated by digital computer programs, and data entry capabilities to allow operator communication with the computer programs. The JPTDS (variant) candidate for use in large hydrofoil ships would have capability for monitoring approximately 120 tracks. It would include all weapon and sensor processing in addition to normal detection and tracking, IFF, TEWA, track correlation and decorrelation routines, and a quick reaction as well as a manual mode of operations.

SECTION 3

NAVIGATION SYSTEMS (SWBS GROUP 420)

3.1 HYDROFOIL SHIP AND NAVIGATION SYSTEM INTERFACES

3.1.1 Operational and Performance Interfaces

(U) The most significant operational characteristics of hydrofoil ships are high speed and maneuverability in a sea state. The hydrofoil ship must be capable of using her speed when offensive and defensive situations require it--in restricted waters and in proximity of other ships without having the navigation system become a limiting factor because of safety. Therefore, special system features are needed to support both piloting and collision avoidance functions of the hydrofoil ship navigation system. The system requires high data rate sensors, automated data processing, and computer supported displays. For foilborne navigation, both true motion and relative motion display options must be provided. It is essential to have a bright display for ship control station use in daylight and capable of being mounted in the ship control console rather than a conventional PPI display. A speed log and depth sounder with digital readout should be provided. It is desirable to have the hydrofoil ship navigation functions fully integrated with the command and control functions.

3.1.2 Technical and Physical Interfaces

(U) A technical interface caused by hydrofoil ship performance is the need to be able to perform all navigation functions in either hullborne or foilborne mode. This means that speed log, depth sounder, and collision avoidance sensors must be provided to operate in both modes. There is no apparent technical limitation in fulfilling this need.

3.2 NAVIGATION SYSTEMS COMPATIBLE WITH HYDROFOIL SHIPS

3.2.1 Open Ocean Navigation

(U) For open-ocean navigation, a worldwide and continuous system for determination of position is required. Currently available are the OMEGA system and the Naval Navigation Satellite System (NNSS). Because of possible wartime vulnerabilities to each system, large ocean escort hydrofoil navigation systems should be capable of obtaining their position from both of these systems. The OMEGA system provides position accuracy to about 1 NM. The worldwide NNSS will provide a position accuracy between 0.1 and 0.25 NM. On the PCH-1 and AGEH-1, the LORAN system is being used. This system does not provide a worldwide coverage. For dead reckoning, either a conventional gyrocompass and speed log combination or an inertial navigation set can be used. The Global Positioning System (GPS) will be tested aboard AGEH-1 in 1978. It also will be a worldwide satellite based system.

3.2.2 Piloting

(U) In confined waters, such as harbors and coastal areas, radar and/or electro-optic devices must be used to obtain range and bearing fixes from known landmarks. The navigation radar must provide a high resolution picture and must have a data rate high enough to track targets at relative speeds to 100 kn. A bright display for the ship control station is considered essential.

3.2.3 Collision Avoidance

(U) A particularly significant problem for all high speed ships is collision avoidance. While hydrofoil ships are not particularly affected by debris or small floating objects such as logs, impact should be avoided. Of major concern is collision with other vessels when maneuvering at high speed in congested water. In high sea states, small targets are particularly difficult to detect with conventional radars. For a hydrofoil ship traveling at 45 kn, an object should be detected at about 1,000 ft to allow adequate craft and operator response and time to avoid impact. Electrooptics systems tested aboard PCH-1 and PGH-1 have demonstrated a capability for small object and debris detection in ample time to permit avoidance maneuvers. Electrooptics systems include Low-Light-Level Television (LLLTV) and Infrared (IR) devices. These devices can operate in either a passive mode or with an illuminator in an active mode. Active electrooptics provides increased detection range and ranging capability. The electrooptics systems are multi-purpose and can also be used for target identification, fire control, radar back up, and routine coastal navigation.

3.3 NAVIGATION SYSTEM TEST AND STUDY RESULTS

3.3.1 General Considerations

(U) Numerous studies and trials have been undertaken in an attempt to define an optimum navigation system for high speed surface ships (References IV.3-1, IV.3-2, IV.3-3, and IV.3-4).

(U) At present, a partial system labeled Tactical Navigation and Collision Avoidance System (TANCAV), which was developed by the crew of HIGH POINT (PCH-1), shows much promise for the optimum display of navigational information aboard fast-moving hydrofoil ships.

(U) Utilizing the features of TANCAV and the technology available from other Navy programs which use the AN/UYK-20 for collision avoidance algorithms, the Hydrofoil Program is developing an integrated Navigation and Collision Avoidance system for PLAINVIEW (AGEH-1) to be installed and evaluated in 1977.

(U) In summation, the unique navigation requirements of hydrofoil ships is well understood, and the technology is well in hand to meet these requirements.

SECTION 4

INTERIOR COMMUNICATIONS (SWBS GROUP 430)

4.1 HYDROFOIL AND INTERIOR COMMUNICATIONS INTERFACES

4.1.1 Operational and Performance Interfaces

(U) There are no operational or performance interface constraints peculiar to hydrofoil ships that preclude the installation of an interior communications system of the required size and complexity.

4.1.2 Technical and Physical Interfaces

(U) Interior communications equipment for hydrofoil ships is essentially the same as that used in other warships of similar size and mission. The system includes telephones, announcing, entertainment, alarm, safety, warning, indicating, metering, integrated controls, recording, and television equipment. Of these, there is a close and interacting relationship between the subsystem and the hydrofoil only in the area of integrated controls. This relationship does not give rise to any unique compatibility requirements, but rather gives direction to the design of the controls which must be developed as part of the vehicle, as well as the combat system.

4.2 INTERIOR COMMUNICATIONS SYSTEMS COMPATIBLE WITH HYDROFOIL SHIPS

4.2.1 Small Hydrofoil Ships

(U) Interior communications systems of modest capabilities and conventional technology are being operated on the PCH-1, PGH-1, and AGEH-1 hydrofoil ships. On the PHM-1, the Philips Intercom System represents a,noteworthy departure from traditional intercom architecture and provides a conceptual basis on which transition to advanced systems may be made.

4.2.2 Future Systems

(U) It is anticipated that in the 1980s most of the hydrofoil interior communications functions will be integrated with exterior communications, navigation, and command and control systems. Data multiplexing will minimize the need for switchboards and control wiring. Fiber optics and optical transmission techniques may be available for data handling free from electromagnetic interference.

4.2.2.1 Central Junction Box

(U) Studies (Reference IV.4-1) have shown that the use of a central junction box greatly reduces the cabling complexity of an interior communications systems. Basic elements of a typical multimission combat system and its operators with intercom needs are essentially independent, interconnected only through processors/ computers. In an interior communications system of low sophistication, each two-way point represents a cable run between those two stations. Borrowing from the Philips system used in PHM-1, the interconnections are made through a central junction box.

4.2.2.2 Data Multiplexing

(U) Studies (Reference IV.4-2) of data multiplexing within a combat system have shown possibilities of several significant benefits:

- Lower cost
- Significant weight reduction
- Simplification and reduction of interconnecting cabling
- Improved damage protection through inherently redundant transmission paths
- Reduction in intercompartment cabling with attendant bulkhead penetrations
- Facilitated system growth and modernization over the life of the ship

A feasible data multiplex system for a large multimission hydrofoil ship could be developed with three data bus cables separately routed through the ship, six remote multiplexers, and a number of input/output boxes to which individual equipments are connected. It is noted that certain signals such as radar video, sonar audio, and pulse train signals are not handled in the data multiplex system. Results from the study show that, in the example used, about 7,700 meters of cable were replaced by about 2,000 meters in the multiplex system, with a weight reduction of about 5,760 kg. The data multiplex system discussed above is being developed for the Navy.

SECTION 5

EXTERIOR COMMUNICATIONS (SWBS GROUP 440)

5.1 HYDROFOIL EXTERIOR COMMUNICATIONS INTERFACES

5.1.1 Operational and Performance Interfaces

(U) Problems operating exterior communications equipment aboard hydrofoil ships do not arise from operational characteristics of the vehicle, but are common in all warships where large numbers of electromagnetic emitters are brought together in a limited space. Mutual interference, distorted radiation patterns, reduced total radiation, and blocking of receiver antennas may arise from physical constraints. Simultaneous operation requirement makes the isolation between HF antennas a special concern.

5.1.2 Technical and Physical Interfaces

(U) There are no technical or physical interfaces causing incompatibilities between hydrofoil ships and exterior communications equipment.

5.2 EXTERIOR COMMUNICATIONS COMPATIBLE WITH HYDROFOIL SHIPS

5.2.1 General Considerations

(U) The hydrofoil ship exterior communications system is required to provide flexible and versatile communication modes for transmitting, receiving, and processing tactical and intelligence data. The types of communications capabilities provided are as follows:

- UHF, VHF, and HF Voice
- UHF and HF Teletype (TTY)
- UHF and HF Digital Tactical Data Link (Link 11 or successor>
- UHF SATCOM
- LAMPS Data Link

The three categories of *communications* provided, (voice, teletype, and digital data), can be transmitted in either clear or secure format. References IV.5-1, IV.5-2, and IV.5-3 address exterior communications requirements and characteristics for hydrofoil ships.

5.2.2 PHM Antenna System Installation

(U) The PHM is capable of performing OMEGA navigational ranging, HF communications, VHF and UHF Line-of-Sight (LOS) communications, UHF Satellite Communications (SATCOM), IFF, radar navigation, radar fire control, and passive Electronic Support Measures (ESM). Each of these systems uses an onboard antenna subsystem, which operates over the frequency spectrum from 10.2 KHz to 12 GHz. The various antenna subsystems and their associated frequencies are listed in Table IV.5-1. The antenna arrangement aboard the PHM is shown in Figure IV.5-1. The ESM antenna set is located atop the mast for clear electromagnetic coverage. Astride the mast at: 20 meters above the foilborne water level are located 4-yd arms, each 1.4 meters long and 90 degrees apart in the horizontal plane. The IFF transponder antenna sits at the end of the forward yard arm, the OMEGA antenna lies on the aft arm, and one UHF LOS/SATCOM antenna on each

Table IV.5-1. PHM ANTENNA SUBSYSTEMS (U)

ANTENNA SUBSYSTEM	FREQUENCY	MODE(S)	POWER	PURPOSE	COVERAGE
OMEGA	10.2 KHZ		-----	Position	omni-directional
HF	2-30 MHz	T_X, R_{cv}	1 KW (Max) 200w (Low Power)	Ship-to-Shore-to-Ship	Omni-directional
VHF	156-162MHz	T_X, R_{cv}	25W	Bridge-to-Bridge	Omni-directional
UHF	225-400MHz	T_X, R_{cv}	30/100w (1000w Growth)	Line of Sight (Link II)	Omni-directional
UHF	240-270 290-320MHz	T_X, R_{cv}	100W (1000w Growth)	Sat Com	Hemispheric
IFF	1010-1110 MHZ	T_X, R_{cv}	500w Peak	Trans-ponder	Hemispheric
IFF	1010-1110	R_{cv}		ISLS	Hemispheric
IFF	1010-1110 MHZ	T_X, R_{cv}	2Kw Peak	Interro-gation	Steerable
ESM	Classified	R_{cv}	-----	Passive Counter-measures	Hemispheric
NAV RADAR	X-Band	T_X, R_{cv}	20 Kw Peak	Surface Navigation	Omni-directional
FIRE CONT. RADAR	X-Band	T_X, R_{cv}	-----	Surveil-lance	←
FIRE CONT. RADAR	X-Band	T_X, R_{cv}	-----	Track	←

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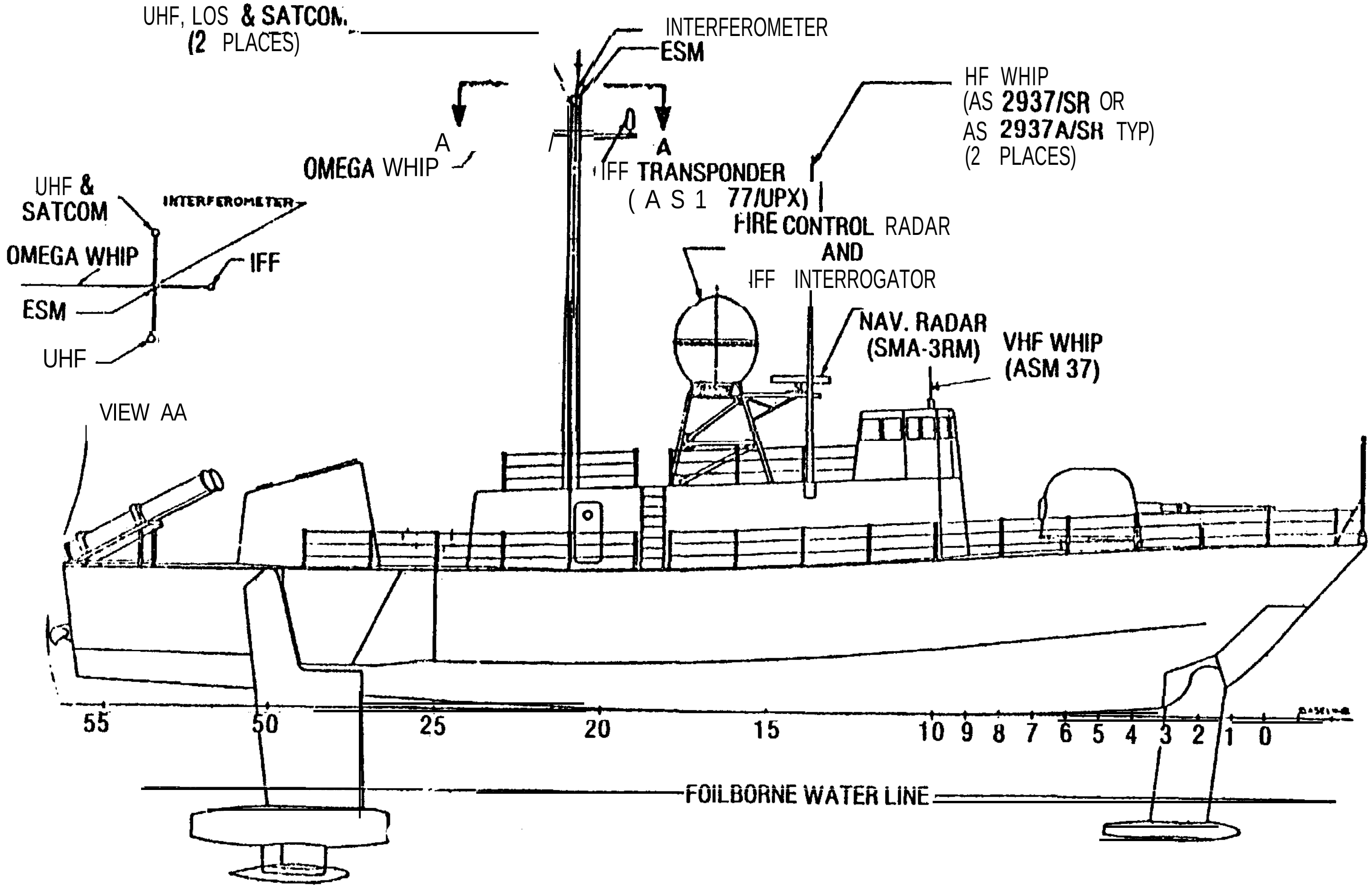

Figure IV.5-1. PHM ANTENNA ARRANGEMENT (U)

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of the two other yard arms. The fire control radar, IFF interrogator, ISLS antenna, and navigation radar are located on the radar support structure. The HF whip antennas are located athwartship. The VHF whip antenna is placed midships on top of the pilothouse giving a short low loss cable to the VHF transceiver mounted in the pilothouse.

5.2.3 PHM Exterior Communication System Performance

(U) The performance requirements of the PHM exterior communications system are listed in Table IV.5-2.

Table IV.5-2. PHM EXTERIOR COMMUNICATION SYSTEM PERFORMANCE REQUIREMENT

VHF	156 - 165 MHz	Line of sight 19 nm
UHF	225 - 400 MHz	Line of sight 12 nm. Simultaneous operation of 2 links separated 10 MHz
HF	2 - 30 MHz	Simultaneous operation of 2 links, 1 KW, with adequate frequency for uninhibited operation. Gapless coverage to 300 nm.

SECTION 6

SURVEILLANCE SYSTEMS (SURFACE) (SWBS GROUP 450)

6.1 HYDROFOIL AND SURFACE SURVEILLANCE INTERFACES

6.1.1 Operational and Performance Interfaces

(U) The operational and performance interfaces between surface surveillance systems and hydrofoil ships are essentially the same as in any other ship. Constraints of weight and space apply here as they do elsewhere. The challenge for the future is to develop multifunction radars that can be integrated with command and control and weapons control systems not only for economies of weight and space but also for enhanced combat effectiveness. The high relative wind to which antennas may be exposed is an operational interface between radars and hydrofoil ships. Radar antennas typically are designed to maintain required rotational speeds in winds up to 75 kn. Antennas for use on hydrofoil ships must be qualified to operate in 100-kn winds. Radomes for rotating antennas can offer advantages in hydrofoil ships.

6.1.2 Technical and Physical Interfaces

(U) There are no technical or physical interface constraints peculiar to hydrofoils that preclude installation of compatible size and weight surface surveillance systems in hydrofoil ships. When available in the future, electronically scanning radars will minimize mechanical design and wind loading problems.

6.2 SURVEILLANCE SYSTEMS COMPATIBLE WITH HYDROFOILS

6.2.1 General Considerations

(U) A reliable surface surveillance capability is required in hydrofoil ships to detect:

- Surface hazards and navigational aids for collision avoidance and plot for geographic orientation
- Surface targets to be engaged with surface-to-surface missiles and guns
- Air targets to be engaged by surface-to-air missiles
- Antiship Cruise Missile (ASCM), approaching at low altitude or diving at high elevation angles, to be engaged by close-in self-defense weapons

(U) Estimated radar cross sections of typical targets to be detected by hydrofoil ships surface surveillance systems are shown in Table IV.6-1. The range of a radar is limited to the radar horizon, which is determined by target and radar antenna heights. Radar horizons for the PCH-1 and AGEH-1 hydrofoils and typical targets of interest are shown in Table IV.6-2.

6.2.2 Surveillance Radars for Large Hydrofoils

(C) For large ocean escort multimission hydrofoil ships (area and close-in AAW and SUW), the surveillance system must include both long- and short-range search radars. Long-range search radar is required to support AAW missile intercept envelopes. Although a long-range search radar may not be required to support point defense AAW weapons, a 3D long-range radar with a relatively high

Table IV. 6-1. TYPICAL NAVIGATION AND MISSION TARGET SIZES (U)

	Estimated Radar Cross-Section	Maximum Height of Center of Reflective Area
Navigation Buoy	¼ m^2	1 ft.
Sonobuoy	¼ m^2	1 ft.
Snorkel	¼ m^2	1 ft.
Cylinder/Sphere	½ m^2	1 ft.
Channel Buoy	1 m^2	4 ft.
Small Craft	1 m^2	4 ft.
Medium Craft	*2 m^2	16 ft.
Low Flying a/c (helo)	2 m^2	200 ft.
Large Combatant Ship	*10 m^3	120 ft.
Land Mass	——	400 ft.

• Upper superstructure only

Table IV.6-2. DETECTION RANGE LIMITATIONS DUE TO HYDROFOIL RADAR ANTENNA HEIGHT CONSTRAINTS (U)

	PCH - I		AGEH - I	
	HULLBORNE	FOILBORNE	HULLBORNE	FOILBORNE
Prcscnt hydrofoil radar antenna heights (hl)	34 ft.	42 ft.	44 ft.	57 ft.
Radar horizon to sea level with present antenna heights: $R = 1.23 \sqrt{h_1}$	7.2 NM	8.0 MN	8.2 NM	9.3 NM
Small craft with 1 m^2 reflective area at 4 ft. height (h_2): $R = 1.23 (\sqrt{h_1} + \sqrt{h_2})$	9.5 NM	10.3 NM	10.6 NM	11.7 NM
OSA/KOMAR with 2 m 2 reflective area at 16 ft. height (h_2):	12 NM	12.9 NM	13.1 NM	14.1 NM
Large combatant ship with 10 m- reflective area at 120 ft. height:	20.7 NM	21.5 NM	21.7 NM	22.8 NM
Low a/c with 2 m^2 reflective area of 200 ft. height	25NM	25 NM	25.6 NM	26.7 NM
LANDMASS and a/c at 400 ft. height:	31.8 NM	32.6 NM	32.8 NM	33.8 NM

scan rate and an Automatic Detection and Tracking (ADT) capability can also be used effectively against pop-up ASCM attack. The following are candidate search hydrofoil application:

- Long-Range
  - AN/SPS-49. 2D lightweight air search radar, 100 Kft altitude coverage out to 70 NM and 150 Kft altitude coverage out to 250 NM. Systems weight about 5 tons.
  - AN/SPS-48C. 3D radar weighing about 10.5 tons. Has ADT capability. Maximum range about 220 NM.
  - AN/SPS-52B. 3D radar with total systems weight of about 9.5 tons. Maximum range about 245 NM.
  - TAS MK 23 (modified). A candidate future air search early warning and air control radar modified for higher power but weighing less than those listed above (Reference IV.5-3).
- Short Range
  - AN/SPS-58(V). Lightweight radar designed primarily for detection and tracking of low-flying, pop-up targets. Intended to supplement long-range air search radars and provide surface search and navigation capability.
  - AN/APS-116-AN/AWG-9. System proposed for detection of low-flying targets. The major modification includes the use of an AN/APS-116 antenna on a rotating pedestal with the AN/AWG-9 weapon control system.
  - MK 92 Mod 1 Surveillance Radar. Short-range surveillance radar from the Mk 92 FCS. Detection ranges specified for the radar against a 1 m^2 target are 25 NM and 22 NM, the lower value applying when the Mk 92 track radar is operating, since both of these radars

share the same power supply. The detection range of this radar is severely affected in a rain environment.

(U) Large hydrofoil ships will also be required to control CAP, ASW fixed-wing and rotary wing aircraft, and to assist in aircraft navigation and in search and rescue operations using aircraft.

SECTION 7

SURVEILLANCE SYSTEMS (UNDERWATER) (SWBS GROUP 460)

7.1 HYDROFOIL AND UNDERWATER SURVEILLANCE INTERFACES

7.1.1 Operational and Performance Interfaces

(U) An escort hydrofoil ship performing ASW search operations has a very important interface between the underwater sensors and the foilborne hydrofoil ships. Noise generated by the fast moving hydrofoil ship severely degrades the ASW search sonar detection capability. Tactics must therefore be devised where rapid foilborne transit alternates with hullborne operations for sonar listening. The search sonar used can either be dipped or towed. If a dipped array is used and it is deployed at depth, an emergency situation may require cutting the cable and dropping the array since system drag precludes towing it at any speeds higher than 5 kn. If a horizontal towed line array is used, it can stay deployed while hullborne or foilborne. In the case of the towed array, two performance factors must be considered. First, the effect of the towed system drag on the speed of the hydrofoil ship, particularly during transition from hullborne to foilborne operation, and second, the effect of the towed system on the maneuverability of the hydrofoil ship.

7.1.2 Technical and Physical Interfaces

(U) A hydrofoil ship engaged in an ASW operation should be foilborne during the attack phase for several tactical reasons. Therefore, unless a towed variable depth sonar is used, the attack sonar must be installed in the forward foil or a forward foil pod. In either case, it is an important physical and technical interface and it presents a significant installation and design effort.

7.2 <u>HYDROFOIL FEATURES AFFECTING ASW OPERATIONS</u>

7.2.1 <u>Speed and Maneuverability</u>

(C) High speed and maneuverability in high sea states are the most important operational characteristics of hydrofoil ships. Both of these characteristics have a potential for providing a very effective ASW escort ship.

7.2.1.1 High Speed

(C) For initial detection, the underwater sensors must provide the highest possible search rate in terms of square miles searched per unit time. In an escort mission, this high search rate must be attained while the searching vessel is, on the average, maintaining the Speed of Advance (SOA) of the escorted forces. Detection performance of all ship-mounted or ship-attached sonars degrades seriously with speeds above 15-20 kn. The high speed capability of hydrofoil ships offers potential usefulness in that it is possible to alternately proceed slowly to provide effective sonar detection ranges and then to proceed rapidly to make good the SOA of the escorted forces. This sprint and search tactic can provide the required sonar search rate.

7.2.1.2 Maneuverability

(U) During the ASW attack phase, the attack sonar should have at least a 270-degree scan angle. At the high required attack speeds where flow noise and cavitation are limiting factors, this is difficult to achieve. The high turning rate capability of a foilborne hydrofoil ship can make it possible to utilize a weaving attack run with an attack sonar having only a forward scan angle of 90 degrees.

7.3 ASW SENSOR SYSTEMS COMPATIBLE WITH HYDROFOIL SHIPS

7.3.1 General Considerations

(U) At this time there are few ASW sonar subsystems that can be placed unmodified on hydrofoil ships or any advanced ships without restricting ship operation. The primary modifications required are hydrodynamic and mechanical for achieving reductions of system drag and weight and increasing sonar operating speeds. These changes will require electronic changes in some sonar types. Since present surface ship sonars cannot be used intact aboard hydrofoils, the ASW sensor system for hydrofoil ships should probably be configured as a multi-array system capable of performing all search and attack sonar functions.

7.3.1.1 Large Hydrofoil Ships

(U) A large hydrofoil ship such as an open ocean escort must be equipped with long range search and direct path attack sonars. It is impractical to use a single sonar for both tasks because of physical size and weight. For long range search sonars the choice is between deployable or ship-based passive towed line arrays and the Active-Passive Reliable Acoustic Path Sonar (APRAPS). For the short-range attack sonar, the choice is primarily one of selecting a transducer array location to assure compatibility with ship construction and ship operation. For this task there are three possibilities:

- Towed Variable Depth Sonar (VDS)
- Pod-mounted
- Conformal array on forward foil and/or strut

7.3.1.2 Small Hydrofoil Ships

(U) On small hydrofoil ships such as the PHM, a below-foil-mounted pod attack sonar can be used. If other payloads of the order of 10 tons can be removed, studies indicate it may be possible to install an APRAPS system or an active VDS from which is streamed a passive towed line array.

7.3.2 Summary of Status of Hydrofoil Compatible Sonars

7.3.2.1 Towed Line Array

(U) While still in a development state for tactical use, the passive towed line array is a generally known system when operated from conventional ships. The towed line array can provide long-range initial detection, classification, and limited localization capability of submarine targets. Present capabilities and experience indicate that long-range detections can be made at speeds under 10 kn. Therefore, a hydrofoil will be required to use a sprint-search mode of operation to maintain the task force SOA. To avoid time lost for retraction, it is desirable to tow the array during the high speed sprint phase. Present array designs will not permit towing at high hydrofoil speeds. One or two test arrays with sufficient mechanical strength for such towing have been fabricated, and limited testing has been done. Successful sprint-search operation requires that the array stabilizes in the horizontal and settles to operating depth rapidly after hydrofoil deceleration. Studies and computations show typical settling times as long as 10 minutes or more. No measurements have been made. 'The settling problem can be reduced if the array is streamed from a depressor or VDS. The Sprint-And-Drift Towed Sonar (SADTOS) concept uses a dynamically controlled depressor from which to stream the array. The EDO Hip Pocket system couples an array to an SQQ-35 VDS weighted depressor. Tests of this system are currently in progress.

7.3.2.2 APRAPS

(U) This system is an active-passive search sonar for providing detection and tracking information using all of the longer range propagation modes found in deep ocean. With the array deployed to RAP depth, the APRAPS may passively detect, classify, and obtain limited localization of noisy targets to ranges of 20-25 miles with only a small gap directly around the hydrofoil. In the active mode, the APRAPS can accomplish detection, classification and localization with similar coverage against any targets. Studies indicate a clear superiority in effective coverage over other search sonars. The validity of the RAP propagation mode has been demonstrated. Feasibility of installing APRAPS on hydrofoil ships has been studied. Success of this system hinges on satisfactory development of the required high speed launch and retrieval system which to date has been subjected only to design studies.

7.3.2.3 VDS

(U) The VDS is an active attack sonar for redetection, tracking, and fire control. Its operation would normally occur while the hydrofoil ship is foilborne closing on a target. The primary advantage of the VDS is its ability to adjust array depth to optimize the direct path propagation range through below-layer operation. Present VDS systems are limited by noise at tow speeds in excess of 15 to 20 kn. VDS towing tests have been made at 30 kn on conventional ships. Hydrodynamic feasibility of a VDS has been demonstrated in high speed towing trials with PCH-1 using a dynamically controlled depressor body. At least one high speed acoustic test has been also conducted with this body equipped with a Mk 48 torpedo transducer. Marriage of current VDS to high speed towing systems may require redesign of the sonar electronics to permit multiplex operation of the system. A Canadian VDS has been proposed for test aboard PCH-1 at high speed (40 knots).

7.3.2.4 Pod-Mounted Array

(U) Except for the mounting, the pod-mounted array subsystem is a conventional ship-mounted active sonar. The pod-mounted array must be capable of operation at all hydrofoil ship speeds. To achieve this capability may require replacement of the usual cylindrical transducer with a flat face torped!o-type transducer. Since there is no variable depth capability, the direct path range is limited by downward refraction and is shorter than that of the VDS. Since the primary purpose of the pod-mounted array is for redetection and fire control, it is essential that it scan at least a forward 90-degree sector at high speed. Also, it is desirable that at least a 270-degree scan be available when the hydrofoil ship is hullborne, to provide a close-in search capability for use at the end of a sprint. On a large hydrofoil ship, it appears feasible to mount a transducer array in the forward pod ahead of the foil and strut as shown in Figure IV.7-1. This location will limit the scan angle of the sonar to the forward 180-degree sector. On small hydrofoils, a below-foil-mounted pod could be added. One version of such a pod is shown in Figure IV.7-2. The hydrodynamics of this pod has shown success in tank model tests (Reference IV.7-1). Fairing of the transducers into the foil and strut has been considered for several years, but only very recently has it been proposed to test and evaluate such a system. The advantage of using conformal arrays is an almost total elimination of additional drag on the forward strut.

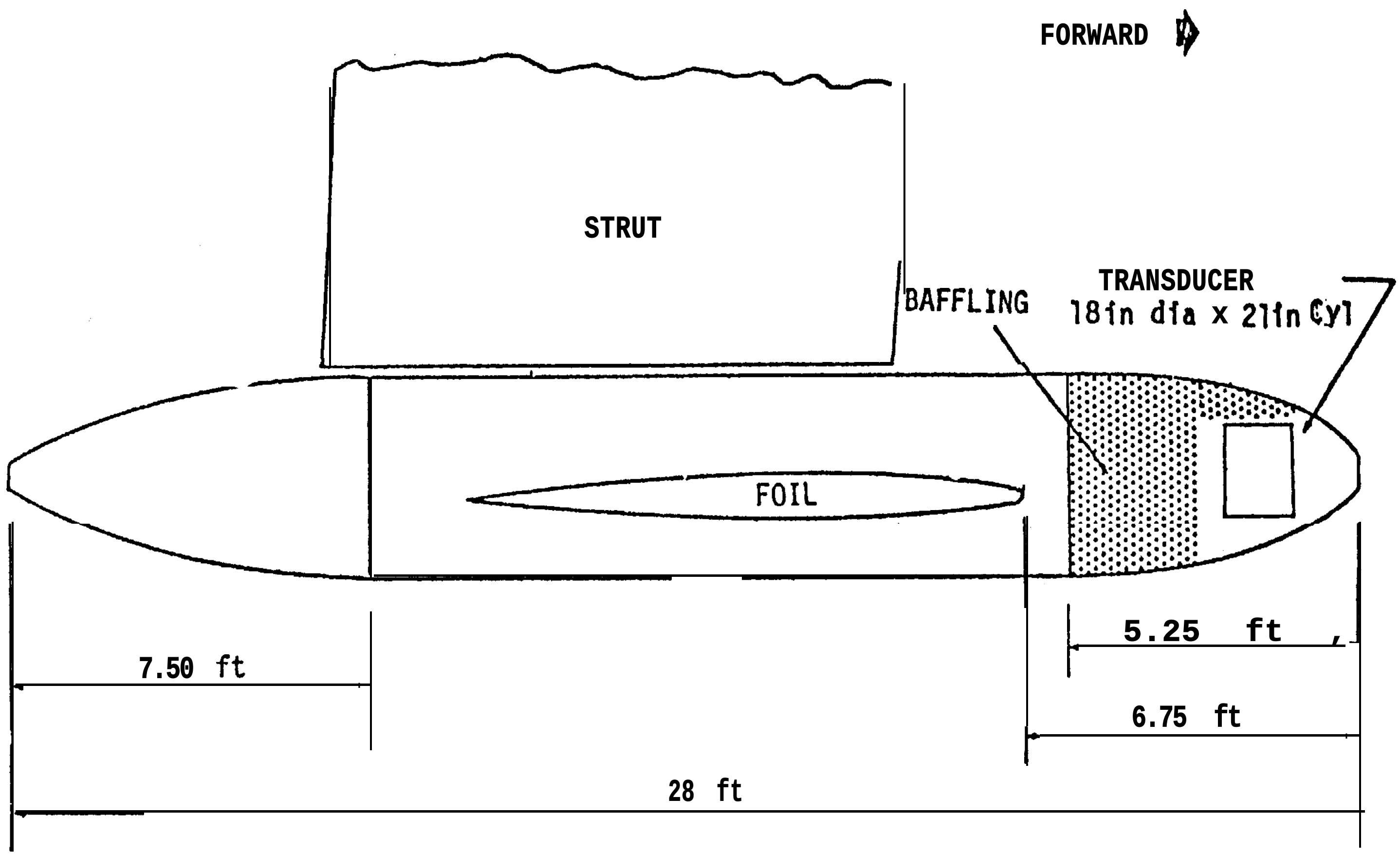

Figure IV.7-1. FORWARD POD ARRANGEMENT SHOWING POSSIBLE CYLINDRICAL TRANSDUCER LOCATION (U)

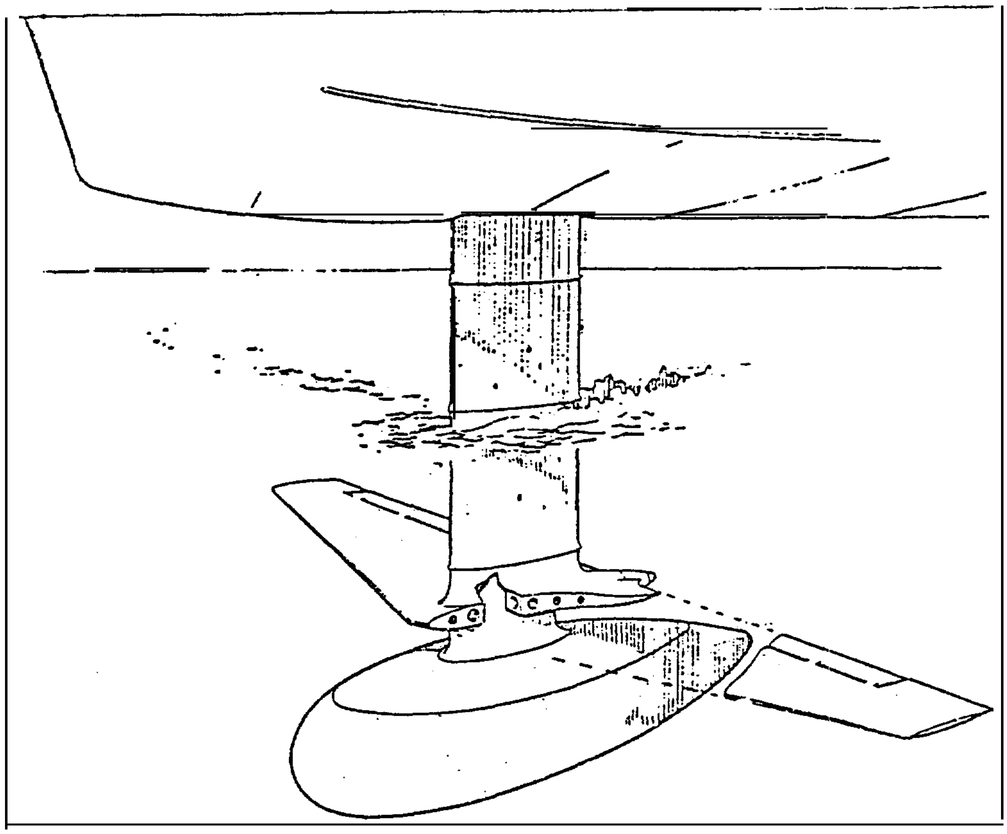

Figure IV.7-2. BELOW FOIL-MOUNTED SONAR POD (U)

7.3.2.5 Signal Processing

(U) With the advent of digital processing and minicomputers, it is feasible to use a single processor to handle several types of sonars. The advantage of a single processor is space and weight reduction in the overall system. To meet operational requirements of large escort hydrofoil ships, separate search and attack displays and controls are necessary. The Proteus processor is an example.

