

PHM
OPERATIONAL
NOTEBOOK

PREPARED BY

HYDROFOIL GROUP
ADVANCED VEHICLES DIVISION
DAVID TAYLOR RESEARCH CENTER

FOR
PMS 314C1
NAVAL SEA SYSTEMS COMMAND

APRIL 1989

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22 MAY 1990

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13 JUN 1990

From: Commander, David Taylor Research Center
To: Commander, Naval Sea Systems Command (PMS 314C)

Subj: PHM OPERATIONAL NOTEBOOK, REVISION 1

Ref: (a) PHM Class Advisory 01/90: Maneuvering Limits for
Emergency Foilborne Operations With One Automatic
Control System (ACS) Vertical Gyro Disconnected,
dated 25 January 1990.

Encl: (1) Revised pages of PHM Operational Notebook (April 1989)

1. In accordance with the PHM Class Advisory, reference (a), the PHM Operational Notebook has been revised to reflect the impact of having one automatic control system (ACS) vertical gyro disconnected. As a result, changes have been made to several pages of the PHM of Operational Notebook. At the same time several minor corrections have been incorporated on other pages of the Notebook.

2. All recipients are requested to remove the appropriate pages and insert the replacement pages, enclosure (1). These changes will constitute Revision 1 to the PHM Operational Notebook. A Record of Change page has also been included.

3. For additional information or clarification, please contact J. Meyer, DTRC, Code 1233, (202) 227-1796.

J. L. BENSON
By direction

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5605
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From: Commander, David Taylor Research Center
To: COMPHMRON TWO

Subj: TRANSMITTAL OF PHM OPERATIONAL NOTEBOOK

Encl: (1) PHM Operational Notebook

Ref: (a) DTRC PHM Technical Support for FY89

1. The first edition of the PHM OPERATIONAL NOTEBOOK is complete.
2. In accordance with reference (a), DTRC has completed the coordination, preparation, review, and distribution of the first edition of the PHM OPERATIONAL NOTEBOOK. A copy of the NOTEBOOK, enclosure (1), is provided for your personal information and use. Approximately 450 additional copies have already been shipped to you for the planned dissemination to PHMRON TWO personnel.
3. It is hoped that the NOTEBOOK proves to be useful, particularly in the indoctrination of new PHMRON TWO personnel. We think we have accurately responded to all the comments and suggestions that were accumulated during the various reviews, and we are ready and anxious to make any improvements or changes that will increase the NOTEBOOK's utility in the future.
4. Comments and suggestions for improving future editions of the PHM OPERATIONAL NOTEBOOK should be sent to DTRC Code 1233 (John Meyer or Mike Malia) at (301) 227-1796.

J. L. Benson

J. L. BENSON
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RECORD OF CHANGES

REV NO.	DATE	ACTION
1	22 MAY 1990	CHANGES ON PAGES: 2-14, 2-15, 2-26, 3-12, 3-23, 3-30, 3-31, and 3-32

INTRODUCTION

This Operational Notebook is intended to provide a brief introduction and quick reference information relating to the operation of the Patrol Combatant Missile (Hydrofoil), (PHM) ships. A brief description is provided of the ship systems, operational features (including design envelope and operating limits) and ships characteristics. More information is available from shipmates, support activities, individual ship documents, and squadron files. Also a brief history of hydrofoil development, further reading, and glossary of hydrofoil terms are included in the Appendix.

This document is based on an earlier PHM Notebook prepared by Boeing Marine Systems. Enhancement and clarification, at the request of NAVSEA PMS 314C1, are credited to Boeing Aerospace Operations and personnel of the Hydrofoil Trials Branch, DTRC Puget Sound Detachment.

PHM OPERATIONAL NOTEBOOK

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1.0 THE PATROL HYDROFOIL MISSILE SHIP

The Patrol Hydrofoil Missile (PHM) ship is a small, fast, surface warfare combatant. Due to the participation of NATO countries at its inception, the PHM was designed and built in metric units. U.S. Navy R&D work and USS *TUCUMCARI* experience supported this design, which achieves higher speeds, greater stability, and better maneuverability in rough weather than conventional surface combatant ships of much larger size. Figures 1-1 through 1-4 show the exterior and interior arrangements of the ship.

The weapons system selection and crew size were influenced by the size and weight of the candidate equipment. Fully submerged hydrofoil lifting surfaces support the entire weight of the ship; 1/3 forward and 2/3 aft. Power to accelerate to the speed at which the foils can support the ship is provided by a waterjet system that is powered by a gas turbine engine. Weight is critical in hydrofoil operation because the foil lift, which supports the ship while "foilborne," has limits much the same as the lift generated by an aircraft wing.

The PHM mission is surface warfare, and it is particularly suited to strike and reposition rapidly in coastal water, choke points, and in operation from a fixed base. Deployed (at-sea and shore) operations have been conducted with FFG 7s and LSTs.

1.1 GENERAL DESCRIPTION

PHM has an all welded aluminum hull and superstructure with high strength stainless steel hydrofoils. Propulsion for the ship is provided by two independent systems: foilborne propulsion is provided by one General Electric LM2500 gas turbine driving a waterjet pump built by Aerojet General and hullborne propulsion is provided by twin waterjet pumps driven by Mercedes MTU diesel engines. Reversing buckets and steering nozzles are fitted to the twin hullborne jet units at the transom to direct the water flow for maneuvering while hullborne. Maneuvering while foilborne is accomplished by the automatic control system, which automatically positions the flaps on the foils and the steerable forward strut in response to helm inputs. The automatic control system provides a stable platform in sea state 5 to fire missiles and the 76 mm gun.

Principal Dimensions

Length: 44.7 meters (147 ft) overall with struts retracted
 40.2 meters (132 ft) overall with struts extended

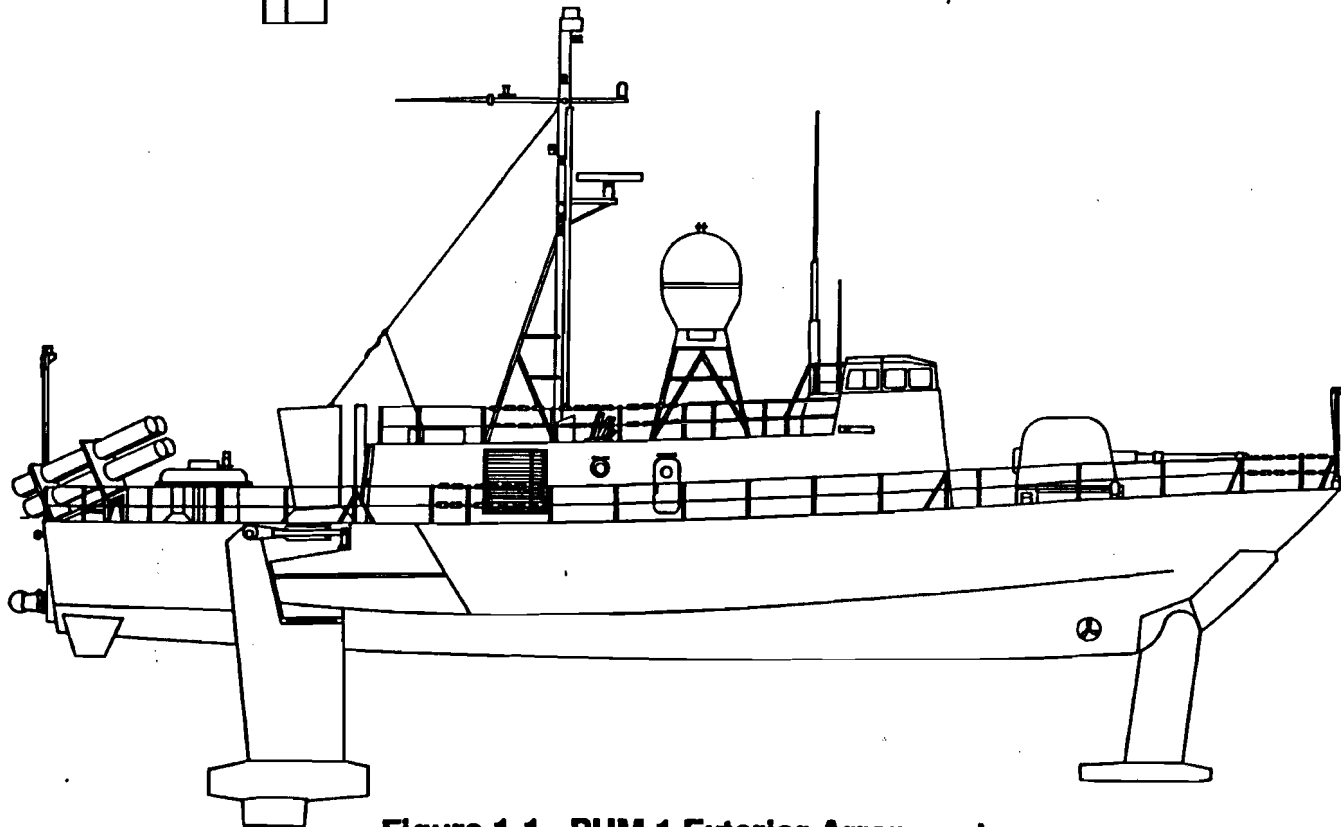
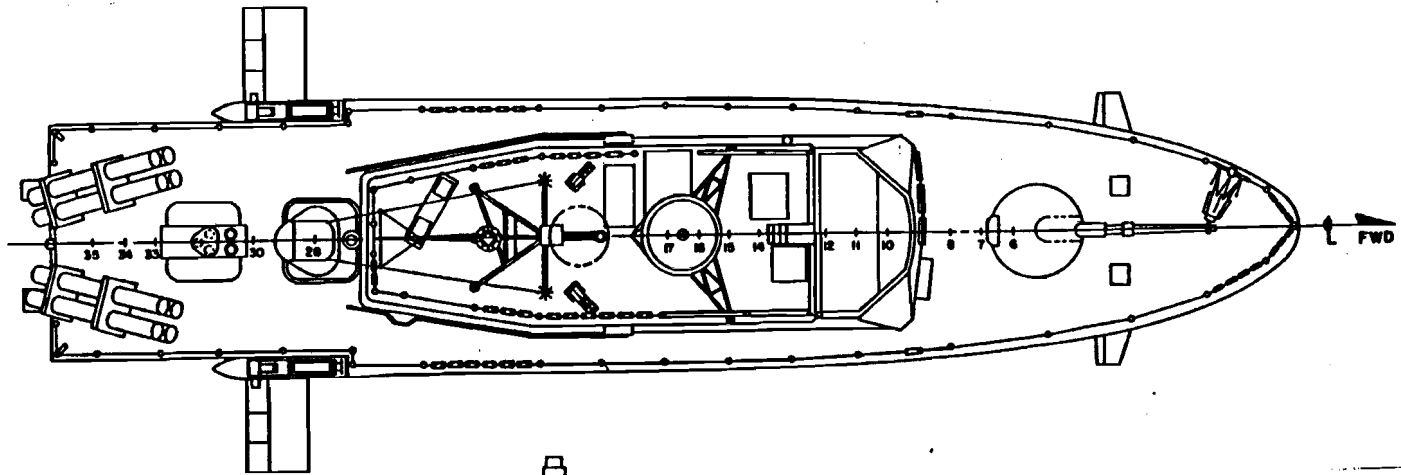


Figure 1-1. PHM-1 Exterior Arrangement

1-3

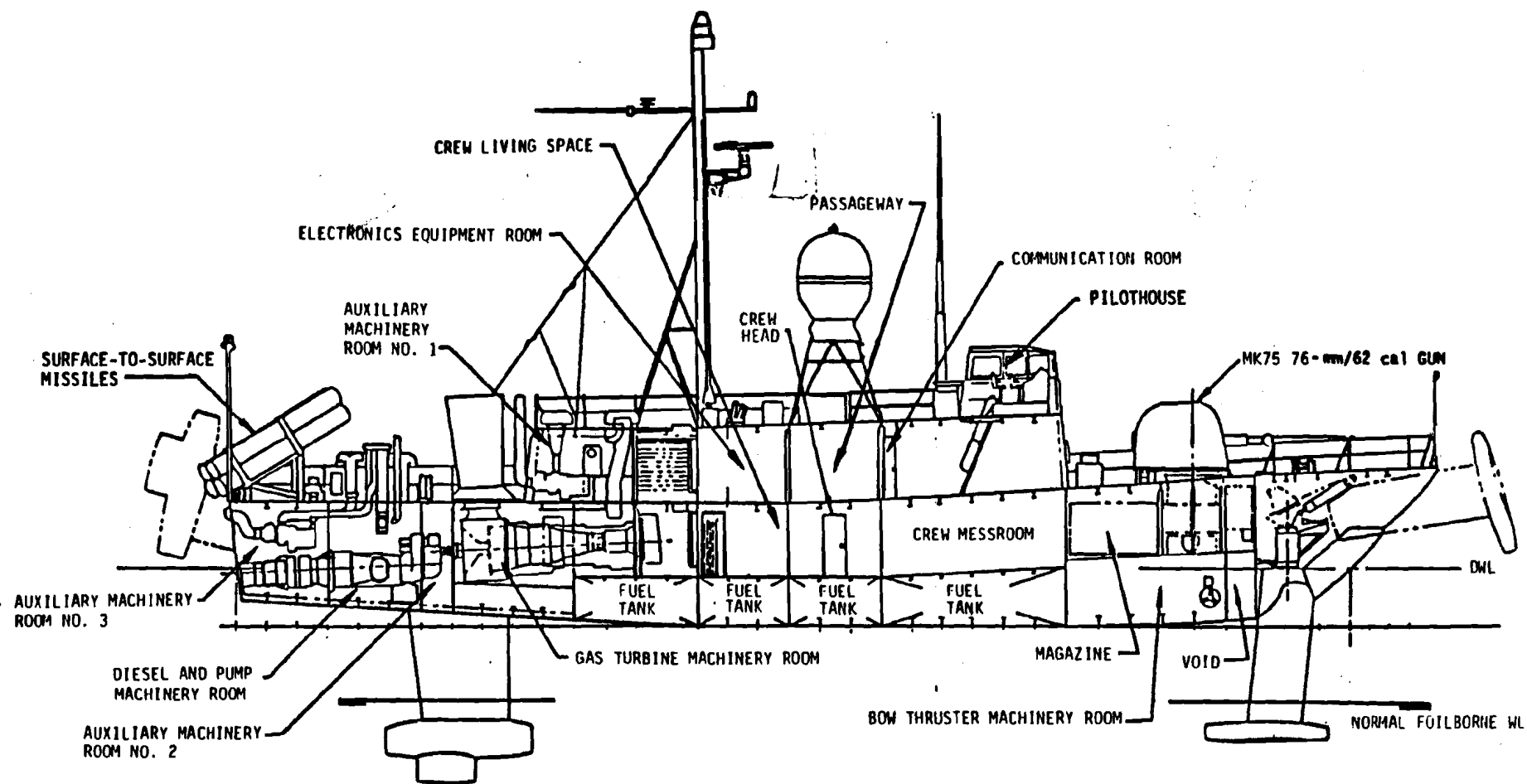


Figure 1-2. PHM-1 Inboard Profile

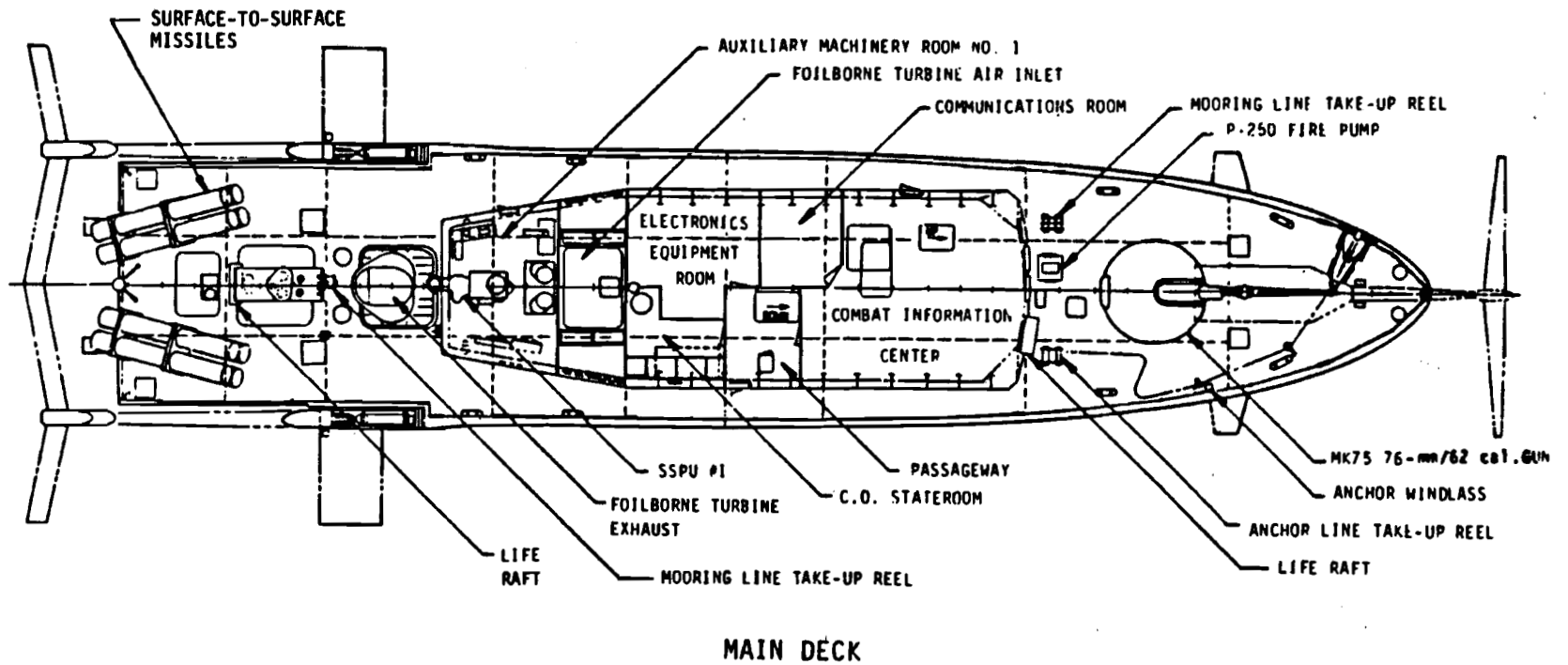
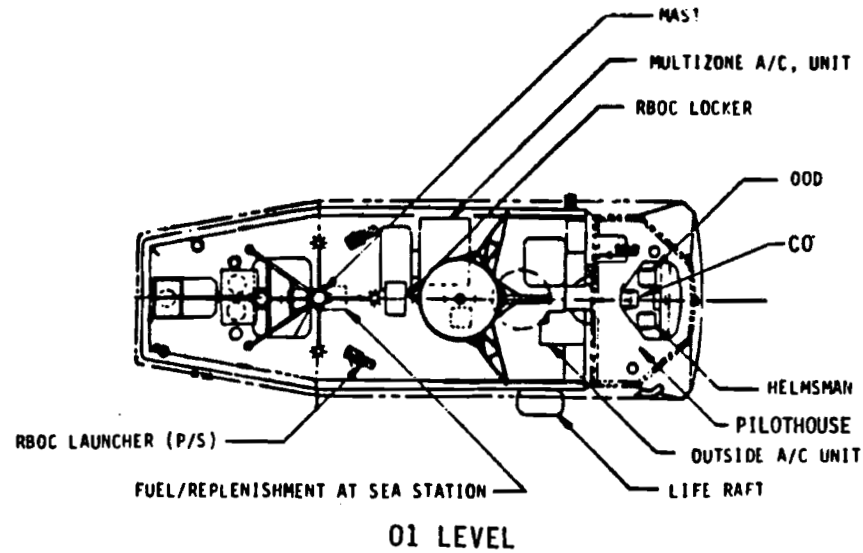


Figure 1-3. PHM-1 Main and 01 Level Deck Plan

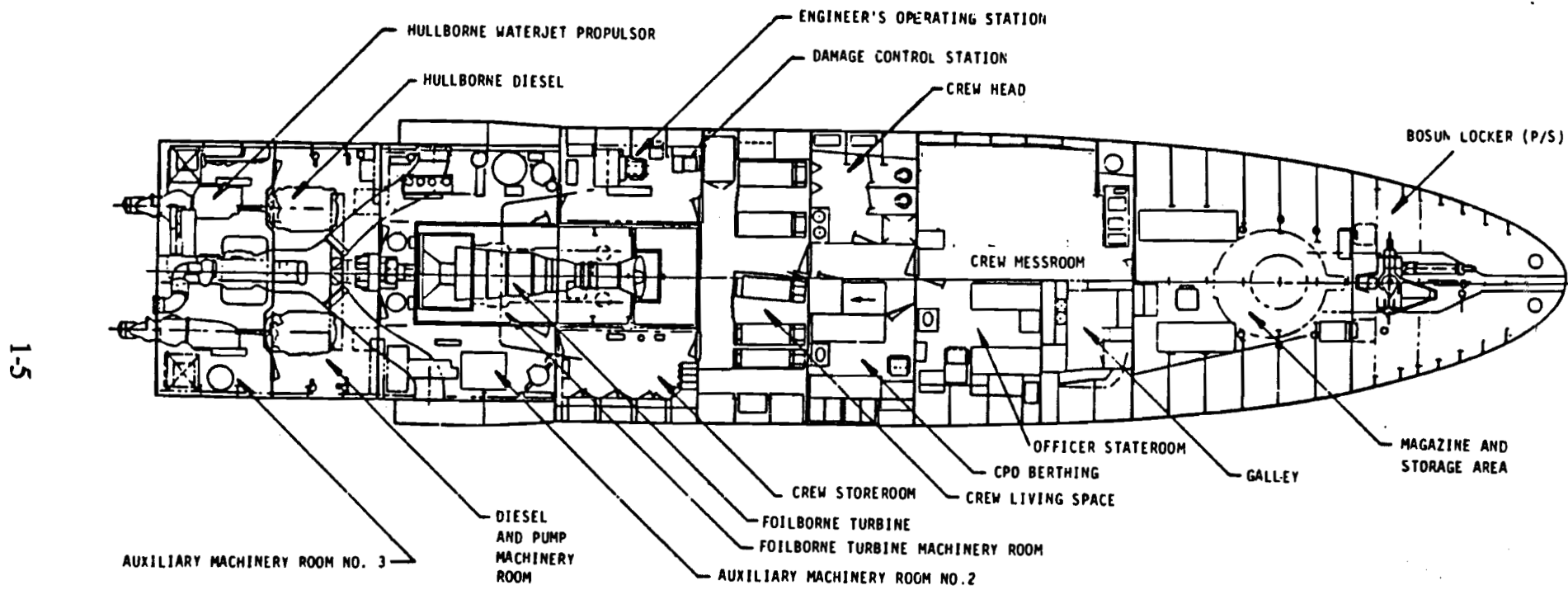


Figure 1-4. PHM-3 Series Platform Deck

Beam: 8.6 meters (28 ft) maximum at the main deck
7.4 meters (24 ft) design at the waterline
14.5 meters (48 ft) aft foil span overall
(This is approximately 3 meters (10 ft) outboard
of the hull.)

Draft: 7.1 meters (23 ft 4 in) hullborne, struts down.
(Lowest point is the aft foil at the centerline.)
2.3 meters (7 ft 6 in) hullborne, struts up.
(Lowest points are the aft fixed fins.)
2.6 meters (8 ft 6 in) foilborne at 2.2 meter
commanded foil depth. (Lowest point is the aft foil
at the centerline.)

Height: 17.7 meters (58 ft) to top of ESM antenna (Hullborne)
6.8 meters (22 ft) to bridge window (Hullborne)

Design Displacement

175 metric tons (172.24 long tons) light ship.

241 metric tons (237.19 long tons) full load.

Armament

- 1 76 mm/62 caliber Oto Melara Mk 75, Mod 1 gun. Total number of rounds is 400. When the gun is fully loaded 80 rounds may be fired without intervention of loading or maintenance personnel. The revolving gun magazine contains two rows of cavities into which 70 rounds can be loaded in the vertical position. The gun feed system accounts for the remaining 10 rounds.
- 8 HARPOON missiles in canisters on stern launchers
- 2 Rapid Blooming Offboard Chaff launchers amidships

Propulsion

- 1 General Electric LM2500 gas turbine driving one axial flow Aerojet pump at 17,000 metric horsepower (hp) (16,767 hp) foilborne.
- 2 Mercedes MTU diesels driving two Aerojet waterjet pumps at 815 metric hp (804 hp) each, hullborne.

- 1 Hydraulically powered Bow Thruster at 3000 psi delivers 546 kilogram force (1200 lbs) left or right.

1.2 MAJOR SYSTEMS

1.2.1 HULLBORNE PROPULSION. As shown in Figure 1-5, the Hullborne Propulsion System consists of twin waterjets driven by MTU diesels with 815 metric hp at 2250 revolutions per minute (RPM). These are 11.8 ft apart delivering 7306 lb of thrust on each side. To steer, they vector 30 degrees right and left, ganged together on a rod with one actuator electrically controlled and hydraulically powered. The waterjet flow from each nozzle can be independently deflected 135 degrees by moving the throttle in the reverse direction. This gives approximately 50 per cent of the thrust at the same ahead RPM. Before getting underway or entering restricted maneuvering areas, a steering bucket and waterflow check should be made. Handling and conning twin waterjets are different from twin screws and rudders because action on the ship is the result of reaction by one or both waterjets. It is necessary to vector the jet to apply a force to the ship, thus steering is ineffective when the waterjet is directed straight down, even if the ship has way on and the helm is hard over. Steering becomes increasingly effective as the magnitude of the waterflow increases, independent of ship speed.

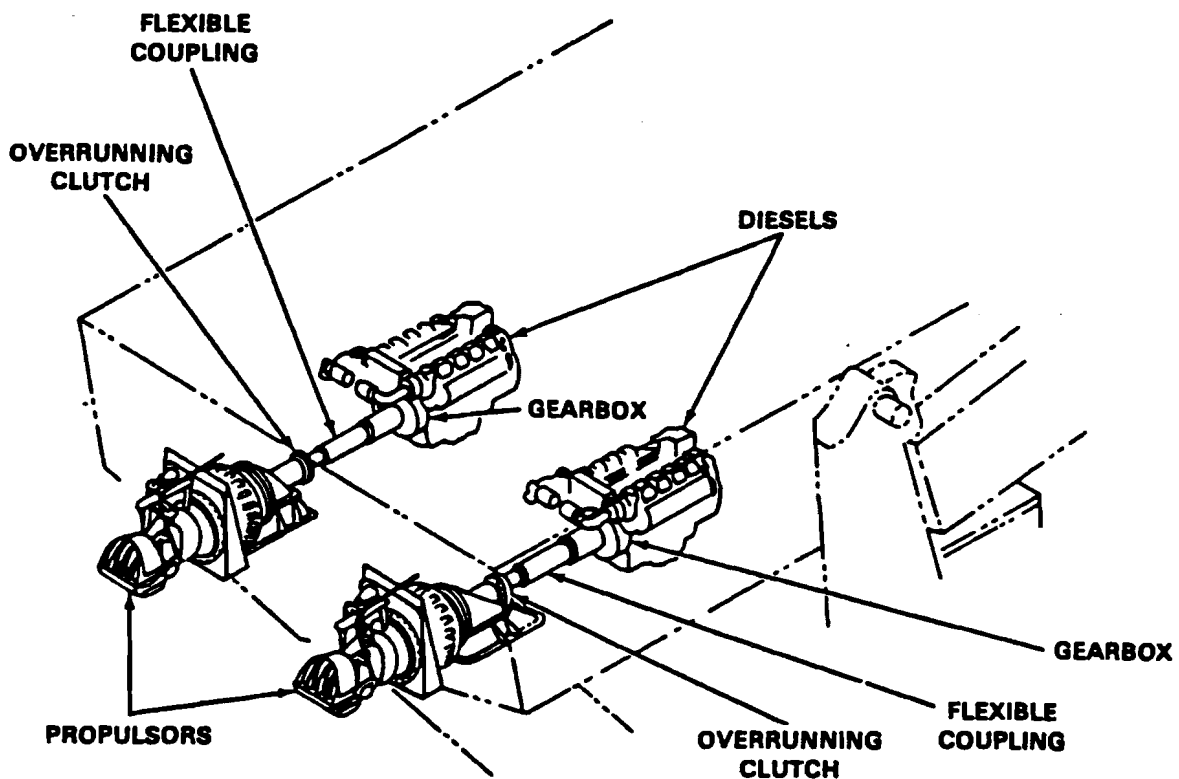


Figure 1-5. Hullborne Propulsion System

Operation and maintenance details are found in the System Operation and Onboard Maintenance (SOOM) Manual, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 5, Chapter 24 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 4, Chapter 22 for PHM-1.

1.2.2 FOILBORNE PROPULSION. Foilborne propulsion is provided by a single Aerojet General waterjet that is driven by a General Electric marine gas turbine, LM2500, delivering 17,000 metric hp at maximum continuous operation. The water enters the hollow aft struts and exits at the transom. The water flow is not reversed or vectored. It exits the hull with a maximum thrust of 85,176 lbs at 17,000 metric hp (100 per cent turbine speed). **Figure 1-6** shows the general arrangement of the components that comprise the system.

The Foilborne Propulsion Control System is comprised of two major components mounted in the Engineering Operating Station (EOS). These are the Foilborne Engine Control System (FECS) and Foilborne Propulsor Control System (FPCS). These systems contain the electronic logic, signal conditioning, meters, switches, sensors, and indicating lights that control and monitor gas turbine propulsor assembly operation.

The gas turbine is started by the operator at the EOS and throttle control is transferred to the helm for foilborne operation. Monitoring of operating parameters is continued at the EOS during foilborne operation. Prior to shut down, control is transferred back to the EOS where the gas turbine is shut down using automatically controlled logic.

Operation and maintenance details are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 2, Chapter 10 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 1, Chapter 7 for PHM-1.

The following diagrams relating to the Foilborne Propulsion Control System are contained in the Engineering Operational Sequencing System (EOSS):

TITLE	CODE
Diagram for Lubricating Oil System	DPLO/002/0382
Diagram for Synthetic Lubricating Oil System	DSLO/004/0382
Diagram for Propulsion Turbine Drain System	DFDS/002/0382

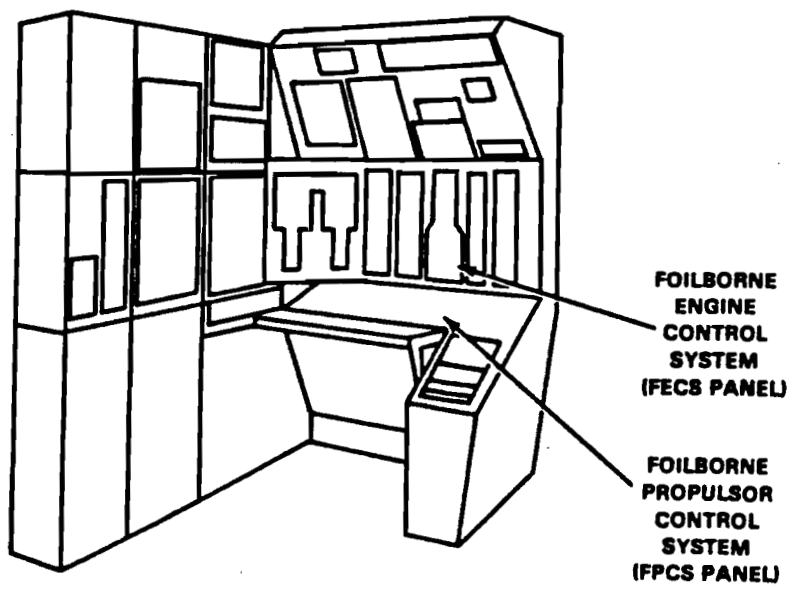
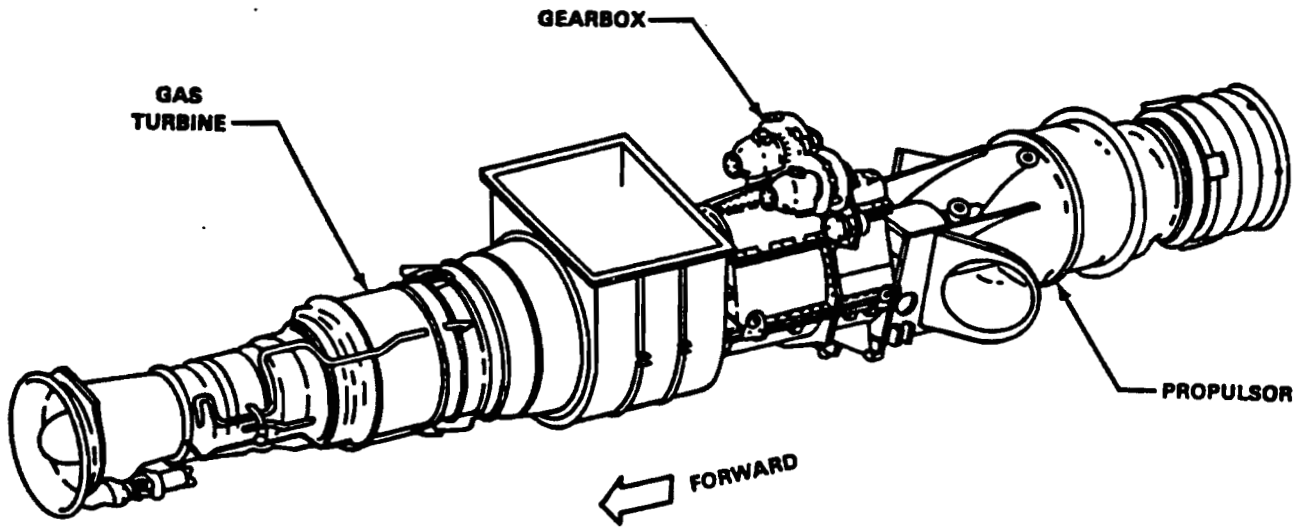


Figure 1-6. Foilborne Propulsion System

1.2.3 SHIP SERVICE POWER UNITS (SSPU). Two SSPUs provide power to the ship's generators, hydraulic pumps, and load compressors (Figure 1-7). The SSPUs are Air Research ME 831-800 gas turbines. The generators are Westinghouse 6QM250D AC, 250 KVA, 260/400V, 400 Hz lightweight units. The use of 400 Hz in lieu of 60 Hz reduces the size and weight of the electrical distribution cables and is compatible with aircraft equipment, but is converted through three solid-state electronic converters to 60 Hz for use with conventional equipment. The hydraulic pumps are variable displacement axial piston pumps with pressure compensator controls developing 3000 psi system pressure. The load compressors start the LM2500 main turbine with air pressure at 35 to 38 psi and motor the turbine at 22 psi. The compressor rotation speed is 54,000 RPM. A containment shroud protects the ship and crew should the compressor rotor fail. SSPU #1 is located in machinery space one and SSPU #2 is in machinery space three.

Normal SSPU control is maintained from the SSPU panel located in the EOS. The PHM electrical system permits the SSPUs to operate individually or simultaneously. When both are operating, each generator shares the ship's electrical load. Each SSPU is capable of supplying the total ship's electrical load. However, reduction in electrical load is necessary for starting the LM2500 when only one SSPU is available.

Operation and maintenance details are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume, 4, Chapter 20 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 3, Chapter 18 for PHM-1.

The following diagrams relating to the SSPUs are contained in the EOSS:

TITLE	CODE
Diagram for SSPU Piping Systems	DSPS/003/0382
Diagram for SSPU Piping Systems	DSPS/004/0382

1.2.4 ELECTRICAL SYSTEM. Two 450V AC, 400 Hz, 3-phase brushless generators, each driven by a SSPU, supply onboard power underway. Two shore power connections are available, one fore and one aft on the deckhouse, and receive power from shore power generators or from other 400 Hz ships alongside. Two switchboards, one in machinery space one and one in machinery space three, and distribution panels in each compartment distribute the electrical power. The electrical control panels at the EOS monitor and control electrical power, test the entire electrical system or output of each unit, and check for any ground faults.

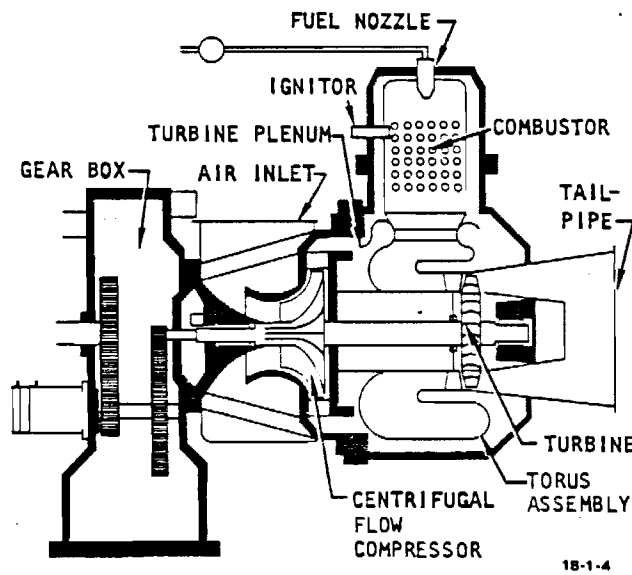
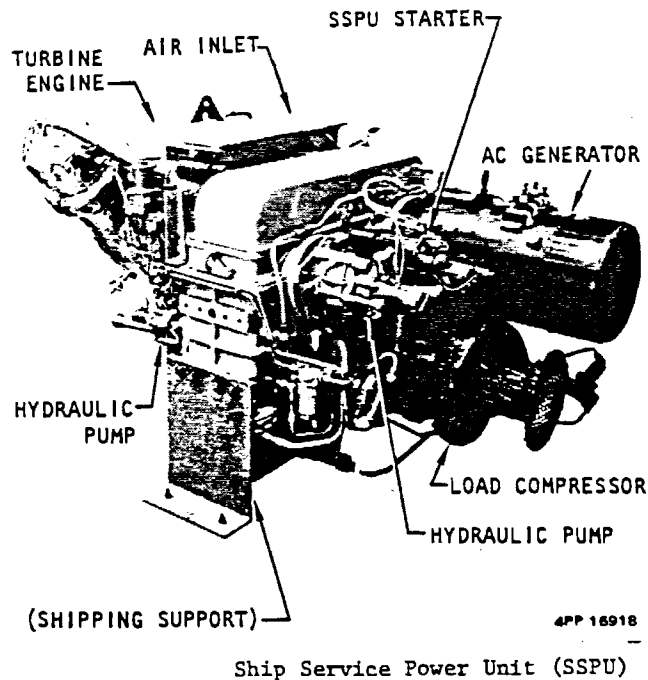


Figure 1-7. SSPU Schematic (Compressor)

A schematic of the Electrical System is shown in Figure 1-8.

Operation and maintenance details are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 4, Chapter 20 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 3, Chapter 18 for PHM-1.

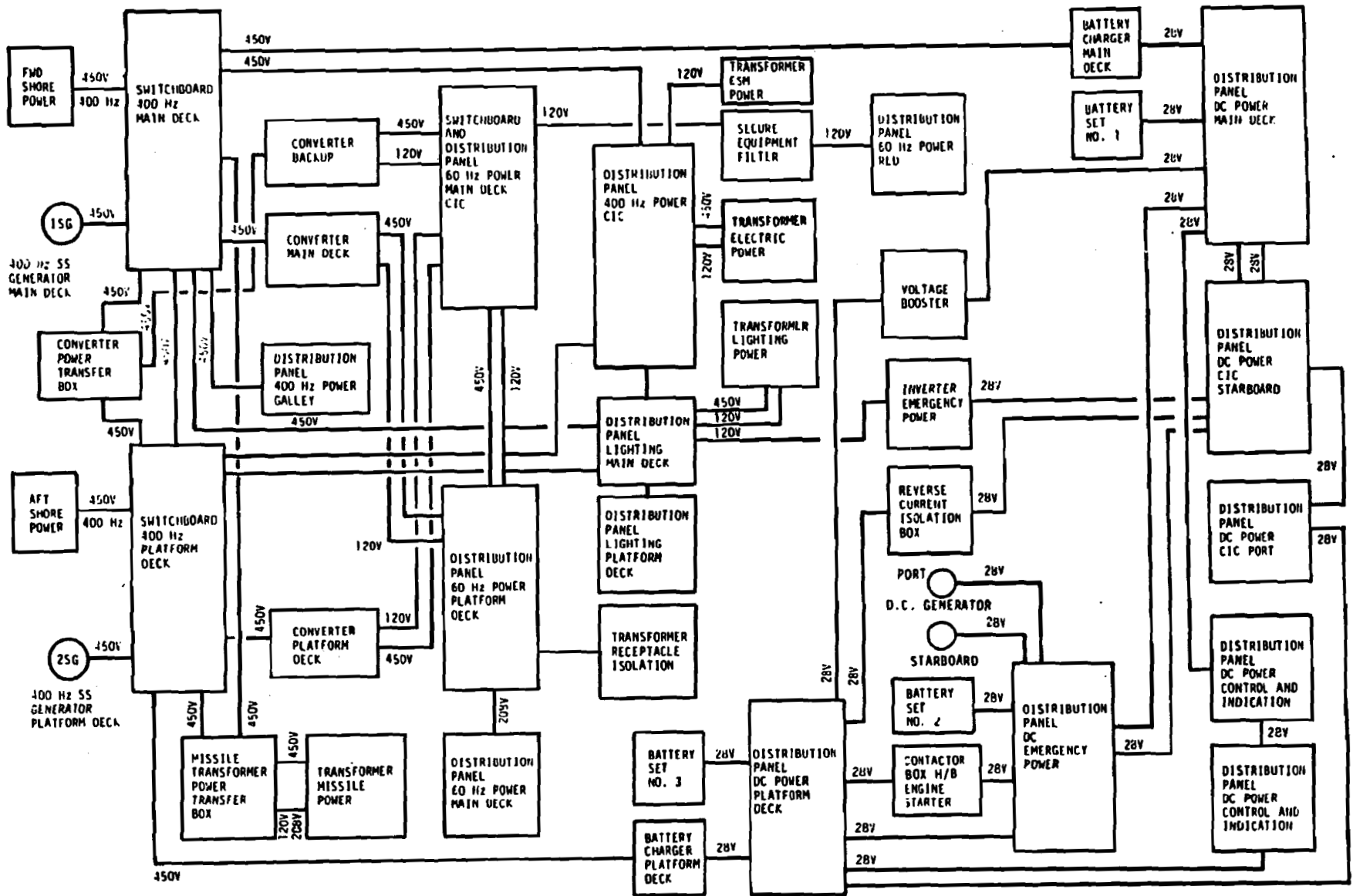


Figure 1-8. Electrical System Functional Diagram

The following diagrams relating to the Electrical System are contained in the EOSS:

TITLE	CODE
Diagram for Electrical Generating System	DLS/140/0884

1.2.5 FUEL OIL SYSTEM. The Fuel System delivers fuel to the diesel engines, to the gas turbine engine, and to the SSPUs. Fuel can be loaded from shoreside or a tender on either the port or starboard side to three of the four tanks. The fourth tank is replenished from any of the other tanks. The fuel delivery system consists of four AC-powered pumps that provide the primary source for normal underway operation; two DC-powered pumps that provide for initial start of the SSPUs with diesels if AC-power is not available and as a back-up to the AC pumps; and one hydraulic pump for use in the event of AC and DC power loss.

The Fuel Piping System is a dual system, with each half containing a coalescent filter/separator and prefilter, capable of meeting all fuel demands. The dual system also makes it possible to service the filter system while underway without interrupting fuel flow to the operating propulsion units.

The primary Fuel System controls for refueling, fuel transfer, and fuel delivery are located at the EOS. Defueling operations are manually controlled by various local manually operated valves. Motor operated valves, normally controlled at the Fuel System panel to supply or shut off fuel to the propulsion engines and SSPUs, may also be closed by interlocks with the Fire Detection System and Engine Control Systems.

Figure 1-9 shows the fuel system control panel located at the EOS.

The following is the capacity of the fuel tanks as determined from the Booklet of Tank Sounding Tables for each ship:

	95% PER CENT CAPACITY	USABLE FUEL
Tank 1	23,960 liters	23,662 liters
Tank 2	12,246	12,036
Tank 3	11,915	11,666
Tank 4	<u>14,641</u>	<u>14,470</u>
Total	62,762 liters	61,834 liters

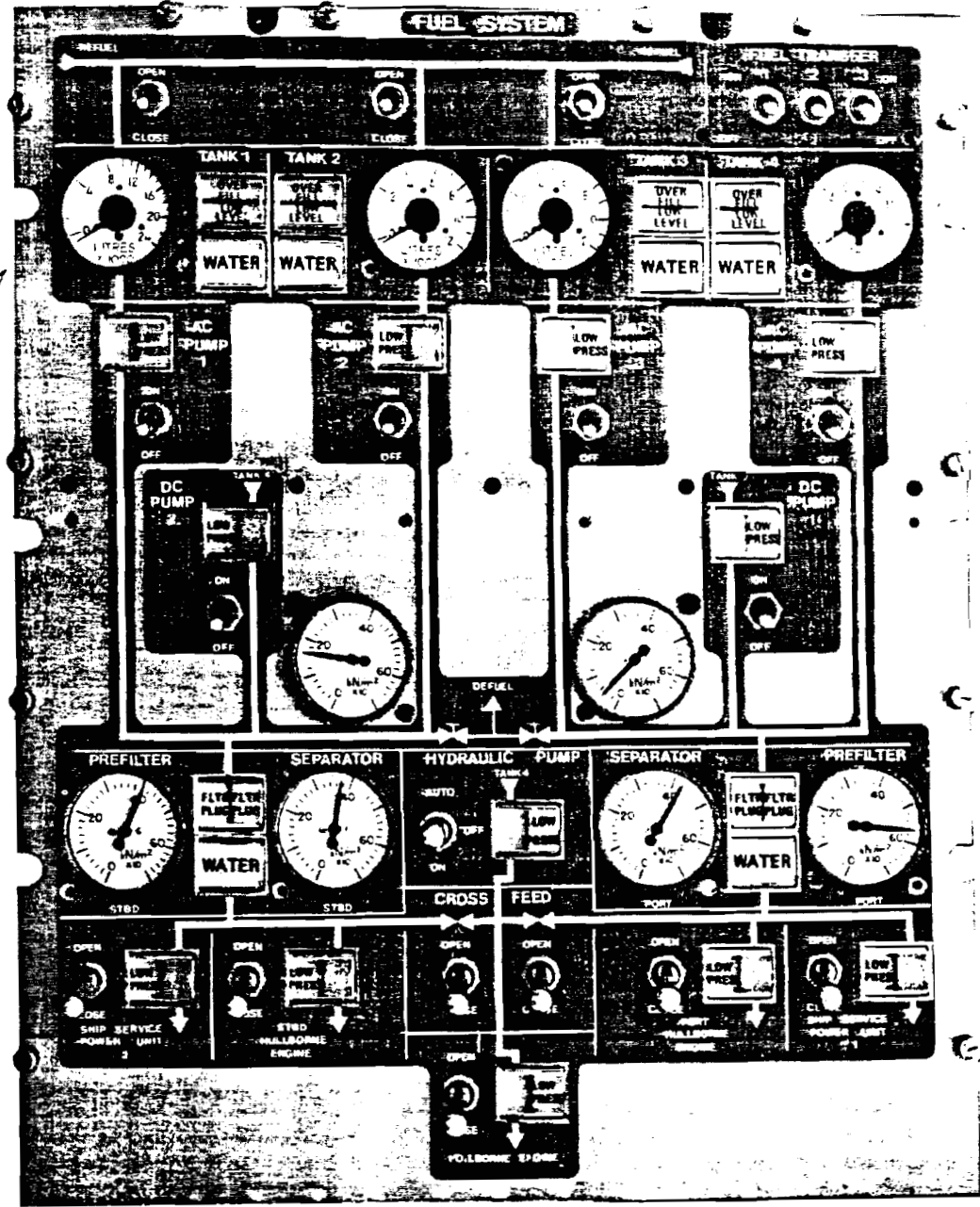
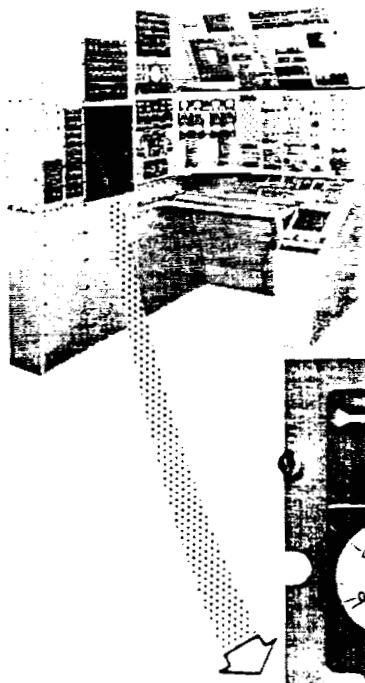


Figure 1-9. Fuel System Panel

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Operation and maintenance details are found in the SOOM, NAVSEA S09PHM-AC-SHP-030/(U) PHM-3 CL, Volume 3, Chapter 12 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 2, Chapter 9 for PHM-1.

The following diagrams relating to the Fuel Oil System are contained in the EOSS:

TITLE	CODE
Diagram for Fuel Oil Service System	DFO/206/0382
Diagram for Fuel Oil Transfer System	DFOT/017/0382
Diagram for Fuel Oil Tank Stripping System	DFOS/105/0581

1.2.6 HYDRAULIC SYSTEM. The Hydraulic System is critical to foilborne operation and therefore has been designed to ensure continued operation in the event of system component failure or damage. Four separate hydraulic systems, as shown in Figure 1-10, provide 20.68 MN/m^2 (3000 psi) pressure. Each system contains MIL-H-83232 hydraulic fluid and is functionally identical, differing only in component location and the functions that it supplies. Dual hydraulic supply is provided for each system function with subsystem isolation fore and aft in the event of major damage. Systems 1 and 2 power the forward hydrofoil flaps, retraction actuator, anchor capstan, and bow thruster. Systems 3 and 4 power the aft hydrofoil flaps, hullborne steering and reversing, and emergency fuel pump and are boosted to 25.86 MN/m^2 (3750 psi) through a pressure intensifier module to power the aft retraction actuators. Pumps for each system are mounted on the foilborne gearbox. Auxiliary pumps for systems 1 and 4 are driven by SSPU No. 1. SSPU No. 2 drives pumps for systems 2 and 3. Table 1-1 shows the hydraulic system functions and power source.

Operation and maintenance details are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 3, Chapter 13 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 2, Chapter 10 for PHM-1.

The following diagram relating to the Hydraulic System is contained in the EOSS:

TITLE	CODE
Diagram for Hydraulic Oil System	DHOS/002/0382

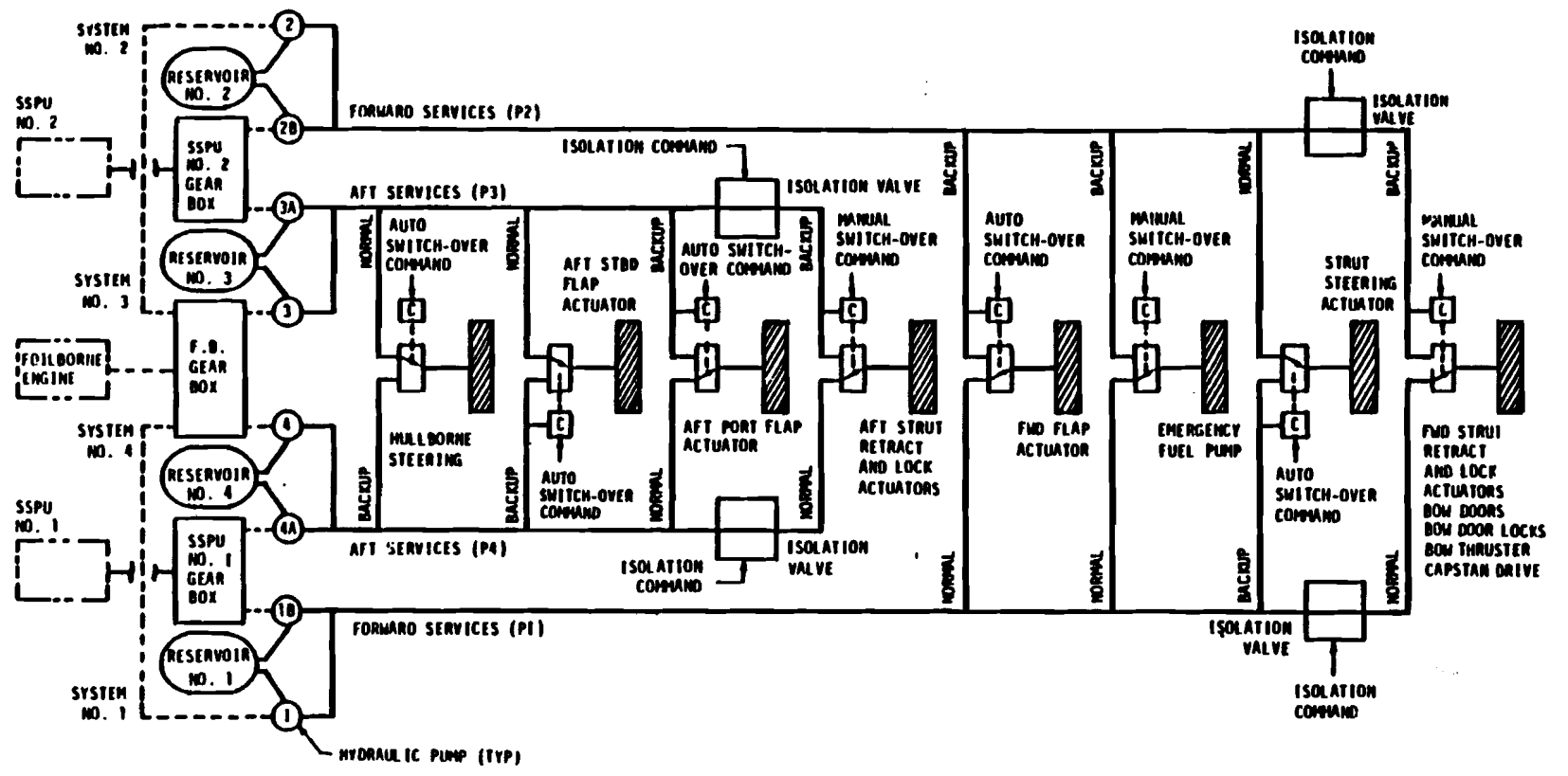


Figure 1-10. Hydraulic System

Table 1-1. Hydraulic Power System Functions

HYDRAULIC SYSTEM	POWER SOURCE		FOILBORNE ENGINE PUMP	FUNCTION
	SSPU	SSPU PUMP		
1 (PRIMARY)	1	1B	1	Forward Flap Actuator, Forward Strut Retract Actuator, Bow Door and Lock Actuators, Forward Strut Uplock and Downlock Actuators, Bow Thruster, Emergency Fuel Pump (Foilborne Engine), and Anchor Capstan.
1 (STANDBY)	1	1B	1	Forward Strut Steering Actuator.
2 (PRIMARY)	2	2B	2	Forward Strut Steering Actuator.
2 (STANDBY)	2	2B	2	Forward Flap Actuator, Forward Strut Retract Actuator, Bow Door and Lock Actuators, Forward Strut Uplock and Downlock Actuators, Bow Thruster, Emergency Fuel Pump (Foilborne Engine), and Anchor Capstan.
3 (PRIMARY)	2	3A	3	Starboard Flap Actuator, Hullborne Steering Actuator and Thrust Reverser Actuators.
3 (STANDBY)	2	3A	3	Aft Strut Retract and Lock Actuators and Port Flap Actuators.
4 (PRIMARY)	1	4A	4	Port Flap Actuator and Aft Strut Retract and Lock Actuators.
4 (STANDBY)	1	4A	4	Starboard Flap Actuator, Hullborne Steering Actuator and Thrust Reverser Actuators.

1.2.7 AUTOMATIC CONTROL SYSTEM (ACS). It is particularly difficult, if not impossible, to manually control a high-speed hydrofoil ship with a fully submerged foil system, particularly operating in rough water. The ship therefore, depends on an ACS that constantly adjusts foil lift through changes in flap angle. These adjustments are made to port and starboard, and to fore and aft foils to maintain trim and keep the hull at a given height above the mean water surface in the presence of disturbances. In order to achieve as high a lift-to-drag ratio as possible in the cruise condition, the foils are designed to operate with relatively small mean flap angles. This then provides adequate reserve to generate the required control forces if the craft is to fly straight and level and remain foilborne in large waves without excessive cresting of the hull or broaching of the foils. The latter refers to a condition when the foil breaks through the water surface and loses its lift.

Control of the ship is separated into hullborne and foilborne modes. A common helm is used for both modes, but foilborne and hullborne ship control are achieved by different systems. A switch provides for selection of the appropriate mode and system. The ACS interfaces with the hydraulic system, strut retraction system, and ship's gyro and also includes a ready and warning system (refer to Paragraph 2.2). Figure 1-11 shows the location of the ACS components.

Automatic foilborne control is based on the concept of "feedback" control. Ship attitudes, rates, and accelerations are sensed and compared with desired values. The differences are processed by an electronic control computer and become electrical commands to hydraulic servo-actuators. The actuators move mechanical linkages to position the control surfaces, and cause a ship response to minimize those differences. The height of the ship is primarily controlled by the forward flap. The ACS maintains the forward foil depth essentially at the commanded depth over the speed range, even though the ship's pitch angle changes. Pitch and roll are primarily controlled by the aft flaps with pitch angle being varied automatically as speed changes. Changing pitch angle as speed varies makes it possible for the flap angles to remain near their mid hydrodynamic range, thus providing the full range of deflections for maneuvering and rough water operation. Figure 1-12 is a block diagram of the ACS.

