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TITLE PROPELLER DRIVES FOR HYDROFOIL SHIPS - A POSITION PAPER

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ABSTRACT

Improved performance, namely range and payload, can be achieved by the selection of propeller drive over waterjet system for foilborne hydrofoil ship operation.

An outline of a development plan for a PHM with a foilborne propeller drive system is presented. This outline includes an approximate cost and schedule for the task.

KEY WORDS

PHM
Waterjet
Propeller
Transmissions
Range
Payload
Hydrofoil
Patrol Hydrofoil Missile (PHM)

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1.0 INTRODUCTION

1.1 Purpose

Significant improvements in the efficiency and effectiveness of hydrofoil ships are obtainable when propeller drive systems replace waterjet propulsors as the propulsive medium. It is the purpose of this document to present a position regarding the feasibility and practicability of the incorporation of propeller drive systems into future PHMs and PHM growth variant hydrofoil ships.

1.2 Background

Current hydrofoil ships being constructed by Boeing Marine Systems are driven exclusively by waterjet propulsion systems. The principal advantage of the waterjet systerm is the comparative simplicity of the power transmission and the attendant reliability that is offered. However, as can be seen on figure 1.2-1, waterjets are not as efficient as propellers throughout the full' speed range under consideration. Figure 1.2-l shows the propulsive coefficient of a waterjet system compared to a propeller drive system. Of particular significance is the large drop in efficiency of the waterjet as the speed drops off. This generally results in a lower full load displacement ship for the same installed horsepower. At cruise speeds the waterjet propulsive coefficient is some 30 percent below that of the propeller equating directly into reduced range for a given installed horsepower. Consequently, ships driven by waterjets are generally considered to be operationally range and/or payload limited.

1.3 Study Limitations

Further range/payload gains are achievable when foil and ship characteristics are matched to the propeller thrust values available. These are beyond the scope of this presentation and will not be further considered.

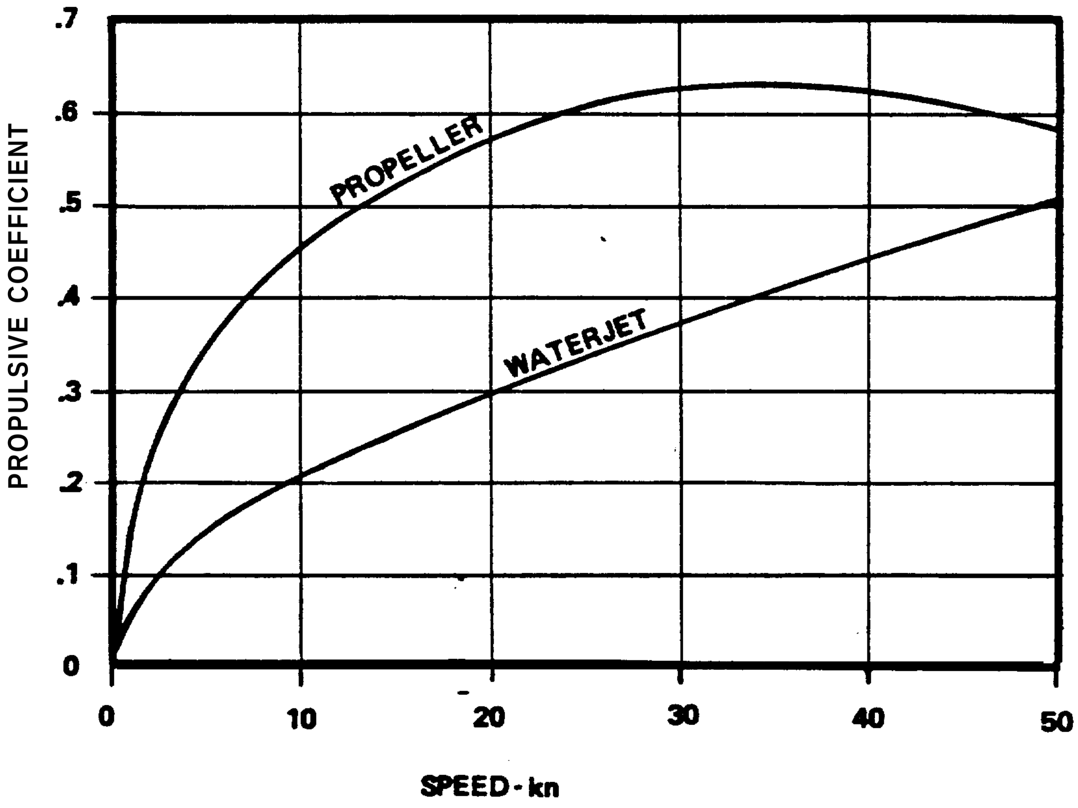


Figure 1.2-1: Typical Hydrofoil Performance

2.0 SUMMARY AND CONCLUSION

2.1 Summary

Foilborne transmission systems for hydrofoil ships are complex arrangements of interconnecting devices that run the full gamut of engineering disciplines. The existing technology in each of these disciplines will allow the design, development, test and manufacture of a successful propeller drive system to be conducted.

All anticipated system components are in a continuing state of development for systems other than for hydrofoil ships. Many helicopter rotor drives, for example, have higher and more critical reliability operational requirements, have similar horsepower level requirements, are equally complex, have achieved high levels of success, and consequentially are able, to provide extensive technological background for the development of a hydrofoil transmission system. Through the Boeing Vertol Company and other competent suppliers the ability to apply this experience with confidence 'is available.

Bevel gear size limits exist due to manufacturing restraints but in practice their size is limited by the capacities of the attendant thrust bearings. These bearings being either size or speed restricted, are a limiting feature of a single mesh gearbox, and require the application of dual mesh gears with the thrust component essentially cancelled as a solution.

Lubrication and leakage, having generated most of the problems experienced by prior designs, are considered critical items and require special attention in both concept and detail design phases.

In addition, and most importantly, the overall ship arrangement must be highly compatable with the transmission configuration being considered. Component and intercomponent stiffness, transmission access, transmission alignment , both initially and during operation, and transmission space requirements require early conceptual consideration in order for the design to be successful.

To recap, no technical reasons exist which preclude the designing, developing, testing, and the manufacturing of a foilborne propeller transmission system for a hydrofoil ship.

2.2 Conclusion

A marked improvement in the operational capabilities of hydrofoil ships is available by the application of propeller drive technology. To plan worthwhile range and for payload improvements, propulsion efficiencies have to be substantially increased and this can be achieved by utilizing propeller drive systems in future hydrofoil ships.

To meet future competition and customer requirements, an advanced program utilizing a propeller drive system for a hydrofoil ship should be established. As a pertinent objective it is suggested that a system powering a PHM-sire ship be chosen and developed to a sufficient degree to provide performance, cost, weight, and scheduling criteria.

In addition, as briefly described in section 4.4, it is suggested that a propeller test program be established for the PCH-1 (HIGH POINT) that would enhance the high speed propeller technologies that will be required for the development of hydrofoil ships.

Expertise, not now available, can be gained during these programs which will form a sound basis for the design and development of propulsion systems for advanced hydrofoil ships.

3.0 DRIVE SYSTEMS

3.1 Drive Systems History

3.1.1 Drive System History Until 1974

Limited historical data is currently available on past and present transmission systems. Figure 3.1-l describes the various power levels, foilborne hours and the major problems that were experienced until 1974. Only the PCH-1, High Point, is still active. Two variants of PGH-1 are now operational with the Israeli Navy, the first having in the order of 1,000 operational hours with the second being recently commissioned. No specific data is available on these two ships.

Component failures until 1974 are charted on figure 3.1-2. PCH-1 is separately reported from 1980 to date and reflects the trend towards better sealing and lubrication, see section 3.1.2.