7.3.3 Hydrofoil Sonar System Synthesis

(U) Combining the sonars into a sonar system must be tailored both to the hydrofoil characteristics and to mission requirements. For a large escort hydrofoil, the ideal sonar system from a sonarman's view should include all four sonar arrays operating into a single processing system with independent search and attack displays. A block diagram of this is shown in Figure IV.7-3. This arrangement would provide full and flexible ASW capability to meet all foreseeable environmental and mission requirements. Such a system, however, would seriously impact stern space and payload needed for other subsystems of the combat system (Reference IV.7-2). Figure IV.7-4 shows a minimal sensor system which would be adequate for most ASW operations, yet would significantly reduce system weight and space requirements. The minimal system consists of an APRAPS for search and a pod-mounted sonar for attack.

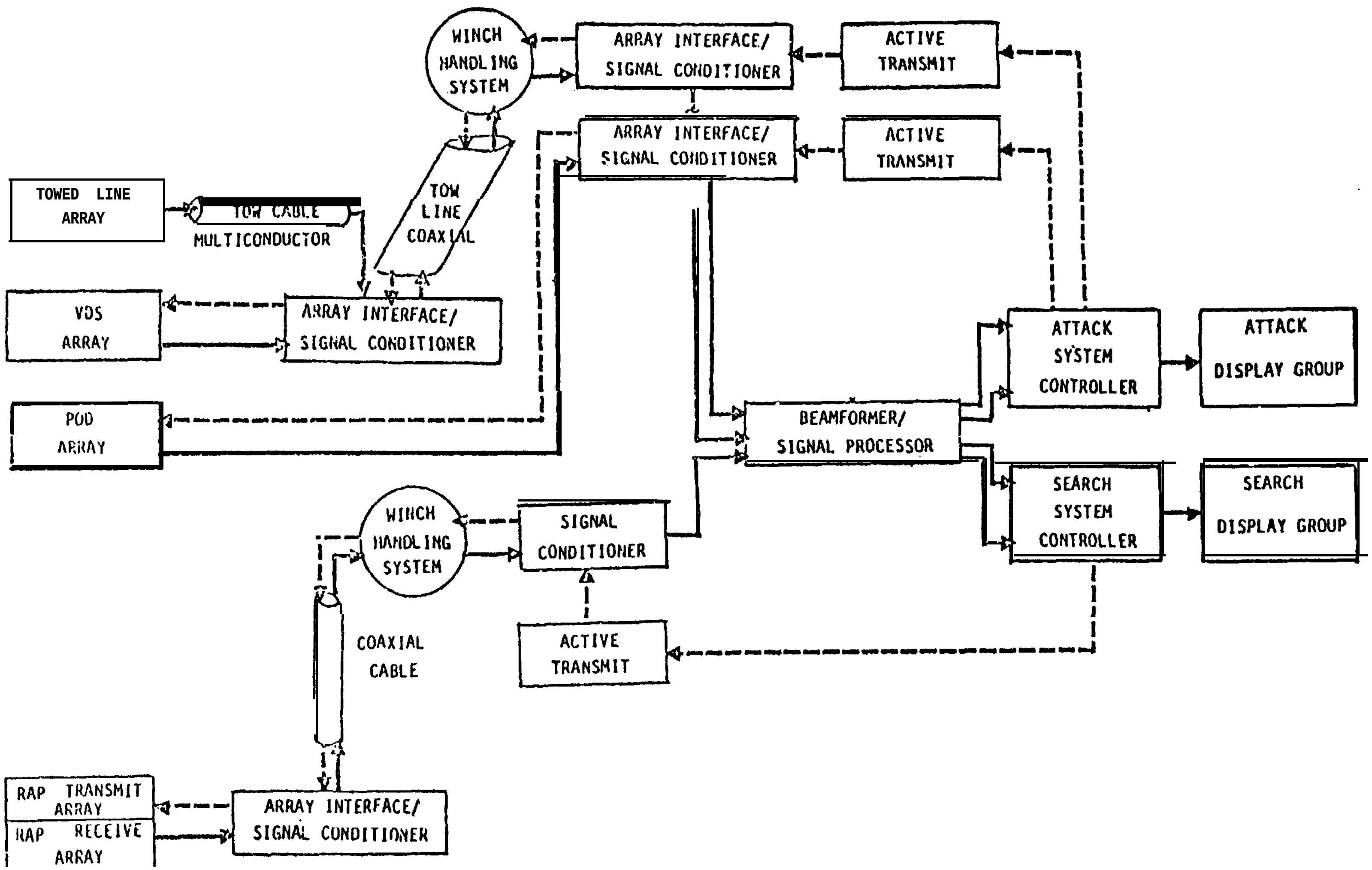

FIGURE IV.7-3. IDEAL SONAR SYSTEM (U)

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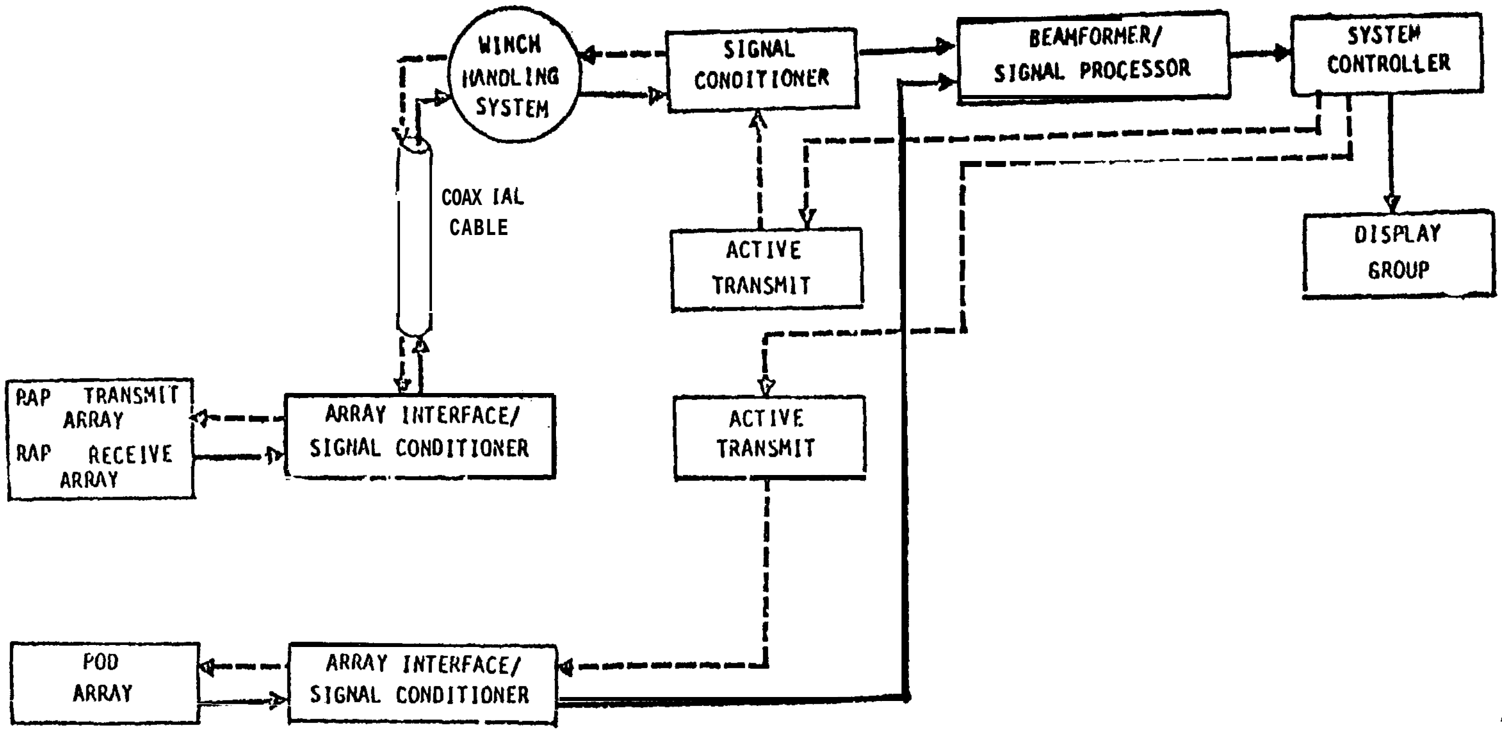

FIGURE IV.7-4. MINIMAL SONAR SYSTEM (U)

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. (U) Selection of sonars for the minimal ASW sensor system is based on the rationale that if projected threat submarine noise levels are correct, the utility of the passive towed line array would be limited to those sectors where high submarine closing speeds are required. Therefore, the APRAPS is considered essential to obtain search coverage. There is no clear choice at this time for the attack sonar. The VDS has the advantage of providing below-layer operation and of being fully retractable to reduce hydrofoil drag. These advantages are gained at the expense of using stern space required for other purposes. A pod-mounted sonar will provide poorer coverage but requires considerably less space and weight allocation.

(U) A feasible arrangement for APRAPS installation is shown in Figure IV.7-5. Space available for sonar launching and retrieval machinery aboard a large escort hydrofoil ship is shown in Figure IV.7-6. Installation on second deck has the advantage to both free the main deck for other uses and provide weather protection for the machinery. Also, this location has the advantage of placing the machinery closer to the waterline, thereby reducing the size and weight of the over-the-stern launching machinery, and lowering the center of gravity of the hydrofoil ship. On small hydrofoil ships, all sonar machinery must be mounted on the main deck at the transom. Illustrative estimates of ASW sensor systems weight, space, and power requirements are given in Table IV.7-1.

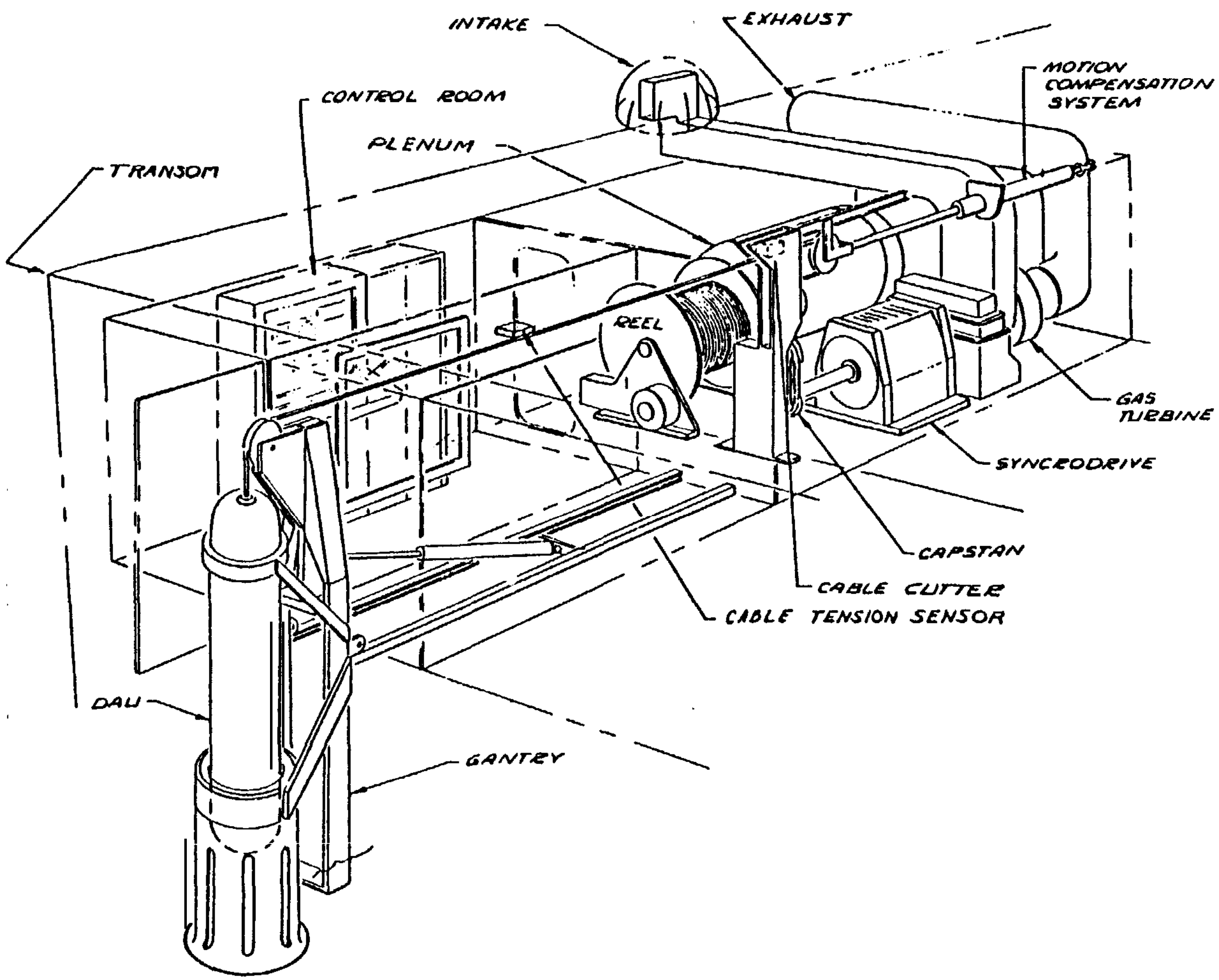

Figure IV.7-5. STERN INSTALLATION OF APRAPS (U)

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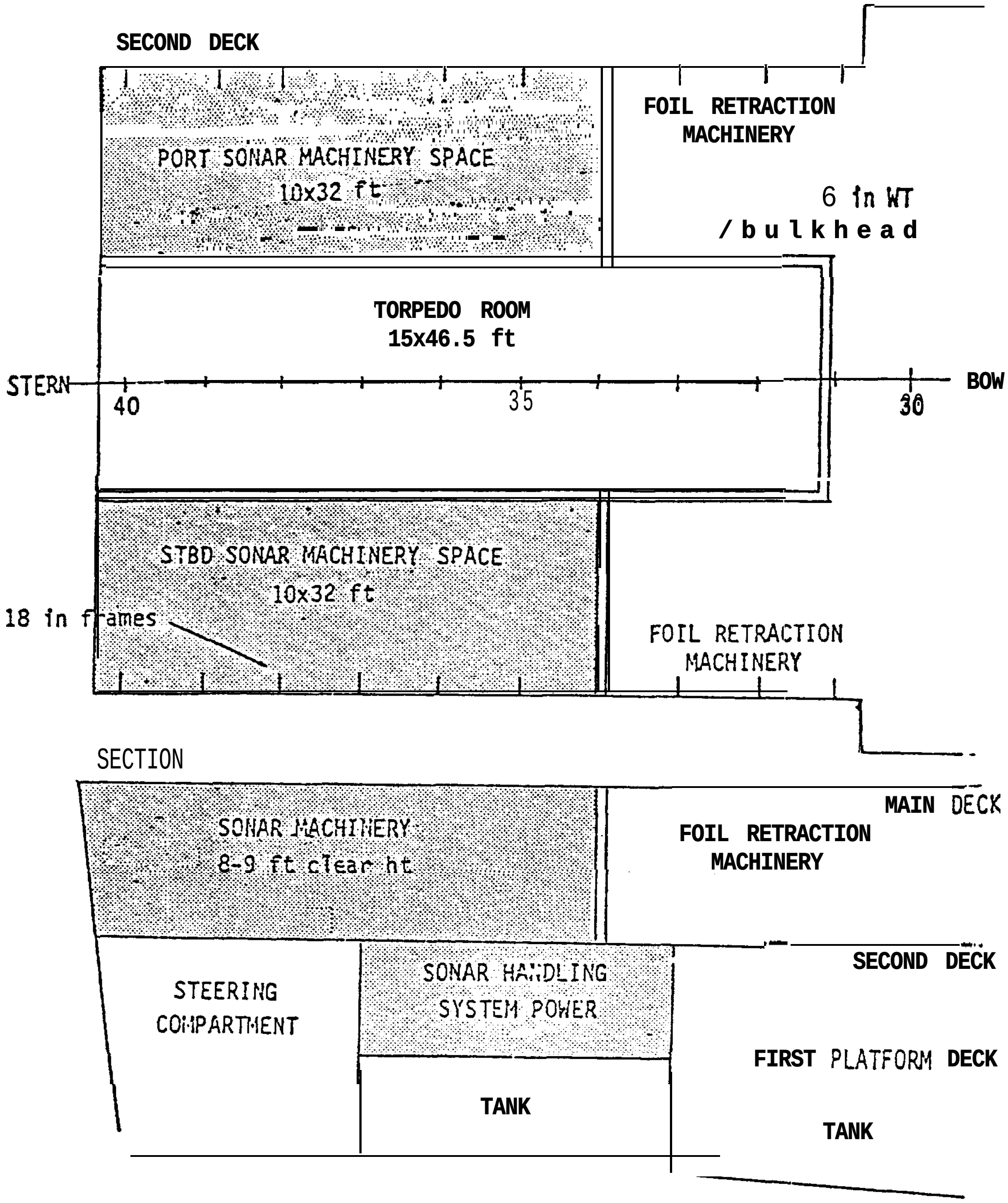

Figure IV.7-6. SONAR HANDLING MACHINERY SPACE (U)

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Table IV.7-1. SONAR INSTALLATION CHARACTERISTICS

SUBSYSTEM	TOTAL WEIGHT	STERN AREA	SONAR AREA	POWER (MAX)	REMARKS
Towed Line Array	17,850 lbs	200 sq ft	2.1 sq ft	29.2 kw	Excludes processor/display
APRAPS	13,600	320	4.3	2.2 + gas turbines	Excludes processor/display
VDS	13,150	240	4.4	19.3	Excludes processor/display
Pod-mounted	4,150	NA	4.4	2.3	Excludes processor/display
Processor	3,450	NA	17	11.4	Excludes processor/display

7.4 HYDROFOIL UNDERWATER SURVEILLANCE TEST AND STUDY RESULTS

7.4.1 Hydrofoil ASW Sensor Research and Development

(U) By far the greatest effort in developing hydrofoil underwater surveillance systems has been spent on systems performance studies, subsystem design studies and experiments, and a few subsystem demonstration trials for hydrofoil ASW sonar systems. There are only two tests dealing with other ASW sensor approaches. They are described in Sections 7.4.1.1 and 7.4.1.2.

7.4.1.1 Magnetic Field Measurements

(C) In 1969, magnetic field intensity measurements were made aboard the PCH-1. It was a feasibility investigation to develop an ASW magnetometer system for classification and localization of submarines from hydrofoil ships. The results showed that hydrofoil ship maneuver noise was a major problem requiring reduction by almost two orders of magnitude to be comparable to the performance of magnetaneters used by ASW aircraft (Reference IV.7-3).

7.4.1.2 Sonobuoy Monitoring Range Extension

(C) Hydrofoil sonobuoy monitoring range extension trials were conducted aboard the PCH-1 in 1971 (Reference IV.7-4). The monitoring range extension was to be achieved by holding the hydrofoil ship antenna aloft by parafoil. The feasibility of flying a parafoil from a foilborne hydrofoil ship had been demonstrated earlier. Due to design of the equipment and inexperience in handling the launching gear, less than one hour of data was obtained. The antenna elevation during that time was estimated to be 140 ft. Enough electronic data were obtained to validate the basic objective of the test: the monitoring range of the sonobuoys could be extended by elevating the hydrofoil ship antenna from a parafoil.

7.4.1.3 Sonar Towline Development

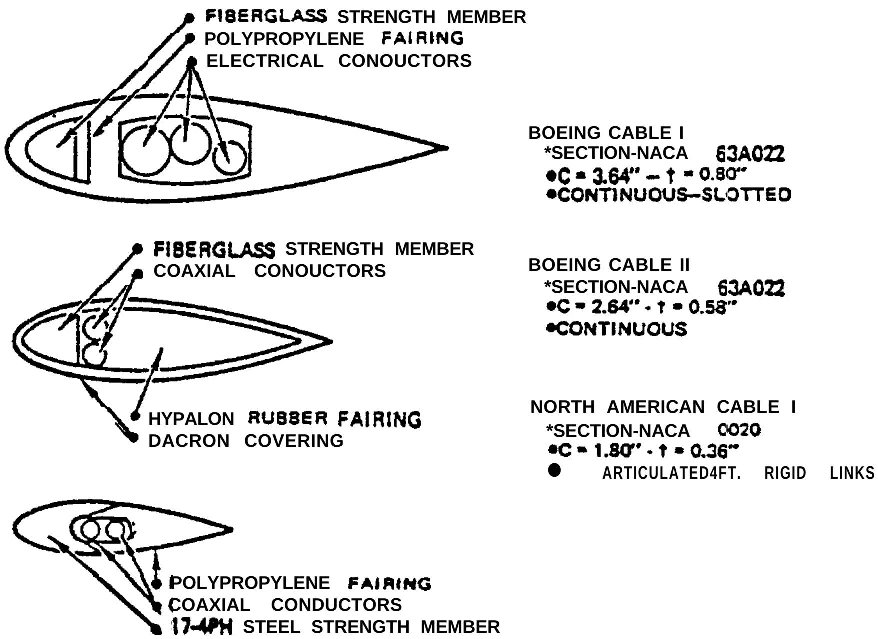
(C) Three faired towlines for high speed towing behind hydrofoil ships were developed and evaluated during the mid 1960s. The towline cross sections and their specifications are shown in Figure IV.7-7 (Reference IV.7-5).

7.4.1.4 High Speed Towing Trials

(U) High speed towing trials with the PCH-1 during 1970 demonstrated hydrodynamic feasibility of towing a dynamically-controlled VDS depressor body (Reference IV.7-6). Stable towing of 400 ft of faired towline (Boeing II design) at speeds up to 42 kn and turn rates up to 4 degrees per second in calm water was achieved. The desired test speed was 45 kn. The towline and depressor body drag decreased the speed by 3 kn.

7.4.1.5 Studies of Towing Effects on Hydrofoil Performance

(U) During the 1960s, a number of analyses and computer simulations were performed to assess seakeeping, maneuverability, and structural effects of towing equipment at high speeds and high sea state (Reference IV.7-7). For example, prior to the high speed towing trials with PCH-1, results of an analysis showed that no adverse effects would be experienced by the foilborne craft while



Item	Constant	Boeing I	Boeing II	North American Aviation
Strength member area	$A_{s.m.}$, in.^{2}	0.199	0.15	0.201
Ultimate tensile capacity	T_{ult}, lb	26 750	25 000	24850
Design factor of safety	S. F.	2 5	2 5	2 5
Working tensile capacity	T_{allow}, lb	10700	10 000	9940
Section chord	C, in	3.64	264	1.8
Section thickness	t, in.	0.80	0.58	0.38

Figure IV.7-7. TOWLINE SPECIFICATIONS (U) towing. Other studies of conceptual large displacement hydrofoil ships also showed that towing would not affect maneuverability and structural loading of foils and struts.

7.4.1.6 High Speed Towing of VDS HS-1001/1007

(U) The Canadian-developed VDS System HS-1001/1007 has been successfully towed at sea to speeds of 30 kn. The towing was not done by a hydrofoil ship. The test results indicate that this system should be capable of towing speeds to 40 kn and acoustic performance to 30 kn.

7.4.1.7 High Speed Towed Line Array Tests

(U) During 1974 towing tank tests were made with arrays of three different designs to investigate towed line array noise due to array vibration. Array acceleration measurements were made at towing speeds up to 40 kn. Significant reduction in acceleration was obtained by applying a tow line antistrumming technique.

7.4.1.8 Below Foil Body Study

(U) Hydrodynamic and structural effects of a below-foil mounted pod on hydrofoil performance have been studied (Reference IV.7-1). The pod is of such size that it could fit below the forward foil of the PCH-1 and could accommodate an ASW attack sonar. The study showed that, due to the added drag, the PCH-1 maximum speed would be reduced to about 43 kn. There would not be any adverse effects on the maneuverability of the hydrofoil ship. A model of this strut foil body configuration has been successfully tested in a towing tank. This configuration is shown in Figure IV.7-3.

7.4.2 <u>Collision Avoidance Sonar Tests</u>

7.4.2.1 Pulsed Doppler Sonar Tests

(U) A pulsed doppler sonar system was evaluated aboard the PCH-1. The tests were conducted late in 1970 and early in 1971. The sonar was a forward-looking system intended for detecting and avoiding subsurface obstacles in the path of a foilborne hydrofoil ship. Head-on runs on various targets were made at speeds up to 38 kn. Closest Point of Approach (CPA) of about 100 ft was obtained.

7.4.2.2 Phase - Comparison Sonar Tests

(U) A phase comparison sonar system was tested aboard the PCH-1 in June of 1971. The system was intended for detecting and avoiding obstacles in the path of a foilborne hydrofoil ship and for detecting navigational hazards and bottom topography abeam of a foilborne hydrofoil ships. Tests were conducted in both the forward-looking and side-looking mode at speeds up to 40 kn.

SECTION 8

COUNTERMEASURES (SWBS GROUP 470)

8.1 HYDROFOIL COUNTERMEASURES

8.1.1 General Considerations

(C) Naval operations during the Vietnam and Israeli-Arab wars have shown that countermeasures are assuming a more prominent position in the modern combat suit. The Israeli Navy credits its countermeasures equipment with its 100 percent success in defense against a large number of SS-N-2 Styx missile launches. Electronic Countermeasures (ECM) other than deception have been generally neglected for US Navy ships. This is primarily because of the inordinately high powers required for self-masking of large radar targets, and the Home-On-Jam (HOJ) capability assumed for Soviet ASCMs. The advent of smaller, high performance ships like the hydrofoil ships coupled with the prospect of Radar Cross Section (RCS) reduction and control, raises the possibility of using off-the-shelf ECM equipment, originally designed for aircraft, to provide countermeasures support for these ships. Improvements and technological advances constantly being made will significantly increase the capabilities of Electronic Warfare (EW) equipment in the next decade. Recent advances in power tube and antenna technology indicate that, in the next decade total ERP (transmitted power combined with antenna gain) for EW offensive jamming purposes will be 20 to 50 times the ERP available today.

8.1.2 Hydrofoil EW Role

8.1.2.1 Small Hydrofoil Ships

(C) For small patrol hydrofoils, the primary functions of the EW system are as point defense against terminal homing ASCM and as a sensor to provide target data to the fire control system. The sensor function is accomplished by the ESM equipment which consists of an antenna, receiver, and processor. The processed signals are compared with stored samples in a general purpose digital computer data bank. The subsystem provides automatic threat warning and Direction Finding (DF). The ASMD self-defense function will be performed by a chaff system such as Rapid Bloom Cffboard Chaff (RBOC).

8.1.2.2 Large Hydrofoil Ships

(C) For large ocean escort hydrofoil ships, one proposed EW mission is area defense of main force ships against long-range ASCM attacks launched from submarine, surface, or airborne platforms. This area ASMD mission would consist of directing noise jamming against reconnaissance search radars, airborne launch platform acquisition radars, and postulated airborne ASCM video data links.

8.1.3 Operational and Performance Interfaces

(U) Results of tests with the installed countermeasures equipment suggest that detectors, classifiers, and jammers are independent of the hydrofoil ship in their design compatibility, function, and performance, provided the antennas are located properly and that emitters from other ships can be coordinated in their usage. Severe Electranagnetic Interference (EMI) problems may be encountered, especially on large ocean escort hydrofoil ships with active jamming systems with high duty cycles. This will impose a severe duty cycle load on the electronic synchronizing system, e.g., AN/SLA-10. The overall time utilization analysis for all emitters and receivers and their interplay must be carefully analyzed. Chaff and IR dispenser packages designed for other ships may not be adequate for large hydrofoil ships depending on the specific values of equivalent radar cross sections. Hydrofoil ships at speeds of 35 to 50 kn and radar frequencies of 8 to 12 GHz may have slightly higher RCS than equivalent displacement ships at their lower speeds. This is because the spray generated at high speeds is reflective at these frequencies and the hydrofoil ship while foilborne stands higher above the sea clutter (about 20 ft). Hydrofoil ships may be able to utilize a combination of tactics and the spray wake to effect a countermeasure by decoying X-band trackers to the wake. The use of RBOC, in conjunction with a rapid foilborne-to-hullborne transition, can be useful in causing confusion and diluting an enemy's effectiveness in tracking a hydrofoil ship with gun FCS radars. This tactic could be used in gaining time to ready a HARPOON launch, set GQ, etc., but it is not expected to be effective for any great length of time or as a penetration aid. In addition, if the GFCS has an optical backup (as have most Soviet systems), the degree of confusion or degradation caused by RBOC is likely to be minimum except in poor visibility conditions.

8.2 HYDROFOIL ECM TEST RESULTS

8.2.1 RBOC and Noise Jammer Tests on PCH-1

(C) The effectiveness of the RBOC with and without noise jamming against GFCS radars was tested aboard the PCH-1 (Reference IV.8-1). The RBOC system is intended as the self-defense ASMD for the PHM. The RBOC round is a mortar-launched cardboard encased payload. A bursting charge causes the chaff to bloom rapidly, giving an equivalent RCS of greater than 300 m^2 less than 5 seconds after the burst. The RBOC is designed for use against active radar homing ASCM. The method employed is the "centroid resolution" method of decoying. This method is limited to ships of small to moderate RCS. The noise jammer used was off-the-shelf obsolescent aircraft equipment. It was found that RBOC used alone while the PCH-1 was foilborne was ineffective against GFCS radars, since the radar operator can readily discriminate between rapidly moving and nonmoving targets. RBOC used in combination with jamming is likely to be much more effective, especially if employed by a trained operator with carefully designed evasive tactics.

8.2.2 Other ECM Equipment Tests

(U) Hydrofoil ships have carried and, to some degree, tested the following ECM equipment:

	PCH-1	PHM-1	PGH-1	P-420 Swordfish
Detector	x	x	x	x
Classifier	x	x		x
Locator	x	x		x
Noise Jammer	x			x
Chaff	x	x		

SECTION 9

FIRE CONTROL SYSTEMS (SWBS GROUP 480)

9.1 HYDROFOIL AND FIRE CONTROL SYSTEM INTERFACES

9.1.1 Operational and Performance Interfaces

(U) In general, hydrofoil ships do not introduce any new Fire Control System (FCS) compatibility problems which are not common to conventional displacement ships. All of the fire control systems in use on existing hydrofoil ships were designed for displacement ships and were adapted to hydrofoil ship use without undue effort. The hydrofoil ships higher speeds, higher wind loads, and faster turn rates are easily accommodated and the much smoother foilborne ride simplifies sensor and weapon stabilization problems. Compensating the higher speeds and turn rates is a simple matter of scaling in the FCS computer. This does not impose torque requirements on stable sensor or weapon mounts because these torque requirements are usually established by ship's ride quality, not maneuverability. The poorer ride quality of displacement ships generally requires stabilization band pass and torque margins well in excess of those required by higher maneuver rates in hydrofoil ships and many times greater than the margins imposed by hydrofoil ship ride quality in either foilborne or hullborne mode. Wind loads on rotating or slewed sensors are mitigated by shields (radomes, etc.) which are standard with FCSs.

9.1.2 Technical and Phvsical Interfaces

(U) There are no technical or physical interfaces which introduce FCS and hydrofoil ship incompatibilities other than those that exist for displacement ships of equivalent size.

9.2 FIRE CONTROL SYSTEMS COMPATIBLE WITH BYDROFOIL SHIPS

9.2.1 PHM Fire Control System

(U) There are currently two candidate FCSs for the PHM. For the PHM (U.S. Variant), it is planned to use the Mk 92 Mod 1 FCS. The German and Italian Variants would use the Dutch HSA FCS WM 28/52 for which the U.S. designation is Mk 94 FCS. The Mk 94 FCS has been installed and is being evaluated aboard the PHM-1. A functional interface layout of the system is shown in Figure IV.9-1. Total system weight, including HARPOON control equipment, is 7,403 lb.

9.2.2 Other Fire Control Systems for Small Hydrofoil Ships

(U) Besides the FCSs for the PHM, the following have been installed and operated aboard small hydrofoil ships. Eeltronica San Giorgio FCS is used on the Italian Navy P-420 SWORDFISH to control the 76mm OTO Melara gun and OTOMAT surface-to-surface missiles. The Hughes SCFCS is on the PCH-1 to control a 40mm gun. Fire control systems which have been considered for small hydrofoil ship application and have been found acceptable are Honeywell Mk 93 and Thompson CSF Vega Pollux. Honeywell has proposed a system which would build on and have substantially greater capability than the Mk 93 FCS, but be less sophisticated and lighter than the Mk 92 Mod 1 FCS.

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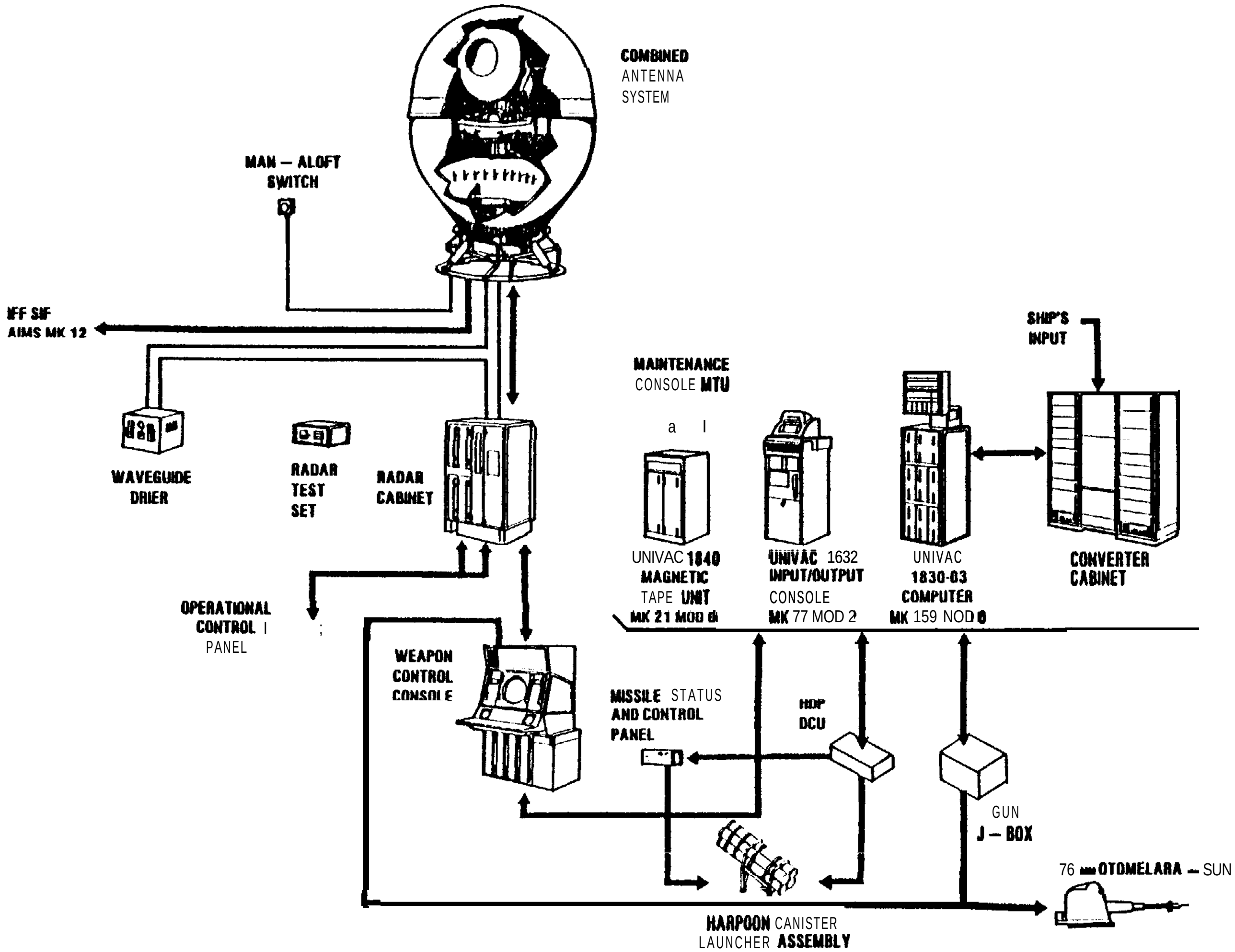

Figure IV.9-1. MK94 FIRE CONTROL SYSTEM (U)

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9.2.3 Fire Control Systems for AAW Missiles

(C) The large ocean escort hydrofoil ships in the 800- to 1200-ton displacement range will have missiles aboard for both area and point AAW defense. The following fire control systems have been studied for compatibility with large hydrofoil ships (Reference IV.9-1).