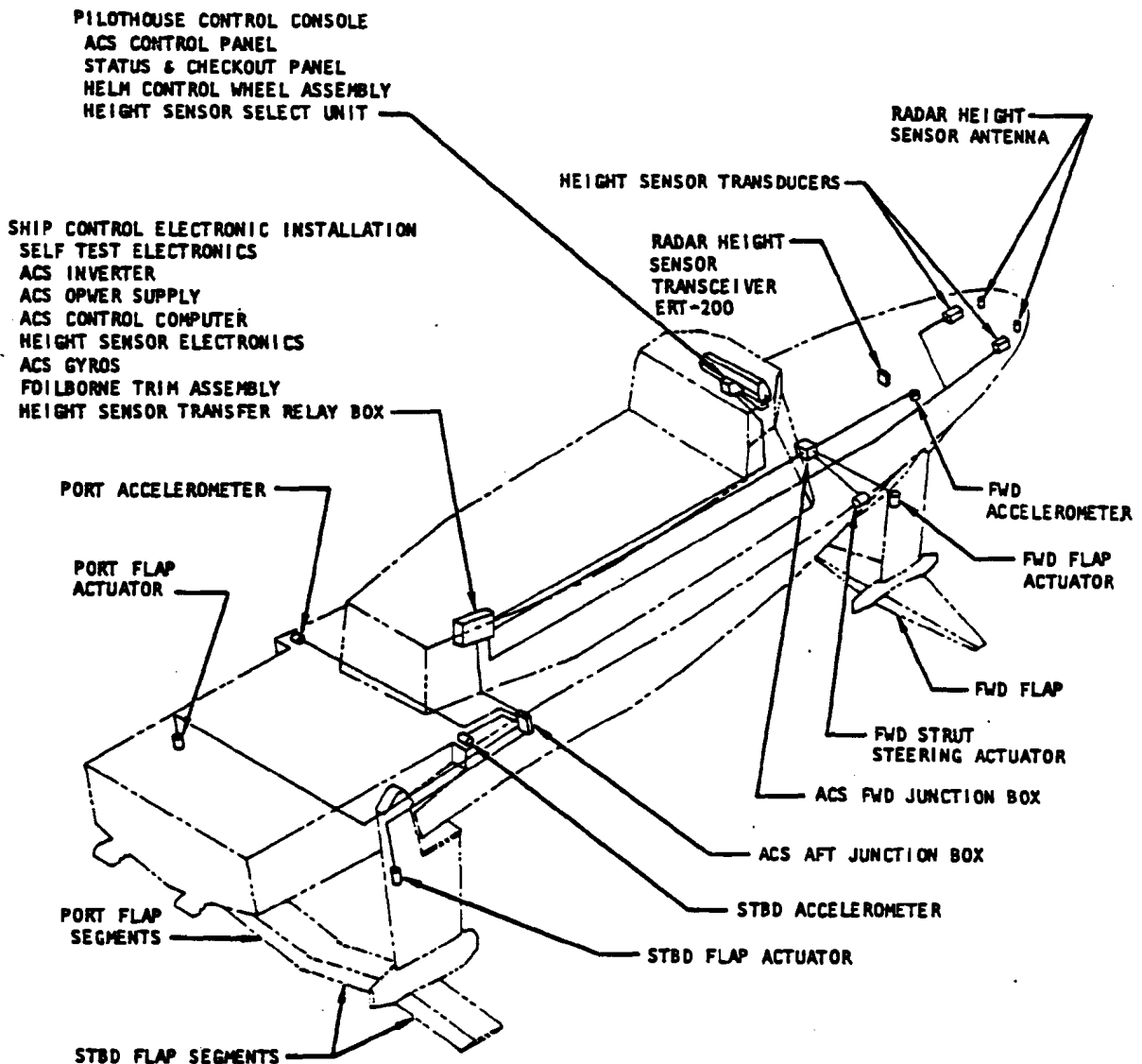


Figure 1-11. ACS Equipment Locations

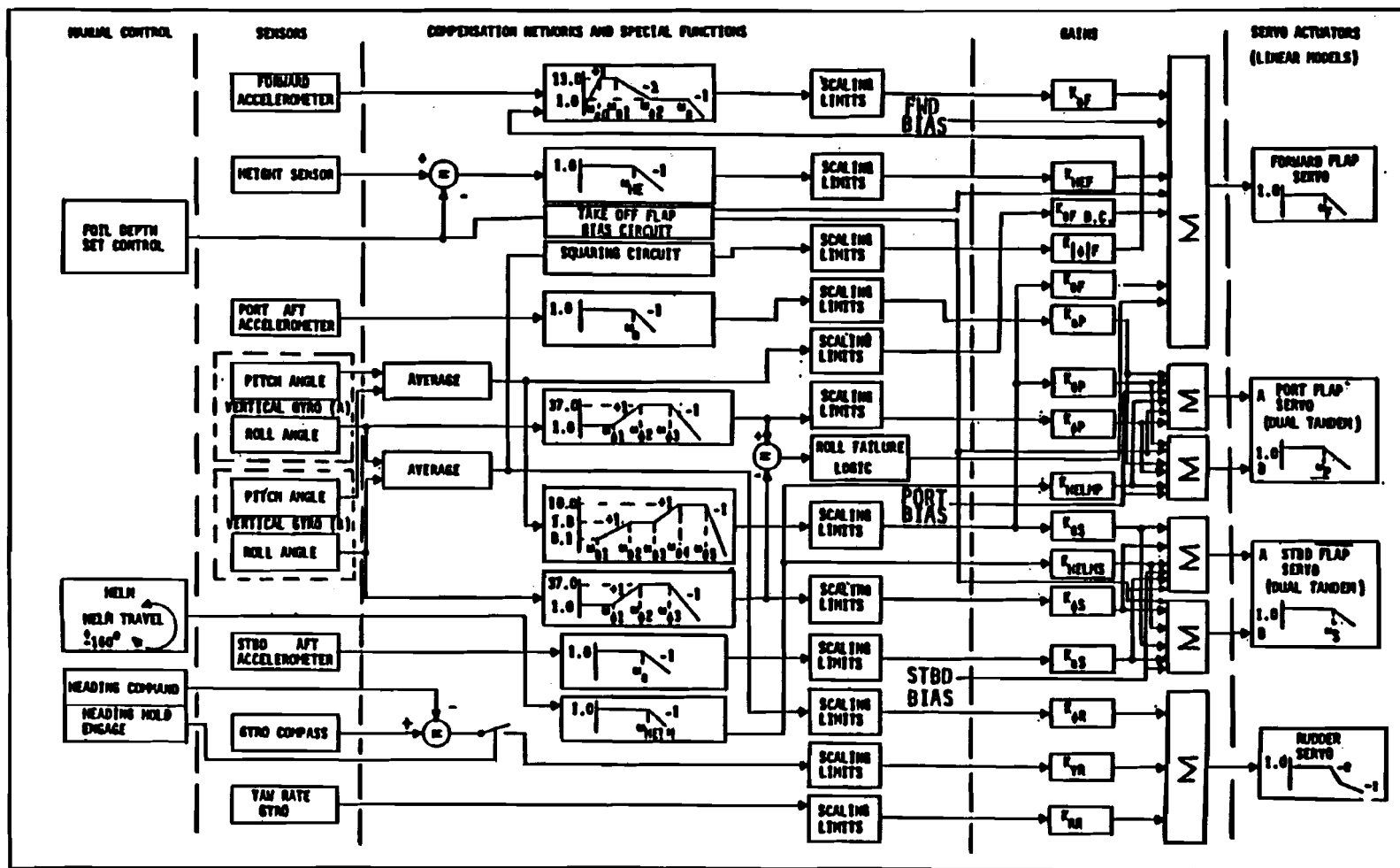


Figure 1-12. ACS Functional Block Diagram

Operation and maintenance details are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 5, Chapter 23 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 4, Chapter 21 for PHM-1.

1.2.8 COMPRESSED AIR SYSTEM. The Compressed Air System provides air pressure to the following systems:

- o Hydraulic System. Pressurize the four system reservoirs
- o Automatic Control System (ACS). Pressurize actuators and associated wiring to assure water free environment
- o Windshield Washer System. Pressurize reservoir
- o Service Outlets. Provide air for maintenance and other uses
- o Sea Chest Blowdown
- o Air Horn.

Pressurized air is obtained from two sources (see Figure 1-13). The prime source, which is at 120 psig, is from either SSPUs second stage bleed. The secondary source, which is at 60 to 90 psig, is from an electrically driven reciprocating compressor located in auxiliary machinery room No. 1. The secondary source is used only when the SSPUs are not supplying a minimum of 60 psig air or are supplying bleed air to the ship's propulsion deicing system.

Operation and maintenance details are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 3, Chapter 19 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 3, Chapter 16 for PHM-1.

The following diagram relating to the Compressed Air System is contained in the EOSS:

TITLE	CODE
Diagram for Ship Service Air System	DSSA/001/0382

1.2.9 SEA WATER SYSTEM. The Seawater System (see Figure 1-14) supplies cooling seawater for the SSPU's oil heat exchangers, the hydraulic system heat exchangers, the compressed air system heat exchangers, the environmental control system chiller unit and for gun cooling. Seawater is

also supplied to the fire extinguishing systems and to the fresh water system for desalination and conversion to potable water. Seawater is also available to the hullborne diesel engines for engine cooling and cutlass bearing lubrication when the ship is foilborne.

The Seawater System is pressurized either by supply pumps which draw from sea chests when the ship is operating hullborne or by the foilborne propulsor second stage bleed when the ship is foilborne. The piping system uses filament-wound, Glass Reinforced Plastic (GRP), but has some titanium pipe also. The pumps are 440V AC, 400 Hz, 3 phase electric motors, with each of four having a 795 Liters/min (210 GPM) capacity at 1138 kN/m² (150 psi) pressure. System controls are in the EOS.

Operation and maintenance details are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 3, Chapter 16 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 3, Chapter 13 for PHM-1.

The following diagram relating to the Seawater System is contained in the EOSS:

TITLE
Diagram for Seawater Cooling System

CODE
DSWS/004/0382

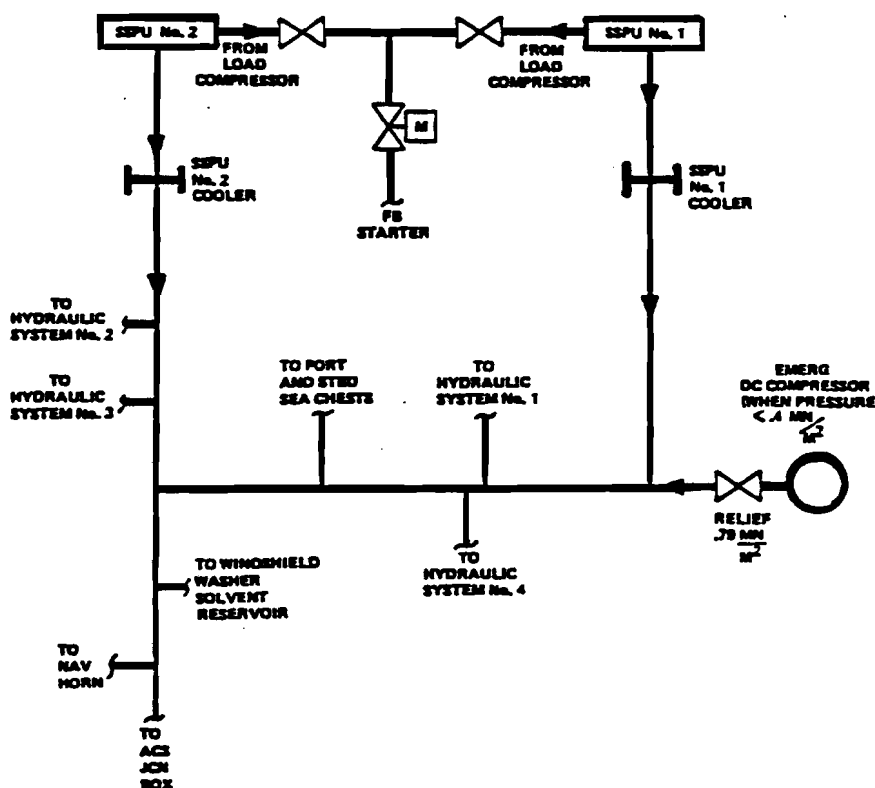


Figure 1-13. Compressed Air System

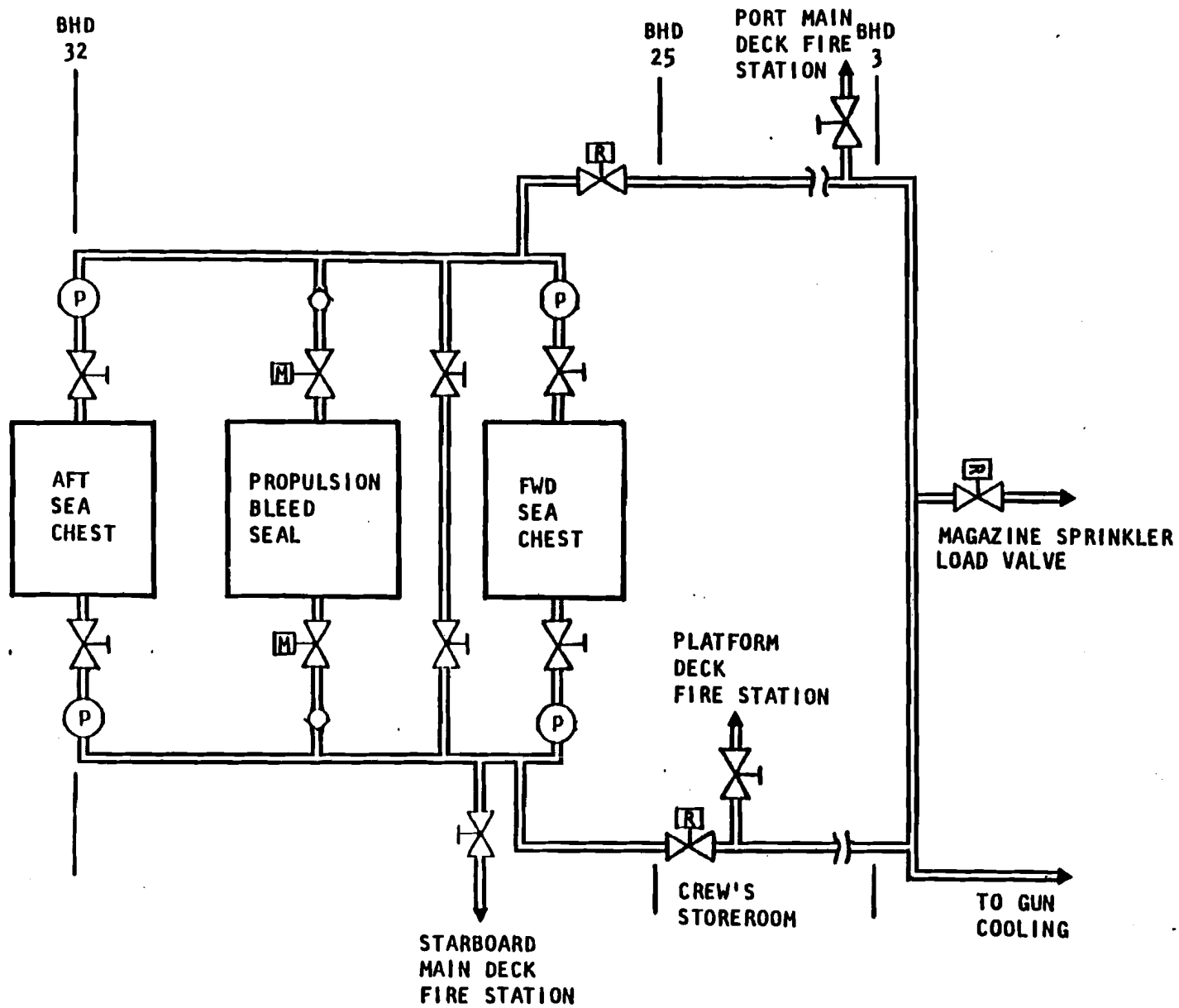


Figure 1-14. Seawater - Simplified Distribution Diagram

1.2.10 FRESH WATER SYSTEM. The Fresh Water System (see Figure 1-15) provides chlorinated potable water for use aboard ship. The system consists of a Desalinator Reverse Osmosis Unit two 500-liter (132-gal) tanks, a 151-liter (40-gal) hot water tank, and the distribution system. Two electric pumps, one for each storage tank, transfer water from the tanks into a stainless steel piping distribution system, which includes an accumulator tank that assists the system regulator in maintaining a constant pressure of 296 kN/m² (43 psi). A Water Purification System is provided to inject a chlorine solution into the water storage tanks fill lines, in proportion to the filling and holding volume. Water for the crew washing services is heated to 54°C (130°F) and boosted to 82°C (180°F) when supplied to the galley dishwasher and range hood washing system.

A fresh water outlet connection is provided for attaching a hose to the ship's 76mm gun cooling system. Water sampling valves are also provided at various locations to enable taking water samples for purification checks. A connection is provided on the main deck to fill the storage tanks when dockside.

Operation and maintenance details are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 3, Chapter 15 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 3, Chapter 12 for PHM-1.

The following diagram relating to the Fresh Water System is contained in the EOSS:

TITLE
Diagram for Aligning Fresh Water System

CODE
DFW/002/0382

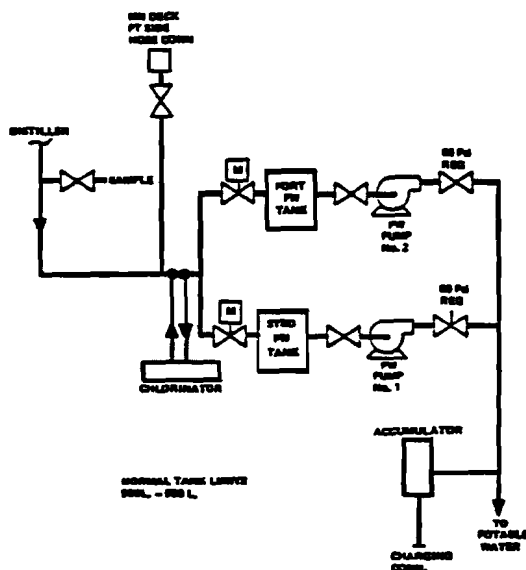


Figure 1-15. Fresh Water System

1.2.11 MAIN DRAINAGE SYSTEM. The Main Drainage System provides the means for pumping the fluids from the bilges and voids and storing it for offloading to a receiving facility or for overboarding.

The Bilge System consists of four electrically driven fixed bilge pumps, two fluid storage tanks, a transfer pump for offloading, and switches in the bilges, voids and storage tanks (see Figure 1-16). Piping is GRP. A portable submersible pump with an 8-meter hose and a 15-meter electrical power cable is provided for pumping bilges and voids not served by fixed pumps. Each bilge holding tank is constructed of fiberglass reinforced epoxy laminate and has a capacity of 500 liters (132 gal).

The bilge flooding panel located on the EOS console provides status and control of the drainage system.

Operation and maintenance details are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 3, Chapter 17 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 3, Chapter 14 for PHM-1.

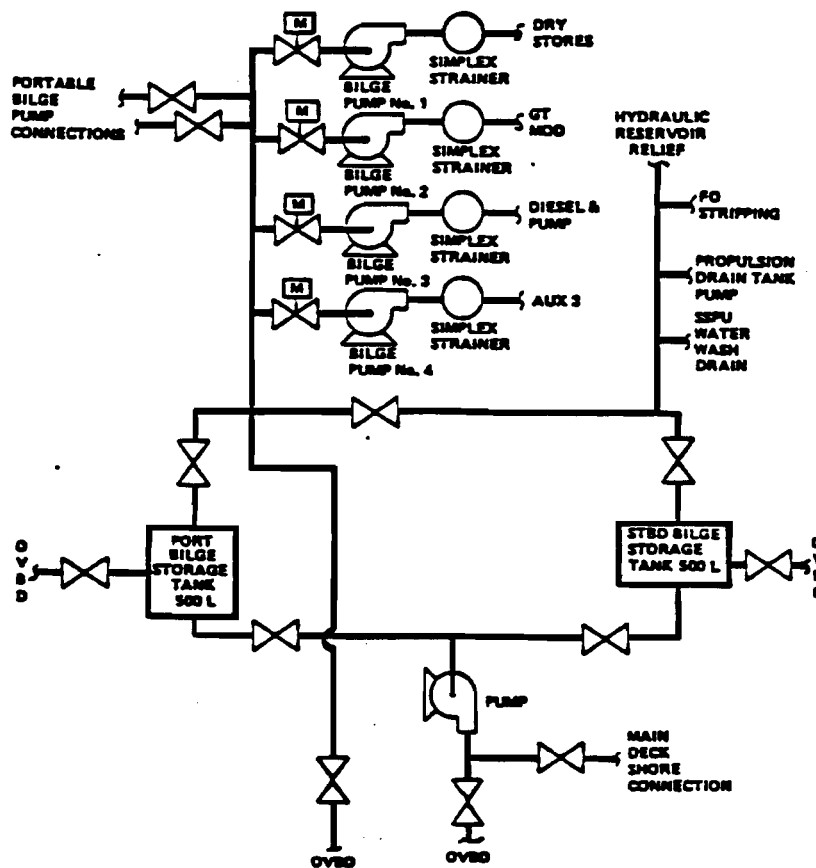


Figure 1-16. Main Drain

The following diagram relating to the Main Drainage System is contained in the EOSS:

TITLE
Diagram for Main Drainage System

CODE
DMDS/131/0382

1.2.12 WASTE WATER AND SEWAGE SYSTEM. Waste water from the lavatories, showers, dishwasher, galley sinks and range hood; drainage from the water fountains; and condensate from the ice maker, refrigerator, freezer, and all air conditioning units are collected by the Waste Water System (see Figure 1-17). The system consists of a network of nonmetallic drain lines feeding three separate collecting tanks, each of which contains a fluid level switch and an automatically operated pump for overboard or receiving facility discharge. The three 2 hp centrifugal pumps use 450V AC, 400 Hz power and 28V DC control voltage. Pump output is 94.6 liters/min (25 GPM) at 24.1 kN/m² (3.18 psi).

The Sewage System, which is separate from the Waste Water System, uses a macerator to reduce the solid waste to a slurry and transfers it to an evaporator, which reduces the volume of the waste products through evaporation of flush and waste water. An electrically driven centrifugal pump is used to transfer the remaining sludge to a dockside receiving system or overboard at sea when conditions permit.

Operation and maintenance details for both the Waste Water System and the Sewage System are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 3, Chapter 18 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 3, Chapter 15 for PHM-1.

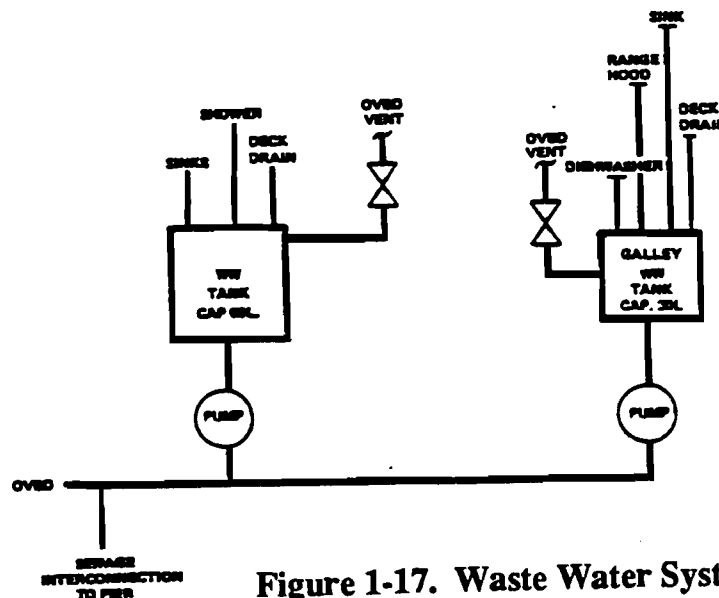


Figure 1-17. Waste Water System

1.2.13 FIRE EXTINGUISHING SYSTEM. The Fire Extinguishing System consists of the sea water Fire Fighting System, the galley ventilator Fire Control System, the portable Fire Extinguishing System, the Magazine Sprinkler System, and the Fire Detection and Extinguishing System. In addition, the gasoline-driven P-250 damage control pump is used as a backup.

The Sea Water Fire Fighting System has two fire stations on the main deck, each with two 1.5-in., 50-ft hoses. The fire main is pressurized from the Sea Water System.

The portable Fire Extinguishing System consists of portable dry powder and CO₂ extinguishers located throughout the ship. The dry powder extinguishers contain potassium bicarbonate.

The Magazine Sprinkler System is pressurized from the Sea Water System. Ten sprinklers are located around the magazine and will flood that area at a rate of 1375 liters per minute (365 GPM).

The Fire Detection and Extinguishing System provides fire detection and extinguishing in five machinery spaces. Three types of fire detection sensors are installed in each of these spaces, i.e., smoke, thermal, and optical (infrared/ultra violet). Halon 1301 is automatically released into the machinery space when the system is triggered by at least two sensors, one of which must be a temperature sensitive detector. Louvers and vents are automatically closed, ventilation fans are shut down, and the appropriate engine or power unit will automatically be shut down upon activation of the Extinguishing System. A warning horn sounds when overheat or fire is detected. The system is monitored and controlled from the EOS; however, the Halon can also be released from outside the affected space with manual lanyards.

Operation and maintenance details are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 1, Chapter 9 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 3, Chapter 20 for PHM-1.

1.2.14 COMMUNICATION SYSTEM. The Communication System consists of interior and exterior systems. The Interior Communication (Intercom) System is the primary system for the purpose of directing the operational functions internal to the ship. It provides station-to-station communications and three conference circuits that link selected stations.

Certain stations have the capability to access the Exterior Communications System, the General Announcing System, and the Recorder System. Figure 1-18 shows the interrelationship of the basic Intercom System with the Exterior Communications System, General Announcing System and the Recorder System.

The Exterior Communication System consists of the switching and integration control of the four transceivers (two UHF and two HF) including input selection and output selection/distribution from a central operators position. The system also provides the ancillary equipment for signal processing and message handling.

Operation and maintenance details for the various communication systems are found in the SOOM, NAVSEA S9PHM-AC-SHP-030/(U) PHM-3 CL, Volume 6, Chapters 25 through 36 for the PHM-3 series and NAVSEA 0905-503-7010 Volume 5, Chapters 23 through 34 for PHM-1.

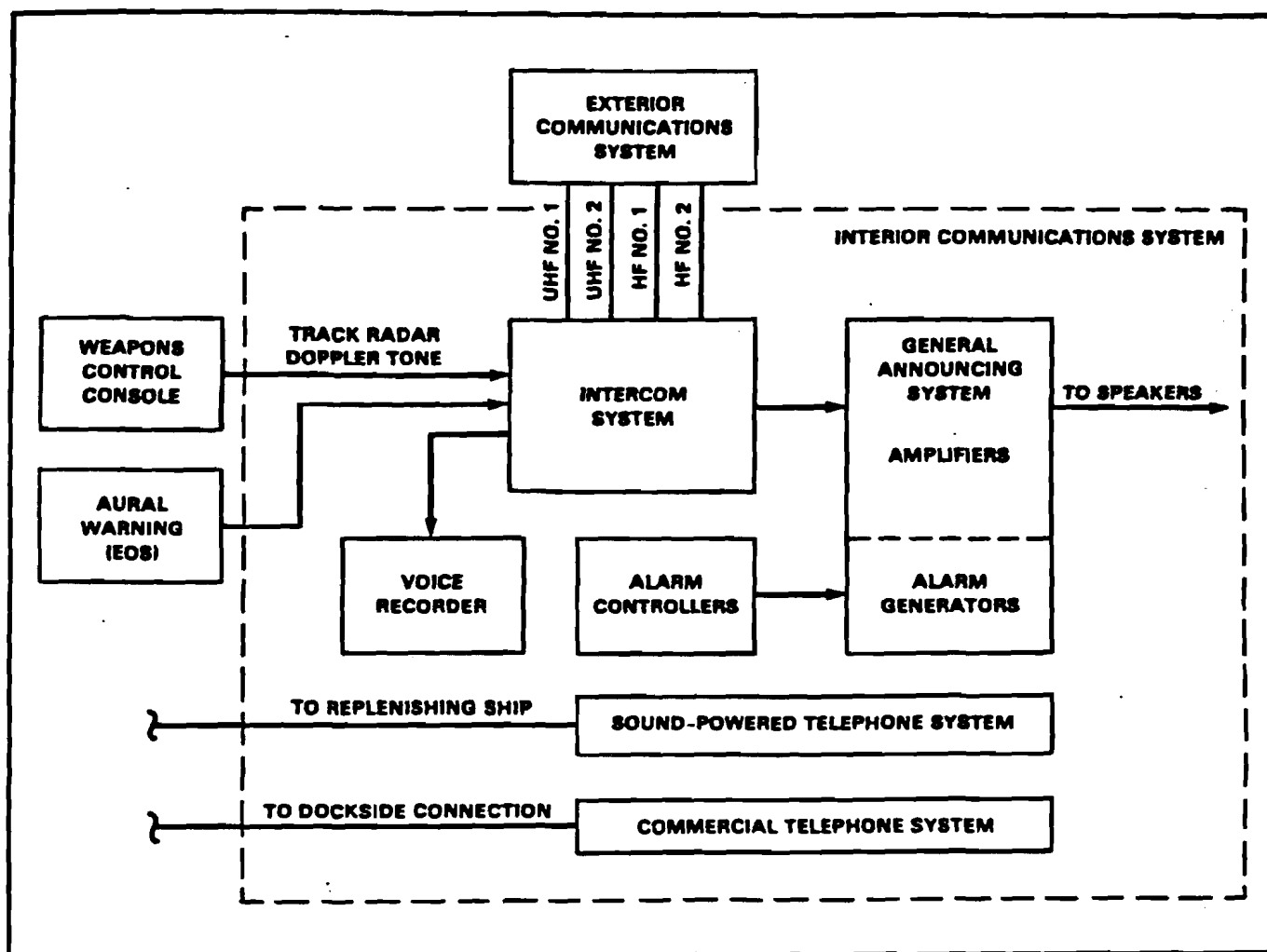


Figure 1-18. Intercom System Interface

1.2.15 HYDROFOIL COLLISION AVOIDANCE AND TRACKING SYSTEM (HYCATS)

INTRODUCTION

Operating at speeds above 40 knots, the PHM hydrofoils reduce the available helmsman and watch team reaction time to critical levels. These fast moving ships further complicate ship control by burdening the watch team with detection and evasion of many more contacts and hazards than slower, less maneuverable ships. HYCATS AN/SSQ-87(V) is an automated and centralized collision avoidance and tracking system that has been developed as a result of these high speed ship requirements, and augments the watch team by computer processing of radar and other sensor data, and through use of special displays. HYCATS replaces the conventional PHM helm and Officer of the Deck (OOD) instrumentation with computer-driven, real-time ship control and command/ controls which are enhanced by computer resources to integrate, support, and execute: automated detection, acquisition, and tracking of course and speed of contacts.

During Operational Evaluation in 1979, USS PEGASUS was cited with a deficiency in safe navigation while operating in congested water ways. This deficiency led to the cooperative development of a High Speed Collision Avoidance and Navigation System (HICANS) by Sperry (now UNISYS), the Naval Sea Systems Command (NAVSEA), and the David Taylor Research Center (DTRC). A pre-production HICANS was installed aboard the USS PEGASUS and testing began in the winter of 1980. The system provided very accurate position location and collision avoidance data.

The HICANS also proved to be very reliable, and allowed for high speed operation while reducing the number of personnel required during navigation of congested or narrow water ways. In 1983 the HYCATS production model was manufactured by UNISYS and installed on five of the ships by the end of 1986. (HICANS is still located aboard the PHM-1 but SHIPALT 117 is scheduled to replace it with HYCATS sometime in the early 1990s).

This section of the PHM Operational Notebook provides a description of HYCATS, and its associated shipboard systems, and its relation to those systems. For complete information on the system consult the HYCATS Technical Manual GH-15-1104.

HYCATS PURPOSE.

HYCATS is operated by the Combat Information Center (CIC) Console Operations Specialist (OS) and the Officer of the Deck (OOD). Located in the CIC, the OS is the primary operator of HYCATS, see Figures 1-19, 1-20, and 1-21. The CIC Console provides control of all the HYCATS functions. The OOD at the Bridge Console can request information from HYCATS and control the operation through communication with the OS.

HYCATS requires inputs from the other ships systems for normal operation. Radar, speed, depth, and heading information is provided from existing shipboard systems. The AN/UYK-44 Computer provides computer function to HYCATS.

HYCATS FUNCTIONS.

The HYCATS operator stations consist of the CIC Console in the CIC and the Bridge Console in the Bridge. Other HYCATS equipment includes the Equipment Converter Group, Video Recorder, Bridge Power Supply, Port and Starboard Pelorus Converter Units, and the AN/UYK-44 Computer. See Figures 1-22, 1-23, 1-24, and 1-25.

The two functional modes of the operation in HYCATS are the Collision Avoidance mode and the Navigation mode. The collision Avoidance mode allows the operator to monitor, track and detect other ships and targets and identifies areas of danger or possible collision. The specific functions include acquisition and tracking of targets, guard ring detection of targets, collision avoidance solutions, and maneuvering solutions. The system also enables the operator to check the outcome of trial speeds and heading without committing the ship to that particular action. The radar inputs used by HYCATS drive the tracking functions and provide information to generate the simulated Plan Position Indicator (PPI) display on the HYCATS monitors. The Navigation mode enables HYCATS to perform navigation calculations, position locating, and piloting of the ship. Functions provided in navigation include dead reckoning, visual position fixing, and turnpoint solutions.

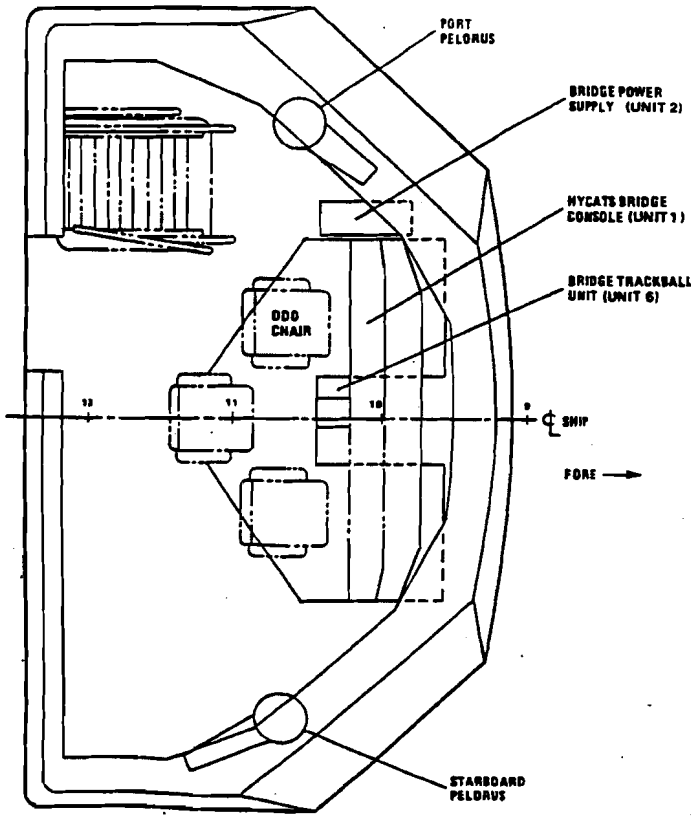


Figure 1-19 PHM Bridge

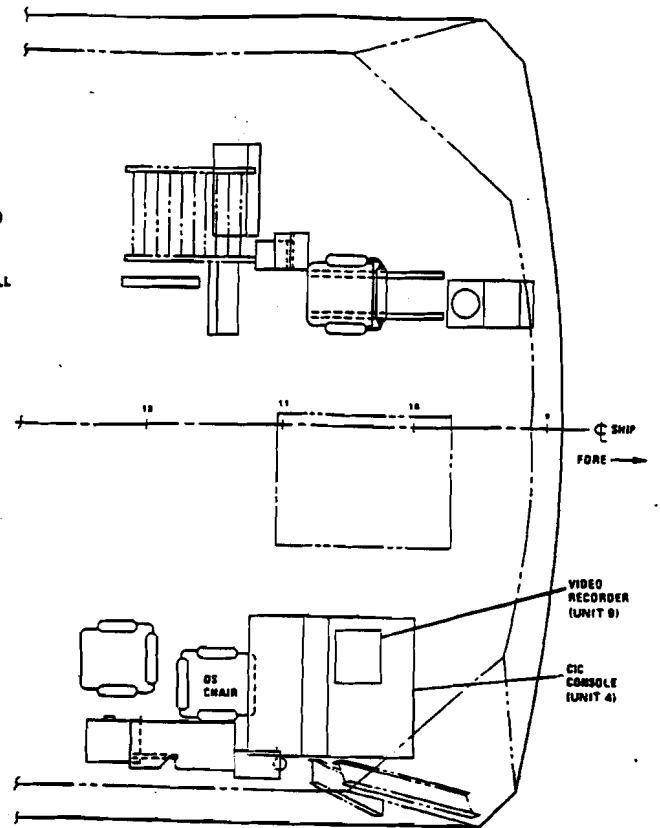


Figure 1-20 CIC

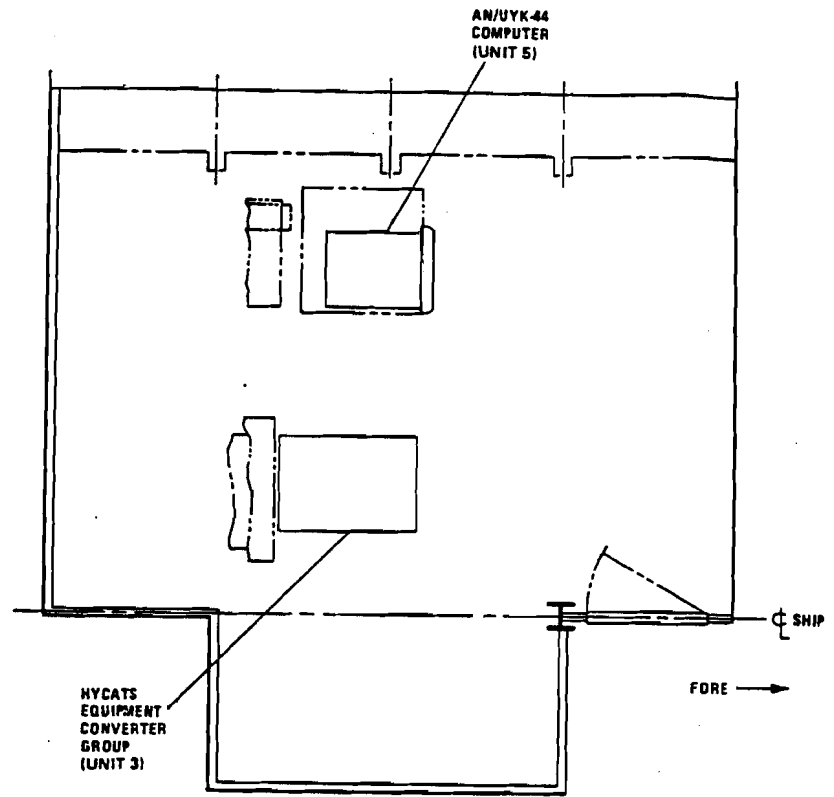


Figure 1-21 Electronics Equipment Room

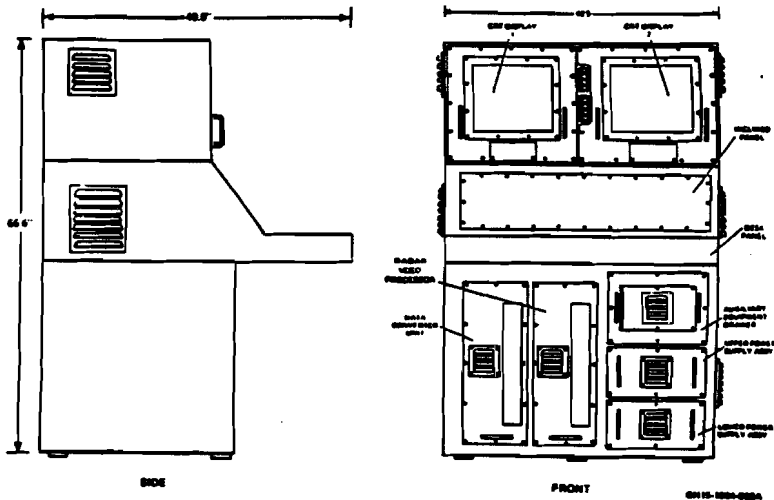


Figure 1-22 HYCATS Console-CIC

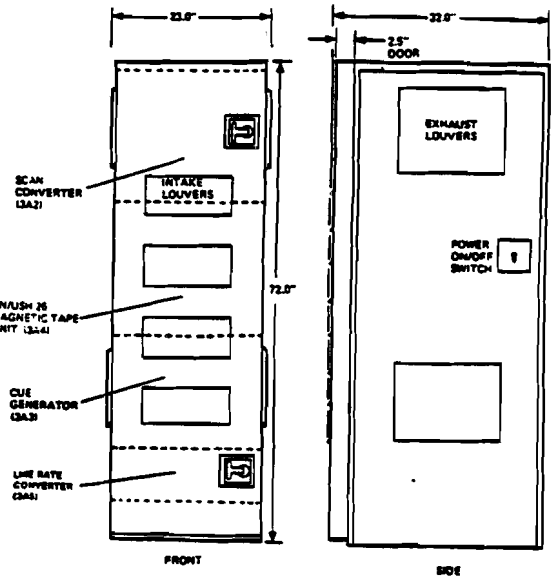


Figure 1-24 HYCATS Equipment Converter Group

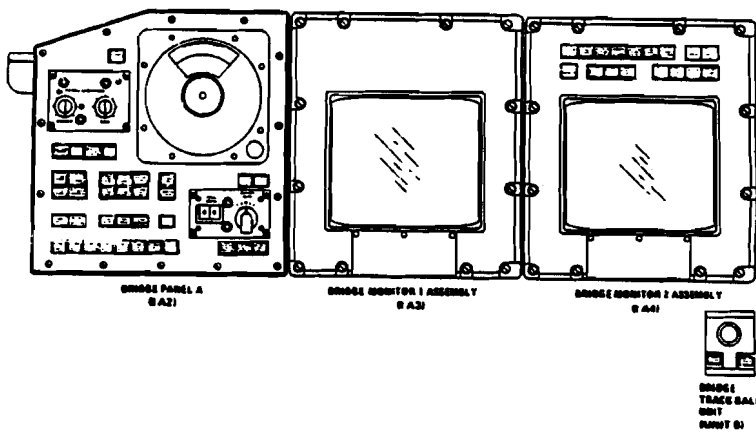


Figure 1-23 Bridge Console and Bridge Trackball Unit

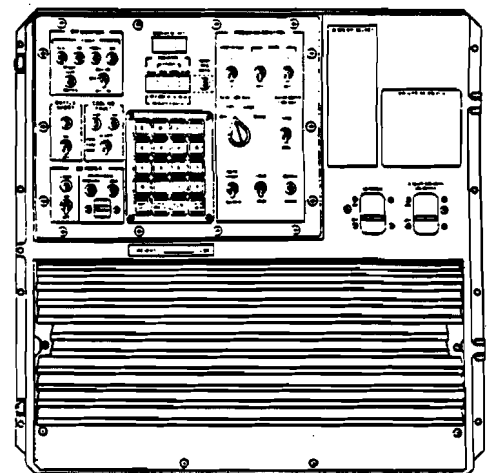


Figure 1-25 AN/UYK 44 Data Processing Unit

HYCATS INTERFACE WITH OTHER SHIP EQUIPMENTS.

HYCATS requires inputs from other ship systems to perform the navigation and collision avoidance functions, see Figure 1-26.

Radar inputs are required for navigation computation and display. The radar can be selected from either the AN/SPS-64 surface search radar or The MK-92 fire control radar. The data appears on the conning display in either raw or processed form. Processing of the data is performed by the HYCATS Radar Video Processor (RVP).

Heading information for the navigation and display is provided by the ship's gyrocompass. Heading information can also be manually entered by the CIC Console operator.

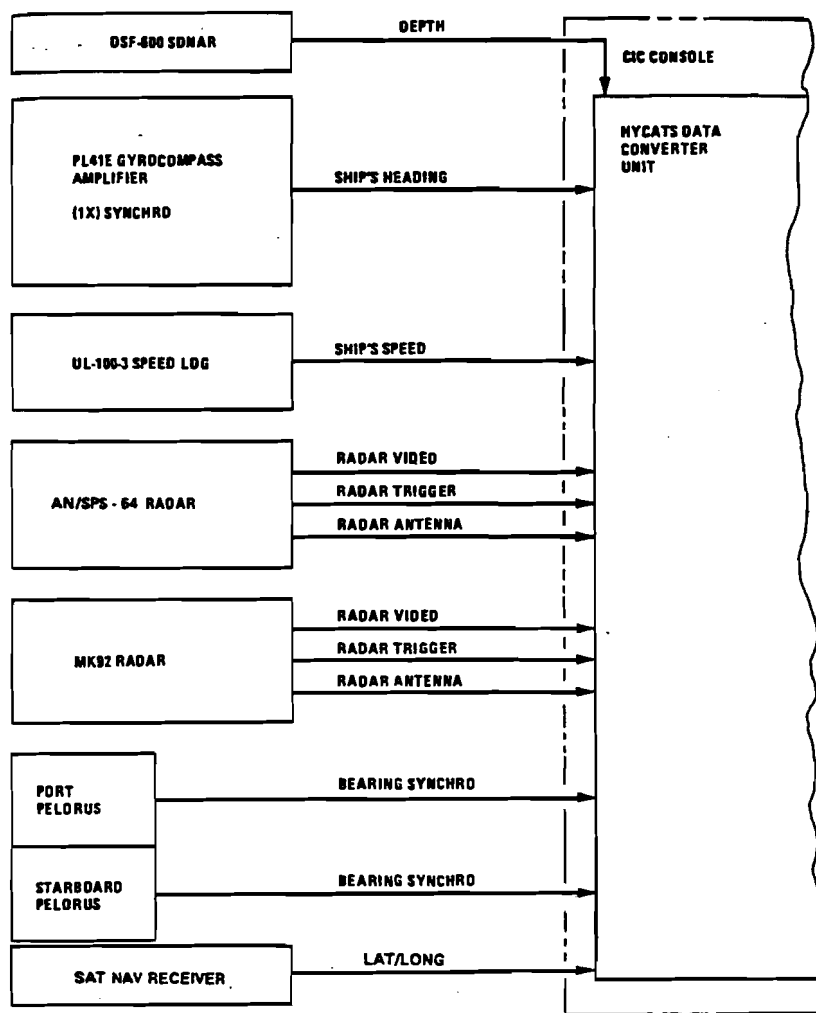


Figure 1-26 HYCATS/Ship Systems Interface

Speed inputs to HYCATS are provided by the ship's UL-100-3 EM speed log. Speed inputs can be provided manually at the CIC Console Simulation Panel.

The Pelorus Converter Units transmit bearing synchro data to HYCATS when the BEARING MARK switch is pressed.

A depth from the DSF-600 Sonar permits display of the depth information on the conning display.

HYCATS PHYSICAL ARRANGEMENT.

The HYCATS units are located at several places on the ship, as shown in Figures 1-19, 1-20, and 1-21. Most of the equipment is located in the CIC. The CIC Console contains the operating controls and monitors for the OS. It also contains the Radar Video Processor, Data Converter Unit, Upper Power Supply Assembly, Lower Power Supply Assembly, Alphanumeric Generator, Matrix Control Cards, and the Video Panel Assembly.

The Equipment Converter Group is in the Electronics Equipment Room (EER) located aft of the CIC. The Equipment Converter Group contains the Cue Generator, Scan Converter, and the AN/USH-26 Magnetic Tape Unit. The AN/UYK-44 Computer is also located in the EER.

The bridge Power Supply and the Bridge Console are located on the Bridge. The Port and Starboard Pelorus Converter Units are located on the respective sides of the bridge.

MODES OF OPERATION.

HYCATS modes of operation are divided into two areas: **Collision Avoidance** mode and **Navigation** mode. Each of these modes is briefly described in the following paragraphs. For detailed information see the HYCATS Technical Manual.

Collision Avoidance Mode. The Collision Avoidance mode is the primary mode of operation of the system. It provides data associated with angle, speed, and distance to other surface targets for safe transit.

The collision avoidance concept is based upon determining and displaying the Points of Possible Collision (PPC) with a target ship and the associated Closest Point of Approach (CPA) contours which surrounds each

PPC, see Figure 1-27. The term PPC is defined as the point along the target ship's projected track at which ownship could collide with the target if each ship maintains its present speed. The bearings to the point of possible collision is analogous to that bearing at which a torpedo, traveling at ownship's speed should be aimed in order to hit the target ship.

The Target PAD is an elliptical area which surrounds the PPC. It encloses the area which is less than the minimum miss distance set at the PADS thumbwheels by the operator.

When several targets are plotted on the collision avoidance display, it may be considered as a two-dimensional, pictorial, time-ordered CPA position matrix. This is achieved because all the CPAs are calculated during the time when they are a danger with respect to ownship, see Figure 1-28.

NAME	SYMBOL
MANUAL TRACK TARGET	☐
AUTOMATIC TRACK TARGET	□
GUIDE	⊙
STATION	⊗
RENDEZVOUS POINT	✕
POINT OF POSSIBLE COLLISION (PPC)	⊕
TARGET PAD	⊖
FALSE ALARM	∩
TARGET IDENTIFICATION	004
PRELIMINARY TARGET VECTOR	-----
TARGET VECTOR	—————

Figure 1-27 Collision Avoidance Mode Symboly

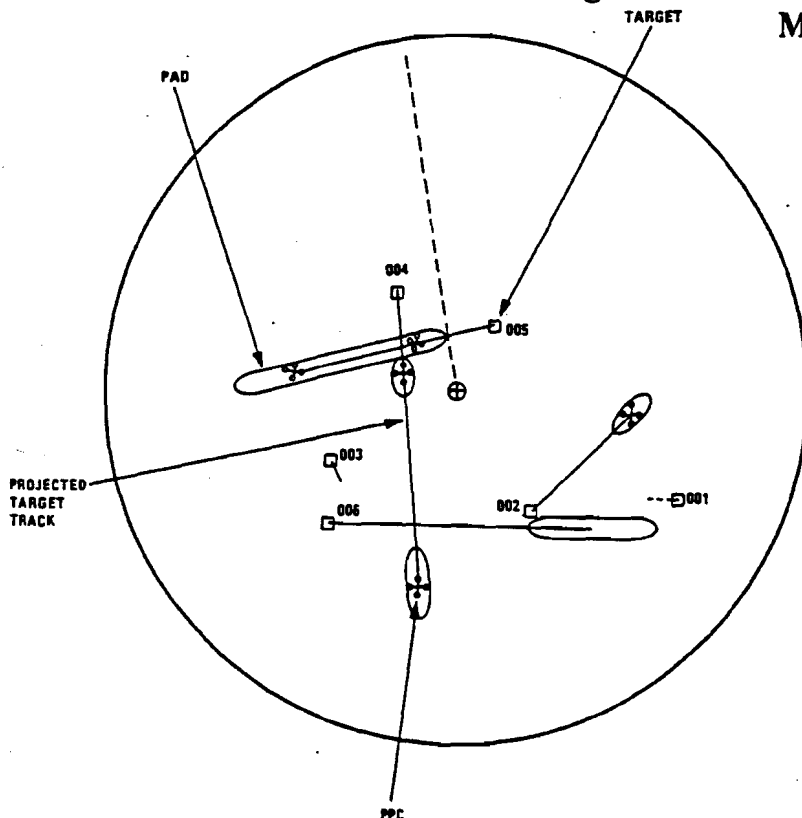


Figure 1-28 Multiple Target Graphic Collision Avoidance Solution

In addition to the graphic CPA data presented on the conning display, alpha-numeric collision avoidance data are displayed on the data display. CPA data for the most threatening targets are continuously displayed. The operator can request data on any other target in track by paging the CPA list forward or backward.

Collision Avoidance Display functions are primarily associated with the development and display of data designed to aid the operator in making decisions necessary to avoid collisions. This data consists of the following in graphic and/or alphanumeric format: target number, target range and bearing, target course and speed, bearing and range to target CPA, time to CPA, time of day at CPA, points of possible collision, and predicted areas of danger.

Navigation Mode The Navigation Mode is presented here in very little detail. See the technical manual for a detailed description of the navigation system. The following paragraphs provide a brief description of the navigation mode including a short discussion of the the High Speed Digital Chart (HSDC) and its use in coastal navigation.

The HYCATS navigation mode provides the capability to support independent operations in open ocean areas and piloting in restricted waters. The navigation displays and controls are located at the HYCATS CIC and Bridge Consoles.

All critical navigation information is effectively combined on one television formatted display. The conning display shows real-time solutions with automated features that reduce operator functions and permit rapid evaluation of traffic hazards. Superimposed with radar is a computer-generated representation of selected nautical charts called a High Speed Digital Chart (HSDC). These depict coastlines, navigation references (aids), shoals, ownship intended tracks, and hazards.

Also displayed are pertinent data regarding ship CPAs, position data, identification, and qualifying data. Visual lines of position are provided based on inputs from the ship's peloruses. Dedicated numerical readouts on the conning display provide information such as time, ship's speed, and heading. Status and alarm displays indicate the selected modes, range scales, and those alerts associated with navigation and collision avoidance.

HYCATS provides for dead reckoning (DR) in open ocean navigation. Position fixing is available in coastal areas where accuracy with respect to local references is required for safe conning of the ship. The navigation functions are described below.

Dead Reckoning. (DR) are computations performed continuously in the digital computer using ownship's heading derived from the gyrocompass, and ownship's speed from the speed log. While underway, the computer will continuously integrate the speed to update ownship's latitude and longitude.

Position updating can be done in open ocean and coastal waters. In the open ocean, external fixes can be periodically put into the system to correct errors in the DR by using the AN/SRN-17 SATNAV/OMEGA receiver. In coastal regions, both AN/SRN-17 and radar fixes can be used for position updating.

HYCATS is equipped with High Speed Digital Charts, a computer-generated chart that displays simulated shoal lines, channel lines, track lines, predominant radar features, and navigation aids such as buoys and fixed lights with associated labels. It uses hydrographic navigation chart data recorded on a magnetic tape cartridge. The software charts permit the computer to correlate and display chart information with a position based on DR or radar position-fixing information. See Figure 1-29 for digital chart display with radar return.

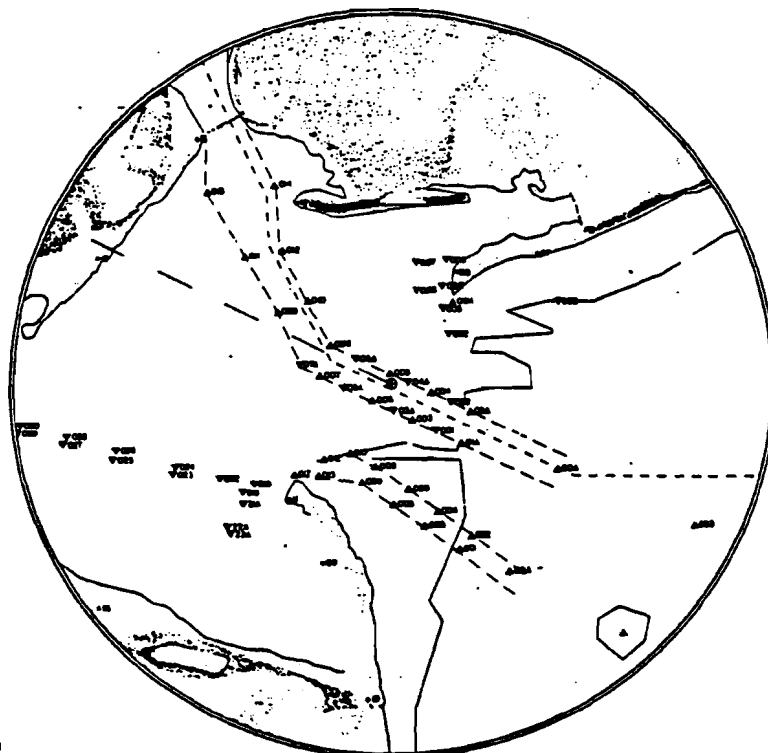


Figure 1-29 Conning Display in Digital Chart Mode

HYCATS SYSTEM ACCURACY

To assure the accuracy and safety of HYCATS extensive operational and maintenance testing was conducted on the system aboard the USS PEGASUS.

The preproduction model of HYCATS was given Factory Acceptance Tests in November of 1980. The 36 Factory Acceptance Tests (FAT) with a duration of 26 operating hours were conducted and observed by Defense Contract Administration Services Personnel. Components were checked sequentially through equipment, subsystem and system-level tests. Calibration was accomplished as software and systems hardware were integrated and the system debugged as necessary to confirm satisfactory operation prior to shipboard installation. In addition, the contractor attained 460 hours of system operation. Reliability and maintainability tests were conducted by the contractor during FAT and for each test performed, the number of failures, type, and description of failures were recorded utilizing the Automated Surface Ship Information System-Technical (ASSIST). Test and operator/maintenance training for ship crews and the MLSG has been conducted throughout the installation of the HYCATS units aboard the PHMs.

At-sea testing commenced after installation and checkout aboard PEGASUS in January 1981. Range testing to assess the system accuracies in the shipboard environment were conducted on PEGASUS using the services of LCU/LCM type craft and a RAYDIST system provided by Naval Air Development Center, as a measurement truth source. Results of system performance during that at-sea test phase were inconclusive. Therefore, additional at-sea testing was conducted using a TRISPONDER ranging system, to provide the necessary truth source to assure the system performance accuracy.

NAVSEA still felt that they had not sufficiently tested the system to assure the accuracy and performance of the system. Additional at-sea tests were performed using a more extensive TRISPONDER Range, other PHMs operating as targets, and a very sophisticated PC based data processing system.

The results of this testing are listed in Table 1-2, taken from the Test Evaluation Master Plan (TEMP)#750 for the HYCATS Test Program.

Table 1-3 provides a list of technical manuals related to HYCATS for further reference.

Table 1-2. HYCATS Threshold and Measured Values

CHARACTERISTICS	THRESHOLD	MEASURED (TECHEVAL)	MEASURED (DT-III A)	MEASURED (DT-III C)
Automatic Target Detection ^a	.9 @ 8 nm	.9 @ various ranges ^g	1.0 @ 9 nm	Not conducted
Target Tracking ^b	45 contacts	45 contacts ^h	Not conducted	Not planned
Tracked Contact Range Error ^c	14 yds RMS	5 yds RMS ⁱ	13.9 yds RMS	11.5 yds RMS
Bearing Tracking Accuracy	1° RMS	0.5° RMS	0.349° RMS	0.18° RMS
Radar Map Match Fix Accuracy	50 yds RMS or .02 of radar range ^d	21 yds	38.92 yds RMS; ^k .0089 of radar range ^l	39.7 yds RMS; ^k 0.012 of radar range ^l
Contact Speed ^e	1 kt RMS	2 kts RMS ^j	0.84 kts RMS	Not conclusively demonstrated
True Course of Contact ^e	2.5° RMS	3.5° RMS ^j	1.67° RMS	Not conclusively demonstrated

NOTES:

- a** Probability of detection of a 10m² target in seas up to State 3 sea. This parameter is premised on HICANS operating with the Mk 94 Radar performing to specifications with no power split between the search and track functions.
- b** Any combination of manual and automatic tracking up to 45 contacts.
- c** Forward Biased Centroid Tracking. Based on the Mk 94 Radar performance in the narrow pulse mode for a point target.
- d** Whichever is the greater.
- e** Assumes a 25-knot target at a range of 10 nm and excludes ownship gyro, radar antenna and log errors.
- f** RMS - Root Mean Square: A method of statistical calculation, defined as the square root of the mean squared and standard deviation squared. $RMS\ Error = \sqrt{(random\ error)^2 + (mean\ error)^2}$.
- g** Performance exhibited between 5 nm and 20 nm range.
- h** Conducted during FAT.
- i** Standard deviation, excluding mean errors.
- j** Included inseparable errors caused by insufficient instrumentation.
- k** Harbor Navigation.
- l** Offshore Navigation.