All systems suffer from some, all, or combinations of the following:

a. overly lightened gear support shafting (too flexible)
b. saltwater leakage
c. inability to tolerate misalignment during ship operation
d. gear shaft fretting
e. lubricating oil supply
f. lubricating oil scavenging
g. lubricating oil temperature control
h. lubricating oil foaming
i. torsional vibration of long slender shafting

Actual gear failures (tooth problems) have not been a problem due possibly to the limited number of hours experienced by the various systems.

SHIP	POWER	YEAR DELIVERED	TOTAL FOILBORNE HOURS	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 bearing failures. Trouble free after delivery to Navy.
(PCH-1) HIGH POINT	3,500 HP	1963	970	Water in transmission system due to seal leaks and salt water inlet piping leaks. Ball bearing retainers failed due to corrosion at 330 hours. Refurbished transmission. Operated trouble free until Mod 1 overhaul at 690 hours. Trouble free since Mod 1 overhaul.
(PGH-1) FLAGSTAFF	3,800 HP	1968	672	During the first 351 hours, systems were essentially de-bugged on the ship rather than in bench tests. Major failures were a fatigue crack in web of an idler gear due to 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 foflborne hours and 300 high speed hullborne taxiing hours trouble free.
(FHE 400) BRAS d'OR	24,000 HP engines split to two 12,000 HP ZEE drives	1968	100	Major design problems eliminated by extensive bench testing. Minor fabrication 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.
(AGEH-1) PLAINVIEW	17,000 HP	1969	198	Coupling wear due to misalignment. New coupling designed to take large misalignments being installed. Major gearboxes have been trouble free.

Figure 3.1-I: Hydrofoil Zee-Drive Transmission History (as of 1974)

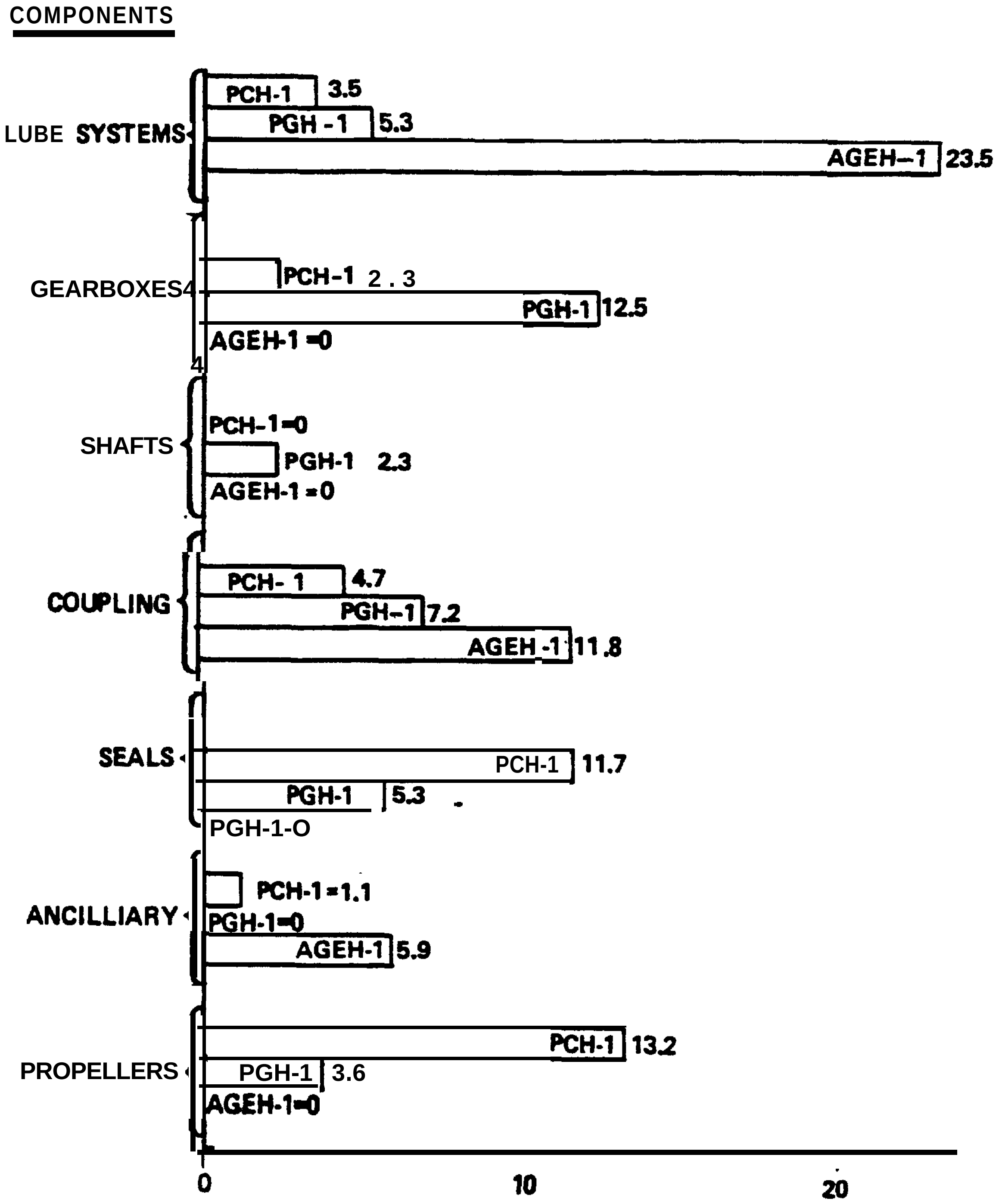


Figure 3.1-2: Failures Per 1000 Foilborne Operating Hours (Through 1974)

3.1.2 PCH-1 History, 1980 through June 1984

a. transmission gearboxes were overhauled in 1980

b. lube oil system was redesigned and rebuilt

c. some saltwater leakage into system occurred

d. water shedding additive was added to lubricating oil

e. a strut fairing became detached damaging a lube oil supply line The ship was drydocked and system flushed

f. lube oil has been and is changed regularly

g. The ship has 200 hours foilborne to date with no problems experienced within the gear transmission components themselves

3.1.3 Failure Prediction and Correction

It can be said that all of the aforementioned problems were correctable. Attention to the causes of the failures and to detail design principles will assure that most of these failures are prevented. There will be components of the system which will experience failure during the qualification testing but these too can be accounted for in the final design.

3.2 IR&D Investigation

3.2.1 Propeller Drive System For the Model 928-80 Hydrofoil Ship

The Model 928-80, presented in reference 1, (0312-80969-1) is a 400-ton multimission ship designed with a General Electric LM 2500 gas turbine as its foilborne prime mover. In this study the engine was rated at 25,000 continuous cruise horsepower and drives a waterjet pump through an epicyclic reduction gearbox.

For comparative purposes a propeller drive system was sufficiently outlined to provide weight and center of gravity location data. This arrangement, the strut portion of which is shown on figure 3.2-1, depicts a propeller and nacelle combination accommodating a stepped shaft helical gearbox positioned below and aft of the foil. The vertical driveshaft is located in the strut trailing edge cavity and behind the basic foil structure. The gearbox is shown as a sealable and testable entity within the nacelle. The nacelle framework is independently mounted to the foil structure. The system is driven by the LM 2500 derated to 19,000 continuous horsepower to suit the cruise design speed propeller thrust requirements.

Figure 3.2-2 is the estimated range-payload curve developed for the Model 928-80. The curves show the waterjet and propeller capabilities and include the effects of rearranged weight and fuel within a constant ship displacement. As can be seen significant range and/or payload improvements are attainable with the propeller drive system.

3.2.2 Other Propeller Drives

Waterjet and propeller drive systems have been studied, reference 1, and compared for applications on ships ranging up to 800 tons. Performance curves essentially follow figure 3.2-2 indicating a consistant advantage for propellers through the full ship range.