9.2.3.1 Mk 74 Mod 9 GMFCS

(C) The Mk 74 Mod 9 can control both standard (MR) missiles and gun systems. The increased tracking range of this FCS will support the increased engagement range of the SM-2 (MR) in its optimized trajectory. The Mk 74 Mod 9 has a significantly greater acquisition range (about 85-100 NM) than the other hydrofoil compatible FCS. The Mk 74 Mod 9 incorporates many advanced ECCM features. It has been proposed to use two Mk 74 Mod 9 systems aboard large hydrofoil ships.

9.2.3.2 Mk 92 Mod 2 Separate Track Illuminator Radar (STIR) FCS

(C) The Mk 92 Mod 2 FCS is capable of detecting and tracking air and surface targets, simultaneously providing fire control solutions for one gun and a medium-range missile such as the SM-1. (MR). The acquisition range of this FCS is about 20-50 NM. The system can acquire airborne targets at speeds below M = 3.

9.2.3.3 Mk 92 Mod 3/2 FCS

(C) This system is a proposed lightweight FCS for hydrofoil application, a variant of the Mk 92 Mod 2. It would give the ship a limited AAW capability by control of SM-1 (MR) with its STIR fire control channel, and a point defense capability by control of SEA SPARROW missiles with the Combined Antenna System (CAS) tracking radar.

9.2.3.4 SEA PHOENIX (Modified AN/AWG-9) FCS

(C) This weapon control system is a proposed shipborne version of the airborne AN/AWG-9. It is primarily for use with the PHOENIX (modified) missile. The acquisition range of the AN/AWG-9 in shipboard Track-While Scan (TWS) mode is about 30 to 50 NM. In addition to the PHOENIX (modified) missile, the SEA I?HOENIX FCS can also control SEA SPARROW missiles.

9.2.4 Future FCS Considerations

(U) Against surface targets, shore targets, and slow (M = 0.9 to 1.2) nonmaneuvering air targets, the existing FCS is generally adequate. These systems will not be able to cope with the projected ASCM threat in the 1980/1990 timeframe. Specifically, the FCS must provide the following improved features in conjunction with new weapons:

- Greatly reduced reaction time from threat detection to defensive measure initiation
- Reduced susceptibility to saturation by multiple air threats
- Reduced susceptibility to electronic countermeasures
- Integrated functions with the Command and Control, Navigation, Surveillance, Countermeasures, and ASW systems and all weapon stores

- Reduced manning requirements for operation and maintenance

Hydrofoil compatibility with the improvement requirements are considered in the following paragraphs.

9.2.4.1 Reaction Time Improvement

(U) Reaction time must be reduced by an order of magnitude from present operational capability. The most likely way to accomplish this task is to automate target identification and track initiation, autanate launch by using a stores management concept similar to that used on the B-52, FB-11, and B-l aircraft, and to launch missiles from vertical launchers. The missiles will need self-contained mid-course and terminal guidance capability to eliminate demand for target illumination by ship's radars. The use of automated track initiation, threat classification, and stores management concepts is consistent with reduced manning and imposes no constraint on hydrofoil ships. Use of "smart" missiles and vertical launch are also compatible with hydrofoil ships.

9.2.4.2 Saturation Elimination

(U) The problem of multiple high performance, maneuvering air targets is reduced to manageable proportions when a TWS multiple target radar is used in conjunction with a "smart" launch and leave missile. Present TWS radars suitable for use on hydrofoil ships, such as AN/AWG-9 system and the Domestar fixed phase array, have been assessed for ship compatibility.

9.2.4.3 ECM Vulnerability Reduction

(U) The adoption of ECCM features like frequency agility, deception jamming, etc., to hydrofoil FCS radars will not penalize hydrofoil ship design. However, automated energy management will be required to coordinate the numerous ship's radiating sources to allow the FCS to function effectively in an ECM environment.

9.2.4.4 FCS Function Integration

(U) Functions must be integrated which can be shared among major elements of the combat system. For example, ship's heading, speed, position, and attitude are all part of inputs for fire control solutions; however, these data are also generated for the navigation system and to some extent the hydrofoil ship flight control system. These data must be generated in the most critical system and then shared by other systems. A highly integrated system is a goal of the Ship Intermediate Range Compat System (SIRCS) program which is expected to impact hydrofoil designs in a favorable way.

9.2.4.5 Reduced Manning

(U) Combining and sharing functions common to more than one element in the combat system will decrease manning level requirements for hydrofoil ships. With the advent of small high speed mini-computers (AN/UYK-20) and the emerging micro-computer technology, nearly all displays associated with FCS and Command and Control system will be computer driven, rather than tied directly to the sensor system. This allows a much more refined display to be presented, and the possibility of the operater interacting with the display-computer combination to effect a greater number of rapid decisions.

SECTION 10

SPECIAL PURPOSE SYSTEMS (SWBS GROUP 490)

10.1 INTERFACE PARAMETERS

(U) Depending on the degree of integration adopted for large future hydrofoil ships, it should be possible to capitalize on proven schemes for centralized display of the status of systems, monitoring for failures, and computer-aided diagnostics and trouble-shooting. The operational concepts for hydrofoil craft are not dependent on such a scheme, but the benefits to the hydrofoil ship would be great because of weight-saving and a decrease in crew requirements. If data multiplexing is adopted, the fault monitoring and automated trouble-shooting should be realizable without significant cost or complexity. The electronic test, checkout, and monitoring equipment required to support the command and surveillance systems of hydrofoil ships are conventional in nature and not particularly affected by vehicle performance features. Such equipments as radar performance monitors, IFF test sets, and built-in test equipment may be treated in the same manner as installed tactical equipments. Portable instruments will be stored in the equipment maintenance areas.

SECTION 11

GUNS AND AMMUNITION (SWBS GROUP 710)

11.1 HYDROFOIL AND GUN INTERFACES

11.1.1 Operational and Performance Interfaces

(U) Gun systems are fully compatible with operational requirements and performance features of hydrofoil ships. The smooth and stable ride of hydrofoil ships makes gun mount stabilization easier and allows effective gun firing to be conducted in sea states higher than 3 and at speeds *over 40* kn. Trials with guns up to 152mm have been successfully conducted with hydrofoil ships. They demonstrated excellent gunnery capability against small surface and shore targets. Unmanned gun mounts that are remotely controlled and fired are the most compatible type for hydrofoil ship application. Ammunition stowage and handling from below are practical. However, for high performance, weight-sensitive ships like the hydrofoil to carry and deliver a large number of expendable ordnance does not appear justifiable. Therefore, shore bombardment is not a primary mission to be considered for hydrofoil ships. For future hydrofoil ships, a difficult trade-off analysis must be made to determine the true value of naval guns (76mm and larger) versus guided missiles and rockets. The cost for a 76mm round, for example, is about $100 with an attendant accuracy of about 5 mils out to 10,000 yd, while missile accuracies are a few feet for "smart" weapons at the same range but with attendant costs in the order of $10,000 or more. The gun mounts that have been tested aboard hydrofoil ships are shown in Table IV.11-1. Gun mounts that have been proposed and considered for hydrofoil application are listed in Table IV.11-2.

11.1.2 Technical and Physical Interfaces

(U) The following are pertinent hydrofoil and gun system technical interfaces:

- The Close-In Weapon System (CIWS) is being designed to be fully operable in severe sea states (up to Sea State 5) and in severe gun shock and vibration environment. However, a stiff foundation must be provided for each installation. If CIWS is to be installed on the superstructure, additional reinforcing must be provided.

- Gun firing noise has caused erroneous signals in acoustic height sensors. These signals sent to the Automatic Control System (ACS) may produce a forward foil broach. To avoid this condition, a more elaborate design of the acoustic height sensor has been used. Radar height sensors presently now in use on PGH-1, PCH-1, and AGEH-1 will eliminate this problem.

- If manned rapid fire guns are to be operated on the deck of a foilborne hdyrofoil ship, a box or tray must be installed to catch ejected shell casings to avoid a missile hazard.

Table IV.11-1. GUN MOUNTS TESTED ON HYDROFOIL SHIPS. (U)

NAME	WEIGHT w/o AMMO (lb)	RATE OF FIRE (rpm)	MUZZLE VEL. (ft/sec)	MAX. HOR. RANGE (yds)	EST. EFF. RANGE (yds)	SLEW RATE (deg/sec)	REMARKS
Mk 56 Mod 2 Twin 20 mm Mk 16/4 Guns	900 w 450 rds ammo	650-800	2730	6650	2000		225 rds/gun ammo stowage. On PGH-1 & PGH-2.
EX 73 Twin 20 mm Mk 16/4 Guns	2200 w 500 rds ammo	650-800	2730	6650	2000	Train 60 El. 30	Armored turret 250 rds/gun ammo stowage. On PGH-2.
Mk 3 Mod 0 40 mm Ml Gun	2275	120	2800	9300			Manual oper. Fed by 4rd clip. On PGH-1 & PGH-2.
Mk 3 Nod 4 40 mm Ml Gun	4200	120	2800	9300			Power driven, stabilized mount. Fed by 4rd clip. Tested on PCH-1.
Mk 75 Mod 1 76 mm/62 OTO Melara Gun	16,500	10-85	3035	17,800	38,400 ft max. alt.	Train 60 El. 35	Remote control. 80 rds in ready service maq. On PHM-1.
M81E1 152 mm Gun	7700	2-4	2240	9800		Train 40	Stabilized mount. Laser range finder. Tested on PGH-1
Ex 83 G.E.	8000	4200	3100	11,000	5000	Train/elev.	Stabilized mount. Laser range finder. Tested on PGH-1.
Mk 2 Mod 0 81 mm Mortar	600	10 Trigger 18 Drop	787	4000			In service on on PGH-1 & PGH-2.

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Table IV. **11-2.** GUN MOUNTS COMPATIBLE WITH HYDROFOIL SHIPS **(U)**

NAME	WEIGHT w/o AMMO (lb)	RATE OF FIRE (rpm)	MUZZLE VEL. (ft/sec)	MAX. HOR. RANGE (yds)	EST. EFF. RANGE (yds)	SLEW RATE (deg/sec)	REMARKS
Close-In Weapons system (CIWS) 20 mm (6 barrel Gatling) Gun	9200 w 1000 rds and FCS	3000	3380	5000	2000	Train 100 El. 50	For ASCM self-defense. Fires inert penetrators. For large hydrofoil.
Vulcan Air Defense System (VADS) 20 ml XM-168 Vulcan Gun	3000	3000 in bursts 1000 cont.	3380	5000	2000	Train 60	1080 rd ammo stowage. Proposed for PGH-1.
OE/OTO Melara GDM-C Twin 35 mm 353 KDA Gun	11,000	550 or single shot	3855	11,900		Train 110 El. 70	Fits same deck mounting as 76/62. 410 rd/gun belt fed. Considered for PHM.

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11.2 GUN SYSTEMS COMPATIBLE WITH HYDROFOIL SHIPS

11.2.1 Small Hydrofoil Ships

(U) On the small gunboat hydrofoil ships (PGHs), which are craft of 60- to 70-ton displacement, guns up to 152mm size have been tested and found compatible. These hydrofoil ships' mission is to patrol coastal and inshore waters. The gun system is their primary battery with which to engage small surface and shore targets. The 152mm gun has been tested and found compatible only in a structural load and craft hydrodynamics feasibility sense. There does not exist such a gun system with suitable ammunition loading and handling equipment for installation on operational hydrofoils. For patrol hydrofoil ships of about 235-ton displacement, for which guided missiles may be the primary battery and the gun system only a secondary battery, guns up to 76mm size are found to be compatible.

11.2.2 Large Hydrofoil Ships

(C) Large future hydrofoil ships for open ocean escort missions will probably have a multimission capability. The long-range Surface-to-Surface (SUW) and Area Anti Air Warfare (AAW) engagements will have to be handled by guided missile systems. Gun systems aboard these hydrofoil ships will be primarily used for ASMD, though small low-value surface and occasional shore targets may be engaged. The following paragraphs highlight such gun systems.

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11.2.2.1 CIWS

(C) The CIWS is an autonomous weapon system with lightweight search and tracking radars. It has been designed as a complementary system against low-flying ACSMs. The system can also accept target designations from other radars and must do so for elevations above 7 degrees. The gun mount is unmanned and remotely controlled. The reaction time is a very quick 3-6 sec. The system uses the six-barrel Gatling type GE 20mm Vulcan gun with a firing rate of 3,000 rounds per minute. The projectile is an inert penetrator sub-calibre slug made of depleted uranium. The intended kill mechanism is detonation of the missile warhead. Maximum effective intercept range against low-flying ASCMs is about 2,000 yd, the minimum range about 50-200 yd. The CIWS uses a closed-loop spotting system to measure and correct projectile miss distance. The system weighs about 10,000 lb (including 1,000 rounds of ammo).

11.2.2.2 Advanced Close-In Gun System

(C) For the next generation of close--in self defense against ASCM that have leaked through wide area and intermediate range AAW defenses, a rapid fire gun system with longer range and higher kill probability than the CIWS can be expected. A typical system would use a 30mm gun with CIWS closed loop fire control concept. It would have a maximum effective range of about 3,000 yards. Such an advanced 30mm gun system, including the fire control radar computing system and 3,000 rounds of ammunition and spares, should weigh approximately 17,000 lb.

11.3 HYDROFOIL GUN SYSTEM TEST AND STUDY RESULTS

11.3.1 152mm Gun Firing Trials on PGH-1

(C) To evaluate the compatibility and weapon effectiveness of a large calibre gun and patrol hydrofoil ship, during 1971, the Army M81E1 152mm gun system was installed aboard the PGH-1 and firing trials conducted with the hydrofoil ship, both hullborne and foilborne. The M81E1 gun mount is gyro stabilized and was equipped with a laser range finder, though it was not utilized. It weighs 7,700 lb. The gun can fire various 152mm projectiles, Cansiter rounds with combustible casings, and Shillelagh guided missiles when equipped with attachable missile guidance system. This equipment was removed from the system and not tested. Maximum range of the gun is 10,000 yd. A total of 125 rounds were fired, 55 of them while the PGH-1 was foilborne at a speed of about 45 kn. From these tests it was found that the M81E1 152mm gun mount is compatible with patrol hydrofoil craft in terms of weight, electronics, structural loading, and craft hydrodynamics. Satisfactory accuracy results were achieved for ranges of about 2,700 yards. The mount stabilization system as configured is satisfactory for foilborne operation. However, the mount as configured for these trials is not suitable for installation in operational hydrofoil ships because ammunition storage and handling capabilities are inadequate. Also, the mount is excessively heavy for hydrofoil ships because of its armor protection.

11.3.2 40mm Gun Firing Trials on PCH-1

(C) Gun firing trials with the 40mm Mk3 Mod 4 gun were conducted during 1968 aboard the PCH-1 to determine gun firing effects on foilborne behavior, to evaluate gun stabilization system, to obtain gun mount shock and vibration data, and to obtain other assorted data on gun and gun crew behavior. Both smooth and rough water trials were conducted. The Mk 3-4 gun mount weighs 5,290 lbs. It has an electronic stabilization system. During trials the gun and gun mount operated normally in both the manual and automatic firing modes. Noise during bursts of rapid fire (150 rds/min) caused erroneous signals to the acoustic height sensors. This produced broach conditions. Broaches were induced gradually, vertical accelerations felt smooth, and the gun crew maintained their balance and functioned normally. A blanking circuit in the 'height sensor electronics solved the erroneous signal problem.

11.3.3 Firing Trials on PGH-1 and PGH-2

(U) The hydrofoil gunboats were delivered with the following weapons: one 40mm Mk 3 Mod 0 gun, two 50-cal Mk 17 Mod 0 twin machine gun mounts, and one 81mm Mk 2 Mod 0 mortar. Eventually, both PGH-1 and PGH-2 had their 50-cal MGs replaced with 20mm Mk 56 twin gun mounts. The PGH-1 also had her 81mm mortar replaced with a 20mm Mk 84 twin mount. All of these weapons have been tested aboard the PGH-1 and PGH-2 without any adverse effects.

11.3.4 76mm Gun Firing Trials

(U) The 76mm Mk 75 Mod 1 (Oto Melara) gun is the primary gun system for the PHM ships. The gun mount without ammunition weighs 16,520 lb. There are 87 rounds in the ready service magazine and loading system. Up to 400 rounds can be stored on the PHM in watertight shipping containers. The gun operates automatically and there is no gun crew in the mount. Two crew members are needed for gun maintenance and loading the ready service magazine. Gun firing trials have recently been conducted in the PHM-1 evaluation tests. The same 76mm gun system has been installed and tested aboard the SWORDFISH, a patrol hydrofoil ship of the Italian Navy.

SECTION 12

MISSILES AND ROCKETS (SWBS GROUP 720)

12.1 HYDROFOIL AND MISSILE INTERFACES

12.1.1 Operational and Performance Interfaces

(C) Launching of missiles from both hullborne and foilborne hydrofoil ships has been successfully demonstrated. Both surface-to-surface and surface-to-air missiles have been successfully launched. Launching produces no adverse effects on either hydrofoil speed or maneuverability. For the area AAW and point defense AAW missiles, vertical launchers offer several advantages over other launcher types. Vertical launches of SEA SPARROW and standard missiles have been demonstrated (the SM-2 was vertically launched from the SES 100B at 65 knots). Vertical launching eliminates blind zones, requires the smallest amount of internal space, and presents little above-deck clearance problems. A larger number of missiles in a ready-to-fire status can be made available than with other launchers and the need for missile reload is thus reduced. Reloading missiles at sea may be an important hydrofoil and missile performance interface. Another important performance interface is the potentially high cross-wind across the deck of a hydrofoil ship. Crosswind effects on the self-erecting missile fins, are well known. Considerable experience and knowledge has been gained in this area recently including the vertical launch of a missile from the SES 100B at 65 knots. This information is directly transferable to the hydrofoil concept.

12.1.2 Technical and Physical Interfaces

(U) Weight and space are two critical interfaces in a high performance ship like the hydrofoil ship. Because of their great weight, trainable area AAW missile launchers are not compatible with hydrofoil ships. Trainable point defense AAW missile launchers are compatible, but vertical launchers for these missiles are preferable.

12.2 MISSILE SYSTEMS COMPATIBLE WITH HYDROFOIL SHIPS

12.2.1 General Considerations

(U) There are a large number of existing and proposed missile systems compatible with hydrofoil ships. Selection and application of any particular system depends on the size and mission of the hydrofoil ship. Small patrol hydrofoil ships can have large surface-to-surface missiles and small surface-to-air missiles installed. Large ocean escort multimission hydrofoil ships can be provided with area and point defense AAW missiles, SUW missiles, and stand-off ASW weapons. In the following paragraphs, compatible missile systems for the various missions are described. Physical and performance characteristics of these missiles are summarized in Table IV.12-1.

12.2.2 Area Defense AAW Missiles

(C) These missiles are intended for wide area defense of high value units against ASCM targets or ASCM launching aircraft targets. They are suitable for installation aboard large escort hydrofoil ships.

Table IV.12-1. PHYSICAL AND PERFORMANCE CHARACTERISTICS OF COMPATIBLE MISSILES (U)

NAME	LENGTH (in)	DIAMETER (in)	WRIGHT (lb)	WARHEAD/ EXPLOSIVE WEIGHT (lb)	MAX. RANGE (nm)	MIN. RANGE (nm)	MAX. ALTITUDE (ft)	SPEED (Mach No.)	WARMUP/ REACTION TINE (sec)	GUIDANCE
STANDARD Missile SM-2 (MR)	176	13.5	1500	137/60	40	1.5	00.000	1.25-3.0	1/15	Mid-course, semi-active homing, home-on-jam
PHOENIX (Modified)	236	15	1600	130/60	30-50	2-5				Mid-course. semi-active homing, active homing, home-on-jam
SEASPARROW	144	8	445	67/20	6	0.75	10,000	1.5	8/9-16	Semi-active RF Tested on AGEH-1
ASMD MISSILE	116.25	5	154.77	21	3	.5			7-29 3-5	Dual Mode (RF/IR)
HARPOON	180.4	13.5	1466	535/300	60	4	Sea skimmer	0.85	15/7	Inertial mid-course, active RF homing Tested on PCH-1 and PHM-1
OTOMAT	190	18	1606	462/132	44	3.3	Sea skimmer	0.9	30/30	Inertial mid-course, active RF homing
EXOCET	205	13.7	1543	350/132	20	2.2	Sea skimmer	0.93	60/30	Inertial mid-course, active RF homing
GABRIEL	132	12.8	882	330/154	22	2.7	Sea skimmer	0.6		Command mid-course, semi-active RF
SEA KILLER UK2 .	185	8	594	154/57	15	3	Sea skimmer	0.0	30/30	Beamrider
PENGUIN	118	11	741	250/103	11	1.4	Sea skimmer	0.0	120/7	IR homing

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12.2.2.1 Standard Missile - 2 (Medium Range)

(C) The SM-2(MR) is a semi-active or passive homing missile. It is a modification of the SM-1(MR) with mid-course guidance and multiplexing capability. This mid-course guidance increases the SM-2(MR)'s maximum range capability to about 40 NM over the maximum range of about 25 NM for the SM-1(MR). It also has a surface-to-surface capability to the radar horizon.

(C) If SM-2 were fitted with an active seeker and used with vertical launchers and a track-while-scan control radar, the combination would increase firepower and reduce weight to make this a highly attractive system for a large hydrofoil.

12.2.2.2 PHOENIX (Modified) Missile

(C) The PHOENIX (modified) is a proposed surface-to-air adaptation of the airborne missile. One configuration consists of the PHOENIX (AIM-54) missile mated to the extended range ASROC booster. This configuration provides the greatest area AAW intercept range capability and has a good intercept capability against aircraft. The PHOENIX (modified) missile has four modes of guidance: sampled data mid-course (via uplink from the SEA PHOENIX FCS), semi-active homing, active terminal homing, and HOJ. The missile does not have a surface-to-surface capability because the guidance utilizes the doppler principle. The PHOENIX (modified) missile has a kinematic intercept range of approximately 70 NM. Intercept ranges against ASCM, however, are limited to less than this value because of PHOENIX FCS limitations. Minimum missile range is either 2 NM or 5 NM, depending on whether the missile has thrust vector control.

12.2.3 Point Defense AAW Missiles

(C) These missiles are primarily intended for close-in self-defense against incoming ASCM and aircraft targets.

12.2.3.1 SEA SPARROW Missile

(C) The SEA SPARROW missile is used in the operational NATO SEA SPARROW Surface Missile System (NSSMS). The missile is a boost-glide, X-band continuous wave guided missile using semi-active homing. There may be severe EMI problems if the NSSMS must be used at the same time when other X-band radars of a combat suit are being used, such as the AN/SPS-55 or SEA PHOENIX surveillance and fire control radars. The SEA SPARROW missile in the NSSMS can be installed aboard large escort hydrofoil ships primarily for AAW self-defense. However, the system also has an SUW capability and the SEA SPARROW missile can be effective against small craft inside the HARPOON missile 4 NM minimum range. Other lightweight systems employing the SEA SPARROW missile have been proposed for installation aboard small patrol hydrofoil ships. A modified NSSMS launcher with only four cells has been proposed for the PHM. A fixed sealed canister type two-cell launcher and aircraft type control and radar system has been proposed for testing aboard the PGH-1.

12.2.3.2 Anti-Ship Missile Defense (ASMD) Missile

(C) The ASMD missile is in development as a short range AAW missile which should compete favorably with rapid-fire guns.

It is autonomously guided by passive ratio frequency (I/J band) mid-course and IR terminal guidance. It is currently not being designed for vertical launch and would require trainable launchers. Its IOC is expected to be easily compatible with a large hydrofoil. The system is compatible with smaller hydrofoils. Its lightweight and simplicity of control make the system attractive for small ships. The system requires only that the missile be pointed at launch within a 10 degree azimuth of the target, 5 degrees of elevation of low-flying targets or 10 degrees of elevation of high targets. A significant advantage of the dual-mode guidance is that the system is still viable in some weather conditions unsuited to IR guidance alone.

12.2.4 Surface-To-Surface Missiles

(C) These missiles are intended as the primary battery against surface ships. They are compatible with both small patrol and large ocean escort hydrofoil ships. They are to be launched from fixed, elevated box launchers which are very reliable, lightweight, and require only deck space. There are available large, long-range antiship missiles like the HARPOON and the Italian OTOMAT, medium-range like the French EXOCET and Israeli GABRIEL, and small, short-range missiles like the Italian SEA KILLER and Norwegian PENGUIN. They are all subsonic low-altitude sea skimmers to improve penetration of air defenses.

(C) The HARPOON is a rocket boosted, jet-turbine sustained, all-weather missile with a 4 NM minimum and about 60 NM maximum range. To achieve over-the-horizon range intercepts, the

HARPOON requires external targeting information (via data link). Because of the 4 NM minimum range, a secondary SUW battery like the SEA SPARROW missile or a 76mm to 127mm gun system is needed for engaging small surface targets. PHM is fitted with 8 HARPOONS.

12.2.5 Stand-Off ASW Weapons

(C) Large escort hydrofoil ships with an ASW mission should ideally have aboard both stand-off and over-the-side ASW weapons. Hydrofoil ships compatible stand-off ASW weapon systems include TARPON and MITOR. MITOR is a weapon system 'built around the Mk 48 torpedo. It will provide the surface fleet with both an ASW and anti-ship capability at extended stand-off ranges. MITOR consists of the basic Mk 48 torpedo to which is added an air flight suit. It includes a strongback, wing, turbojet sustainer, booster, and aerodynamic control surfaces. The initial operational range of MITOR will be 60 NM but additional range out to several hundred miles can be achieved by carrying more jet propulsion fuel. Guidance during cruise will be achieved by a preprogrammed autopilot with provision for mid-course update via a low frequency RF link. During air flight maximum use will be made of existing torpedo components. The MITOR can be canister launched.

(C) The TARPON concept uses a HARPOON missile to deploy a Mk 46 Mod 1 torpedo to a maximum range of 60 NM. In this system, the second detection must be made by the Mk 46 Mod 1 torpedo after splashdown. It is, therefore, necessary that the tracking provided by the initial detection sonar be sufficiently accurate so that the inaccuracies in the fire control solution, when added to the circular error probability of the HARPOON missile, are significantly smaller than the acquisition range of the torpedo. The TARPON needs a splashdown point CEP of 500 yd at extreme ranges. To accomplish this, the HARPOON missile requires equipment to provide midcourse guidance. The TARPONs will be launched from fixed elevated box launchers.

(C) The ALWT program generates the possibility of obtaining a more effective weapon than TARPON by developing an ASW standoff missile which uses ALWT as a payload. Such a missile would have a greater explosive charge than the Mk 46 warhead of TARPON and if ALWT goals are met would double the acquisition range of the Mk 46. This missile would be much lighter than MITOR and only slightly heavier than TARPON. Thus it would not have the SUW capability of MITOR because of the warhead size difference.

12.3 HYDROFOIL MISSILE TEST AND STUDY RESULTS

12.3.1 SEA SPARROW Test on AGEH-1

(U) To evaluate compatibility of launching small AAW missiles from a foilborne hydrofoil ship, SEA SPARROW launching tests were performed aboard the AGEH-1 in December 1972. Three missiles were fired from a lightweight prototype canister launcher mounted on main deck aft. The AGEH-1 was operating in Sea States 3 to 4. One missile was launched while hullborne at 6 kn, the other two while foilborne at 40 kn. No degradation in craft performance resulted from these firings. A review of structural responses revealed no detrimental effects to the installed machinery, equipment, hull-girder system, or ablative blast shield. The effective crosswind for the foilborne launches was 30 kn and 45 kn. The usual weather-vaning was not observed during these launches, but the wind did affect missile attitude in the opposite direction.

12.3.2 HARPOON Tests on PCH-1

(U) To evaulate compatibility of launching large ASCM from small foilborne hydrofoil ships, HARPOON launching: tests were made aboard the PCH-1 in December 1973 and January 1974. Two missiles were launched from a canister launcher mounted on the main deck aft. This was the initial assessment of the canister configured HARPOON. The missiles were launched while the PCH-1 was foilborne at speeds of 38 and 40 kn, the first launch on a straightaway run, the second with a turning rate of about 4 degrees per second. Three height sensors were used during these tests: the PCH-1 Mod 1 ultrasonic sensor, the PHM prototype sensor which is an ultrasonic sensor with a blanking circuit added, and a Sundstrand AHV-6 radar height sensor. Launching a HARPOON missile from the PCH-I does not produce any significant ship motions, providing a height sensor is used which is not adversely affected by acoustical noise. Forward foil broach is caused by erroneous signals from the Mod 1 ultrasonic sensor during periods of high noise from the missile booster. The PHM prototype and the AHV-6 radar height sensors performed properly.

No structural aggravation or deterioration was noted on the PCH-1 as a result of the launchings. Recently, a HARPOON missile has also been successfully launched from a canister launcher (aboard the prototype PHM.

12.3.3 Large Hydrofoil AAW Missile Suit Study

12.3.3.1 AAW Missile Arrangement

(C) Weapon system studies (Reference IV.12-1) for large open ocean hydrofoil ships have indicated one desirable candidate AAW missile suite consisting of 16 Standard Missile-2 (SM-2) missiles for area AAW defense and of 10 NATO SEA SPARROW Missile System (NSSMS) missiles for point defense. There are several important advantages to storing and launching these missiles from vertical launchers on a space and weight limited ship like the hydrofoil ship. Figure IV.12-1 shows an outboard profile of a feasible weapon arrangement for an 1,100-ton hydrofoil ship. The SM-2 and NSSMS vertical launchers are placed in the aft portion of the deckhouse. The fire control radars and NSSMS illuminators are located on centerline for clear angle of coverage to use the 360-degree launch flexibility of vertical launchers. The estimated weight of this 16 SM-2, 10 NSSMS installation in such a configuration is 56.3 tons for the entire system including fire control. Preliminary designs of the ship using weight and moment of this configuration have not yet been accomplished.

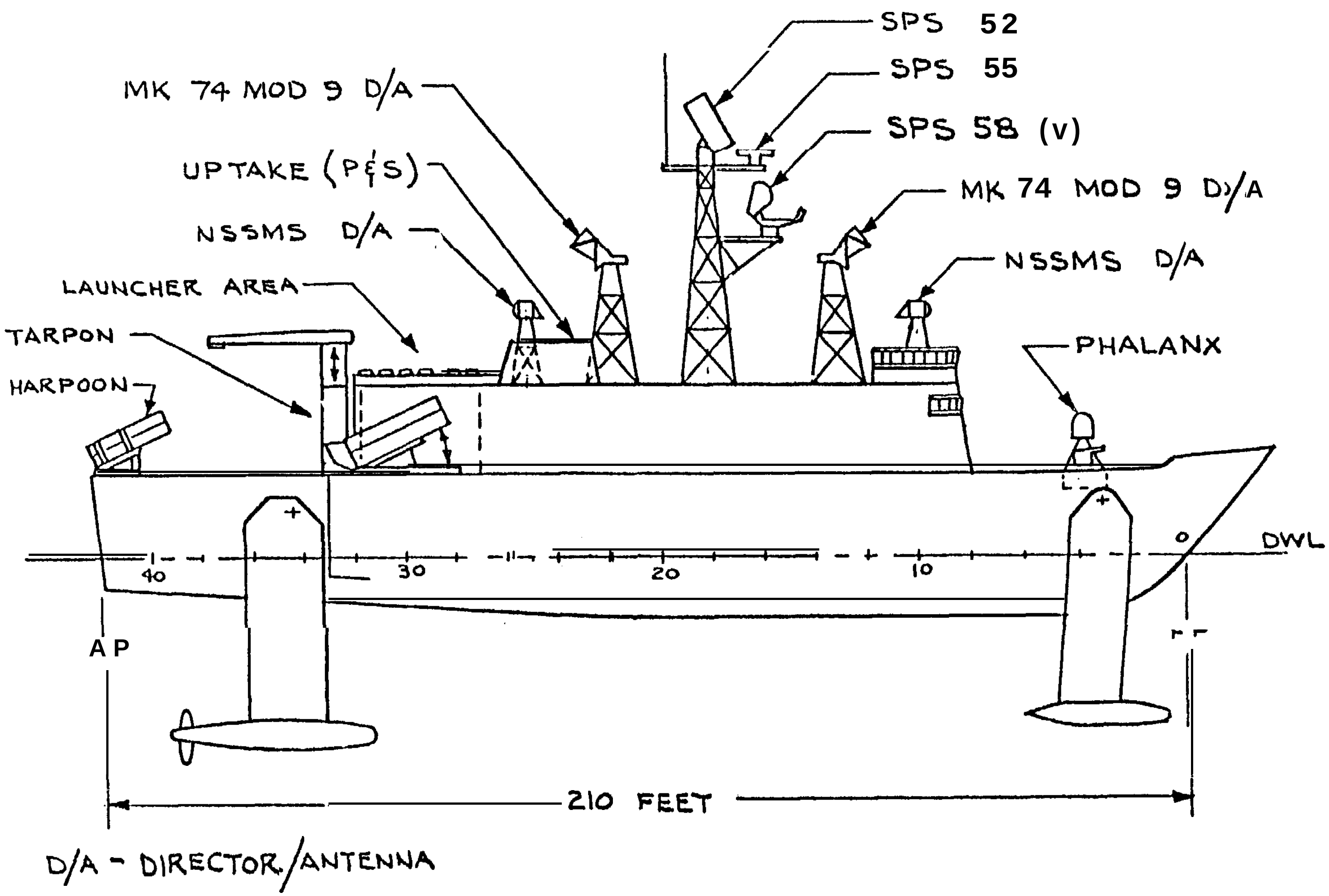

Figure IV.12-1. OUTBOARD PROFILE WEAPON ARRANGEMENT (U)

12.3.3.2 Missile Vertical Launch

(U) The results of a vertical launch feasibility study which were used for the weapon arrangement discussed in Section 12.3.3.1 are shown in Figures IV.12-2, IV.12-3, and IV.12-4. The vertical launch canister, plenum unit, and exhaust riser concepts are shown. Vertical cell launchers are preferred over other types for AAW missiles because they eliminate launcher blind zones and launcher pointing offset problems, have the lowest weight, require the smallest amount of internal space, and present little above-deck clearance problems. Figure IV.12-5 shows the vertical launcher layout. Exhaust for all missiles is through vertical risers. This arrangement allows a 30-ft centerline clear space aft on the main deck, assuming HARPOON canister launchers and triple tube torpedo launchers are placed just forward of the transom. This clear space will be required for Underway Replenishment (UNREP) from ships or from helicopters.