**Table 1-3. Technical Manuals Related to AN/SSQ-87(V)
Technical Logistics Data**

<u>TITLE</u>	<u>NUMBER</u>	<u>DATE</u>
Preliminary Technical Manual for Hydrofoil Collision Avoidance and Tracking System (HYCATS) AN/SSQ-87(V)	GH-15-1004	6/85
Preliminary Technical Manual for Hydrofoil Collision Avoidance and Tracking System (HYCATS) AN/SSQ-87(V) System Components	GH-14-1002	10/85
Preliminary Technical Manual Cue Generator Volume 1 Section 1 through 6	1B4362	
Preliminary Technical Manual Scan Converter Unit Volume 1 Section 1 through 6	1B4363	
Preliminary Technical Manual for HYCATS Data Converter Unit (DCU)	GH-14-1001	9/85
AN/USH-26(V) Technical Manual Operation Instructions Maintenance Instructions Parts List Installation Instructions Recorder-Reproducer Set, Signal Data AN/USH-26(V) Volume 1	0910-LP-048-9980	6/81
Preliminary Technical Manual for Radar Video Processor	GR-14-1048	9/85
HYCATS AN/SSQ-87(V)		
Operators Handbook		
Data Processor Set AN/UYK-20	0967-LP-598-1010/1090	
Magnetic Tape Cartridge Unit AN/USH-26		
Scan Converter Hazeltine Manual	1B-4230 and 4233	
Cue Generator Hazeltine Manual	1B-4235 and 4215	
CRT Displays (14 and 17 inch) Hartman Manual		
CRT Console Model 1420 Hazeltine Maintenance Manual		
TRAINER ONLY		
Chart Image System GAP Manual (6652 IQMM)		
Camera System Model 7920-010 COHU Technical Manuals		
A. High Resolution Monochrome Television Camera Controls Series 6900/7900B Series	6XX-570(B)	
B. Variable Scan Rate Sync Generator Model 7900-2000 and Model 2700-500	6X-673	
C. Television Cameras 2000 Series (for 10 and 20 Megahertz Systems)	6X-314(B)	

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2.0 OPERATIONS

Navigation of PHM is based on PHMRON TWO standard navigation procedures. Reference is made to Section 1.2.15 which briefly describes the Hydrofoil Collison Avoidance and Tracking System (HYCATS).

2.1 COMMAND LANGUAGE

Reports to the OOD, EOS, CIC, and captain are essential and follow standard naval reporting procedures. At least 50 reports require notifying the captain. Each function aboard ship is critical and many are unique. On a ship with a small crew, coordination and reporting are particularly important and required by all hands.

2.1.1 PILOTHOUSE COMMANDS (HULLBORNE AND FOILBORNE)

Control of foilborne and hullborne operations is from the pilothouse, supported by EOS and CIC. The OOD and helm share responsibility, and the captain monitors everything.

Orders and responses for control of the ship for foilborne and hullborne operation are conveyed as presented in Table 2-1.

Table 2-1 Pilothouse Commands

Steering Orders to the Helmsmen

<u>COMMAND</u>	<u>MEANING</u>
Right (Left) five (ten, etc.) degrees rudder	Place the hullborne nozzles at the indicated angle, verifying by the console angle indicator. When the diesels are secured, place the forward strut at the indicated angle (not more than 12 deg).
Right (Left) at ____ (1 to 10 degrees) per second	When foilborne, turn the helm in the appropriate direction to attain, the ordered turn rate using the turn rate indicator as a guide.
Increase your rudder to Right (Left) _____ (number of degrees)	When hullborne, increase the ordered nozzle angle or strut steering angle to the indicated number of degrees.

Table 2-1 Pilothouse Commands (Continued)

Increase to ____ (1 to 10 degrees) per second	When foilborne, increase the turn rate in the appropriate direction to that ordered.
Ease your rudder to Right (Left) _____ (number of degrees)	Reduce the angle of the nozzles, or forward strut, from current ordered to new ordered angle.
Ease to _____ (1 to 10 degrees) per second	When foilborne reduce the turn rate to that ordered.
Shift your rudder	When hullborne, this command directs the helmsman to turn the ship in the exact opposite of the present ordered turn. If, for example, the ship is turning right at 30 deg of rudder this order would cause a turn left at 30 deg of rudder.
Steady course (degrees)	Place the ship on the course indicated by the gyro compass. The course will be ordered using three digits (i.e., "Steady course zero nine zero").
Steady as you go	Steer the course that the ship is heading when order is received. The helmsman should note and report the course on the gyro and adjust the helm as required to steer that course.
Rudder amidships	When hullborne, place the nozzles, or forward strut, at zero angle.
Rollout	When foilborne, stop the turn. May be used in conjunction with a final ordered course (i.e., "Rollout two three zero").
Mind your helm	A warning that the ship is not being steered accurately and a command to steer the course ordered.

Table 2-1 Pilothouse Commands (Continued)

How is your rudder?	A question to the helmsman which requires a response stating the angle of the nozzles, or the forward strut.
Mark your head	A command to the helmsman to announce the ship's present heading.
Very well	Proper response by the conning officer to a statement or report by the helmsman or lee helmsman. It indicates understanding as well as acknowledgement.
Come Right (Left) to course (degrees)	Put the helm right or left and steer the course ordered. This order should be used for small course changes (less than 5 deg) when the rate of turn is left to the discretion of the helmsman.
Steer _____ (degrees)	For course changes of 1-2 deg, when the direction is obvious this command may be used.
Continue right (left) to course _____ (degrees)	When in the middle of a turn the conning officer desires to change the final course, he will give this order, and the turn will be carried out to the new course at the rudder angle, forward strut angle or turning rate already in effect. If the new course is short of the old course, the conning officer will simply order "Steady on course _____".
Steer _____ (course) by _____ (gyro/magnetic compass/heading hold).	Take the ordered action. When steady, report "Sir, steady on course _____ by (gyro/magnetic compass/heading hold)".
Bow thruster orders will be given as "bow left, bow right, bow stop."	

Responses by the Helmsman to Steering Orders

(1) Repeat the order given followed by "Aye, aye, sir" if understood.

Examples: "Right 15 degrees rudder. Aye, aye, sir."
"Right 15 degrees rudder. Steady course zero nine zero. Aye, aye, sir."
"Rudder amidships. Aye, aye, sir."
"Shift my rudder. Aye, aye, Sir."

(2) Report to the conning officer that the ordered action has been taken.

Examples: "Sir, my rudder is right 15 degrees, no course given."
"Sir, my rudder is right 15 degrees, coming to course zero nine zero."
"Sir, my rudder is amidships."
"Sir, my rudder is left (right) 15 degrees, no course given."

(3) Report to the conning officer when a new ordered course has been reached. (Include the magnetic heading).

(4) If the conning order is not understood, request "Orders to the Helm."

(5) If the conning officer does not acknowledge your report, repeat it until he does.

(6) If a rudder order has been given without a course to steer, report the ship's head to the conning officer every 10 even degrees.

EXAMPLE: "Sir, my rudder is left 15 degrees, no course given, passing 300... passing 290."

The conning officer may then order the helmsman to "belay your heading". An important point to make here is that any order changing the position of the rudder, forward strut, or turning rate, negates and supersedes the

Table 2-1 Pilothouse Commands (Continued)

previous order. Therefore, if the order "Right 15 degrees rudder, steady course 300" is given and followed by "Ease your rudder to right 10 degrees," there must be a new course ordered, as well. Otherwise, the proper response by the helmsman in the above example would be "Ease my rudder to right 10 degrees, Aye, Aye, Sir. Sir, my rudder is right 10 degrees, no course given. Passing 290," etc.

Orders to the Lee Helmsman or Helmsman if No Lee Helmsman is Assigned

(1) Diesel engine orders will be given in the following sequences. Engine, direction, amount, speed (if applicable). More specifically, (starboard, port, all) engines (ahead, back) for (knots).

Examples: "All engines ahead 1,800 for 10 knots."
"All engines back 800."
An acceptable alternate command could be "All back 800."

(2) The order "all stop" shall mean to place the diesels at 600 RPM with the buckets in the neutral position using the throttle detent position as a guide. NOTE: The term "IDLE" is not to be used.

(3) Foilborne turbine commands will be given as percentages followed by a desired speed (if applicable).

Example: "Turbine to 60%."

In this example, the lee helmsman will advance or retard the turbine throttle to indicate the proper percentage on the panel indicator. If the conning officer specifies an incorrect associated speed, the lee helmsman will come to the ordered percentage of turbine power and report the correct correlating speed.

Responses by the Lee Helmsman to Engine Orders

(1) Lee Helmsman responses will include a verbatim repeat of orders followed by a report showing the positions of all engines on line.

Table 2-1 Pilothouse Commands (Continued)

Example: "Starboard ahead 600. Port back 600. Aye, aye, sir, engines answer starboard ahead 600, port back 600."
All engines ahead 1,200 Aye, aye, sir. Sir, all engines answer ahead 1,200.
"Turbine to 80 percent. Aye, aye, sir. Sir, turbine answers 80 percent.

(2) If the orders are not understood, request "Orders to the lee helm."

Foilborne Operation

<u>COMMAND</u>	<u>MEANING</u>
Configure for flight	Perform preflight checklist and align panel switches in the configuration for foilborne operation in accordance with EOP. Set depth to 3.2m. When ready for flight, indicator lighted, report: "Sir, configured for foilborne, have a ready for flight light, green board, foil depth set 3.2.
Raise the ship set foil depth ____m.	1.) Helmsman adjust to prescribed foil depth setting and the ship is lifted out of the water. (After meeting EOP requirements for foilborne operations).
Set depth	Adjust the depth setting T-bar to achieve the ordered foil depth.
Land the ship	Retard the turbine throttle to idle, allowing the ship to settle into the water. Then report: "Sir, the ship is hullborne."

Table 2-1 Pilothouse Commands (Continued)

Emergency land the ship	Lower the depth setting T-bar all the way is drive the ship into the water while simultaneously retarding the throttle to idle. Then report "Sir, the ship is hullborne."
Go to UNREP/TEST ENABLE Go to strut steering, etc.	Select the ordered ACS mode and report (EXAMPLE: "Sir, UNREP/TEST ENABLE assigned.")
Extend (retract) the struts, fore and aft or Extended (retract) the forward (aft) strut	Take the ordered action, ensuring ACS mode is in STRUT CENTERING. When action complete, report (EXAMPLE: "Sir, forward strut extended.")

Orders to Linehandlers

Take in all lines (line number)	Release the indicated line(s) from the pier or float and bring it (them) onboard.
Cast off all lines (line number)	Release the indicated line(s) from the ship and send it (them) to the pier (float).
Check (line number)	Continue to keep a strain on the indicated line but do not hold it to the point of breaking.
Hold (line number)	Keep the indicated line in its present state, taking a strain up to and including parting.
Take the slack out	Heave around until there is a slight tension on the line.
Slack line (number)	Pay out a sufficient amount of line so that there is no tension on it.

Table 2-1 Pilothouse Commands (Concluded)

Shift line (number) to (location)	Slack the indicated line, remove it from its present location, and attach it to the ordered location (cleat, bollard, or bitts).
Single up line (number)	Take in all but one length of line.
Double up line (number)	Pass an additional length of line to the pier or float and back again or, in an eye-to-eye double, pass the onboard eye to the same location as the singled eye of the line.

2.1.2 DOCKING COMMANDS

Table 2-2 lists the rudder and engine commands associated with the docking maneuvers.

Table 2-2. Conning Officer Orders for PHM Docking Maneuvers

COMMAND (U.S. Naval Command Language) *Naval Shiphandling, p.42, Comdr. R.S. Crenshaw, Jr., U.S.N.	MEANING
Put over (all) line _____	Pass the lines to the pier, place the eye over the bollard, but take no strain on lines.
Take a strain on one	Put line number one under tension
Slack one	Take all tension off line number one
Ease one	Let line number one out until it is under less tension, but not slacked
Take number two to the capstan	Lead the end of line number two to the capstan, take the slack out of the line, but take no strain
Heave around on two	Apply tension on line number two with the capstan
Avast heaving	Stop the capstan
Hold what you've got	Hold the line as it is
Hold five	Do not allow any more line to go out on number five (CAUTION - This risks parting the line).

**Table 2-2. Conning Officer Order for PHM Docking Manuevers
(Continued)**

COMMAND	Meaning
Check five	Hold heavy tension on line number five but render it as necessary to prevent parting the line
Surge five	Hold moderate tension on line number five, but render it enough to permit movement of the ship (used when moving along the pier to adjust position)
Double up	Pass an additional bight on all mooring lines so that there are three parts of each line to the pier
Single up	Take in all bights and extra lines so there remains only a single part of each of the normal mooring lines
Take in all lines	Used when secured with your own lines, (also means to have the ends of all lines cast off from the pier and brought on board)
Cast off all lines	Used when secured with another ship's lines in a nest (also means to cast off the ends of the lines and allow the other ship to retrieve her lines)
Suggested Command Language	
Bow right or bow left	Bow thruster moves ship's bow as ordered
Bow stop	Bow thruster off
All (port) (stbd)	Port or starboard or both

**Table 2-2. Conning Officer Orders for PHM Docking Manuevers
(Continued)**

COMMAND	MEANING
Engine(s) ahead	
Idle	Move throttle to position bucket ahead
One third	Further move throttle to 900 rpm ahead
Two thirds	Further move throttle to 1,200 rpm ahead
Standard	Further move throttle to 1,800 rpm ahead
Full	Further move throttle to 2,100 rpm ahead
Flank	Further move throttle to max. rpm ahead
 Engine(s) back	
Idle	Move throttle to position bucket to reverse
One third	Further move throttle to 900 rpm reverse
Two thirds	Further move throttle to 1,200 rpm reverse
Full	Further move to 1,500 rpm reverse
 Helm right or left	
Degrees 30 ^o , 60 ^o , 90 ^o . etc.	Rotate wheel to move bow right or left
Full	Rotate wheel to protractor degrees
	Rotate hard over helm

2.2 CAUTION AND WARNING SYSTEM

A ready and warning system monitors the status of equipment critical to foilborne operation. The ACS Control Panel Assembly mounted to the left of the helmsman on the main console contains the primary Ready and Warning indications. A READY FOR FLIGHT light indicates that 21 conditions have been met and that the ship's control system and supporting systems are ready for foilborne operation. If a malfunction or anomaly occurs and creates an impending, critically unsafe situation, a LAND warning light and an audible alarm come on. Malfunctions or anomalies of lesser importance but of consequence to the performance of the foilborne control system, such as quality degradation or loss of a backup, cause the CAUTION warning light to come on.

All of the following conditions must exist before the READY FOR FLIGHT light will come on:

- (1) Automatic Control System mode switch in FOILBORNE
- (2) Hullborne steering control in FOILBORNE LOCK
- (3) ACS power normal
- (4) Port ACS gyro normal
- (5) Stbd ACS gyro normal
- (6) Height sensor normal
- (7) Roll circuit normal
- (8) Ship's gyro compass ON
- (9) Pressure on all four hydraulic systems above 12 MN/m²
- (10) All four hydraulic systems normal (not shuttled)
- (11) Aft struts extended and locked
- (12) Fwd strut extended and locked
- (13) Foilborne depth sounder transducer activated
- (14) Foilborne speed transducer activated
- (15) ACS alarm disable switch OFF.

The CAUTION string is not activated until the ACS Mode Switch is placed in the FOILBORNE position. Any of the following will cause the CAUTION Light to come on and the READY FOR FLIGHT Light to extinguish.

- (1) Hullborne steering switch not in FOILBORNE LOCK
- (2) ACS single power failure
- (3) Port ACS gyro failure
- (4) Stbd ACS gyro failure
- (5) Height sensor failure
- (6) Ships gyro compass not operational

- (7) Pressure on any of the four hydraulic systems below 12 MN/m²
- (8) Any of the four hydraulic systems shuttled (not normal)
- (9) Loss of secondary feedback power to the ACS actuators.

The Land string is not activated until the Hullborne Steering Control Switch is placed in the FOILBORNE LOCK position. Any of the following will cause the LAND Light to come on, the alarm to activate, and the READY FOR FLIGHT Light to extinguish.

- (1) ACS mode switch not in FOILBORNE
- (2) Double power failure in the ACS
- (3) Failure of both ACS gyros
- (4) Failure in the ACS roll circuit
- (5) Hydraulic pressure on both aft systems below 12 MN/m²
- (6) Hydraulic pressure on both fwd systems below 12 MN/m².

The System Status Panel and the Strut Control and Status Panel, located in the pilothouse overhead console, display the status of the various equipment critical to foilborne operation. The Strut Control and Status Panel is the primary means of controlling the position and movement of the struts and foils and for selecting the appropriate speed and depth sounder transducers. The status lights on the System Status Panel are coordinated with the READY FOR FLIGHT, CAUTION, and LAND lights on the ACS Control Panel. A yellow warning light on the System Status Panel will cause the CAUTION light to illuminate. Likewise, a red warning light will cause the LAND light to illuminate and the warning horn to sound. The following is a brief explanation of the cause for a warning light to illuminate on the System Status Panel.

Automatic Control

ACS Power

SGL FAILURE. One of several ACS power failures. Could also be due to a power transient when switching the ACS mode switch into FOILBORNE. If this is the case, pushing the POWER RESET button will restore power to normal.

CRIT FAILURE. Critical ACS power failure. Land the ship immediately.

Height Sensor

FAILURE. Have lost return signals on both sonic height sensors. Ship will land unless the Radar Height Sensor is selected.

Port and Starboard Gyro

FAILURE. Failure in port or starboard gyro.

DUAL FAILURE. Failure has occurred in both the port and starboard gyros. Land the ship immediately.

Roll Circuit

FAILURE. Critical failure has occurred in the roll channel. The ship will automatically land in response to the forward flap being driven full up.

Gyro Disconnect Switches

Allow the operator to disconnect either gyro in an event of a failure and continue foilborne operation on one gyro only in emergencies with the following guidelines:

- (A) Operation should normally be limited to helm angles of not more than 20° . Helm angles above 20° but below 30° can be used in calm water for short periods, but must be approached cautiously, constantly monitoring roll angle.
- (B) Minimize turning time. Monitor the roll indicator to be sure that the difference between Roll A and Roll B is always less than 10° . Any failure in a turn is particularly unsafe.
- (C) Limit rough water operation to Sea State 4 and below.
- (D) Use of depth set of approx. 2.2 meters, along with a throttle setting of approx. 3 knots below calm water design speed.

Hydraulic Shuttles

Strut Steering

SHUTTLE. Pressure on hydraulic system No. 2 is below 12 MN/m^2 .

Forward Flap

SHUTTLE. Pressure on hydraulic system No. 1 is below 12 MN/m^2 .

Port Flap

SHUTTLE. Pressure on hydraulic system No. 4 is below 12 MN/m².

Starboard Flap

SHUTTLE. Pressure on hydraulic system No. 3 is below 12 MN/m².

Hydraulic Supply

Forward Hydraulic Supply

SGL FAILURE. Pressure on systems 1 or 2 below 12 MN/m².

DUAL FAILURE. Pressure on systems 1 and 2 below 12 MN/m². Land the ship immediately.

Aft Hydraulic Supply

SGL FAILURE. Pressure on systems 3 or 4 below 12 MN/m².

DUAL FAILURE. Pressure on systems 3 and 4 below 12 MN/m². Land the ship immediately.

Ships Gyro

Gyro Compass

FAILURE. Ship gyro has failed. Heading hold function is no longer available.

ACS Self Test

Self Test

ON. ACS self test panel has been activated. This can occur only if the ACS mode switch is in TEST ENABLE/UNREP.

2.3 DESIGN ENVELOPE AND OPERATING LIMITS

The PHM's were designed to operate within a specific design envelope. As with other ships, operating limits are imposed to provide the means of keeping the ship and its various systems within the desired envelope. These boundaries and limits provide for the safety of the crew and preserve the reliability and life of the machinery. Most of the operating limits for the PHM's are similar to those for other ships; however, there are some that are peculiar to a hydrofoil ship and to waterjet propulsion systems. The design envelope and boundaries relating to ship operation are shown in Table 2-3. Specific machinery operating limits are contained in the Operating Limits Chart, Table 2-5, Code OMC/001/0581 of the EOSS. An example of this Chart is presented as Table 2-4.

1. WEIGHT AND CENTER OF GRAVITY

Foilborne operation has many of the same characteristics as an aircraft in flight. These characteristics enable the ship to maneuver with ease and provide a smooth ride in rough seas. However, along with the advantages of the aircraft type of operation, come some constraints. As an aircraft has a maximum weight at which it can operate safely, a hydrofoil has a maximum weight (or foil loading) at which it can be operated. Operation above this value could result in structural damage to some components in the foil system. The draft boundary shown below represents the maximum weight (or foil loading) that should be considered for foilborne operation.

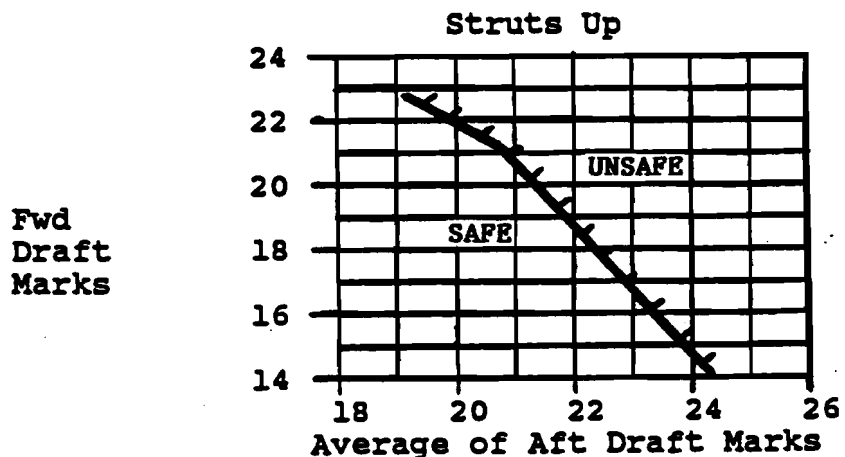


Table 2-3. Operational Design Envelope

Table 2-3. Operational Design Envelope (Continued)

2. SHALLOW WATER OPERATION

In addition to the normal hazards associated with shallow water operation, such as sea chest and heat exchanger contamination, there is an additional item to be considered with water jet propulsion. That is the ingestion of debris into the propulsor. Operation in shallow depths can result in the ingestion of abrasive material such as loose coral, gravel, coarse sand or other loose debris from the bottom. This type of material causes increased wear of the pump impeller and lining. Also, larger objects, such as cans and water-logged wood, could be ingested that would block the inlet or pump impeller. The ingestion of material is greatly aggravated by the use of high power in reverse because of the waterjet being vectored under the ship and stirring up any debris or loose material on the bottom. Thus, when docking or undocking in shall water, the use of high power in reverse should be minimized.

3. HULLBORNE DIESEL OPERATION

	PHM-3	PHM-1
Maximum Continuous RPM	2250	2200
Maximum Intermittent RPM	2330	2340
<p>MTU specifics that this power setting is to be used no more than 2 hours in every 12 hours of operation.</p>		
Maximum Reverse RPM	1850	1850
<p>There is a stop in the throttle quadrant that mechanically limits the reverse RPM to approximately 1850. However, power settings over 1600 RPM may not be effective because the propulsor tends to recycle aerated water due to the waterjet being deflected under the ship in the vicinity of the propulsor inlet. The RPM and amount of degradation experienced will be dependent upon sea conditions and ship trim.</p>		

Table 2-3. Operational Design Envelope (Continued)

4. POWER TURBINE OPERATION

The foilborne power train design is based on assumed operation of 20,730 hours during the design life of the ship. The assumed distribution of hours at various turbine power ratings are displayed in the following table:

PROPULSION SYSTEM OPERATING CONDITIONS	TURBINE RPM (PERCENT)	TOTAL HOURS DURING SHIP LIFE
Battle Override (Max. Intermitent)	105	150
Rated Power (Continuous)	100	5880
Cruise Condition (Best fuel rate)	97	6100
Underway Replenishment (Turbine Taxi)	70	600
Idle	25	<u>8000</u>
TOTAL		<u>20730</u>

Of particular significance is the limited time assumed at power turbine RPM's above 100 percent. Of the total foilborne hours of 12130, approximately half are assumed to be at 97 percent or less and only a very limited time is above 100 percent. Assuming an average year of 360 hours foilborne would allow only 4.5 hours at 105 percent. While the LM 2500 is operating at less than its full power capabilities even at 100 percent, the remaining components of the power train do not have that reserve capacity. Excessive time at higher power turbine settings will reduce the life expectancy of the gearbox and pump.

Take off should be achieved in less than one minute in calm water and in less than three minutes in the design sea state (sea state 5). Additional power does not significantly reduce take off time and will result in increased maintenance on the gearbox and pump.

Table 2-3. Operational Design Envelope (Continued)

5. FOILBORNE SPEED

The best fuel economy and maximum range can be achieved at approximately 97 percent power turbine RPM. This setting will vary from ship to ship and will also be effected by ship weight and center of gravity location. Boeing Document D312-80248-7, PHM3-SERIES AVERAGE SHIP PERFORMANCE, shows the speed for the best range for the average of the ships as determined during the initial sea trials prior to delivery.

In addition to the speed limit imposed by the maximum power, there is another very important limit in hydrofoil operation. This involves cavitation and ventilation of the strut and foil system. These phenomena are discussed in Section 3.2. Cavitation is a function of ship speed. Ventilation becomes more likely at high speeds. Either can cause a loss of lift or a loss of control. The foil section chosen for the PHM's should be relatively cavitation free for speeds as high as 8 knots above the calm water design speed. However, this is a theoretical number and operation at speeds above design speed (DS) plus 2 knots should be approached cautiously. Operation above plus 8 knots is in an area of hydrodynamic uncertainty, and abrupt and uncontrolled ship behavior could be experienced.

6. FOILBORNE TURN RATE

The calm water design turn rate can be achieved at approximately 145 degrees of helm input. Larger helm angles do not have as smooth and steady response, especially at shallow depth command. Also, at 145 degrees of helm there is a margin available for additional course corrections should they become necessary.

A 180 degree heading change can be accomplished at maximum helm. However if the ship is heavily loaded it will probably land prior to completing a 360 degree turn because of forward foil lift limitations.

Table 2-3. Operational Design Envelope (Continued)

7. FOIL DEPTH SETTINGS

The foil depth can be set as low as 1.0 meter. A shallow depth settings reduces the amount of strut that is in the water. This reduces strut drag and thus increase ship speed for a given power setting in calm water. However, if the water is choppy, the ride will deteriorate as depth is decreased. In rough water a deeper setting is required to keep the foils and water inlets in the water as the ship goes through waves. A nominal setting for rough water operation is 2.2 meters. This setting is recommended for operation in seas up to and including Sea State 5, which was the design sea condition for the ship. In seas greater than Sea State 5, increasing the depth setting will generally improve the ride quality up to a setting of approximately 2.7 meters. A deeper setting can cause excessive cresting of the waves.

Table 2-4. Operating Limits

OPERATING LIMITS CHART							OC NO. OMC
PARAMETER	NORMAL OPERATING RANGE	OPERATING LIMIT		OPERATING LIMIT EXCEEDED			
		OPERATING LIMIT	AMBER WARNING LIGHT ILLUMINATES	RED WARNING LIGHT ILLUMINATES	WARNING HORN SOUNDS	AUTOMATIC SHUTDOWN	BATTLE OVERRIDE CAPABILITY
GAS GENERATOR SPEED (G. G. SPEED)	56 to 100% (100%-8800 RPM)	104% MAXIMUM	NO	NO	NO	NO	N/A
POWER TURBINE SPEED (P. T. SPEED)	20 to 100% (100%-3000 RPM)	110% MAXIMUM	NO	YES 110%	YES	YES	NO
GAS GENERATOR EXHAUST GAS TEMPERATURE (EGT)	370° to 727°C	738°C MAXIMUM	YES	YES 760°C	YES	YES	YES
GAS TURBINE OUTPUT POWER (POWER)	2 to 100% (100%-16,220 metric horsepower)	110% MAXIMUM	OVER TORQUE INDICATION	NO	NO	NO	N/A
GAS GENERATOR VIBRATION (VIBRATION CHANNEL 1)	0 to 0.08mm	0.10mm MAXIMUM	YES	YES 0.18mm	YES	YES	YES
GAS GENERATOR VIBRATION (VIBRATION CHANNEL 2)	0 to 0.15mm	0.18mm MAXIMUM	YES	YES 0.25mm	YES	YES	YES
POWER TURBINE VIBRATION (VIBRATION CHANNEL 1)	0 to 0.08mm	0.10mm MAXIMUM	YES	YES 0.18mm	YES	YES	YES

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Table 2-4. Operating Limits (Continued)

OPERATING LIMITS CHART				OC NO. OMC			
PARAMETER	NORMAL OPERATING RANGE	OPERATING LIMIT		OPERATING LIMIT EXCEEDED			
		OPERATING LIMIT	AMBER WARNING LIGHT ILLUMINATES	RED WARNING LIGHT ILLUMINATES	WARNING HORN SOUNDS	AUTOMATIC SHUTDOWN	BATTLE OVERRIDE CAPABILITY
POWER TURBINE VIBRATION (VIBRATION CHANNEL 2)	0 to 0.15mm	0.18mm MAXIMUM	YES	YES 0.25mm	YES	YES	YES
FUEL TEMPERATURE INTO GAS TURBINE (FUEL IN)	38° to 57°C	60°C MAXIMUM	YES * *	NO	NO	NO	N/A
ACCESSORY GEARBOX SCAVENGE OIL TEMPERATURE (ACCESS C. D.)	82° to 127°C	132°C MAXIMUM	YES	YES 171°C	YES	YES	YES
SUMP A SCAVENGE OIL TEMPERATURE (SUMP A)	82° to 127°C	132°C MAXIMUM	YES	YES 171°C	YES	YES	YES
SUMP B SCAVENGE OIL TEMPERATURE (SUMP B)	82° to 127°C	132°C MAXIMUM	YES	YES 171°C	YES	YES	YES
SUMP C SCAVENGE OIL TEMPERATURE (SUMP C)	82 to 127°C	132°C MAXIMUM	YES	YES 171°C	YES	YES	YES
SUMP D SCAVENGE OIL TEMPERATURE (SUMP D)	82° to 127°C	132°C MAXIMUM	YES	YES 171°C	YES	YES	YES

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Table 2-4. Operating Limits (Continued)

OPERATING LIMITS CHART							OC NO. OMC
PARAMETER	NORMAL OPERATING RANGE	OPERATING LIMIT		OPERATING LIMIT EXCEEDED			
		OPERATING LIMIT	AMBER WARNING LIGHT ILLUMINATES	RED WARNING LIGHT ILLUMINATES	WARNING HORN SOUNDS	AUTOMATIC SHUTDOWN	BATTLE OVERRIDE CAPABILITY
LUBE OIL TEMPERATURE INTO GAS TURBINE (OIL IN)	57° to 100°C	104°C MAXIMUM	YES	NO	NO	NO	N/A
FUEL SUPPLY PRESSURE INTO GAS TURBINE (FUEL SUPPLY)	18 to 340 KN/m ²	34 KN/m ² MINIMUM	YES	NO	NO	NO	N/A
FUEL FILTER DIFFERENTIAL PRESSURE (FUEL FILTER ΔP)	0 to 48 KN/m ²	190 KN/m ² MAXIMUM	YES	NO	NO	NO	N/A
LUBE OIL SUPPLY PRESSURE INTO GAS TURBINE (LO SUPPLY)	140 to 350 KN/m ²	41 KN/m ² MINIMUM BELOW 91% G.G. SPEED 138 KN/m ² MINIMUM ABOVE 91% G.G. SPEED	NO	YES	YES	YES	YES
LUBE OIL SUPPLY FILTER DIFFERENTIAL PRESSURE (LO SUPPLY FILTER ΔP)	0 to 138 KN/m ²	138 KN/m ² MAXIMUM	YES	NO	NO	NO	N/A
LUBE OIL SCAVENGE FILTER DIFFERENTIAL PRESSURE (LO SCAV FILTER ΔP)	0 to 138 KN/m ²	138 KN/m ² MAXIMUM	YES	NO	NO	NO	N/A

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Table 2-4. Operating Limits (Continued)

OPERATING LIMITS CHART							OC NO.	OMC
PARAMETER	NORMAL OPERATING RANGE	OPERATING LIMIT		OPERATING LIMIT EXCEEDED				
		OPERATING LIMIT	AMBER WARNING LIGHT ILLUMINATES	RED WARNING LIGHT ILLUMINATES	WARNING HORN SOUNDS	AUTOMATIC SHUTDOWN	BATTLE OVERRIDE CAPABILITY	
LUBE OIL SUPPLY LEVEL	4 to 27.3 liters	27.3 liters MAXIMUM 4 liters MINIMUM	YES	NO	NO	NO	N/A	
COMPRESSOR INLET AIR TEMPERATURE - Tt2 (INLET TEMP)	-29° to 38°C	N/A	N/A	N/A	N/A	N/A	N/A	
COMPRESSOR INLET AIR PRESSURE (INLET PRESS)	0 to 1 KN/m ² lower than atmospheric pressure (STD PIN=101.3 KN/m ²)	N/A	N/A	N/A	N/A	N/A	N/A	
PROPULSOR GEARBOX LUBE OIL SUPPLY PRESSURE	276 to 414 KN/m ²	190 KN/m ² MINIMUM	NO	YES	YES	NO	N/A	
PROPULSOR THRUST BEARING TEMPERATURE (THRUST BRG TEMP)	60° to 75°C	94°C	NO	YES	YES	NO	N/A	
PROPULSOR INLET PRESSURE PORT SIDE INLET (PORT INLET)	-30 to 250 KN/m ² ***	*	NO	NO	NO	NO	N/A	
PROPULSOR INLET PRESSURE STARBOARD SIDE INLET (STBD INLET)	-30 to 250 KN/m ² ***	*	NO	NO	NO	NO	N/A	

22-24

Table 2-4. Operating Limits (Continued)

OPERATING LIMITS CHART				OC NO. OMC			
PARAMETER	NORMAL OPERATING RANGE	OPERATING LIMIT		OPERATING LIMIT EXCEEDED			
		OPERATING LIMIT	AMBER WARNING LIGHT ILLUMINATES	RED WARNING LIGHT ILLUMINATES	WARNING HORN SOUNDS	AUTOMATIC SHUTDOWN	BATTLE OVERRIDE CAPABILITY
PROPULSOR DISCHARGE NOZZLE PRESSURE (NOZZLE)	1700 KN/m ² MAXIMUM (AT 250 KN/m ² INLET PRESSURE)	NO	NO	NO	NO	NO	N/A
PROPULSOR GEARBOX LUBE OIL INLET TEMPERATURE (OIL IN)	33° to 49°C	63°C	NO	YES 63°C	YES	NO	N/A
PROPULSOR GEARBOX BEARING TEMPERATURES (1 THROUGH 8)	60° to 75°C	93°C	YES	NO	YES	NO	N/A
PROPULSOR GEARBOX LUBE OIL OUTLET TEMPERATURE (OIL OUT)	55° to 71°C	93°C	YES	NO	NO	NO	N/A
PROPULSOR GEARBOX LUBE OIL SUPPLY LEVEL	88 to 120 liters	88 liters MINIMUM	YES	NO	NO	NO	N/A
<p>* -45 KN/M² with foils extended or retracted at constant power (steady state operation). -50 KN/M² during takeoff and ship operating modes where power and ship speed are changing (transient operation). NOTE: OPERATING PROPULSOR WITH INLET PRESSURE BELOW THE OPERATING LIMIT CAUSES SEVERE CAVITATION, WHICH WILL DAMAGE PUMP INTERIOR AND REDUCE OPERATING LIFE. ** The fuel high temperature light on the FECS may illuminate when the throttle is reduced from a high power setting to the idle position. The light may remain on for about two minutes. *** Inlet pressure to 340 KN/M² can occur for short duration when foilborne propulsion power is rapidly reduced while operating at maximum ship speed.</p>							
CODE OMC/001/0581				PAGE 5 OF 5			

2-25

2.4 OPERATIONAL EXPERIENCE

This section represents the experience of the men of PHMRON-TWO. It is presented with the goal of passing on lessons and information learned, so each crew member can grow through the knowledge of its predecessors rather than repeat unnecessary lessons or continually "reinventing the wheel."

Docking and Undocking

Hullborne

Foilborne

2.5 CARIBBEAN WEATHER

2.5.1 HURRICANES IN THE CARIBBEAN. Tropical cyclones are called hurricanes in the Caribbean. They are called typhoons in the western Pacific Ocean and by many names in other parts of the world. In the Caribbean, they are detected early in development and are closely tracked. The slower their movement, the more they tend to swing west and remain in warmer water. As they build up speed the warm water has less influence over their path and they curve northward at a faster rate. The following information pertains to Caribbean hurricanes in the northern hemisphere, directions are reversed if applied to hurricanes south of the equator.

The hurricane and storm warning service was established primarily to aid marine interests. Warnings are issued whenever winds, weather, sea conditions, storm surge, or other conditions that will be hazardous to marine operations are expected. These warnings are given wide distribution by commercial radio and television, Coast Guard radio, daily newspapers, and by visual warning displays. Storm information is also broadcast over National Bureau of Standards Time and Frequency Radio Stations WWV, Ft. Collins, Colorado, and WWVH, Kauai, Hawaii. During the hurricane season (June through November), ships are asked to be especially watchful for signs of hurricanes and report them by radio immediately. Satellite weather pictures are also used to locate hurricanes. These pictures are especially useful in areas of the ocean infrequently crossed by routine shipping. Special reports are obtained from weather reconnaissance planes dispatched to keep track of hurricanes. Coastal radar reports are extremely valuable in defining the size and intensity of hurricanes when they are within about 200 miles of the station.

A "hurricane watch" is an announcement to the public by the press, radio, and television whenever a tropical storm or hurricane becomes a threat to a coastal area. Naval warnings are issued by message and give latitude and longitude of the center, course and speed of the central eye, and the average wind velocity. It is customary to keep a plot of these positions and times and a projection of the storm path.

2.5.1.1 Visual Signs of a Hurricane. The first sign of a distant hurricane is a long, heavy swell, within a characteristic, slow 15- to 30-second period. This swell, generated from wind waves near the hurricane center, travels 30 to 40 knots faster than the storm center. The next sign is the presence of numerous cumulonimbus (thunderstorm) clouds in active bands. These clouds are several hundred miles ahead of the storm. The day

after these clouds have passed there are bright skies and above-normal temperatures. Then the barometer starts to drop, and the wind may come from an unusual direction. The next day, very high cirrus clouds arrive, seeming to converge in the direction of the storm center. These are followed by filmy cirrostratus clouds which often produce halos around the Sun and Moon and brilliant ruby and crimson sunrises and sunsets. Middle-level altostratus clouds, usually mixed with altocumulus, arrive next, followed by cumulus congestus and heavy rain showers. The barometer falls rapidly; the wind increases; and finally, as the center of the storm approaches, a heavy black wall of cloud appears.

If you are dead ahead of the center, bring the wind on the starboard quarter (160 deg relative) and make best speed on this course. This will get you away from the center most quickly and put the ship in the safe semicircle of the storm.

If in the safe or navigable semicircle, bring the wind on the starboard quarter (130 deg relative) and make best speed.

If in the dangerous semicircle, bring the wind on the starboard bow (45 degrees relative) and make as much headway as possible.

If necessary to heave to, do so and head to sea. There is a theory that ships caught in a tropical cyclone should shut down engines completely and drift with the storm. This seems to work well for some types of ships, but top-heavy men-of-war, as well as other ships fully loaded and of deep draft, might be in danger if this dead-in-the-water procedure were to be followed, except near the eye, where seas come from all directions.

Proximity to land areas, coastlines, or islands must be taken into account in maneuvering. An evasive course that brings you close to shore is dangerous, particularly if you are in the sector of the storm with onshore winds.

2.5.2 CARIBBEAN HURRICANE CHARACTERISTICS. A typical 100 knot West Indian hurricane usually has these characteristics:

CAUTION: The average speed and direction given cannot be relied on for any particular hurricane. A storm may stop, speed up, slow down, or change direction at any time. Use all sources to keep continuously informed of the activity of any storm.

Typical Winds

50 to 100 miles from eye	64 kn or more
200 to 300 miles from eye	24 kn or more
Inside the eye (10 to 35 miles in diameter)	12 kn or less, confused area

Winds generally incline toward the eye at 20 to 30 deg from the isobars but tend to flow parallel to isobars at the eye wall. Gusts of 30 per cent to 50 per cent above steady velocity may be expected.

2.5.3 SPEED OF STORM'S ADVANCE. South of 30°N, the speed of advance of a tropical cyclone is usually between 12 and 16 Knots.

North of 30°N, the speed of advance of a tropical cyclone is usually between 17 and 30 Knots.

In conjunction with any of the above signs, a falling barometer, which exceeds 0.1" (3.4 mbs) in 24 hours, exclusive of normal diurnal fluctuation, is an indicator of tropical storm development in the area. Pressure value of 5 mbs or more below normal, to 1008 mbs or lower, also indicates the development of a storm.

2.5.4 EVADING HURRICANE DAMAGE. PHM's go to sea or another port prior to hurricane arrival. The danger of high wind velocities and water surges from all directions requires precaution to avert damage from other boats and debris being carried toward the PHM at the mooring. When the wind peaks, it may be necessary to operate diesels to relieve the strain on the moorings.

When at sea, vessels in the Straits of Florida may not have sea room to maneuver to avoid a storm track and should try to make the harbor. Vessels unable to reach a port and having sea room to maneuver usually follow these rules:

Determine bearing, distance, and track of storm from official warnings, or from your own calculations if there are no warnings. Planning should be directed primarily to avoiding the dangerous semicircle, which is the right half of the storm along the direction of motion. Here, the speed of storm movement is added to the existing winds; on the other side of the storm, the storm speed is subtracted.

Determine bearing of the storm by the direction from which swells are arriving and by adding 115 deg to the direction from which your observed true wind is blowing.

To determine your semicircles:

1. If the wind gradually veers (shifts clockwise), you are in the dangerous semicircle.
2. If the wind gradually backs (shifts counterclockwise), you are in the navigable semicircle.
3. If the wind is steady in direction and increases in strength as the glass falls, you are on or near the storm track, ahead of it.

Use radar to keep track of the storm; the eye of the storm is a very good radar target.

Do not try to outrun or cross the T of a hurricane; it usually means trouble. The main difficulty arises from the front-running swells of a hurricane, which build rapidly in size with the approach of the center. These swells can cut down your speed by several knots, while the hurricane keeps on its own appointed pace or speeds up.

If sea surface temperature charts are available and your maneuvering plans permit, avoid areas of warm waters. Hurricanes move along these areas if their speed is slow; say 10 knots or less. If the storms are moving fast (16 knots or more), warm water has little influence.

3.0 CHARACTERISTICS

PHM differs from conventional ships in its design, materials, construction, systems, equipment, and control.

The design is based on use of lightweight materials, aluminum construction, aircraft systems and equipment, and the need for a foilborne Automatic Control System (ACS) to provide continuous control of foilborne ship motions. The weight of each part of the design has been carefully allocated and controlled.

Selection of materials follows the aeronautical practice of providing required strength with the minimum of weight. Aluminum, titanium, stainless steel, and plastic are used to build PHMs. These materials have characteristics which require construction methods and repair procedures different from those of conventional steel ships.

Shipboard Systems have been selected to respond to the requirements for light weight and a small crew. Equipment incorporated in these systems had to fit into the size, weight, and power constraints of a small ship and they are as automatic as practical to reduce crew demands.

A fully submerged foil system lifts the hull above the water, and develops the forces needed for stability and control. Computer-controlled, hydraulically actuated control surfaces on the foils and struts develop forces that are powerful enough to control the ship in heavy sea conditions as well as during naval operations such as UNREP, gun firing and missile launches.

3.1 HYDROFOILS

The ship's foilborne lift is provided by a fully submerged hydrofoil system as shown in Figure 3-1. The hydrofoils are arranged in a configuration with 32 per cent of the total area forward and 68 per cent aft. Flaps on the trailing edges of the foils provide lift control. Hydraulic actuators provide power to raise and lower the struts, to operate the flaps, to operate the uplock and downlock pins, to steer the forward strut, and to open and close the bow doors. Local control panels are provided for emergency operation of the forward and aft struts, by manually activating switches in a step-by-step sequence.

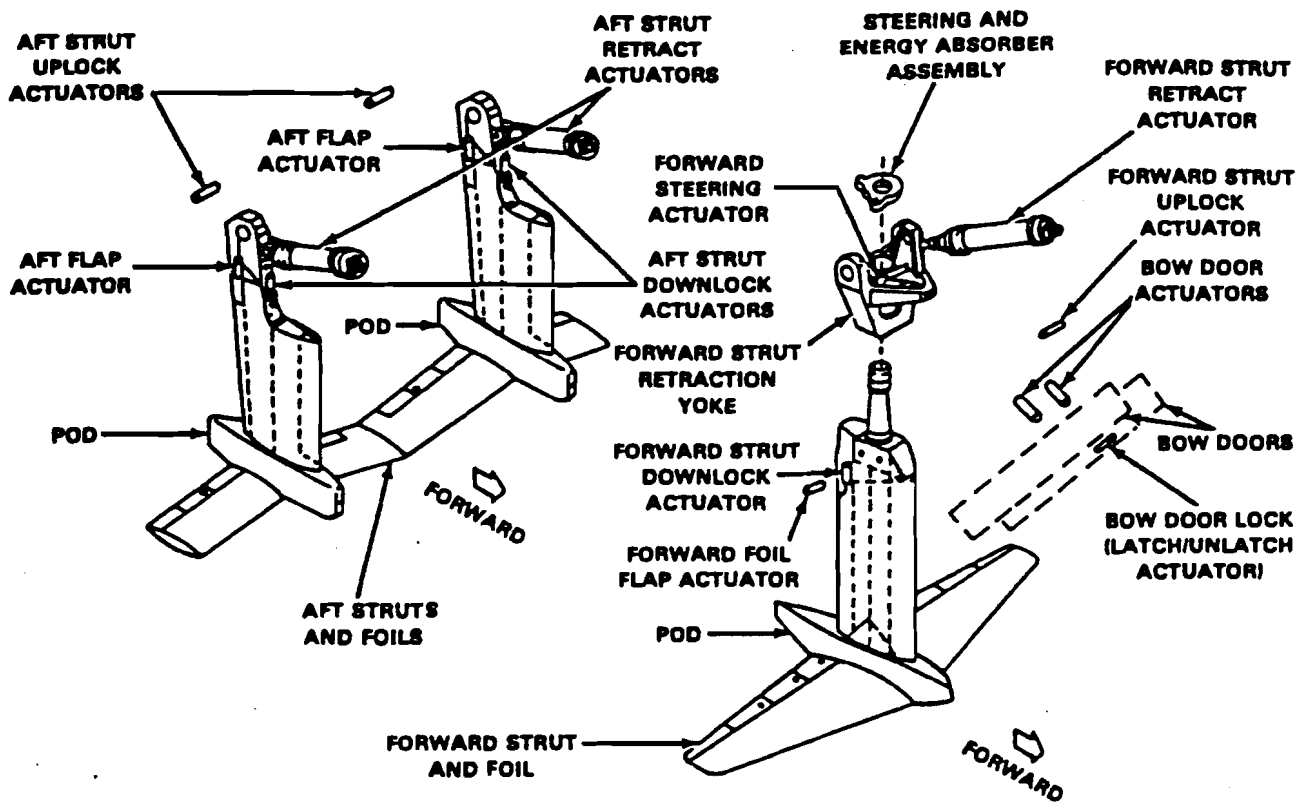


Figure 3-1. Struts, Foils, and Actuators

The characteristics of the lift system are presented in Table 3-1. The forward foil is tapered with an aft sweep to the leading edge. A rectangular plan form is used for the aft foil with 12 degree negative dihedral both inboard and outboard of each of two struts. The foils are attached to the struts using multiple bolts in single shear through dual, machined mating lugs.

The forward strut is a combination welded and machined assembly consisting of spars, ribs, and skins of 17-4PH corrosion-resistant steel. The forward strut is steerable and swivels 12 degrees either side of center to provide directional control during hullborne or foilborne operation. A king post mounted on top of the strut provides the steering pivot element and rotates within two spherical bearings mounted in a retraction yoke. The forward foil system can be retracted forward 105 degrees.

Table 3-1. Lift System Characteristics

FORWARD STRUT

Aerodynamic Section	Modified NACA 16 Series Section
Thickness Ratio	16% at Baseline (WL 0) 12% at Nominal Flying Waterline (WL-2440)
Chord	1.7m
Length (Pivot to Foil Chord Plane)	7.0m

FORWARD FOIL

Aerodynamic Section	NACA 16 - 306.5, $\alpha = 0.8$
Area	13.09m ²
Aspect Ratio	5.5
Span	8.5m
Taper Ratio	0.3
Root Chord	2.37m
Tip Chord	0.71m
Flaps	25% Chord
Foil Loading	67,700 N/m ²

AFT STRUTS

Aerodynamic Section	Modified NACA 16 Series Section
Chord	3.15m at WL 1110 2.63m at WL-3105
Thickness Ratio	15.7% at WL 1110 11.2% at WL-3105
Length (Pivot to Foil Chord Plane)	7.897m

AFT FOILS

Aerodynamic Section	NACA 16 - 306.5, $\alpha = 0.8$
Area	28.1m ²
Aspect Ratio	7.5
Span	14.51m
Taper Ratio	1.0
Chord	1.937m
Dihedral	-12 deg.
Flaps	25% Chord
Foil Loading	55,813 N/m ²

Note: WL (Waterline) is the vertical distance in millimeters from the keel (baseline), with + being up.

The aft struts are a welded and machined assembly including the propulsion water duct and consist of spars, ribs, and skins of 17-4PH corrosion-resistant steel designed as a beam column. The aft system is normally retracted aft 104 degrees. With the addition of another link, the aft foil system can be rotated aft 150 degrees for maintenance.

Movable surfaces (flaps) on the trailing edges of the foils (25 per cent of the foil chord) provide control and lift at takeoff and control during flight. Flaps are segmented with each segment mechanically attached to the foils by self-aligning hinges. Hinge moments are transferred between segments by means of shear keys. This arrangement prevents binding of flap hinges when the foil is deflected under load during foilborne operations. The control surfaces are powered by hydraulic actuators connected with push rods and linkages to the flap segments nearest the pods.

Pod fairings, installed at the intersections of the foils and struts enclose the foil/strut structural connections and flap control linkages. They provide for smooth flow and reduce the likelihood of cavitation and/or ventilation. The forward section of each aft pod serves as the waterjet propulsion inlet. The forward pod houses the foilborne speed and fathometer transducers.

3.2 HYDRODYNAMICS

The principals of hydrodynamics are very similar to those of aerodynamics. The same basic fundamentals of aerodynamics apply, with the main difference being that water is approximately 840 times more dense than air. Because of this difference in density, a much smaller lifting surface (wing), is required to support a hydrofoil ship than an aircraft of the same weight.

An aircraft wing and a hydrofoil generate lift by using a shape that develops a lower pressure on the top surface than on the bottom surface. Thus, there is an upward lifting force. The lower pressure on the top surface is primarily due to the fluid particles on the top having to travel further than those on the bottom. These particles that have farther to go must travel at a higher speed than those on the bottom surface so that both the upper and lower surface flows can meet at the foil trailing edge at the same time. If they did not meet at the same time, a void would develop that would be in violation of physical flow laws. The variation of speed in a flow results in

pressure variations as determined by Bernoulli's theorem. This theorem is one of the most important relations in elementary fluid dynamics. (A simple and well known application of this theorem is the venturi tube.) Since the upper surface flow is at a higher speed than the lower surface flow, its pressure must then be lower. Figure 3-2 shows typical pressures developed on a foil moving through the water at greater than 40 knots. The ram pressure noted is that which is developed on an object when the relative fluid velocity is brought to zero. The flow characteristics around the foil on a hydrofoil are determined using many of the same techniques used in aircraft wing design. However, two phenomenon that are unique to hydrofoil operation are cavitation and ventilation.

Cavitation is a phenomenon that occurs on submerged surfaces foils and struts when the absolute pressure of the water flowing by the foil or strut is reduced to near the vapor pressure. (about 100 to 250 lb/ft²). When this happens, vapor pockets or cavities are formed in the water on the surface of the foil or strut. Cavitation reduces the foils ability to develop lift because the water becomes a vapor and the pressure can not get any lower. This transition is not necessarily smooth, as the forming and collapsing of the vapor pockets (cavities) can result in buffeting and vibration. Cavitation not only disrupts the normal flow characteristics but also can cause surface erosion. Figure 3-3 shows typical foil lift characteristics as a function of angle of attack for normal and cavitated flow.

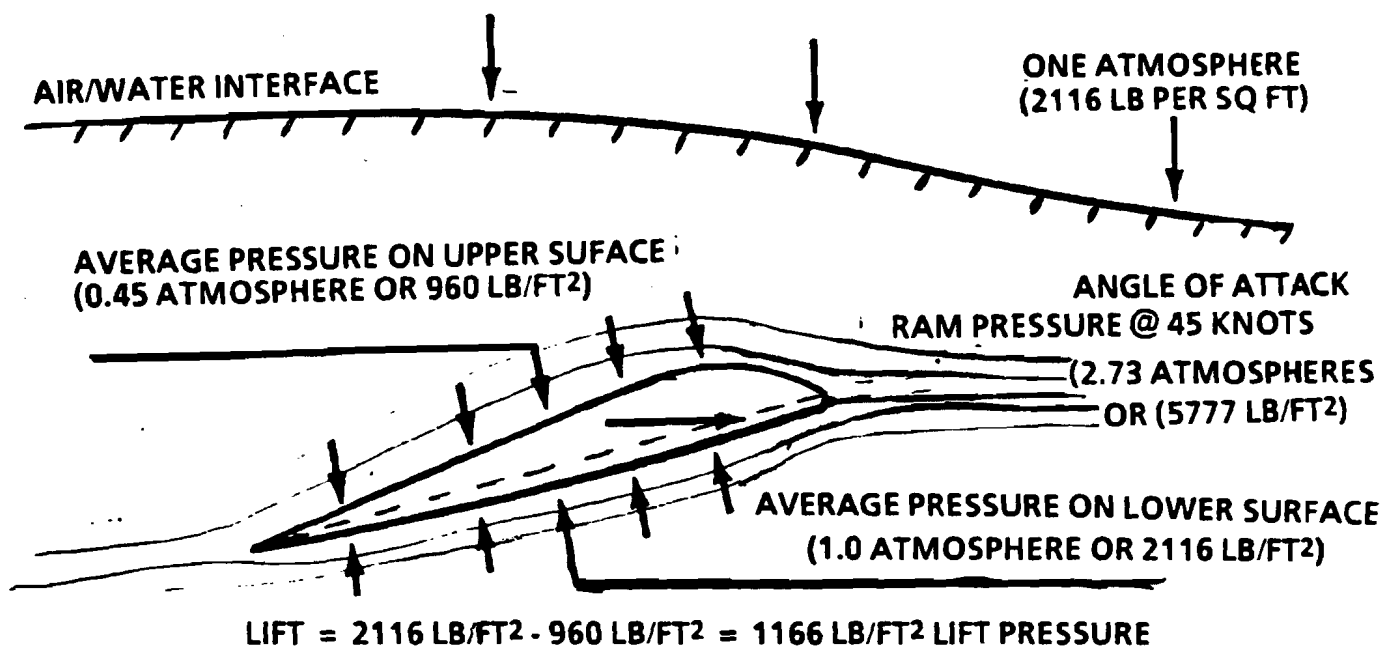


Figure 3-2. Typical Foil Pressures

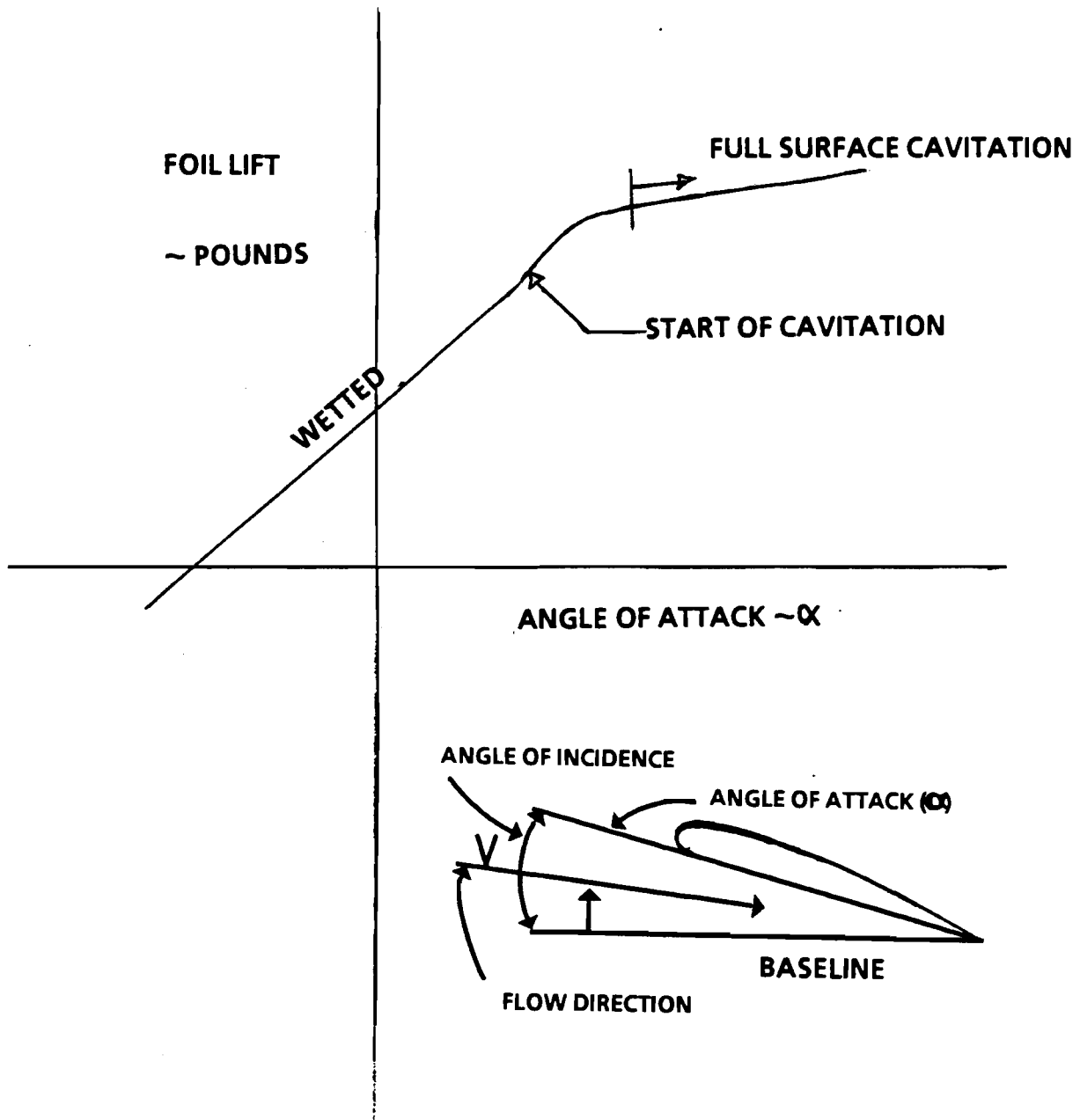


Figure 3-3. Typical Foil Lift Characteristics

Ventilation is a condition whereby a submerged area on the strut or foil becomes exposed to atmospheric pressure (unwetted). Normally, when the foil system is moved through the water at a high speed, the pressure is much lower than the atmospheric pressure; however, as long as there is no path for air to reach the low pressure areas, they remain wetted. The struts usually have low pressure along their surfaces, but there is near zero net side force because of their symmetrical shape. However, when the strut ventilates on one side, the pressure on that side is much higher than on the wetted side.