3.2.3 Future Investigations

Significant demonstrated and theoretical performance improvements using propeller system as opposed to waterjets raise issues that require further investigation, analysis and development. These are:

a. new missions with increased endurance requirements

b. increased range and/or payload requirements

c. life cycle cost reduction

d. comparison with competitive technologies (SES, SWATH, etc.)

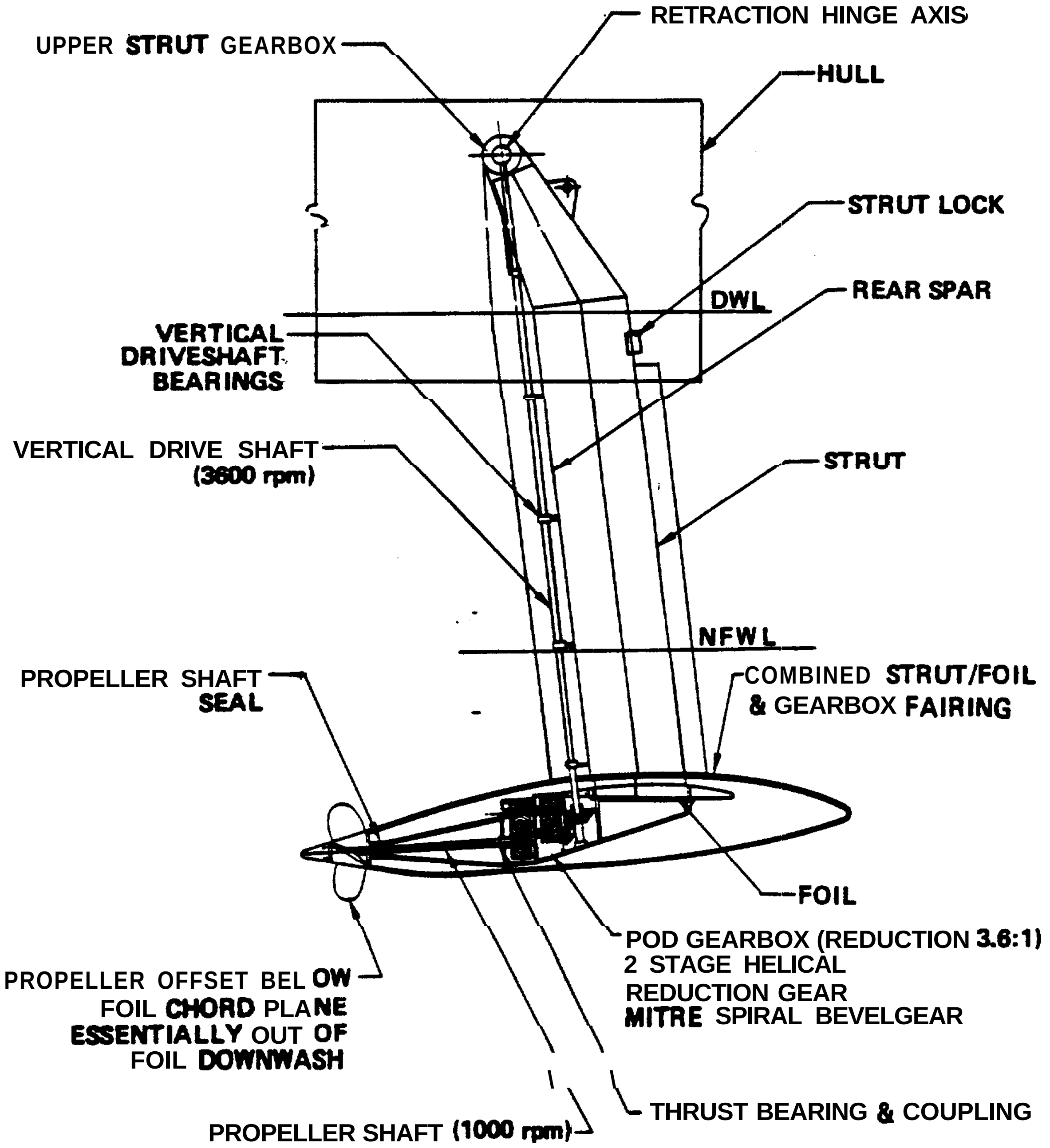


Figure 3.2-I: Strut Arrangement, Model 92860 Propeller Drive System

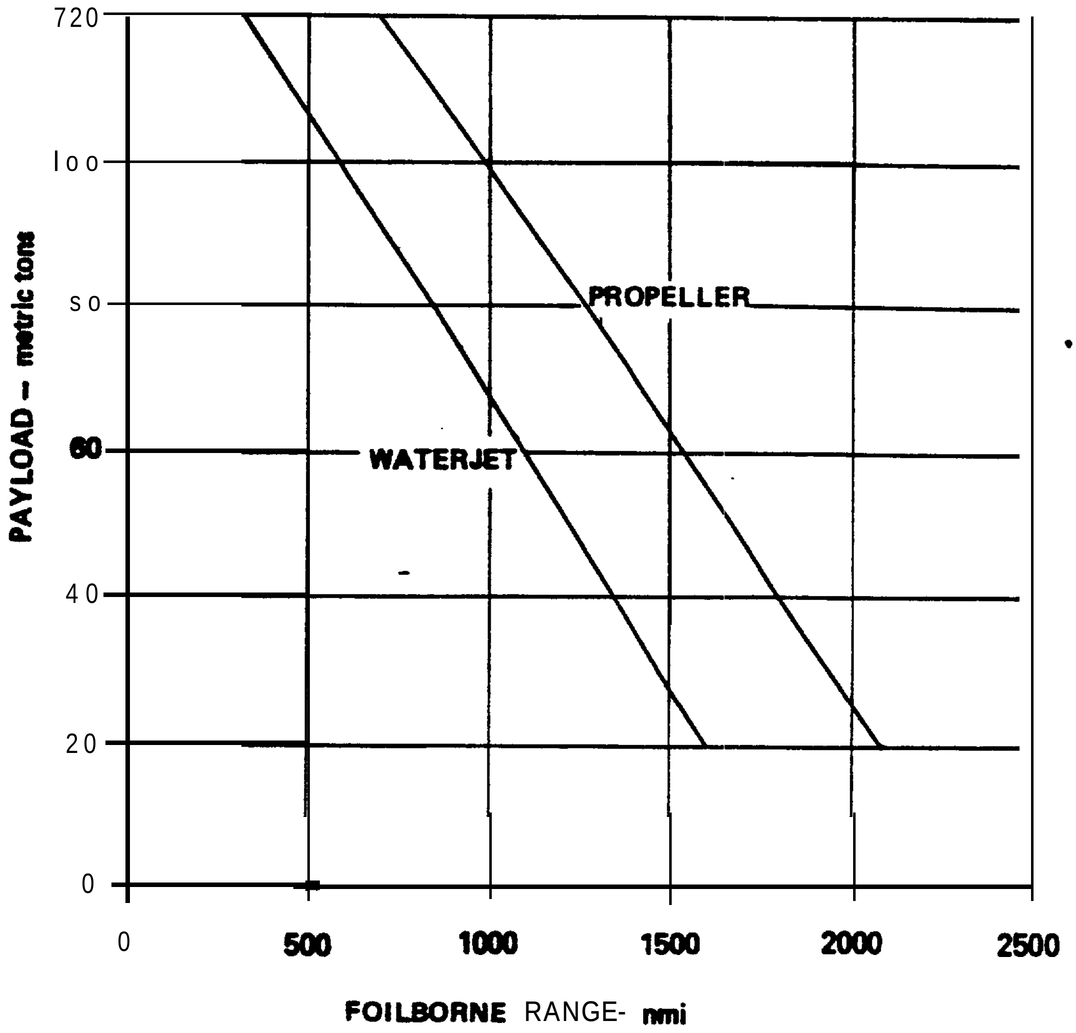


Figure 3.2-2: Foilborne Performance — Model 928-80

3.3 New System Design

3.3.1 Design Goals

Generalized design goals for both ship and systems are as follows:

a. high reliability

b. minimum initial and life cycle costs

c. high efficiency

To achieve these goals, activity in the following disciplines, as a minimum, is required:

a. Hydrodynamics ---
   nacelle
   strut
   propellers
   foils
   nacelle, propeller, strut and foil interaction

b. Mechanical systems ---
   gearing
   sealing
   lubrication
   shafting
   couplings

c. Vibration ---
   propeller
   gearing
   shafting

d. **Noise ---**
  acoustic signatures - propeller
  acoustic signatures - gear train
  shipboard noise

e. **Engine installation ---**
  exhaust (location and configuration)

f. **Weight control ---**
  component weights
  ship configuration weights

g. structures
  arrangements
  stiffness
  interaction - hull and foil systems

h. cost
  component cost
  configuration cost

i. Scheduling

3.3.2 Conceptual Transmission Arrangement

3.3.2.1 Propulsion System Outline

A block diagram of a conceptual hydrofoil propeller drive system is outlined on figure 3.3-1. This particular system is one-half of a full ship system and describes the primary elements required to transmit power from the ship's hull, through the retraction hinge, down the strut to the propeller nacelle and on to the propeller. A brief description of the components from turbine to propeller follows:

a) a twin shaft-free turbine power plant with power takeoff preferably at the compressor end (cold end). The turbine is envisioned as being installed cold end forward allowing (1), power takeoff

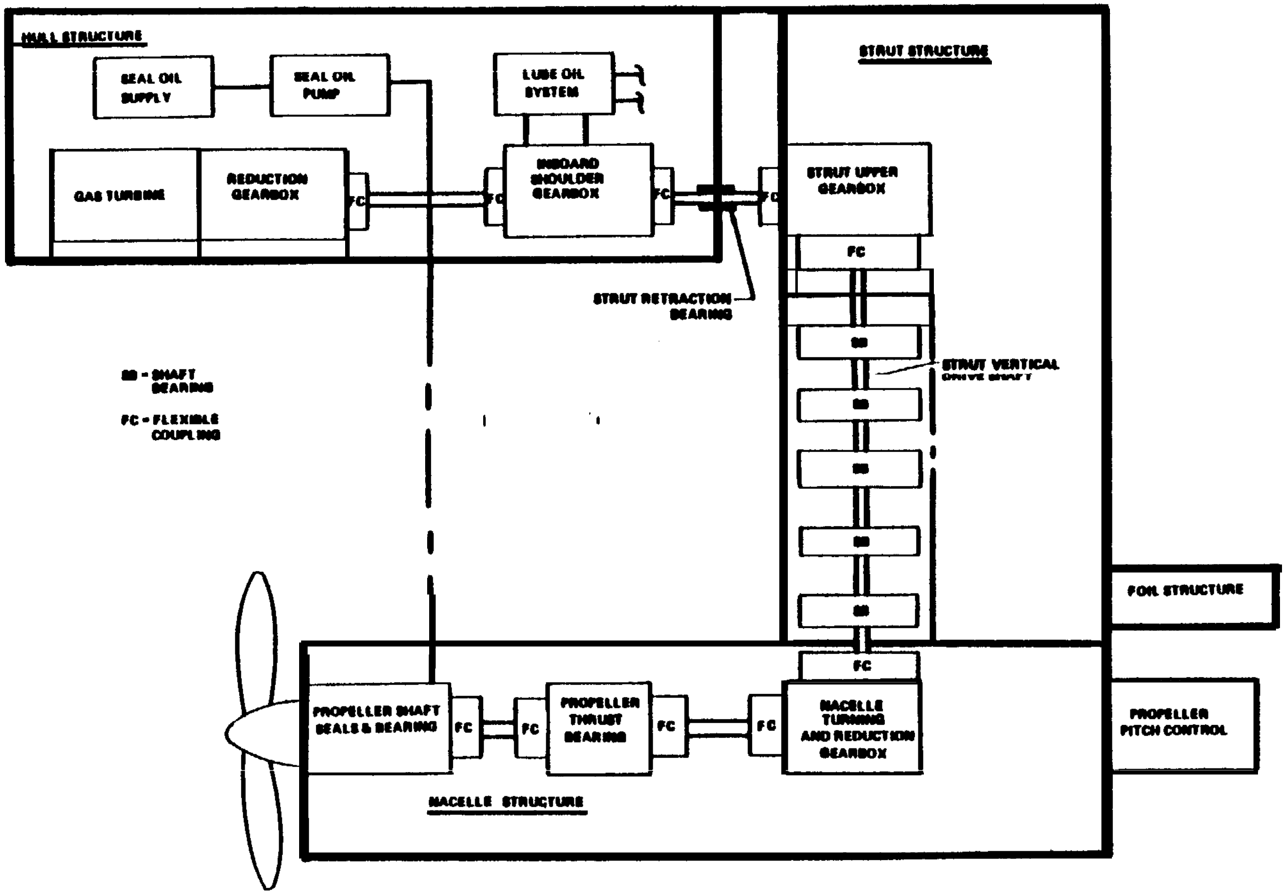


Figure 3.3-1 : Block Diagram - Propeller Drive System

forward to a shoulder gearbox, (2), exhaust directly astern through transom, (3), clean air intakes and (4), minimum impact on ship arrangement.

b) an engine mounted reduction gearbox using an epicyclic gear train with a reduction of approximately 3:1. This reduces the output shaft speed to 3,000 rpm from 11,000 rpm at the turbine.
(DDA 570 rpm)

c) an inboard shoulder gearbox with a 1:1 ratio spiral bevel gear set which essentially redirects the shafting outboard to align with the retraction hinge axis.

d) a strut upper gearbox with 1:1 ratio spiral bevel gear set which redirects shafting from a lateral attitude through the retraction axis into a vertical attitude down the strut structure.

e) a series of shaft bearings controlling the vertical drive shafting and at the same time forcing shaft compatibility with the expected underway strut structural deflections.

f) a nacelle turning and reduction gearbox which again redirects and reduces shaft direction and speed. This is accomplished by a 1:1 ratio spiral bevel gear set driving an epicyclic gear train with a reduction of 3.6:1 to provide an output shaft speed on the order of 1,000 rpm.

g) a propeller shaft seal centerline bearing assembly housing propeller shaft radial and thrust bearings and oil and sea water shaft seals.

h) a propeller configuration as selected by test and analysis (variable or fixed pitch, single, tandem or contrarotating).

i) a series of shafts interconnecting the above components, in each case interconnected with flexible couplings and running in oil and watertight housings.

3.3.2.2 Lubrication System

Figure 3.3-2 is a schematic of a lube oil system set up around one of the gearboxes shown in figure 3.3-l. The diagram is largely self explanatory being similar to that used on PHM. However, the overall lube oil system envisioned for the propeller drive arrangement under discussion will become more sophisticated due to the differing thermal requirements, differing delivery and scavenging requirements of the various gearboxes. For example, the nacelle mounted gearbox and the shoulder gearbox will run at considerably different ambient temperatures possibly requiring separate lube oil systems. In this case, each gearbox would carry a dedicated arrangement similar to that shown on figure 3.3-2.