12.3.3.3 Closed Breech Vertical Launcher

(U) In a feasibility study (Reference IV.12-2), closed breech vertical canisters have been considered for launching AAW missiles. Use of these tubes would obviate the need for plenum doors, plenum chambers, and exhaust risers and provide a harder shipping container than the normal double-ended canister. In the closed breech launcher, the exhaust gases pass up around the missile

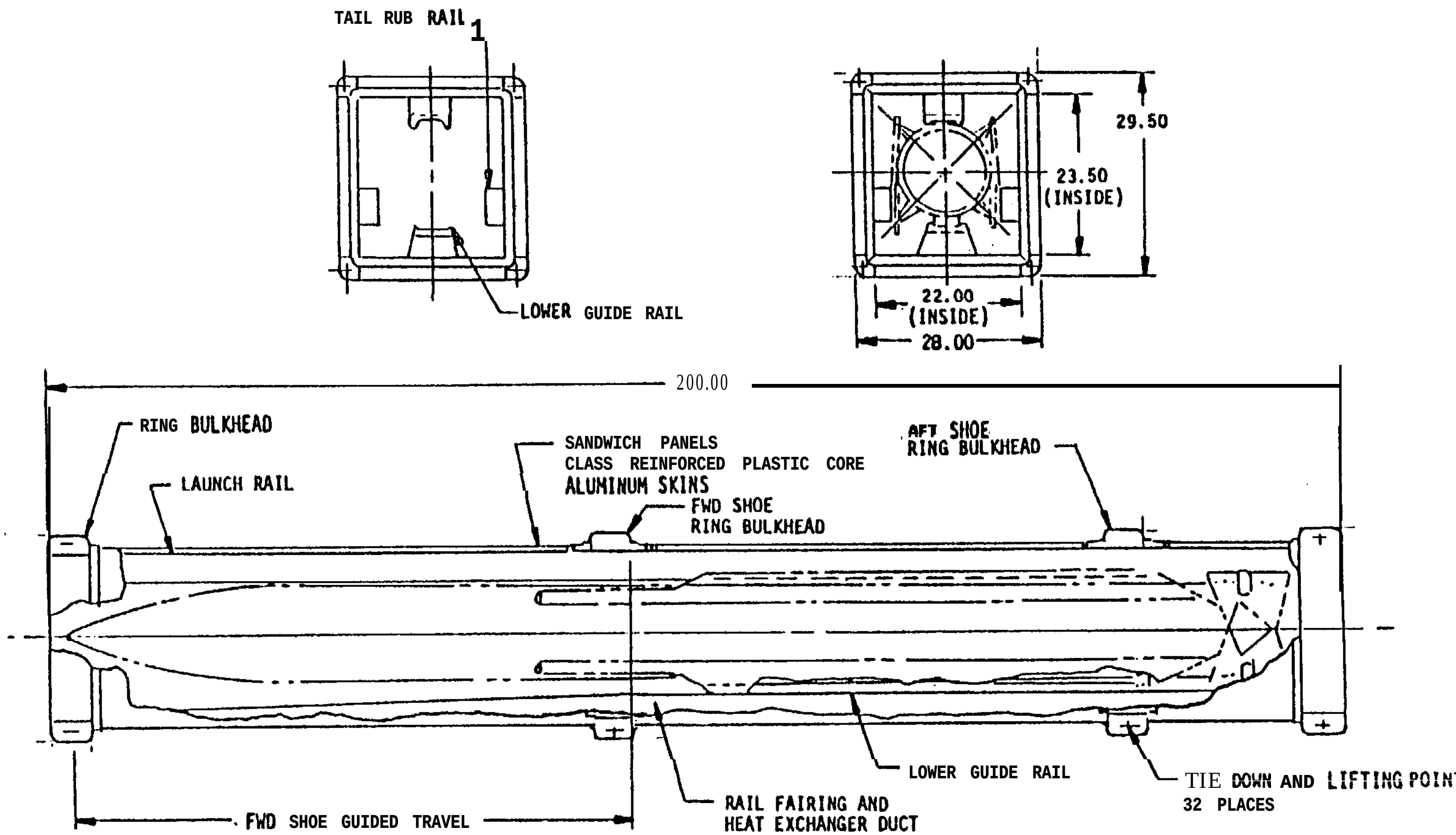

Figure IV.12-2. VERTICAL LAUNCH CANISTER LAUNCHER, GENERAL DYNAMICS CONCEPT (U)

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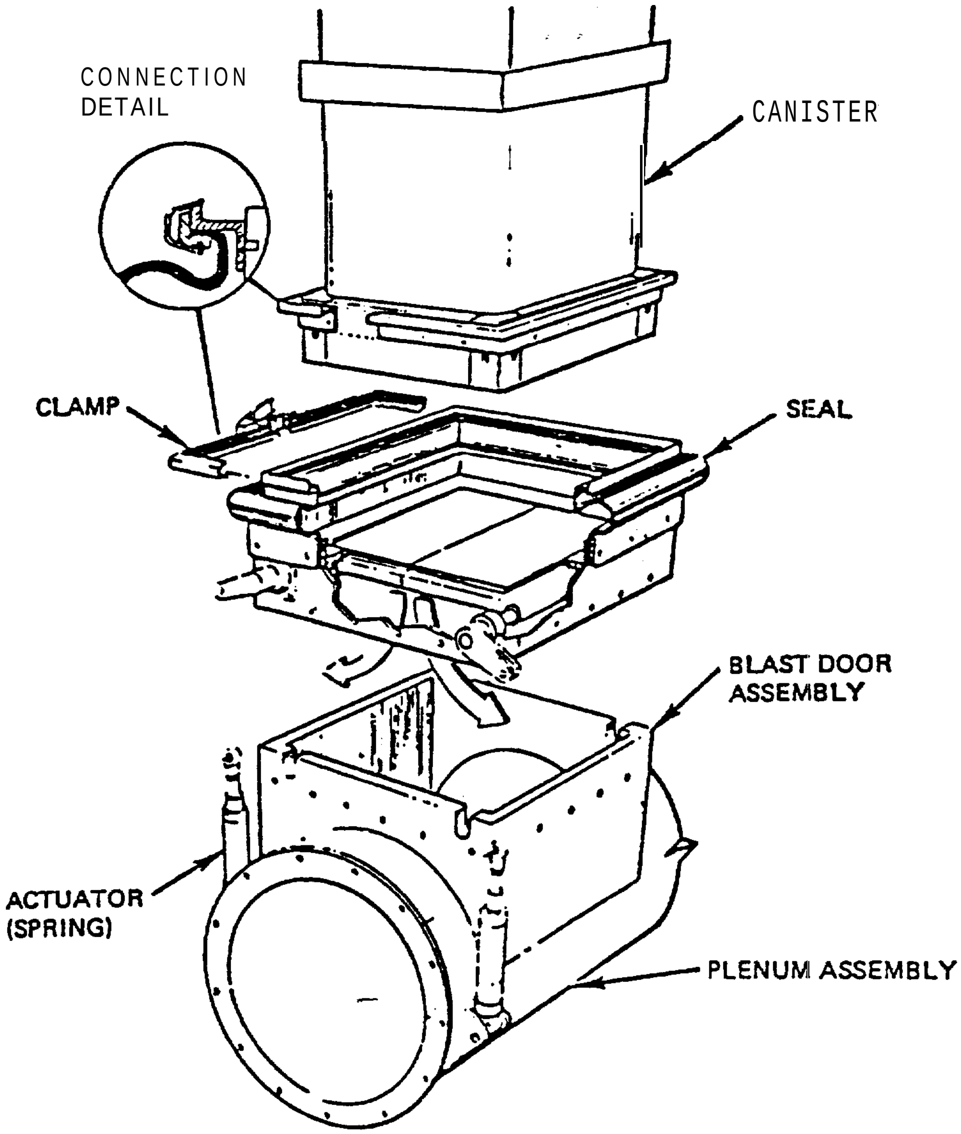

Figure IV.12-3. PLENUM UNIT AND DOORS, GENERAL DYNAMICS CONCEPT (U)

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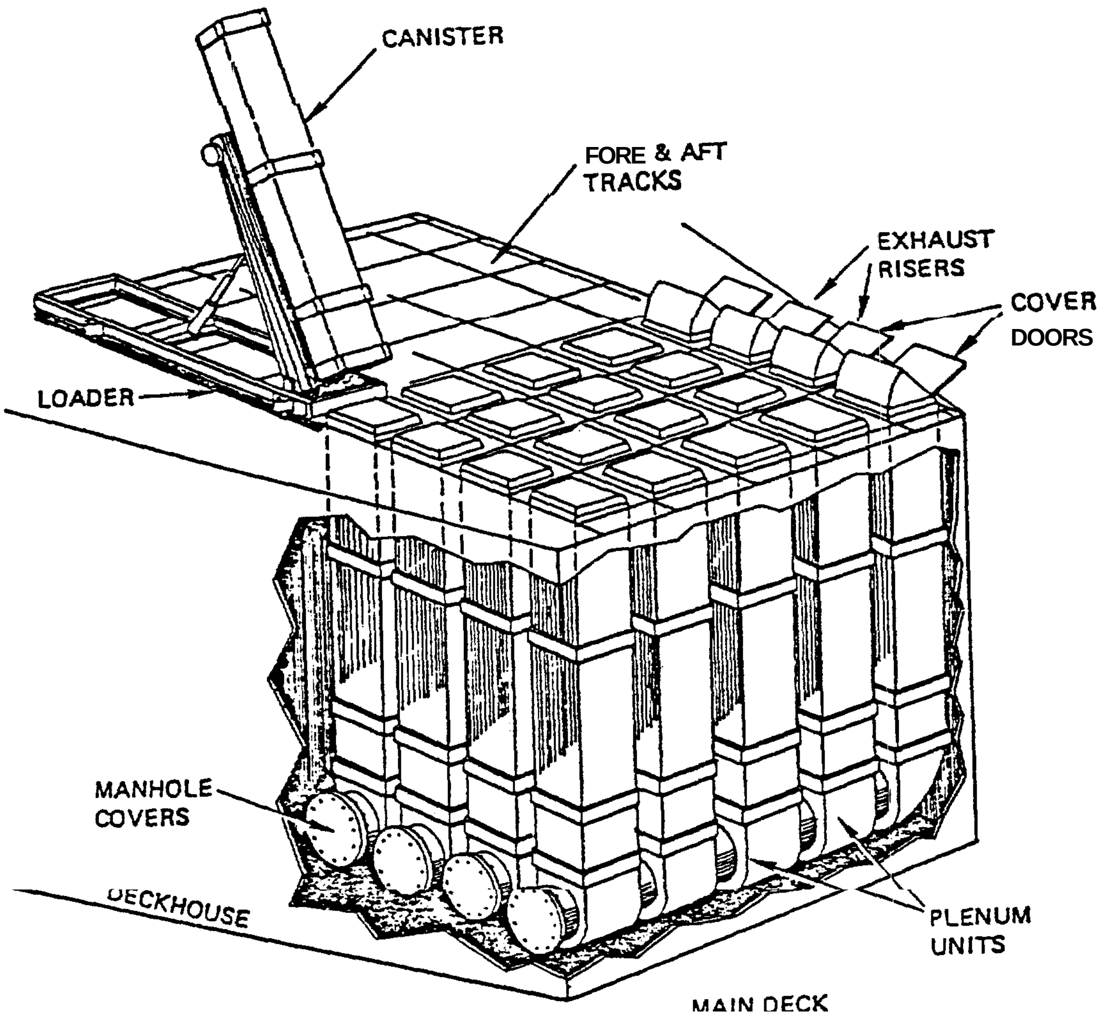

Figure IV.12-4. VERTICAL LAUNCH SYSTEM, GENERAL DYNAMICS CONCEPT (U)

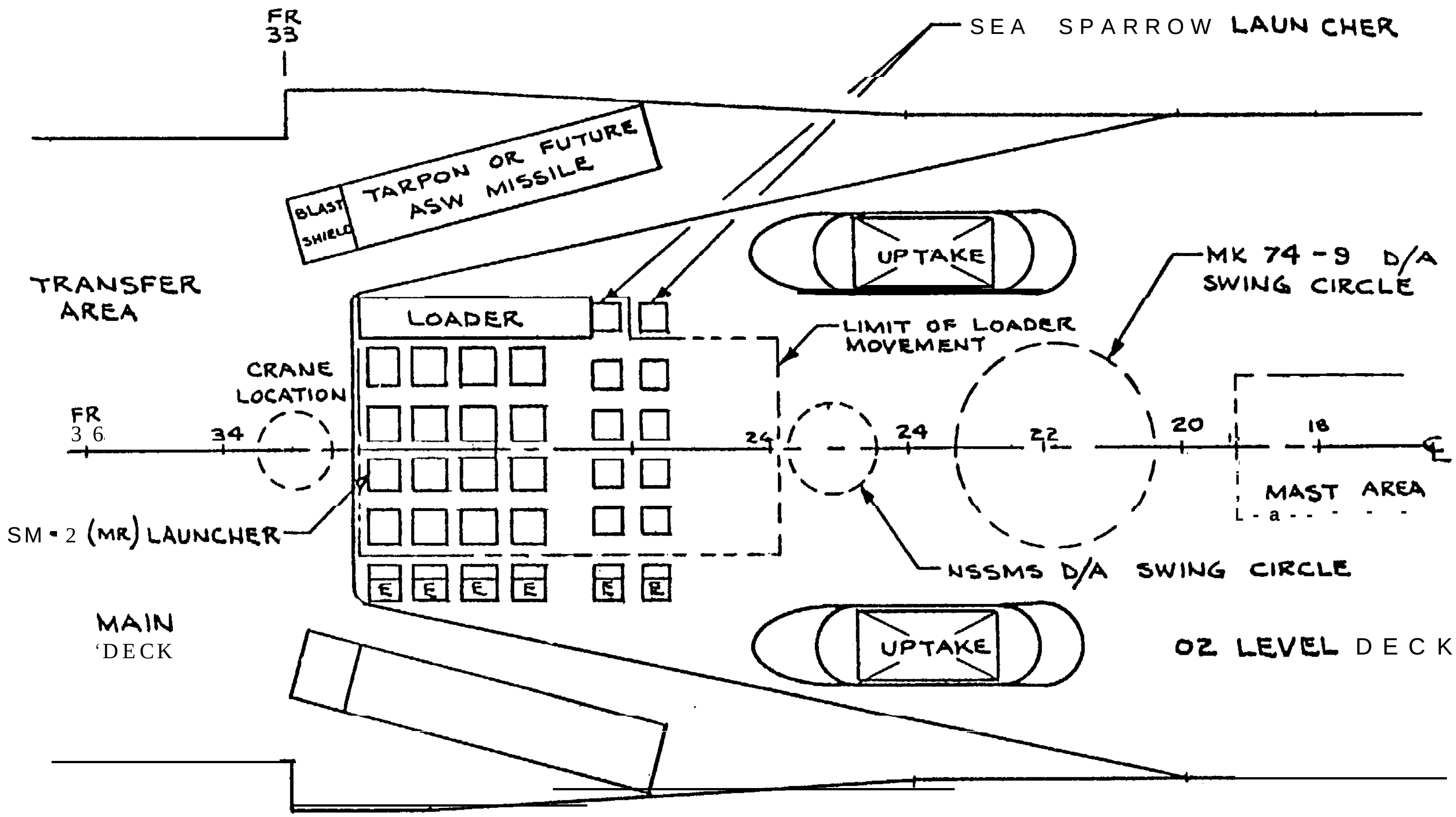

Figure IV.12-5. VERTICAL LAUNCHER AND DIRECTOR/ANTENNA LAYOUT (U) into the atmosphere through the open tube cover. The missile is subjected to hot gas pressure a fraction of a second during normal launch. During restrained inadvertent firing of the booster/sustainer, the missile is subjected to high pressure and temperature throughout burning. Thermal protection of the missile warhead will be needed and the diameter of the canister will be slightly larger than for a double-ended canister. From this concept, a reduction in launcher weight, complexity, and cost can be foreseen. Trade-off studies and preliminary designs are required.

12.3.3.4 Rearming at Sea

(U) A study (Reference IV.12-1) has been conducted to determine the feasibility of rearming the AAW missile launchers at sea for the hydrofoil configuration shown in Figure IV.12-1. Rearming the SM-2 and NSSMS missile launchers at sea will be accomplished by first transferring individual missiles in canisters from the transfer-at-sea area on main deck to the 02 level deck using a crane located at the aft end of the deckhouse. The 02 level deck at the location of the missile cavities will be fitted with fore and aft and athwartships tracks. A loader capable of reaching any missile cavity will be placed on these tracks. The general layout of this equipment is shown in Figure IV.12-5. The loader will be hydraulically operated and capable of receiving the missile in its canister in a horizontal position. The arrangement of the loader and the tracks is shown in Figure IV.12-4. The loader could be transferred to and from a supply ship to reduce dead weight. This would preclude missile transfer by helicopter unless a helicopter also transferred the loader. The crane in the main deck transfer area could also be used for loading TARPON weapons.

12.3.4 Missile Ejector Launcher

(U) A proposal has been made to apply the technology developed for airborne missile launchers to developing a low weight, low cost missile ejection launch system for hydrofoil ship applications. The system would be based on the PHOENIX ejection launcher and have the following main features:

- Capability of launching missiles from 550 to 1,500 lb in weight
- Eliminates motor exhaust blast deflectors
- 100 percent reliability demonstrated in use.

SECTION 13

MINES (SWBS GROUP 730)

13.1 HYDROFOIL AND MINE INTERFACES

13.1.1 Mine-Laying Interfaces

(U) At this time, there is no obvious reason why a hydrofoil ship could not be configured for minelaying either as a designed or alternate mission. A hydrofoil minelayer would have a transit speed advantage over a conventional surface minelayer that would be of great advantage in tactical minelaying. This capability would be useful in defensive minelaying at the outset of a war to mine initially strategic areas of shallow water to provide an anti-submarine or antisurface threat. During an amphibious operation, they could be used to seal off quickly the sides of an objective area against penetration by submarines. Hydrofoil ships have an all-weather advantage over aircraft in tactical minelaying, particularly when an enemy considers a period of bad weather as the time to start an offensive. While the hydrofoil ship obviously suffers a speed advantage compared to aircraft, it does provide improved minelaying accuracy. An advanced hydrofoil ship would have a payload advantage over naval aircraft used for minelaying. Studies (Reference IV.13-1) have been made to compare minelaying accuracies of various platforms with the caveat that the accuracies are dependent on navigation system accuracies and distance to land:

Aircraft	+ 40 to 100 ft
Conventional minelaying ship	± 20 ft
Hydrofoil minelayer	+ 20 ft

A hydrofoil ship can be presumed to be more vulnerable than an aircraft and less vulnerable than a conventional ship in waters controlled by or subject to penetration by enemy aircraft, relative to the exposure time involved. Both hydrofoil ships and conventional ships are vulnerable to defensive minefields, but the hydrofoil ship should be less vulnerable foilborne than a conventional ship to some classes of mines.

13.1.2 Minesweeping Interfaces

(U) If future operations require that minesweeping units sweep larger areas in a shorter period of time,, then hydrofoil craft are the vehicles within state-of-the-art which can perform such a mission. In addition to the high speed sweep capability, hydrofoil craft have other advantages applicable to minesweeping. A hydrofoil ship could maintain her sweep speed in much higher sea states than conventional displacement type craft (probably up to Sea States 5 or 6). Another advantage of hydrofoil craft is their relative immunity to conventional pressure signature mines while foilborne. An important disadvantage to hydrofoil minesweepers will be higher initial costs. At present there does not exist any hydrofoil craft configured for high speed minesweeping.

13.2 HYDROFOIL MINELAYING AND SWEEPING STUDY RESULTS

13.2.1 Hydrofoil Mine Warfare Study

(U) A feasibility study on a minelaying configuration of the PHM was made during 1974 for the Federal Republic of Germany. The study (Reference IV.13-2) assessed the feasibility of replacing the missiles and launchers with various types and numbers of U.S. and German mines. The study considered the quick removal of the missile equipment and installation of mine rails on each quarter for carrying the following totals of mines:

Mine Type	Number
DM 11	22
DM 21	32
DM 39	18
MK 52	24
MK 55	14

One arrangement for such an installation is shown in Figure IV.13-1. It was concluded that these loads appear feasible except that the DM 39 installation would exceed the specified full load displacement by 2 metric tons at the expense of future growth margin. However, it also concluded that the minelaying configuration based on the above mine loads would be marginally feasible from the viewpoint of acceptable limits of center of gravity height. The estimated time for reconfiguration to a minelaying mission was, 10 hours and 17 hours back to a missile configuration.

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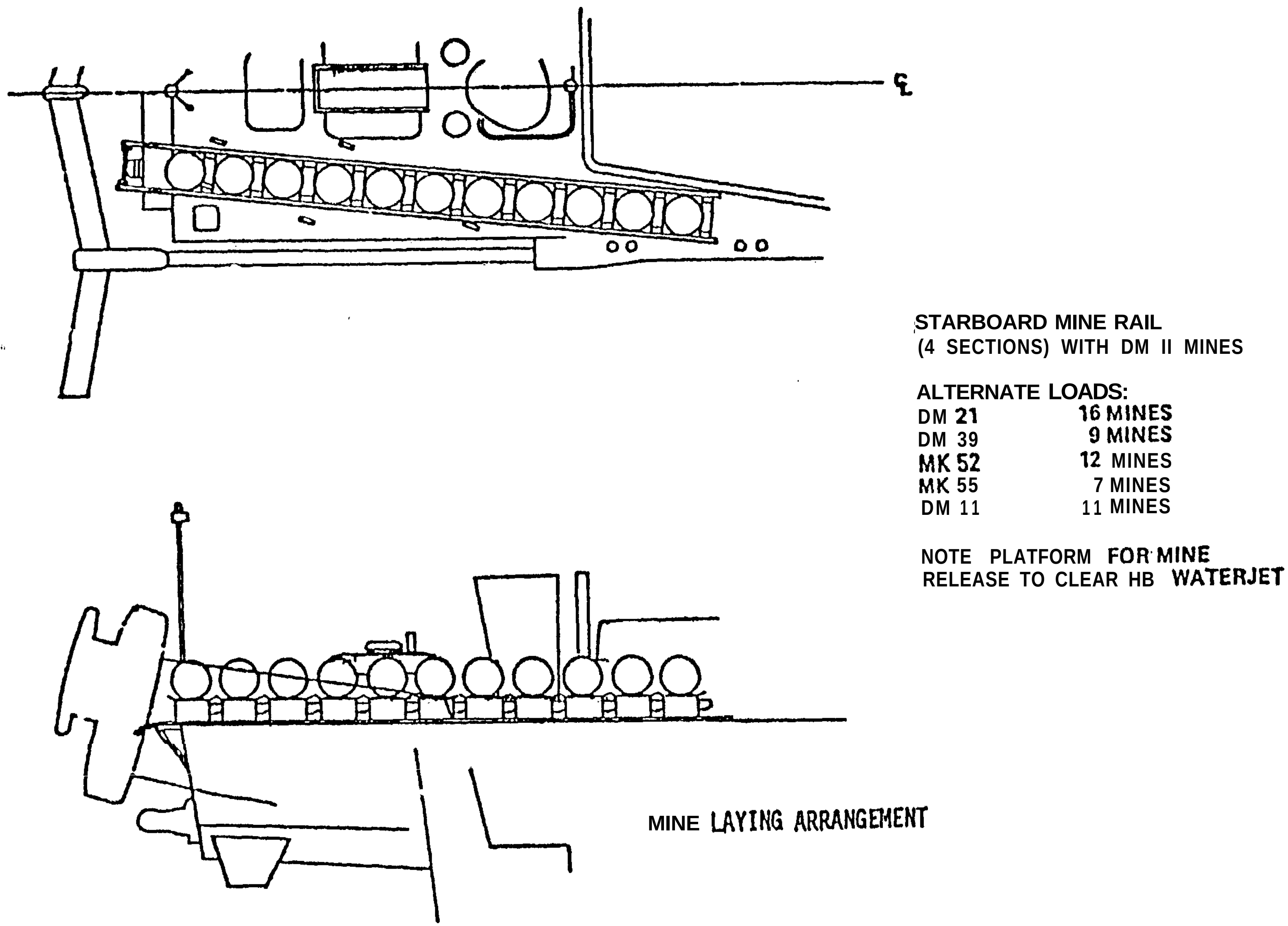

Figure IV.13-1. MINELAYING ARRANGEMENT (U)

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13.2.2 Minesweeping Hydrofoil Craft

(U) A preliminary investigation of shipborne minesweeping hydrofoil craft was made in 1962 (Reference IV.13-3). Two categories of minesweepers were investigated, one that can be handled by 26,000-lb Welin davits, the other to be lifted by standard 30-ton cranes. The conclusions from the study were that it is feasible to use hydrofoil craft for minesweeping operations at flying speeds up to 30 kn.

SECTION 14

TORPEDOES (SWBS GROUP 750)

14.1 HYDROFOIL AND TORPEDO INTERFACES

14.1.1 Operational and Performance Interfaces

(C) Feasibility of launching torpedoes from both hullborne and foilborne hydrofoil ships has been demonstrated in launching trials aboard PCH-1 and AGEH-1. Torpedoes that have been tested are the Mk 44 Mod 1 and Mk 46 Mod 1. No adverse effects from the high speed launchings were observed on either the performance of the hydrofoil ships or the performance of the torpedoes. The torpedo tubes were located amidships and angled 45 degrees on the bow and 90 degrees abeam. These locations and launch angles indicated no incompatibility. For the conceptual designs of large open ocean hydrofoil ships, various torpedo tube locations and geometries have been considered. Results of a recent study (Reference IV.14-1) indicate that there are some tube locations and launch angle combinations which potentially cause a launching incompatibility. The areas swept by the foils and the torpedo water impact points 'for various launch kinematics were considered. Figures IV.14-1 and IV.14-2 show the water entry points for second deck bow-launched and main deck quarter-launched torpedoes, both hullborne and foilborne. In both hullborne and foilborne cases the torpedoes enter water in the area swept by the after foils for the 30-degree bow-launched installation. If the torpedoes failed to start, the submerged

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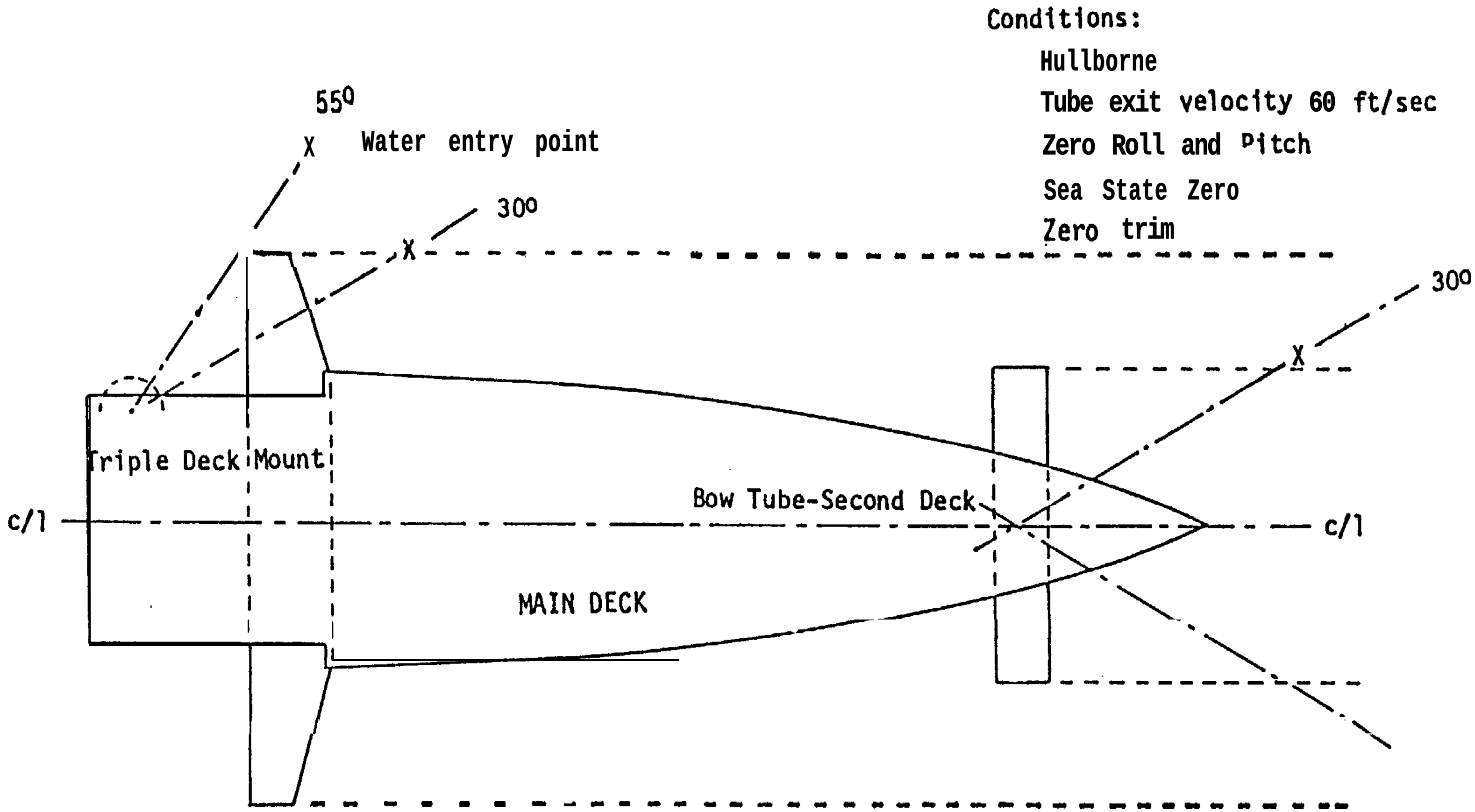

Figure IV.14-1. WATER ENTRY POINTS AND SWEPT AREAS OF FOILS (U)

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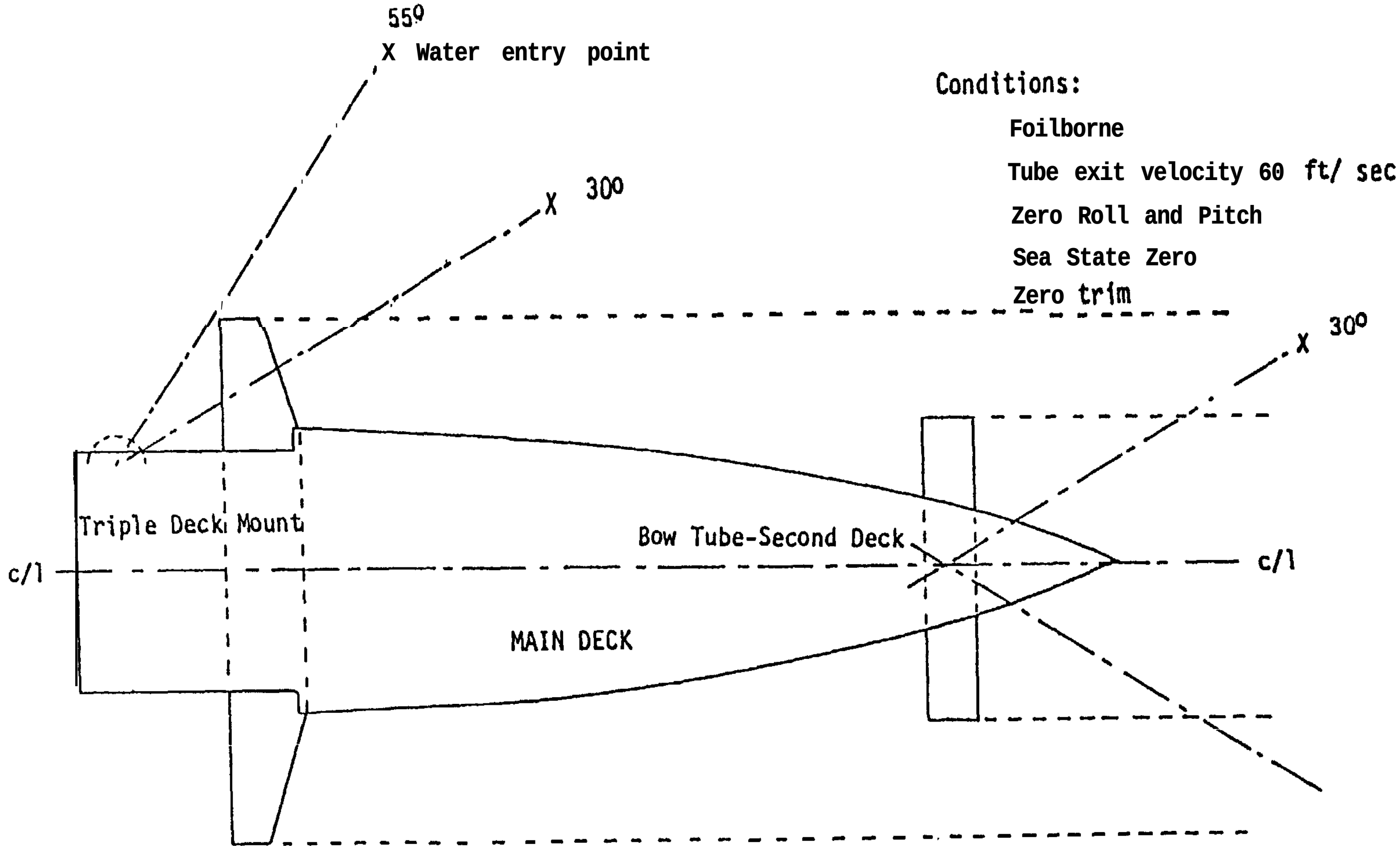

Figure IV.14-2. WATER ENTRY POINTS AND SWEPT AREAS OF FOILS (U)

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foils could strike the torpedoes. A 55-degree quarter launch will clear the after foils in all cases. Studies (Reference IV.14-2) have shown that the ASW weapon with the highest kill probability against sophisticated future submarines is the Mk 48 torpedo with a wire-guidance option. Launching of this torpedo from a hydrofoil ship has not been demonstrated. There is some concern about launching a wire-guided torpedo forward and about launching the Mk 48 from a large foilborne hydrofoil ship with a high drop height. To alleviate these concerns, a second deck Mk 48 installation with the tubes angled outboard and aft at 150 and 210 degrees has been considered. Study shows (Reference IV.14-1) that the water entry points for this arrangement also fall within the area swept by the aft foils. For the Mk 48 torpedoes, second deck stern launch is probably required to avoid wire interference and minimize drop height. From a water entry safety point-of-view, both stern launch and main deck quarter launch are satisfactory.

14.1.2 <u>Technical and Physical Interfaces</u>

(U) There are no technical or physical interfaces between hydrofoil ships and torpedo weapon systems which would prevent installation of suitable launch tubes, torpedo handling equipment, and spares and provision of sufficient torpedo stowage space required for an effective ASW weapon system.

14.2 TORPEDOES AND ASW WEAPON SYSTEMS COMPATIBLE WITH HYDROFOIL SHIPS

14.2.1 Small Hydrofoil Ships

(C) The Mk 46 torpedo is the available and compatible ASW weapon for small hydrofoil ships. A small hydrofoil ship in this sense has less than 300-ton displacement. Study results (Reference IV.14-3) indicate that an effective ASW system could be assembled and installed aboard a small hydrofoil ship. The weapons part of the system could consist of two Mk 32/9 triple tube launchers, 12 Mk 46 Mod 1 torpedoes, and torpedo handling equipment. The weight of the weapons would be about 6 tons including torpedo fire control. In the future, the Advanced Lightweight Torpedo (ALWT) will be available and compatible with small hydrofoil ships. The characteristics of the Mk 46 Mod 1 and the ALWT are given in Table IV.14-1.

14.2.2 Large Hydrofoil Ships

(C) For large hydrofoil ships of 800 to 1200 ton displacement, the Mk 46 Mod 1, ALWT and Mk 48 Mod 1 torpedoes are compatible. Characteristics of these torpedoes are shown in Table IV.14-1. While the Mk 48 is physically compatible with large hydrofoils, arrangements would represent large compromises because of reload space required, and weight excess over an effective ALWT installation could cause fuel of mission system payload compromise which may cause the Mk 48 to be rejected in future trade studies. The Mk 48 torpedo is roughly seven times heavier than the Mk 46 Mod 1, and carries almost seven times the explosive load. Reference IV.14-2 shows that

TABLE IV.14-1. COMPATIBLE TORPEDO CHARACTERISTICS (U)

	MK 46 MOD 1	MK 48 MOD 1	ADVANCED LIGHTWEIGHT TORPEDO (ALWT) *
Length (in)	102	230	To be determined
Diameter (in)	12.75	21	To be determined
Weight (lb)	508	3415	To be determined
Explosive Weight (lb)	100 PBXN-103	645 PBXN-103	To be determined
Operating Depth (ft)	20-1500	lo-2500	10-2500 (goal)
Speed (knots)	45	Runout 40 or 55 Search 28 or 40 Homing 28 to 55	55 (goal)
Endurance (yds)	10,500 at 750 ft depth	22,300 at 100 ft depth at 55 knots	15,000 (goal)
Detection Range (yds)	1600 max. active	5000 max. active: 4000 passive 10 dB target	3000 (goal)

*Required size and effectiveness of the ALWT is presently under study.

significantly higher kill probabilities against future submarine threats are obtained with the Mk 48 over the Mk 46 because of the limited Mk 46 warhead. The Mk 48 provides a considerable SUW capability.