This differential pressure causes a force to be exerted sideways on the strut. The force is proportional to the ventilated area (if the ventilated area is large, a side force of many tons can result). The force due to ventilation will push the strut sideways causing the ship to veer off course. The veering reaches a limit when (1) the ventilation force is balanced by the increase in dynamic pressure on the wetted side of the strut due to the sideways motion or (2) the cause of the ventilation is cleared allowing the strut to rewet.

Strut ventilation may be caused by irregularities on the strut surface, by undesired air leakage paths in the strut, and/or by flow angle changes over the strut. For example, the basic cause of the ventilation could be an irregularity on the surface near the leading edge whose effect is dormant until it is triggered by a change in the flow angle over the strut. Surface irregularities can be dents, projections, marine growth, or foreign objects caught on a strut such as pieces of plastic or kelp.

The unbalanced forces resulting from strut ventilation may cause the ship to conduct an unscheduled turn. If the ventilation is on the forward strut, improper action by the helmsman to stop the turn could increase the flow angle over the strut, which will (1) enlarge the ventilated area, (2) increase the side force, and (3) inhibit rewetting. However, if the helmsman recognizes the abnormal motion is due to strut ventilation and turns in the direction of the skid, the strut should immediately rewet. Figure 3-4 shows how the correct helm action will clear the ventilation while the opposite action will aggravate the situation.

Frequent and significant skidding due to strut ventilation are generally attributable to correctable faults. Relatively small defects on the strut leading edge or seemingly insignificant air paths can cause large areas of ventilation to be triggered by an abrupt change in flow angle. Such changes can be caused by a wave crossing at an angle with respect to the

strut or by a steering movement of the strut. Frequent strut ventilation should be reported so that struts can be surveyed for irregularities.

Ventilation can also occur on the foils. This would generally be preceded by foil cavitation followed by air finding a path to fill the cavity. Foil ventilation also occurs when a foil broaches the surface. In this case, air is brought down with the foil as it reenters the water. This type of ventilation is generally wiped away and lift restored to normal before the ship has settled enough for the hull to contact the water. Figure 3-5 shows typical pressures on a foil when ventilation occurs. As the foil sinks due to

TOP VIEW OF FORWARD STRUT AND WATER FLOW

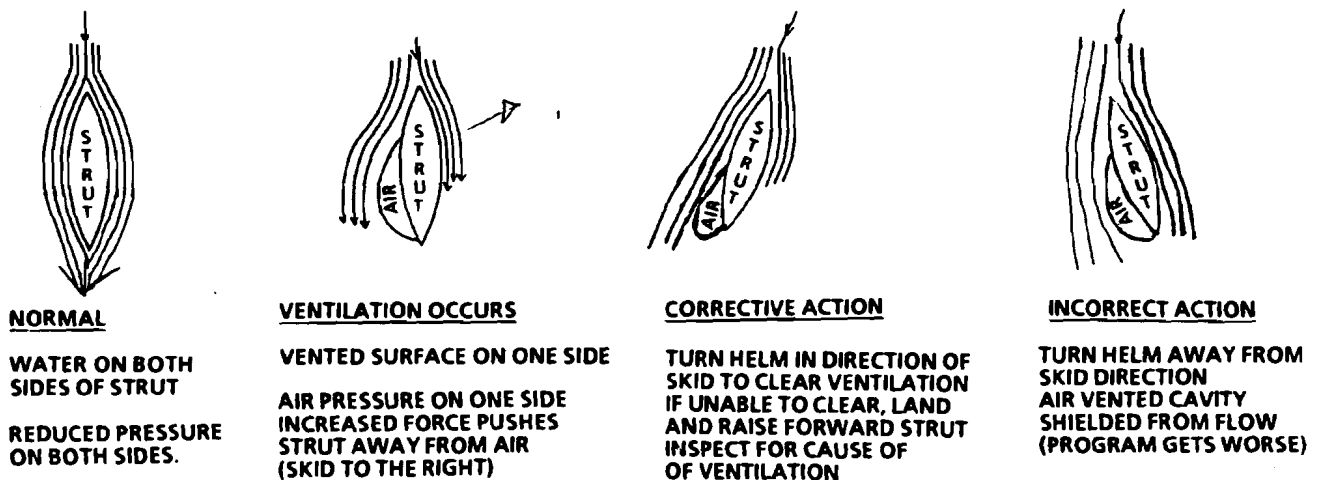
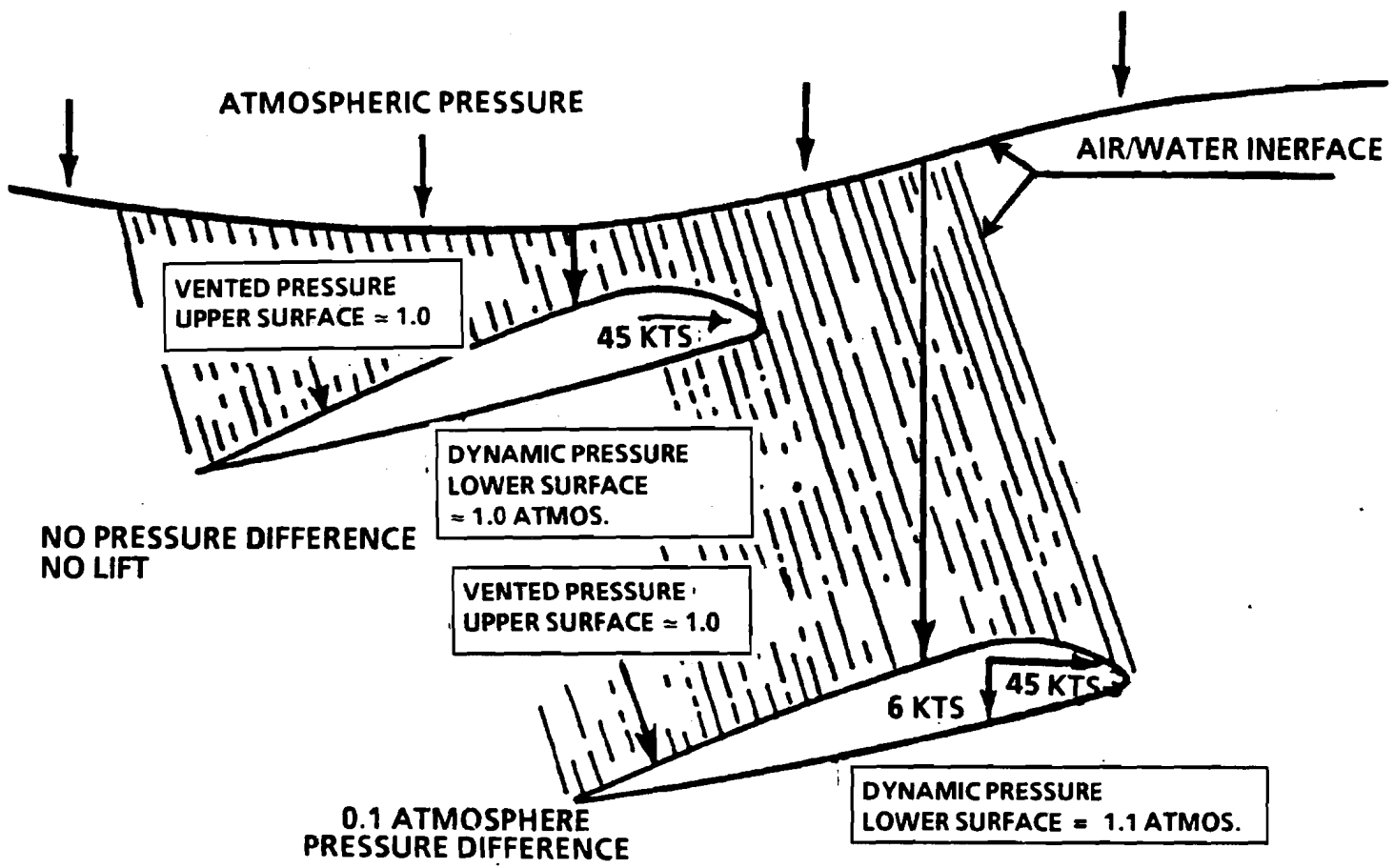


Figure 3-4. Forward Strut Ventilation and Corrective Action

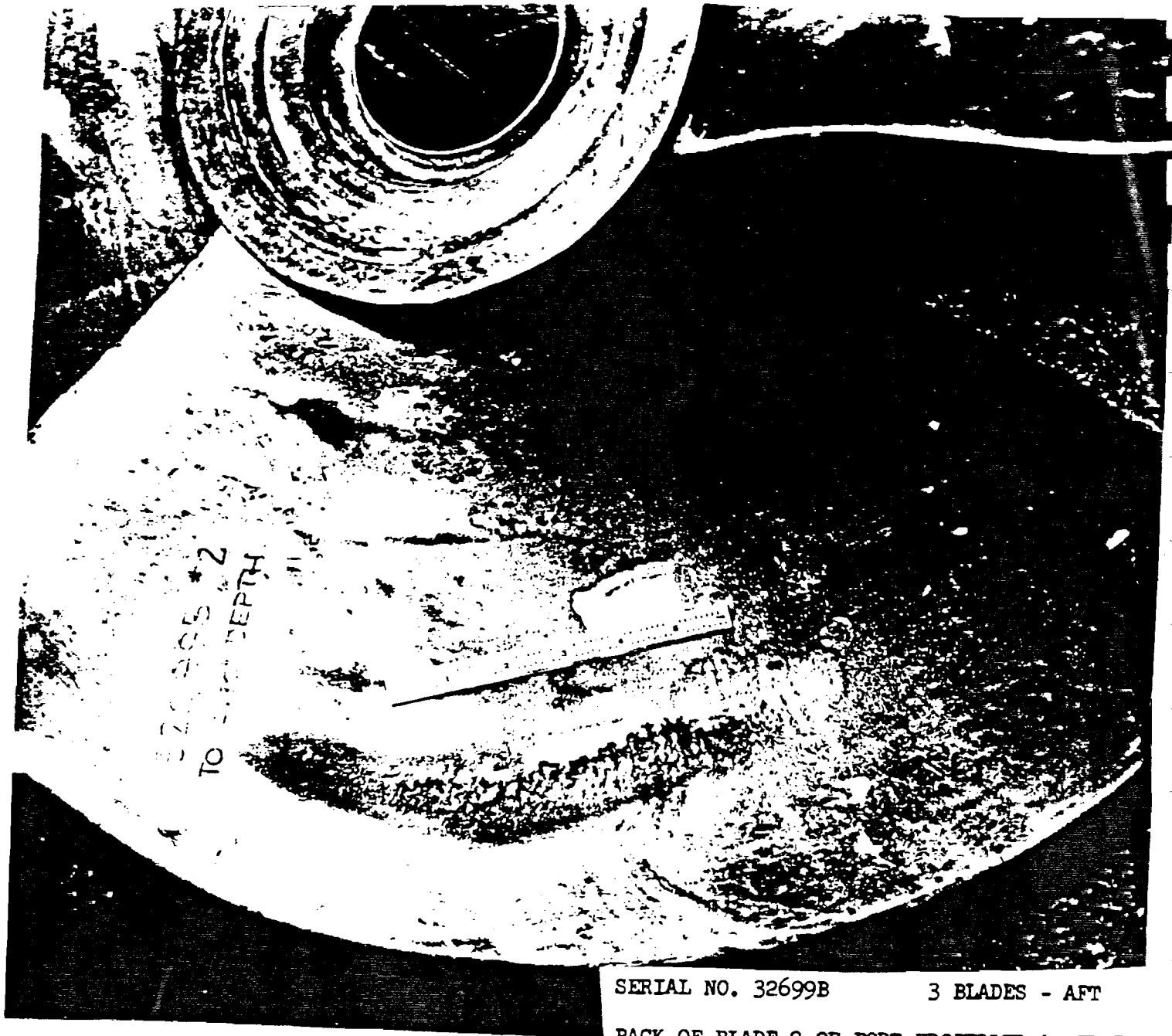


(VENTILATED FOIL CANNOT PROVIDE THE REQUIRED LIFT OR CONTROL FORCES)

Figure 3-5. Foil Ventilation Due to Foil Broach

the loss of lift, the pressure on the bottom tends to increase. However, this increase is not enough to offset the atmospheric pressure acting on the upper surface and the foil will continue to move downward until the ventilation has cleared or the hull contacts the water. The control surfaces on the vented foil will have little authority until wetted flow returns.

Figure 3-6 shows erosion of material on a propeller due to cavitation. The material was eroded to a depth of 0.277 inches in less than 72 hours of operation. Similar damage can occur to struts and foils, as well as pump impellers and ducting, if cavitation is allowed to persist.



SERIAL NO. 32699B

3 BLADES - AFT

BACK OF BLADE 2 OF PORT PROPELLER AFTER 71:53
FOILBORNE USE DURING 10 MAY TO 4 JUNE 1968.
MAX. EROSION DEPTH SHOULD READ .277".

7 JUNE 1968

NO. 2A266475

Figure 3-6. Erosion Due to Cavitation

Figure 3-7 and Figure 3-8 are sketches provided to record foil observations. It is desirable to observe the struts and foils on occasion and record any areas of cavitation damage for future reference.

In summary, ventilation can result in the sudden application of very large forces on a hydrofoil ship. This can occur with little or no warning, but is more likely to happen at the higher speeds, in high sea state operation, or during rapid maneuvering. Thus, one must be particularly alert for sudden, abrupt changes in ship motion when operating at these conditions. Also, cavitation, with or without ventilation, can result in the loss of stability and control due to a reduction in control surfaces effectiveness.

Figure 3-7. PHM Fwd Strut and Foil Observations.

DATE _____ TIME _____ SHIP _____

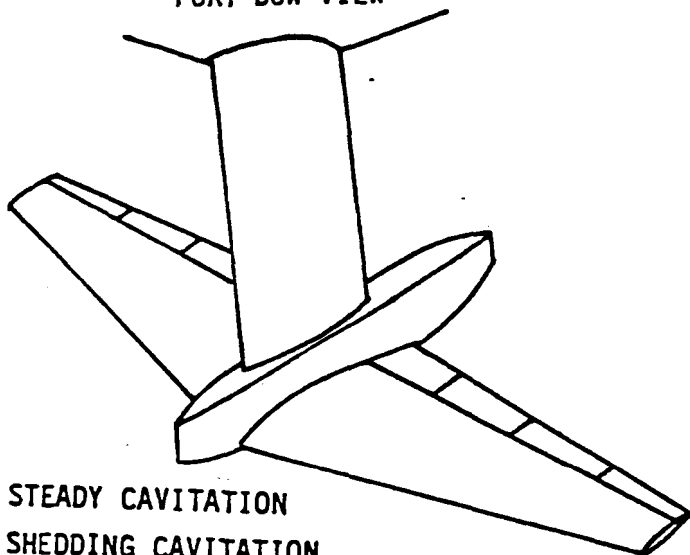
OBSERVER _____ SPEED _____

WEIGHT _____ FOIL DEPTH _____

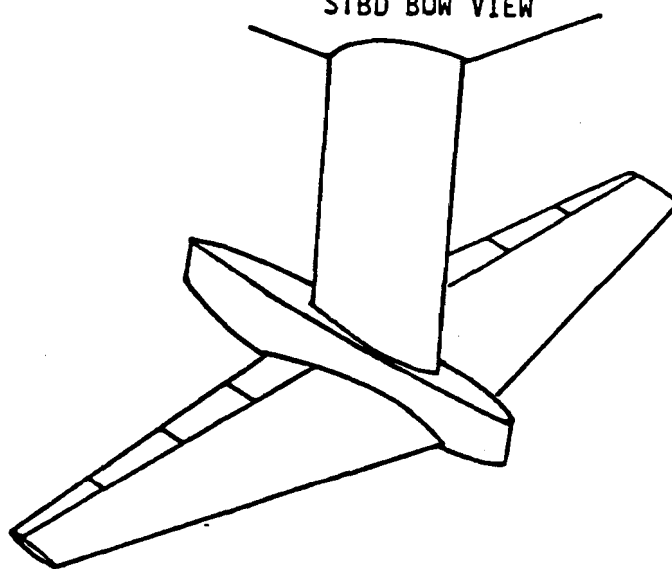
COMMENTS: _____

SKETCH OF OBSERVATIONS

PORT BOW VIEW



STBD BOW VIEW



- 1 STEADY CAVITATION
- 2 SHEDDING CAVITATION
- 3 STREAKED CAVITATION
- 4 VENTILATION PATH
- 5 VORTEX

Figure 3-8. PHM Aft Strut and Foil Observations.

DATE _____ TIME _____ SHIP _____

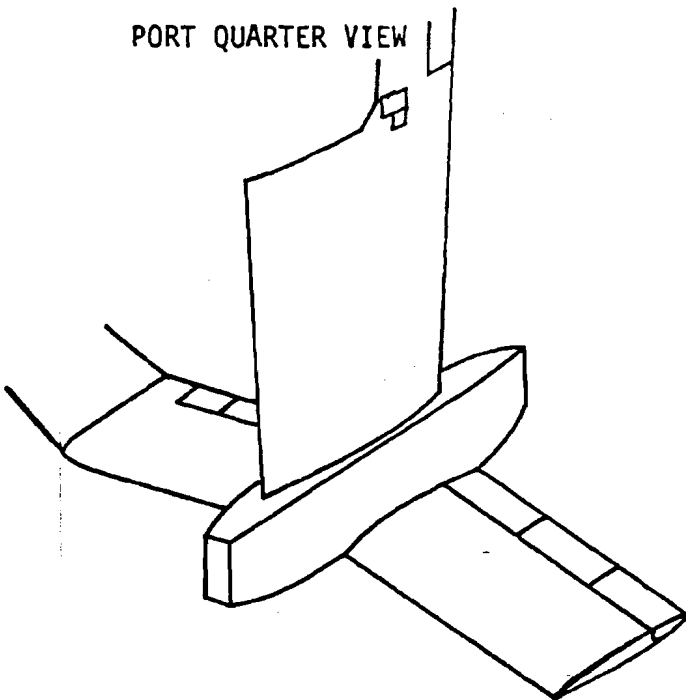
OBSERVER _____ SPEED _____

WEIGHT _____ FOIL DEPTH _____

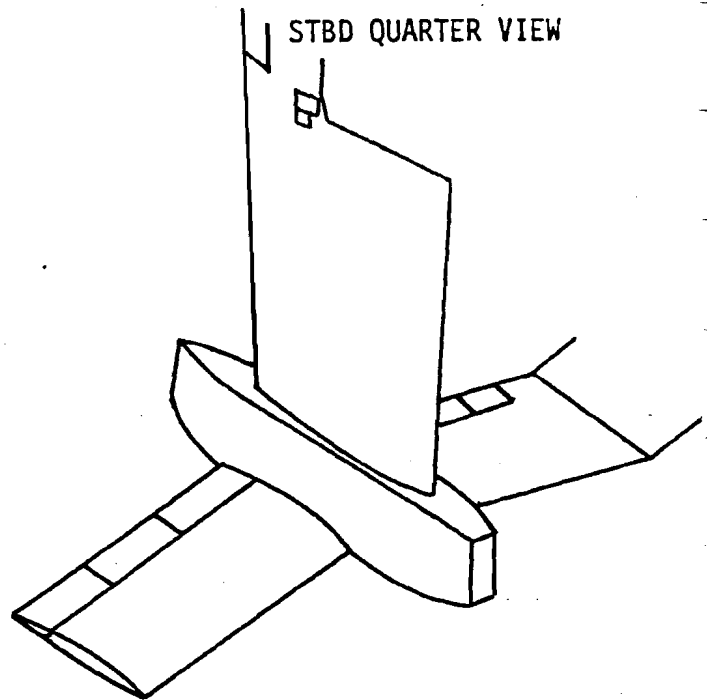
COMMENTS: _____

SKETCH OF OBSERVATIONS

PORT QUARTER VIEW



STBD QUARTER VIEW



- 1 > STEADY CAVITATION
- 2 > SHEDDING CAVITATION
- 3 > STREADED CAVITATION
- 4 > VENTILATION PATH
- 5 > VORTEX

Rev 1

3.3 WATERJET CHARACTERISTICS

PHM propulsion is provided by waterjets. This eliminates many of the gearbox, shafting, and maintenance difficulties of earlier hydrofoil propeller designs. Operating and maintaining a waterjet system is different from a ship using water screws for propulsion. These differences are discussed in the following sections.

PHM has two low-speed waterjets driven by diesels and one high-speed waterjet driven by the LM2500 gas turbine. The direct, inline drive train from the LM2500 gas turbine to the high speed axial flow waterjet eliminates the need for a right angle power transfer that is required for a propeller configuration. The two diesel driven axial flow waterjets, which use movable nozzles and reversing buckets for maneuvering, also minimize complicated gearbox and shafting requirements for hullborne operation.

3.3.1 THEORY OF JET PROPULSION. The principle of jet propulsion is derived from an application of Newton's laws of motion. These laws state that when a force is used to accelerate a fluid or give it a change in momentum, there is an equal and opposite reaction force. This opposite reaction force of the fluid on the engine (pump) is called the thrust. Thus, the theory of jet propulsion is based on the reaction principle. All objects that move through fluids, including fish and swimmers, must follow this basic propulsion principle.

The waterjet propulsion force is developed inside the propulsor and not by thrusting against the sea or air outside the propulsor. With the propulsor nozzle bolted to the ship, the net effect is to introduce a force on the ship in the direction opposite to the waterjet flow.

3.4 HULLBORNE

3.4.1 HULLBORNE CHARACTERISTICS. While in the hullborne mode, PHM characteristics are dramatically effected by whether the struts are extended or retracted. Wind and current effects and maneuvering characteristics with the struts down are similar to those for a larger deep draft vessel. When the struts are retracted, they increase the sail area and reduce the draft to approximately 2 meters (6 feet), making the PHM significantly more sensitive to wind. The center of pressure is near midships,

so PHM lies beam to the wind. If the forward foil is extended and the aft foil is retracted, the ship will lie more nearly into the wind. Normally, if the aft foil is extended, the forward foil is also extended to improve maneuverability; however, if only the aft is extended the ship will lie with its quarter to the wind. With foils retracted, the ship's center of gravity is raised and foil damping is eliminated, therefore, the ship's motions, especially roll, become exaggerated in waves.

The foils act as a brake when they are near the surface during retraction or extension and slow the ship considerably. Also, when the aft foils cut the waterjet flow of either the foilborne pump or the hullborne pumps, it creates a fountain of spray unless the foilborne turbine is secured and the hullborne jets are deflected for near zero speed.

PHM handling characteristics are different from but not any more difficult to master than conventional ships. The waterjet handling concept has been labeled a vector concept, in that waterfall has magnitude and direction, as math vectors have. Thrust is the reaction to that waterfall in both magnitude and direction. This applies to the bow thruster as well as to the hullborne waterjets. This force is applied to the ship at the nozzle. The waterjet produces more thrust in air than it does in water because the back pressure is less in air.

The thrust reverser is a bucket-shaped device moved with a flexible cable from a hydraulic actuator inside the hull. The actuator is controlled by an electrical signal generated at a throttle assembly located at the helm or EOS. The steering is controlled with one electro-hydraulic actuator that moves the port nozzle, with a tie rod connecting the port and stbd nozzles. Steering response checks should be made prior to entering an area of restricted maneuverability. Debris around the intake and nozzle or reverser should be avoided. Thrust will be lost if the intake suction is lost. Looking over the stern to see the flow of water into the intake is a good way to be sure good suction and thus propulsor thrust.

The hullborne propulsor will cease to develop thrust if the inlet gets so close to the surface that it begins to ingest air. The same is also true for the bow thruster. Figure 3-9 shows the draft boundary where each of these units will lose effectiveness. The most likely condition to cause a problem is when the ship is light and the aft foils are extended. If the ship has a list, one hullborne propulsor will lose effectiveness even earlier than indicated by the figure.

Figure 3-10 shows hullborne speed as a function of diesel RPM for both ahead and astern operation. This figure represents the average characteristics for the PHM 3 series at the time of delivery.

The bow thruster is either off or pushing to port or starboard. It is designed to provide 1200 pounds of thrust at the hub of the thruster propeller perpendicular to the keel. It loses effectiveness at ship speeds above 5 knots and can be overdriven (forced to windmill) when taking off in a tight turn. It takes approximately 1 second for the propeller to start to rotate from the time the switch is activated. Four to five seconds are required to develop full side thrust.

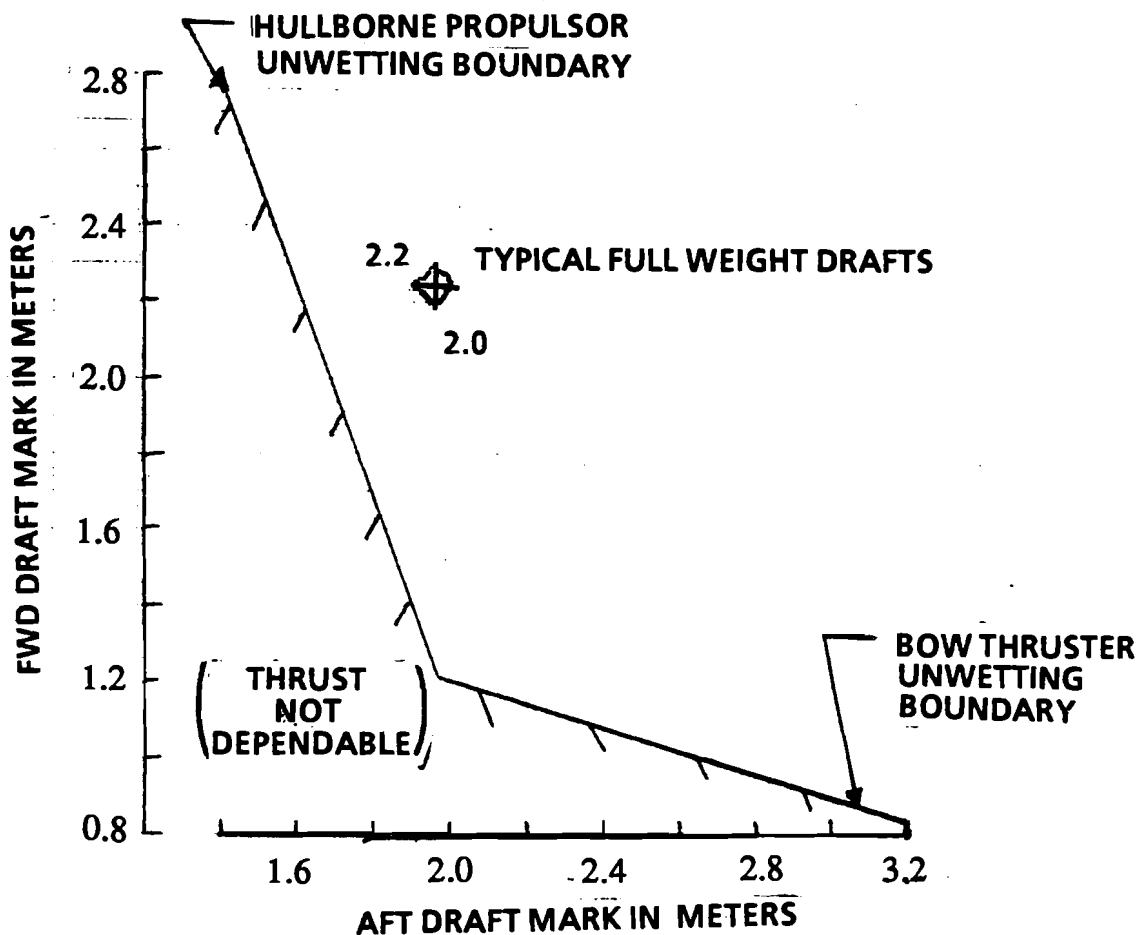


Figure 3-9. Draft Boundary for Developing Thrust

3-16

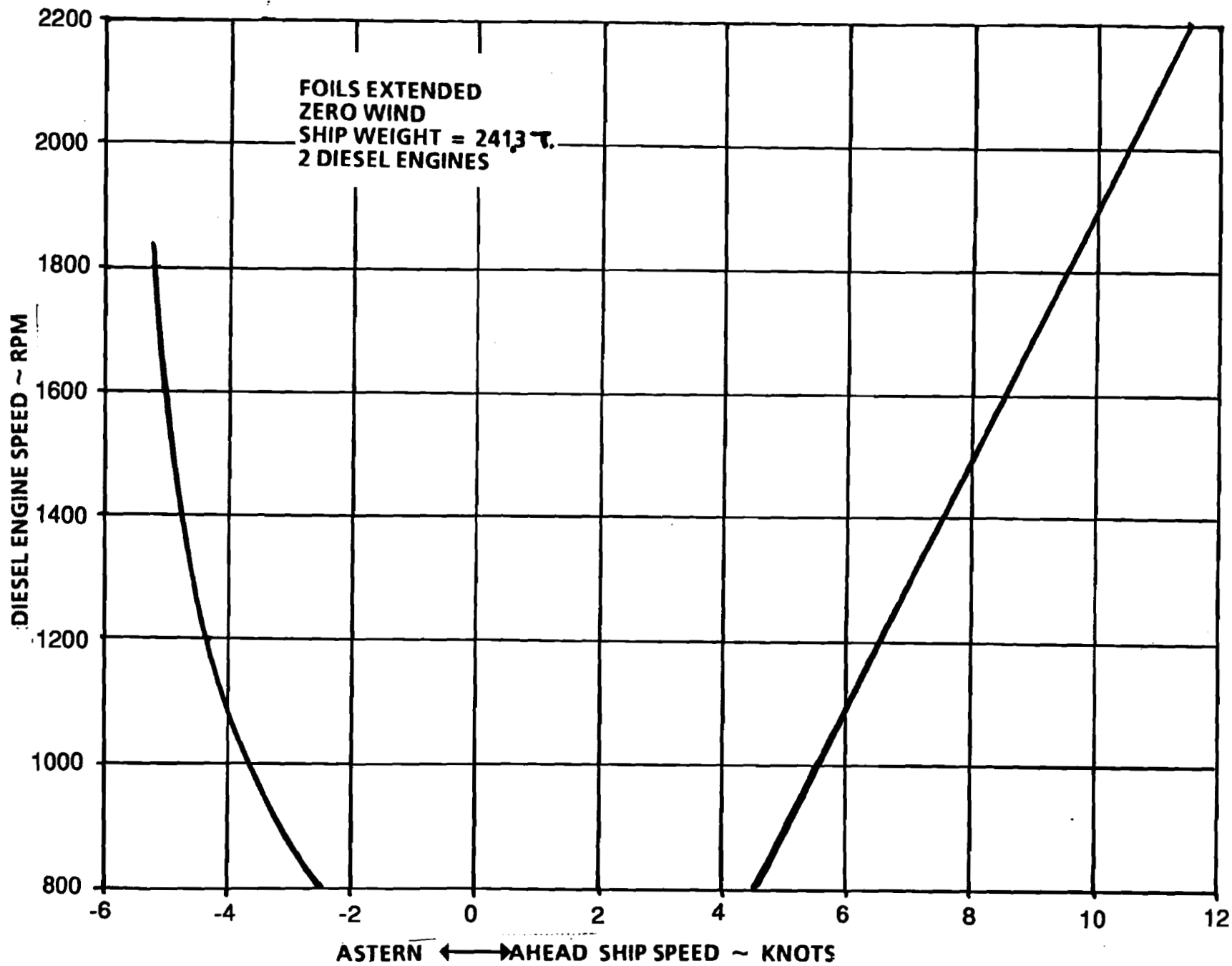


Figure 3-16 Hull Performance Curve for Ship

3.4.2 PHM DOCKING MANEUVERS

NORMAL APPROACH

Using rudder and engine commands (see paragraph 2.1.2), the normal approach for steering toward the berth and rounding up alongside can be aided by the use of the bow thruster to position the bow or help steer, keeping in mind that the bow thruster loses effectiveness at speeds above approximately 5 knots. With the struts in the retracted (up and locked) position, the foils and struts can be observed. With the struts extended (down and locked), the response characteristics change and the tips of the foils, which extend out beyond the sides of the ship, cannot be seen. Therefore, their extremities must be estimated.

This approach starts from the position shown in Figure 3-11 at approximately 900 RPM ahead on both diesels. Avoid approaching at steep angles or at an angle less than the moored heading. Steering depends on the vectoring of the waterjet flow, in both magnitude and direction; therefore, if diesels are stopped and the ship is coasting, it is necessary to steer with the bow thruster. It is also very effective to use a large helm input and a small throttle adjustment on one engine.

Stopping one engine and using the other for steering is one way to slow down the approach, but response is also slower and wind may prevent reducing to one engine. When backing down, the diesel waterjets reverse about 140 degrees. 1200 RPM in reverse provides forces about equal to 900 RPM ahead. Momentum builds quickly so the backing bell should be kept on only as long as needed to stop.

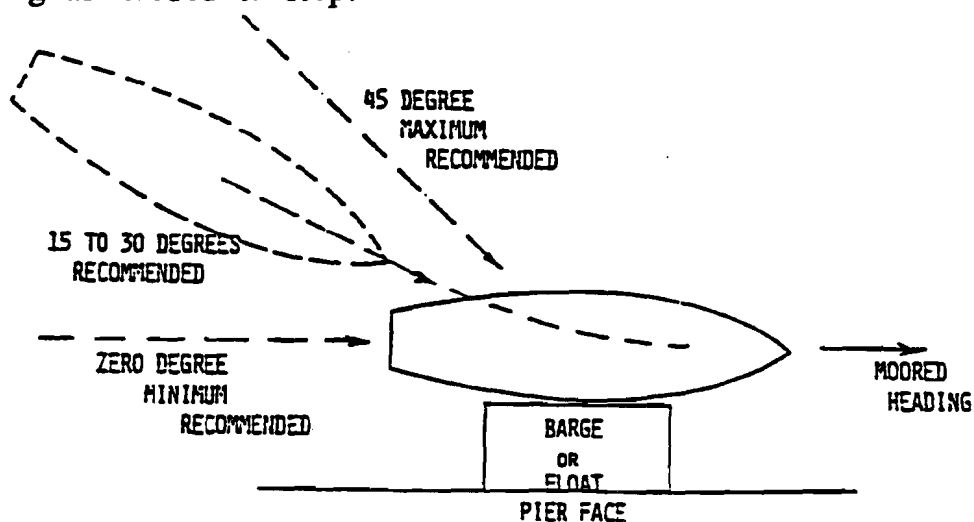


Figure 3-11. Normal Approach

SIDEWAYS APPROACH

PHM can be maneuvered sideways into a constrained berth (Figure 3-12). The procedure is to stop the ship opposite the berth. Order idle rpm ahead on both engines, place rudder in direction of berth. Do not allow forward motion. Use rapid stop engines, shift rudder, and reverse engines at idle. Report as necessary. All that is wanted is to swing the stern. At the same time judicious use of the bow thruster, in the direction of the berth will keep the ship parallel to the berth. Remember: No Head Way or Stern Way is allowed! This requires some practice, but is a very safe maneuver, since there are no screws or rudders. If you shift your rudder prior to stopping your engines, you will negate the swinging motion of the stern.

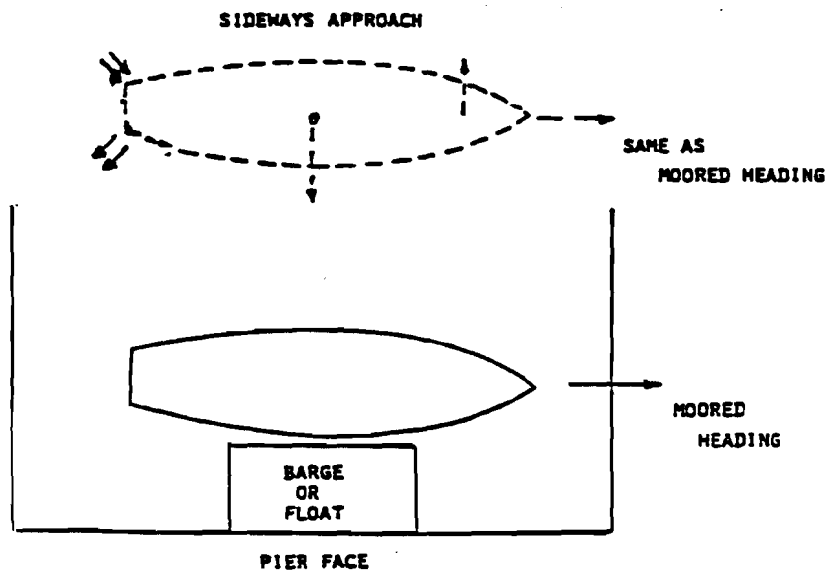


Figure 3-12. Sideways Approach

SIDESLIP APPROACH

The diesel waterjets and the bow thruster work together for sideslip approaches (see Figure 3-13). The diagonal movement of the ship allows holding the moored heading from the channel all the way to the final berth position. The approach starts when the final position bears approximately 30 degrees relative to the moored heading and proceeds as follows:

- a. Order 900 RPM ahead on one or both diesel engines and full left (or right) rudder turning away from the berth, thereby swinging the stern toward the berth.
- b. Note the swing and pulse the bow thruster in short pulses to keep the ship parallel to the final position.
- c. Observe the direction of motion and add or decrease diesel RPM to correct the sideslip angle toward the final position.

The bow thruster is used to hold heading and the diesels are used to control the speed and the angle of approach. If this method is used when the forward strut is extended, STRUT CENTERING should be selected on the ACS control panel. If the STRUT STEERING position is selected, the forward strut will tend to move the bow away from the berth.

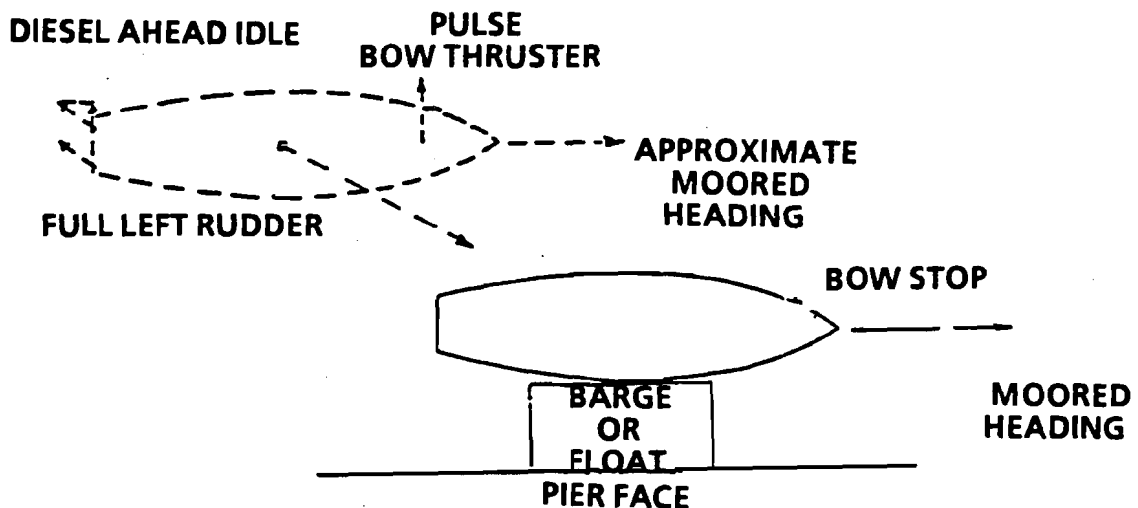


Figure 3-13. Sideslip Approach

Mastery of this approach in a variety of wind and water currents usually signifies an understanding of PHM handling and docking characteristics. If the ship overstands the desired position, recovery is effected by shifting the rudder and using opposite bow thruster or by backing without shifting the rudder and reversing the bow thruster direction.

BACK-IN APPROACH

When it is necessary to present the stern of the ship to a close corner (e.g., when loading missiles with a limited arm crane), the normal approach is to back in. With one or both diesels backing, the ship may be steered into a close corner using standard commands (see Figure 3-14). If desired, the bow can be controlled with the bow thruster.

The approach is executed similar to that of any ship; however with the struts retracted, PHM becomes more sensitive to the wind and may be caught by strong gusts, or currents more easily than another vessel. When the struts can remain extended to the final berth position, the ship is less effected by wind and gusts but is somewhat more effected by the current.

If the ship overstands a safe and reasonable position, recovery occurs as expected by shifting the rudder and going ahead on the diesels. However, with the bow thruster, the bow and stern can be simultaneously maneuvered away from danger.

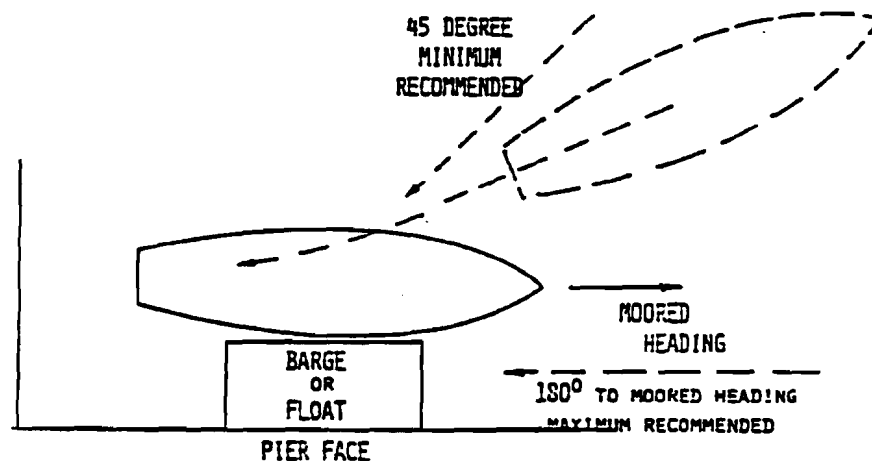


Figure 3-14. Back-In Approach

BACK-IN SIDESLIP APPROACH

PHM may also be sideslipped while backing. The procedure is to start from the diagonal position shown in Figure 3-15, order both diesels back at approximately 900 RPM and as soon as sternway commences, order full rudder in the direction of the berth. The bow is controlled by pulsing the bow thruster. The approach can be adjusted by adding speed to increase sternway or by stopping an engine to decrease sternway.

When about 2 meters from the desired position, stop the diesels and bow thruster. If the ship tends to overstand a safe position, recovery can be initiated by going ahead on the engines without any change to the rudder and using the bow thruster in the opposite direction. The buckets are protected by the aft foil structure when the struts are retracted but not when they are extended.

Wind and sea can make this method difficult and use of a No. 1 and 3 spring line may increase the safety of the ship if properly managed.

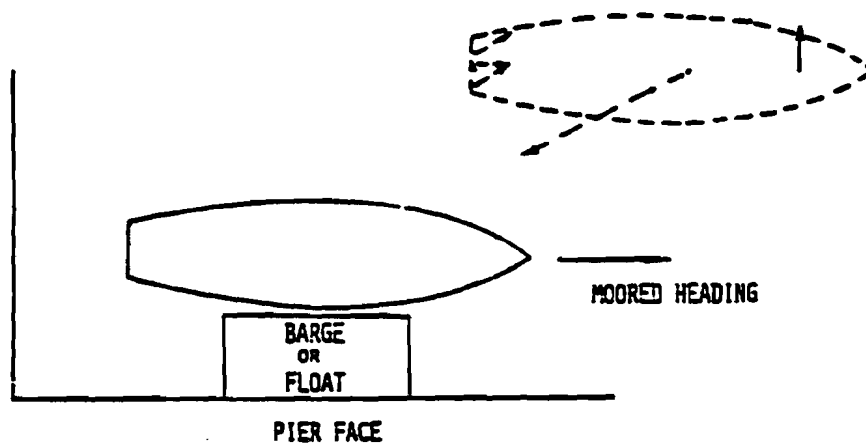


Figure 3-15. Back-In Sideslip Approach

3.5 FOILBORNE

When PHM is in the foilborne mode, the ship's attitude (pitch and roll), rates, and accelerations are controlled by the Automatic Control System (ACS). Paragraph 1.2.7 describes the ACS and Paragraph 2.2 describes the Ready and Warning System that alerts the crew to failures in systems that support foilborne operation.

The transition from hullborne to foilborne operation is relatively simple. Once all the supporting systems are operating and configured properly, it is only required that an appropriate depth set be selected and the throttle be advanced. The recommended depth command is 3.2 meters. Take-off bias signals are introduced to the forward and aft control surfaces when the depth command is set between 3.0 and 3.5. Thus a setting of 3.2 ensures that these bias signals will be introduced during takeoff. These bias signals change the ship attitude during takeoff so that the drag of the hull and foil system is minimized; thus, the thrust available for acceleration during take off is maximized. The ship can take off in calm water without these flap biases; however, it will overshoot the commanded depth by approximately a half meter. Figure 3-16 shows predicted ship response during a normal take off.

While foilborne, the ship attitude is controlled by the ACS. The pitch attitude is automatically changed as a function of speed in order to minimize drag and maintain flap deflections near their mid hydrodynamic range. Figure 3-17 shows typical foilborne trim characteristics obtained from one of the PHM-3 Series ships during trials conducted prior to delivery. Figure 3-18 shows ship speed as a function of power turbine RPM. This curve represents the average of the PHM-3 Series at a point in time, in calm water and at a weight of 241 metric tons. It is desirable to record certain ship parameters during steady operating conditions for comparison with past and future data. This data is useful not only in determining if there has been any deterioration in ship performance but can indicate the possible cause. More flap deflection than normal can indicate a hydrodynamic problem on either the forward or aft foil/flaps while more power for the same speed can indicate a pump and/or foil system problem, etc. Figure 3-19 and Figure 3-20 are samples of data sheets that can be used to record this type of data.

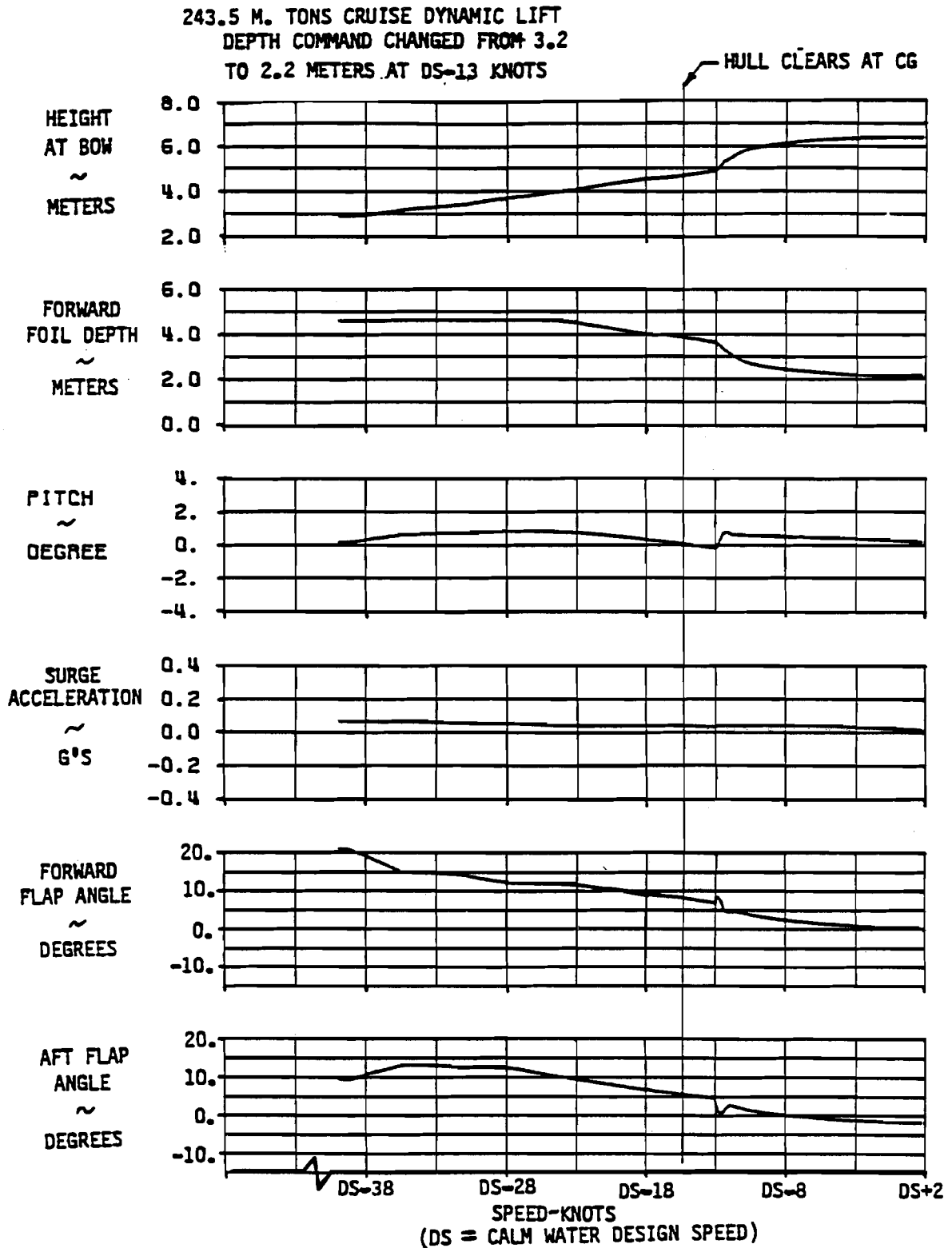
All turns are performed in a coordinated (banked) fashion. The banking is accomplished automatically by the ACS. Because all turns are

coordinated, the relationship between helm angle and turn rate is relatively constant for all normal operating foil depths and speeds. **Figure 3-21** shows the mathematical relationship between turn rate and turn diameter at various speeds. **Figure 3-22** through **Figure 3-24** show typical foilborne turning characteristics obtained from one of the PHM-3 Series ships during trials conducted prior to delivery. Also shown are curves derived from a simulation for "Stb Gyro Disconnected". See Section 2.2, sub-paragraph "Gyro Disconnect Switch" (page 2-14) under Automatic Control, for one gyro operation guidelines.

The normal landing procedure in either calm water or rough water is to reduce power to idle and let the ship settle in the water as it slows down. A more rapid landing can be accomplished by increasing the depth command along with reducing power. A third procedure is an emergency landing, which is initiated automatically for certain failures in the ACS. It can also be initiated manually by moving the depth command firmly against the down stop (maximum depth setting). An emergency landing results in the forward flap being deflected to its mechanical up stop at maximum rate, which causes the hull to descend into the water as rapidly as possible (less than 2 seconds). **Figure 3-25** and **Figure 3-26** show predicted landing characteristics for a normal and a rapid landing.

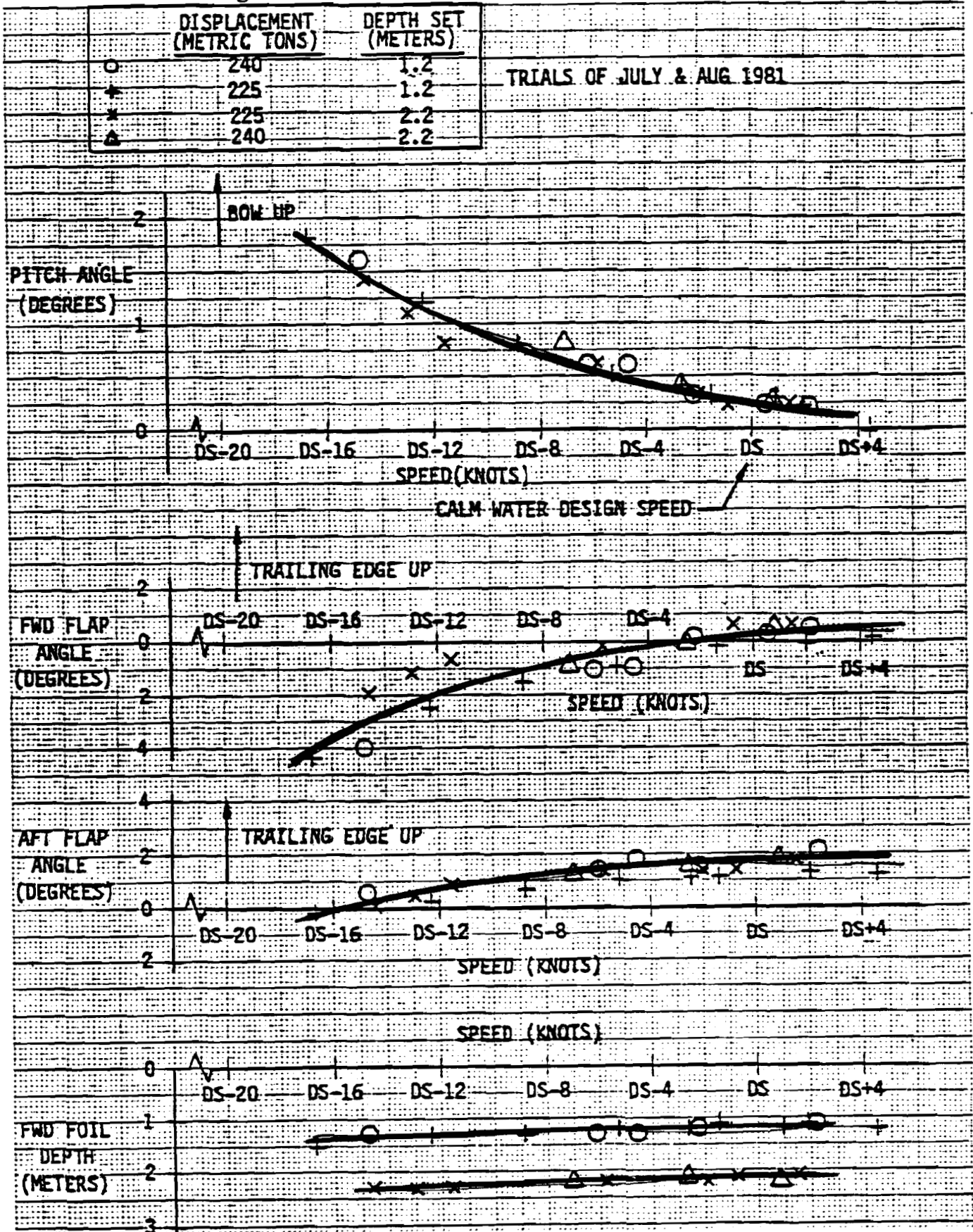
The reliance of the ship on the ACS to provide basic ship response characteristics, ride quality, and safety dictate that it must be reliable and have adequate redundancy incorporated. A safety analysis conducted during the PHM design indicated that the ship had the capability for continued foilborne operation for more than 80 per cent of possible single level failures. However, there are some failures that can result in large motions, particularly those associated with the roll control channels.