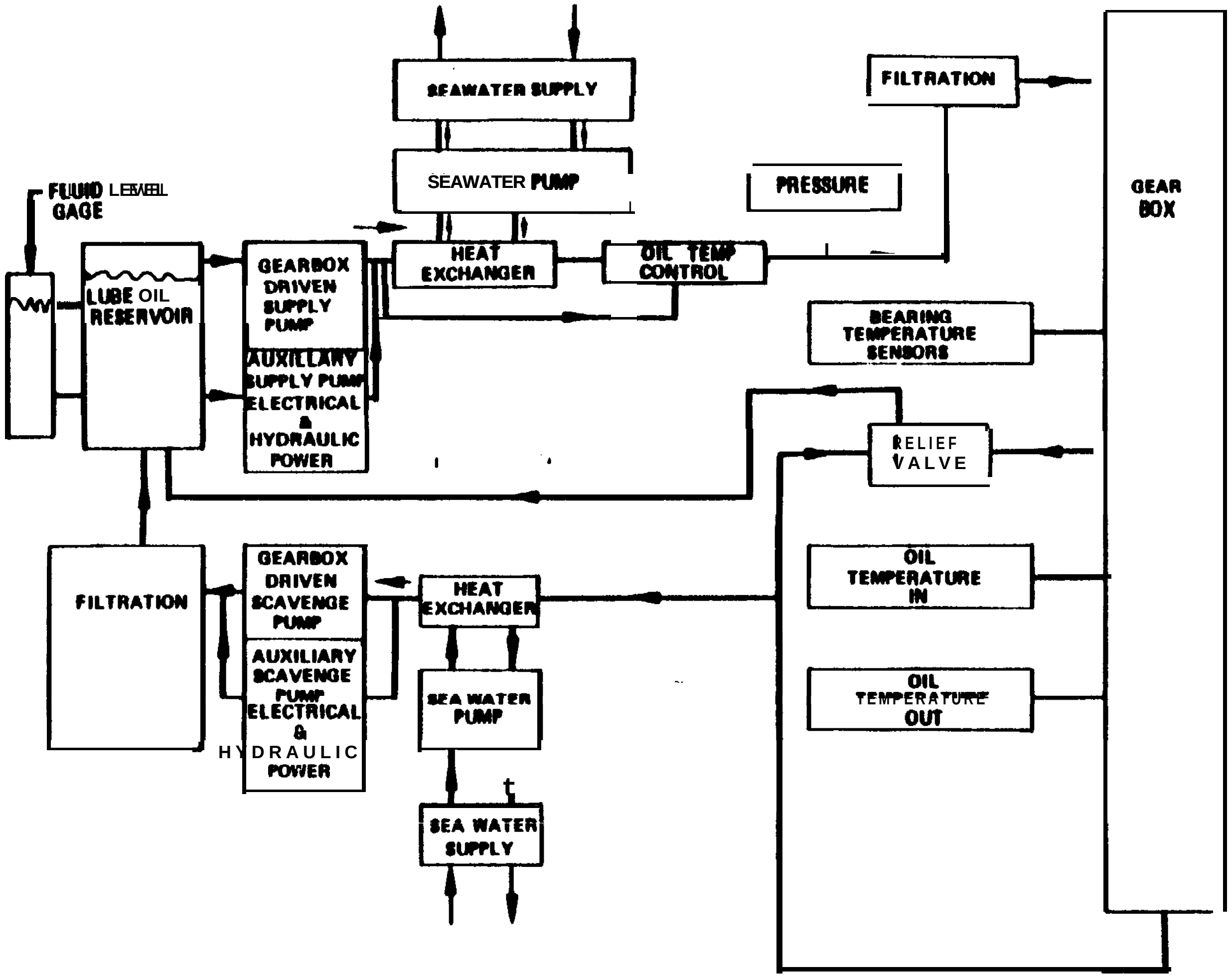


Figure 3.3-2: Block Diagram —*General Lube* Oil System

4.0 TESTING

4.1 General Testing

A key element to the success of a foilborne transmission system will be an effective test program.

The basic objective of a test program is to advance the various components and the complete system through the development and production status prior to final installation and usage.

The degree of risk throughout the system depends largely on the design criteria initially selected. Conservative design criteria will significantly increase the chances of achieving the test objectives. Component testing also increases the chances of overall early system test success.

4.2 Component Testing

Figure 4.2-l outlines the test objectives for each major component. These are objectives which should be accomplished early in order to meet the basic overall objectives. In this manner, deficiencies exposed at the component level can be corrected without necessarily impacting the full program.

COMPONENT	TEST OBJECTIVE
3EVEL GEARBOXES	Tooth fatigue strength Tooth surface durability Tooth lubrication (scoring) Tooth contact Gear centrifugal effects Fretting Bearing performance Bearing race retention Lube oil circulation Vibration performance
EPICYCLIC GEARBOXES	Tooth fatigue strength Tooth surface durability Tooth lubrication (Scoring) Tooth contact Planet Load sharing Bearing performance Vibration performance Lube oil circulation Fretting
Propeller Shaft Assembly	Thrust bearing performance Radial bearing performance Seal oil tightness Seawater tightness Lube oil circulation
Strut Shafts	Vibration performance Straight shaft bearing performance Deflected shaft bearing performance Deflected shaft fatigue life Lube oil circulation
Flexible Couplings	Misalignment capability Lubrication (if applicable) Vibration performance

FIGURE 4.2-1: COMPONENT TEST OBJECTIVES

4.3 Prototype System Testing

While most test objectives can be met by testing at the component level, water tightness, lubrication, vibration and performance objectives for the total system can only be met by some form of at-sea testing.

Some of these objectives can be met by mounting a partial transmission system to a barge and running the drive train dockside in a stationary environment. However, this arrangement could require a special propeller and engine installation and would not necessarily provide performance data of consequence.

As a more advanced alternative, a craft could be purchased or built on which underway testing, both stationary and at design speeds, could be accomplished. Again, performance data might be limited in its scope, particularly at the higher speeds.

To attain the complete test objectives an ideal test arrangement would be an entire transmission system installed in a ship of interest and fully tested at sea. For a follow-on PHM series program, as an example, the lead ship, PEGASUS, could be modified and used in this manner. This approach would be high-risk, high-cost and logistically unjustifiable requiring an extensive downtime for the ship modifications. However, an at-sea test program using a modified JETFOIL as the test vehicle could be utilized to attain the test objectives. Section 5.0 outlines a propeller drive design for a PHM. It consists of identical systems, one port, one starboard operating independently of each other. The power level for this concept is approximately twice that required to power a JETFOIL. Consequently, a system designed essentially for the PHM and modified for installation in the JETFOIL center strut would allow comprehensive system test objectives to be met. In addition, a unique opportunity would be available to make dynamic viable comparisons between waterjet and propeller devices on the same ship. This, of course, would require a major JETFOIL redesign involving, at least, the aft center strut, aft machinery spaces, exhaust, air and fuel systems and ship hullborne steering system.

4.4 Propeller Testing

Current propeller technology infers a significant improvement in propeller efficiency when properly matched contrarotating propeller arrangements are applied.

PCH-1 (HIGH POINT) uses a tandem propeller arrangement with propeller shafts driven in opposite directions by a common pinion gear on the gearbox downshaft. This gearbox and nacelle arrangement lends itself naturally to the coaxial shafting necessary for contrarotating propellers and would allow a new design to be "plugged" directly into the downshafting now on the ship. An ideal test bed is therefore available for the full sire development of a nacelle with contrarotating propellers which would enhance the data base needed for the evaluation of propeller drives for PHMs and other hydrofoil ships.