(C) When available the ALWT will be physically compatible with large hydrofoil ships. The ALWT will enjoy advanced technology to the extent that it will be rid of Mk 46 weaknesses and have performance of a lesser order than the Mk 48, but sufficient in all respects to produce a high probability of kill. While the characteristics are not yet firm, it can be expected that ALWT will be about 25 percent of Mk 48 weight and will be slightly larger than the Mk 46 Mod 1.

(C) For a large multi-mission hydrofoil ship of 1985-1990, the ASW torpedo system will probably be the ALWT torpedo. In earlier large hydrofoils Mk 46 and/or Mk 48 torpedoes would be used. If ASW standoff weapons are fitted, whatever system is developed by the Navy of TARPON, ALWT warhead cruise missile, or MITOR would be used. These weapons are regarded as missiles in the SWBS.

14.3 HYDROFOIL TORPEDO TEST AND ASW WEAPON STUDY RESULTS

14.3.1 Mk 44 Torpedo Tests on PCH-1

(C) In March of 1968, high speed torpedo launching trials were conducted aboard the PCH-1. Six Mk 44 Mod 1 torpedoes were launched out of Mk 32 torpedo tubes to determine launching effects on hydrofoil ship behavior and to determine any damage or adverse effects on torpedo operating characteristics caused by high speed launch. The tubes were located amidships and angled forward at 45 degrees. The following conclusions were reached from these trials (Reference IV.14-4):

- Reactions of launchings on foilborne hydrofoil ship stability were negligible.
- Mk 44 torpedoes can be successfully launched at foilborne speeds of 40 and 45 kn.
- Tube angle depression of 5 degrees gives no apparent advantage over 0 degrees.
- Launch conditions must be programmed so that the torpedoes see the target first after enabling because the ship's radiated noise and wake affect torpedo homing.
- Torpedoes will acquire and home on foilborne ship radiated noise at ranges of 1,700 yd or less and will attack the hydrofoil ship wake at ranges up to 700 yd.

14.3.2 Mk 46 Torpedo Tests on AGEH-1

(C) In February 1972, foilborne torpedo launching trials were conducted aboard the AGEH-1. Five Mk 46 Mod 1 torpedoes were launched from Mk 32 Mod 5 torpedo tubes. The triple tubes were located about amidships with the top tube 22 ft above the flying waterline. The launchings were done at forward 45-degree angles and 90-degree angles abeam. The main objective was to evaluate hydrofoil ships' foilborne launching capabilities and determine Mk 46 homing and dynamic behavior. The torpedoes were launched successfully from a straight course at speeds of 40 and 45 kn and both tube angles. Torpedo deployment in turn was cancelled. Torpedo gyroscopes deflected upon water entry, but programmed headings were achieved during the dive period. Homing logic and acoustic circuits operated normally, resulting in valid target acquisition to ranges over 2,000 yards.

14.3.3 ASW Weapon System Studies

(C) For a large ASW hydrofoil ship, Mk 46, ALWT, and/or Mk 48 torpedoes are considered feasible over-the-side ASW weapons. One study (Reference IV.14-2) indicated a quantity of eight Mk 48 torpedoes as a weapon suit with possible launching location on the second deck in the bow and the tubes angled at either 30 degrees or 150 degrees to the centerline. The weight of the torpedoes and handling equipment is estimated at 17 tons. Another recent study (Reference IV.14-1) for weight and space purposes considered the following ASW over-the-side weapon suits:

18 Mk 46 torpedoes located in after torpedo room, launched astern from two tubes	7.1 tons
18 Mk 46 torpedoes in Mk 32 triple tubes, one on each quarter	8.4 tons
8 Mk 48 torpedoes located in after torpedo room, launched astern from two tubes	17.1 tons
8 ALWT (750 pounds) located in after torpedo room, launched astern from two tubes	5.2 tons
12 ALWT located in after torpedo room, launched astern from two tubes	7.0 tons
8 ALWT in Mk 32 triple tubes, one on each quarter	6.7 tons
12 ALWT in Mk 32 triple tubes, one on each quarter	8.5 tons

The study recommends the 18 Mk 46 torpedoes in an aft torpedo room while the ALWT is not yet available, then going to 12 ALWT located in an aft torpedo room when the advanced torpedo becomes available. Preliminary deck layouts for main deck triple tube locations and second deck aft torpedo room arrangement were also considered in this study. Figure IV.14-3 shows a main deck quarter Mk 32 triple tube installation. It allows ample room for sonar machinery on the second deck. The figure also shows possible HARPOON and TARPON installations on the main deck. Figure IV.14-4 shows an after torpedo room for Mk 46 or ALWT on the second deck. This space will accommodate 18 Mk 46 torpedoes or 12 ALWTs. Figure IV.14-5 shows a second deck centerline installation of an aft torpedo room for eight Mk 48 torpedoes. Sonar mechanical equipment is split on either side, one for APRAPS, the other for VDS and/or towed line array. The Mk 48 room is 45 ft long as required for loading.

14.3.4 Nontorpedo ASW Weapon Study

(U) A study has been recently conducted (Reference IV.14-5) to investigate feasibility of developing hydrofoil ASW weapon system alternatives to the acoustic homing torpedo. It was motivated by the observation that ASW weapons are becoming increasingly sophisticated and prohibitively expensive. The study concluded that a relatively inexpensive high sink speed underwater rocket with limited guidance could be developed and effectively used by a hydrofoil using overfly tactics and short range imaging attack sonar. Compatibility of such a system with hydrofoil ships has not been established.

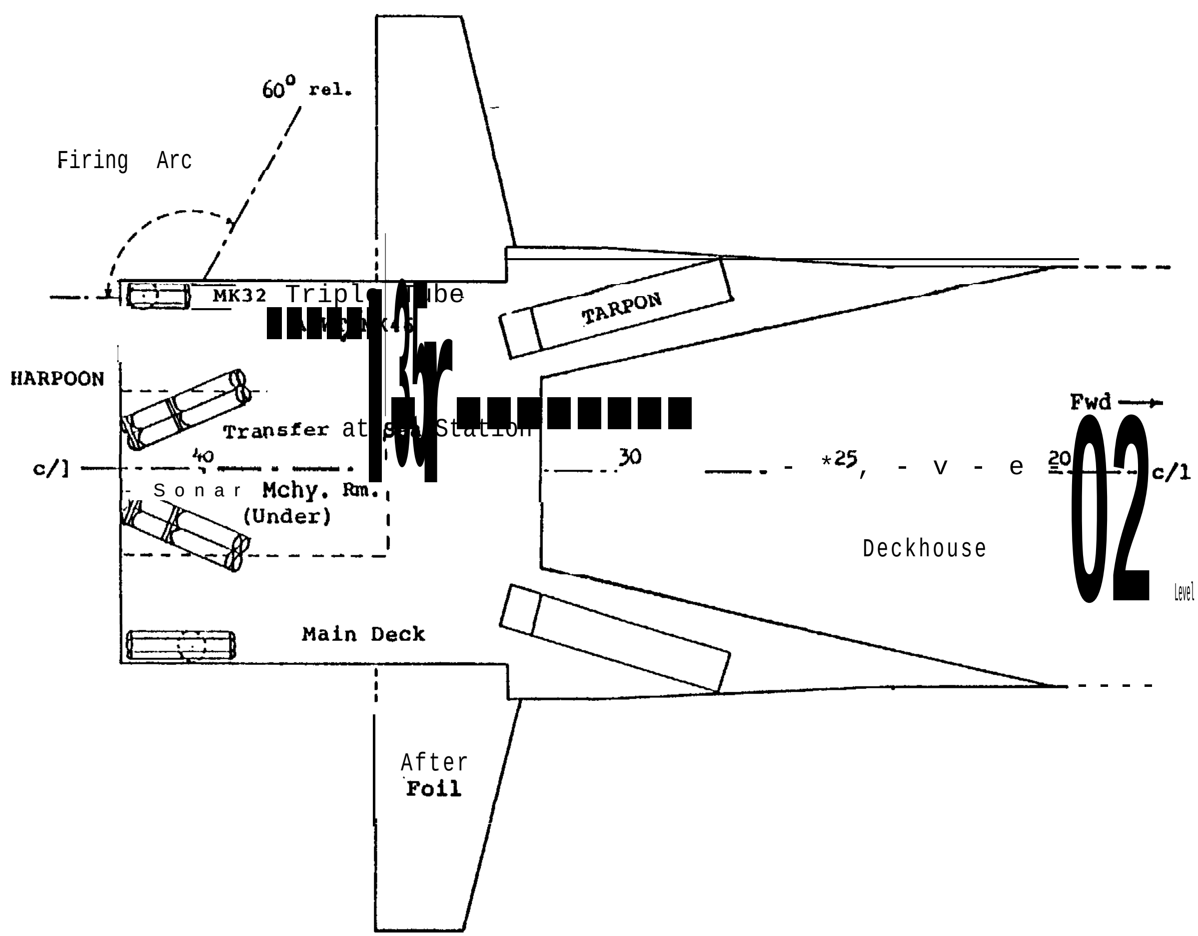

Figure IV.14-3. TORPEDO TUBE LOCATION – MATNDECK AFT ALTERNATE FOR ALWT/MK 46 TORPEDOES (U)

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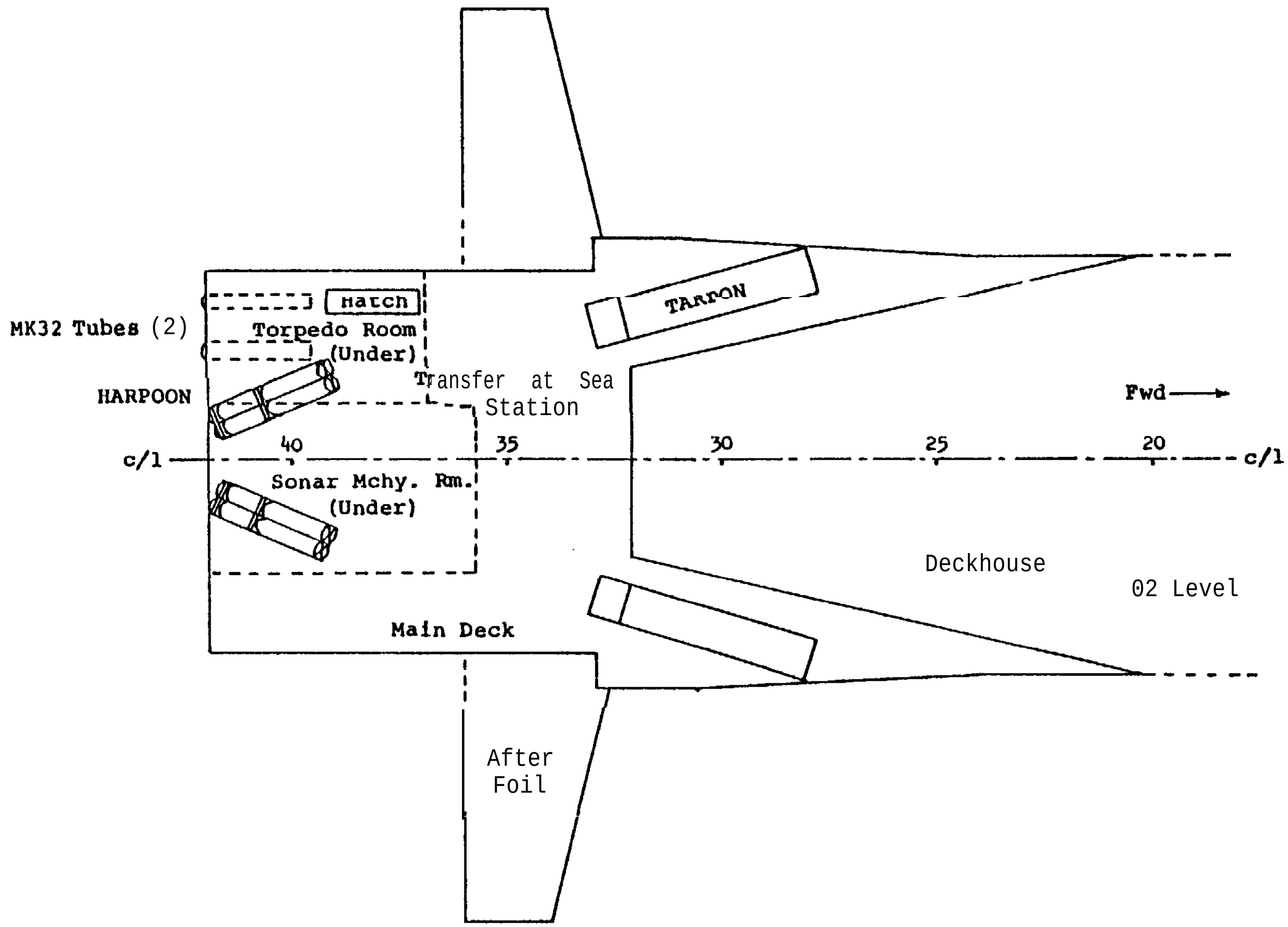

Figure IV.14-4. TORPEDO TUBE LOCATION - STERN TUBE ALTERNATE FOR ALWT/MK46 TORPEDOES (U)

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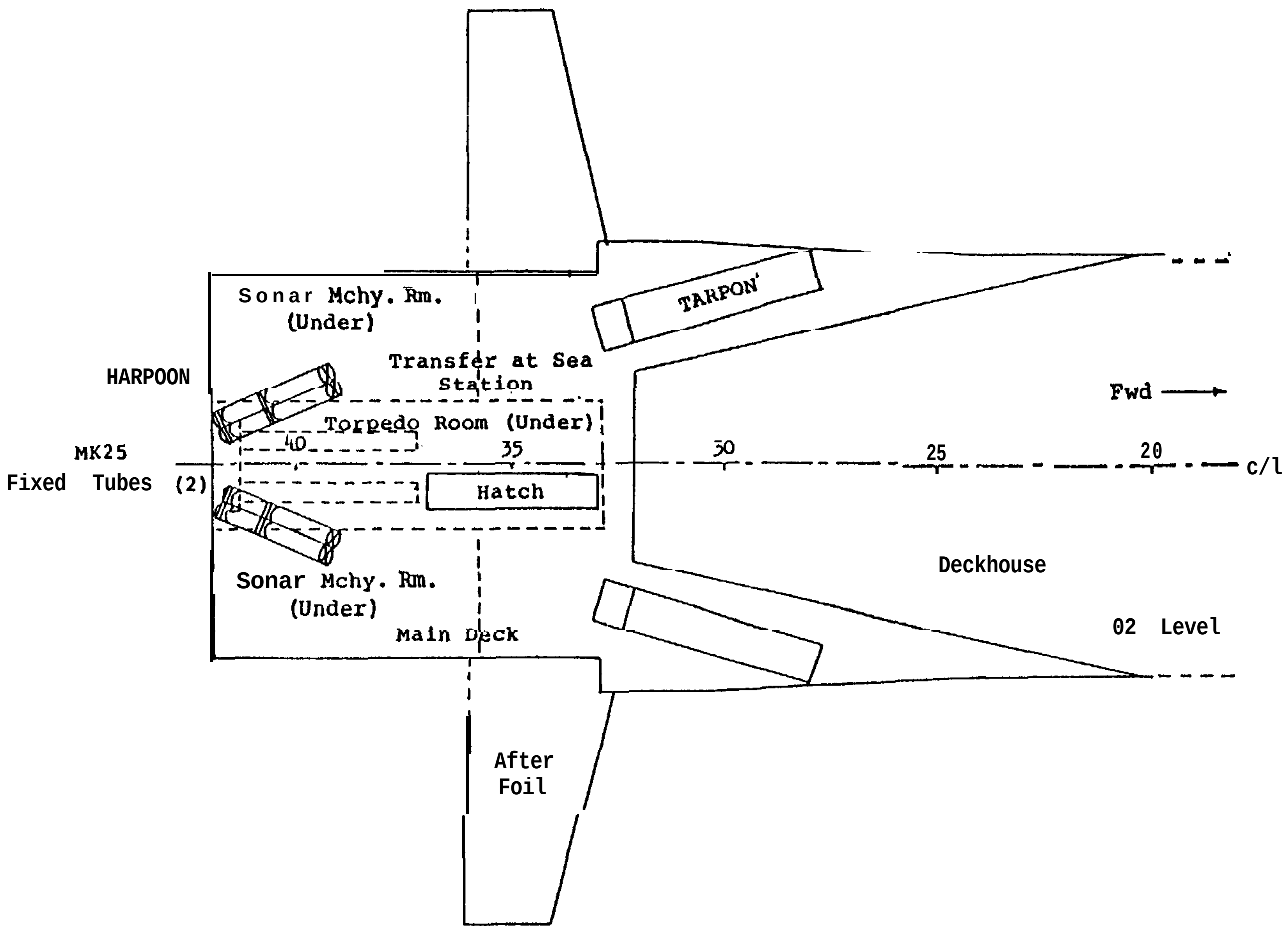

Figure **IV.14-5.** TORPEDO TUBE LOCATION - STERN TUBE ALTERNATE FOR MK48 TORPEDOES (U)

SECTION 15

SMALL ARMS AND PYROTECHNICS (SWBS GROUP 760)

15.1 INTERFACE PARAMETERS

(U) Inasmuch as small arms and pyrotechnics are not installed in ships but rather are allowance items for which stowage is provided, there are no compatibility features or interface parameters meriting discussion. Operation of hydrofoil ship and small arms and pyrotechnics affects the performance of neither. Both small arms and pyrotechnics have been and will be accommodated in Navy hydrofoil ships. Small arms locker and ammunition storage is provided below decks. Pyrotechnic materials stowage is in one or more topside lockers, with ready stowage for specific devices on the bridge and at emergency locations.

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V. VULNERABILITY AND SURVIVABILITY

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V. SURVIVABILITY AND VULNERABILITY

Section 1

INTRODUCTION

(U) This section reviews hydrofoil ship vulnerability and survivability in the context of the various hazards which a hydrofoil ship could experience in its lifetime.

(U) In this section, attempts are made to compare the significance, the differences, and the differing implications, of the various hazards as they pertain to hydrofoil ships, compared with conventional surface ships.

(U) Most of the hazards identified and discussed have not been encountered by hydrofoil ships and most are impractical to evaluate on the basis of specific tests. Therefore, this section can only discourse rather than provide a basis for assessment supported by analyses or data.

(U) The following definitions relate to the scope and content of this section.

a. Hazard

A hazard is any factor which can degrade, or contribute to degradation or disablement of, hydrofoil mission capability, ship performance, and safety.

b. Vulnerability

Vulnerability is a measure of the susceptibility of a hydrofoil ship to the effects of hazards.

c. Survivability

Survivability is a measure of the capability of a hydrofoil ship to sustain the effects of the hazards.

1.1 VULNERABILITY AND SURVIVABILITY

(U) The various factors which may be considered as hazards, or as sources of hazards, are identified herein. Factors which are considered to be of greater potential consequence for hydrofoil ships than for conventional surface ships are identified by an asterisk. Factors which are considered to be of lesser potential consequence for hydrofoil ships than for conventional surface ships are identified by a shaded circle. Factors which are considered to be of equal consequence for hydrofoil ships and conventional surface ships are not marked.

(U) The various factors considered in this review of hydrofoil ship vulnerability and survivability are categorized:

a. Static factors

b. Navigational Factors

c. Environmental Factors

d. Combat Factors

Dynamic factors such as stability and fatigue are addressed elsewhere in this document.

1.1.1 Static Factors

(U) Static factors are factors which can influence readiness or availability for service when a hydrofoil is assigned or needed. They include hazards which might be experienced when in port or when undergoing construction, overhaul, or repair.

a. Drydocking *

b. Corrosion *

c. Fracture *

1.1.2 Navigational Factors

(U) Navigational factors are factors which can influence ship performance or military capability.

a. Navigation *

b. Grounding •

c. Flooding •

d. Mooring, Berthing *

1.1.3 Environmental Factors

(U) Environmental factors are factors which can influence ship design or performance:

a. Sea Ice *

b. Sea Conditions •

c. Boarding Seas •

d. Topsides Snow, Ice Accretion *

e. Floating Objects, Debris *

f. Wave Impact

1.1.4 Combat Factors

(U) Combat factors are factors which can influence ship performance or military capability. They are subcategorized as follows:

1.1.4.1 Hydrofoil Ship Signature

(U)
a. Radar

b. Acoustic

c. Pressure

d. Magnetic

e. Infrared

1.1.4.2 Weapon Effects

(U)
a. Blast Overpressure - Air Burst, Explosive
- Air Burst, Nuclear
- Other Weapons

b. Shock *

c. Electromagnetic Radiation, Nuclear

d. Contamination, Nuclear, Biological, Chemical

e. Weapon Strikes, Projectile, Missile,, Mine, Ballistic Fragment *

f. Flash

1.1.4.3 Induced Effects

(U)
a. Explosion *

b. Fire *

c. Electra-Mechanical Malfunction *

d. Structural Failure *

1.1.4.4 Protective Measures

(U)
a. Redundancy and Separation *

b. Protective Systems *

c. Speed and Maneuvering •

- - -

Section 2

STATIC FACTORS

2.1 DRYDOCKING

(U) Drydocking is normally a low hazard for any ship. It represents a lower hazard for a conventional surface ship than for a hydrofoil, for reasons which will be discussed. It is a lower hazard for any ship when effected in a graving dock than when effected in a floating dock.

(U) As a rule, drydocking damage is not common, and seldom is catastrophic damage incurred. However, when it occurs, it occasions significant delay and added cost.

(U) There have been no drydocking incidents involving hydrofoil ships. However, drydocking is a more complex problem for hydrofoil ships than for conventional surface ships and so represents a somewhat greater hazard.

(U) Assuming that drydocking is required for work on the underwater hull and on the foil system, or foil system propulsion machinery components, then a hydrofoil must be capable of being docked such that the extended foil system can be accommodated. This means that the ship must either enter dock with the foils extended, or it must enter dock with the foils retracted, assuming retractability, following which the foils will be extended.

(U) Keel blocking in most drydocks is 4 feet high and is 6 feet high in some cases. These heights are adequate for any conventional surface ship. If the foils are to be lowered in dock, a hydrofoil ship requires far higher keel blocking, to allow the foils to clear the dock floor. A hydrofoil ship such as AGEH-1 requires a keel block height of about 20 feet. The problems of docking hydrofoil ships then become complicated by applicable combinations of the following considerations:

a. Foil systems are fixed, or are retractable

b. Retraction is radial, or is vertical

c. Radial retraction is athwartships or fore and aft

d. Foil system arrangement is airplane, canard, or tandem

e. Foil system configuration is inverted tee, inverted pi, or a combination of both

f. Maximum flooded depths, and maximum distance between wing walls, of dock

g. Size of ship, particularly below keel depths of foil system

(U) The key issue is that of obtaining sufficient water depth in which to swim the ship into the dock so as to clear the keel blocking. The issue is simplified if the ship has retractable foils which can be extended after the ship is seated. However, radial athwartships extension will influence the size of dock which can be used. This issue is simplified if the ship is capable of radial fore and aft extension.

(U) These problems can be simplified further by not erecting keel blocks but instead erecting foil blocks. The ship can then be swum in with foils extended, seated on its foils, and then supported by keel blocking, erected after the dock has been pumped out. However, no hydrofoil ship has been docked in this manner. The technique is feasible and may be demonstrated with AGEH-1 in 1977.

(U) Past experience indicates that hydrofoil ships with retractable foil can be drydocked with foils retracted. Therefore, conventional docking can be used. Repair to foil systems can be readily accomplished with foils retracted.

2.2 CORROSION

(U) Corrosion is an insidious, persistent, but low hazard for any ship, given proper inspection and maintenance. Superficially, it is a lower hazard for an aluminum ship than for a steel ship. The main source of corrosion risk for aluminum hull ships is the proximity of steel ships, or of scrap metals in the water, particularly when in shipyards or repair facilities.

2.3 FRACTURE

(U) With the advent of the all welded ship, fracture was, for a time, a very serious hazard in surface ships. It was attributable to high stress concentrations in the structure, or to high stresses which were locked into the structure as a result of poor weld sequencing. These problems have long been overcome.

Section 3

NAVIGATION FACTORS

3.1 NAVIGATION

(U) Hydrofoil ship navigational hazards may be attributable to:

a. Possible incidents resulting from the high speed of a foilborne hydrofoil ship.

b. Possible incidents due to the disproportionately deep draft of a hullborne hydrofoil ship operating with its foils extended.

(U) Item a listed above is of significance in inshore waters, or in waters heavily traveled by shipping, in which the foilborne hydrofoil ship must be alert to natural hazards and to the hazards that can be posed by other shipping which might, on occasion, include other high performance ships.

(U) When foilborne at speed, the hydrofoil ship is very maneuverable, and enjoys the flexibility of rapid transition from high speed to lesser, very low, or zero speed to avoid hazards. The latter capabilities have often been used, and are the subjects of specific operations trials plans and trials reports. The main deficiency which hydrofoil ships, and other high performance ships face, at present, is the lack of a navigation system which is responsive in terms of real time plotting, identification, display and data presentation, and update capability compatible with the high mobility of the hydrofoil ship.

(U) Responding to this deficiency, the crew of PCH-1 devised and assembled a prototype high performance ship Tactical and Navigation Collision Avoidance Video (TANCAV) system which has been in everyday use in PCH-1. The system is presently completing evaluation under a trials plan and the findings will be reported. Initial procurement has started for an integrated navigation and collision avoidance system based on refinement and improvement of the PCH-1 prototype unit. This new system will be installed in AGEH-1 for formal evaluation and potential future use in naval ships.

(U) Item b listed above is of significance because a hydrofoil ship, when operating hullborne with foils extended, has a deeper limiting water depth than the displacement or dimensions of the ship itself would make apparent. To illustrate, the 320 ton AGEH-1 has a hullborne draft of 26 feet when the foils are extended. This is equivalent to the draft of an 18,000 ton cruiser. Therefore, it introduces a sensitivity to the risks of grounding because a hullborne hydrofoil ship would be more limited by water depth than say, a destroyer. However, there are other factors involved, as discussed in Subsection 3.2.

3.2 GROUNDING

(U) Grounding is a hazard of navigation.

(U) Any ship is limited by its draft to the depth of water in which it can safely operate. Unlike conventional surface ships, a hydrofoil ship can operate at three drafts, namely:

a. Hullborne, foils retracted

b. Hullborne, foils extended

c. Foilborne

(U) Its draft will be the least in case c and greatest in case b. In case b the draft of a hydrofoil ship is disproportionate to its size, if compared with conventional surface ships. However, the variable draft capability of hydrofoil ships offers a measure of operational flexibility, with variations in the hazards associated therewith.

a. Hullborne, Foils Retracted. A hydrofoil ship operating in this mode, can operate in more shallow water than, say, a destroyer. However, should it ground or strike a submerged object, the hull envelope could be penetrated. The hazard would be the same as for a conventional surface ship under similar circumstances. If grounded, a hydrofoil ship could acquire a measure of added buoyancy by extending its foils, if the latter was feasible.

b. Hullborne, Foils Extended. A hydrofoil ship operating in this mode would require much deeper water than, say, a destroyer. Should a hydrofoil ship ground on, or strike a submerged object with its foils, hull damage could be avoided or minimized if the struts were designed with breakaway joints. With the latter, a hydrofoil ship would be less vulnerable than a conventional ship because the hull of the latter would take the ground or impact the submerged object. If grounded or otherwise held by a submerged object, a hydrofoil ship might be able to free itself by unlocking its foils.

c. Foilborne. Operating in this mode, hydrofoil ships will require significantly less operating water depth than, say a destroyer, and could be operating at least as fast as the maximum speed of the latter. If either type of ship was required to operate in uncharted waters, the hydrofoil ship might be somewhat less vulnerable than the destroyer if it was operating in a water depth greater than that of its hullborne, foils extended, draft.

(U) For the future, two types of protective measures should be investigated and developed.

(U) The first is strut breakaway joints. Such joints are provided in PGH-1 and the commercial Jetfoil, but have only been initially investigated by the U.S. Navy for naval hydrofoil ships. Continuation of such investigation is recommended, and should include segmented foil systems.

(U) The second is a structural foil impact energy absorption system to protect hulls against impact by the foils. The PHM-1 has such a system installed.

3.3 FLOODING

(U) Flooding is a hazard of navigation and could result from collision or grounding.

(U) Hydrofoil ships are designed to U.S. Navy subdivision and damage control standards, and so the hazard of flooding is nominally the same in hydrofoil ships as in conventional surface ships.

3.4 MOORING, BERTHING

(U) When mooring, berthing, transiting locks, or securing alongside tenders or other ships, hydrofoil ships must have space to ensure clearance for their foil tips, which usually extend beyond the beam of the ship in either the extended or retracted positions. This means that the foils are vulnerable, or capable of damaging other ships, tugs, fuel lighters, etc. Common practice is to provide camels to ensure adequate clearance. However, the use of camels may not always be feasible and, moreover, there may be occasions when the clear space demands of hydrofoil ships may be greater than can be provided or tolerated.

(U) In order to reduce foil tip problems the foil tips should be contained within the beam of the the ship as in the case of the commercial jetfoil or as shown in Subsection 5.1, or the ships should be designed with hinged or retractable tips.

Section 4

ENVIRONMENTAL FACTORS

4.1 SEA ICE

(U) If hydrofoil ships are to be considered for general purpose combatant service, and if the latter should necessitate operation in any form of sea ice, then measures must be taken to protect hydrofoil ship hulls and foil system struts for hullborne navigation in sea ice. Aluminum hulls in hydrofoil ships are of light scantling construction. For navigation in ice, they would have to be strengthened by closing up the bow frame spacing and reinforcing shell plating along the water line.

(U) Hydrofoil ship navigation in sea ice has not been considered in the past and so there have been no investigations of its implications in terms of lightweight strengthening principles, criteria, and techniques. Protection against ice must also include consideration of foil operating and retracting mechanisms which might otherwise be damaged or jammed by ice.

4.2 SEA CONDITIONS

(U) The sea itself is the greatest hazard which faces any ship. Heavy seas induce responsive ship motions, increase the difficulty of ship control and maneuvering, and can cause severe structural and exposed equipment damage. As a rule, all conventional surface ships have to reduce speed as sea conditions worsen.

(U) When operating foilborne, a hydrofoil ship is less vulnerable to sea conditions than are conventional surface ships, because their hulls are raised clear of the sea surface. They are able to travel and maneuver at far higher speeds, without loss of platform stability or reduction of heading options, than can conventional surface ships, and can do so without damage or impairment of combatant capability.

(U) Small hydrofoil ships such as PGH-1 and PGH-2 (70 tons displacement) have operated at speeds in excess of 40 knots in sea state 4. The somewhat larger PCH-1 (120 tons displacement), has operated at speeds in excess of 40 knots in upper sea state 5. The large hydrofoil ship AGEH-1 (320 tons displacement) is designed to operate at much higher speeds in even higher sea states in a modified configuration.

(U) The performance and foilborne seakeeping attributes and experience of hydrofoil ships are discussed elsewhere in the Hydrofoil Technology Assessment Document.

(U) The area in which hydrofoil ship experience and data is limited is hullborne seakeeping, particularly at higher hullborne speeds. Existing hydrofoil ships are designed with a hullborne and a foilborne mode of propulsion. Their designed 'hullborne speeds range from 6-15 knots. However, by using their foilborne propulsors, they are capable of much higher hullborne speeds. Such speeds can be achieved without loss of platform stability, ship motion being controlled by the foil systems.

(U) Generally, hydrofoil ships will outperform conventional surface ships when operating foilborne, or hullborne with foils extended. When hullborne, they will not experience the hazard of hull slamming which conventional surface ships experience.

4.3 BOARDING SEAS

(U) Boarding seas are not considered to be particularly consequential for hydrofoil ships provided that propulsion exhaust openings are located sufficiently high as to preclude water entry. PCH-1 has its exhausts in the transom and some water has been shipped while hullborne with gas turbines operating. Another circumstance is possible-shipping of water across the weather deck during replenishment operations. These factors will be more significant in hydrofoil ships of less than 300 tons, because of their lower freeboard.

4.4 TOPSIDES SNOW, ICE ACCRETION

(U) Topsides snow and ice accretion is a hazard for any ship, but it has implications for hydrofoil ships which differ significantly from its implications for conventional surface ships. Particularly important considerations in the case of hydrofoil ships are:

a. Full hull and topsides exposure when foilborne.

b. High speed and, therefore, probably heavier accretion on the front of weapons, superstructure, and masts.

c. Possibly heavy local accretion due to foil system spray plume.

(U) In conventional surface ships, the size of the crew enables details to be formed for snow and ice removal, and steam is usually available to aid the work. A fair buildup of snow and ice can be tolerated without noticeable reduction of ship performance or safety, although continuing accretion will reduce the stability margin, eventually creating a serious hazard. There were cases in World War II of ships capsizing on the Murmansk run due to excessive topsides accretions.

(U) In hydrofoil ships, the comparatively, or proportionately smaller crews will limit manpower available for snow and ice removal, and steam is not usually available. Oil fired or waste heat boilers could be installed, or hot air drawn from the combustion air exhaust system, or bled from the propulsion engines, could be used instead of steam. Accretions on a hydrofoil ship, from the stability and safety considerations, are comparable to the same considerations in the case of a conventional surface ship. However, for a hydrofoil ship, the possible pattern of localization of buildup could influence a longitudinal center of gravity shift thereby influencing the ship's weight distribution on the foils. Should such a shift be significant, foilborne flight control might be impaired.

(U) Snow and ice accretion on hydrofoil ships has not been a consideration in hydrofoil ship experience to date. However, if hydrofoil ships are to be designed for general combatant service with the Fleet, and if such service is to include operation in Arctic waters or on the fringes thereof, then the subject must be investigated in the future.

4.5 FLOATING OBJECTS, DEBRIS

(U) Floating objects and debris other than ice are not particularly hazardous for surface ships. Often the bow wave carries objects clear so that they pass alongside. A hydrofoil ship operating hullborne with foils retracted would probably experience the same risk as a conventional surface ship.

(U) A hullborne hydrofoil ship with foils extended could suffer some damage, probably minor, if the ship encountered floating objects or debris which could become lodged in lift surface control mechanisms.

(U) A foilborne hydrofoil ship would be more susceptible to incidents of encounter with floating objects or debris principally because of speed, and also because of absence of a bow wave. The latter factor is important with reference to living creatures such as dolphins and whales with which there have been incidents. The lack of a bow wave, and probably the reduced pressure field of a foilborne hydrofoil ship eliminates, or reduces, the awareness of such mammals to the presence of the ship, with the result that they are struck.

(U) There have been several cases of foilborne impact with floating objects and debris:

a. PGH-2, PCH-1, and AGEH-1 have struck floating or submerged logs while operating in Puget Sound. PGH-2 crash landed once as a result of such an incident. AGEH-1 has struck large logs without damage, and it is likely that ships of 300 tons and larger will not be particularly vulnerable to log impact. Smaller ships could, on occasion, suffer damage. However, such incidents would be far from common in the open seas.

b. PGH-1, PGH-2, and PHM-1 have struck whales and dolphins. PGH-1 suffered damage to the tail strut as a result of such an incident, and PGH-2 suffered bow strut damage as a result of such an incident. PHM-1 has experienced fouling of a waterjet pump inlet as a result of striking a dolphin. In no cases was the damage serious, although in all cases foilborne operation was prevented. In the PHM-1 incident, after retracting the foil and cleaning the inlets, foilborne operation was resumed. However, PGH-1 and PGH-2 had to return to port for repairs.

4.6 WAVE IMPACT

(U) When foilborne, it is fairly common, particularly in swells, for the bottom to experience wave impact. This is a routine occurrence, and is a design factor which has been considered in the existing ships, and no damage has been suffered as a result of it.