Figure 3-16. Ship Responses During Takeoff

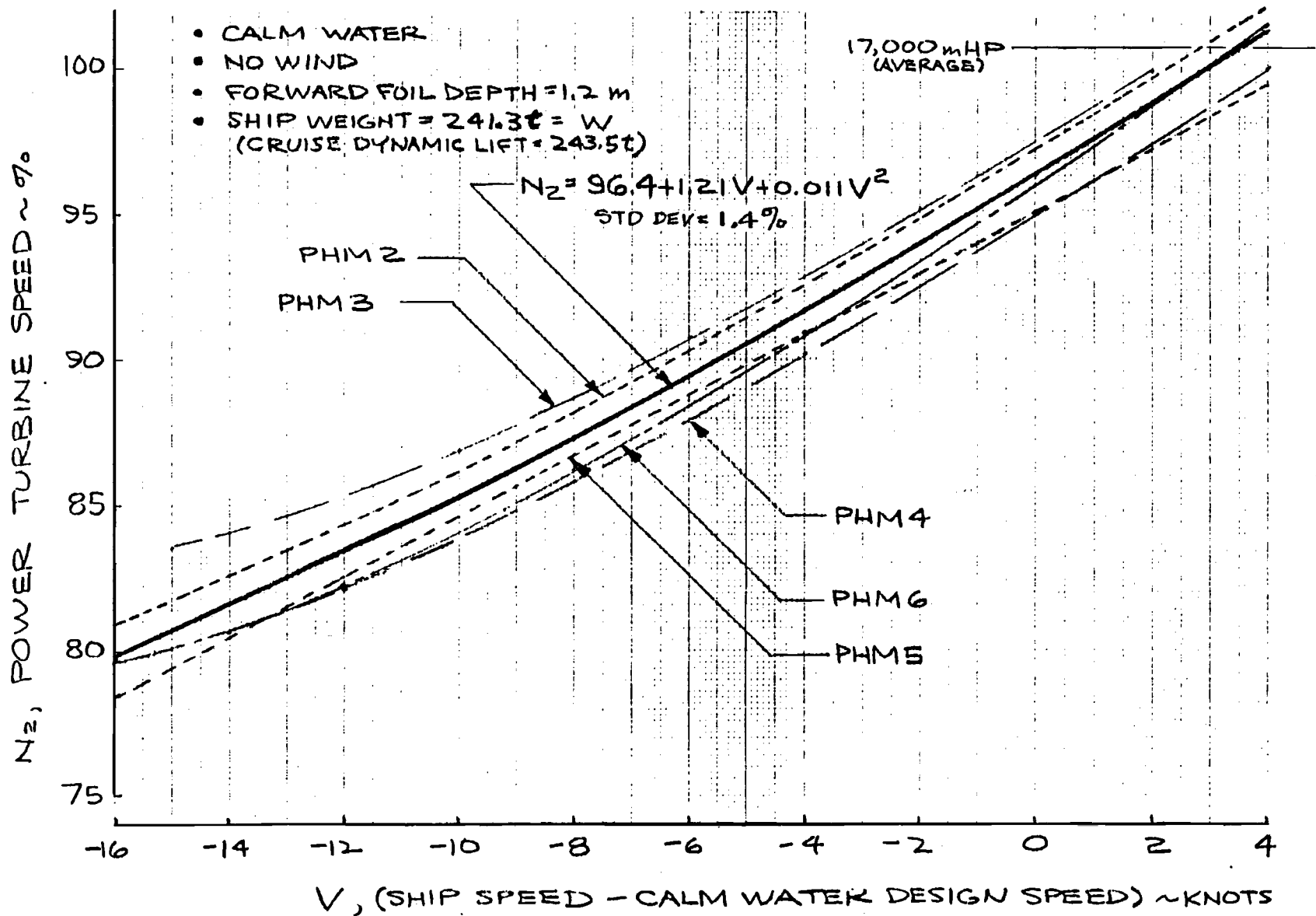


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Figure 3-17 TAURUS (PHM-3) Trim Characteristics



3-26



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Figure 3-18. Foilborne Speed-Power

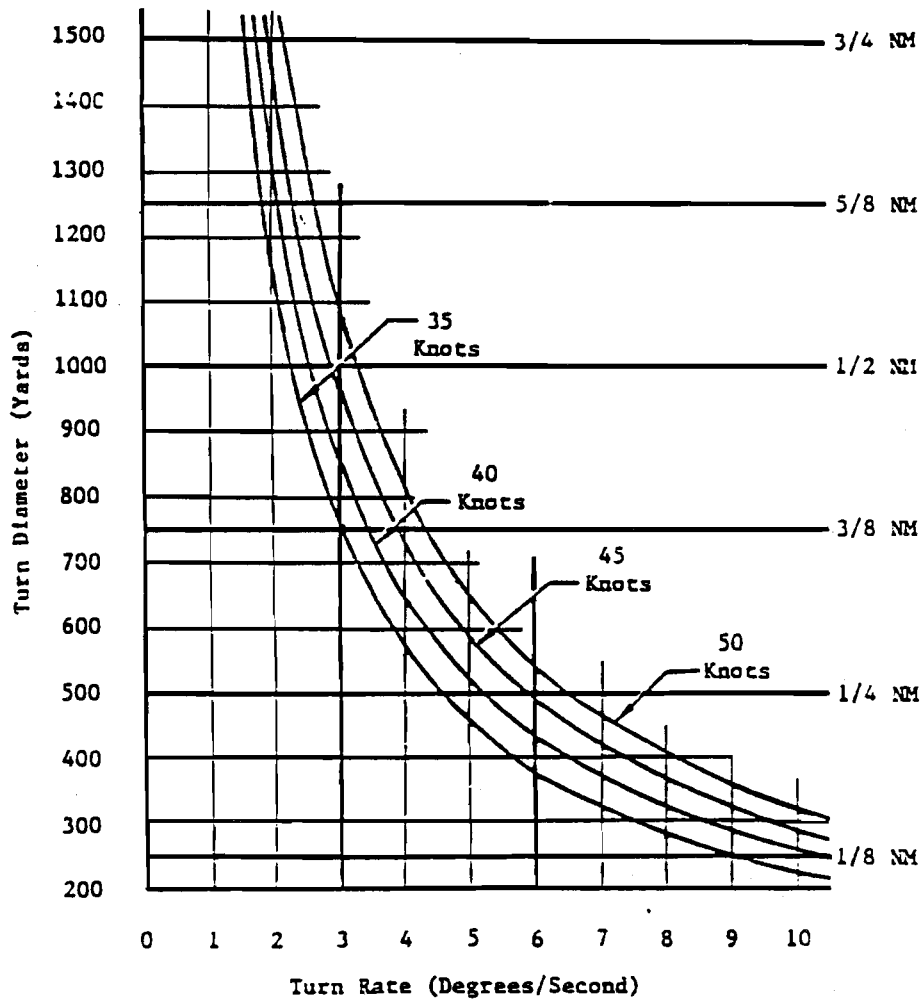


Figure 3-21. Foilborne Turning

	DISPLACEMENT (METRIC TONS)	DEPTH SET (METERS)	TRIAL DATE
○	240	1.2	8-3-81
+	225	1.2	8-11-81
x	225	2.2	7-27-81

□ -- STBD GYRO DISCONNECTED

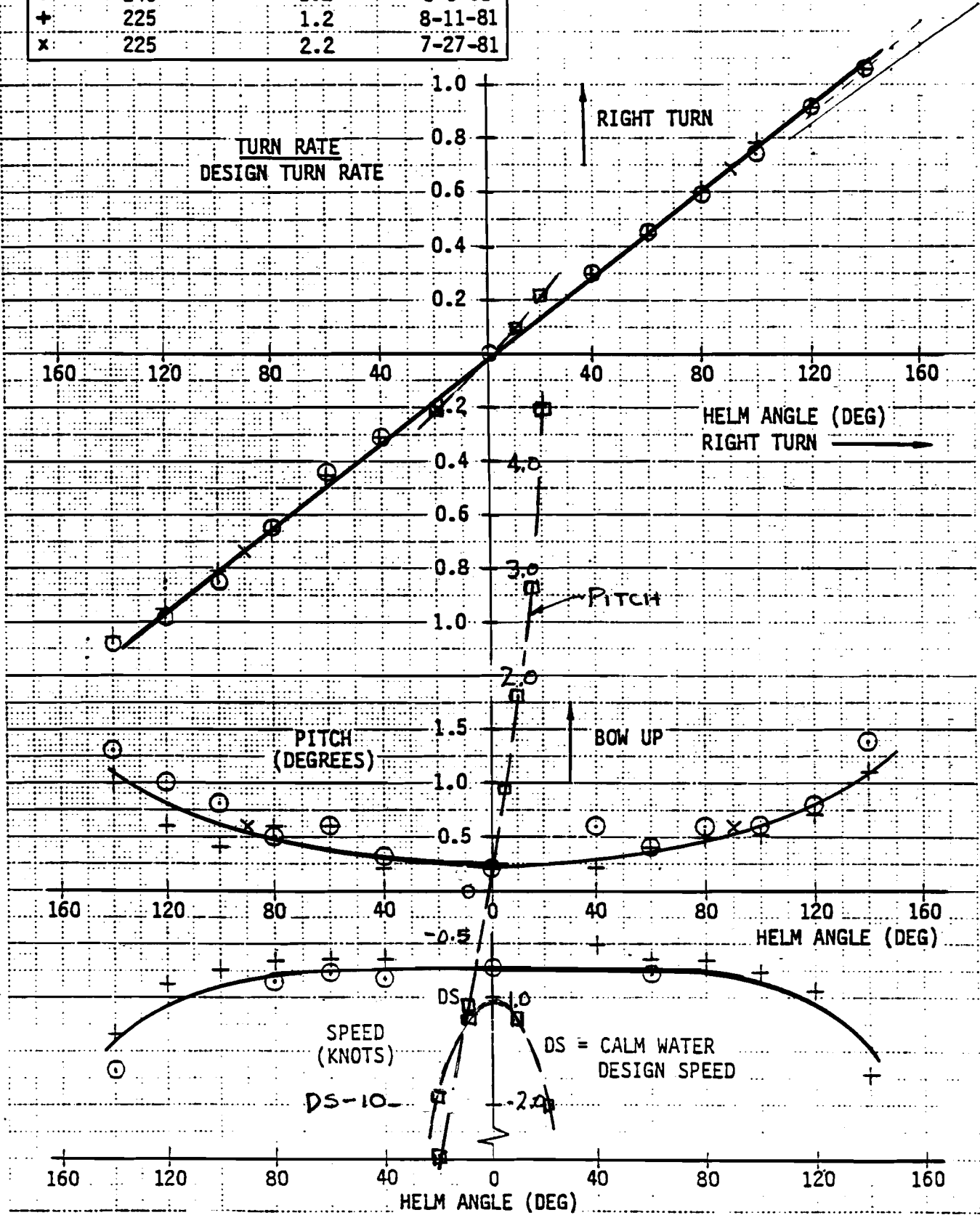


Figure 3-22 TAURUS (PHM-3) Turning Characteristics (1)

	DISPLACEMENT (METRIC TONS)	DEPTH SET (METERS)	TRIAL DATE
○	240	1.2	8-3-81
+	225	1.2	8-11-81
x	225	2.2	7-27-81

□--STBD GYRO DISCONNECTED

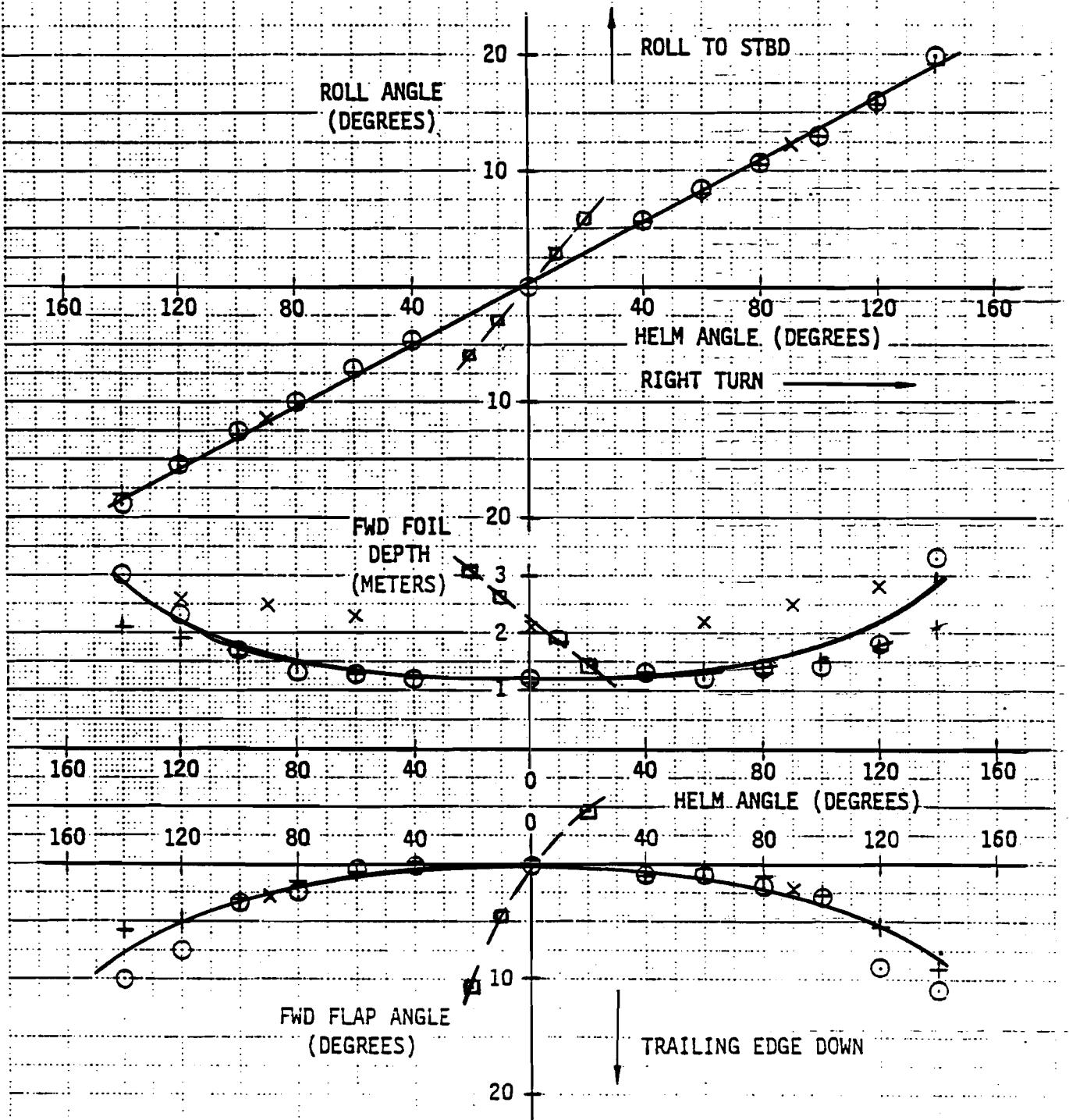


Figure 3-23 TAURUS (PHM-3) Turning Characteristics (2)

	DISPLACEMENT (METRIC TONS)	DEPTH SET (METERS)	TRIAL DATE
○	240	1.2	8-3-81
+	225	1.2	8-11-81
x	225	2.2	7-27-81

□--STBD GYRO DISCONNECTED

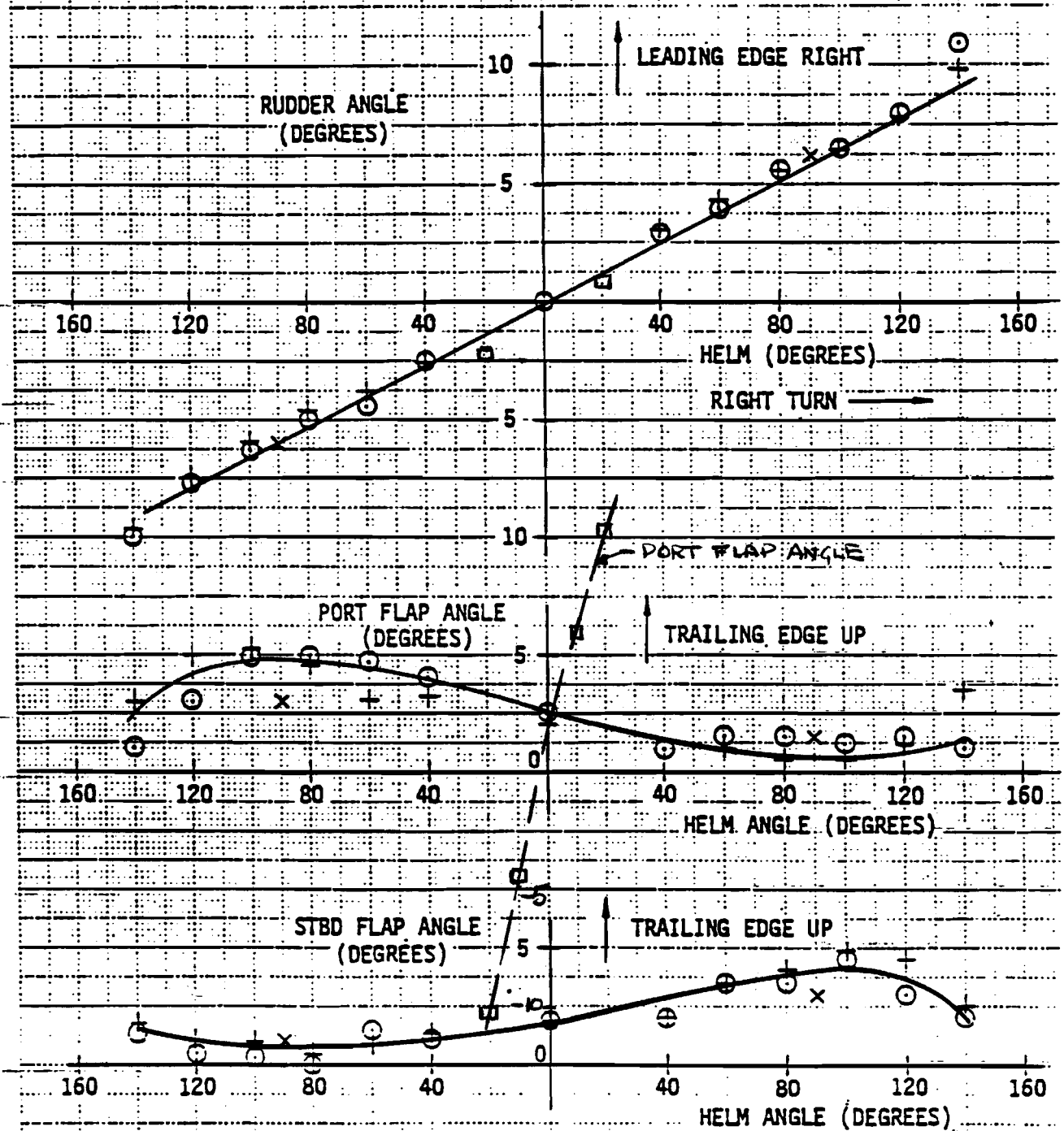


Figure 3-24 TAURUS (PHM-3) Turning Characteristics (3)

3.6 ROUGH WATER

One of the main advantages of a hydrofoil is its ability to provide a relatively smooth ride while operating at high speed in rough water. Operation in rough water is essentially the same as smooth water until sea conditions exceed the design conditions. The design sea condition for PHM was mid sea state 5, with a significant wave height of 3 meters (10 feet) and a significant wave period of 6.73 seconds. Significant wave height is the average height of the 1/3 highest waves, and significant wave period is the average period of the 1/3 highest waves. Factors that affect rough water operation are wave height, wave period, wind speed and direction, weight, and heading with respect to the sea.

Operation in rough water is greatly effected by the depth command. If the setting is too shallow, the forward foil will broach (penetrate the air/water interface) and lose lift frequently. If the setting is too deep the hull will contact the top of the waves frequently (cresting), resulting in sharp vertical motions and speed reduction. The recommended depth command for operation in the design sea is 2.2 meters. This setting is a compromise between broaching and cresting. Minor broaching is accompanied by a small pitch change and lift is reestablished almost immediately. Full broaching of the forward foil can result in the ship pitching down as much as 5 degrees and the hull might contact the surface before normal flow is reestablished. Broaching tends to result in greater changes in ship motion than cresting; therefore, the depth command is generally biased toward more cresting than broaching. Also, the fine bow and V-shaped hull of PHM were selected with the idea of minimizing the effects of wave impacts at high speed. However, in large seas, the increased frequency of cresting will result in a speed reduction which eventually could cause the ship to become hullborne. In seas greater than sea state 5, increasing the depth settings will generally improve the ride quality up to a settings of approximately 2.7 meters. For long period waves, the ship will respond to the surface and contour (follow) the surface. For shorter period waves, the ship will platform, that is, not respond significantly to the wave surface and thus provide a stable platform for tracking and firing weapons. Remember that each increase in sea state number means an order of magnitude (10 times) increase in the energy content of the sea; thus, going from sea state 5 to 6 results in a very significant increase in wind and waves.

Take off in conditions up to design seas is accomplished in the same general manner as in calm conditions. However, in higher sea states large waves may increase hull drag to the point that the ship cannot become foilborne. If this occurs, the following options should be considered:

- (1) Select the high torque limit for the takeoff.
- (2) Turn to a heading that puts the waves on the quarter or stern.
- (3) Wait for a sequence of smaller waves.
- (4) Use the depth command to raise the ship at approximately 25 knots (pop-up takeoff).

Running down a trough in the waves when taking off reduces the number of wave encounters and is frequently the easiest and smoothest way to take off in large seas. Foilborne operation in conditions exceeding the design sea can be improved if a heading can be used that reduces the effects of hull cresting and foil broaching, such as a bow to quartering heading.

Operation in large seas can result in large changes in indicated speed. This is particularly true in quartering and following sea headings. Speed variations of 10 to 15 knots are common. Some of this is due to the variation in the wave orbital velocity (velocity of water particles) and some to the change in ship speed. For instance, a 12-foot high wave, 100 feet long would have a orbital velocity of 5 knots, which would result in a +5 to -5 knots indicated speed variation on the EM Log for no change in actual ship speed.

On JETFOIL passenger hydrofoils, a special technique has been developed that involves using the depth control in large seas. The depth command is varied to raise the ship as a large wave is encountered and lower the ship when coming down the other side. When done properly, which takes some practice, this reduces hull cresting and foil broaching. This practice has become a regular means of keeping foilborne during encounters with large waves in the English Channel and Canary Islands.

When hullborne in rough water, the PHM rides well with the struts extended. If the ACS is active, the control surfaces will help stabilize the ship. However, at certain combinations of speed and sea conditions (particularly low speeds) the ACS should not be activated to avoid having the control surfaces continually slamming into their stops.

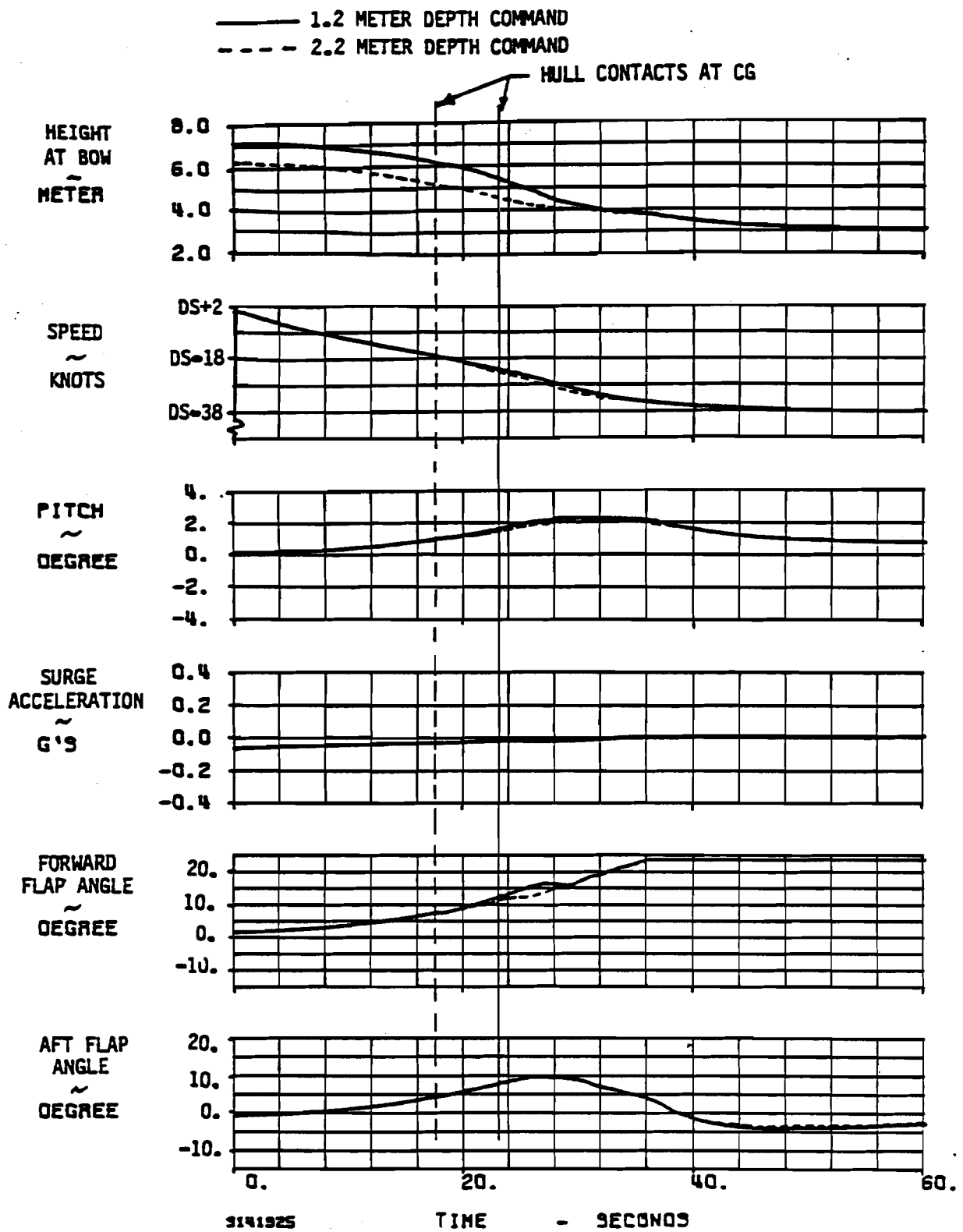


Figure 3-25. Ship Responses During a Normal Landing

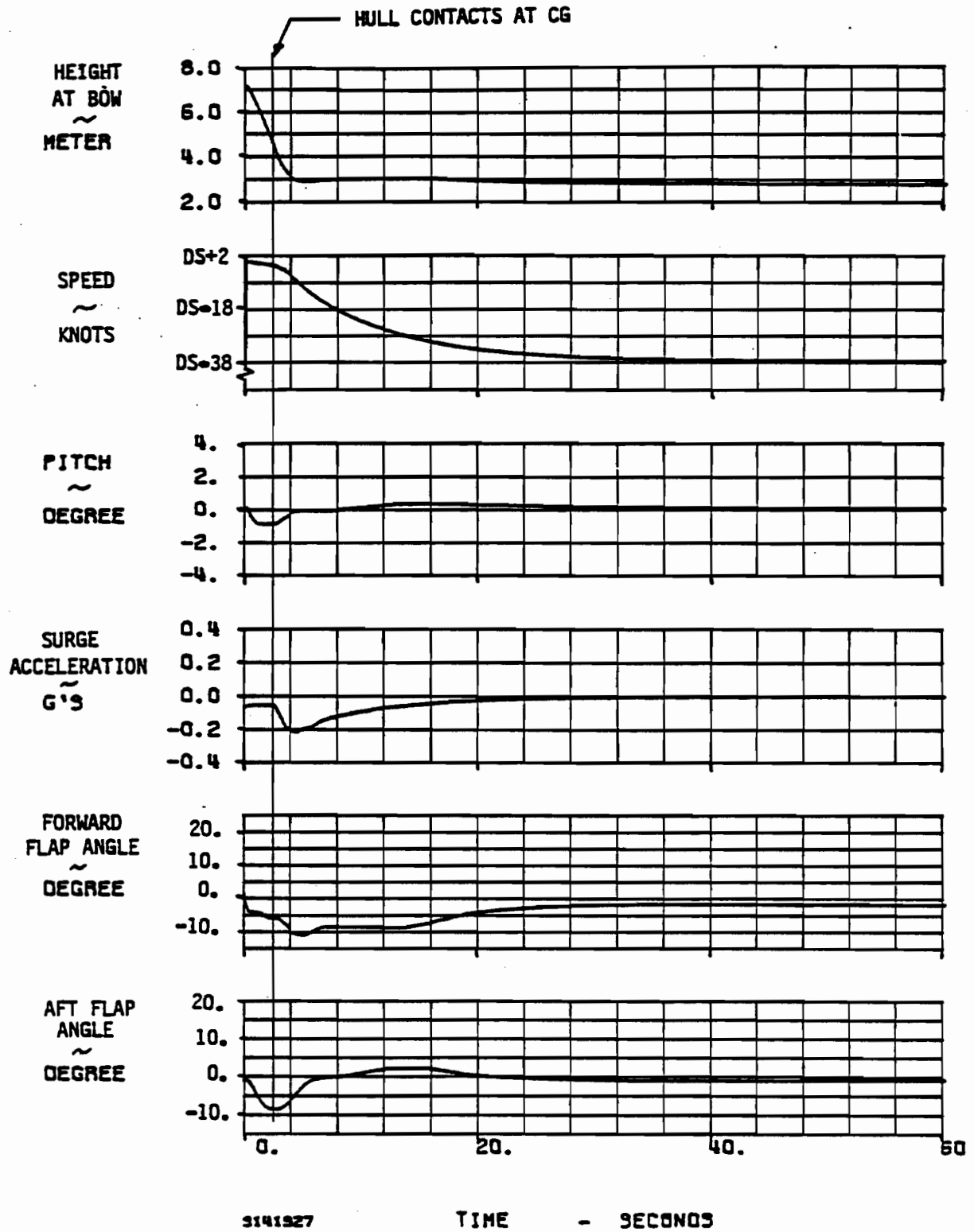


Figure 3-26. Ship Responses During a Rapid Landing

3.7 UNDERWAY REPLENISHMENT (UNREP). UNREP is generally conducted having the diesels and the turbine on the line, the struts extended, and the ACS in UNREP. This provides the best maneuverability and operational flexibility. For 12 knots UNREP speed, the turbine is set at approximately 40 per cent RPM and the diesels at 1500 to 1800 RPM.

The UNREP system for onboard loading of light cargo and personnel from another ship is comprised of onboard hoisting replenishment fittings that may be used on either side of the mast, safety harnesses, removable lifelines, and the sound-powered telephone outlet.

The replenishment-at-sea hoisting fittings that are rigged to the main mast for onboard loading of light cargo and personnel consist of highline, inhaul, and fairlead padeyes and hoisting lines as shown in Figure 3-27. Baxter bolts are located in the 01 level deck for the fairlead padeye. Cargo is transferred using a 3-inch fiber rope. Personnel are transferred using a 4-inch fiber rope.

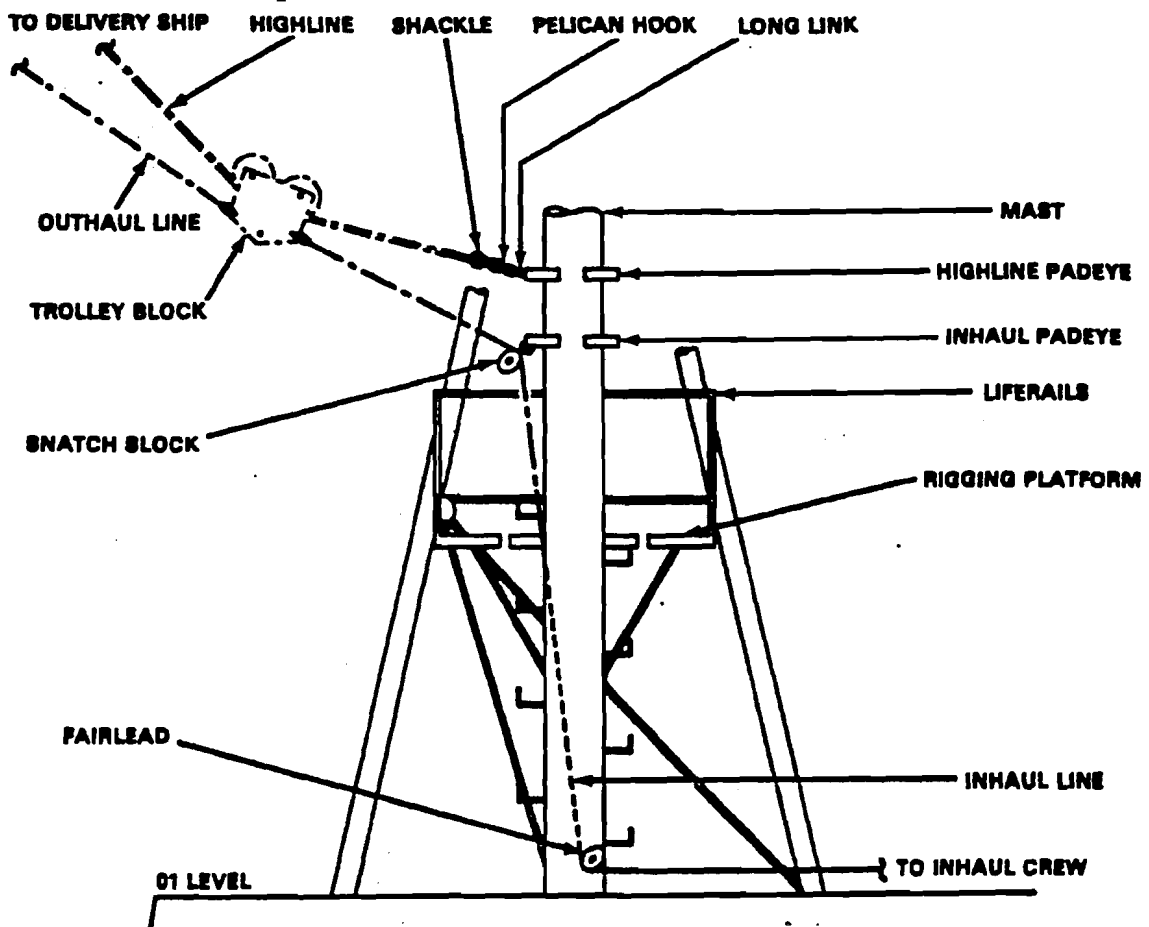


Figure 3-27. Underway Replenishment Rig

Safety harnesses with tether lines connected to snap hooks are provided for personnel security while handling the rigging for refueling and replenishment operations. The lifeline installed outboard of the refueling and replenishment stations are removable to avoid interferences during underway operations. The sound powered telephone plug-in outlet is located at the base of the mast.

A fueling station, consisting of a 63.5 mm (2.5 inch) fill line with a capped fueling nipple, a fuel delivery pressure gage, and a fuel bleed sampling valve, is located on each side of the Main Deck deckhouse (for inport refueling) and on the 01 level (for unrep refueling). All four tanks can be replenished in 1 hour when receiving fuel at 1000 liters/min (264 GPM) at 276 to 1370 kN/m² (40 to 200 psi). Automatic closure of the fill line, when the tank(s) are at 95 per cent full, is made by shutoff valves that are activated by level transmitters located in each tank. EOS should keep track of fill times and rates and advise the bridge of the time remaining alongside.

NOTE: The fueling rate should be limited to 775 liters/min (205 GPM) for JP-5 and to 725 liters/min (192 GPM) for DFM-2. If higher fueling rates are required, then fueling should be closely monitored and reduced to the recommended rate at 90 per cent capacity to prevent overflow.

3.8 TACTICAL MANEUVERING: A PHM SUCCESS STORY

Tactical maneuvering in the face of the enemy means simply being in position to hit and not be hit. Tactical maneuvering of the PHM in a wide variety of circumstances is essentially the same as for any other ship. However, a foilborne PHM with accurate gun control adds a new dimension to tactical maneuvering of surface ships against aircraft. CDR. Erich Ashburn of USS *Pegasus* was the first to learn to defeat aircraft from NAS Miramar on the Pacific Missile Range offshore from Pt. Mugu, California. He demonstrated this to Admirals Bird, Monroe, and Walters during DSARC II OPEVAL.

To conduct high-speed runs against the ship, the services of A-4, A-6, and F-4 aircraft were obtained. If the pilots had fuel and time remaining on station when the required exercises were completed, they usually asked

for and received "free time." To gain from this time and learn how to fight PHM, the pilots were encouraged to attack in any manner they considered effective.

CDR. Ashburn quickly recognized the advantages of fighting the airplanes at his highest foilborne speed. Adding a very long extension cord to his ICK, he was able to keep the airplanes in sight by moving around the pilothouse and out on the 01 level as needed. The Tactical Action Officer (TAO) and the Combat Information Center (CIC) team directed the gun and monitored the aircraft ranges and bearings.

When attacking, the aircraft were watched visually and as soon as they were committed it was possible with practice to estimate the phase of the attack, angle of approach, weapon release point, and pullout maneuver, and determine the best killpoints on both the approach and retirement. This became a game and pilots showed up just for the free time. It was rumored that NASA pilots flying in the naval reserve also came out to see this ship that could outmaneuver them.

On the day of the demonstration for the three admirals, CDR. Ashburn put a high-intensity flashing light into the breech of the gun. It was a yacht life jacket 100,000 candle power zenon lamp, so that the flashes could be seen down the bore. He also had the ballistics control dialed out of the gunfire control system. He reasoned that this would aim the gun directly at the pilot. With the admirals aboard, he carefully explained his game plan for the free time. After the free time, one of the admirals radioed to the pilots and asked them if they had seen the flashing light. They replied "Oh yes Admiral, on every run." It had worked at every Mach number.

The practice, TAO and CIC coordination, discussions with naval aviators, and the ship's maneuverability all combined to make the demonstration a success.

APPENDIX A

A BRIEF HISTORY OF HYDROFOIL DEVELOPMENT

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A BRIEF HISTORY OF HYDROFOIL DEVELOPMENT

PREFACE

Hydrofoil development leading to the introduction of PHMs into the fleet spans a period of about seventy years. This section of the PHM OPERATING NOTEBOOK on the history of hydrofoil development will first describe the early years during which experimenters, innovators and inventors such as Forlannini in Italy and Alexander Graham Bell in Canada struggled to make a hydrofoil "fly". Hydrofoil developments in Germany started about 1927 with von Schertel and Tietjens. The U. S. Navy, encouraged by these developments, started an R & D program which resulted in such craft as LANTERN, the XCH-4, HIGH POCKETS and HIGH TAIL. A description of several hydrofoil landing craft is followed by Canadian developments leading to the BRAS D'OR. In parallel with the U. S. Navy's hydrofoil landing craft work during the 1950s, major contributions to hydrofoil development were made by SEA LEGS and the Maritime Administration's HS DENISON.

These craft were followed by several high speed test craft: HYDRODYNAMIC TEST SYSTEM (HTS), FOIL RESEARCH SHIP HYDROFOIL (FRESH-1), LITTLE SQUIRT, and the Canadian R-X CRAFT. In parallel with the latter, The U S Navy developed the "Famous Four" hydrofoils: HIGH POINT, FLAGSTAFF, TUCUMCARI, and PLAINVIEW during the 1960s.

PHM started as a NATO concept with an agreement between the Federal Republic of Germany, Italy and the United States. Events that evolved from these beginnings and why the PHM is the way it is will also be described.

Several sources have been drawn upon to provide this brief history. They include: W. M. Ellsworth's document: "Twenty Foilborne Years, The U S Navy Hydrofoil, HIGH POINT", 1987; R. Johnston's paper: "History of U.S. Involvement in Developing the Hydrofoil", from the Nova Scotia International Hydrofoil Society (I. H. S.) Conference, 1982; Chapter V of the Naval Engineers Journal on "Modern Ships and Craft" of February, 1985; M. Eames' paper: "A Review of Hydrofoil Development in Canada", from the Nova Scotia I.H.S. Conference, 1982; and E. A. Jones paper: "RX Craft, A Manned Model of the RCN Hydrofoil Ship BRAS D'OR", J. Hydronautics, July 1967.

EARLY TEST CRAFT

During the late 1800s and early 1900s there were a number of inventors and experimenters in North America and abroad who were interested in

hydrofoil concepts. For instance, in 1907 Wilbur and Orville Wright experimented with a hydrofoil catamaran on the Ohio River near Dayton. Unfortunately, these tests were stopped by low water in the river and, to the later benefit of the aviation industry, they turned their attention elsewhere.

Enrico Forlanini, was an Italian engineer whose interests included airships, aircraft and helicopters. His hydrofoil developments started in 1898 with a series of model tests from which he arrived at several simple mathematical relationships. These allowed him to proceed with the design and construction of a full scale craft.

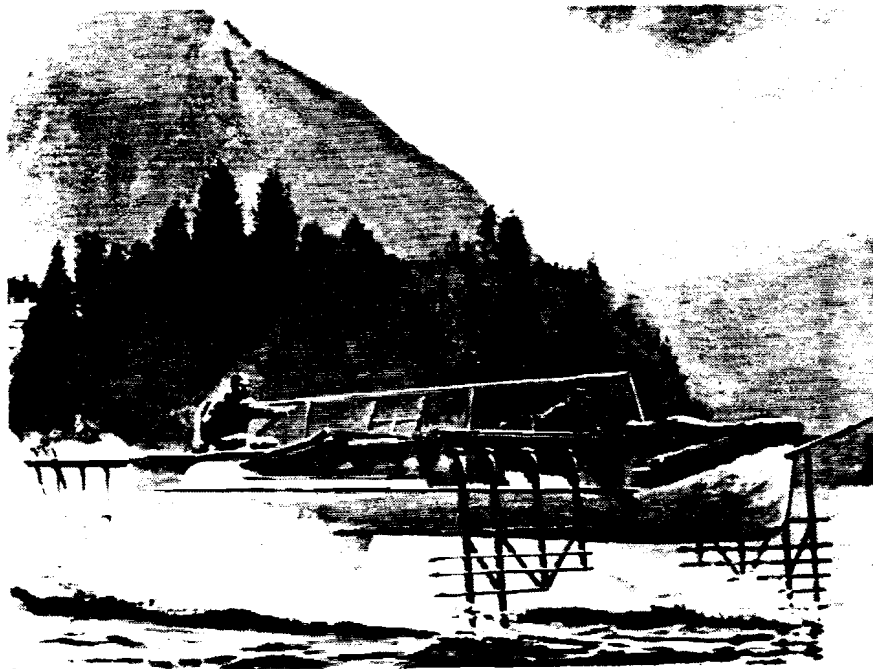


Figure 1- Forlanini's Hydrofoil on Lake Maggiore in 1906

Forlanini's designs were characterized by a "ladder" foil system. You can see from an old photograph in Figure-1 what is meant by this aptly named ladder foil. Forlanini's model experiments had shown him that lift was proportional to the square of speed, therefore less foil area was required as speed increased. He conveniently obtained this decrease in foil area with the ladder scheme. The craft weighed about 2,650 pounds and had a 60 hp engine driving contrarotating coaxial airscrews. Although designed to fly at a speed of 56 mph, records show that during tests on Lake Maggiore, Italy in 1906 a speed of 42.5 mph was obtained.

Although the foil system was a rather complicated structure, Forlanini's craft operated well and represented an advancement in the state of the art. He obtained a number of British and American patents on his ideas and designs, most of which were aimed at seaplane applications.

Some of the most spectacular hydrofoil experiments of the Early Years were those of Alexander Graham Bell, the same one who invented the telephone. He was born in Scotland in 1847, but went to Canada in his early years and later the United States to pursue his career as a teacher and scientist. He returned to Cape Breton Island, Canada, which became his second home, alternating between Washington, D. C. and Baddeck. This is where he constructed his famous laboratory and workshops. One building served as Bell's boat building facility; there was another building which served as the home of Canada's first aircraft manufacturing company, the Canadian Aerodrome Company. It was in this complex that Bell worked on eugenics and the twinning of sheep, on solar stills and condensation of fog for the production of drinking water, on kites and aeroplanes. He carried out extensive research in the areas of electricity, sound and speech, having a dedicated interest in improving the teaching of the deaf.

Alexander Graham Bell's attention to hydrofoils in 1906 was in connection with Bell's work on airplanes. He was concerned with the possibility of taking off and landing on water, which he considered safer than land. His experiments did not get underway until 1908, a year after the Wright brothers had considered a similar solution, as mentioned earlier. Foil sections were developed empirically by Bell's colleagues Frederick W. (Cassey) Baldwin and Phillip L. Rhodes, a New York naval architect. Experiments with small scale models and full scale craft, which he called *HYDRODROMES*, continued for about five years, but were interrupted by a world tour that Bell and Baldwin undertook in 1911. They visited Forlanini in Italy where they witnessed tests on his 1.6 ton hydrofoil on Lake Maggiore. It is understood that Bell purchased some of Forlanini's patents.

Bell's work culminated in the HD-4, see Figure-2, which set a world speed record of 70.85 miles per hour in 1919. It weighed about 11,000 lbs. and was 60 ft long. The main torpedo-shaped hull, about six feet in diameter, was constructed of 1/2 inch wood planking reinforced with wire and canvas. The two rectangular pontoons were 14 feet 9 inches long and were attached on 20-foot centers. The craft was powered by two 12-cylinder, 350 hp water-cooled Liberty aircraft engines. These drove airscrews to produce a combined total thrust of 3400 pounds. The most significant design feature was what came to be called the Bell-Baldwin *ladder* foil system. There were three main sets of foil ladders which produced lift: two forward under the sponsors and one after under the hull. The aft foil ladder was steerable and acted as a rudder. In addition, there was another ladder foil placed at the nose of the craft. This so-called preventer foil, which came clear of the water at high speed was designed to avoid plough-in particularly

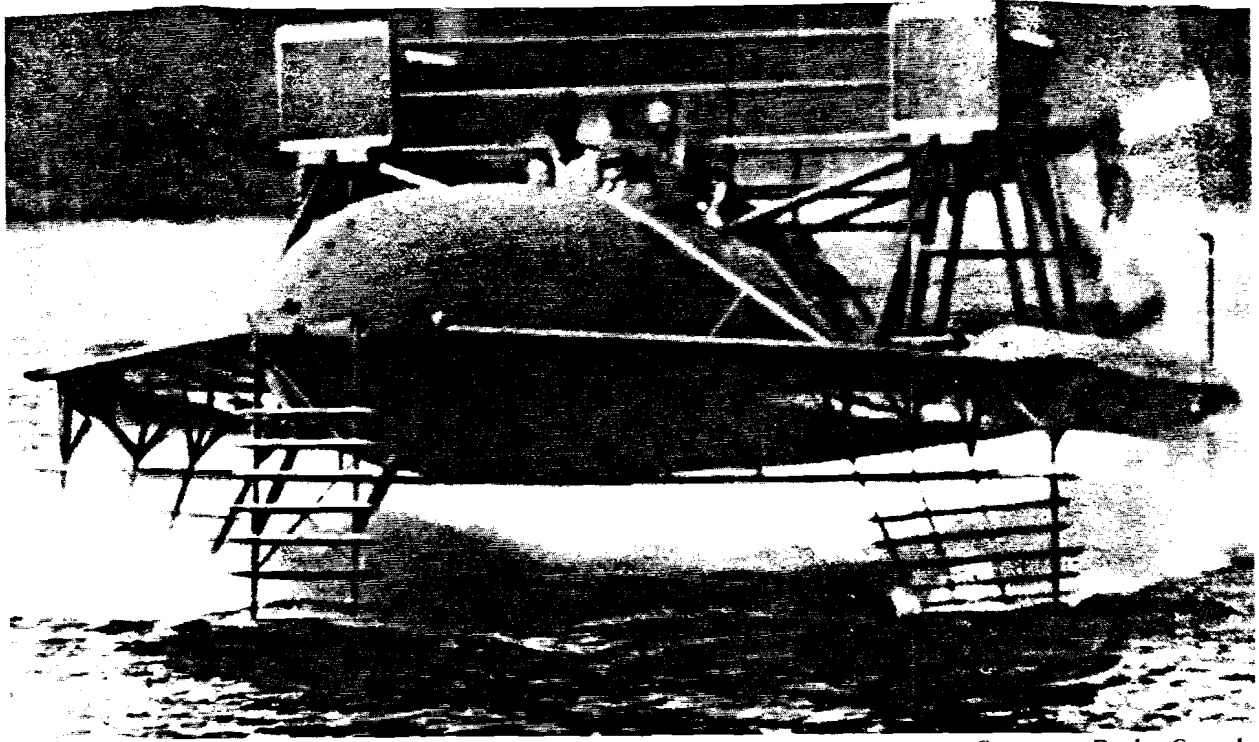


Figure 2. Bell-Baldwin Hydrofoil HD-4

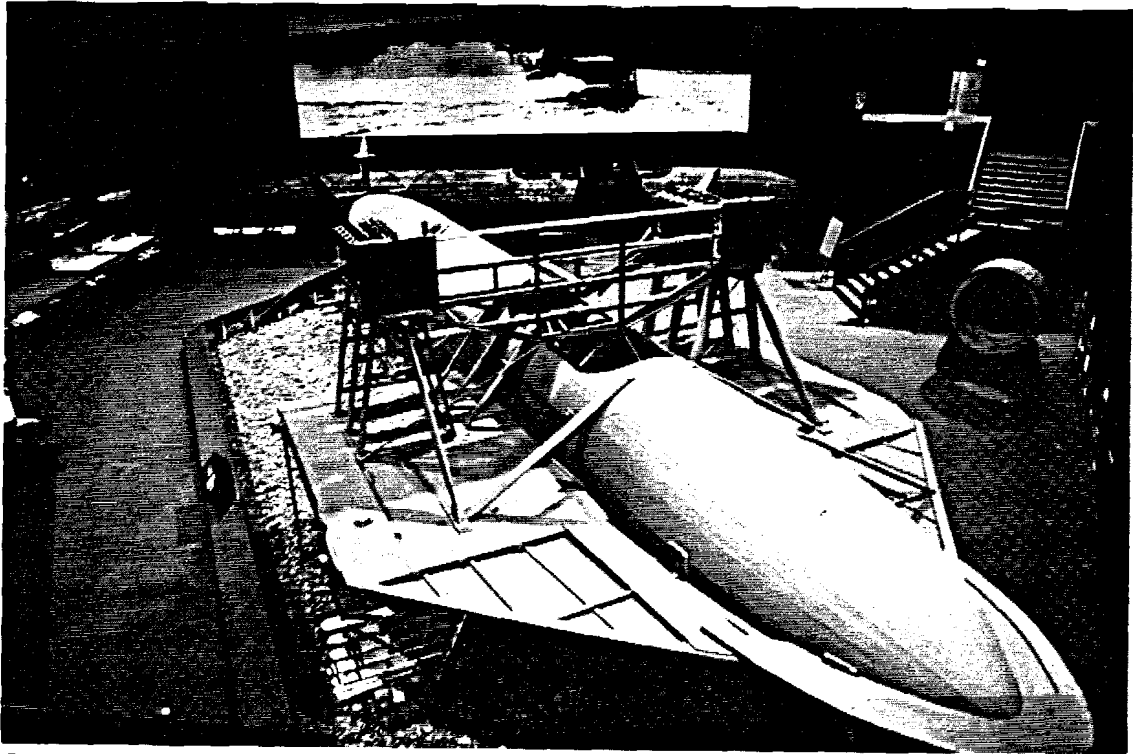
Courtesy Parks Canada

during takeoff. It may also be noted that there were three sets of wooden airfoils attached above the hull, as originally proposed by Forlanini to give added damping in choppy water.

The HD-4 represented a remarkable accomplishment, even by modern standards. Between 1918 and 1939 Baldwin and Rhodes continually sought to interest the U.S. Navy in the military applications of hydrofoil craft. In this they were unsuccessful. Some say it was because of a tendency of the Bell-Baldwin craft to porpoise. During this same period, about a dozen small hydrofoil pleasure craft, up to 35 feet in length, were designed under the direction of Phillip Rhodes. These were reported to have been quite successful. Alex Barbour and J. Birette, of the Parks Canada Bell Museum in Baddeck, Nova Scotia, completed in 1979 a full-scale replica of the HD-4 which is now on display in the museum. See Figure-3.

EUROPEAN DEVELOPMENTS

Perhaps the most significant new thrust in development of the hydrofoil concept did not come until 1927. It was during that year that Baron Hanns von Schertel began to experiment with hydrofoil craft in Germany, a year after he began studies at the Technical University in Berlin-Charlottenburg. Von Schertel described some of his hydrofoil experiences as follows:



Courtesy Parks Canada

Figure 3. Full-Scale Reconstruction of HD-4

The first trial runs in Berlin on Lake Wannsee with a boat powered by a very obsolete aircooled aircraft engine and propelled by an air screw, finished catastrophically. The old engine did not give enough power for taking off. When I noticed that the steering control was nearly ineffective I cut off the ignition, but the motor was already so much overheated that it went on running perfectly by self-ignition. The boat approached more and more the numerous, frantically escaping boats which had gathered around me and I had to count myself very lucky that I did not hit one of the fleeing boats with the propeller. The adventure finished with me crashing into an island on the lake. I abandoned the fully-submerged foil system for the seventh test boat built in 1935, in which all acquired experiences had been incorporated. The craft was provided with a V-shaped front and aft foil with trapezoid outer portions. She performed fully satisfactorily under all weather conditions on the Rhine River. With only 50 hp she carried seven persons at a speed of nearly 30 knots. This craft proved for the first time that a hydrofoil is a fast and economical means of transportation and that its seaworthiness could no longer be doubted. This attracted

representatives of the German Navy, Air Force, Ministry of Transportation and Finance and finally brought about the partnership with Gotthard Sachsenberg, with his shipbuilding organization.

In 1937, after a demonstration trip from Mainz to Cologne on the Rhine River, the Cologne-Dusseldorf Steamship Co. placed, with Gebruder Sachsenberg A.G. at Dessau, the world's first order for a commercial hydrofoil boat. To be on the safe side, the Schertel-Sachsenberg syndicate decided to build a larger test boat. It was completed at the outbreak of WWII and was later demonstrated to the German Navy. The war, however, prevented the fulfillment of the original order.

During WWII, von Schertel and the shipbuilder Sachsenberg collaborated in the construction of a number of hydrofoil boats for the German Navy. Research and design was under the direction of Prof. Georg Weinblum. (It may be noted that after WWII Prof. Weinblum, along with other German scientists, came to the David Taylor Model Basin when German scientists and engineers were recruited by the U.S. Navy under OPERATION PAPERCLIP.) In 1941, they launched the 1-ton VS-6. **Figure-4**, a mine-layer hydrofoil. It was 52.5 feet in length and was capable of speeds up to 47 knots. It was powered by two Hispano-Suiza gasoline engines of 1560 HP. In 1943 the 80-ton VS-8, **Figure-5**, was launched. It was 150 feet long and was designed to carry tanks and supplies to support Rommel's North African Campaign. The VS-8, although originally designed for a top speed of 45 knots, was actually limited to 37 knots. This was because the only engine that could be made available at the time was a Mercedes-Benz diesel with 1800 HP. The underpowered craft was stable in head seas but came off the foils in some tests in following seas. Further, in 1944 it suffered a casualty due to sabotage and was eventually beached. At this point it was decided to concentrate on further improvements to the VS-6. Meanwhile, another 17-ton craft, VS-7, **Figure-6**, designed by Dr. Otto Tietjens, was built in Schleswig at the Vertens Yacht Yard. Tietjens had begun his earlier experiments in Philadelphia, PA in 1930 before returning to Germany and continuing his work in parallel with von Schertel.

Comparison tests of the VS-6 and VS-7 were run and the latter proved to be much faster, attaining speeds up to 55 knots. However, the VS-7 demonstrated much poorer stability and maneuverability than that of the von Schertel boat.

The final hydrofoil craft in this series was the 46-ton VS-10. It was 92 feet long and was designed as a torpedo boat capable of speeds up to 60

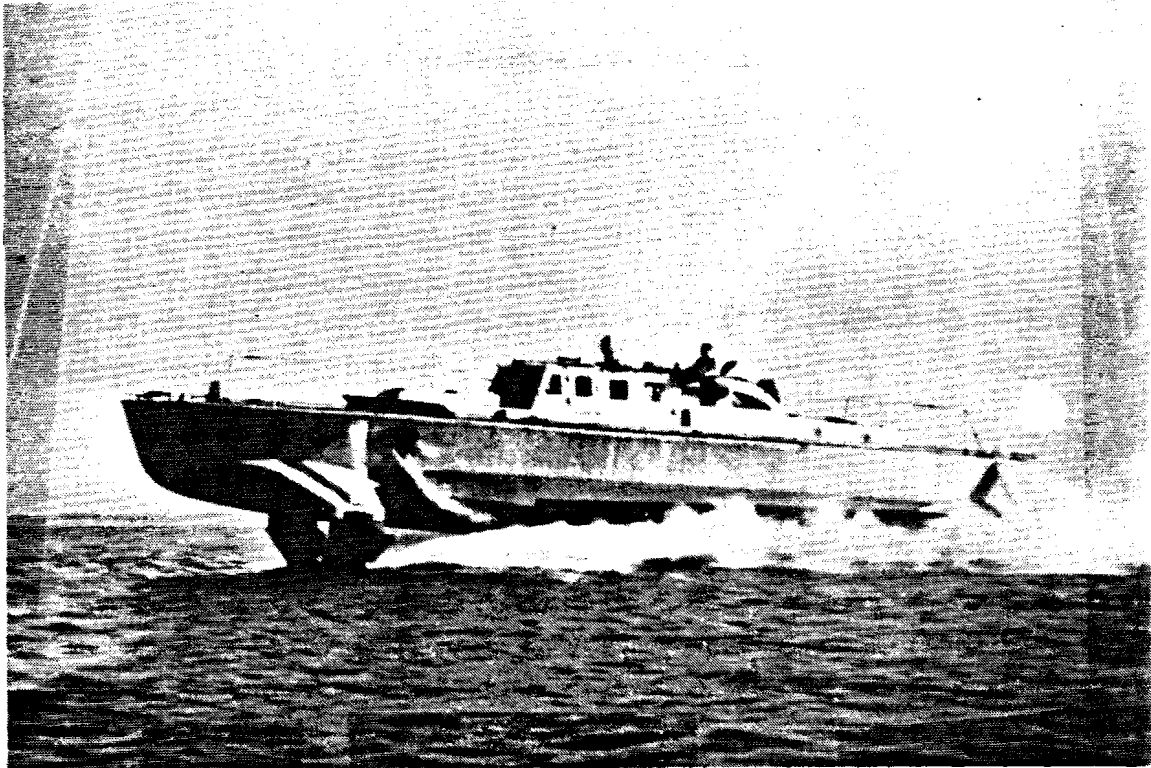


Figure 4. Schertel-Sachsenberg Hydrofoil VS-6

knots. Unfortunately, the day before its launching, it was completely destroyed in an air raid.

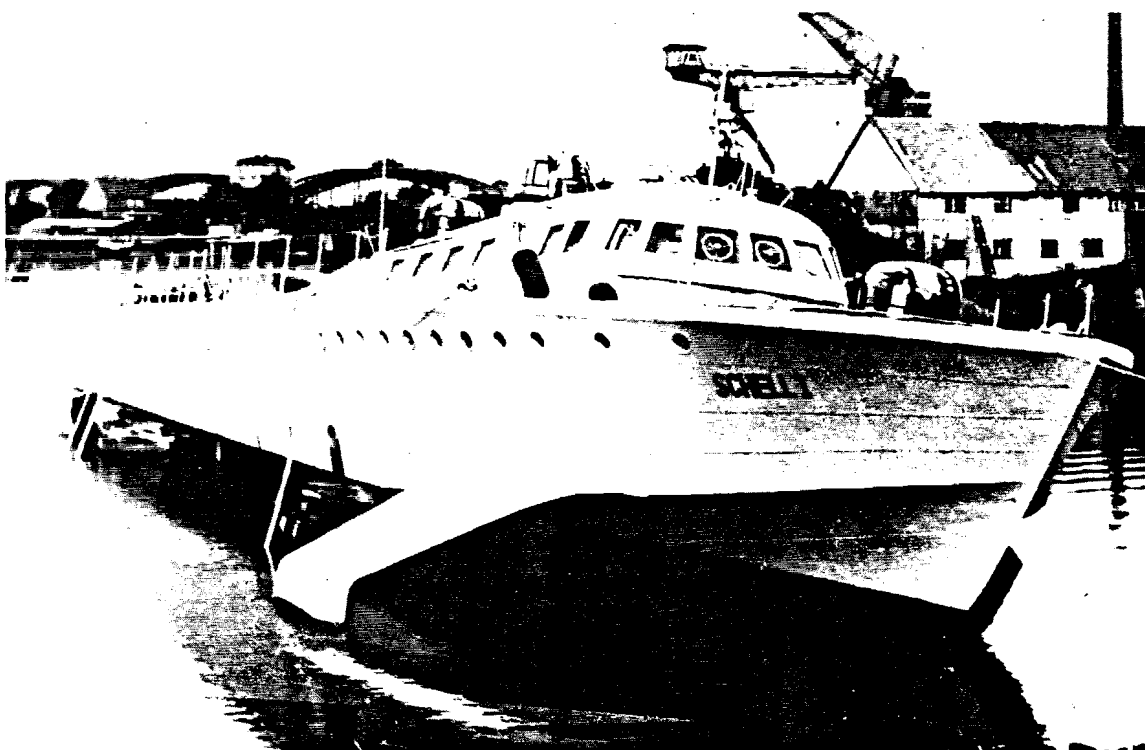


Figure 5. Schertel-Sachsenberg Hydrofoil VS-8

The last hydrofoils constructed by Schertel-Sachsenberg before the end of WWII were two small, single seat torpedo boats. They were designed to launch a torpedo over the stern and escape at 50 knots. Tests of these boats were interrupted by the war's ending.

After WWII, it was forbidden in Germany to build boats with speeds in excess of 12 knots. This led von Schertel and his partner Sachsenberg to move to Switzerland. There, in 1952, at a small shipyard in Stansstad, they completed the PT-10, Freccia d'Oro, (Golden Arrow), Figure-7. This 7-ton craft had 32 seats and was capable of speeds up to 35 knots. On 29 May 1952, the Konsortium of Schertel and Sachsenberg joined with the Kredit and Verwaltungs-Bank Zug, to form Supramar, A.G. based in Lucerne. That same year the Freccia d'Oro began the world's first hydrofoil passenger service on Lake Maggiore. In 1954 Supramar gave their first license to build craft of their design to the Leopoldo Rodriquez Shipyard in Messina, Italy.