5.0 PHM PROPELLER DRIVE PLAN

To demonstrate potential PHM performance improvements and to establish an approximate schedule and cost estimate for a propeller drive system, a plan for a PHM equipped with propeller drives, following the block diagram on figure 3.3-1, is briefly outlined below:

5.1 Assumptions

a. Displacement increased to 250 metric tons
b. Accommodations unchanged
c. Ship's interior forward of Frame 21 unchanged
d. Ship's interior aft of Frame 21 revised to suit new propulsion systems
e. Aft foil system essentially unchanged
f. Relocated hullborne propulsion
g. Retraction systems unchanged

5.2 Plan

a. Establish preliminary performance criteria.

b. Establish preliminary mechanical and structural criteria.

c. Establish preliminary design of ship system.

d. Select candidate power plants.

e. Establish preliminary drive train geometry.
  gehrbox envelopes
  propeller shaft location
  vertical driveshaft location

f. Select preliminary propeller configuration.

g. Develop preliminary nacelle arrangement.

h. Develop preliminary structural arrangement.

i. Establish preliminary cost estimate

j. Conduct in-house preliminary design reviews

k. Prepare proposal to customer

l. Receive design go-ahead

m. Prepare prototype design package
   - select final power plants
   - select final overall system arrangement
   - develop and test models (hydrodynamic)
     - propeller
     - nacelle
     - propeller nacelle and foil combinations
   - establish final gearbox envelopes
   - establish system structural arrangements
   - select supplier
     - propeller system plus propeller testing
     - drive train plus gear testing
     - engines
   - prepare prototype drawings

n. Conduct customer design review

o. Produce prototype hardware

p. Test and check hardware
   - component
   - system
   - shipboard

q. Obtain production contract
   - Prepare production drawings
   - Produce and supply production hardware

5.3 Schedules

Schedule and cost estimates are shown on figures 5.3-1 and 5.3-2. Estimates are very approximate but provide an insight into the time frame and cost magnitude of the task.

5.4 Propeller Drive System

To further assist in the plan development, a conceptual design of the propeller drive system, shown on figure 5.3-3, was developed. Salient features are as follows:

a. Two Allison 570K engines
b. lateral drive through the strut retraction axis
c. vertical driveshaft in trailing edge of strut
d. combined foil/strut fairing and propeller nacelle
e. propeller essentially below and out of foil wake
f. transom exhaust
g. air intake at ship's side
h. transmission as shown on figure 3.2-1 and as described in section 3.2.1.

5.5 Performance

Figures 5.5-1 and 5.5-2 were developed to give insight into component sizing and horsepower levels required. For comparative purposes a range estimate was also made. Figure 5.5-1 superimposes a family of varying diameter propeller thrust curves on a PHM drag curve. Figure 5.3-3 shows a concept using a 4.25-foot diameter propeller. This, the smallest plotted diameter, was arbitrarily selected in order to keep transmission torques low. This choice provides a thrust to drag margin at takeoff of 44 percent and sufficient thrust to maintain near design cruise speeds in high sea states. Propeller r.p.m. at takeoff and at cruise are 1,000 rpm and 1,100 rpm respectively.

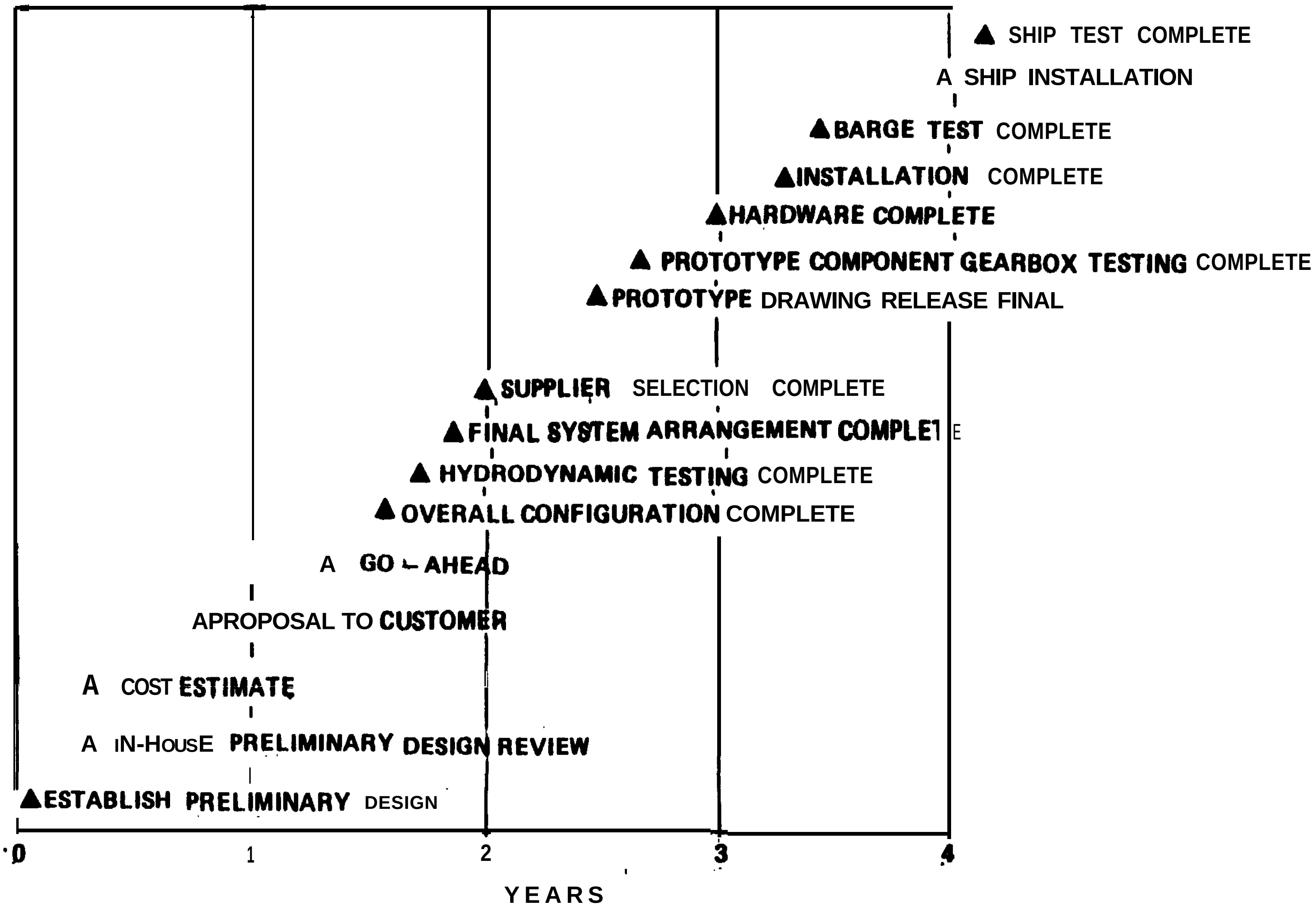


Figure 5.3-1 : Schedule-Propeller Drive System

COSTS

LABOR

- ENG 60,000 hrs 6 $75/ hr = $4,500,000
- SHOP & TEST 89,000 hrs @ $73/hr = $6,500,000