Section 5

COMBAT FACTORS

5.1 HYDROFOIL SHIP SIGNATURES

(U) The Advanced Hydrofoil Development Program has been concerned about the signatures of hydrofoil craft for some time. Inherent in the smaller size and highly maneuverable vehicles is the reduction in detectability. The challenge is to design these ships with minimum radar cross section, low infrared signature and reduced radiated noise to further enhance the probability of not being detected.

(U) To understand the signature characteristics of hydrofoil ships, considerable data has been collected. The bulk of that data is from measurements of hydrofoil ship characteristics. The weakness in the state-of-the-art of signatures, which applies to all vehicles, is the lack of design criteria and analytical methods to predetermine the ship signature during the design process and to modify design features to minimize a particular signature.

(U) The overall approach of the Advanced Hydrofoil Development Program has been as follows:

- Collect and analyze the data available on hydrofoil ship signatures
- Identify areas where further data is needed

- Acquire necessary additional data
- Identify sources of high signature levels especially peculiar to hydrofoil craft.
- Conduct experiments with signature control techniques
- Document the signature characteristics and means of signature control for use in trade off analysis and hydrofoil ship system design.

(U) Program constraints have reduced the scope of efforts in the signature area. However, a significant data base does exist. A summary of the significant signature efforts accomplished to date is documented in the secret supplement of this report. This summary is treated separately to maintain the confidential classification of this volume.

(U) Two additional documents not covered! in the supplement which will provide an informed understanding of hydrofoil ship signatures are References V.5-1 and V.5-2.

(U) Table V.5-1 is a summary of signature data developed by the Advanced Hydrofoil Development Program. In general, it has been found that the signatures of hydrofoil ships fall into a fairly logical pattern with conventional ship signature work. Some of the notable exceptions are the impact of the hydrofoil ship dual mode of operations (Foilborne vs Hullborne) on signature, the effect of strut and foil characteristics on the acoustic and pressure signatures, and the advantages/disadvantages of a hydrofoil ship's maneuvering characteristics on signature control.

Table **V.5-1.** HYDROFOIL SIGNATURES DATA

TYPE OF SIGNATURE		CRAFT EVALUATED: PGH-1	PGH-2	PCH-1	PHM-1	AGEH-1	DESIGN CRITERIA ESTABLISHED	ANALYTICAL TOOLS AVAILABLE
RADAR CROSS SECTION		Fully shaded	Fully shaded	Fully shaded			Partially shaded (half)	
ACOUSTIC	AIRBORNE	Fully shaded	Fully shaded					
	UNDERWATER	Partially shaded (half)	Partially shaded (half)	Partially shaded (three quarters)	Partially shaded (one quarter)	Partially shaded (three quarters)		Partially shaded (half)
INFRARED		Fully shaded	Fully shaded	Fully shaded	Open		Partially shaded (half)	Open
MAGNETIC		Fully shaded	Fully shaded	Fully shaded		Fully shaded		
PRESSURE					Partially shaded (one quarter)	Fully shaded		

FULLY SHADED – TRIALS CONDUCTED AND DATA ANALYZED

PARTIALLY SHADED – TRIALS CONDUCTED; UNCERTAINTIES INDICATED BY AMOUNT OF SHADING

OPEN – **PAPER STUDIES CONDUCTED**

(U) It should be emphasized that, to date, the measurements have been made on the hydrofoil ship as built. No design or development effort to reduce or control signatures was undertaken prior to the referenced trials. For example, no hydrofoil ship has been designed to reduce radiated noise. Initial effort has been started to mask the propellers on PCH-1 by air venting. All hydrofoil ships can have reduced radiated noise if known quieting techniques are applied.

(U) It is anticipated that as requirements for signature levels evolve, conventional signature reduction techniques will be utilized in the design process to meet the stated requirements.

5.2 WEAPONS EFFECTS

(U) Material contained in the following subsections has been adopted from Reference V.5-3. Other references are appropriately identified in the text and are defined on page V.5-34.

5.2.1 Shock*

(U) The shock effects of underwater explosions are manifested by direct underwater shock transmission, gas globe venting, and an associated uplift of the water surface, usually in the form of a water column. The principles and theory of underwater explosion shock are well understood and have been demonstrated by tests with

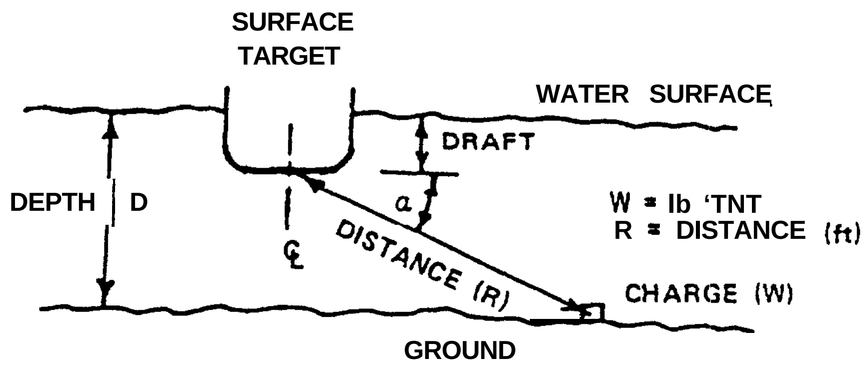
* References V.5-4, V.5-5, and V.5-6

conventional surface ships. One hydrofoil ship, namely PGH-1, has undergone foilborne shock testing. No hydrofoils have experienced hullborne shock testing.

(U) Detonation of an underwater charge first generates a shock front which is directly transmitted into any structure within range. Deformations may be induced in supported plates, particularly if they are airbacked. Supporting structures also carry the shock to equipment and further damage may result. Damage to equipment and the underwater hull are usually correlated with the attack geometry and charge weight by use of the shock factor concept defined in Figure V.5-1.

(C) At a free water surface, an underwater explosion will give rise to an appreciable water column. This is illustrated by the time lapse photographs of Figure V.5-2. The effects of the uprising water column on the control of a foilborne hydrofoil could be severe if the ship happened to be close in to the water column.

(C) There is little knowledge of the shock resistance of aluminum hulls. Current practice is to estimate the shock resistance of aluminum hulls as about 65 percent of the resistance of steel hulls. Current estimates of shock factors for hull rupture are 0.7 to 0.85 for steel hulls, and 0.47 to 0.54 for aluminum hulls. It is more than likely that future hydrofoils, and other advanced craft will be of aluminum construction, therefore it is probable



SHOCK FACTOR: $Q = \frac{\sqrt{W}}{R}\left(\frac{1 + \sin a}{2}\right)$

Figure V.5-1. GEOMETRY USED TO DEFINE SHOCK FACTOR

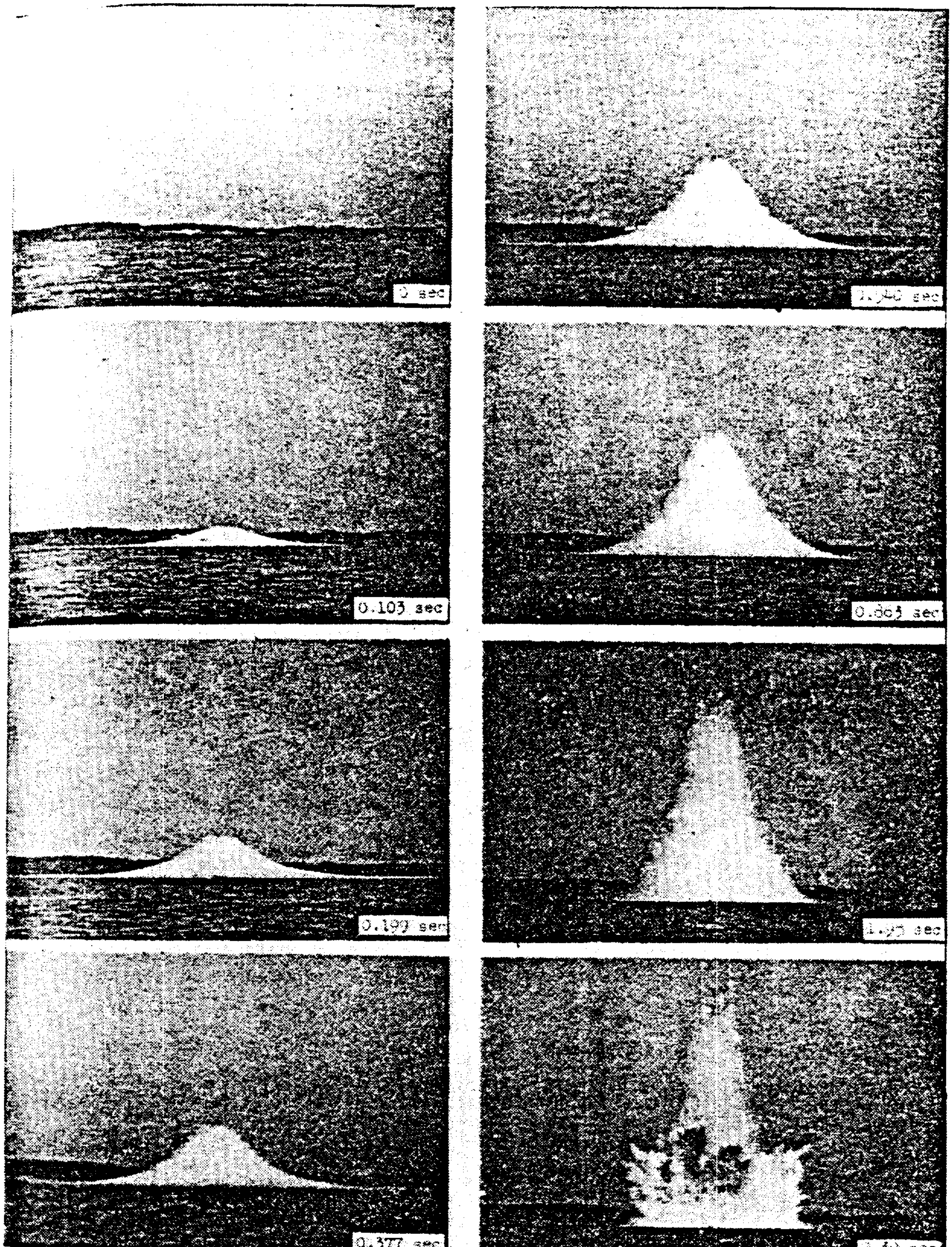


Figure V.5-2. DOME AND PLUMES ABOVE AN EXPLOSION (U)
(THE CHARGE WAS 1750 LB OF TORPEX ON A SOFT MUD BOTTOM UNDER 40 FT OF WATER.)[88]

that the U.S. Navy will have to initiate a meaningful shock test program to provide data for use in the design of such ships.

(C) In a foilborne hydrofoil, shock can only be transmitted through the foil system, with the result that the hull and internal equipment should be susceptible to damage only through the foil system foundations. This has been borne out by tests conducted with PGH-1 in 1971 up to a shock factor of 0.16 (Reference V.5-5). At this value, inspection revealed only slight deformation and extrusion effects limited to the pod-strut fairings. Such damage was not enough to cause any performance degradation. Conventional surface ships have suffered weapon system impairment at shock factors of about 0.1 (Reference V.5-5).

(C) On the basis of these tests, and assumptions that the underwater strut-foil assembly is sufficiently resistant and that hull mounted equipment is safe up to a maximum velocity of 6 ft/sec, (Reference V.5-5) estimates that the foil-borne PGH-1 would be safe at a horizontal distance of 13.7 m (45 ft) from the shockwave of a 522 kg (1,150 lb) HBX-1 influence fuzed mine submerged 19.8 m (65 ft) deep in shallow water. This applies only for shock wave initiated damage. The risks due to surface water disturbance remain to be investigated principally in terms of height sensor and ship control response factors. The surface disturbance radius for damage is larger than for the direct shockwave, and so the radius of 36.6 m

(120 feet) was considered as the closest safe approach distance for PGH-1. For larger hydrofoils, the estimating base for safe approach distance is uncertain. Certain scaling assumptions must be made and may have to be revised as a result of tests.

(U) Reference V.5-5 estimates that for hydrofoils of 58 to 711 tonnes (57 to 700 tons), and charge weights of approximately 137 to 907 kg (300 to 2,000 lb) HBX-1, the lethal horizontal standoff in the foilborne mode is at the edge of the surface spray dome. For foilborne craft of 58 to 173 tonnes (57 to 170 tons), the shock damage range is within the spray dome radius; for a 711 tonne (700 ton) displacement hydrofoil, the shock damage radius may be similar to or even larger than the dome radius.

(U) Reference V.5-6 reports on tests of a towed MK 105 hydrofoil minesweeping platform tested up to a shock factor of 0.30. It was concluded that for ground mine charge sizes of 90 to 545 kg (200 to 1,200 lb) HBX-1 and the 6 to 24 m (20 to 80 ft) depths likely to be encountered in operational situations, the shock wave phase of the explosion does not produce any significant damage to the basic structure or equipment in areas outside that covered by the upsurging water column. The major hazard to the MK 105 platform is the water column, and it is estimated that the platform will suffer appreciable damage if overlapped by 15 percent or more of the water column surface breakthrough boundary. Estimated lethal regions for the MK 105 device are depicted in Figure V.5-3. It should be noted, however, that the MK 105 platform uses a surface piercing foil system

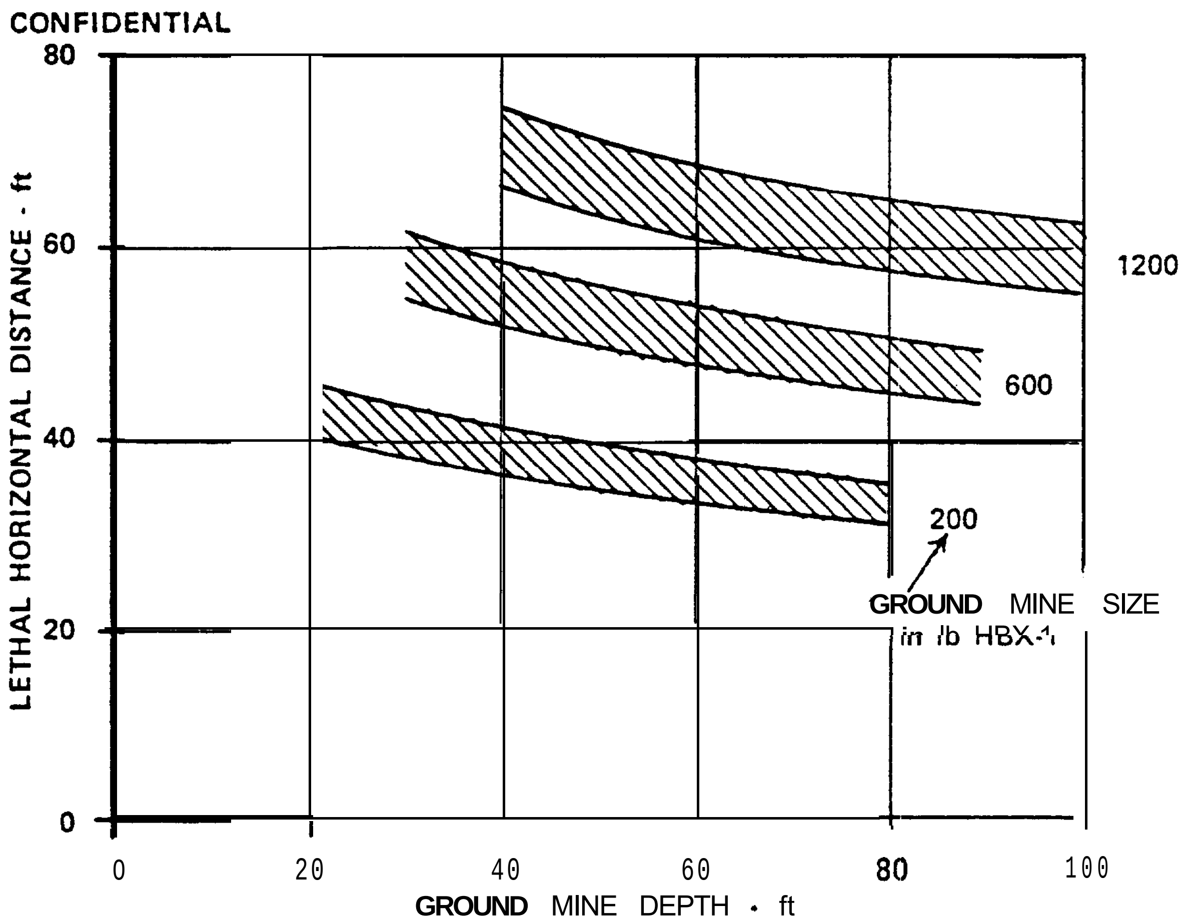


Figure V.5-3. LETHAL STANDOFFS FOR GROUND MINES (U)
MK 105 HYDROFOIL MINESWEEDING SLED.

as distinct from submerged foil systems on current Navy hydrofoil ships and therefore the shock vulnerability and water column damage potential may not necessarily be similar or as severe.

(U) While the preceding data is directly addressed to vulnerability from torpedoes and mines, it has some applicability to projectiles or missiles which miss the hydrofoil and explode underwater.

5.2.2 Weapons Strikes

(U) Most weapons will inflict damage on steel ships even when armored. Aluminum ships will be as susceptible to such damage as steel ships although it remains to evaluate evasive actions and counter measures which, coupled with high speed and maneuverability, and rapid stopping distance, may offer means to reduce the probability of strikes.

(C) On an equal weight basis, aluminim exhibits greater resistance to fragment and projectile penetration than steel. On an equal thickness basis, aluminum is significantly less resistant to blast than is steel. Figure V.5-4 presents plots of predicted penetrations into aluminum by steelfragments of various weights and striking velocities. Also shown in this figure are the fragment characteristics for two representative anti-ship missile warheads. Typical plating thicknesses for destroyer sized ships are 4.8 to 6.4 mm (3/16" to 1/4") for the superstructure and 6.4 to 15.9 mm (1/4" to 5/8") for the hull and decks. Equivalent thicknesses for

Anti-Ship Missile Fragment Characteristics

Warhead Weight (lb)	250	1000
Total Number of Fragments	8600	60,000
Average Fragment Weight (grains)	104	12
Number of Fragments Greater than 50 grains	4200	10,000
Fragment Initial Velocity (fps)	5000	7960

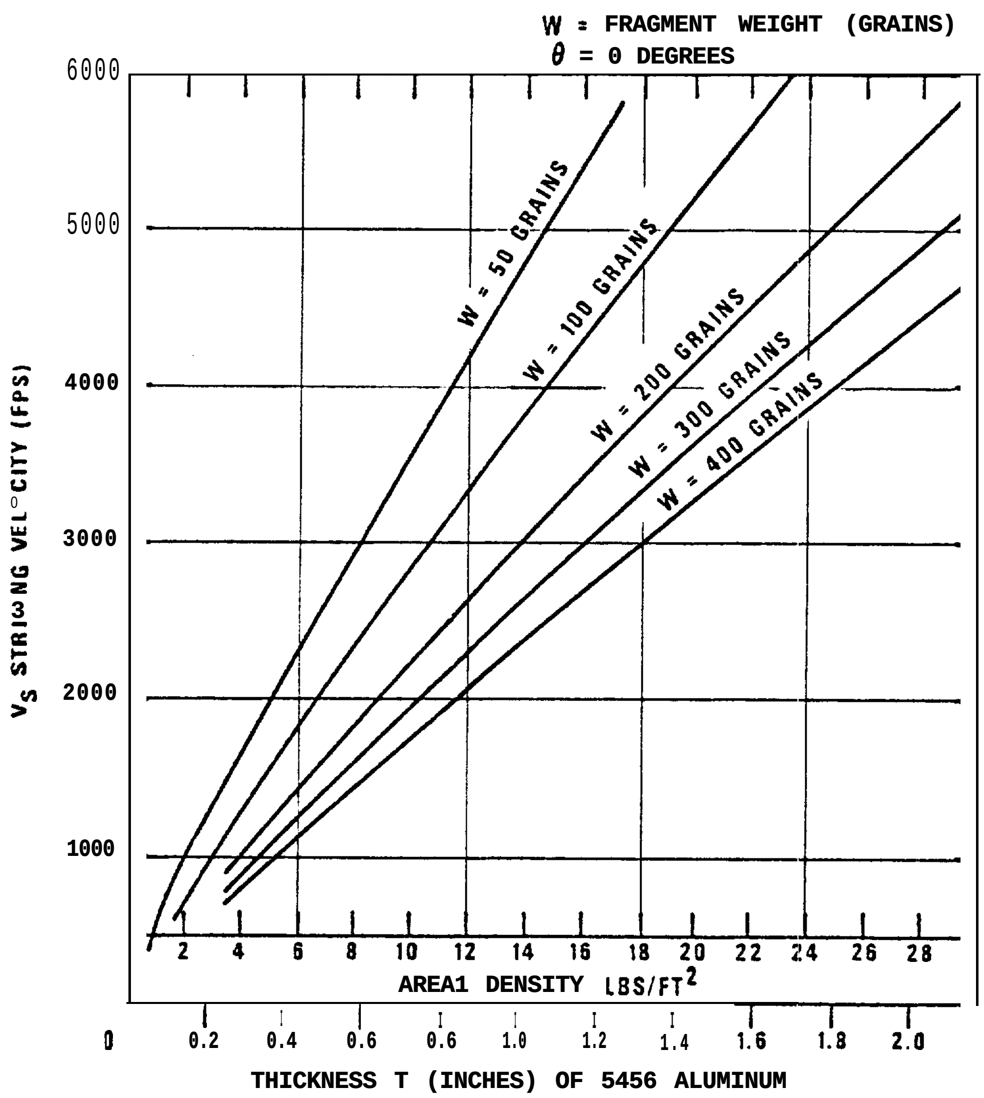
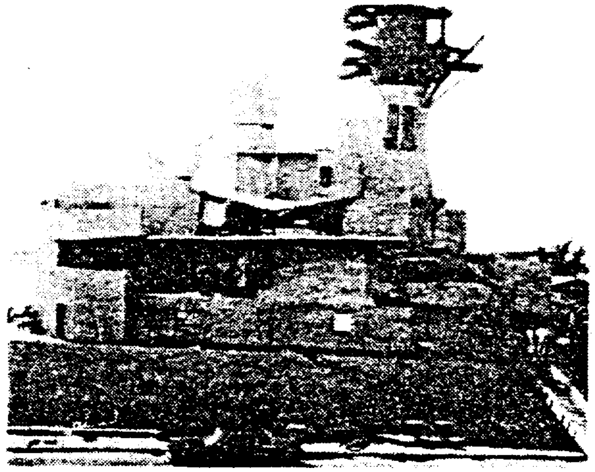


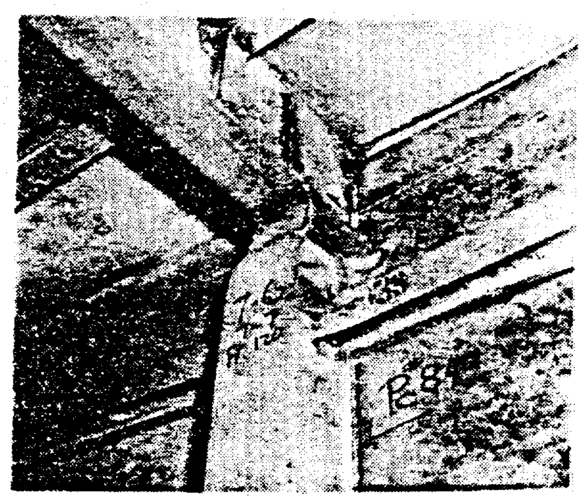
Figure V.5-4. PENETRATION OF ALUMINUM BY STEEL FRAGMENTS a large hydrofoil will be approximately 3.2 mm (1/8") for the superstructure and up to about 12.8 mm (3/8") for the hull and decks. Currently, U.S. Navy combatants tend to use aluminum superstructures and so the topsides vulnerability of hydrofoils is expected to be similar to that of equivalent sized ships in the fleet,, Figure V.5-5 depicts blast damage to a DLG superstructure. Existing ships are vulnerable to topside fragmentation damage, as has been amply demonstrated by battle damage experienced during the Vietnam War, Reference V.5-7.

(U) Also, blast damage to ship structure from contact and internal bursts of HE warheads may be greater for aluminum-hulled hydrofoils. For the same warhead, blast damage radii for aluminum structure are estimated to be 1.7 times greater than for the equivalent steel structure although the basis for this in terms of designed blast resistance associated with hydrofoil extruded panel hull construction has not been determined. The lack of water backing of hydrofoil hull plating when the ship is foilborne is expected to result in more extensive hull damage from internal weapon bursts. Data from battle damage and limited experiments indicates that water backing greatly increases the rupture resistance of hull plates. Current estimates are that blast damage radii for water-backed hull plates are on the order of 1/3 to 1/2 those for equivalent air-backed plates (Reference V.5-8). However, there has been no evaluation of possible benefits of the relief of internal damage by venting



(a) DLG-16 Deckhouse Exposed to 10 psi (C)

(b) DLG-16 Door Exposed to 6 psi (C)



(c) DLG-16 Deckhouse Frame Exposed to 6 psi (C)

Figure V.5-5. AIRBLAST DAMAGE TO ALUMINUM DECKHOUSE (U)

[redacted]

of an internal explosion through the theoretically lower rupture resistance of nonwater backed aluminum plating or via blowout panels. Water backing may contribute to reducing plate rupture risk, thereby contributing to containment of the blast, or explosive effects. A foilborne hydrofoil does not have to assure watertight integrity when foilborne, and so, in combat at least, may be less impaired by hull rupture. A conventional surface ship would have to retain watertight integrity.

(C) In contrast to a conventional surface ship, hull damage to a foilborne hydrofoil will not result in flooding until it becomes hullborne. Thus, in those cases where the extent of hull holing is not too extensive, and the propulsion and foil systems are not damaged to the point where the ship cannot continue to fly, it is possible that temporary repairs could be made to restore the water-tight integrity of the hull before the ship returns to the hullborne mode.

(C) Figure V.5-6 shows the extent of structural damage to a small steel-hulled frigate caused by a HARPOON cruise missile hit. The warhead explosion has completely destroyed the main deck across the full width of the ship over a length of 16.5 meters (54 ft) and the hull sides down to the water line. Damage to the ship girder is extensive and it is in danger of failing. Similar damage to a foilborne hydrofoil could result in the loss of girder strength. This would probably prevent foilborne operations since adequate

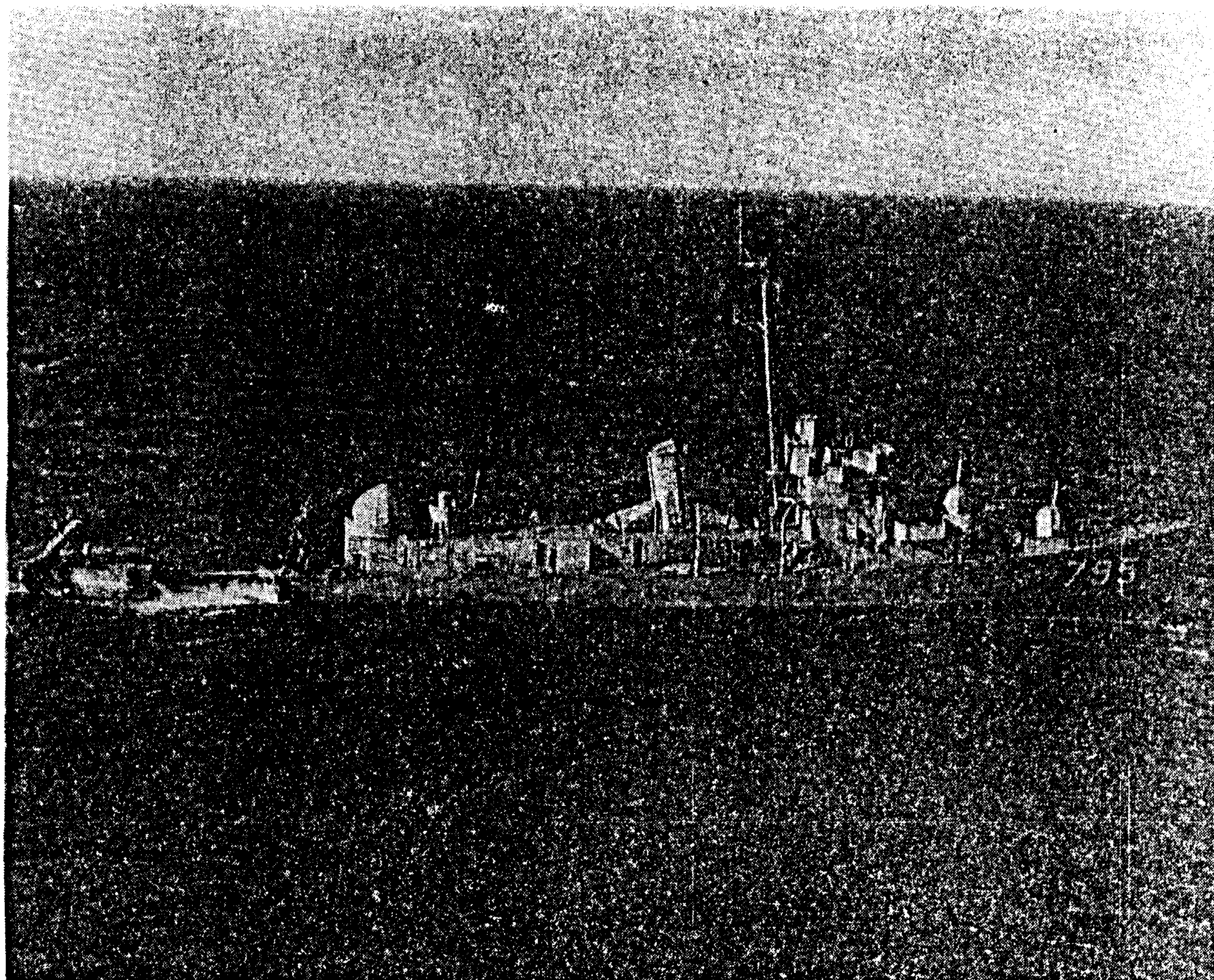


Figure V.5-6. HARPOON WARHEAD BLAST DAMAGE TO EX-GUNASON (DE-795)

UNCLASSIFIED

strength would be available to support the concentration of foil lift loads at the strut-to-hull attachment points. In the hullborne mode, like the conventional surface ship, the overall load is distributed and supported by hull buoyancy.

(C) Fire is a frequent consequence of weapon strikes and is a serious threat to unprotected aluminum structure. It is discussed further in 5.3.2 below.

5.3 INDUCED EFFECTS

5.3.1 Explosion

(U) The risk of explosion is always present in a warship, whether its cause is accident *or* enemy action. Potential hazards include compressed gas or high pressure fluid containers, missiles, ammunition and other explosive devices, combustible fluids, and such mechanical components as turbines or switchgear. Compressed gas or high pressure fluid containers can explode if internal safe pressures are exceeded, say as a result of malfunction of pressure regulators or as a result of a fire, and of course may be ruptured by ballistic fragments. Stowed explosive devices can become susceptible to explosion as a result of mechanical action if stored in spaces in which ambients are improperly maintained, or if a fire occurs, or if struck by projectile fragments. Gasifying combustible fluids leaking from a pipe or container can result in an explosion as a result of a spark or fire. Turbines can explode if they lose rotor blades, and switchgear explosives are not a rarity.

(U) Protection against the risk or possibility of explosion includes:

a. Providing as much separation as possible between potential hazards, and locating them away from vital spaces, systems and equipment, as feasible.

b. Providing adequate protection in the form of suitable enclosures, shrouding, blowout patches, or other methods, to permit the effects of an explosion to be released external to the ship.

(U) None of the existing hydrofoil ships, other than PHM-1, normally carry weapons and ammunition. None, including PHM-1, have really been designed around considerations of vulnerability and survivability. Therefore, vulnerability and survivability are really new considerations which merit appropriate study and development because of their potential impact upon arrangements, structure, levels of redundancy in distributive systems, weight, space, and cost.

5.3.2 Fire

(U) Fire, both in port and at sea under peacetime and wartime conditions, has been the single greatest source of damage and injury from the earliest times. The primary consequences of shipboard fires are, as indicated in Figure V.5-7, damage to ship structure and installed equipment, secondary explosions from munitions, and personnel casualties.