In 1955 Rodriquez started production of the 32-ton PT-20, a 72-passenger hydrofoil with a cruise speed of 35 knots, Figure-8. The first of the series was named Freccia del Sole. It was built to satisfy maritime regulations and became the first passenger hydrofoil to receive class certification. As of this writing more than 150 hydrofoils have been built

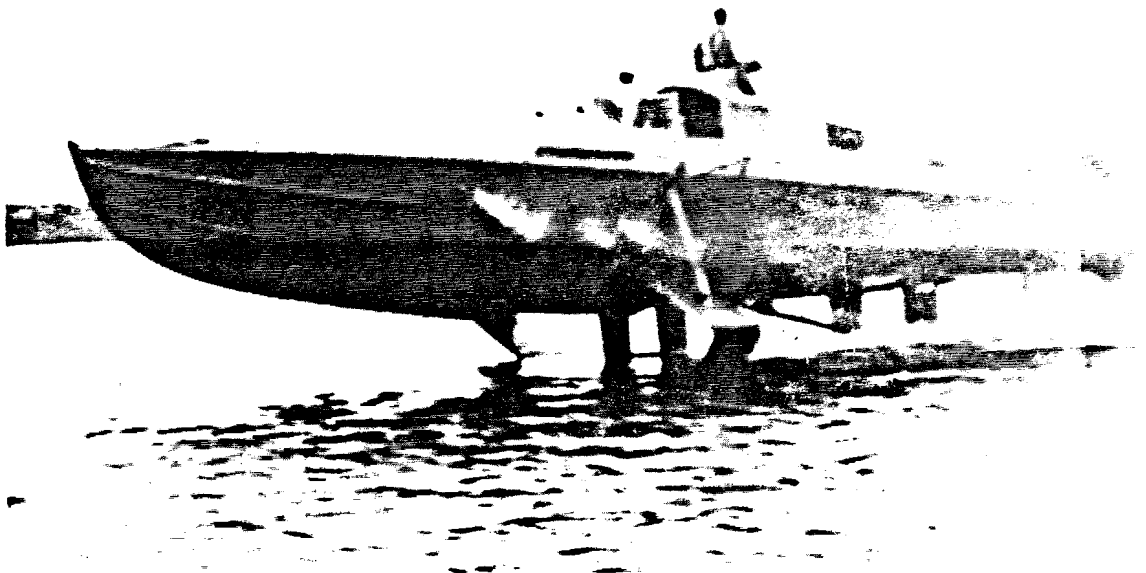


Figure 6. Tietjens Hydrofoil VS-7

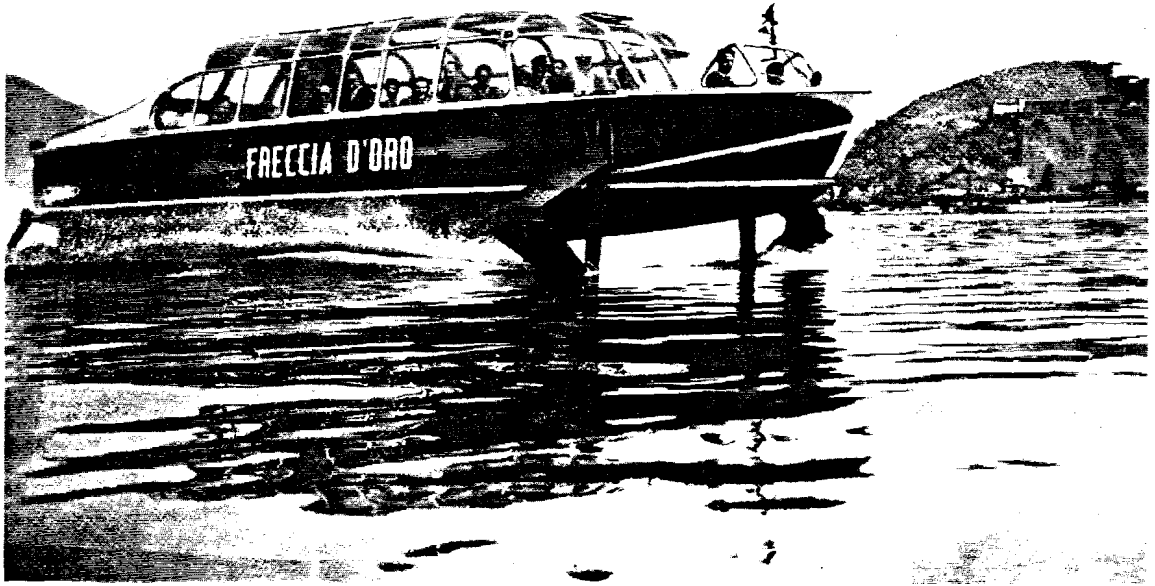


Figure 7. Supramar Hydrofoil PT-10, FRECCIA D'ORO

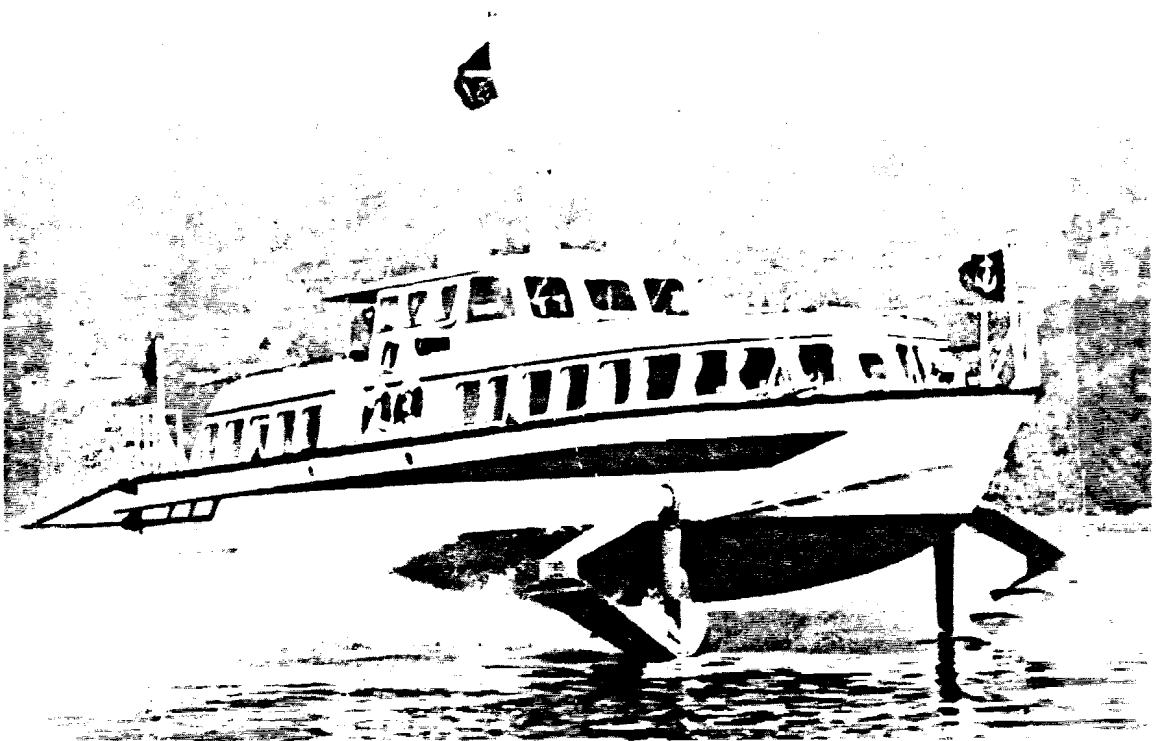


Figure 8. Supramar/Rodriquez Hydrofoil PT-20

under license to Supramar of which by far the largest number were built by Rodriguez up until 1971. Then Rodriguez undertook production of their own craft which were designated the RHS series (Rodriguez Hydrofoil Ship). **Figure-9** shows the RHS-160 passenger hydrofoil which is configured to carry about 160 passengers. The latest commercial hydrofoil in this series is the 200-passenger SUPER JUMBO RHS-200, shown in **Figure-10**.

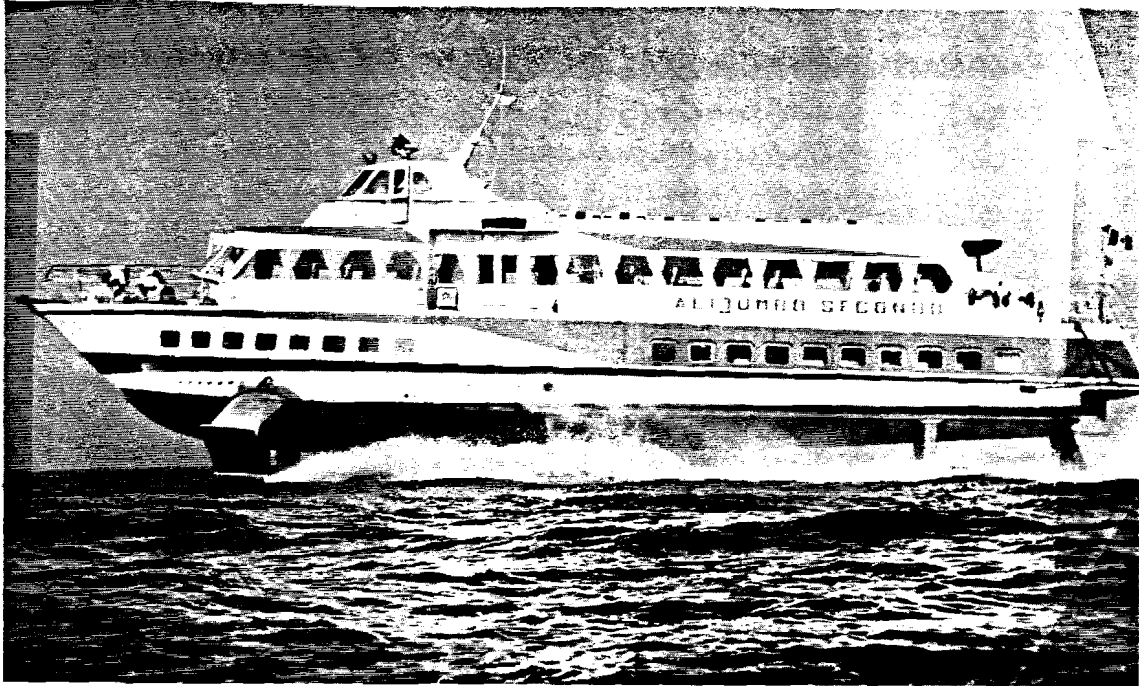


Figure 9. Rodriguez Hydrofoil RHS-160

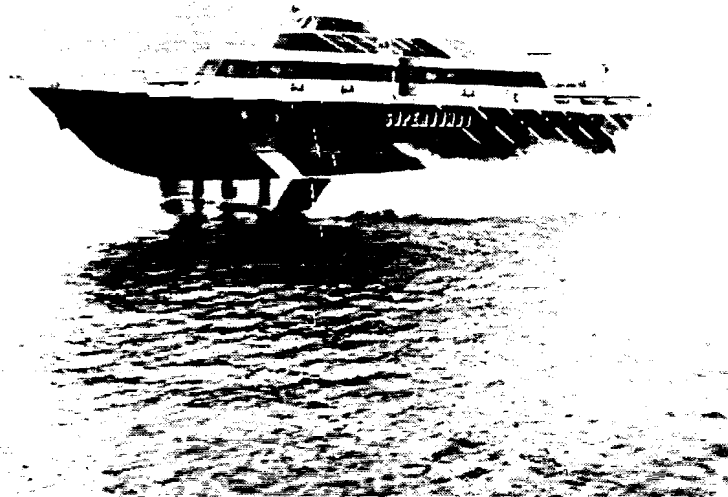


Figure 10. Rodriguez Hydrofoil RHS-200

EARLY U.S. NAVY DEVELOPMENTS

In the United States at the end of WWII, the work of such pioneers as von Schertel and Tietjens did not go unnoticed by the U.S. Navy. The Office of Naval Research, and the Navy's Bureau of Ships, with some support from the Bureau of Aeronautics, initiated in about 1947, a research program to further develop the hydrofoil craft concept. The objective was to establish a technology base adequate for the generation of criteria for design of operational craft to meet projected military requirements. A variety of analytical and experimental projects were undertaken by industrial contractors as well as private, university, and government laboratories. The Bureau of Ships' David Taylor Model Basin was one of the leading laboratories in this program. Studies were focused on design of optimum foil sections, cavitation, and ventilation phenomena, hydroelastic instability, structures and materials, hull form, propulsion, control, and many other technological problem areas.

R. Johnston, in his Nova Scotia paper, relates a series of events in the 1950's that had a significant impact on the development of hydrofoils in the U. S. One of them was the investigation of a trans-ocean, hydrofoil cargo carrier. Dr. Vannevar Bush, who was president of Carnegie Institution and scientific advisor to the President of the United States, had become concerned over the extensive shipping damage inflicted during World War II by only a few submarines. He directed a study seeking a solution to sustain trans-ocean operations in the event of hostilities involving a considerable number of submarines. One of the potential solutions envisioned was a hydrofoil cargo-carrier. The hydrofoil, with its speed and small submerged area, was considered virtually impervious to torpedo attack.

An organization was formed to design and build a 3500-ton hydrofoil cargo carrier with a destroyer-type hull in the 1951 to 1954 time frame. The Office of Naval Research (ONR) was given the program management responsibility for the U. S. Navy, and was supported by the Bureau of Ships, the Bureau of Aeronautics, and the David Taylor Model Basin (now David Taylor Research Center). The research was undertaken by the Hydrofoil Corporation of America, a non-profit organization formed by Dr. Bush. Gibbs and Cox was contracted to perform experiments that would lead to the design of the hydrofoil, and Bath Iron Works was selected as the construction yard. There were many contributors to the much needed technology to accomplish such an ambitious task, along with a series of Project Officers and Project Managers. Bob Johnston, then the ONR Project Manager, remembers the periodic personal reporting sessions with Dr. Bush on the progress of the

program. As time went on, the program became more and more overwhelming and impractical based on the inadequate state of hydrofoil knowledge at

that time. In 1954 it was concluded that to develop the propulsion system for a 3500-ton hydrofoil would tax the total capability of the U. S. industry. On this note the project ended.

Although the hydrofoil cargo-carrier was put aside, a number of hydrofoil initiatives resulted from the project. Gibbs and Cox entered the hydrofoil design field and made major contributions to stimulate hydrofoil technological development. The Hydrofoil Corporation of America assembled a technical group that derived basic hydrodynamic theories for submerged foil systems. One of the concepts that was investigated was the Constant Lift Control System (CLCS). The objective was to have the foils adjust automatically to the changes in angle of incidence due to the so-called orbital motions in waves.

This concept led to a test hydrofoil named LANTERN, shown in Figure-11, which was built to evaluate the CLCS. It was designed and built by THE HYDROFOIL CORPORATION, Annapolis, Maryland, and was one of the earliest hydrofoils using electronic controls. The 22,000 pound LANTERN first flew in 1953, had tandem submerged foils, displaced about 10 tons, was 35 feet long with a beam of 22 feet. The control system was a straight adaptation of an aircraft automatic control system. The craft was unusual from another point of view - the foils struts and hull were all the same shaped section, namely a symmetrical 24% thickness ratio NACA section. LANTERN was powered by a 200 horsepower Chrysler marine engine, had a takeoff speed of 14 knots and a maximum speed in calm water of only 18 knots.

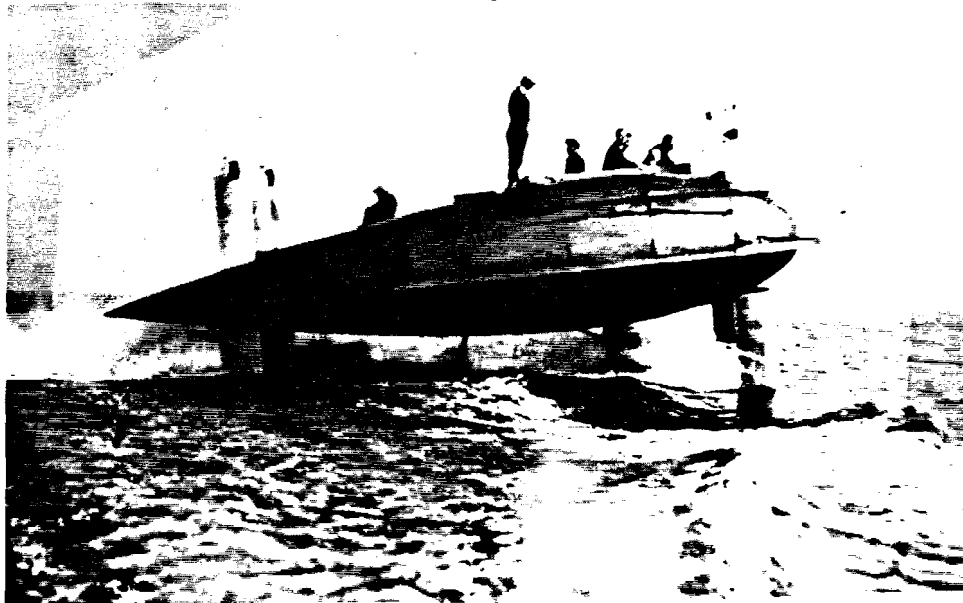


Figure 11. Hydrofoil Corporation LANTERN, HC-4

In the same time frame, a second test craft, designated the XCH-4 (Experimental Carl Hydrofoil No. 4), Figure-12, was completed by John H. Carl and Sons in Long Island, New York. This craft, known as the "Carl Boat" after the principal designer, William P. Carl, was 54 feet long, 19 feet in beam, and displaced 16,500 pounds. A system of ladder foils on two struts forward and a single strut afts supported the seaplane-like hull. Two 450 HP Pratt & Whitney R-985 Wasp Jr. air-cooled engines with air propellers were mounted on the top of the hull to power the craft. The ladders were comprised of V-foils which permitted smooth transition from the hullborne to the foilborne mode. In 1954 this craft attained a speed of about 74.4 mph in smooth water, exceeding Bell's record set in 1919. Because of the XCH-4's appearance, a story is told of an observer who called the Coast Guard during XCH-4 trials to report that a seaplane had been trying unsuccessfully to take off for several days and undoubtedly needed assistance.

Shortly after final tests of the XCH-4, Bill Carl left J.H. Carl and Sons to form his own company, Dynamic Developments, Inc. His partner in this venture was Bob Gilruth, another hydrofoil enthusiast. They initially developed and produced a hydrofoil fit for conversion of small runabouts. Grumman Aircraft Engineering Corp. purchased an interest in the company as a base for their entry into their hydrofoil market. Eventually they acquired the company.

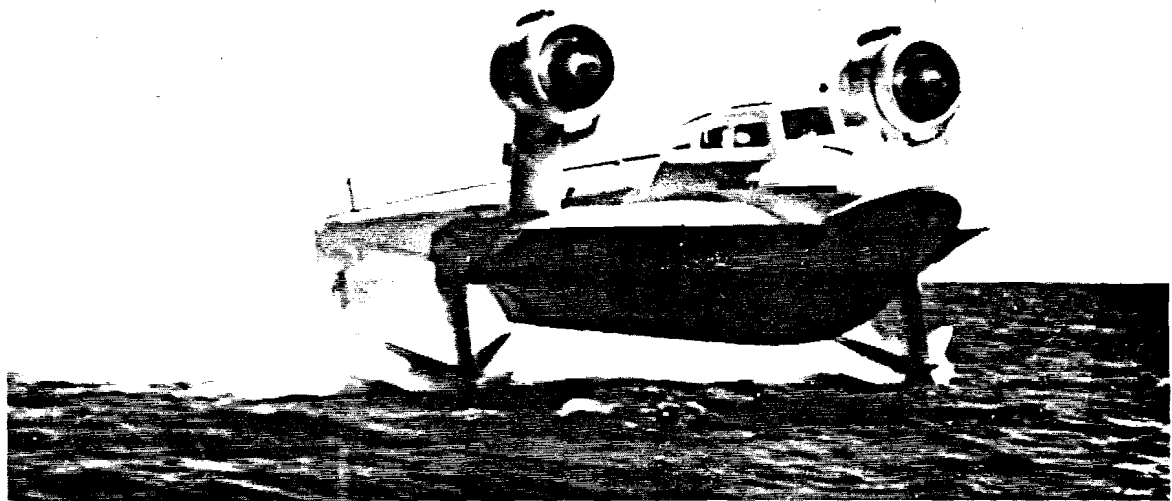


Figure 12. Experimental Carl Hydrofoil XCH-4

In 1951 the Office of Naval Research contracted with the Baker Manufacturing Co. of Evansville, Wisconsin for the construction of two 22-foot hydrofoils. These projects were directed by Gordon Baker, who has been described as a mechanical genius. The first of these hydrofoils was "HIGH POCKETS", shown in Figure-13, with a surface piercing foil configuration. The craft had four retractable "V"-foils which could be steered and rotated to provide a capability of banking into a turn.

The hull, of conventional form, was constructed of fiberglass reinforced plastic. It was 24 feet long overall with an extreme beam of about 15 feet including the V-foils on each corner. The maximum design displacement was 6000 pounds. The foils were solid extrusions of 24S-T4 aluminum of NACA 16-510 uniform section shape. The craft was powered by a Chrysler Crown Special gasoline engine, rated at 125 BHP, connected to a single propeller through a V-drive. The 45-degree V-foils proved significantly better in a seaway than the von Schertel *hoop* design. The craft operated in 5 to 6-foot waves off Pensacola, FL, attaining speeds up to about 35 knots.



Figure 13. Baker Hydrofoil, HIGH POCKETS

HIGH POCKETS was used extensively to demonstrate the capabilities of hydrofoil craft including the first flight by a CNO when ADM Carney was given a demonstration in the summer of 1953.

The second Baker hydrofoil, known as "HIGH TAIL", shown in Figure-14, had a controllable fully-submerged foil system. The three-foil system; one forward and two aft, had three mechanical sensors, one touching the water ahead of each foil. These sensors provided the input for controlling foil lift. Propulsion was provided by a propeller driven by an inboard marine engine through an angled shaft. The forward foil and struts were mounted on a vertical axis which provided steering while flying. The foils, sensors, and propeller were all hydraulically retractable for operating in shallow water. Since the foils were quite small, lift control was obtained by changing foil incidence, or angle, relative to a fixed reference using a mechanical-hydraulic autopilot.

Even though Baker's mechanical genius led to a very workable mechanical-hydraulic autopilot, the conclusion was that future autopilots should be electro-hydraulic. Gordon Baker's contributions during this experimental stage of hydrofoil development was considered significant and helpful for future design decisions.

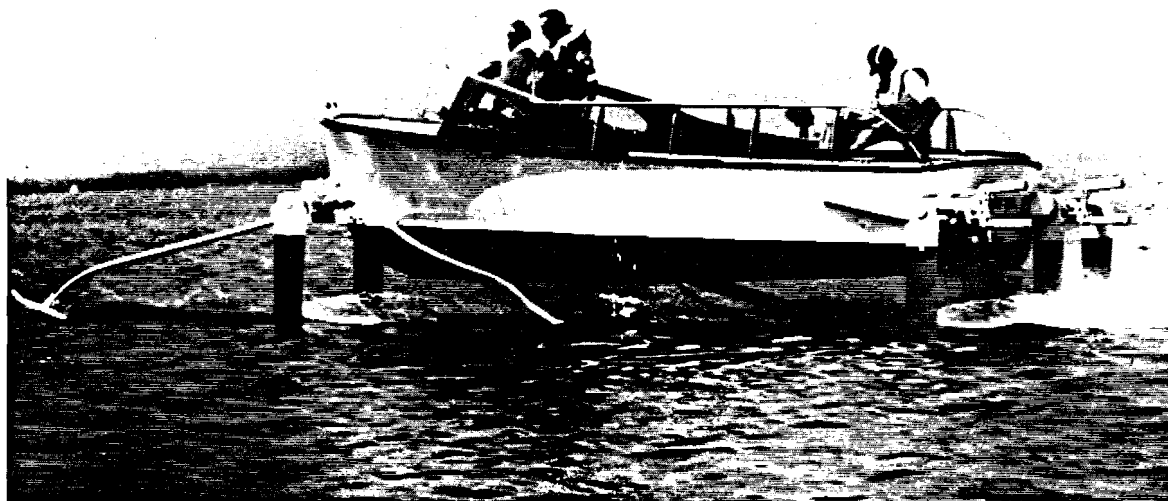


Figure 14. Baker Hydrofoil, HIGH TAIL

THE LANDING CRAFT DIVERSION

In 1953 the Navy' focus shifted to the applicability of hydrofoils for landing craft. It is understood that this was motivated by the availability of funds to develop and purchase a large number of new LCVPs. It was the Marine Corps desire to increase the speed of approach to landing on the beach. They noted that these speeds during the Korean War landings had not changed perceptibly since William the Conqueror headed for a beach in 1066.

A craft which contributed to the landing craft program and also the development of the modern hydrofoil is known as "HALOBATES", designed and completed in 1957 by the Miami Shipbuilding Corporation. The craft is shown in Figure-15 with "feeler" arms adapted from the Hook system. The name, HALOBATES, was suggested by the Marine Laboratory of the University of Miami since HALOBATES is a sea going insect which has forward extending feelers. The hydrofoil HALOBATES, a modified small landing craft, was 35.5 feet long with a beam of 11.7 feet and a full load displacement of 31,000 pounds. A 630 hp gasoline engine provided power for the craft which demonstrated speeds up to 34 knots in 5-foot waves. The design was complicated by the use of many ball and screw actuators necessary to provide retraction of the foil and propulsion system for the landing craft requirement. However, in spite of its relative success, this configuration led to a comment which in essence said: "If this is the way hydrofoils are to be built, we have no use for them in the Navy!". The feeler concept was certainly objectionable, and so, went their way.

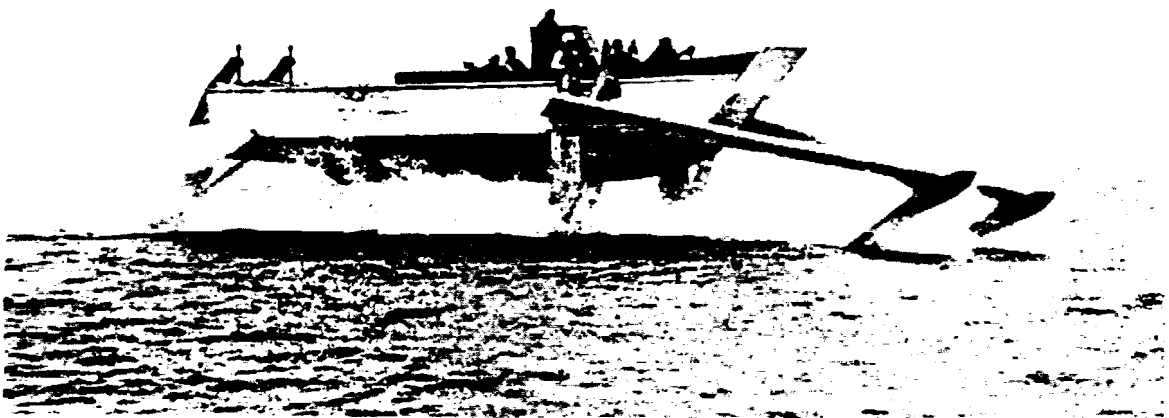


Figure 15. HALOBATES With Feeler Arms

An interesting aspect of the HALOBATES design was associated with the landing craft requirement. Not only did the foil and propulsion systems have to retract, but they were to continue to operate during the retraction process, that is, the craft was to be capable of flying continuously from relatively deep water up to the point it became hullborne as the water became very shallow. The aft propulsion "out-drive", shown in **Figure-16**, had not only to provide thrust during retraction, but remain steerable at all times.

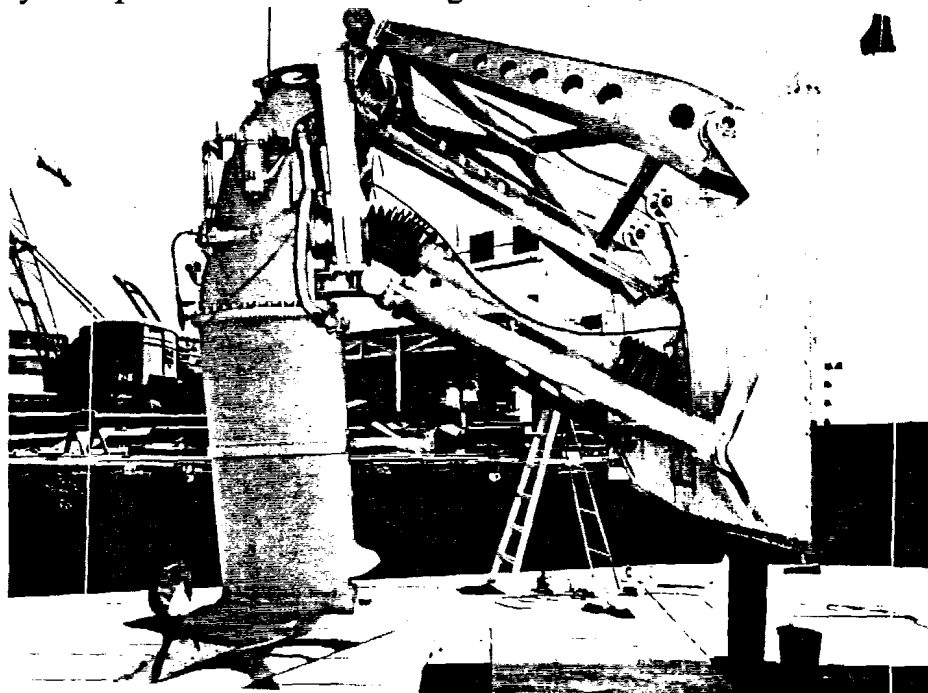


Figure 16 - HALOBATES Retractable, Steerable Propulsion System

Because of objections to its feelers, HALOBATES was reconfigured with an electronic automatic foil control system. The feelers were removed and a step-resistance incorporated along the leading edge of the two forward struts. This feature provided a height signal, based on wetted length, to the autopilot, which in turn controlled foil lift. Also, it was decided to replace the reciprocating gasoline engine with an AVCO T-53 gas turbine engine having about 1,000 hp.

Figure-17 shows the reconfigured craft. Note that the smokestack is not a steam boiler, but the exhaust duct for the gas turbine. This gas turbine installation marked a notable technological "first" for hydrofoils in particular, and in the marine field in general.

The second LCVP(H) was built by Baker Mfgr. Co. in the early 1960's and was named HIGHLANDER, **Figure-18**. It had four surface-piercing V-foils which were retractable and it could carry a payload of 8,000 pounds to the beach at 40 knots. It too was a modified LCVP much the same as HIGH POCKETS. It weighed about 10 tons in the light condition.

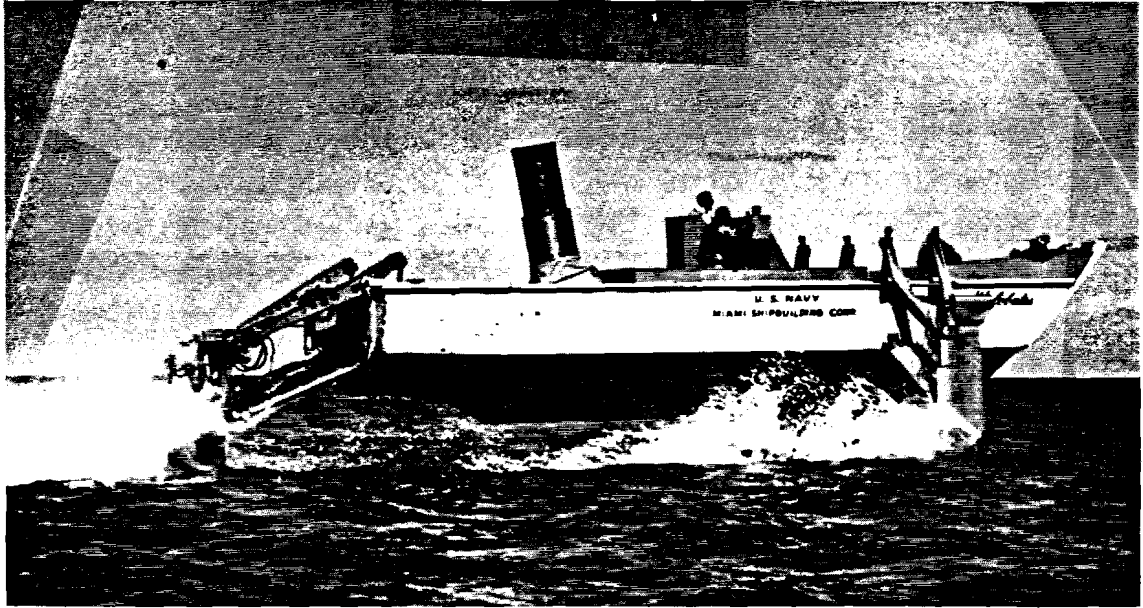


Figure 17. HALOBATES With Gas Turbine and Automatic Control System

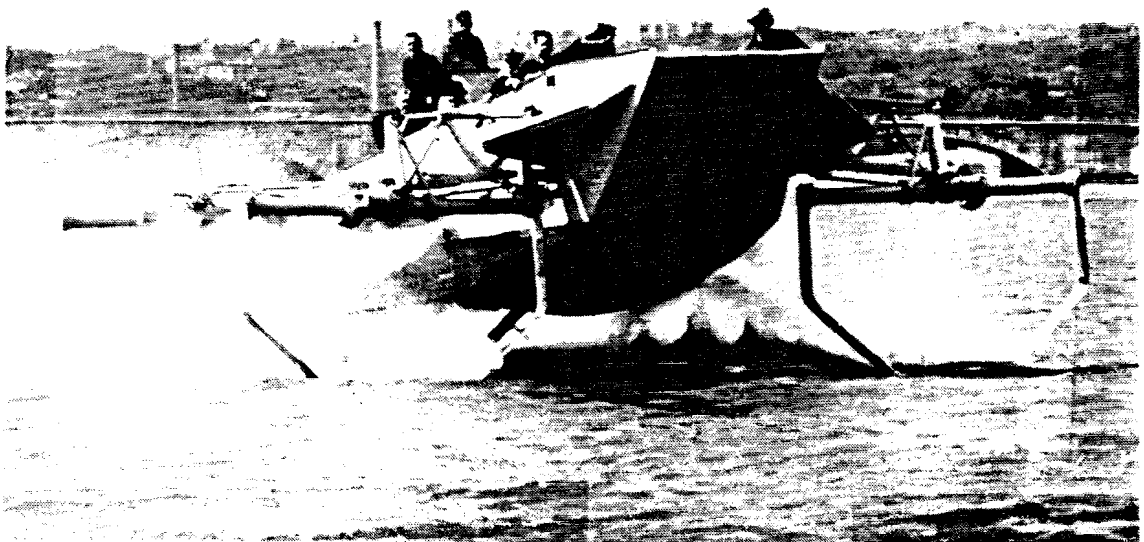


Figure 18. Baker Hydrofoil, HIGHLANDER, LCVP(H)

During this period the U.S. Army also became interested in the potential of foils to increase the speed of their amphibious DUKW. Miami Ship, building, working with Avco-Lycoming, was given a contract in 1957 to demonstrate a "flying" DUKW. An Avco T-53 gas turbine engine was installed along with an electronic autopilot like that in HALOBATES. Retractable submerged foils were attached to complete the modification. Trials were run near Miami, Florida during which a speed of about 30 knots was achieved in calm water compared to the DUKW's normal water speed of around 5 knots.

In spite of the mechanical complexity of the Flying DUKW, Figure-19, as well as other disadvantages, the U.S. Marine Corps continued to have interest in the use of hydrofoils on wheeled amphibians. This led to their award of contracts for two competing designs of an LVHX. The LVHX-1, Figure-20, was built by Avco-Lycoming, and the LVHX-2, Figure-21, by FMC. Both were designed to meet the same requirement with aluminum hulls 38 feet long and a capability of carrying a 5-ton payload at a speed of 35 knots. LVHX-1 had a submerged-foil system and LVHX-2 employed surface-piercing foils forward with a single submerged foil aft.

During the trials program that followed it finally became clear that the complexities and costs of such features as foil retraction and high speed gas turbine propulsion presented too great a penalty to pay for the increased water speed. As a result, further pursuit of hydrofoil landing craft was terminated.

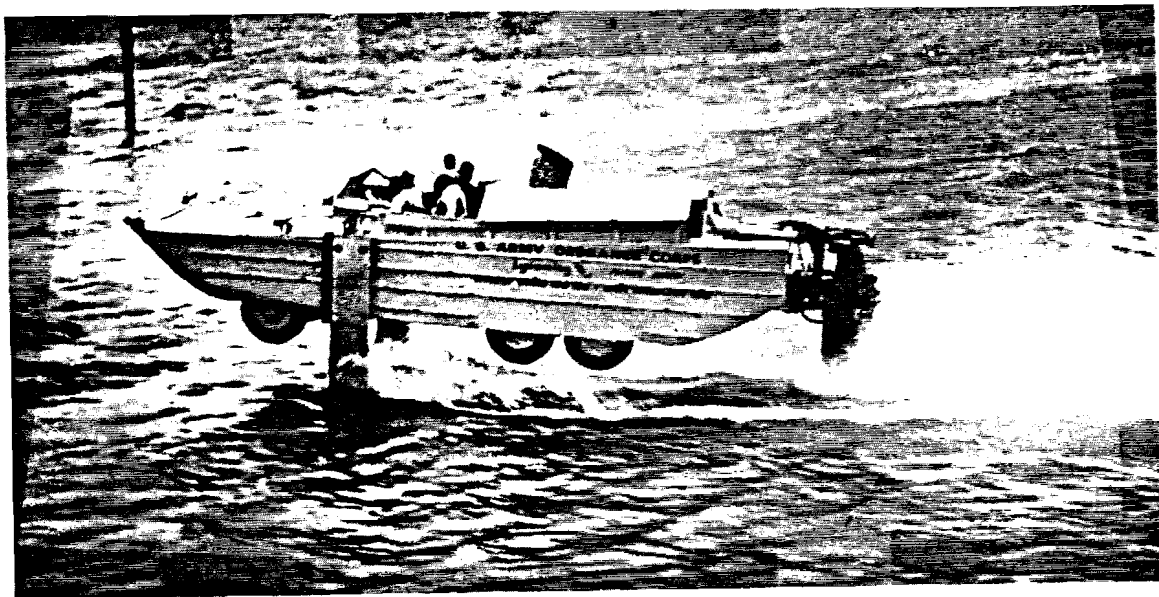


Figure 19. Miami Shipbuilding Flying DUKW

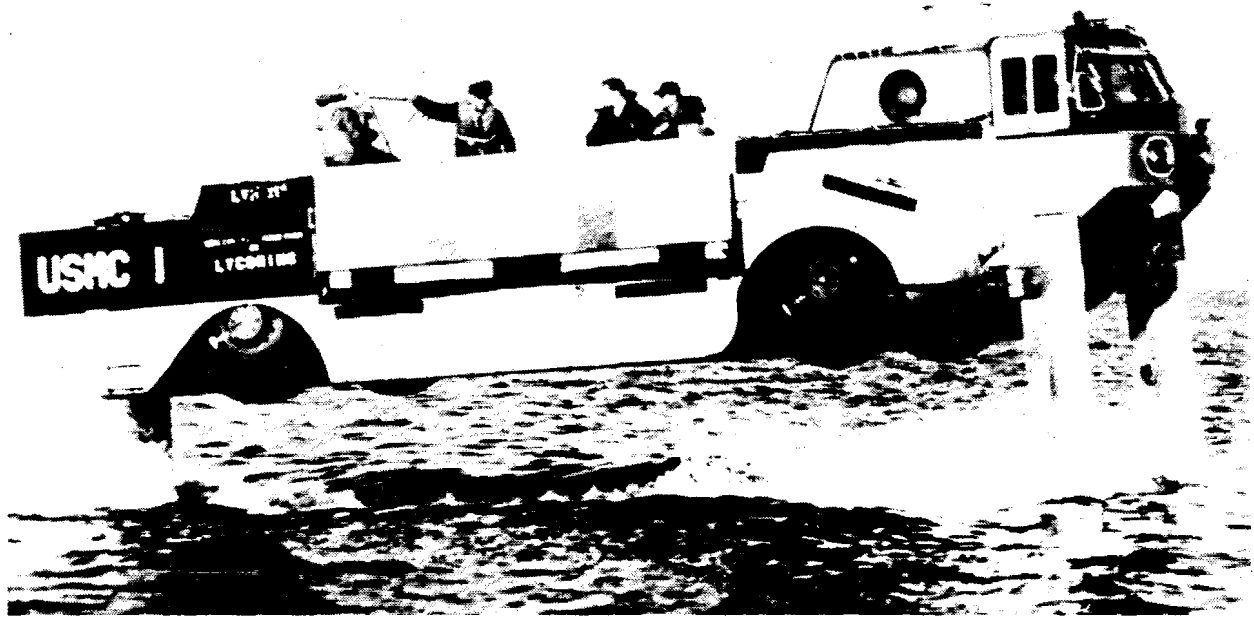


Figure 20. Avco Lycoming Hydrofoil Amphibian LVHX-1

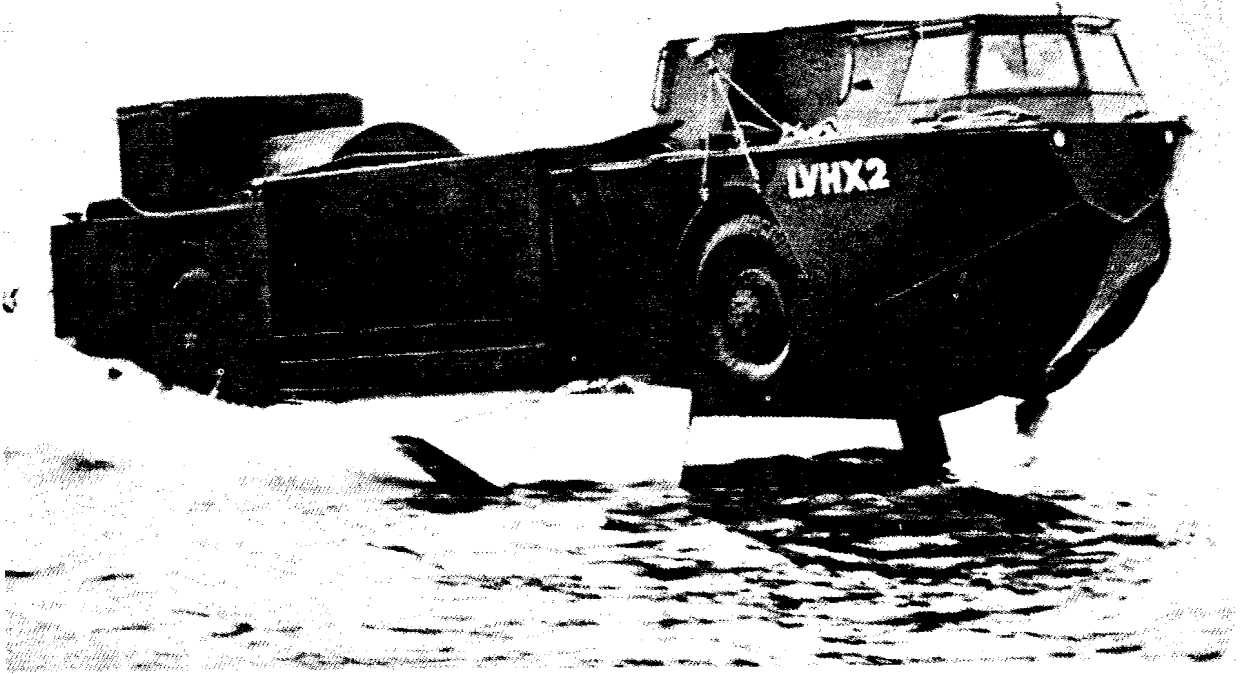


Figure 21a. Foilborne

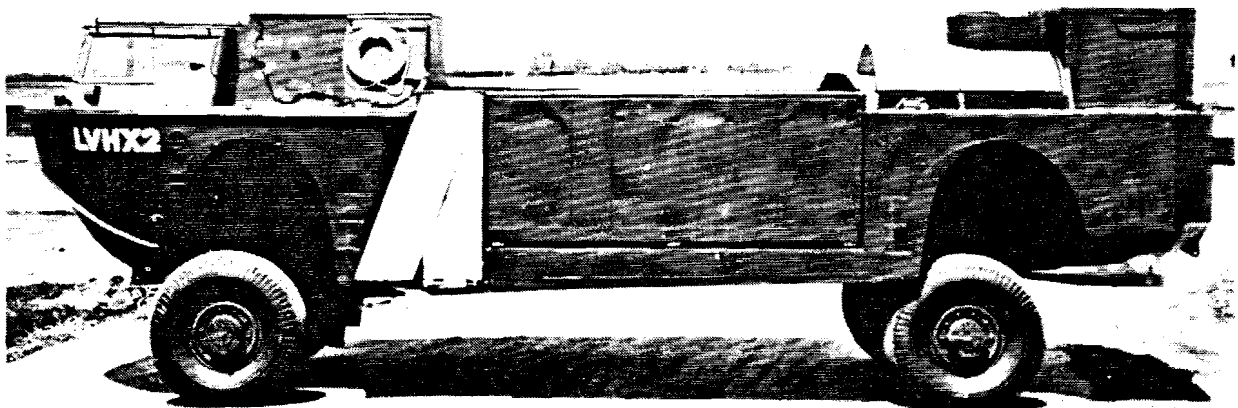


Figure 21b. On Wheels
Figure 21. FMC Hydrofoil Amphibian LVHX-2

THE CANADIAN CONNECTION

After WWII, in Canada there was also a rekindled interest in hydrofoils. In 1948 Duncan Hodgson, a former Canadian naval officer, commissioned Bell and Baldwin's associate, Phillip Rhodes, to design a hydrofoil craft capable of setting a new world water speed record. Hodgson was subsequently persuaded to divert his craft to a demonstration of the military potential of the hydrofoil. In 1951 a project for this purpose was initiated at the Naval Research Establishment, Dartmouth, Nova Scotia. Michael C. Eames, a naval architect at NRE, was charged with the responsibility for this project. (He remains today as Canada's leading authority on hydrofoils and other advanced naval craft.) The hydrofoil designed by Rhodes was 45 feet long with a displacement of 5 tons. It was officially designated R-100 and unofficially named MASSAWIPPI in recognition of its having been built on Lake Massawippi in Quebec. The initial ladder foil configuration clearly reflects Rhodes' earlier association with the Bell-Baldwin team. In trials conducted by NRE this first design was found to be unsatisfactory. As a result, a complete redesign was made, **Figure-22**. The new foil system permitted an increase in displacement to 7.5 tons. Further trials in 1956 demonstrated good performance and speeds up to 45 knots were achieved in 6-foot waves.

An important joint U.S.-Canadian effort was included in the R-100 trials. The U.S. provided a three-bladed supercavitating propeller, designed according to Marshall Tulin of DTMB, for evaluation on the Canadian craft.

After an initial structural failure of the blades, a strengthened version was successfully demonstrated. This led to later use of this type of propeller on both U.S. and Canadian hydrofoils.

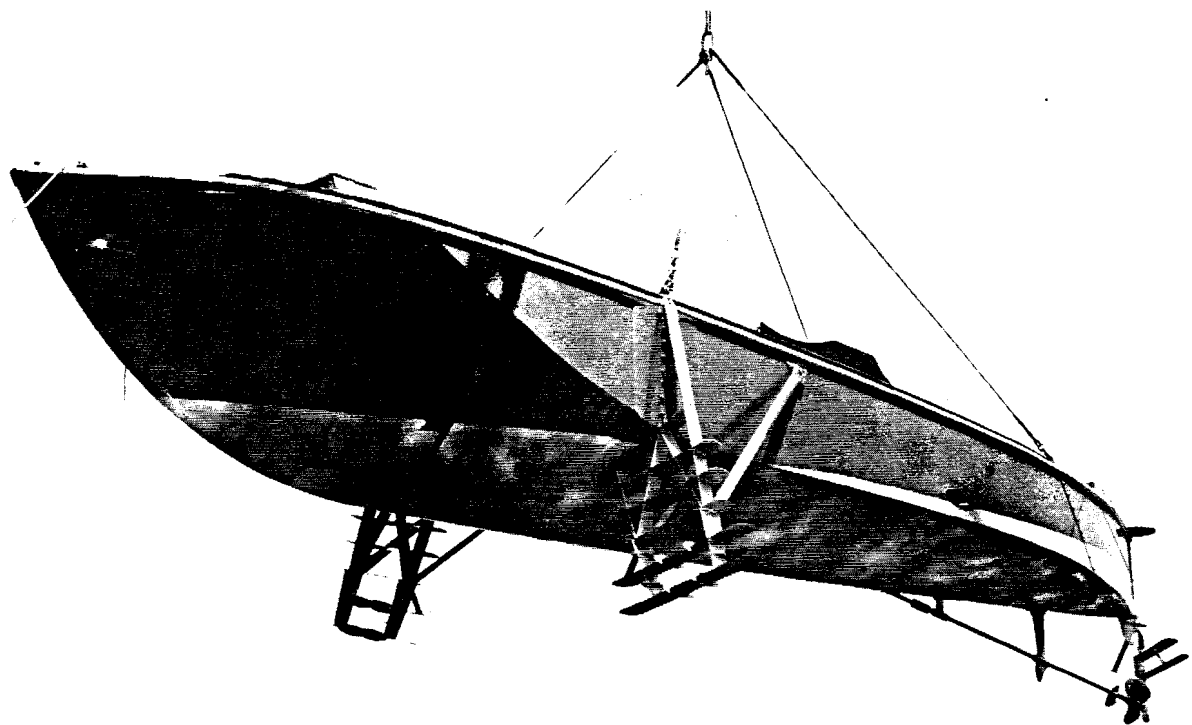


Figure 22a. Original Foils

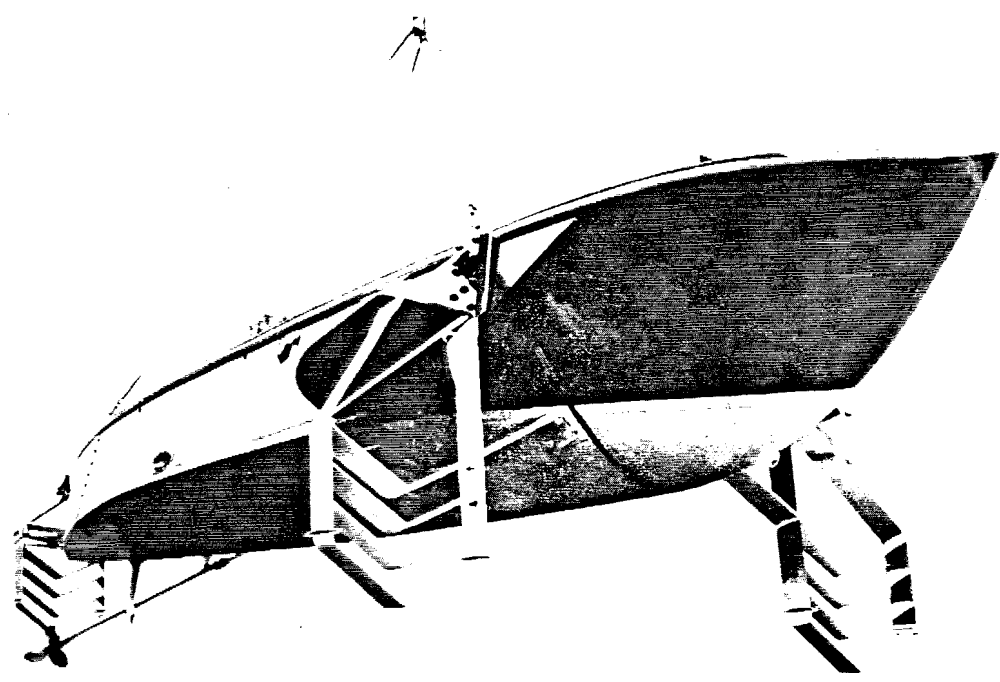


Figure 22b. Modified Foils

Figure 22. Canadian Hydrofoil, MASSAWIPPI, R-100

With encouragement from the United Kingdom along with successful trials of R-100, Canada decided to fund another test craft which was built in England by Saunders-Roe. This 17-ton craft, designated R-103, Figure-23, was initially named BRAS D'OR, and later renamed BADDECK. It had several design features of special note. Although the foil configuration was similar to that of the modified R-100, the foils and struts, instead of being solid, were built up of aluminum sheet riveted over aluminum ribs and stringers. The hull was also aluminum instead of wood as used in R-100. Of particular note is the use of a center strut which housed a right-angle bevel gear transmission driving propellers on each end of the propulsion pod. This represented a significant departure from the long inclined shaft used in R-100. Power was supplied by two 12-cylinder Rolls Royce Griffon gasoline engines with a rating of 1,500 HP at 3,000 RPM.

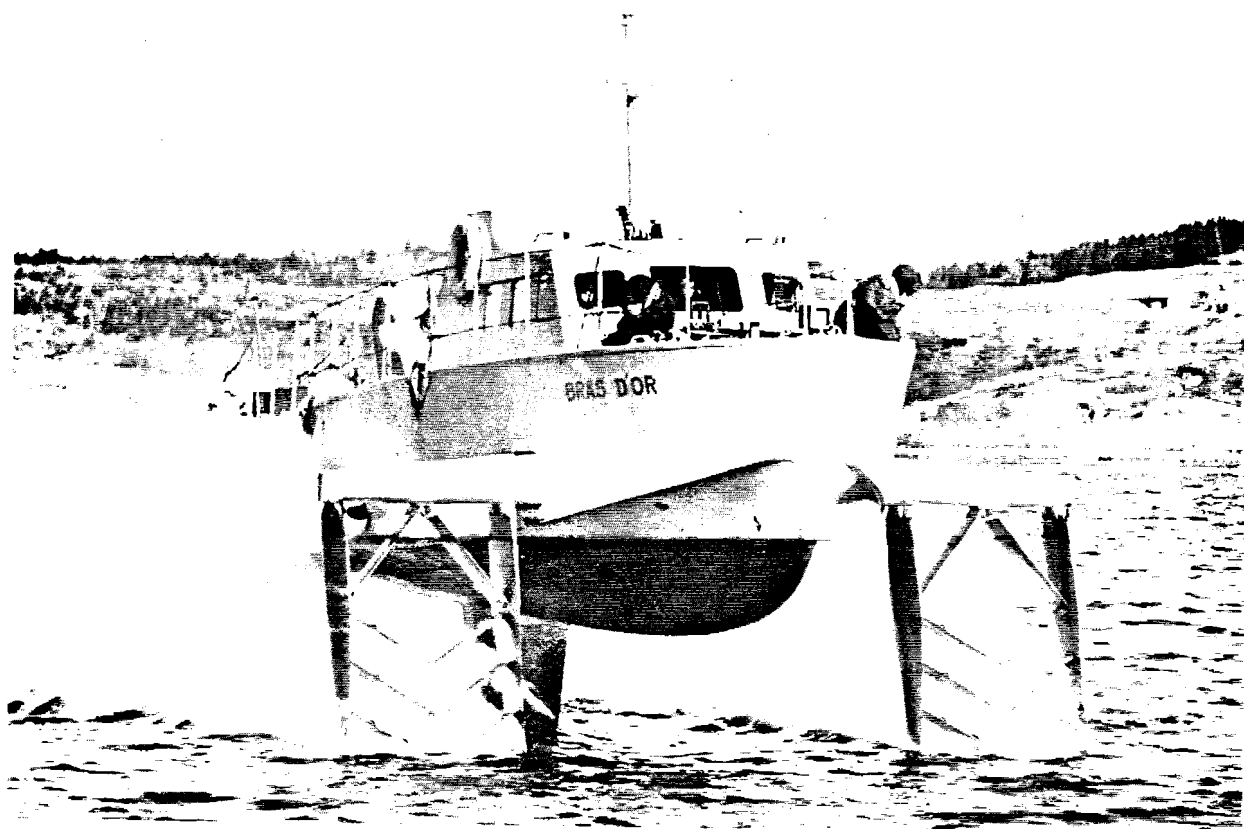


Figure 23. Canadian Hydrofoil R-103, Built by Saunders-Roe

The trials of R-103, which began in 1958, proved to be somewhat of a disappointment. There was, however, one particularly important result that strongly influenced hydrofoil design philosophy. The Canadians concluded that the Bell-Baldwin airplane configuration was not the best approach to design of a surface-piercing hydrofoil for operation in rough seas. To the contrary, it was decided that the forward foil should be relatively insensitive to angle of attack and act as a trimming device allowing the main stern foil to

respond in advance of an incoming wave. The forward foil should, therefore, be small relative to the main lifting surfaces. Thus, it was concluded that a canard arrangement was essential for good seakeeping with surface-piercing foils.

In 1959, with continued confidence in the value of hydrofoils for the Canadian Navy, NRE undertook a study of design requirements for a nominal 200-ton ASW hydrofoil ship designated R-200. The design concept that resulted was reviewed in January 1960 by experts from the U.S., U.K., and Canada with the conclusion that the concept was sound. By this time the U.S. was well underway with their program to construct a 120-ton ASW hydrofoil with a fully-submerged foil system and autopilot control. It was agreed that the U.S. and Canadian approaches would be complementary in expanding the data base and providing the opportunity for comparison of two quite different designs.

In August 1960 a contract was awarded to DeHavilland Aircraft of Canada to carry out engineering studies and to determine the technical feasibility of the R-200 design. Based on the positive conclusions that resulted, a second contract was awarded to develop a preliminary design. Other work was also supported to carry out model tests and an in-depth examination of some of the more critical system details. In May 1963 this led to award of a three-phase contract to DeHavilland which called for preparation of contract plans and specification, detailed design and construction, and the conduct of performance trials. DeHavilland, in turn, subcontracted fabrication of the hull and installation of ship systems to Marine Industries Ltd. in Sorel, Quebec. During construction on 5 November 1966, there was a disastrous fire in the main machinery space which almost caused termination of the program. In spite of the delays and cost increase, however, the ship, designated FHE-400 and named BRAS D'OR, was completed. It arrived in its slave dock in Halifax, N.S. on 1 July 1968 to begin a long series of trials. Figures-24 and Figure-25 show various views of FHE-400 which, although no longer operational, remains even today the most sophisticated and advanced design of a surface-piercing hydrofoil. Its design and extensive trials program contributed significantly to the technical data base and this was invaluable in complementing the U.S. development program.