MATERIAL@ 30% LABOR COST = $3,300,000

TOTAL' $14,300,000

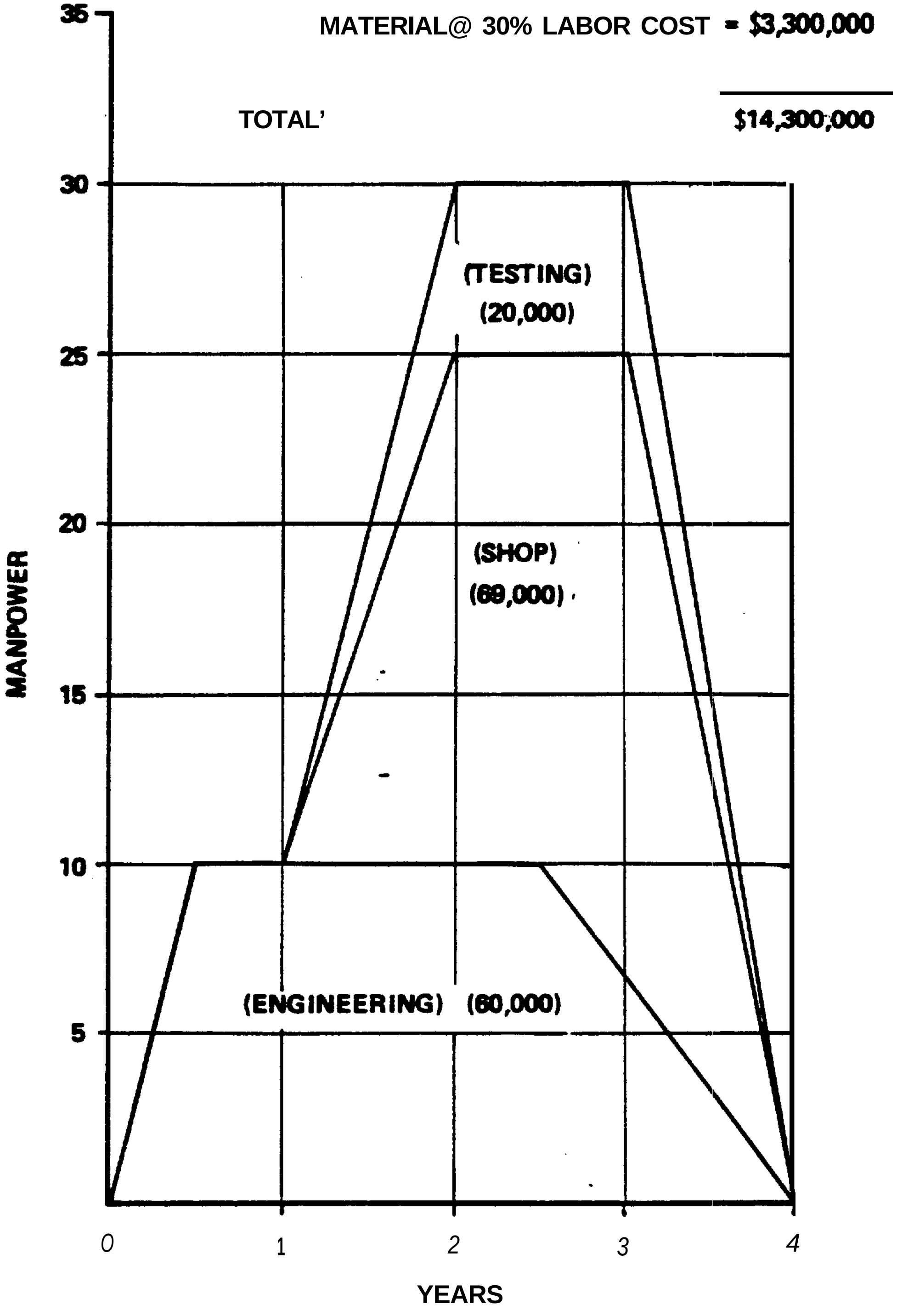


Figure 5.3-2: Cost Estimate — Propeller Drive System

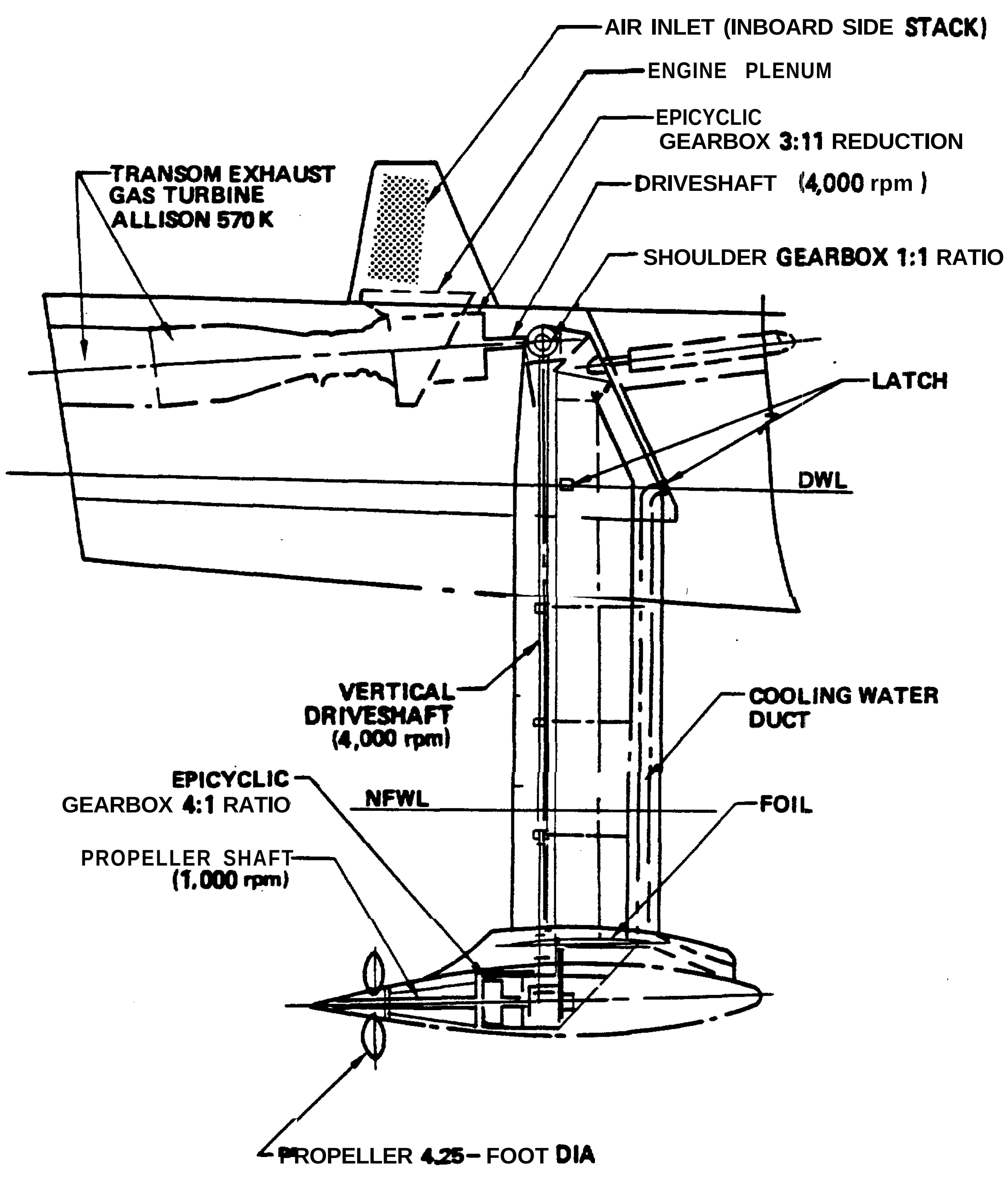
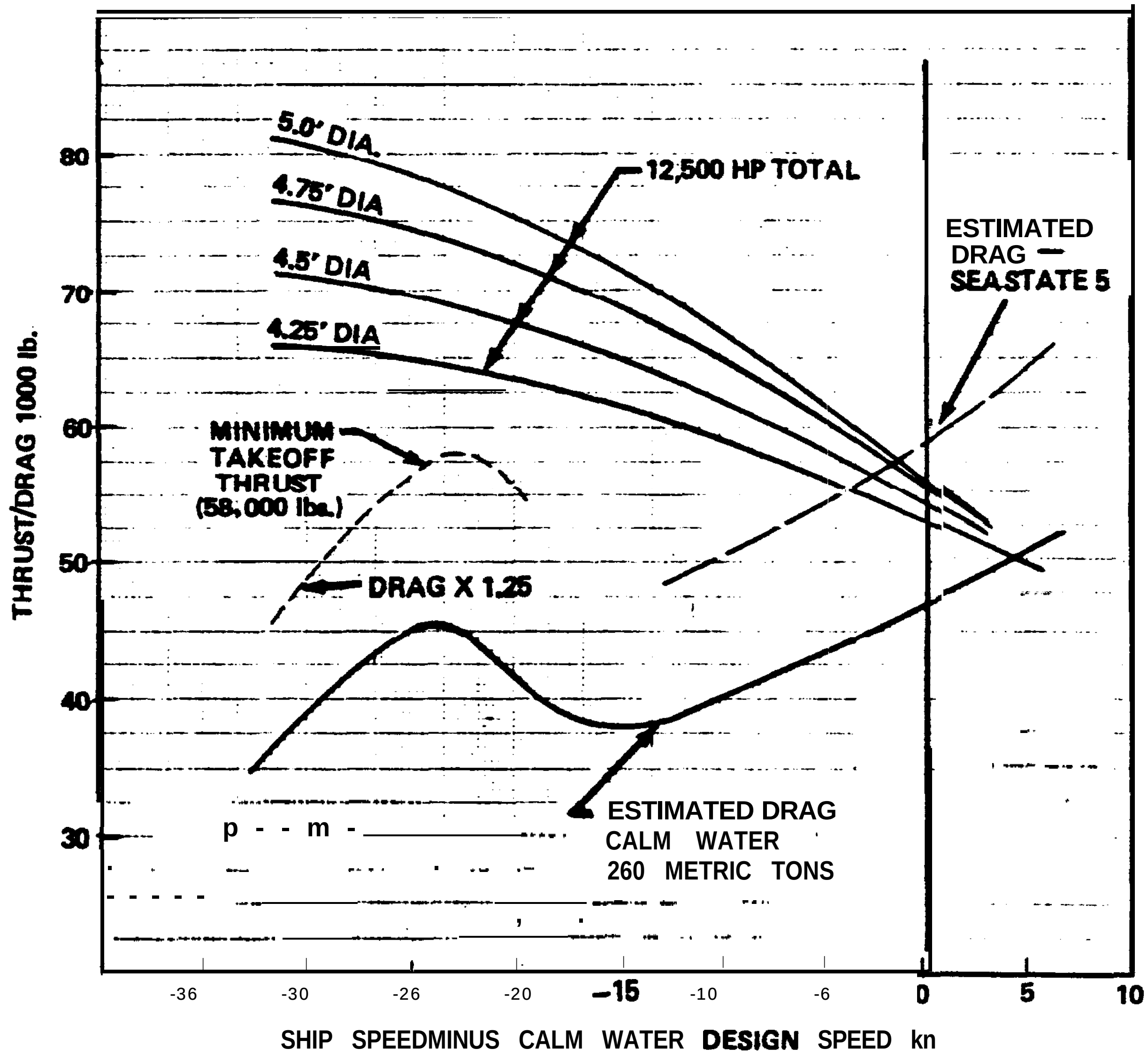