(U) Aluminum structure is more susceptible to fire than is steel structure. Figure V.5-8 shows the extensive damage possible in aluminum ship structure due to a fire that was not rapidly

PRIMARY CONSEQUENCES

DAMAGE PRODUCING EVENT	STRUCTURAL DAMAGE	EQUIPMENT DAMAGE	SECONDARY EXPLOSION	FIRE	FLOODING	PERSONNEL CASUALTIES
WEAPON HIT	X	X	X	X	X	X
EXPLOSION	X	X	X	X	X	X
FIRE	X	X	X			X
COLLISION	X	X		X	X	X
GROUNDING	X	X			X	X
HEAVY WEATHER	X	X			X	X
MATERIAL/ PERSONNEL FAILURE OR MALFUNCTION	X	X	X	X	X	X

Figure V.5-7. CRITICAL DAMAGE CAUSES

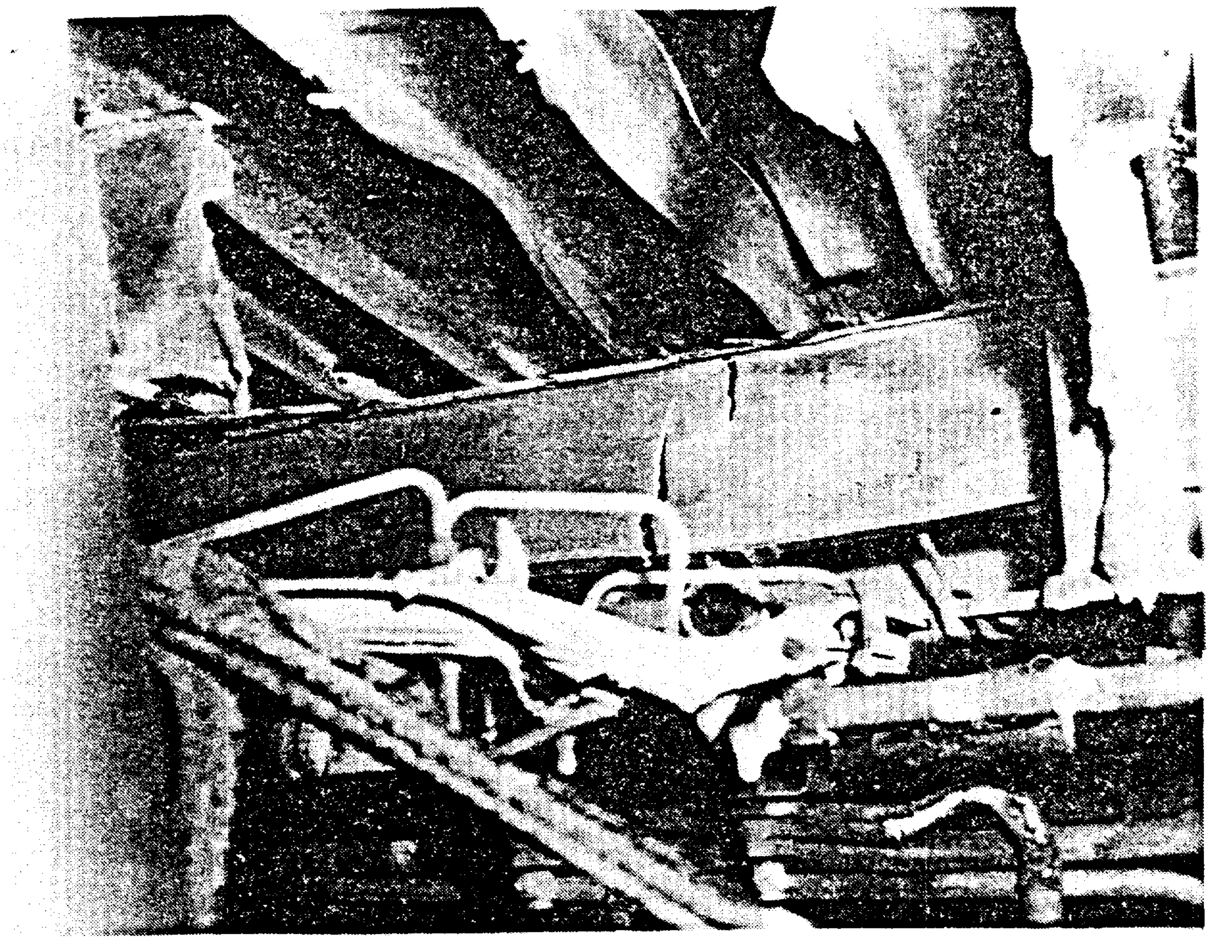
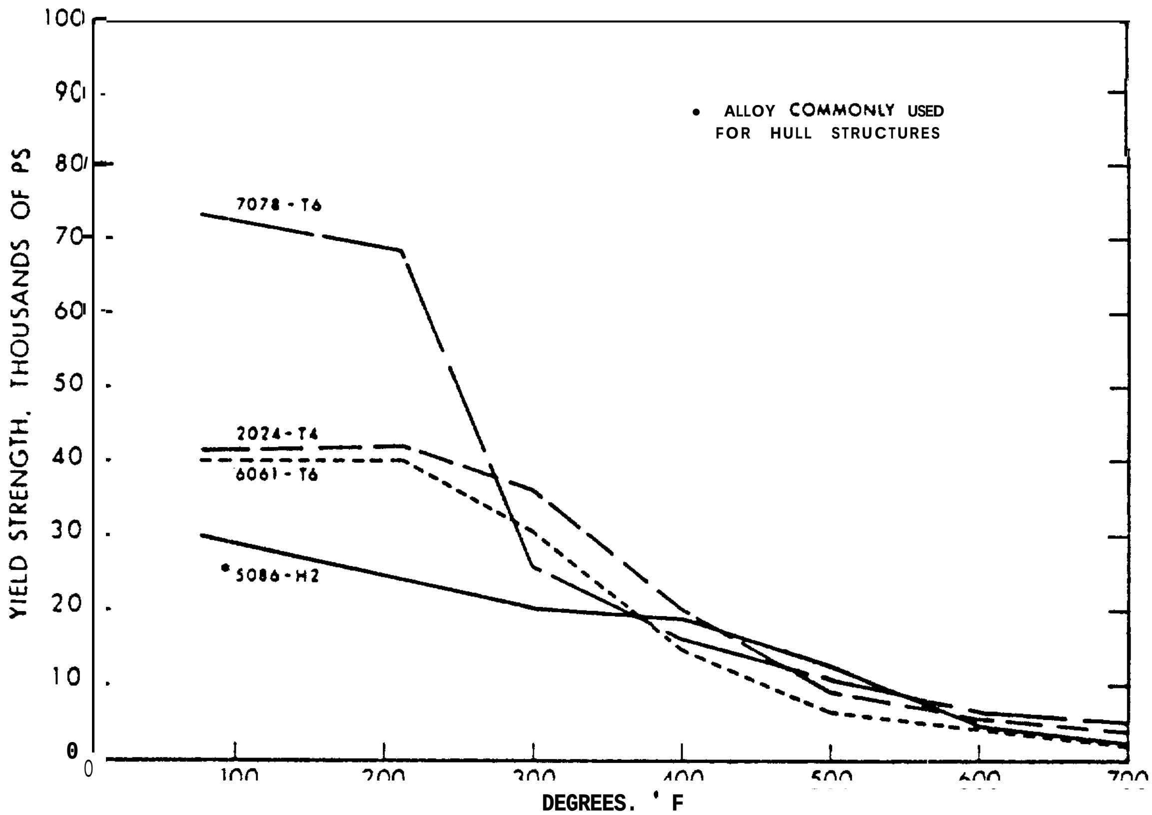


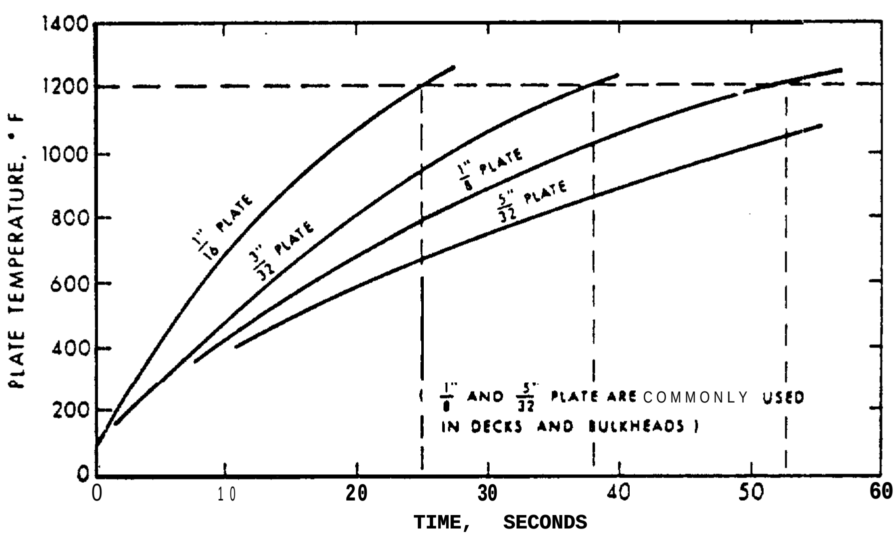
Figure V.5-8. FIRE DAMAGE TO ALUMINUM SHIP STRUCTURE controlled. This fire occurred in the Canadian hydrofoil BRAS D'OR (FHE 400) while the ship was in the final stages of construction and was caused by hydraulic fluid, spraying from a leaking 60 psi hydraulic line and igniting when it impinged on an exposed portion of a hot auxiliary gas turbine exhaust duct. Damage to primary structure was sufficient to have possibly led to structural failure and loss of the ship had it been underway in even moderate seas at the time of the fire. This is only one of many examples that point out the need for a high degree of fire protection on aluminum ships (Reference V.5-9). Fire damage in the superstructure of USS BELKNAP was extensive and drastic.

(U) The firefighting systems of existing hydrofoils have been designed on the basis of current practice for conventional surface ships. However, a new fire detection and foam fire fighting system has recently been installed in AGEH-2.

(U) The steel structure of most naval vessels assists in containing fire and so allows time for damage control action. The lightweight aluminum construction of hydrofoils, on the other hand, does not allow much time for firefighting before major damage can occur. Aluminum is extremely vulnerable to the high temperatures produced by a fire, especially liquid fuel fires which are most common in machinery spaces, and there is a risk that the structure around a burning compartment will be weakened before the fire is brought under control. Figure V.5-9 shows the effect of elevated temperature on yield strengths of aluminum alloys and times for typical plates to reach melting temperature.



Yield Strengths of Aluminum Alloys Versus Temperature



Temperature of Aluminum Plate Exposed to 1500° F

Figure V.5-9. THERMAL SENSITIVITY TO ALUMINUM

(U) Figure V.5-10 shows time-temperature characteristics of aluminum exposed to a 1,000°C (1,832°F) flame, when unprotected, and when protected by various foam insulation systems. The weight penalty associated with the use of current standard marine fire insulation materials makes imperative the development of lightweight insulating materials for fire protection of aluminum ship structures.

(U) Aluminum softens at 400°F, sags under its own weight at 800°F, and melts at approximately 1100°F. While the results shown in the figure are derived from small scale panel tests, it appears that lightweight insulation systems to protect aluminum ships from fire can be developed. This might be especially beneficial in some cases where incipient fires are started (paper, trash, etc.) by small weapons or fragments that are not accompanied by catastrophic blast damage.

(U) Water is still the best agent for extinguishing many types of fires and for cooling hot areas to prevent reflash where fires have been extinguished by other agents,

(U) Aluminum structures exist in most modern U.S. Navy ships, including most destroyer types. Large aluminum superstructures are used in the DD-963 class, and massive aluminum superstructures are used in the LHA Class. It would be only prudent to conduct the testing and detecting necessary to ensure that cost and weight effective fire fighting and detection systems will be developed for use in aluminum main hulls or superstructures. Such tests were planned in the hulk of PGH-2 but have not been conducted to date.

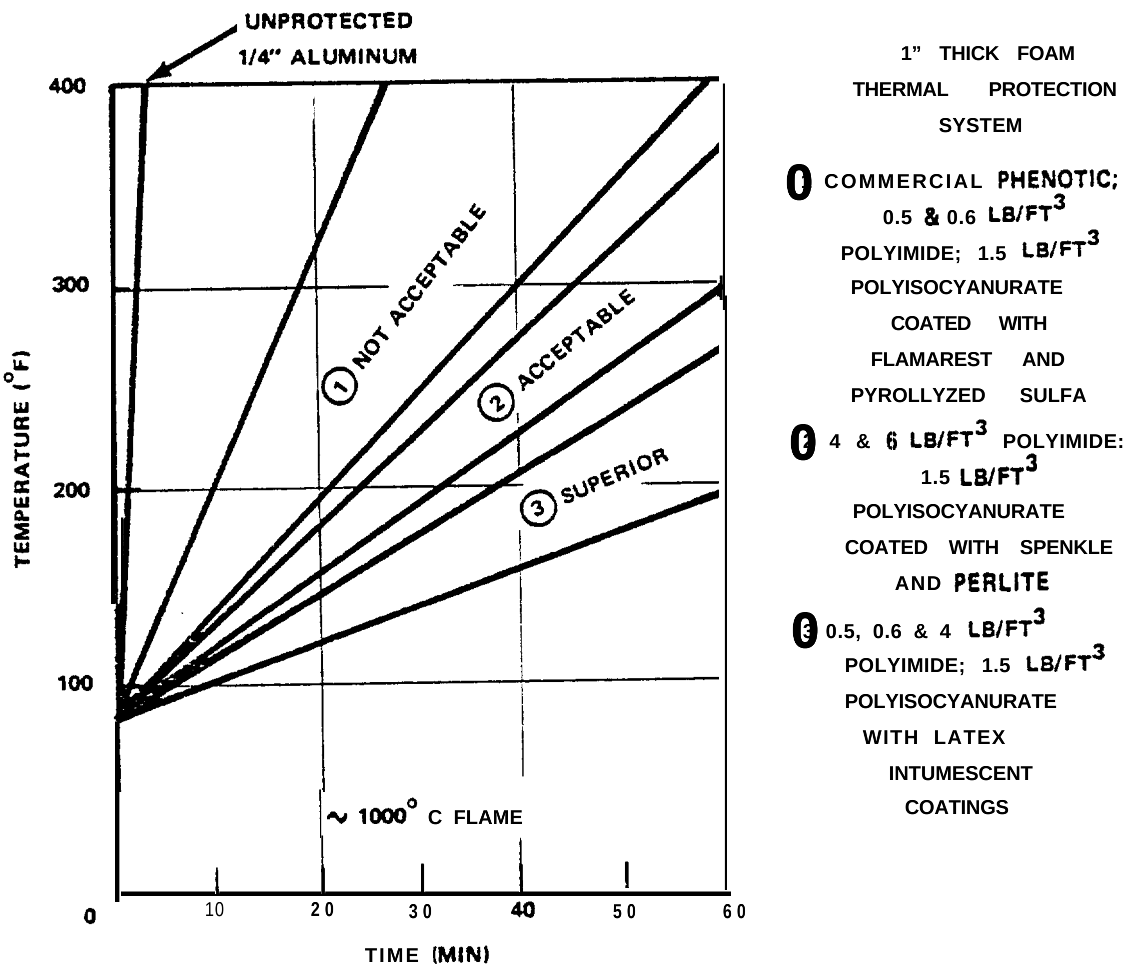


Figure V.5-10. THERMAL PROTECTION OF ALUMINUM STRUCTURE

5.3.3 Electrical and Mechanical Plant Damage

(U) Ships can be damaged, disabled, or lost as a result of fire, flooding, explosion, shock, or weapons strikes, either because of direct damage to vital electrical and mechanical plant, components and equipment, or as a secondary result of incidents.

(U) Hydrofoils are as susceptible to such occurrences as any ship, although they possess the kernel of features which enhance their flexibility and survivability, namely dual modes of propulsion. The more dramatic effects of electrical and mechanical damages are alleviated in ships in which the hullborne and foilborne propulsion plants are effectivelly separated physically; emergency generators should also be provided in all hydrofoil ships, located remote from the machinery spaces.

(U) While it may not prove to be feasible in all hydrofoils, both PCH-1 and AGEH-1 are capable of foilborne operation using one foilborne propulsion engine, driving one side propulsion train.

(U) There have been no unique transmission gear, shafting, or bearing problems in hydrofoils. However, there have been some malfunctions such as an early expansion problem in the PGH-1 lower level gear box, repeated PCH-1 coupling problems due in part to structural deflection, and AGEH-1 coupling problems also due to structural defelection. Most of these could have been prevented by adequate pre-installation test programs.

(U) Critical electro-mechanical machinery should be suitably tested before installation in the ship, and the tests should reflect the shipboard installation as realistically as possible.

(U) Aluminum ships can experience appreciable dimensional change as a result of direct sunlight. This means that the aligment of electro-mechanical systems can be difficult to obtain initially and to maintain. It is desirable that electro-mechanical installations shall be designed to be as compact and as integral (common foundations) as possible.

5.3.4 Structural Failure

(U) Hydrofoil ships embody lightweight, high stress structure. The structure is designed for the loads which the ship must bear. The loads include the customary static and hydrostatic loads as well as large static and dynamic loads concentrated at the foil system foundations. All hydrofoils are designed to withstand wave impact loads.

(U) The question arises, however, as to the residual strength of hydrofoil structures when damaged, say by fire or weapons strikes. Naturally, the design of hydrofoil structures is based upon stress margins represented by customary, empiric factors of safety. The high concentrations of loads when foilborne, and the need to conserve weight and cost has, in the past, led to designs compatible with design loads with, perhaps, little adequate provision for reserve strength in case of damage. To provide the latter in future designs, such measures may be taken as increasing the numbers of longitudinal girders, distributing them uniformly around the cross-section of the ship, and utilizing HY or stainless steel in their fabrication. Basically, hydrofoil structural arrangement is the same as in conventional surface ships. Because of weight, space, cost, and reserve strength considerations, other arrangements might also be considered.

5.4 PROTECTIVE MEASURES

(U) Ship survivability after sustaining damage depends upon decisions made in the design process. Ship features over which the designer has some control and which significantly influence warship survivability after experiencing weapons hits or an accident, are those which affect its capability to sustain damage without sinking, loss of mobility, or loss of weapons. The specific design features involved are:

a. Compartmentation

b. Ordnance Stowage

c. Redundancy and Separation

d. Protective 'Systems' and Damage Control

e. Speed and Maneuvering

5.4.1 Compartmentation

(U) Compartmentation refers generally to those structural features designed into a ship to preserve watertight integrity and limit the extent of flooding, maintain stability, retard the spread of fires, and contain explosion effects. Hydrofoils are designed to the same flooding criteria as other U.S. Navy ships of the same size.

5.4.2 Ordnance Stowage

(U) Ordnance stowage practices can have a significant impact on ship survivability. Preferably, significant quantities of ordnance should be stowed in below-the-waterline magazines, with adequate ballistic and fire protection to minimize the likelihood of magazine mass detonation, the consequences of which are usually loss of the ship. Since hydrofoils hulls are fully exposed above the water surface during foilborne operations, their magazines have less intrinsic protection than conventional displacement ships whose major magazines are normally located below the waterline. In this case, the design solution could be a combination of limiting the quantities of ordnance in any one magazine, adequate separation of individual magazines, and providing sufficient ballistic protection to preclude ship kill by a "cheap," that is, small warhead weapon.

5.4.3 Redundancy and Separation

(U) The manner in which the arrangements of a ship and the arrangement and distribution of systems and components are devised can have a significant effect on vulnerability. Arrangement can be used to reduce system vulnerability by effecting separation of components, the desirable separation being not less than two damage radii for the largest weapon to which the ship is likely to be exposed. However, any separation will be beneficial, since it will reduce the likelihood of several components being inactivated by a single hit.

(U) Frequently, critical components can be provided with a significant degree of ballistic protection through shielding by noncritical components or by other means. By designing future hydrofoils to effect remote separation between the foilborne and hullborne propulsion plants, separately enclosing the respective propulsion engines, splitting the ship service electrical power generators between the foilborne and hullborne propulsion plant spaces, providing cross connection capability between the foilborne propulsion power trains, and between the hullborne propulsion power trains, a high measure of both fire and electro-mechanical redundancy and survivability can be provided. Such measures will enhance basic propulsion and electrical systems reliability.

(C) Figure V.5-11 presents an example of the influence that arrangements can have on ship combat survivability. The figure shows Surface-to-Surface Missile (SSM) system Pks for a guided missile destroyer (DDG) attacked from broadside by cruise missiles carrying Semi-Armor Piercing (SAP) Warheads containing 250 lb. of HE.

(U) It is planned for future hydrofoils to investigate and control ship and distributive systems arrangements by utilization of priority routing concepts. The latter entails categorizing the various ship spaces, systems and components as vital, essential,

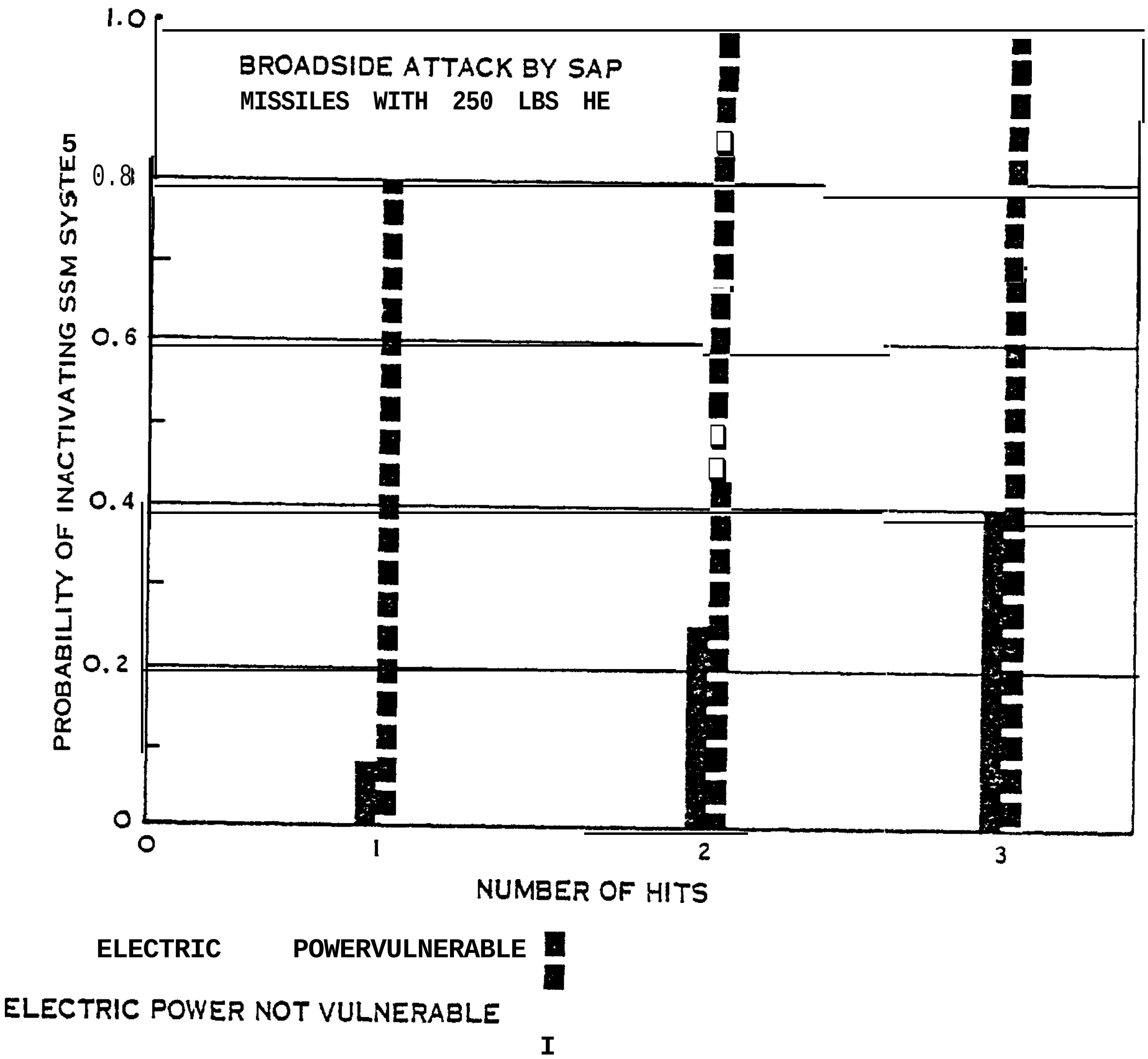


Figure V.5-11. INFLUENCE OF ARRANGEMENTS ON DDG SSM SYSTEM VULNERABILITY (U) and general and of influencing their arrangement, location or routing through the ship to provide for separation, redundancy, protection, and accessibility for maintenance and repair.

5.4.4 Protective Systems and Damage Control

(U) Structural protection involves the selective use of ballistic armor, side protection systems, hardened topside structure, watertight and fire resistant bulkheads, and damage tolerant primary structure, to improve ship survivability. Since hydrofoil ships tend to be weight sensitive, extensive application of ballistic armor and other heavy protection systems does not presently appear feasible due to unacceptable payload and range penalties. However, this should not preclude consideration of incorporating such protection on a very selective basis when a vulnerability analysis can demonstrate a significant survivability payoff for a limited weight penalty. The use of ballistic protective blankets in control spaces is a reasonable consideration.

(U) Damage control is concerned with ship design features, system and capabilities for fire detection and extinguishing, counter flooding and dewatering, explosion venting, shock hardening of installed equipment, damage repair and care of injured personnel.

(U) In the past, many damage control functions such as fire detection and extinguishing, containment of flooding and repair of damage, have been labor intensive rather than equipment intensive. The highly automated nature of the propulsion and combat systems envisioned for future hydrofoils when coupled with the relatively small crews required, suggest new approaches to damage control in the form of automatic, possibly self-activating systems.

5.4.5 Speed and Maneuvering

(U) Hydrofoil ship speed and maneuverability offers potential for protection under some circumstances. The full extent to which hydrofoil ships can exploit their speed and maneuverability in tactical situations has not been effectively investigated. Such investigations are in planning as the Hydrofoil Program looks toward further trials with PUM-1, PCH1, and AGEH-1.

(U) Some limited work has been performed, principally by PGH-2 in the Mediterranean operating against aircraft attacks in exercises off Italy.

(C) PGH-1 has operated with Fleet Units off San Diego and has demonstrated fire control radar break-lock capabilities.

REFERENCES

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VI. PRODUCIBILITY

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VI. HYDROFOIL SHIP PRODUCIBILITY

Section 1

INTRODUCTION

1.1 DEFINITION OF PRODUCIBILITY

(U) The following definition governs this review of hydrofoil ship producibility.

(U) Producibility is defined as a combined process of technical and manufacturing coordination and planning which seeks to integrate design features and fabrication capabilities in a composite plan for the quantitative manufacture of a product, within an established cost target and time frame, consistent with a standard of quality necessary to assure the required performance and life of the product.

1.2 GENERAL COMPARISON OF HYDROFOIL SHIPS

(U) Table VI.l-1 provides a general comparison of selected information pertaining to 10 types of hydrofoil ships developed in the past 15 years.

1.3 GENERAL DISCUSSION

(U) A ship is an entity comprising the hull, superstructure, masts, weapons, sensors, machinery, electrical, electronic, distributive, outfit and furnishings, and appendage systems. In the hydrofoil ship the foil/strut is a major appendage. Therefore, a discussion of producibility must be a discussion of the planning, principles, techniques, standards, and practices associated with

Table VI.1-1a. COMPARATIVE HYDROFOIL INFORMATION, GENERAL

SHIP	OWNER	DESIGNER	CONSTRUCTOR	SIZE ** LOA	B	D	TONS	CONFIGURATION
DENISON	MARAD	GRUMMAN	GRUMMAN	31.88 (104.6)	7.01 (23.0)	4.27 (14.0)	81.20 (80)	AIRPLANE: SURFACE PIERCING FWD SUBMERGED AFT
HIGH POINT (PCH-1)	USN	BOEING	MARTINAC SHIPBUILDING	35.27 (115.7)	9.54 (31.3)	3.96 (13)	116.10 (112.3)	CANARD SUBMERGED
PLAINVIEW (AGEH-1)	USN	GRUMMAN	LOCKHEED SHIPBUILDING	64.53 (211.7)	12.26 (40.21	6.65 (21.8)	314.96 (310)	AIRPLANE SUBMERGED
BRAS D'OR (FHE-400)	CANADA	DEHMAVILLAND	MARINE INDUSTRY	46.18 (151.5)	6.55 (21.5)	4.57 (15.0)	203.2 (200)	CANARD SURFACE PIERCING
DOLPHIN	GRUMMAN	GRUMMAN	BLOHM & VOSS	22.8 (75)	5.73 (18.7)	3.66 (12)	55.88 (55)	AIRPLANE SUBMERGED
VICTORIA	NIEDERMAIR	GIBBS & COX	MARYLAND SHIPBUILDERS	19.75 (64.6)	4.88 (16)	-- --	37.59 (37)	CANARD SUBMERGED
FLAGSTAFF (PGH-1)	USN	GRUMMAN	BOEING	22.25 (73)	6.51 (21.45	3.61 (11.84)	68.58 (67.5)	AIRPLANE SUBMERGED
TUCUMCARI (PGH-2)	USN	BOEING	GUNDERSON SHIPBUILDING	22.71 (74.5)	5.94 (19.5)	3.66 (12)	58.34 (57.42)	CANARD SUBMERGED
JETFOIL	VARIOUS	BOEING	BOEING	24.43 (90)	9.45 (31)	2.59 (8.5)	107.70 (106)	CANARD SUBMERGED
PEGASUS (PHM-1)	USN	BOEING	BOEING	39.32 (129)	8.41 (27.6)	4.15 (13.6)	235.61 (231.9)	CANARD SUBMERGED

** Upper number in meters or metric tone; lower number in feet or long tone

Table VI.l-lb. COMPARATIVE HYDROFOIL INFORMATION, SUBSYSTEM

SHIP	HULL MATERIAL	FOIL SYSTEM MATERIAL	PROPULSION FB	PROPULSION HB	PROPULSOR FB	PROPULSOR HB	LIFT CONTROL	STEERING	PASSENGERS
DENISON	ALUM RIVETED	4.30 STEEL	1-LM1500 GT	-T58 GT	PROPELLER	WATERJET	INCIDENCE AFT	TAIL STRUT	4/17
HIGH POINT (PCH-1)	ALUM WELDED, PARTIAL EXTRUDED PANELS	HY-80 HY-130 STEEL	Z-PROTEUS PT1273 GT	l DIESEL	2-PUSH/PULL PROPELLERS	PROPELLEK	FLAPS	BOW STRUT	22(Mod 1)
PLAINVIEW* (AGEH-1)	ALUM WELDED, ALL EXTRUDED PANELS	HY-80 WY-100 HY-130 STEEL	2-LM1500 (4-LM1500)* GT	2-DIESEL	2 SUPER CAVITATING PROPELLERS	2 PROPELLERS	INCIDENCE	TAIL STRUT	27
BRAS D'OR FHE-400	ALUM WELDED, ALL EXTRUDED PANELS	MARAGING STEEL	1-FT4-A GT	1-DIESEL	2 PROPELLER:	2 PROPELLERS	INCIDENCE	BOW STRUT	2
DOLPHIN	ALUM RIVETED	6061-T6 ALUM	1-RR TYNE 621/GT	2-DIESEL	1 PROPELLER	1 PROPELLER	INCIDENCE	TAIL STRUT	4/60-120
VICTORIA	ALUM WELDED EX-TENSIVE EXTRUDED PANELS	NY-80 STEEL	2-LM100 CT	L-DIESEL	1 PROPELLER	1 PROPELLER	INCIDENCE	BOW STRUT	3/75
FLAGSTAFF (PGH-1)	ALUM WELDED AND RIVETED EXTENSIVE EXTRUDED PANELS	6061-T6 ALUM	l-RR TYNE 621/10 GT	2-DIESEL	1 PROPELLEK	2 WATERJET	INCIDENCE	TAIL STRUT	13
TUCUMCAHI (PGH-2)	ALUM WELDED	17-4 PH STAINLESS STEEL	l-PROTEUS 15 M/530 GT	1-DIESEL	WATERJET	1 WATERJET	FLAPS	BOW STRUT	13
JETFOIL	ALUM WELDED EX-TRUDED PANELS	15-5PH STAINLESS STEEL	2-ALLISON 501-K20A GT	N/A	WATERJET	N/A	FLAPS	BOW STRUT	2 OR3/ 190-250
PEGASUS (PHM-1)	ALUM WELDED EX-TRUDED PANELS	17-4PH STAINLESS STEEL	1-LM2500 CT	Z-DIESEL	WATERJET	2 WATERJET	FLAPS	HOW STRUT	2

* Ship designed for 2 additional engines and transmission/foil modifications for high speed test and evaluation.

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designing, fabricating, installing, assembling, and integrating the various systems, considering cost, time, quality, and operating performance and maintenance.

(U) None of the existing hydrofoil ships has truly been designed for production. If costs, construction time, and quality are to be improved, greater attention must be given to producibility from the outset, and design and manufacturing must be more closely coordinated than has, in general, been the case in the past. This is particularly important in the case of warship design and construction, because of the significantly greater complexity of the payload and internal systems. It is advocated that every ship in the future should be approached as if it were to be produced in quantity so that engineering and manufacturing would jointly plan, simplify, and standardize, on the basis of general industrial experience. With 10 different types of hydrofoil ships as a background, with practical experience distributed among aerospace and marine firms, it can scarcely be considered that hydrofoil ship design and construction is an excursion into the unknown.

Section 2

BACKGROUND

2.1 GENERAL

(U) During the past 15 years, 10 different types of hydrofoil ships have been developed in North America; nine, including five naval hydrofoil ships, in the United States and one naval hydrofoil ship in Canada. Twenty-one ships have been constructed; namely, one each of DENISON, HIGH POINT (PCH-1), PLAINVIEW (AGEH-1), BRAS D'OR (FHE-400), FLAGSTAFF (PGH-1), VICTORIA, and PEGASUS (PHM-1), two of TUCUMCARI design (PGH-2, now scrapped and an Italian Navy version, SWORDFISH, constructed in Italy), two of DOLPHIN (constructed in Germany), and ten of JETFOIL produced to date. Only JETFOIL and PHM were seriously projected for production, and to date only the former has entered production. Both have undergone significant redesign to improve producibility, and a measure of redesign has been progressively effected in JETFOIL for the same reason.

2.2 DESIGN AND CONSTRUCTION

(U) Nine of the 10 different types of hydrofoil ships were designed by aerospace firms; namely, Boeing Aerospace Company (BAC)*, DeHavilland of Canada, and Grumman Aerospace Corporation (GAC).

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*The Marine Systems Division is now responsible for hydrofoil ships at The Boeing Company.

One type was designed by a naval architect, Gibbs and Cox. Of the 16 ships actually constructed:

- DENISON was designed and built by GAC.
- AGEH-1 was developed to the contract design stage by GAC but was contracted by the Navy to Lockheed Shipbuilding and Construction Company (LSCC) for detail design and construction.
- PCH-1 was designed by BAC but construction was subcontracted to Martinac Shipbuilding.
- BRAS D'OR was designed by DeHavilland but construction was subcontracted to Marine Industries.
- VICTORIA was designed by Gibbs and Cox but was constructed by Maryland Shipbuilding and Drydock.
- PGH-1 was designed and constructed by GAC.
- PGH-2 was designed by BAC but was subcontracted to Gunderson Brothers.
- DOLPHIN was designed by GAC but two ships were subcontracted to Blohm und Voss.
- JETFOIL was designed by BAC and ten ships have been placed under production to date by BAC.
- PHM-1 was designed and constructed by BAC. A follow-on production contract from the Navy is in prospect.
- The Italian Navy SWORDFISH was designed by a subsidiary of The Boeing Company, was based on the original design by BAC, and was constructed by the Italian subsidiary of The Boeing Company.

(U) Of the 16 ships, 9 were constructed by the same firm as designed them.' Six of the remaining seven ships were designed by aerospace firms, one by a naval architectural firm, and all seven were constructed by shipbuilding firms.

2.3 DESIGN VARIATIONS

(U) Among the 10 differing ship types a variety of design variations exists, which expand the scope of experience beyond the apparent.

2.3.1 Similarities

(U) Common among the 10 types of hydrofoil ships are:

- Gas turbine engines for foilborne power
- Diesel engines for hullborne power
- Automatic flight control systems
- Aluminum construction
- All welded construction with the exceptions of DENISON and DOLPHIN, which are extensively riveted, and PGH-1 which is partially riveted.

2.3.2 Differences

(U) Variations among the 10 types of hydrofoil ships are:

- Canard configuration (PCH-1, BRAS D'OR, VICTORIA, PGH-2, JETFOIL, and PHM-1) versus airplane, or conventional configuration (DENISON, AGEH-1, PGH-1,' and DOLPHIN).
- Foil System Materials:
  - Maraging steel (BRAS D'OR)
  - HY-80, l-K-100, HY-130 steel (PCH-1, AGEH-1, and VICTORIA)
  - 4130 Steel (DENISON)
  - 6061-T652 Aluminum (PGH-1 and DOLPHIN)
  - 7079-T611 (DENISON aft foil)

- •• 17-4 PH Stainless Steel (PGH-2) and 15-5 PH Stainless Steel (JETFOIL)
- • ▯ 17-4 PH Stainless Steel (PHM-1)

- Surface piercing foils (BRAS D'OR), combined surface piercing and submerged foils (DENISON), and submerged foils (PGH-1, AGEH-1, PGH-2, VICTORIA, DOLPHIN, JETFOIL, and PHM-1).
- Hard drive (DENISON, PCH-1, BRAS D'OR, AGEH-1, PGH-1, VICTORIA, and DOLPHIN) versus waterjet (PGH-2, JETFOIL, and PHM-1) propulsion, including hullborne waterjet propulsion in PGH-1 and DOLPHIN.
- Variable extent of use of extruded structural panels (PCH-1, AGEH-1, PGH-1, BRAS D'OR, VICTORIA, JETFOIL, and PHM-1).
- Variable extent of use of extruded versus fabricated shapes.
- Vertically retractable foil system (PCH-1, wet), versus radial, athwartship main foil system retraction (DENISON, AGEH-1, PGH-1, PGH-2, and DOLPHIN) versus radial, force and aft, main foil system retraction (JETFOIL and PHM-1).

2.4 PRODUCIBILITY STATUS

(U) The foregoing summarizes the comprehensive background of hydrofoil ship design and construction experience. It is emphasized, however, that the sum of experience is derived principally from the construction of individual ships rather than from the production of several ships. Specific production experience is limited. Nevertheless, the experience which has been gained is sufficiently diversified that, on the one hand, it must dispel any sense of mystique concerning the construction of hydrofoil ships and confirm the feasibility of constructing hydrofoil ships. On the other hand, this experience should provide confidence that, given proper coordination and planning, the production of hydrofoil ships in the future is entirely within the bounds of present capabilities.

Section 3

CONSTRUCTION OF EXISTING HYDROFOIL SHIPS

(U) This chapter discusses briefly the construction of several existing hydrofoil ships, expanding more fully on some than on others where particular factors merit specific discussion.

3.1 GENERAL

(U) The design and construction of hydrofoil ships has followed a wandering path between aerospace and marine firms, as indicated in Section 2, Background. The net result is that each ship has been a project of its own with very little transfusion of design or construction experience from one to another.

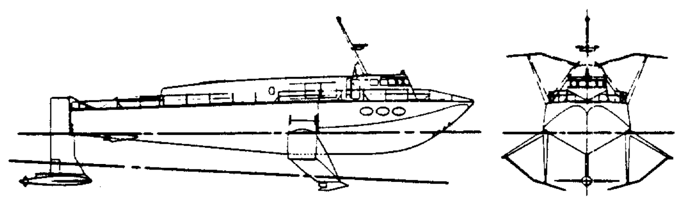
3.2 GENERAL REVIEW OF CONSTRUCTION OF EXISTING HYDROFOIL SHIPS

(U) Where producibility has either directly or indirectly influenced the design and construction of existing hydrofoil ships, it has tended to do so only in the hull structure. Therefore, herein, a general review of the construction of the existing hydrofoil ships will concern the structure. In all cases, the foil systems were separately constructed as discrete assemblies which were mounted after the hulls were completed.