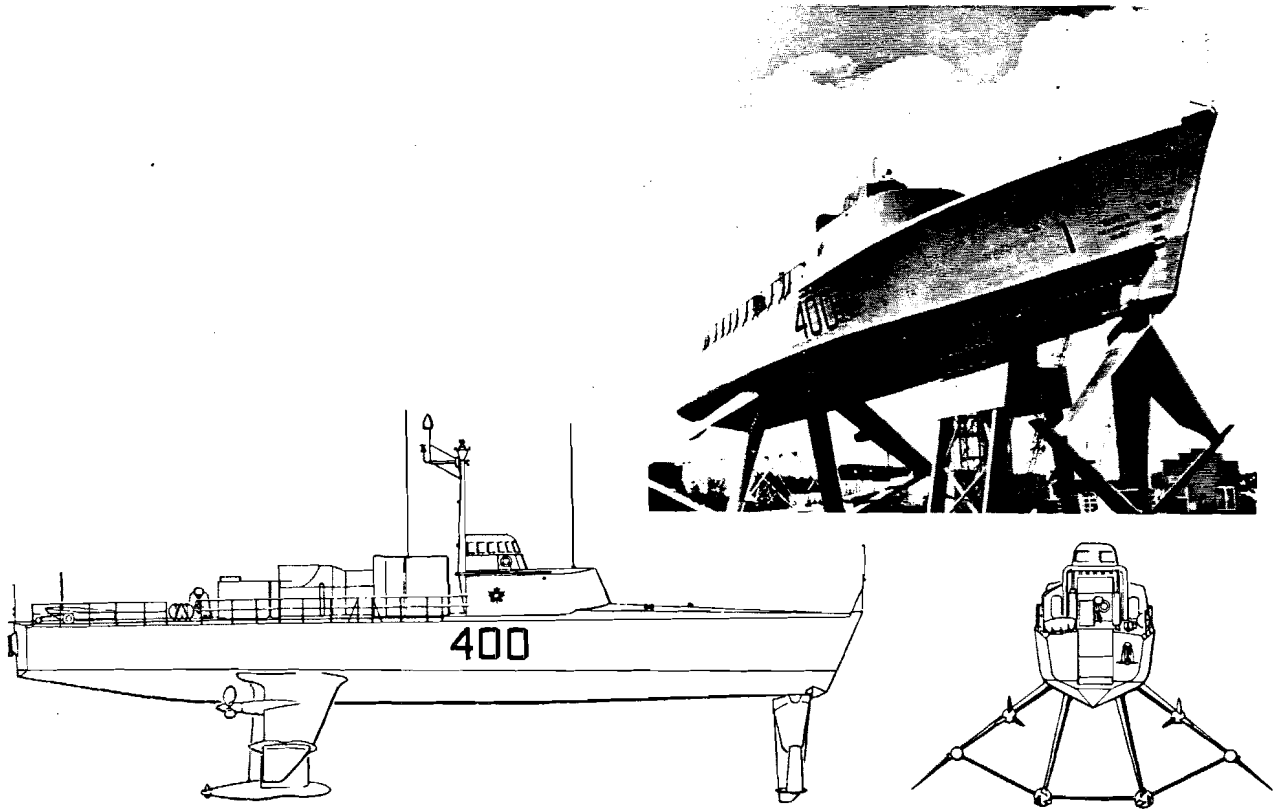


Figure 24. Views of Canadian Navy Hydrofoil, BRAS D'OR, FHE-400

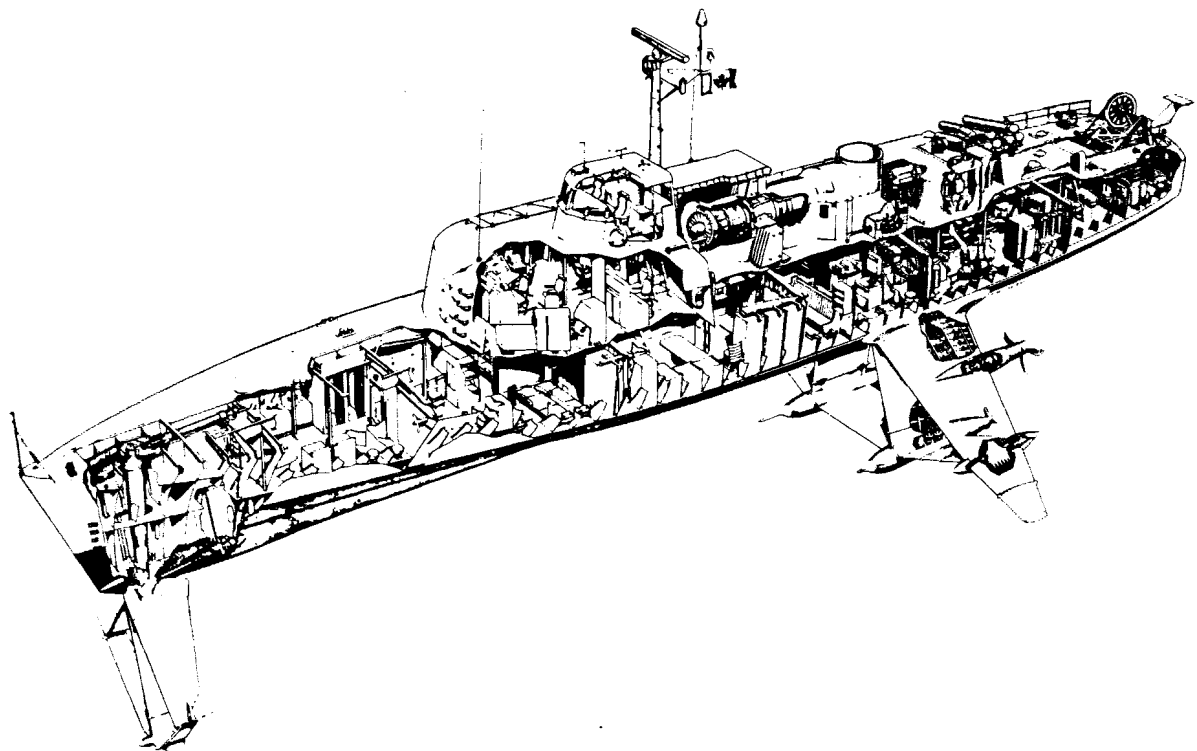


Figure 25. Cutaway View of HMCS BRAS D'OR, FHE-400

DEVELOPMENT OF SEA LEGS

In parallel with efforts to develop a hydrofoil landing craft, the U.S. Navy was pursuing another line of endeavor which was to have a much more far-reaching impact on the future of hydrofoil craft. During the early 1950's, with Navy support, the Gibbs and Cox firm of naval architects, designed a versatile testcraft which was built by Bath Iron Works. This craft, **Figure-26**, was aptly named the BIW. It was configured to test a variety of different foil arrangements and types as well as different control schemes. It was 20 feet long with a 5-foot beam and displaced about 1,800 pounds. It was powered by a 22-HP outboard motor. In carrying out this program, Gibbs and Cox assembled an excellent technical team under the direction of Tom Buermann which included Dr. John Breslin, Dr. S.F. Hoerner, L.E. Sutton, and Richard Browne among others. It was on BIW that the sonic height sensor was developed.

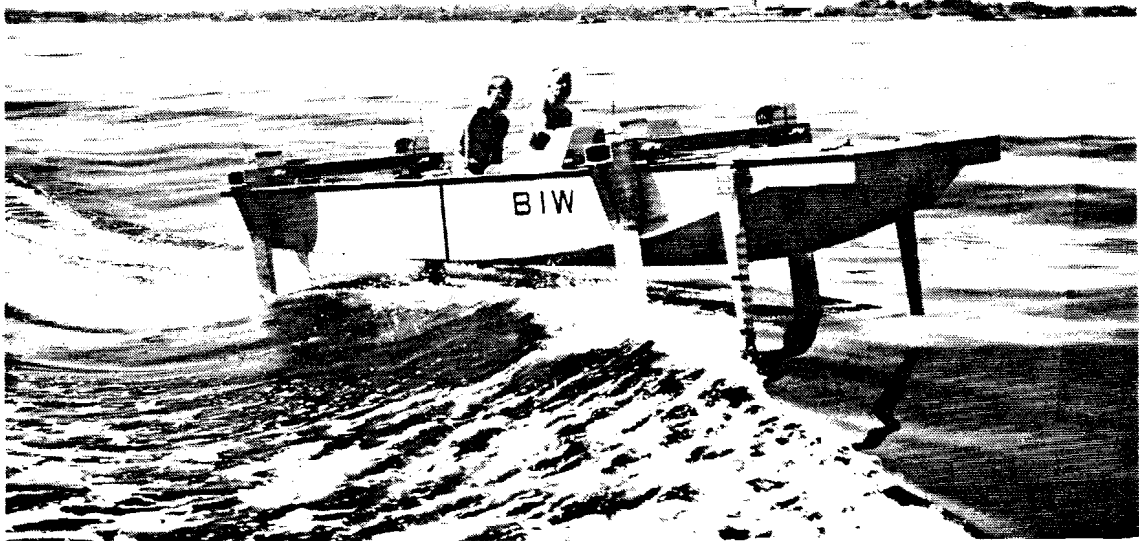


Figure 26. Gibbs and Cox/Bath Iron Works Hydrofoil BIW

With the knowledge gained from this test craft, in 1954, Sutton and Browne undertook the modification of a Chris-Craft hull, adding fully-submerged foils in a canard arrangement and an electronic autopilot stabilization system developed by the Draper Laboratory of MIT. This new test craft was named SEA LEGS, **Figure-27**. The hull was 28.5 feet long

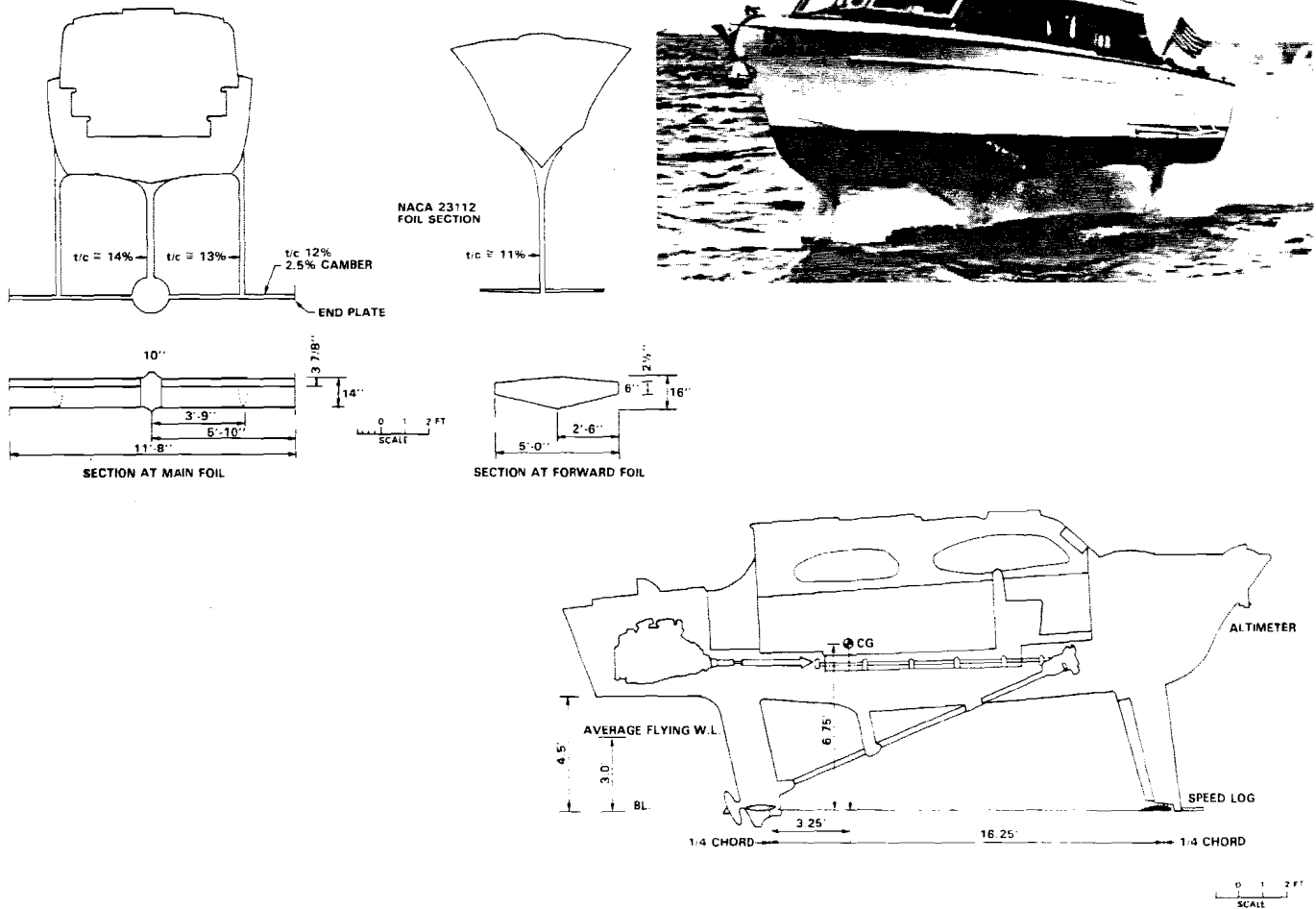


Figure 27. Gibbs and Cox Hydrofoil Test Craft, SEA LEGS

with a 9-foot beam. As modified, it displaced about 5 tons. It was powered by a 235-H.P. Chrysler marine gasoline engine connected to a 19-inch propeller thru a V-drive and angled shaft, Figure-27. The foils were of aluminum with a German "Walchner" section shape, 12% thick. Forward foil area was 4.6 square feet and the aft foil was 11.7 square feet. The electronic autopilot contained 160 vacuum tubes. Signal input to control flying height was obtained from a bow-mounted sonic height sensor similar to that developed on BIW.

SEA LEGS made its first flight in 1957 and demonstrated excellent seakeeping performance in rough seas at speeds up to 27 knots. During the latter part of 1957 and early 1958, the craft continued to provide demonstrations for Navy military and civilian visitors. In June 1958, at the urging of CDR R. W. (Randy) King of BuShips (now a retired Rear Admiral) the Chief of Naval Operations. ADM Arleigh Burke, approved a demonstration trip to the Washington, D.C. area. With hasty preparations for the trip underway, LCDR Ken Wilson (now also a retired Rear Admiral) who was then liaison officer in the Preliminary Design Branch of BuShips, made arrangements for SEA LEGS to be escorted by a Navy torpedo boat, the PT-812.

After a false start and return to the Gibbs and Cox pier in New York due to failure of a foil control attachment, the craft finally got underway for Cape May on 15 July. CDR Wm. MacNicholson was aboard was official Navy observer. (Now retired as a Captain, he was another of the key ED's in BuShips who believed strongly in the future of Navy hydrofoils). At that time, he was the Project Officer responsible for all small craft design in BuShips Code 440.

On the afternoon of 16 July 1958, SEA LEGS arrived at the Navy's small boat facility on the Severn River in Annapolis, Maryland and was lifted from the water by a Navy floating crane. During the sometimes eventful voyage it had averaged 23 knots in seas up to 4 to 5 feet and clearly demonstrated its superior seakeeping performance compared to that of the PT boat, outrunning the larger boat all the way.

After a week of successful demonstrations in the Annapolis area, on 26 July SEA LEGS undertook the 170-mile run to Washington. LCDR Ken Wilson was aboard as the Navy's representative. They arrived at the Naval Gun Factory pier at 1540 hours after a relatively uneventful trip down Chesapeake Bay and up to the Potomac River. The following day, Sunday, 27 July, they took aboard the CNO, ADM Arleigh Burke; the VCNO, ADM James Russell; the Chief of BuShips, RADM Albert Mumma; and CAPT Robert Madden, Director of Ship Design Division. (CAPT Mac Nicholson recalls that, 15 or 20 minutes before the CNO party was due to arrive, they "blew a tube" on the warm-up run and crash landed. Dick Browne managed to fix her in the nick of time just before the Admiral arrived.) This was undoubtedly one of the SEA LEGS most important demonstrations. After 1 hour and 15 minutes, during which all VIP's took a turn at the helm on a trip to Mt. Vernon and back, the demonstrations were completed to everyone's satisfaction.

During the days that followed, SEA LEGS continued to show her unique capabilities to a wide spectrum of visitors. These included many other Navy officers of flag rank, congressional representatives, including Senator Saltonstall of Mass., and numerous members of the press, radio, and television. The craft got underway for the return to New York on 19 August 1958 and arrived back in New York on 20 August after covering 1851 miles of which 1751 were on foils. The total flight time was 56 hours 12 minutes. The visitor box score for her successful demonstrations included a 3 Congressman, 17 Admirals, 3 Marine Corps Generals, 3 Assistant Secretaries, and numerous other important civilian and military visitors for a total of 375. This was a truly impressive accomplishment and one that had significant impact on the Navy's future course of action.

THE MARITIME CONNECTION

In 1955, as a result of the commercial application of hydrofoils in Europe and the research being sponsored by the U.S. Navy, a growing interest in this promising new type of waterborne transportation developed within the Maritime Administration. The Honorable Clarence Morse, Maritime Administrator at that time, became a most outspoken advocate for hydrofoil craft. The Coordinator of Research, Charles R. Denison, was also enthusiastic about the future commercial potential of the hydrofoil and in 1958 sponsored an extensive parametric study carried out by Grumman Aircraft Engineering Corporation and its affiliate Dynamic Developments, Inc. The purpose of the study was to determine the type of hydrofoil craft best suited to future express-cargo and passenger applications and establish design criteria for such craft. Speeds of 50 to 200 knots, displacements from 100 to 3,000 tons, and ranges from 400 to 3,600 nautical miles were considered. Foil sections shape and arrangement, appendages, weights, power plants and propulsors, hull form, and autopilots were covered including several preliminary designs for oceangoing vessels. Based on the favorable results of this study MARAD contracted with Grumman in 1959 for design studies of two test craft. One was to have conventional power and the other provision for a *lightweight aircraft nuclear plant* when such a system became available. This led to MARAD's award, on 18 January 1960, of a contract to Dynamic Developments to build an 80-ton experimental craft capable of speeds up to 60 knots powered by gas turbine engines. Provision was to be made for a second phase wherein the subcavitating foil system would be replaced by supercavitating foils. This was to permit the attainment of speeds up to 100 knots using the same power plant. Most unfortunately, Charles Denison, whose vision and enthusiasm was in great part responsible for this program, suffered an untimely death before the ship got beyond the early design stages. It was in his memory that the ship was later christened HS DENISON.

The DENISON program followed the same tradition of joint sharing of costs which had characterized early MARAD studies and experiments. The contributions by MARAD to the costs of design and construction was \$1.5M with Grumman and 73 other companies investing some \$5M to \$7M of their own funds.

Shortly after the death of Charles Denison, in light of a National Academy of Science study which recommended that MARAD focus and significantly increase their R&D program, a decision was made to consolidate MARAD efforts. At that time the most significant of these were the nuclear-powered merchant ship SAVANNAH and the DENISON program. James Higgins up to this point had been MARAD's naval architect coordinator for SAVANNAH. In that program emphasis was being shifted to installation of the reactor plant. With his role thus being considerably reduced, he was charged with taking over and pulling together the consolidated R&D program which included responsibility for continuation of hydrofoil development.

In January 1961 MARAD contracted with Stanford Research Institute for a study of the economic aspects of commercial hydrofoils and an evaluation of possible U.S. trade routes. At the same time efforts continued on construction of HS DENISON and the craft was launched on 5 June 1962 at Oyster Bay, Long Island. Sea trials began only four days later.

Figure-28 shows the 95-ton HS DENISON foilborne. The length overall was 104.6 feet, the maximum hull beam was 23 feet, and the maximum draft hullborne with foils extended was 15.4 feet. (It may be noted that the bridge provided no view aft. On one occasion this led to a grounding at speed due to the inability to run ranges in a restricted channel. This deficiency was noted by CDR Mac Nicholson when he was an observer during the trials. As a result, he later insisted that the PCH pilothouse have visibility aft.) The foil system consisted of two surface-piercing units forward which carried 85% of the load and a single fully-submerged foil aft carrying the remaining 15%. Foils and struts were of 4130 steel and provision was made for full retraction as shown in **Figure-29**. The hull was of 5456 aluminum with both welded and mechanically-fastened structures. Main propulsion was provided by a single MS-240 General Electric gas turbine rated at 14,000 SHP. This was a marine version of GE's J-79 jet engine. MARAD obtained two J-79's from the Navy and baled them to GE who then provided the marine version by addition of a free power turbine. This was accomplished for the sum of one dollar. It may be noted, however, that this proved to be a good investment since it was the basis for GE's later LM series of marinized gas turbines which have been used extensively in Navy ships, including the PHM.

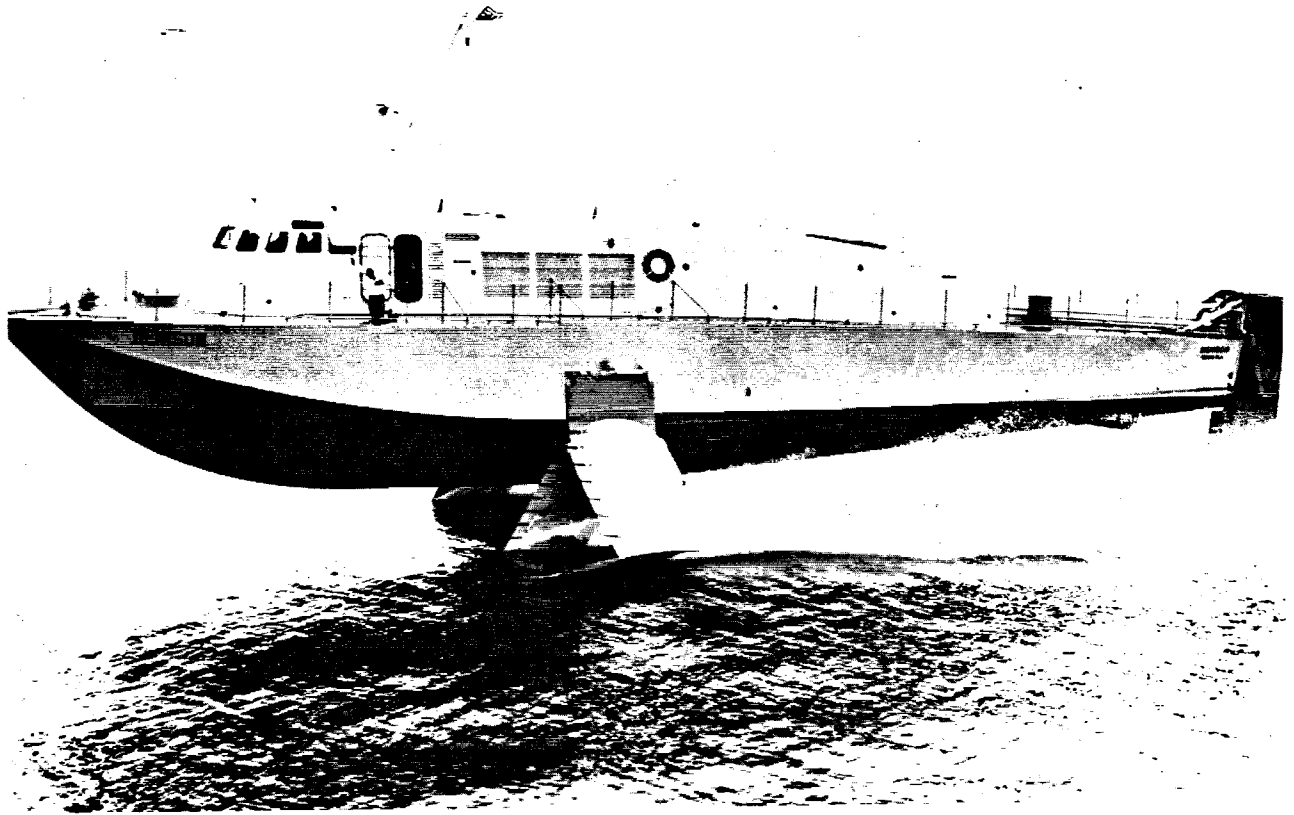


Figure 28. Grumman-Built MARAD Hydrofoil, HS DENISON

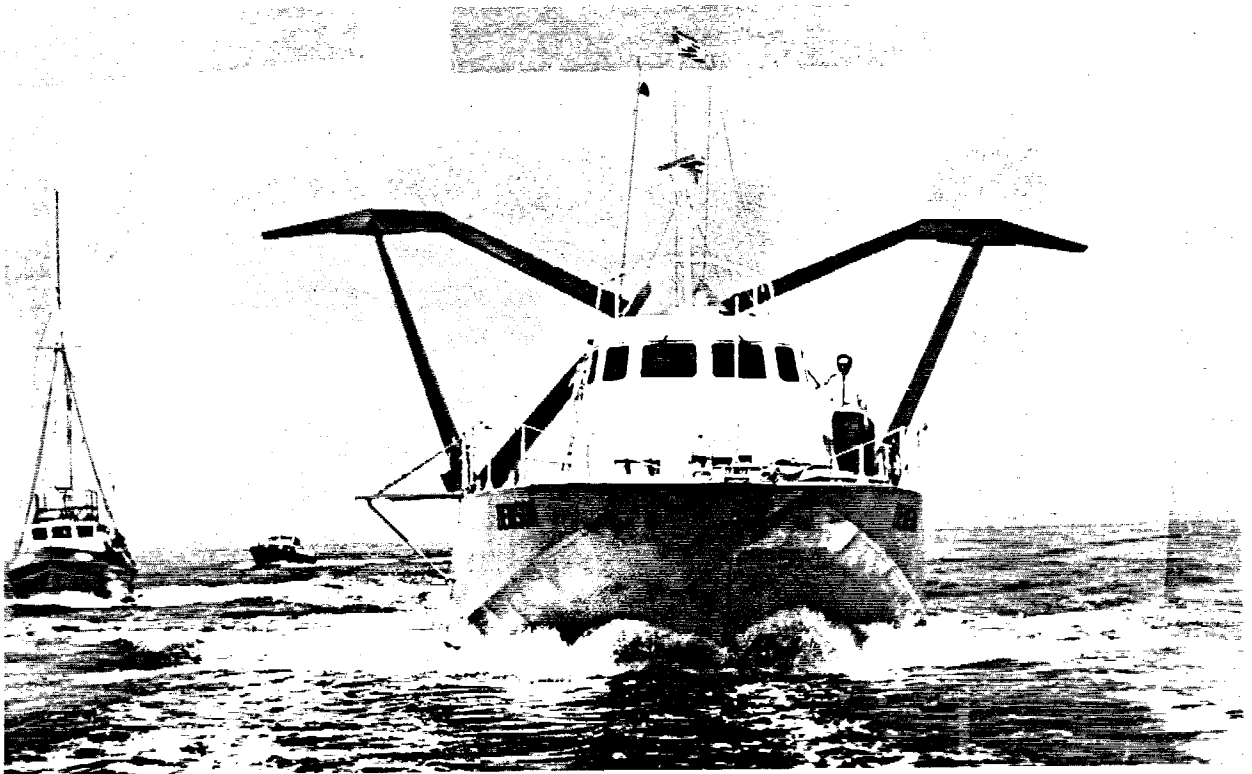


Figure 29. HS DENISON With Foils Retracted

Power was transmitted through a right-angle bevel-gear drive to a supercavitating propeller, as shown in Figure-30. The propeller was designed by Marshall Tulin who, at that time, had just left DTMB to join with Phil Eisenberg in founding Hydronautics, Inc. The spiral bevel gears, 20 and 21 inches in diameter and turning at up to 4,000 RPM, were also built by GE and represented the most stringent requirement, by far, of any which previously had been manufactured.

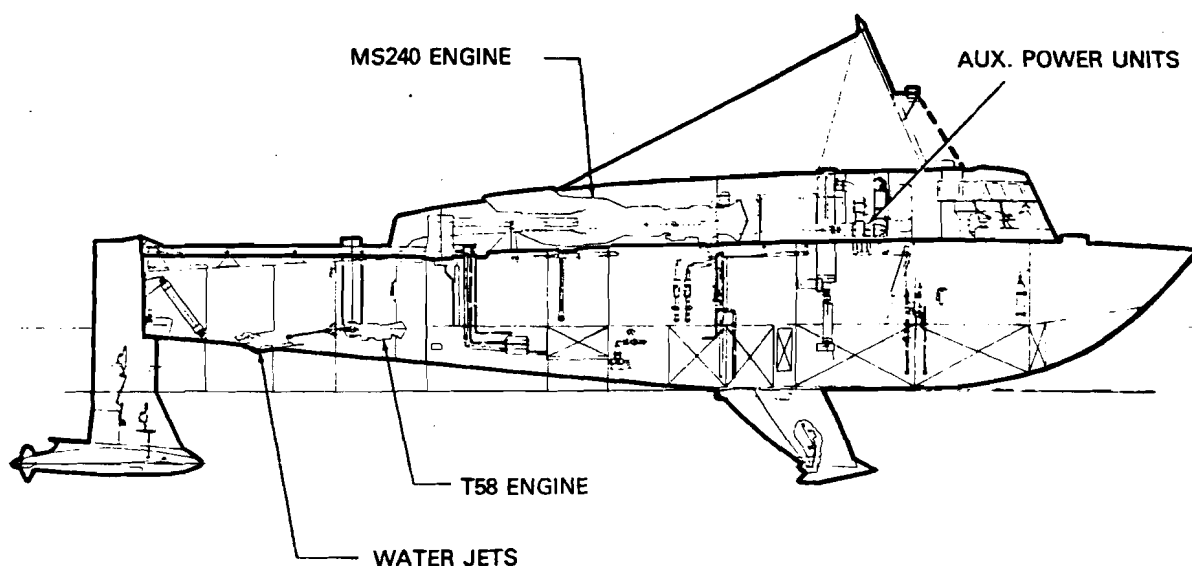


Figure 30. HS DENISON Machinery and Systems

The first trials of DENISON in rough water are of particular interest and a brief description is presented below.

Operation in rough water was initiated in waves of three to four feet. Upwind and downwind runs were made over a buoyed five-mile course at speeds from 50 to 60 knots. The ship proved stable on all headings and during maneuvering with foilborne controls set in the manual mode and with automatic pitch control engaged. At fixed power settings, downwind speed was approxi-

mately two knots greater than upwind. Ship trim on a downwind course averaged one quarter degree less than on a reciprocal heading.

Take-offs were made at normal power settings on upwind, downwind, and crosswind headings with no appreciable difference in craft behavior being observed. Transitions to foilborne attitude were rapid and smooth, requiring only the normal amount of control to establish steady-state foilborne operation.

During later voyages, operations continued in typical winter weather with winds of 30 to 45 knots and seas of 4 to 6 feet. The temperatures were below freezing on occasion, but no icing problems were encountered by DENISON during displacement or foilborne conditions. In comparison, the 30-foot escort boat was unable to proceed out of sheltered waters at these times due to heavy icing on the deck and superstructure.

Foilborne runs were made on all headings. One crosswind take-off was aborted following heavy spray ingestion through a cooling fan duct in the auxiliary power unit compartment but, otherwise, the ship proved stable and dry during runs both upwind and downwind. The transition to foilborne attitude was quick and clean when proceeding head to the wind and sea, but somewhat prolonged downwind, with attending touch-downs before reaching stable flight. Runs were made at speeds of 50 to 55 knots with the stability augmentation system in the manual mode. No hull impacting was monitored or felt by the operating crew.

Although, in 1962, the Navy was already well underway with acquisition of the PC(H) hydrofoil subchaser, the guidance design of the world's largest hydrofoil ship AGEH-1, and the design and construction of the foil research craft FRESH-1, there was still criticism coming from the Department of Defense and the Congress over the Navy's failure to exert even more development effort. As a result of this criticism, CAPT James Stillwell, BuShips, came to Jim Higgins with the offer to cooperate with MARAD in the second, highspeed phase of the DENISON program. In discussions among Higgins, Stillwell, and Ralph Cooper of ONR, agreement was reached where in the Office of Naval Research would put up \$600K for design and BuShips

would provide \$2.5M to construct and install a supercavitating foil system on HS DENISON. MARAD agreed to act as contracting agent and operate the boat during test and trials. BuShips transferred the \$2.5M to MARAD with a hold on spending pending further negotiations. As time went by all seemed to be on track until the Navy, without alerting MARAD, changed course and decided to proceed with design and construction of their own high speed for foil research craft, designated FRESH 1. They subsequently withdrew the \$2.5M for DENISON Phase II. This contributed significantly to an eventual decision by MARAD to terminate the DENISON program and any further efforts toward development of commercial hydrofoils.

It is clear that the MARAD program, and more particularly the HS DENISON, contributed in large measure to the growing technology base for design of hydrofoil craft. Many of DENISON's subsystems were at the leading edge of the state-of-the-art and knowledge gained thereby was invaluable in further developments by the U.S. Navy. It is unfortunate that it did not also fulfill the bright future originally forecast for the employment of commercial hydrofoils in U.S. service.

LARGE SCALE TEST HYDROFOILS

The era of large scale test craft was embarked upon specifically to identify and solve major hydrofoil technical problems. The technical data base for committing the hydrofoil community to speeds of 80 to 100 knots did not exist. Therefore, industry, the U. S. Navy, and the Canadians joined their talents and financial resources to build the test craft described here.

HYDRODYNAMIC TEST SYSTEM

The Boeing jet-propelled research hydroplane, or Hydrodynamic Test System (HTS), shown in Figure-31, was put into operation in 1961. This lobster-shaped craft had provision for placing foil models of about 0.50 - square feet and other shapes in the water between the "claws". This 16,000 pound, 38-ft long craft with an Allison J-33 turbo-jet engine having a thrust of 4,600 lb, was capable of speeds up to about 80 knots. The starboard cockpit carried the driver, and the test observer was in the port cockpit. The instrumentation of the craft was such that a complete polar (lift and drag versus angle of attack) at one depth and speed could be obtained in a run time of 30 seconds. The test facility operated on Lake Washington on calm, quiet water during daylight hours. It proved to be indispensable in adding to the knowledge of hydrodynamics of high speed foils at that time.

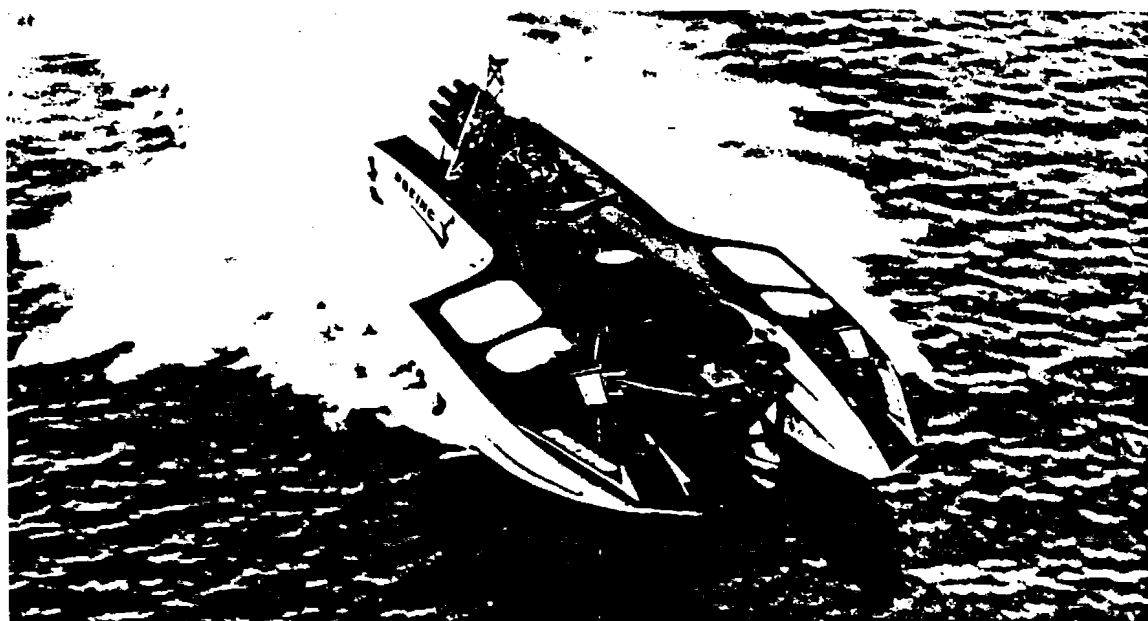


Figure 31 - Boeing Hydrodynamic Test System

FRESH-1

The Foil Research Ship Hydrofoil, known as FRESH-1 was designed and built by the Boeing Company, under Navy contract, in the 1962-1963 time frame. The purpose of this 53-ft long test vehicle was to evaluate a variety of foil designs and foil system arrangements at high speed. The twin-hull catamaran arrangement provided a large clear space between the hulls, within which different foil systems could be mounted. Unlike the HTS, these foils actually supported the 16.7-ton test vehicle in the foilborne mode of operation. There was complete freedom for the arrangement and location of foils relative to each other on this craft. FRESH-1, shown in Figure-32, was powered by a Pratt & Whitney JT3D-3 turbo fan engine having a rating of 17,000 pounds of thrust. It was selected because it was a relatively expedient way of obtaining the required high speed thrust (overall propulsive efficiency was not an important consideration) and it permitted the investigation of foil systems without interference from propellers or waterjets.

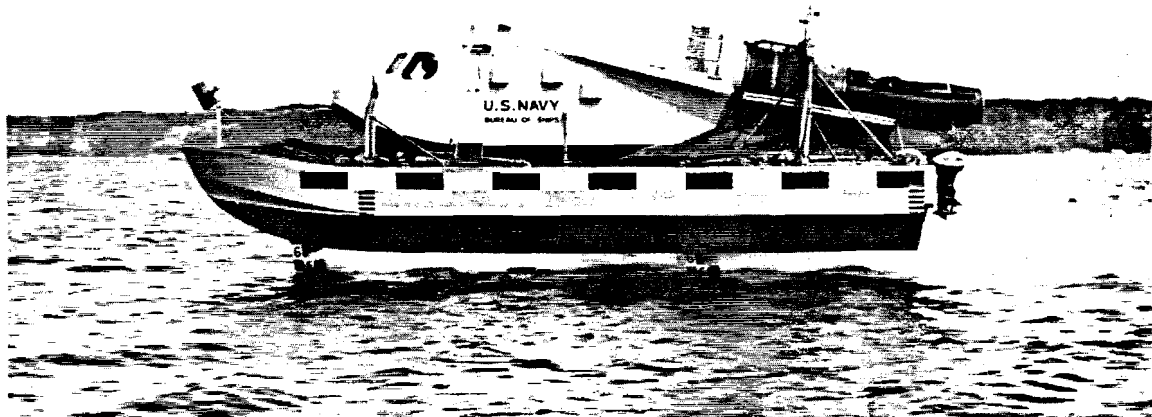


Figure 32 - FRESH-1

During the early trials of FRESH-1, there was concern over the possible problems of flutter, divergence, and rudder reversal. To examine these hydroelastic phenomena, it was necessary to examine a series of test conditions interpreting and evaluating results at each stage before moving on to the next. To overcome the delays in such a procedure, a telemetry system was employed to provide instantaneous data in a mobile shore station. With this system, it was possible to move more rapidly through various tests.

Extensive hullborne and foilborne trials were conducted by Boeing during the first half of 1963. On May 3, 1963 the craft attained a speed of 80 knots, exceeding the hydrofoil speed record set by the XCH-4 in 1954 of 63 knots. The FRESH-1 speed record of 80 knots still stands unchallenged at this writing.

In July of 1963 a series of test runs were made, and at a speed of 70 knots the craft went out of control and completely turned over! Fortunately, the two man crew and a member of the Trials Board, who were on the craft at the time, sustained only minor injuries. Damage to FRESH-1 was light except for considerable deformation of the first stage blading in the jet engine, and later extensive corrosion of other metal parts of the engine.

As mentioned above, FRESH-1 was extensively instrumented so an analysis of the data made possible a complete reconstruction of the events leading up to the accident. It was reported that a loss of flap effectiveness due to the formation of cavities in the flow permitted a gradual increase in flying height during the run and this was not detected until the foils were in the near-broach condition. At the very shallow foil submergence, the craft lacked both the lateral stability and rudder effectiveness and went into a divergent yaw to starboard. Ultimately, the port foil completely overloaded and stalled with a resulting rapid roll to port causing the craft to capsize.

Following the accident, the FRESH-1 was completely refurbished and changes were made to prevent a recurrence of a loss of directional stability. The JT-3D jet engine was replaced with a reconditioned YTF-33 jet engine acquired from the Air Force. Upon completion of this work, additional trials were successfully conducted by Boeing, and then accepted by the U. S. Navy in July 1964. Test continued only for a short time before the craft was laid up due to the de-emphasis of the 100 knot goal in preference to a reliable 50 knot hydrofoil.

LITTLE SQUIRT

It was also about this time that designers were intrigued with the idea that a waterjet could propel a hydrofoil boat. This led to the design and construction by the Boeing Company of a company-sponsored research craft called LITTLE SQUIRT, consisting of a small 5500 lb, 20 foot run-about with a stepped W-form hull shown in Figure-33.

The boat used a centrifugal pump producing a flow rate of 3600 gallons of water per minute out the stern; hence its name. The pump in turn was powered through a reduction gear by a 425 hp Boeing gas turbine engine.

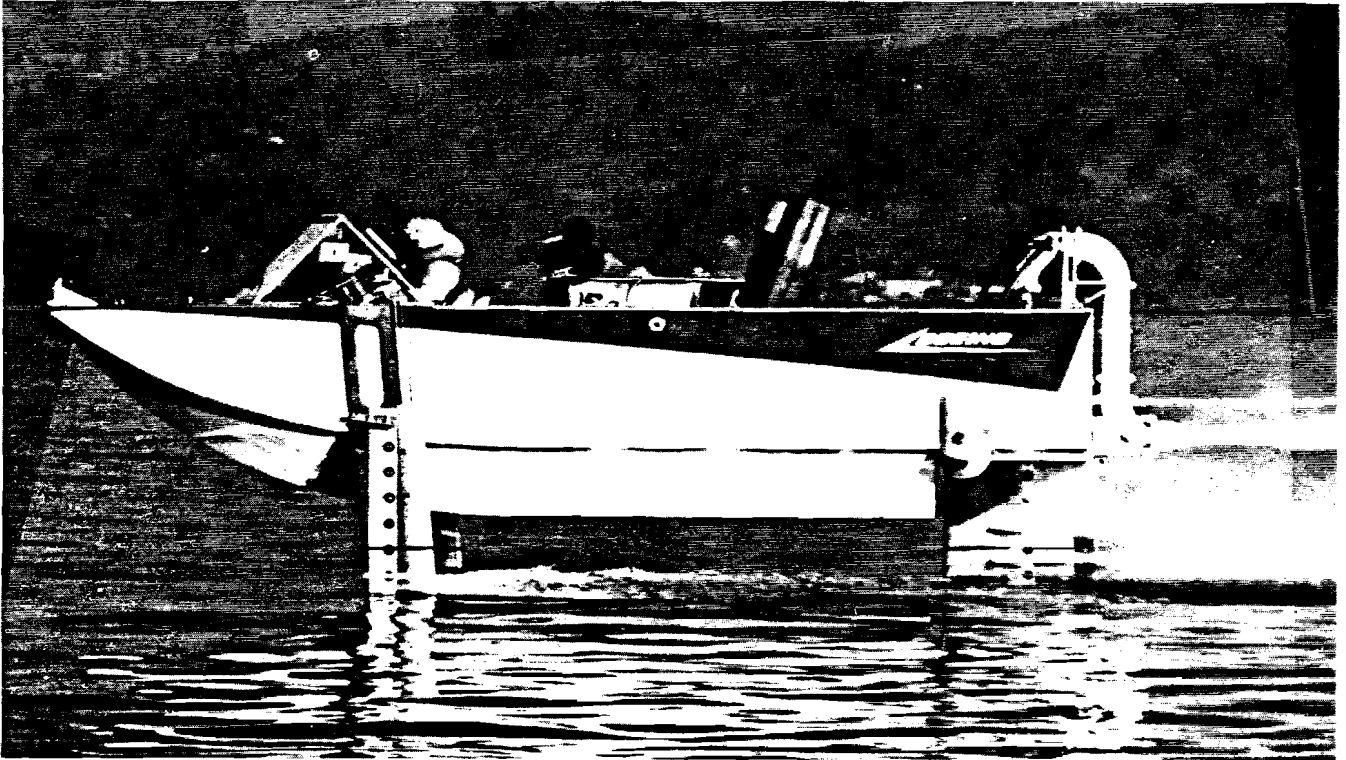


Figure 33. Boeing Waterjet Test Craft, LITTLE SQUIRT

It was at that time that Boeing had such a small gas turbine as one of their product lines, and anticipated wide use of such engines on trucks and small craft.

Two foils were placed forward on the craft and one aft, as seen in **Figure-34**. It is interesting to note that the area of the single aft foil was equal to the sum of the areas of the two forward foils. Each foil had trailing-edge flaps, but in addition, lift was controlled by changing the incidence of each foil. The flaps were used for lift augmentation during takeoff and were retracted for the cruise, foilborne condition. The automatic control system used an acoustic height sensor. It measured the distance between a fixed point on the bow of the boat to the mean, or average water surface.

This test craft accumulated about 110 hours of foilborne operation on Lake Washington and Puget Sound, sometimes operating in 3-foot waves. LITTLE SQUIRT achieved speeds of up to 45 knots and established the technical basis for proceeding to the waterjet propulsion designs for TUCUMCARI, and subsequently the U. S. Navy PHM hydrofoils and also the Boeing commercial JETFOIL hydrofoil.

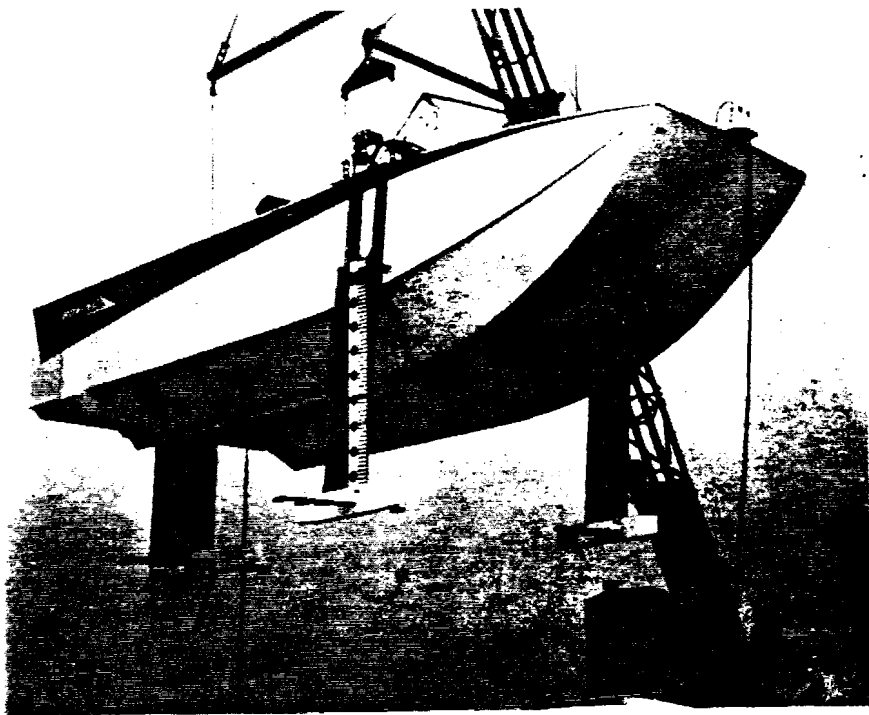


Figure 34. View of LITTLE SQUIRT Showing Foils

CANADIAN R-X CRAFT

In 1960 the Naval Research Establishment (NRE) of the Canadian Defense Research Board proposed a 200-ton, 50-to 60-knot, open-ocean anti-submarine hydrofoil ship for the Royal Canadian Navy. This hydrofoil became known as the HMCS "BRAS D'OR" (FHE-400), described earlier, designed by DeHaviland Aircraft of Canada Ltd. One of NRE's major contribution to this project was the use of a 3.5-ton research test craft, R-X.

R-X, shown during tests in **Figure-35**, was designed and constructed to investigate the characteristics of different hydrofoil configurations and to allow rapid change of hydrofoil design features. Her major use was a long series of tests in connection with the FHE-400, the details of which were described earlier. For this purpose the R-X was equipped with a canard foil system and was operated as a quarter-scale dynamic model of the FHE-400. **Figure-36** shows the similarities between the R-X craft and its larger counterpart.

The original intention was to use the R-X primarily to check DeHaviland's analog computer and design predictions for the dynamic behavior of the BRAS D'OR foilborne in waves. However, as tests evolved the R-X had a more important role to play in demonstrating problem areas that would have been overlooked by conventional design and model test approaches.

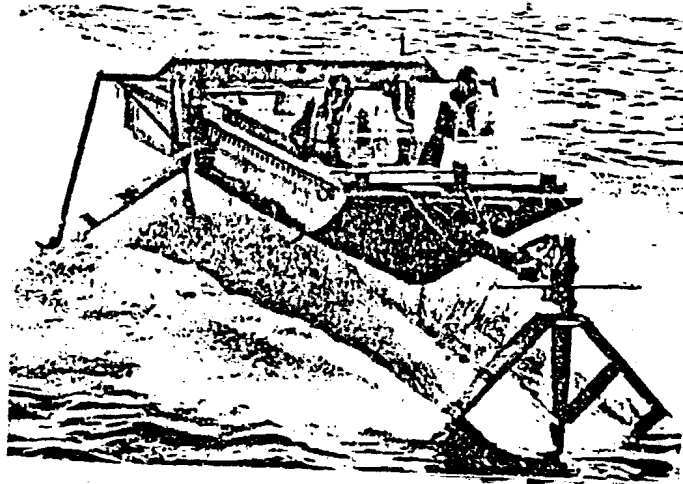


Figure 35. R-X Test Craft With FHE-400 Foils

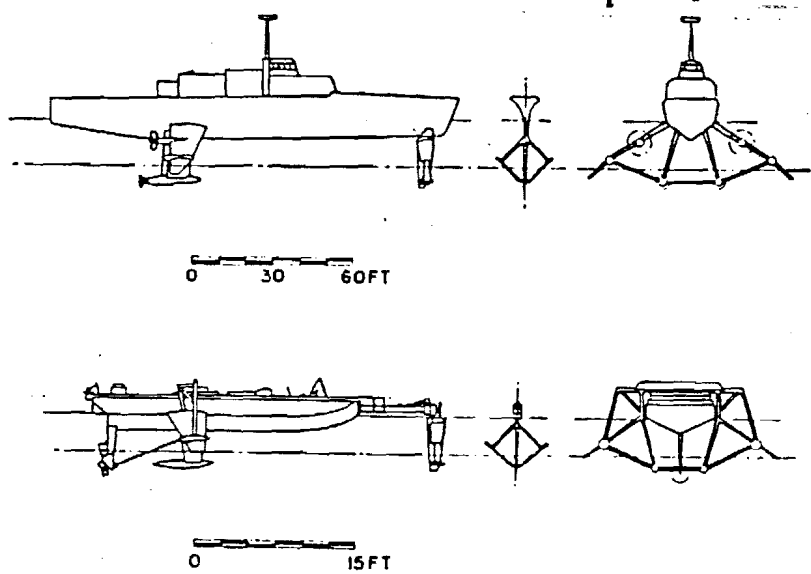


Figure 36. Outline Comparison of R-X and FHE-400 Hydrofoils

The craft had a hull length of 25 feet, a beam of 6 ft, and a depth of 3 ft. A water-cooled Chrysler Imperial Type M-45 marine engine, with modifications to increase its power rating to 365 hp, was used to drive a conventional propeller on an inclined shaft. As can be seen from the hull cross section diagram in Figure-37, the engine and fuel tanks were located at the craft's center of gravity, just forward of the main foil.

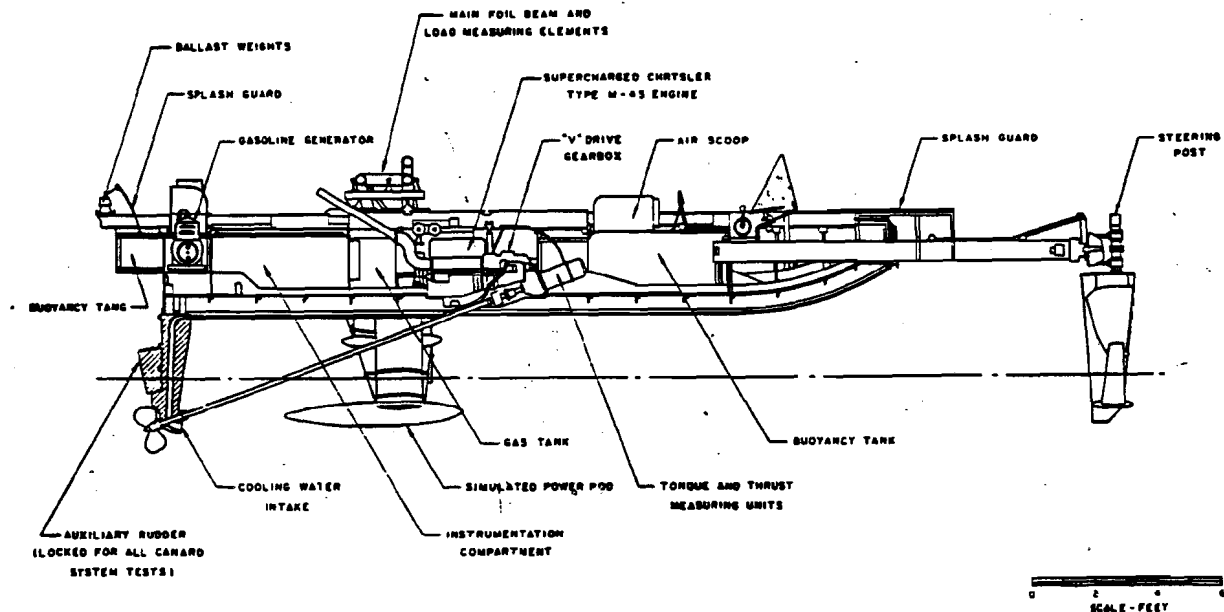


Figure 37. R-X Test Craft Hull Cross Section

The foil system of the R-X was designed by DeHaviland at a very early stage of the development program. The bow foil, in particular, was modified many times from the original design to reflect full-scale design progress. These changes were required to alleviate the craft's pitching motions in waves. It was recognized at the outset that the design of a diamond-shaped surface piercing bow foil, carrying 10% of the ship's weight, for operation at 50-knots in waves would present many difficulties. Fluctuations of immersion and angle of attack due to wave action and ship pitch would be more pronounced at the bow than at the main foil and could lead to ventilation and cavitation.

The R-X was instrumental in providing solutions to these difficulties, and lead to designs which made the BRAS D'OR a successful hydrofoil ship. One of the important lessons learned was the value of open-water tests with a manned model as an integral part of the design process for advanced marine vehicles.

U. S. NAVY DEVELOPMENTAL HYDROFOILS

One of the best ways to see the entire scope of the U. S. Navy hydrofoil development in general, and the "Famous Four" R & D hydrofoils in particular, is by way of a plot of ship weight against time over the time frame of 1958 to 1985 as shown in Figure-38.

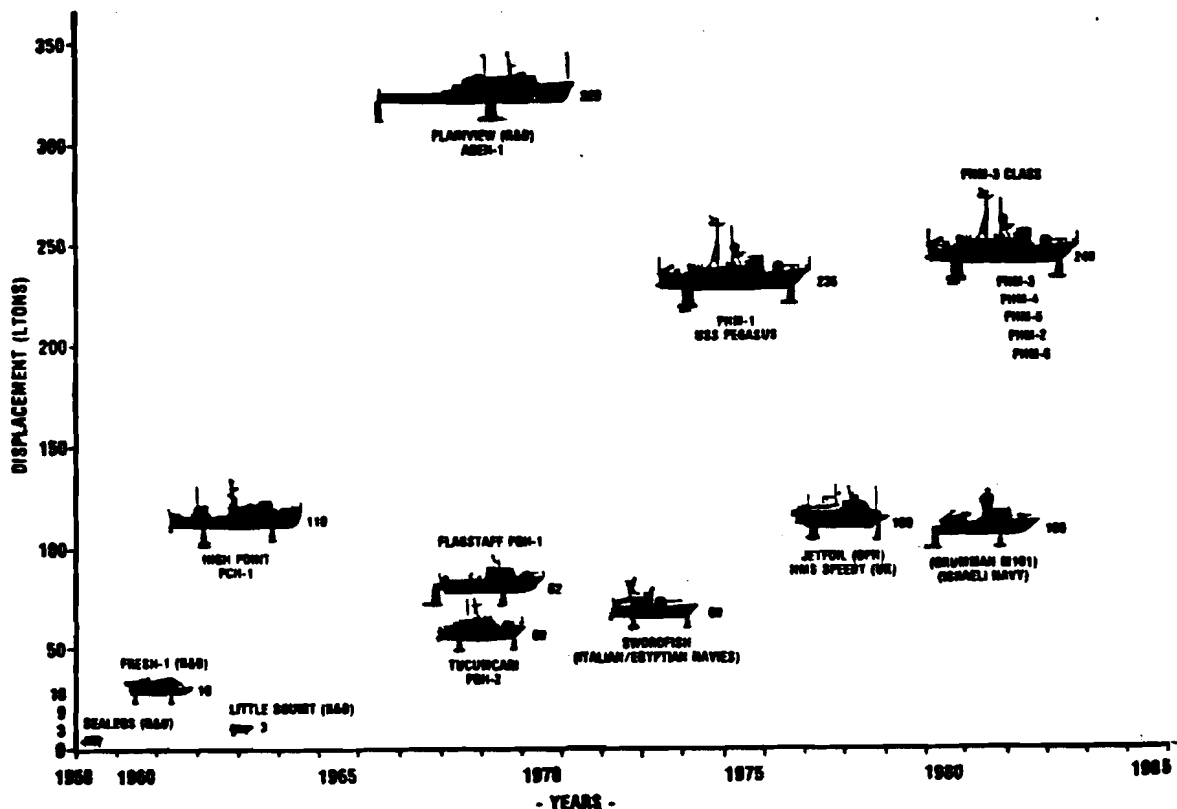


Figure 38 - U. S. Hydrofoil Military Development: 1958 to 1985

At the lower left corner of the illustration we see SEA LEGS, FRESH-1, and LITTLE SQUIRT. These, as mentioned previously, provided the technical basis for the four U. S. Navy R & D hydrofoils, and later the PHM-1 Class hydrofoil ships.

HIGH POINT

HIGH POINT (PCH) was designed by the Bureau of Ships, built by the Boeing Company under U. S. Navy contract, and delivered in August of 1963. It was originally intended for off-shore ASW. The concept was to use the PCH as a small, high-speed, sonar platform, equipped with ASW torpedoes to sortie from harbors in advance of a convoy. Using its speed to move quickly over a larger area, the PCH could protect the departing convoy and its larger ASW escorts at its origin when they are most vulnerable. However,

development of a sonar suitable for effective utilization of the ship's unique capabilities was never prosecuted. In this connection the ship was to be delivered to the Pacific Fleet for operation by the Mine Force. However, as a result of numerous technical problems arising during early Navy trials, it was recognized that the hydrofoil state-of-the art was not adequate to produce a fleet hydrofoil with acceptable operational reliability. In spite of this the initial version of HIGH POINT underwent extensive calm and rough-water trials. Because the ship displayed some shortcomings, a decision was made in October of 1964 to perform extensive repairs and refurbishment. Further modifications were made by Boeing during 1968 and 1969 under the "Mod-1" program.