Figure 5.3-3: PHM *Propeller Drive System*



KaMeWa PROPELLER
No. **398.B**
P/D = 1.3
HUB SUBMERGENCE = 72 ft.

Figure 5.54 : ***Max Power Performance*** PHM – ***Displacement*** 250 Metric Tons

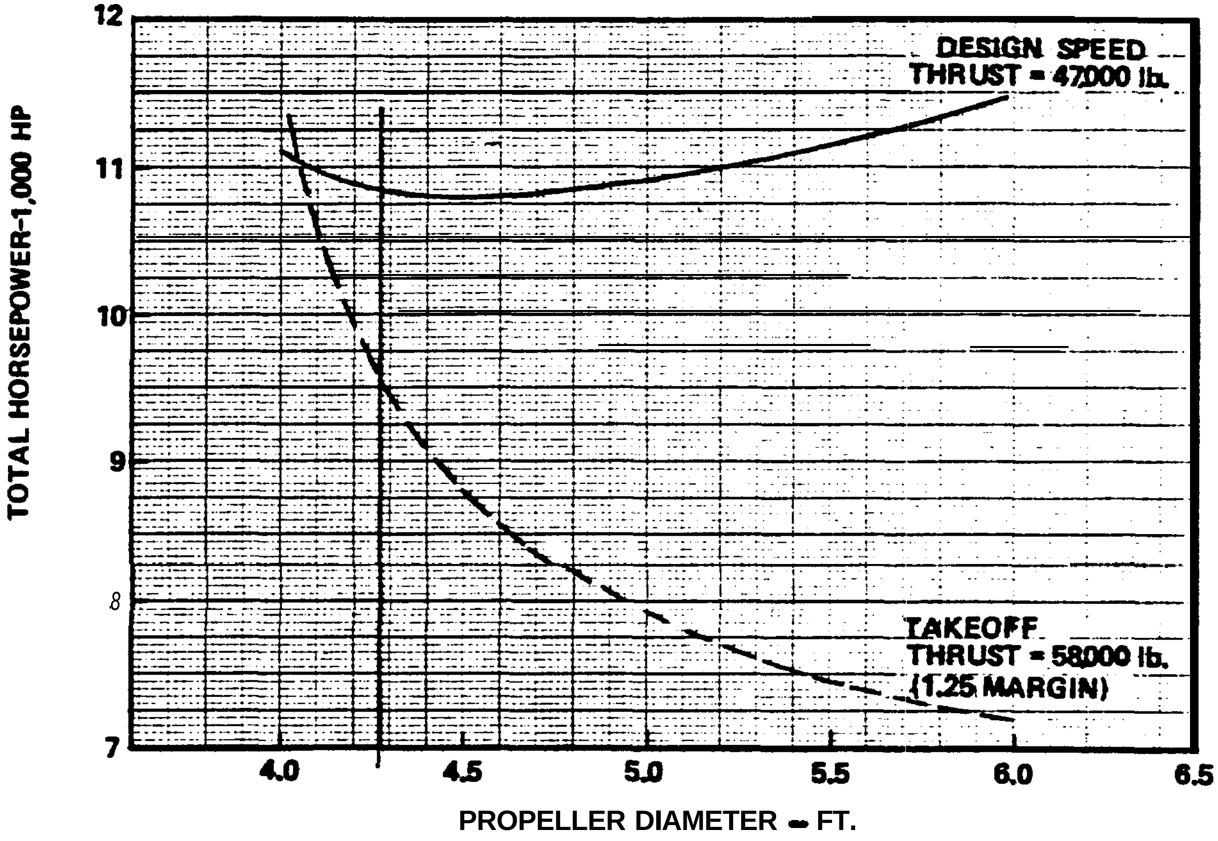


Figure 5.5-2: Takeoff /Design Speed **Requirements,PHM** – 250 Metric Tons

Figure 5.5-Z describes power requirements for varying propeller diameters at takeoff and cruise speeds. For example, for the propeller diameter initially selected, the total ship requirement is 9,500 horsepower at takeoff (25 percent margin) and 10,800 horsepower at cruise. Combined horsepower available from the two engines selected is 14,340 intermittent and 12,890 continuous. These values offer considerable margins and, at this stage, can be considered as allowances for system growth.

For the range estimate, a calculation using Allison 570K engines, a single diesel ships service power unit (SSPU), existing PHM 3 payload, 250 metric tons displacement, 52 metric tons usable fuel and the cruise drag from figure 5.5-l was made. This calculation results in a 41 percent increase in the ship's range over the PHM 3, Ship System Specification Requirement (reference 2).

REFERENCE

1. Boeing Document D312-80969-1, "400- and 800-Ton Point Designs of Multimission Hydrofoil Combatants", December 1983.

2. "Ship System Specifications for Building Patrol Combatant Missile (Hydrofoil) PHM 3 Series", NAVSEA 0902-00-039-4011, Confidential

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ACTIVE SHEET RECORD

		ADDED SHEETS						ADDED SHEETS			
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REVISIONS

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