(U) In two cases, the AGEH-1 and PHM-1, a limited level of modularity was adopted. In AGEH-1 the bottom box beam structure and the bow were discrete prefabrications. In PHM-1 the fuel tanks were discrete prefabrications. In all cases the superstructures were discrete prefabrications.

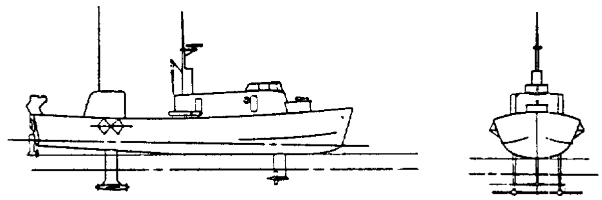
(U) All ships received machinery and distributive systems installations after the hull structure was essentially complete, and the installations were only marginally influenced by producibility considerations.

3.2.1 DENISON



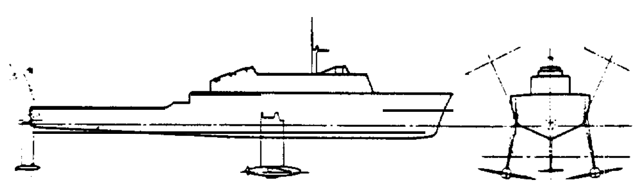
(U) DENISON was the first significant United States hydrofoil ship. She was designed and constructed under a Maritime Administration contract by GAC. Due to her high performance characteristics, the use of aluminum construction posed many problems because of a lack of general industrial experience, at the time, in the use of aluminum in high performance hulls. Scantlings were light. Uncertainties as to the post weld strength of aluminum, and concern over possible deformation, or oil canning as a result of welding, led to a decision to use riveted construction. Frames and bulkheads were welded prefabrications, several structural members were extrusions, but there was extensive use of riveting in other parts of the structure. Structural subassemblies, such as the center vertical keel, frames, and bulkheads were prefabricated.

3.2.2 PCH-1



(U) PCH-1 was a significant forward step in hydrofoil construction. The ship, based on a Navy contract decision, was detailed by BAC with support by W. C. Nickum Associates under a U.S. Navy contract. The ship was constructed by Martinac Shipbuilding under subconstract from The Boeing Company. The ship was of all-welded construction and was, the first to use extruded paneling, which was employed in 40 percent of the structure. Structural members such as floors, frames, and bulkheads were prefabricated subassemblies. In general, PCH-1 embodied perhaps the most straightforward and simplest structural design.

3.2.3 AGEH-1



(U) AGEH-1 was three times as large as PCH-1 and was at the time the largest aluminum ship in the world. She is still the largest of the hydrofoil ships. She was designed for two configurations, the nominal initial configuration, and a high speed modified configuration. The latter would include installation of two more gas turbine engines, reduction gears, new shafting and bevel gears, and supercavitating foils. At the time of construction, and because of her comparatively large size, weight was a dominating consideration in detail design. In part, in the interests of conserving weight, a great deal of piecework was eliminated.

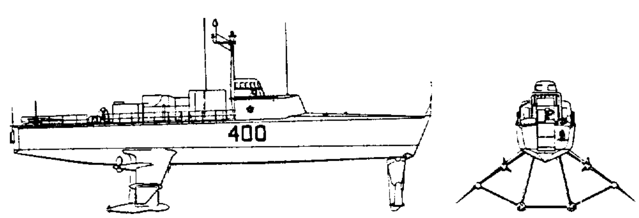
(U) The Contract Design of the ship was developed by GAC. The ship was awarded to LSCC for detail design and construction under a U.S. Navy contract. Lockheed subcontracted the detail design and component construction as follows::

- Arrangements, structure and internal systems, W. C. Nickum Associates, Seattle, Washington
- Propulsion plant and transmissions, G.E. Corporation, Lynn, Massachusetts
- Foil systems, Lockheed Aircraft Corp., Burbank, California
- Hydraulics, Rucker Corporation, Oakland, California
- Automatic Control System, Hamilton Standard, Windsor Locks, Connecticut

(U) The overall design was managed and coordinated by LSCC, which also constructed and assembled the ship. The ship was of all-welded construction and employed extruded paneling in 90 percent of the structure. The extruded panels were of different types but in general were 40 ft long. Therefore, a seam welder, capable of welding the full length of as many panels as were desired, was fabricated to produce large shell, deck, and bulkhead panels. Large shell, deck, and bulkhead subassemblies were prefabricated in a production flow, as were frames, beams, floors, girders, and side girders. Lesser parts were standardized and prefabricated in batches. Despite the fact that only one ship was required, AGEH-1 construction was significantly influenced by production principles including work flow, operations sequencing and repetition, work staging, and work stations. The ship was constructed in a covered floating dock. About 85 percent of the fabrication and construction work was performed within the dock. As a result, space, tooling, and manpower were extremely constrained, necessitating production policy to the extent that it was beneficial in a single end item contract.

(U) Partial modularity was employed. The bottom box beam was prefabricated and was over 100 ft long, 16 ft wide, and 5 ft deep. The bow was 30 ft long, 25 ft wide, and 25 ft deep.

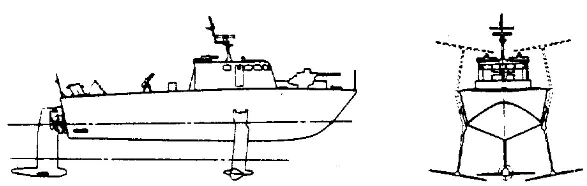
3.2.4 BRAS D'OR



(U) BRAS D'OR was designed by DeHavilland of Canada and constructed by Marine Industries, under Canadian government contract. The ship was of all-welded construction and, of all the hydrofoil ships, made the most extensive and efficient use of extruded paneling which is used in 95 percent of the structure, although there was a substantial diversity of extrusions used.

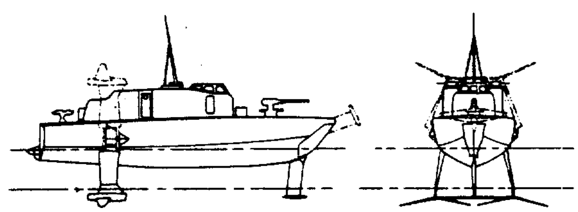
(U) As in the case of AGEH-1, a long seam welder was used. Also, as in AGEH-1, master butts were used extensively to capitalize upon the large prefabricated panels although more frequent butt shifting occurred, including shifting within the ends of some panels. The shell, deck, bulkheads, frames, floors, and beams were all prefabricated, again with evidence of preplanning and flow as in AGEH-1. Also, as in AGEH-1, piecework was minimized in terms of chocks and brackets. Frames were not cut out to receive crossing stiffeners but instead landed on the faces of the stiffeners, a practice which was also partially used in PCH-1. Superior efforts were made even beyond those in AGEH-1 to protect the material, and to maintain work area and ship cleanliness.

3.2.5 PGH-1



(U) PGH-1 and PGH-2 were separately designed and constructed within a common time period. PGH-1 was designed and constructed by GAC under a U.S. Navy contract. The ship was of welded and riveted construction. Extruded paneling was used in 70 percent of the structure and honeycomb paneling was used in 50 percent of platform deck. A seam welder was used for panel fabrication and master butts were used extensively. Construction was straightforward and sturdy.

3.2.6 PGH-2



(U) PGH-2 was comparable in size to PGH-1, both having been developed under essentially identical specifications. The ship was designed by The Boeing Company, under a U.S. Navy contract with support by W. C. Nickum Associates. The ship was constructed by Gunderson Brothers under subcontract from The Boeing Company. The ship was of all-welded construction and employed no extruded paneling. Construction was conservative, including substantial butt and seam weld shifting, necessitating manual welding throughout. Bulkheads and frames were prefabricated.

3.2.7 VICTORIA

(U) VICTORIA was designed by Gibbs and Cox and constructed by Maryland Shipbuilding and Drydock Company for a private owner. VICTORIA was of all-welded construction and used extruded paneling in 65 percent of the structure.

3.2.8 DOLPHIN

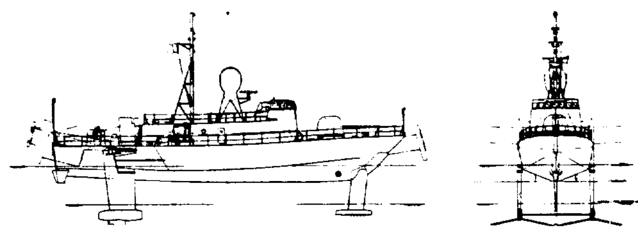
(U) DOLPHIN was designed by GAC as a private venture. Two ships were constructed by Blohm and Voss, Germany, for GAC. The ship was of riveted construction and in general was constructed similar to DENISON.

3.2.9 JETFOIL

(U) JETFOIL was designed and constructed by BAC as a private venture, and is in production by The Boeing Company.

(U) Construction is a combination of extruded and fabricated material. Floors, frames, and bulkheads are prefabricated. Some floors, particularly in the bow, are of open tubular strut construction. In earlier versions, plating, including extruded panels, was individually straked, and butts were shifted as in PCH-1 and PGH-2. A master butt was used in the bow. Subsequently, planning has been changing toward a level of modularity and a more extensive use of master butts. Substantial piecework and detailing was involved in the first ships. Facilities are capable of producing up to five ships simultaneously. Presently, the ships are constructed phased, progressively rather than simultaneously.

3.2.10 PHM-1



(U) PHM-1 is the latest U.S. hydrofoil ship of signi-cance. The ship was designed and constructed by BAC under contract to the U.S. Navy. Initially two ships were to be constructed, following which a production decision would be made.

(U) PHM-1 is of all-welded construction and employs extruded panels in about 40 percent of the structure. Floors, bulkheads, and frames were prefabricated.

(U) The PHM-1 design has been extensively revised to improve producibility. In the initial ship, butts are shifted extensively in the shell and decks, and extruded panels had to be erected piecemeal. Substantial piecework and detailing were required and the structure was so elaborate that there was considerable difficulty in controlling warpage due to the rarity of heat inputs required in welding the varying sizes and materials used.

3.3 GENERAL NOTE

(U) From a producibility standpoint, BRAS D'OR, AGEH-1, and PGH-1 reflect definite plans to reduce work, conserve cost, optimize standardization, and minimize detail.

Section 4

COMPARISON OF U.S. NAVY HYDROFOIL SHIPS

(U) The five U.S. Navy hydrofoil ships identified in Table VI.1-1 are compared herein. The comparisons are limited to the hull structure because it is only in the hull structure that, in some of the ships, there was any meaningful effort, for differing reasons, to exploit producibility.

(U) The information contained in Tables VI.4-1 through VI.4-5 is based upon measurements and calculations made against drawings which were developed for ship construction. They do not necessarily reflect the as-built condition of the ship.

(U) The information presented is not consistent among all of the ships. This is because of differing design policy, structural configuration, and construction practice. Manual welding was more extensive in one ship than another due, in part, to plating or panel arrangements and details. For example, PHM-1 made far more extensive use of fabricated shapes than did AGEH-1 which used extruded shapes. PHM-1 employed more detailed methods for stress distribution, resulting in many more variations in scantlings and piecework. Nevertheless, the information presented is indicative of the measure to which producibility affected design and construction.

(U) Comparison of the information in Table VI.4-6 can lead only to general conclusions as to the producibility of the various ships. The important factors in Table VI.4-6 are reorganized as in Table VI.4-7 to depict a gradation of the various ships.

Table VI.4-1. SHIP PCH-1

1. Hull Volume
   - 1.1 $V = 729.57\ m^3$
   - 1.2 $V = 25{,}780\ ft^3$
2. Lightship Weight
   - 2.1 $W_1 = 88{,}655$ kg
   - 2.2 $W_1 = 195{,}276$ lbs.
   - 2.3 $\frac{W_1}{V} = 121.52\ kg/m^3$
   - 2.4 $\frac{W_1}{V} = 7.575\ lbs/ft.^3$
3. Total Structure Weight
   - 3.1 $W_2 = 30{,}109$ kg
   - 3.2 $W_2 = 66{,}320$ lbs.
   - 3.3 $\frac{W_2}{V} = 41.270\ kg/m^3$
   - 3.4 $\frac{W_2}{V} = 2.573\ lbs/ft.^3$
4. Weight, Items Tabulated
   - 4.1 $W_3 = 21{,}901$ kg.
   - 4.2 $W_3 = 48{,}241$ lbs.
   - 4.3 $\frac{W_3}{V} = 30.019\ kg/m^5$
   - 4.4 $\frac{W_3}{V} = 1.871\ lbs./ft^3$

ITEM	AREA		# EXTRUDED PANEL	# PARTS	TOTAL WELD LENGTH		MACHINE WELD LENGTH		MANUAL WELD LENGTH	
	m^2	ft^2			m	ft.	m	ft.	m	ft.
SHELL	398	4,280	26	490	1,094	3,590	265	870	829	2,720
DECKS	416	4,410	70	440	549	1,800	-	-	549	1,800
TRANSVERSE BULKHEADS	116	1,250		640	199	2,620	-	-	799	2,620
FRAMES			-	1,860	1,091	3,580	-	-	1,091	3,580
TOTALS	930	10,000	-	3,430	3,533	11,590	265	870	3,268	10,720

5. # PARTS / LENGTH OF SHIP
   - 5.1 = 97.2 Parts/m
   - 5.2 = 29.64 Parts/ft
6. TOTAL WELDING / LENGTH OF SHIP
   - 6.1 = 100.16 m/m
   - 6.2 = 100.17 ft/ft
7. MACHINE WELDING / TOTAL WELDING
   - 7.1 = 0.075 m/m
   - 7.2 = 0.075 ft/ft
8. MANUAL WELDING / TOTAL WELDING
   - 8.1 = 0.925 m/m
   - 8.2 = 0.925 ft/ft.

*Based on drawings - not as built.

Table VI.4-2*. SHIP AGEH-1

1.	**Hull Volume**	1.1 $V = 2305.60\ m^3$		
		1.2 $V = 81.470\ ft.^3$		
2.	Lightship Weight	2.1 $W_1 = 245,616$ kg	2.3	$\frac{W_1}{V} = 106.530\ kg/m^3$
		2.2 $W_1 = 541,005$ lbs.	2.4	$\frac{W_1}{V} = 6.641\ lbs/ft^3$
3.	Total Structure Weight	3.1 $W_2 = 92,850$ kg.	3.3	$\frac{W_2}{V} = 40.212\ kg/m^3$
		3.2 $W_2 = 204,517$ lbs.	3.4	$\frac{W_2}{V} = 2.510\ lbs/ft.^3$
4.	Weight, Items Tabulated	4.1 $W_3 = 53,897$ kg	4.3	$\frac{W_3}{V} = 23.377$ kg/m3
		4.2 $W_3 = 118,717$ lbs.	4.4	$\frac{W_3}{V} = 1.457\ lbs/ft.^3$

ITEM	AREA		% EXTRUDED PANEL	# PARTS	TOTAL WELD LENGTH		MACHINE WELD LENGTH		MANUAL WELD LENGTH	
	m^2	$ft.^2$			m	ft.	m	ft.	m	ft.
SHELL	934	10,040	50	700	1,771	5,810	1,117	3,665	654	2,145
DECKS	1,701	18,290	98	1,320	3,007	9,865	2,387	7,830	620	2,035
TRANSVERSE BULKHEADS	329	3,540	90	1,150	1,594	5,230	838	2,750	756	2,480
FRAMES			10	6,150	1,881	6,170	576	1,890	1,305	4,200
TOTALS	2,964	31,870	-	9,320	8,253	27,075	4,918	16,135	3,335	10,940

5.	# PARTS / LENGTH OF SHIP	5.1 = 144.43 Parts/m
		5.2 = 44.02 Parts/ft.
6.	TOTAL WELDING / LENGTH OF SHIP	6.1 = 127.89 m/m
		6.2 = 127.89 ft/ft
7.	MACHINE WELDING / TOTAL WELDING	7.1 = 0.596 m/m
		7.2 = 0.596 ft/ft
8.	MANUAL WELDING / TOTAL WELDING	8.1 = 0.404 m/m
		8.2 = 0.404 ft/ft

*Based on drawings - not as built.

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Table VI.4-3*. SHIP PGH-1

1. Hull Volume
   - 1.1 v = 294.32 m^3
   - 1.2 V = 10,400 $ft.^3$
2. Lightship Weight
   - 2.1 W_1 = 57,824 kg
   - 2.2 W_1 = 129,367 lbs.
   - 2.3 $\frac{W_1}{V}$ = 196.466 kg/m^3
   - 2.4 $\frac{W_1}{V}$ = 12.241 $lbs/ft.^3$
3. Total Structure Weight
   - 3.1 W2 = 18,449 kg
   - 3.2 w2 = 40,638 lbs.
   - 3.3 $\frac{W_2}{V}$ = 62.683 lbs/ft^3
   - 3.4 $\frac{V_2}{W}$ = 3,900 $lbs/ft.^3$
4. Weight, Items Tabulated
   - 4.1 W_3 = 10,269 kg
   - 4.2 W_3 = 22,620 lbs.
   - 4.3 $\frac{W_3}{V}$ = 34.891 kg/m^3
   - 4.4 $\frac{W_3}{V}$ = 2.175 $lbs/ft.^3$

ITEM	AREA		% EXTRUDED PANEL	# PARTS	TOTAL WELD LENGTH		MACHINE WELD LENGTH		MANUAL WELD LENGTH	
	m^2	ft^2			m	ft.	m	ft.'	m	ft.
SHELL	219	2,355	80	490	256	840	137	450	107	350
DECKS	219	2.355	40	710	171	560	143	470	27	90
TRANSVERSE BULKHEADS	105	1,125	90	430	649	2,130	341	1,120	308	1,010
FRAMES	-			990	405	1,330	--		405	1,330
TOTALS	543	5,835	-	2,620	1,481	4,860	621	2,040	a97	2,780

5. $\frac{\#\text{PARTS}}{\text{LENGTH OF SHIP}}$
   - 5.1 = 117.75 Parts/m
   - 5.2 = 35.89 Parts/ft.
6. $\frac{\text{TOTAL WELDING}}{\text{LENGTH OF SHIP}}$
   - 6.1 = 66.56 m/m
   - 6.2 = 66.56 ft/ft.
7. $\frac{\text{MACHINE WELDING}}{\text{TOTAL WELDING}}$
   - 7.1 = 0.419 m/m
   - 7.2 = 0.419 ft./ft.
8. $\frac{\text{MANUAL WELDING}}{\text{TOTAL WELDING}}$
   - 8.1 0.572 m/m
   - 0.2 = 0.572 ft/ft.

*Based on drawings - not as built.

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Table VI.4-4*. SHIP PGH-2

1. Hull Volume
   - 1.1 V = 237.89 m^3
   - 1.2 V = 8406 $ft.^3$

2. Lightship Weight
   - 2.1 W_1 = 42,347 kg
   - 2.2 W_1 = 93,276 lbs.
   - 2.3 $\frac{W_1}{V}$ = 178.011 kg/m^3
   - 2.4 $\frac{W_1}{V}$ = 11.096 $lbs/ft.^3$

3. Total Structure Weight
   - 3.1 W_2 = 12,833 kg.
   - 3.2 W2 = 20,267 lbs.
   - 3.3 $\frac{W_2}{V}$ = 53.945 kg/m^3
   - 3.4 $\frac{W_2}{V}$ = 3.363 $lbs/ft.^3$

4. Weight, Items Tabulated
   - 4.1 W_3 = 8,713 kg
   - 4.2 W_3 = 19,192 lbs.
   - 4.3 $\frac{W_3}{V}$ = 36.626 kg/m^3
   - 4.4 $\frac{W_3}{V}$ = 2.283 $lbs/ft.^3$

ITEM	AREA		℄ EXTRUDED PANEL	# PARTS	TOTAL WELD LENGTH		MACHINE WELD LENGTH		MANUAL WELD LENGTH	
	m^2	ft^2	ft.		m	ft.	m			ft.
SHELL	223	2,400		590	344	1,130	-	-	344	1,130
DECKS	177	1,900		380	495	1,625	-	-	495	1,625
TRANSVERSE BULKHEADS	71	760		630	1,050	3,445	-	-	1,050	3,445
FRAMES				2,815	1,143	3,750	-	-	1,143	3,750
TOTALS	471	5,060	-	4,415	3,032	9,950		-	3,032	9,950

5. $\frac{\text{\# PARTS}}{\text{LENGTH OF SHIP}}$
   - 5.1 = 194.41 Parts/m
   - 5.2 = 59.26 Parts/m

6. $\frac{\text{TOTAL WELDING}}{\text{LENGTH OF SHIP}}$
   - 6.1 = 133.51 m/m
   - 6.2 = 133.51 ft/ft.

7. $\frac{\text{MACHINE WELDING}}{\text{TOTAL WELDING}}$
   - 7.1 = 0 m/m
   - 7.2 = 0 ft/ft.

8. $\frac{\text{MANUAL WELDING}}{\text{TOTAL WELDING}}$
   - 8.1 = 1.000 m/m
   - 8.2 = 1.000 ft/ft.

*Based on drawings - not as built.

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Table VI.4-5*. SHIP PHM-1

1. Hull Volume	1.1 $V = 702.41\ m^3$		
	1.2 $V = 24,820\ ft.^3$		
2. Lightship weight	2.1 $W_1 = 172,004$ kg	2.3	$\frac{W_1}{V} = 244.877\ kg/m^3$
	2.2 $W_1 = 379,864$ lbs.	2.4	$\frac{W_1}{V} = 15.264\ lbs/ft^3$
3. Total Structure Weight	3.1 $W_2 = 45,948$ kg	3.3	$\frac{W_2}{V} = 65.415\ kg/m^3$
	3.2 $W_2 = 101,209$ lbs.	3.4	$\frac{W_2}{V} = 4.070\ lbs/ft.^3$
4. Weight, Items Tabulated	4.1 $W_3 = 28,102$ kg	4.3	$\frac{W_3}{V} = 40.122\ kg/m^3$
	4.2 $W_3 = 62,076$ lbs.	4.4	$\frac{W_3}{V} = 2.501\ lbs/ft.^3$

ITEM	AREA		# EXTRUDED PANEL	# PARTS	TOTAL WELD LENGTH		MACHINE WELD LENGTH		MANUAL WELD LENGTH	
	m^2	ft^2			m	ft.	m	ft.	m	ft.
SHELL	469	5,040	22	4,600	4,015	15,000	1,606	5,530	3,130	10,270
DECKS	460	4,950	00	400	1,521	4,990	911	2,990	610	2,000
TRANSVERSE BULKHEADS	177	1,900	65	2,400	2.445	8,020	613	2,010	1,832	6,010
FRAMES				5,600	2,074	9,130	1,149	3,770	1,725	5,660
TOTALS	1,106	11,890	-	13,080	11,655	30,240	4,359	14,300	7,297	23,940

5.	# PARTS / LENGTH OF SHIP	5.1 = 332.66 Parts/m
		5.2 = 101.4 Parts/ft.
6.	TOTAL WELDING / LENGTH OF SHIP	6.1 = 297 m/m
		6.2 = 297 ft/ft.
7.	MACHINE WELDING / TOTAL WELDING	1.1 = 0.374 m/m
		7.2 = 0.374 ft/ft.
8.	MANUAL / TOTAL WELDING	8.1 = 0.626 m/m
		0.2 = 0.626 ft/ft.

*Based on drawings - not as built.

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Table VI.4-6. SUMMARY OF TABLES VI.4-1 THROUGH VI.4-5

ITEM	LEAST	2	3	4	GREATEST
1. Length of Ship	PGH-1	PGH-2	PCH-1	PHM-1	AGEH-1
2. Volume of Ship	PGH-2	PGH-1	PHM-1	PCH-1	AGEH-1
3. Lightship Weight	PGH-2	PGH-1	PCH-1	PHM-1	AGEH-1
4. Lightship Weight / Volume	AGEH-1	PCH-1	PGH-2	PGH-1	PHM-1
5. Total Structure Weight	PGH-2	PGH-1	PCH-1	PHM-1	AGEH-1
6. Total Structure Weight / Volume	AGEH-1	PCH-1	PGH-2	PGH-1	PHM-1
7. Weight, Items Tabulated	PGH-2	PGH-1*	PCH-1	PHM-1	AGEH-1
a. Weight, Items Tabulated / Volume	AGEH-1	PCH-1	PGH-1	PGH-2	PHM-1
9. # Parts	PGH-1*	PCH-1	PGH-2	AGEH-1	PHM-1
10. # Parts / Length of Ship	PCH-1	PGH-1*	AGEH-1	PGH-2	PHM-1
11. Total Welding	PGH-1*	PGH-2	PCH-1	AGE:H-i	PHM-1
12. Total Welding / Length of Ship	PGH-1*	PCH-1	AGEH-1	PGH-2	PHM-1
13. Machine Welding	PGH-2	PCH-1	PGH-1	PHM-1	AGEH-1
14. Machine Welding / Total Welding	PGH-2	PCH-1	PHM-1	PGH-1	AGZH-1
15. Manual Welding	PGH-1	PGH-2	PCH-1	AGEH-1	PHM-1
16. Manual Welding / Total Welding	AGEH-1	PGH-1	PHM-1	PCH-1	PGH-2

• Does not include riveted butts and seams.

Table VI.4-7. PRODUCIBILITY GRADATION

ITEM	LEAST	2	3	4	GREATEST
Volume of Ship	AGEH-1	PCH-1	PHM-1	PGH-1	PGH-2
Lightship Weight / Volume	AGEH-1	PCH-1	PGH-2	PGH-1	PHM-1
Total Structure Weight / Volume	AGEH-1	PCH-1	PGH-2	PGH-1	PHM-1
Parts	PGH-1	PCH-1	PGH-2	AGEH-1	PHM-1
Parts / Length of Ship	PCH-1	PGH-1*	AGEH-1	PGH-2	PHM-1
Total Welding	PGH-1*	PGH-2	PCH-1	AGEH-1	PHM-1
Total Welding / Length of Ship	PGH-1*	PCH-1	AGEH-1	PGH-2	PHM-1
Machine Welding	AGEH-1	PHM-1	PGH-1	PCH-1	PGH-2
Machine Welding / Total Welding	AGEH-1	PGH-1	PHM-1	PCH-1	PGH-2
Manual Welding	PGH-1	PGH-2	PCH-1	AGEH-1	PHM-1
Manual Welding / Total Welding	AGEH-1	PGH-1	PHM-1	PCH-1	PGH-2

* Does not include riveted butts and seams

(U) On the basis of Table VI.4-7, the producible order of the evaluated ships are AGEH-1, PGH-1, PCH-1, PGH-2, and PHM-1. This is not intended to be an absolute conclusion, but is rather a limited conclusion based on the information considered in the tables, which is based, in turn, upon the original drawings and data to which the ships were constructed. It is noted that cost has not been included as a factor of comparison. Due to differing design bases, contracting policy, technical considerations, and change order influences, it would be unrealistic to compare the various ships on a delivered cost per ton basis, adjusted for the inflation differential over the past 15 years.

(U) PHM-1 emerges with a low rating. Suffice it to say that producibility is a feature of the ship acquisition contract, that PHM-2 was discontinued, having started construction, and that the Navy investigated specific studies aimed at improving PHM producibility. These studies included:

- Hull and Deckhouse Improvement
- Piping System Integration Improvement
- Foils and Struts Improvement
- Fabrication Plan for Hull Structure
- Fabrication Plan for Foils and Struts
- Maintenance Access Improvement
- 60 Hz Electrical Load Reduction
- 60 Hz Shore Power Provision
- Compartment Test Plan

- Static Converter Design Improvement
- Environmental Control System Producibility
- Electrical Cable Installation
- 400 Hz Electric Motors
- SSPU and Air Compressor Review
- Nonmetallic Materials Testing and Selection
- Structural Fatigue and Fracture Control Plan for Strut/Foil System
- Electrical Generator Test
- Construction Planning
- Ship Specification Finalization
- Foilborne Propulsor Production Improvements

(U) As a result of these studies the structural design of PHM-3 has benefitted as shown in Table VI.4-8, which, when compared with Table VI.4-5, depicts the improvements. Tables VI.4-9 and VI.4-10, when compared with Tables VI.4-6 and VI.4-7, indicate further how PHM-3 is improved overall relative to PHM-1.

(U) The foregoing discussions and information do not include the foil systems. Generally the foil systems have been individually fabricated for each ship and producibility has not been an influential factor. Within the last two years, however, there have been two developments which contribute to enhancing foil system producibility.

Table VI.4-8. SHIP PHM-3

1. **Hull Volume**	1.1	$V = 702.41\ m^3$		
	1.2	$V = 24{,}820\ ft.^3$		
2. Lightship **Weight**	2.1	$W_1 = 181{,}601\ kg$	2.3	$W_1 / V = 258.540\ kg/m^3$
	2.2	$W_1 = 400{,}003\ lbs.$	2.4	$\frac{W_1}{V} = 16.116\ lbs/ft^3$
3. Total Structure Weight	3.1	$W_2 = 41{,}498\ kg$	3.3	$\frac{W_2}{V} = 67.622\ kg/m^3$
	3.2	$W_2 = 104{,}623\ lbs.$	3.4	$\frac{W_3}{V} = 4.215\ lbs/ft.^3$
4. Weight, Items Tabulated	4.1	$W_3 = 30{,}818\ kg$	4.3	$\frac{W_3}{V} - 43.875\ kg/m^3$
	4.2	$W_3 = 67{,}883\ lbs.$	4.4	$\frac{W_3}{V} = 2.135\ lbs/ft.^3$

ITEM	AREA m^2	AREA ft^2	% EXTRUDED PANEL	# PARTS	TOTAL WELD LENGTH m	TOTAL WELD LENGTH ft.	MACHINE WELD LENGTH m	MACHINE WELD LENGTH ft.	MANUAL WELD LENGTH m	MANUAL WELD LENGTH ft.
SHELL	469	5,040	22	2,060	3,730	12,238	1,686	5,532	2,044	6.706
DECKS	460	4,950	80	410*	2,070	6,191	1,100	3,609	970	3,185
TRANSVERSE BULKHEADS	177	1,900	65	600	1,920	6,300			1,920	6,300
FRAMES	-	-	-	1,400	2,790	9,153		, -	2,790	9,153
TOTALS	1,106	11,890	-	4,470	10,510	34,482	2,786	9,141	7.724	25,342

*DOES NOT INCLUDE FASTENERS

5. $\frac{\#PARTS}{LENGTH\ OF\ SHIP}$	5.1	= 113.68 Parts/m
	5.2	= 34.65 Parts/It.
6. $\frac{TOTAL\ WELDING}{LENGTH\ OF\ SHIP}$	6.1	= 267 m/m
	6.2	= 267 ft/ft.
7. $\frac{MACHINE\ WCLDING}{TOTAL\ WELDING}$	7.1	= 0.265 m/m
	7.2	= 0.265 ft/ft.
8. $\frac{MANUAL\ WELDING}{TOTAL\ WELDING}$	8.1	= 0.735 m/m
	8.2	= 0.735 ft/ft.

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Table VI.4-9. SUMMARY OF TABLES VI.4-1 THROUGH VI.4-4 AND VI.4-8

ITEM	LEAST	2	3	4	GREATEST
1. Length of Ship	PGH-1	PGH-2	PCH-1	PHM-3	AGEH-1
2. Volume of Ship	PGH-2	PGH-1	PHM-3	PCH-1	AGEH-1
3. Lightship Weight	PGH-2	PGH-1	PCH-1	PHM-3	AGEH-1
4. Lightship Weight / Volume	AGEH-1	PCH-1	PGH-2	PGH-1	PHM-3
5. Total Structure Weight	PGH-2	PGH-1	PCH-1	PHM-3	AGEH-1
6. Total Structure Weight / Volume	AGEH-1	PCH-1	PGH-2	PGH-1	PHM-3
7. Weight, items Tabulated	PGH-2	PGH-1*	PCH-1	PHM-3	AGEH-1
8. Weight, Items Tabulated / Volume	AGEH-1	PCH-1	PGH-1	PGH-2	PHM-3
9. # Parts	PGH-1*	PCH-1	PGH-2	PHM-3*	AGEH-1
10. # Parts / Length of Ship	PCH-1	PHM-3*	PGH-1*	AGEH-1	PGH-2
11. Total Welding	PGH-1*	PGH-2	PCH-1	AGEH-1	PHM-3*
12. Total Welding / Length of Ship	PGH-1*	PCH-1	AGEH-1	PGH-2	PHM-3
13. Machine Welding	PGH-2	PCH-1	PGH-1	PHM-3	AGEH-1
14. Machine Welding / Total Welding	PGH-2	PCH-1	PHM-3	PGH-1	AGEH-1
15. Manual Welding	PGH-1	PGH-2	PCH-1	AGEH-1	PHM-3
16. Manual Welding / Total Welding	AGEH-1	PGH-1	PHM-3	PCH-1	PGH-2

* Does not include riveted butts and seams.

Table VI.4-10. PRODUCIBILITY GRADATION

ITEM	LEAST	2	3	4	GREATEST
Volume of Ship	AGEH-1	PCH-1	PHM-3	PGH-1	PGH-2
Lightship Weight / Volume	AGEH-1	PCH-1	PGH-2	PGH-1	PHM-3
Total Structure Weight / Volume	AGEH-1	PCH-1	PGH-2	PGH-1	PHM-3
Parts	PGH-1*	PCH-1	PGH-2	PHM-3*	AGEH-1
Parts / Length of Ship	PCH-1	PHM-3*	PGH-1*	AGEH-1	PGH-2
Total Welding	PGH-1*	PGH-2	PCH-1	AGEH-1	PHM-3
Total Welding / Length of Ship	PGH-1*	PCH-1	AGEH-1	PGH-2	PHM-3
Machine Welding	AGEH-1	PHM-3	PGH-1	PCH-1	PGH-2
Machine Welding / Total Welding	AGEH-1	PGH-1	PHM-3	PCH-1	PGH-2
Manual Welding	PGH-1	PGH-2	PCH-1	AGEH-1	PHM-3
Manual Welding / Total Welding	AGEH-1	PGH-1	PHM-3	PCH-1	PGH-2

• Does not include riveted butts and seams

On the basis of Table 4-10 the most to least producible ships, in order, are PCH-1, PCH-1, AGEH-1, PHM-3, and PGH-2

(U) A study was performed under a Navy contract to investigate the fabrication of HY-130 steel foil systems for the PHM. The contract was planned in two phases, preliminary design, and detail design. The latter phase was not started. Out of the study emerged a concept for breaking the foils and struts down into a number of subassemblies which could be manufactured independently and bolted together to form the foils or struts. The intent of such breakdown was to provide a means for replacing possibly damaged portions of the foil systems rather than having to replace an entire foil.

(U) Out of the study came certain approaches to the configuration of spars, ribs, and skins which promised to reduce the problems of tolerance and distortion control and obviate the one side welded closer skin.

(U) A new AGEH-1 HY-130 Tail was constructed within the past year and embodied fabrication concepts of the PHM study. This large structure has been constructed in a straightforward manner, without any difficulties, and was completed on time and within cost.

Section 5

FEASIBILITY OF HYDROFOIL SHIP PRODUCTION

(U) Ten different types of hydrofoil ships, ranging in size from 20 m (65 ft) to 65 m (210 ft) and in displacement from 38 m tons (40 tons) to 341m tons (336 tons) have been constructed by a variety of firms. There is little question as to the feasibility of constructing hydrofoil ships.

(U) However, if in the future hydrofoil ships are to be produced in any quantity, greatly improved planning, engineering, and manufacturing coordination must be demanded.

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VII. BIBLIOGRAPHY

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II.C No bibliographic entries.

II.D No bibliographic entries.

III Extensive listing (755 listings) available in a separate document as DTNSRDC ASDB# 10U07662 as: "'Advanced Ship Data Bank Hydrofoil Document Listing, Complete Listing, Performance"

Speed-Power	HOC
Range-Endurance	DEH
Maneuverability	AGEH-1
Ship-Craft Stability	PHM-1
Seakeeping-Kindliness	PCH-1 (Mod 0)
Craft Internal Environment	PCH-1 (Mod 1)
Payload Capabilities	PGH-1
	PGH-2
	SWORDFISH
	FRESH-l
	FHE-400

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IV No bibliographic entries.

V No bibliographic entries.

VI No bibliographic entries.