PCH-1 is about 116 ft long, has a maximum hull beam of 32 ft (38 ft across foil guards), a draft of 8.5 ft with foils retracted, 19.0 ft with foils extended, and displaces about 125 tons. Power for foilborne operations is provided by two British-built Rolls Royce Proteus gas turbine engines driving four propellers, two at the bottom of each of two aft struts. A diesel engine provides power to a steerable out-drive for hullborne, low speed maneuvering. The canard foil system has a forward foil with a span of 20 feet and an aft foil with a span of about 36.5 feet.

HIGH POINT has been the "work horse" of the hydrofoil research and development community for almost three decades, and as of this writing has accumulated almost 2000 foilborne hours. Figure-39 shows HIGH POINT during one of its many application demonstrations.

An excellent comprehensive treatment of HIGH POINT is provided by William M. Ellsworth in "Twenty Foilborne Years". He describes the events leading up to the ship's acquisition, detailed design and construction, trials, and its utilization as an R & D ship to refine the criteria for future hydrofoil designs, and explore the mission utility of hydrofoils and other high speed advanced vehicles. Lessons learned from this unique ship are highlighted as is the story of the many devoted people who were the backbone of the U. S. Navy's hydrofoil research and development program.

During her many years of operations HIGH POINT provided much data essential to resolving such important design issues as the following:

- o Canard vs. Conventional (Airplane) Foil Configuration.
- o Flap vs. Incidence Foil Control.
- o Platforming vs. Contouring of Waves.
- o Submerged vs. Surface-Piercing Foils.
- o Banked Turns vs. Flat Turns.

- o Water jet vs. Propeller Propulsion.
- o Fixed vs. Rotatable Forward Strut.
- o Retractable vs. Nonretractable Struts & Foils.
- o Subcavitating vs. Supercavitating Propellers.
- o Radar vs. Sonic Height Sensors.
- o Analog vs. Digital Autopilots.

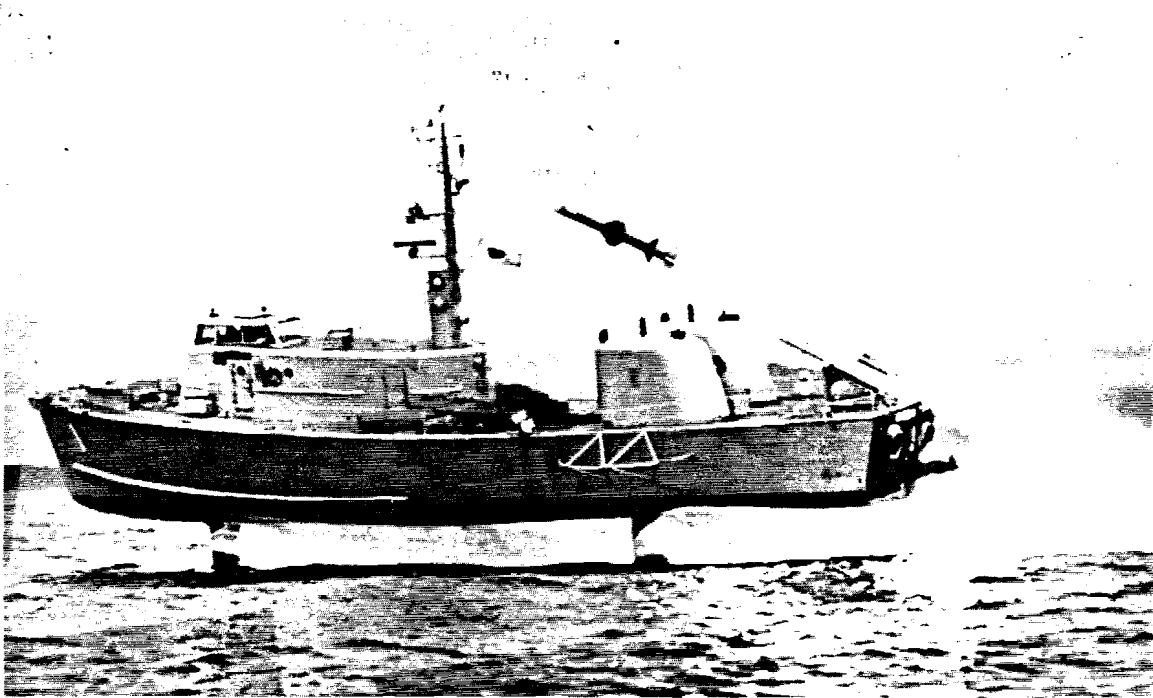


Figure 39. HIGH POINT During First Firing of Harpoon Missile from a Hydrofoil

With respect to mission equipment and tactical applications of hydrofoil ships, HIGH POINT also made many contributions to the knowledge base. Many of the mission systems on the PHMs were first evaluated on PCH-1. She also participated in several Fleet exercises which gave visibility to this new ship concept and offered the opportunity to evaluate hydrofoil mission applications. Examples of some of the systems tested on PCH and roles include:

- o HARPOON Missile Firing.
- o Canadian Variable-Depth Sonar (HYTOW).
- o Depressor Towed Array System (DTAS).
- o Hydrofoil Pressure Acoustic Magnetic (HYPAM) Minesweep System.
- o MK 44 Acoustic Torpedo Firing.

- o 40mm Gun Firing.
- o Helicopter Refueling Foilborne.
- o Helicopter Foilborne Personnel/Supply Transfer.
- o ALR-66 Electronic Support Measure (ESM).
- o Hydrofoil Collision Avoidance & Tracking System (HYCATS).
- o Ship At-Sea Refueling & Cargo Transfer.
- o Deception & Decoy Systems.
- o Aids to Night Foilborne Operations (LLTV, FLIR, etc.)
- o Bottom Contouring & Oceanographic Survey Systems.
- o U.S. Coast Guard Coastal Roles.

No one can question the value of HIGH POINT's many contributions to the design and utilization of both commercial and military hydrofoil craft. A Squadron of six PHMs at Key West, Florida, is perhaps the best testimonial to her rightful place in the long history of hydrofoil development.

FLAGSTAFF (PGH-1)

Two hydrofoil patrol gunboats were built for U. S. Navy fleet operational evaluation in the late 1960s. Although they were designed and built to the same performance specification, their configurations were very different. PGH-1 was propeller driven and had a conventional (airplane) configuration, whereas TUCUMCARI (PGH-2) was waterjet propelled and had a canard foil configuration. Delivered to the Navy in 1968, they both saw service in Vietnam between September 1969 and February 1970, making them the first U.S. Navy hydrofoils in combat.

FLAGSTAFF, shown in Figure-40, designed and built by Grumman Aerospace Corporation, was 74 feet long with a maximum beam of 37 feet and a displacement of about 69 tons. Draft with foils retracted was 4.2 ft, and 13.5 ft with foils extended. This hydrofoil, with its conventional foil configuration, carried 70% of the lift on the forward, main foils and 30% of the lift on the aft foil. Manning consisted of 4 officers and 12 enlisted men.

Power for foilborne operation of FLAGSTAFF was provided by a single Rolls Royce TYNE 621/10 marine gas turbine engine with a maximum continuous rating of 3,450 hp at 14,500 rpm. This drove a single 45 inch diameter variable pitch supercavitating propeller located on the lower end of the aft strut through a set of right angle bevel gears. Hullborne propulsion consisted of two Detroit diesels at 160 hp each driving Buehler waterjets.

In February 1970, FLAGSTAFF was assigned to operate as part of the Amphibious Forces based in San Diego. In 1974 the Navy loaned FLAGSTAFF to the U.S. Coast Guard for several months for evaluation in performing their

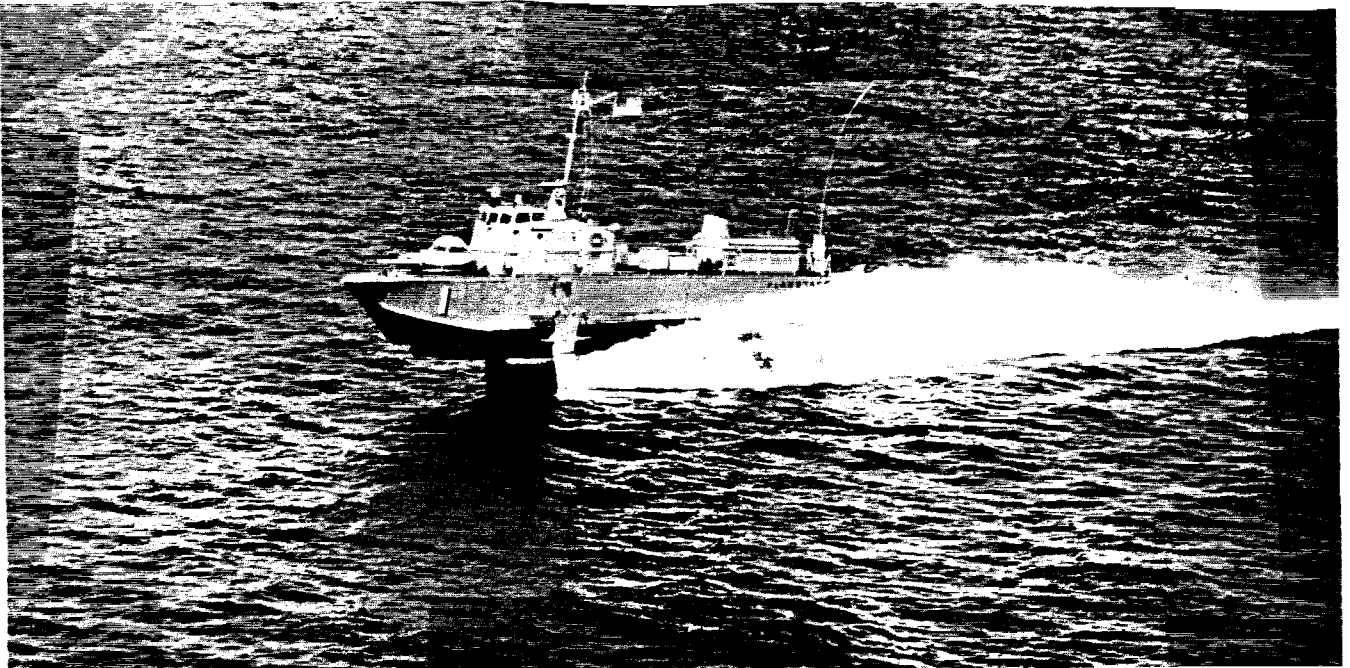


Figure 40. Grumman-Built PGH-1, FLAGSTAFF

expanded 200-mile offshore coastal patrol role. As a result of this experience, agreement was reached in 1976 to turn over the ship to the Coast Guard for operation off the New England Coast. It was recommissioned as a Coast Guard Cutter with the designation WPGH-1. The ship was employed to evaluate the use of hydrofoils for Coast Guard duties including the enforcement of laws and treaties, fisheries and contraband reinforcement, and search and rescue. FLAGSTAFF was decommissioned in September 1978 due to problems with its machinery.

In an article in *High-Speed Surface Craft* of December 1983 it was reported that FLAGSTAFF sat afloat at a small boat pier in a salvor's possession at Warwick, Rhode Island in what was described as "a rather disreputable condition".

TUCUMCARI (PGH-2)

The second hydrofoil gunboat built for U. S. Navy operational evaluation was the Boeing-built TUCUMCARI, see Figure 41. Its canard foil configuration, like HIGH POINT, placed 30% of the ship's weight on the forward foil, and 70% on the aft foil. Another feature which made it different from FLAGSTAFF was that the foils had individual flaps for lift control rather than incidence control. The waterjet, which provided thrust for foilborne operations of TUCUMCARI, had its water inlets located at the juncture of each aft strut and foil.

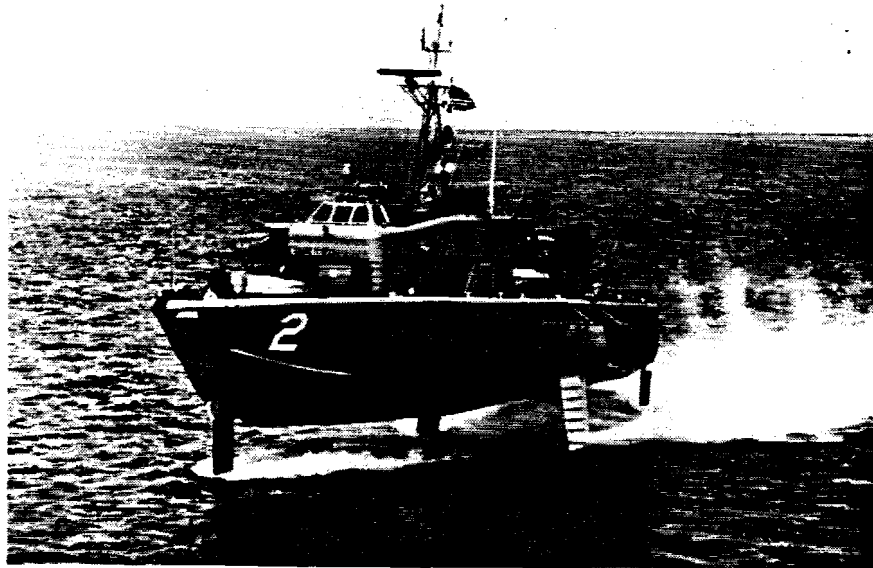


Figure 41. Boeing-Built PGH-2, TUCUMCARI

Both gunboats had gas turbines for their foilborne propulsion systems. In the case of PGH-2, a PROTEUS engine provided 3200 hp to give this 57-ton hydrofoil a speed in excess of 40 knots. It was 72 ft long had a beam of 35.3 ft, with a draft of 4.5 ft with foils retracted and 13.9 ft with foils extended. The crew consisted of 1 officer and 12 enlisted personnel.

Following its deployment to Vietnam, TUCUMCARI was sent to Europe for a NATO tour and demonstrations. From April until October 1971 she operated in European waters, visiting seven NATO countries while performing numerous demonstrations and combat exercises. These exercises undoubtedly had a significant influence on the later decision to procure a NATO fast patrol hydrofoil. TUCUMCARI logged 390 hours of foilborne time in European waters which also enhanced confidence in the potential of hydrofoil ships.

Upon return from Europe, TUCUMCARI was assigned to the Amphibious Force in the Atlantic Fleet. It was a sad ending to a distinguished period of performance, when in November of 1972, while conducting night exercises with the 2nd Fleet, she ran onto a coral reef north of Vieques Island. The ship was salvaged and transported to her base in Norfolk, Virginia where it was determined not to attempt repair of the extensive damage. In 1973 she was transported to the David Taylor Research Center for structural and material testing. In spite of this rather un auspicious ending, TUCUMCARI can take credit in providing the technology base and confidence to proceed to the PHM program.

PLAINVIEW (AGEH-1)

In December 1960, the Bureau of Ships had issued a circular of requirements for a hydrofoil research ship designated the AGEH-1. It was to be a 50-knot experimental oceangoing ship with provision for future conversion to achieve speeds up to 90 knots. This was to be accomplished by addition of two more gas turbines and a supercavitating strut foil system. Its purpose was to provide criteria for design of future Navy hydrofoil ships and to explore the utility of such ships for antisubmarine warfare and other mission applications.

Proposals were submitted by a number of contractors, Grumman Aircraft Engineering Corporation (now named Grumman Aerospace Corporation) was selected as the contractor based on their submission which consisted of two different concepts. One had fixed foils which could be retracted only with a crane at dockside. The other had a fully self-contained foil retraction system. The fully-retractable design was selected and, on 26 October 1961, Grumman was awarded a cost-type contract for the guidance design of AGEH-1. There was a provision in the contract whereby, if the Navy did not like Grumman's estimate of the cost of detail design and construction, they had the option to go out for bids in a new competition. The Grumman team included Newport News Shipbuilding Corp. and General Electric Co. Grumman was designated the Program Manager and principal designer and it was proposed that they build the foils and install the transmission. Newport News was to be involved in the design of the shipboard systems and the hull, and would be the hull builder and outfitter. General Electric had the responsibility for the propulsion system.

The guidance design took about one year. The preliminary design and weight estimates were submitted and approved in February 1962. The contract drawings and final draft of the specifications were signed off by RADM James, Chief of BuShips, on 9 October 1962. Grumman's estimate for detail design and construction was about \$17M. Since the Navy had budgeted \$12M for the buy, they exercised the option to recompetete the procurement. Additional bids were received, all of which were in the neighborhood of \$17M, except for the bid of Puget Sound Bridge and Drydock Co. in Seattle, WA. (Later to become Lockheed Shipbuilding and Construction Co.). They bid a shade under \$12M and, on 9 July 1963, were awarded a fixed-price contract for detail design and construction. The contract for this 320-ton advanced hydrofoil, the largest ever constructed, was only seven pages long. (The actual cost of the ship, including changes, was close to \$21M.)

Major subcontractors to Lockheed included W.C. Nickum & Sons for engineering and detail design, Rucker for the design of the hydraulic system, General Electric for the design and construction of the hullborne and foilborne transmissions, Hamilton Standard for the automatic control system, and Lockheed California for design and construction of the strut/foil system.

The keel was laid on 8 May 1964 and the ship was launched on 28 June 1965. It was christened PLAINVIEW in honor of Plainview, NY and TX. The sponsor was Mrs. John T. Hayward, wife of VADM J.T. Hayward, USN (ret), former President of the Naval War College. The Prospective Officer in Charge was LT Hugh Burkons. He was later transferred to become OIC of HIGH POINT. He was relieved by LT Stephen J. Duich just before PLAINVIEW got underway for the first time on 4 August 1967. The ship made its first foilborne flight of 11-1/2 minutes on 21 March 1968 but, it was nearly a year later, on 3 February 1969, when it began Preliminary Acceptance Trials. On 1 March 1969, the Navy reluctantly took delivery and assigned the ship to HYSTU for administrative and technical control. This was nearly 3-1/2 years later than the originally projected delivery date. Much of this delay was due to 3 major strikes during the construction period. PLAINVIEW was far from problem free at time of delivery. It seemed clear, however, that the Navy's best course of action was to undertake its own program of deficiency correction if the ship was every to become fully operational.

Final Contract Trials were begun on 21 January 1970 and on 2 March 1970, the Navy accepted the ship. On 9 July 1970, LCDR Stephen J. Duich was relieved by LT Wm. J. Erickson as OIC.

PLAINVIEW's characteristics are given in Table-1. Figure-42 shows the ship with foils retracted and Figure-43 shows the ship foilborne. Figure-44 is a cutaway view with which was published in the December 1968 issue of Popular Mechanics magazine and is reprinted with permission.

This 320-ton hydrofoil possessed many unusual characteristics, the most significant of which were:

The largest hydrofoil ship in the world at that time. It has subsequently been surpassed by the Soviet BABUCHKA hydrofoil at about 400 tons.

The largest high-speed aluminum hull.

The highest subcavitating foil loading at 1460 pounds per square foot. The design foil loading for PHM, for example, is about 1250 psf.

The largest vehicular hydraulic system with a pressure of 3600 psi at 1000 gallons per minute.

The highest power Zee-drive transmission incorporating two 15,000 horsepower units.

The largest high-speed supercavitating propellers with a diameter of 5.2 feet and a design rotational speed of 1700 rpm.

The highest design sea state capability at high speed.

TABLE 1

PLAINVIEW CHARACTERISTICS	
Foil Configuration	Airplane
Length Overall	212 Feet
Extreme Beam, Foils Down	70.8 Feet
Full Load Draft Hullborne	
Foils Up	6.4 Feet
Foils Down	25.0 Feet
Full Load Displacement	320 Long Tons
Hullborne Propulsion	
(2) Packard Diesels	1200 Shaft HP
(2) Thrust Producers	5-Bladed Subcavitating Propellers
Foilborne Propulsion	
(2) GE LM-1500 Turbines	28,000 Shaft HP
	Continuous
(2) Thrust Producers	4-Bladed TI Super-cavitating Propellers
Maximum Hullborne Speed	15 Knots
Calm Water Takeoff Speed	33 Knots
Maximum Foilborne Speed, SS 0-5	50 + Knots
Maximum Normal Turn Rate	6.0 Deg/Sec
Minimum Turn Radius (At 40 Knots)	215 Yards
Foil/Strut Material	HY-80/100 Steel (Coated)
Foil Control Incidence	(22 Deg/Sec)

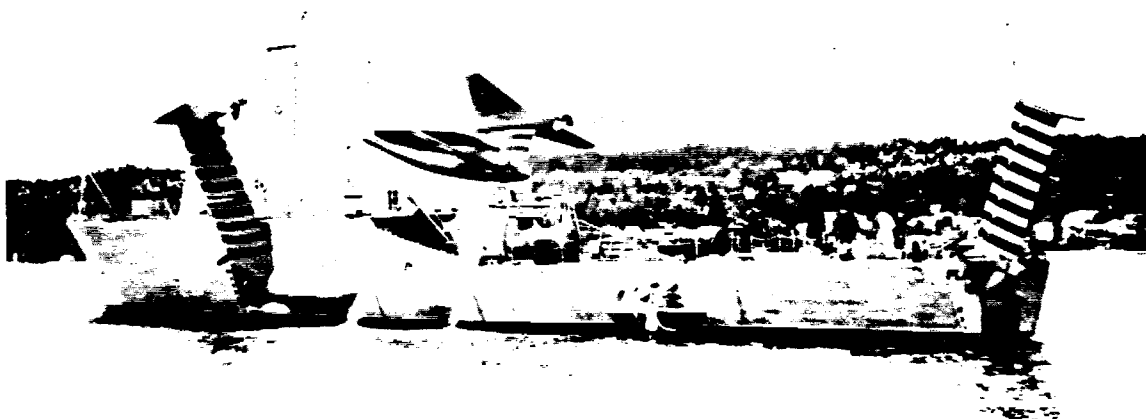


Figure 42. PLAINVIEW with Foils Retracted

As can well be appreciated, PLAINVIEW's assignment to HYSTU was a considerable additional burden on the Unit, particularly since there were many problems and deficiencies to overcome. This was to be expected, however, with a first-of-a-kind, one-of-a-kind, sophisticated and complex system. Fortunately, at the time of PLAINVIEW's delivery, the problems with HIGH POINT had become much more manageable and the focus of attention could be directed more to the bigger ship during this early period.

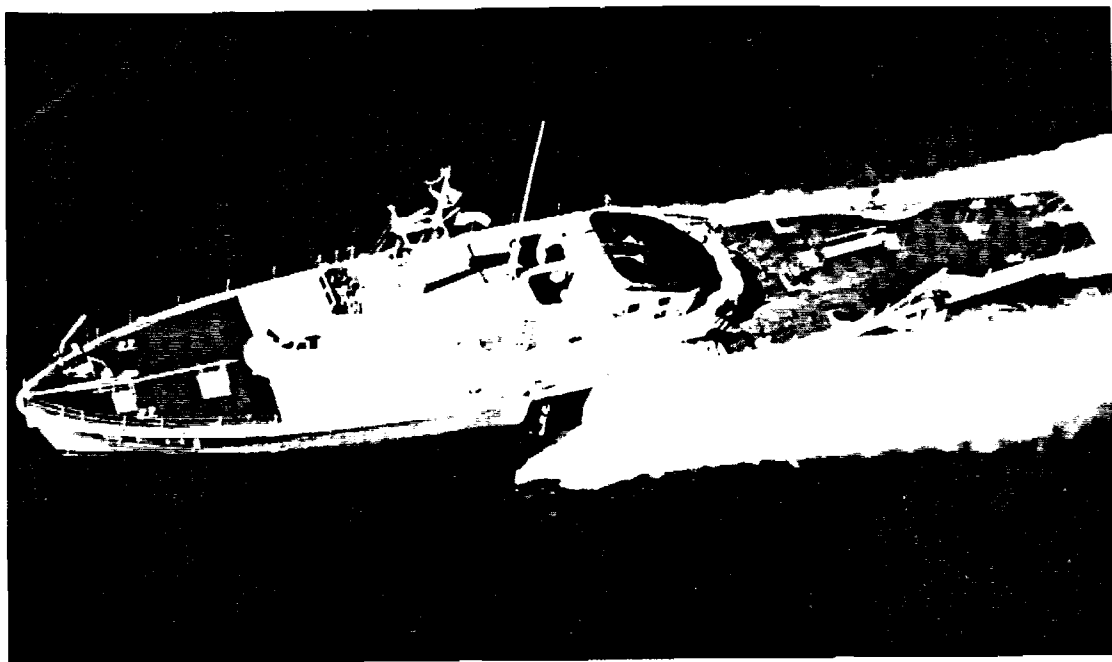
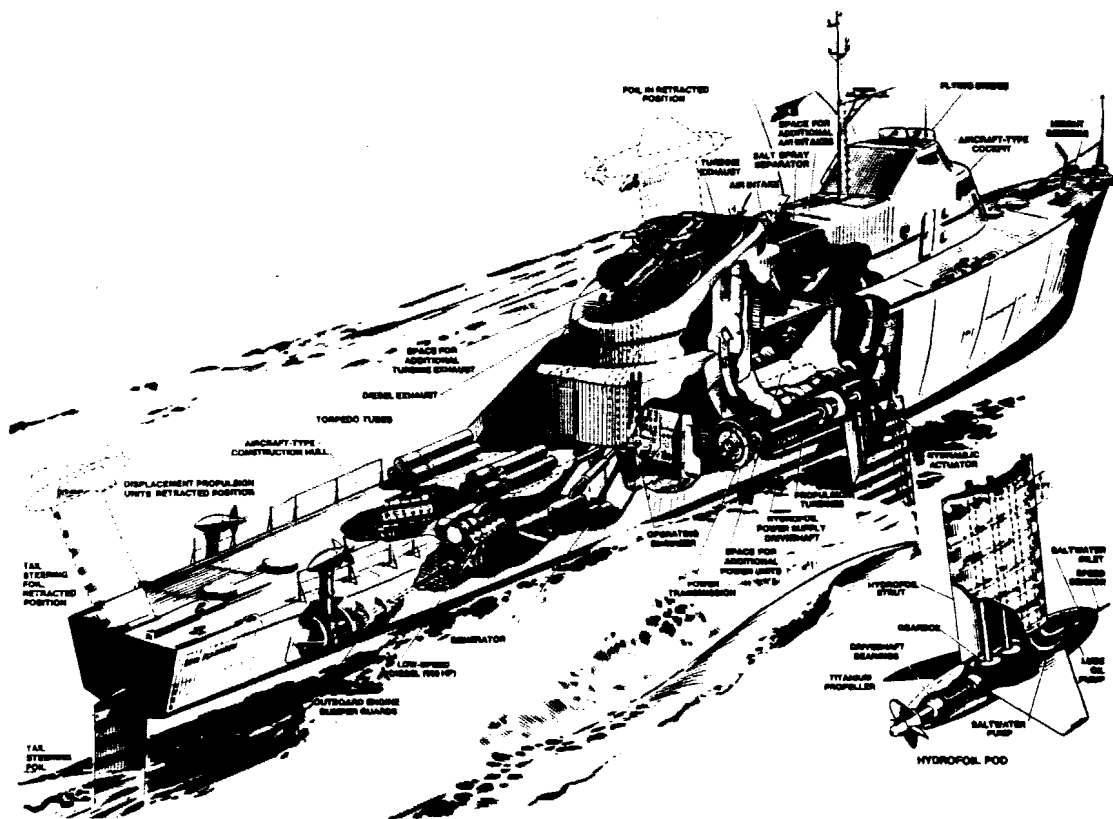


Figure 43. PLAINVIEW Foilborne



Courtesy Popular Mechanics

Figure 44. Cut-Away View of PLAINVIEW

For four years after delivery of PLAINVIEW, the story of trials and tribulations was a repeat of the early problems with HIGH POINT. Finally, on 16 May 1974, what was to be a two-year overhaul and modification effort, was begun at Todd Shipyard in Seattle. This included the following major items.

- o A new hydraulic system with all welded piping.
- o Disassembly and refurbishment of the main struts and foils.
- o A new incidence control system.
- o A new tail strut of HY-130 steel, built by Grumman.
- o The Hydrofoil Universal Digital Autopilot, taken from PCH.
- o A radar height sensor in place of the sonic unit.

Unfortunately, soon after returning to the trials program with significantly increased availability, PLAINVIEW fell victim to the Congressional budget knife. She made her last foilborne flight on 17 July 1978, ending with a total of 268 foilborne hours and without ever being

tested to the limits of her rough water capability. The ship was officially inactivated on 22 September 1978 and towed to the inactive fleet at Bremerton. In May of 1979, the hull, without the struts and foils, gas turbines, and other special equipment, was sold to a private party for the sum of \$128,000. It was understood that it was to be converted for use as a fishing boat. This was either unsuccessful or was never attempted. The final indignity for this once-proud and beautiful ship can be seen in Figure-45 which shows it resting on a mud flat near Astoria, Oregon.

The story of PLAINVIEW is told in much more detail in a paper entitled "A Ship Whose Time Has Come--And Gone," by R.J. Johnston and W.C. O'Neill, AIAA/SNAME Advanced Marine Vehicles Conference, Baltimore, MD, October 2 - 4, 1979.

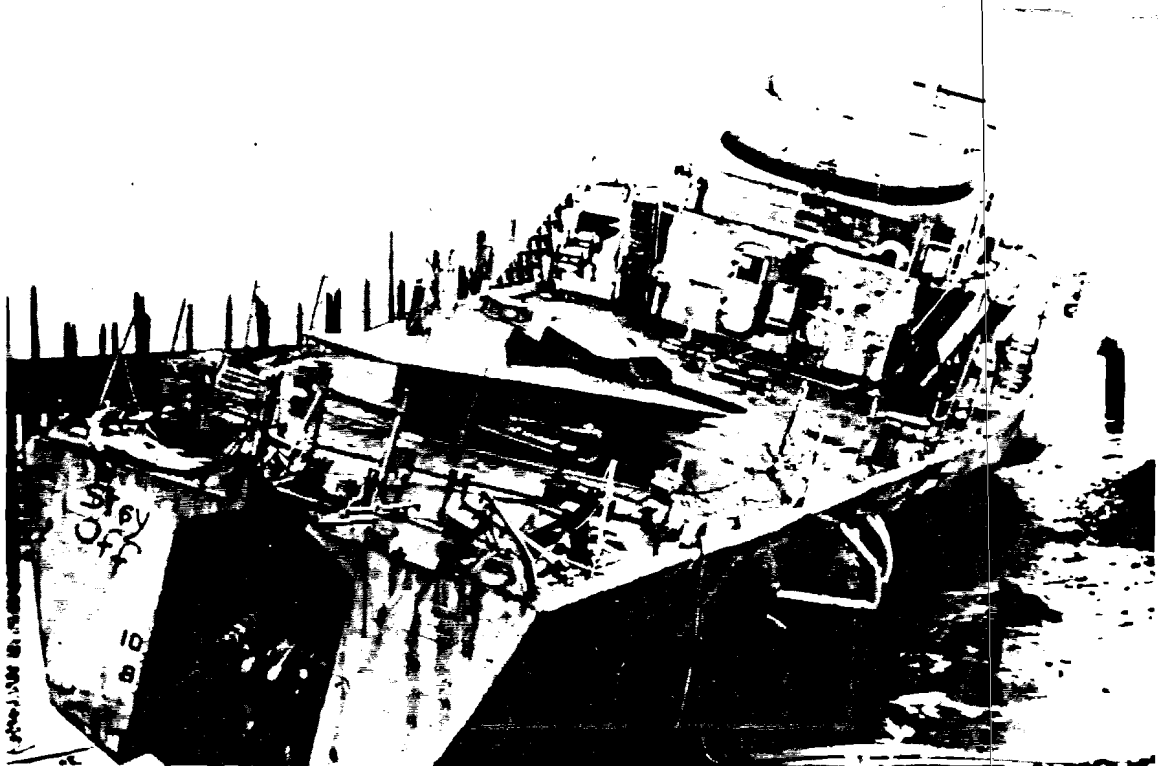


Figure 45. PLAINVIEW Abandoned on a Mud Flat Near Astoria, OR

A comparison of physical and performance characteristics of the four U. S. Navy developmental hydrofoils just described and the PHM-1 is show in Table-2.

TABLE 2

CHARACTERISTICS OF U. S. NAVY HYDROFOILS

	<u>PCH-1</u>	<u>AGEH-1</u>	<u>PGH-1</u>	<u>PGH-2</u>	<u>PHM-1</u>
Full Load Displacement (Tons)	126	320	69	58	231
LOA (Ft.)	115	212	74	72	146
Max. Beam (Ft.)	32	40	21.5	19.5	27.6
Draft (Ft.)					
Foil Up	8.6	6.3	4.3	4.4	6.0
Foil Down	19.8	25	13	13	22
Speed (KTS)					
Hullborne	12	13	9	9	11
Foilborne	High*	High*	High*	High*	High*
Foil Configuration	CANARD	AIRPLANE	AIRPLANE	CANARD	CANARD
Max. Cont. HP.	6200	28000	3200	3200	18000
Gas Turbine	PROTEUS(2)	LM1500(2)	TYNE	PROTEUS	LM2500
Propulsor	PROPELLER	PROPELLER	PROPELLER	WATERJET	WATERJET

*Greater than 40 knots.

PHM BEGINNINGS

In 1970 NATO indicated a need for a fast, seaworthy missile ship to operate in the Mediterranean, North Sea, and Baltic waters. One of the needs was to counter the Soviet OSA KOMAR missile boats. Comparisons were made between planing hulls, catamarans, hydrofoils and hovercraft. The hydrofoil was identified as best at meeting the requirements based on proven U.S. Navy technology. The NATO group that subsequently drafted the military requirements for the PHM realized that a modern hydrofoil, when equipped with antiship missiles became a formidable surface combatant. This was because of its unique capabilities for high-speed, all-weather operations over distances and mission durations consistent with operations of the more conventional fast patrol boats. The PHM program was launched in November 1971 with a letter contract to Boeing for PHM-1. Italy, Germany and the United States Navy became partners under a Memorandum of Understanding a year later.

A contract was awarded in 1973 to the Boeing Company for the feasibility study and the design and construction of two PHMs. While the initial contract called for two lead ships, program cost growth forced the suspension of work on the second ship in August 1974. The completion of PHM-2 was later incorporated into the production program as shown in the schedule of major PHM events of **Figure-46**. The keel of USS PEGASUS was laid on 9 May 1973, and she was christened and launched on 9 November 1974. She made her first flight on 25 February 1975. However, before delivery of PEGASUS (PHM-1) to the U. S. Navy in 1977, Italy and Germany had decided to drop out of the program. Because of higher than anticipated costs, only one ship was completed at that time.

The U.S. acquisition process historically requires about a 7-year development cycle for the definition, design and first unit construction of a new ship platform. As the schedule of major events shows, about six years elapsed from the signing of the contract for the design and construction of the PHM lead ship and its commissioning.

It is interesting to note that the NATO patrol missile hydrofoil (PHM) was the first U.S. Navy ship program to complete all aspects of the design, construction, technical evaluation, and independent operational evaluation as required by DOD Instruction 5000.1 which set forth the "fly-before-buy" policies required of selected DOD system acquisition programs. The extensive predelivery test and evaluation program, including problem resolution and corrective actions, account for more than a 2 1/2 year time span from launch to delivery.

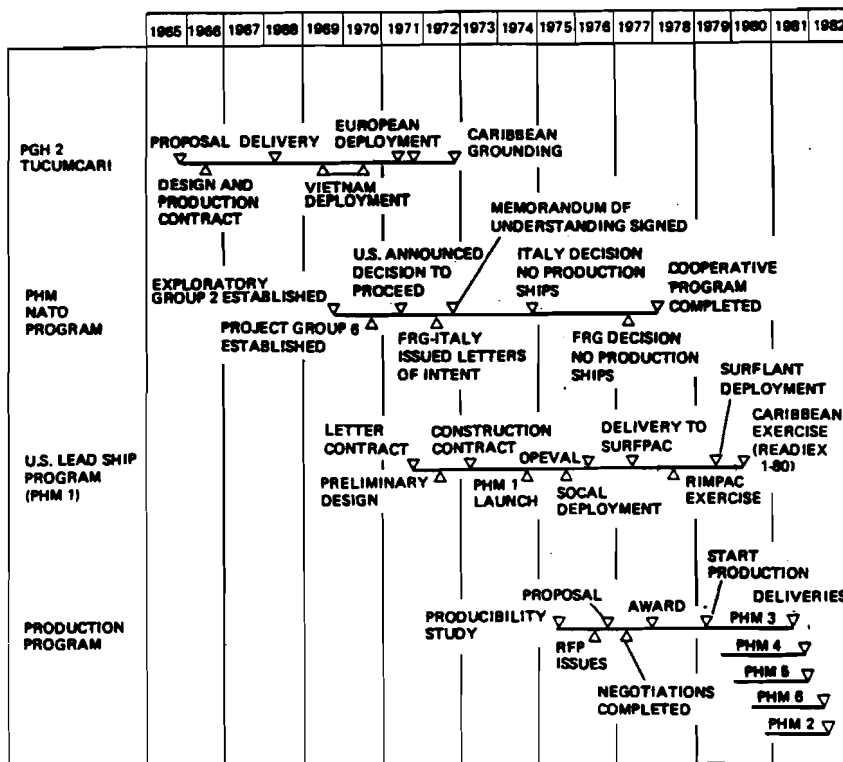


Figure 46. Major Events Leading to Operational PHM Squadron

In the late 1971-early 1972 time frame it was necessary to determine the feasibility of designing a hydrofoil to meet the performance goals of the three participating governments. The objective was examined from the standpoint of three alternative mission suites, in particular the surface-to-surface missiles. The feasibility baseline design and parametric studies were to provide the data and alternatives which would allow the participating governments to select the primary performance and major configuration characteristics to be incorporated in the standard design. Baseline ship cost estimates were also developed to provide information on the effect of configuration choices on cost.

The initial effort determined that the performance goals could be attained with any of the three mission suites, but the displacement in each case was greater than a target value which had become 170 tons. In fact, by the time the feasibility baseline design was completed in April 1972, the design full load displacement was established at 228 metric tons including a 9.5 metric ton margin for growth during the service life.

Another major task in the first days of the hydrofoil contract was to study the feasibility of designing and constructing the ship using metric units in order to achieve the objectives of a cooperative design in the most cost-effective manner. The approach involved review of each major element

of the design specifying metric units for new elements and using imperial units for elements already developed in those units. The initial cost impact was estimated to be about five percent on design, five percent on procurement and an initial ten percent impact on maintenance and support items. The decision to 'go metric' can now be viewed as very favorable. The engineering designers had no problem in changing their thinking to metric equivalents. This represented a significant first in U.S. shipbuilding experience.

The hull lines were developed to satisfy considerations related to accommodations, weight, intact and damaged stability, a two-compartment flooding criteria, seakeeping, hullborne resistance, takeoff resistance, and foilborne wave impacts. The hull was designed as an all-welded structure fabricated primarily from 5456 aluminum alloy.

The use of a canard foil system was established at the outset of the program. The forward foil/strut system has a steerable tee configuration which stows ahead of the bow in the retracted position. The aft foil system was a pi configuration with retraction rearward behind the transom for shallow-water, hullborne operation. These retraction constraints along with the strut length requirements dictated by sea state, determined the location of the foils relative to the hull. The final distribution of foil area, fore and aft, was then determined by the ship center of gravity location. The length of the struts was chosen to allow foilborne operation in 5-meter maximum height waves. The basic material chosen for the foils and struts was a martensitic, precipitation-hardening corrosion resistant steel, 17-4PH.

The propulsion plant went through more of an evolutionary process during the feasibility baseline design period than any other major system. The foilborne system was initially conceived as two double-impeller centrifugal waterjet pumps driven through two combining reduction gearboxes by four General Electric LM500 gas turbines. The hullborne system designs initially consisted of a single AVCO TF25A gas turbine engine driving a controllable, reversible-pitch propeller through a V-box.

Since the foilborne propulsion system has a major cost impact on the ship, its selection was of primary importance. The hullborne system was of secondary importance and was largely dictated by the foilborne system. Criteria used in the selection process were many, but the important considerations included risk, availability, cost, arrangement/access, other commercial and military applications, and performance.

The LM500 engine was not a qualified U.S. Navy marine engine at the outset of the hydrofoil development program, and it was estimated that appreciable cost would be required to accomplish its qualification. Other engines considered at the time were the LM1500 and LM2500. Both resulted in heavier ships, increased machinery weights, larger machinery spaces, larger intake and exhaust ducts, and higher per-engine costs. The LM1500 was a first generation turbine which GE planned to phase out of its production. On the other hand, the LM2500, while more costly, was a second generation engine with a substantially higher compression ratio and turbine inlet temperature resulting in much lower fuel consumption, even when operated at lower power levels. The decision to select a single LM2500 engine was based upon the desire to standardize gas turbines in use by the U.S. Navy since LM2500 engines are used in the FFG and DD-963 classes. The LM2500 engine is rated at considerably higher power output than necessary for a ship sized to meet the PHM specification. The engine fuel control was therefore modified to limit the power output to the 17,000 horsepower needed to meet the specification performance, and the propulsor and gearbox were designed for the reduced power.

For the foilborne propulsor the choice of the single engine, mounted on the ship centerline, narrowed the selection of waterjet pump to a single or a twin-pump consideration. The twin-pump system required a complex power train system which included gearboxes, flexible couplings and shafting spanning the beam of the ship. This twin configuration was initially adopted as the feasibility baseline design. However, complexity and technical risk caused the later selection of a single pump with integral gearbox, direct-driven by the engine, with the inlet ducting (water) spanning the ship. Either a single centrifugal or a mixed-flow pump could have satisfied this configuration decision. Three companies responded to the pump requirement specification.

One company proposed a mixed-flow, single-stage pump; the second proposed a mixed-flow, two-stage pump; and the third (the Tucumcari supplier), proposed a double-impeller, centrifugal pump. After consideration of risk, cost and performance, the second proposal was chosen. The foilborne propulsor has been very successful with no changes in performance but with some changes in materials and fabrication techniques between the lead ship and production ships.

The foilborne gearbox on the lead ship experienced some problems early in testing. These problems were analyzed, and corrections were made. The production ship design accounted for these corrections, and the

following design modifications were made: 1) capability was increased from 16,200 to 17,000 metric horsepower with a battle override rating of 19,680 metric horsepower, 2) rolling element bearings were changed to journal bearings, 3) increased gear tooth strength resulted in decreased tooth bending and contact stresses, and 4) all main gear elements were made integral with their shafts.

After the selection of the single foilborne propulsor, the hullborne propulsion system became a twin system. Twelve candidate hullborne systems were quickly reduced to three. They were: two ST6J-77 turbines and controllable-pitch propellers; two MTU (Motoren-und Turbinen-Union) MB 8V331TC80 diesels and controllable-pitch propellers; and two MB 8V331TC80 diesels and waterjets. The MTU diesels were selected due to lower cost, low specific fuel consumption and good availability. The diesels also had excellent cold start and response time capability, a desired attribute for cold weather operations. Also, early in the program, there was a desire to find some potential Federal Republic of Germany equipment suppliers to increase the European equipment content in the ship. The choice of diesel has proven to be excellent. The only changes from lead ship to production have been a change in designator, MB 8V331TC81, and a very minor increase in continuous power from 750 to 815 metric horsepower.

The choice of hullborne waterjet propulsor over Controller Pitch (CP) propeller was based on least cost, best availability, simplicity, direct access for maintenance, and very low underwater damage vulnerability.

The electrical system feasibility baseline design called for two redundant gas turbine driven generator sets of 200-kW each. Power would be 120/208-volt, three-phase, 400-Hertz a.c. The required 450-volt, 60 Hz a.c. power; the 120-volt, three-phase, 60-Hz a.c. power; and the 28-volt d.c. power would be obtained through power conversion equipment. An auxiliary power unit would provide 60-kW of 400-Hz a.c. power for in-port use, battery charging, and emergency supply to navigation and radio equipment.

The selection of the voltage and frequency for the a.c. power system involved a long and arduous process to meet differing standards of the three countries. Boeing's airplane experience favored the four-wire "Wye" system at 120/208 volts. Also, 400-Hz frequency resulted in lighter, higher speed motors and generators. All aircraft equipment is qualified to this type of system. U.S. Navy ship experience, on the other hand, has all been three-wire "Delta", 450-volt, 60-Hz. The final system chosen for the lead ship and for production was a "Delta" three-wire, 450-volt, 400 Hz system.

The 400-Hz equipment is smaller and lighter than comparable 60-Hz equipment. The two Westinghouse 200-kW (250-kVA) 450-volt, 3-phase, 400 Hz generators have proven to be very reliable. Problems occurred in the lead ship in attaining the reliability goals in some of the 400-Hz equipment, e.g., the centrifugal pumps in the seawater distribution system. The production ship's system took these problems into account. Another problem area was the solid-state frequency converters which are used to convert 400-Hz to 60-Hz. On the lead ship, frequency converter failures necessitated removal of the entire unit for repair. These units weigh over 400 pounds and are cumbersome to remove. On the production ships, a significant effort was made to improve frequency converter reliability, and the units were redesigned to enable fault detection and maintenance actions to be made at the "card" level.

The hydraulic and automatic control systems are worthy of mention. The hydraulic systems operate at a standard 3,000 psi (20.68 MN/m²) constant pressure. Proven aircraft hardware, mostly from the Boeing 747 aircraft, was used where possible. The hydraulic pumps, tube fittings, tubing material, and filters were all taken directly from the 747.

In the case of the foilborne control and hullborne steering actuators, an automatic shuttle valve was specifically developed for the hydrofoil program which rapidly transfers the user actuator from a failed supply to the alternate, thus assuring continued safe foilborne operation.

The hydrofoil program pioneered the use of a new hydraulic fluid, a synthetic hydrocarbon. This new fluid provides a much greater resistance to fire and explosion than its predecessor. At the same time it overcomes the serious shortcomings of phosphate ester-base fluids which have proven to be incompatible with the saltwater environment.

The hydraulic actuators on the patrol hydrofoil were for the most part specifically designed and developed for this program. The four foilborne control actuators, the hullborne steering actuator, two hullborne thrust reverser actuators and the strut retraction actuators all were designed, manufactured and qualified to military specifications including rigorous environmental and life testing.

While the automatic control system (ACS) derived much of its basic approach from the earlier TUCUMCARI and HIGH POINT designs, major technology advances as well as considerable electronic equipment obsolescence

had occurred during the intervening years. At the same time, the then current performance and equipment requirements were considerably more extensive and stringent than for the previous programs. Therefore, the foilborne control system and hullborne steering systems were designed and developed specifically for the PHM program.

As mentioned previously, the events leading to the rare occasion on which all six PHMs are seen flying in formation as shown in Figure-47 started with a letter contract with the Boeing Company in November of 1971. Listed below are the key, important dates for the PHM-1, and the remaining ships that make up the PHM Squadron 2 in Key West.

Boeing Letter Contract for PHM-1	Nov 1971
Boeing Construction Contract for PHM-1	Feb 1973
PHM-1 Launch	Nov 1974
PHM-1 OPEVAL	Feb 1976
PHM-1 Delivery to SURFPAC	May 1977
PHM-1 Commissioning	July 1977
PHM-1 SURFLANT Deployment	July 1979
PHM-1 Caribbean Exercise	Jan 1980
PHM-3 Series Contract Award	Oct 1977

SHIP	KEEL LAYING	LAUNCH	DELIVERY	COMMISSION-ING DATE	ARRIVAL IN KEY WEST
PHM-1	9 MAY 73	9 NOV 74	21 JUNE 77	9 JULY 77	17 JULY 80
PHM-2	12 SEP 80	13 APR 82	17 SEP 82	15 JAN 83	17 FEB 83
PHM-3	30 JAN 79	8 MAY 81	7 OCT 81	10 OCT 81	11 AUG 82
PHM-4	10 JUL 79	16 SEP 81	26 JAN 82	26 JUNE 82	11 AUG 82
PHM-5	7 JAN 80	5 NOV 81	10 MAY 82	18 SEP 82	15 DEC 82
PHM-6	13 MAY 80	17 FEB 82	29 JULY 82	13 NOV 82	17 FEB 83

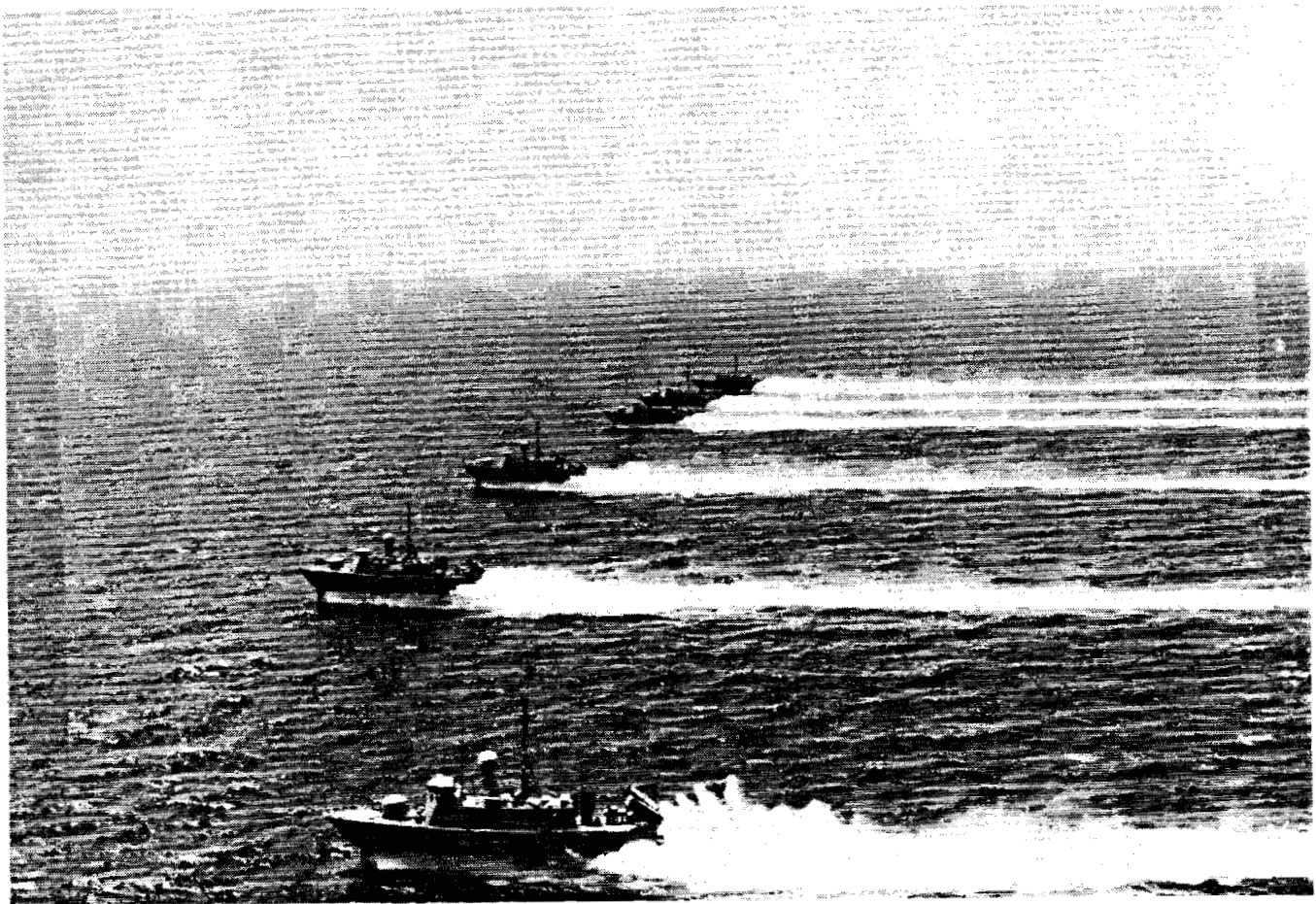


Figure 47. PHMs Flying in Formation, April 1983

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APPENDIX B

GLOSSARY OF HYDROFOIL TERMS

Airplane Foil Arrangement - A foil system in which the main foil assembly is located forward of the vehicle's center of gravity and whose foil area (lifting surface) represents the major portion (65% or more) of the total foil lifting area. The remaining area is given to a smaller foil located aft of the center of gravity.

Air Stabilized Foil - A lifting foil utilizing the controlled ventilation of air to modulate lift for purposes of achieving craft stability and control.

Base Ventilated - Air or water jet used to provide side force forward of the center of gravity of the craft to assist in maneuvering. Thrust vector can be varied.

Breguet Range - The approximate range of a craft based upon the average values of propulsion efficiency, specific fuel consumption, the ratio of initial to final gross weight, and assuming a constant lift to drag ratio; named after L. Breguet, who first suggested the simplified formula applied to airplanes.

Broach - The unwetting of a foil with resultant loss of lift due to the foil coming near to or penetrating the air-water interface.

Canard Foil Arrangement - A foil system in which the main foil assembly is located aft of the vehicle's center of gravity and whose foil area (lifting surface) represents the major portion (65% or more) of the total foil lifting area. The remaining area is given to a smaller foil located well forward of the center of gravity.

Chine, Hard - Angular intersection of the side and bottom of a craft's hull, as opposed to a round bilge, which is sometimes called a "soft" chine.

Continuous Foil - A main foil system in which the foil area is one continuous section as opposed to being split in the center.

Contouring - The motion of a craft when tending to follow the surface wave profile rather than tending to travel horizontally over the waves.

Conventional Foil Arrangement - Same as airplane arrangement.

Cresting - The condition of foilborne operation of a hydrofoil caused by contact of the lower part of a hull and keel with the crests of the larger waves. The contact is brief and does not prevent the craft from remaining foilborne. Also called furrowing.

Dihedral Foil - A foil whose intersection with its strut forms an angle greater than 90° . (Such as PHM aft foils)

Fences - Small fins placed on surface-piercing struts or foils to prevent ventilation air from migrating down a strut or along a foil. The fences are attached to the strut or foil so as to be parallel to the direction of the fluid flow.

Flap Control - A method of controlling the lift of a submerged hydrofoil system by varying the angle of trailing edge flaps on the foils.

Flying Height - The flying height is the distance between the keel and the mean water surface while foilborne. This provides a measure of actual keel clearance.

Foil - Lifting surface designed to support all or part of the weight of a waterborne craft at an appropriate forward speed.

Foilborne - A hydrofoil craft is said to be foilborne when the hull is raised completely out of the water and wholly supported by lift from its foil system.

Foil Broaching - Sudden breaking of the water surface by a foil or part of a foil, resulting in a loss of lift due to air flowing over the foil's upper surface.

Foil Depth - The distance between the foil and the mean water surface while foilborne.

Fully Cavitating - Refers to the formation of a gaseous cavity in the liquid flow past a body, e.g., a foil, and which terminates downstream behind the body.

Fully Submerged Foil System - See Submerged Foil System.

Hullborne - Operating condition of a hydrofoil craft or ACV in which the weight of the craft is supported by the displacement of its hull.

Hump - The hump or peak formed on the graph of resistance against speed for planing craft, hydrofoil, or ACV's, due primarily to maximum wave-making drag of the hull and induced drag of the foils.

Hump Speed - Speed at which the hump occurs.

Hump Drag - The drag at Hump Speed.

Incidence Control - The method of controlling the lift of a submerged hydrofoil system by varying the angle of incidence of the foil or foils.

Ladder Foils - A hydrofoil system consisting of several small parallel foils such that as speed is increased fewer foils are required to support the craft. The remaining foils are then above the water surface and contribute no hydrodynamic drag.

Pi Foil - A foil system consisting of a continuous foil connected to the main hull by two vertical struts, the entire assembly thus resembling an inverted Greek letter π .

Planing - Operating mode of a high-speed craft in which most of the vehicle weight is supported by hydrodynamic lift rather than by static buoyant forces and which is characterized by a clean flow separation at transom and chine.

Platforming - An operating mode of a hydrofoil craft in which the center of gravity of the craft is constrained to travel in straight and level flight with the hull clear of the waves, rather than conforming to the wave profile.

Seakeeping - General term describing the performance, controllability, and dynamic response of a vessel in a seaway.

Seakindliness - Quality of a craft/ship behavior in waves characterized by easy motions (i.e., low accelerations), dry decks, absence of propeller racing and slamming, and easy steering.

Seaworthiness - Condition of a vessel being fit for a sea voyage, i.e., able to stand heavy weather in safety.

Slamming - Violent impact between sea waves and a portion of a craft's hull, resulting in large plating loads due to the large relative velocity. This can occur subsequent to a forward foil broach.

Split Foil - A main foil system with the foil area divided into two, either to facilitate retraction, or to permit the location of the control surfaces well outboard, where foil control and large roll correcting moments can be applied for small changes in lift.

Strut - Steamlined, column-like appendage or support for foils or components of water propulsion systems.

Subcavitating Foil - A general classification given to foils similar in section-shape to subsonic airplane wings. These foils are designed to operate effectively (high lift-to-drag ratio) in fully wetted, non-cavitating flow conditions.

Submerged Foil System - A foil system employing totally submerged lifting surfaces. The depth of submergence is controlled by mechanical, electronic, or pneumatic systems which alter the angle of incidence of the foils or flaps attached to them to provide stability and control. Also fully submerged foil system.

Supercavitating Foils - A general classification given to foils designed to operate efficiently at high speeds while fully cavitated. Since at very high speeds foils cannot avoid cavitation, sections are designed to induce the onset of cavitation from the leading edge and cause the cavities to proceed downstream and beyond the trailing edge before collapsing. Lift and drag of these foils is determined by the shapes of the leading edge and undersurface.

Superventilating Flow - Cavitating flow, with cavity, artificially vented to the atmosphere or a source of pressurized air.

Surface-Piercing Foil System - A foil system in which the lifting surfaces that are partly submerged at foilborne speed. The system is stabilized by the varying submerged foil area. The lift produced is proportional to the submerged foil area.

Take Off - The transition from hullborne operation to foilborne operation.

Tandem Foil Arrangement - A foil system in which the area of the forward foil(s) is between 35% to 65% of the total foil area.

Taxi - Hydrofoil craft operations with struts down and main engine running but craft not foilborne. Examples are: proceeding at reduced speed in restricted channels to or from berth; operating above design sea states to maintain heading and reduce rolling; and, to reduce radar signature by lowering craft to displacement mode.

Transcavitating Foils - Foils designed to have no abrupt changes of loading as they pass from the fully wetted flow region through partial cavitation to the fully cavitating flow region at high craft speeds. Also called transiting foil.

Ventilation - Process by which a ventilated flow is formed and maintained. "Natural Ventilation" exists when a continuous or intermittent flow of air is created by means of the flow itself, as from the free surface in the case of a surface piercing, ventilated strut. "Forced ventilation" exists when the air is continuously supplied into the cavity by auxiliary means such as a pump.

Waterjet - A water propulsion system consisting of an inlet, a duct, and an exit nozzle, or combination thereof, with a pump located in the duct for transferring energy from a prime mover to the fluid. The system is used for propelling low-speed craft where low draft is required and for propelling high-speed craft as an alternative to a mechanical transmission and propeller system.