PATROL COMBATANT MISSILE HYDROFOIL— DESIGN DEVELOPMENT AND PRODUCTION— A BRIEF HISTORY

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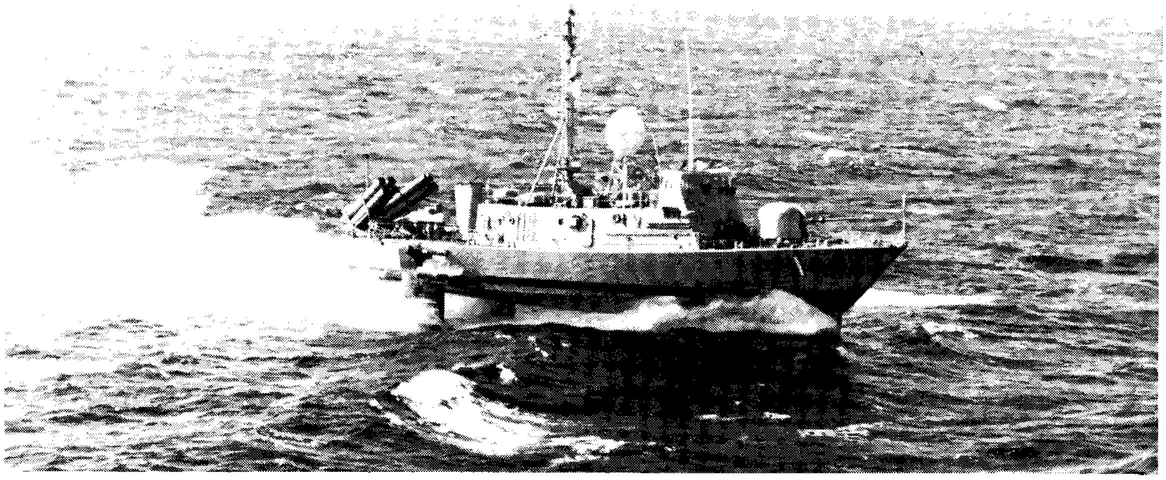


PATROL COMBATANT MISSILE (HYDROFOIL)

Design, Development and Production - A Brief History

by David S. Olling and Richard G. Merritt, Boeing Marine Systems

INTRODUCTION

In 1972 three NATO navies formally agreed to proceed with the joint development of a warship project. The United States took the leadership before the "Memorandum of Understanding" was signed by the Federal Republic of Germany and Italy and awarded a letter contract to The Boeing Company for the feasibility study and the design and construction of two Patrol Combatant Missile (Hydrofoil) lead ships.

Earlier in 1970, the NATO Naval Armament Group (NNAG), composed of representatives of eleven NATO nations, had recommended that a hydrofoil with fully-submerged foils was the answer to the operational requirements for a common fast patrol boat carrying surface to surface missiles. The NNAG had studied different concepts of vehicles, but the final choice of the group was a ship configuration based on the PGH 2, Tucumcari, also built by Boeing, which would be the prototype for future fast patrol boats. The original concept had called for an operational displacement of 140 tons. However, in meeting the requirements of the participating governments and, in particular, the U.S. Navy, it was determined that the minimum displacement that could do the job was a design of 228 metric tons, references 1 and 2.

While the initial contract called for two lead ships, program cost growth forced suspension of work on the second ship in August 1974. Its completion (PHM 2) was later incorporated into the production program, reference 3.

Major Events

Developing a new, sophisticated naval ship system requires a considerable investment of time, talent and money. The U.S. Navy acquisition process, historically, results in about a 7-year development cycle for the definition, design and first unit construction of a new ship platform, references 4 and 5. As the schedule of major events shows, figure 1, nearly six years elapsed from the signing of the letter contract for the design and construction of the lead ship, USS Pegasus, in November 1971 to her commissioning in July 1977. The earlier examination of ship alternatives and configuration choices required over two more years. Again, referring to the major events chart, figure 1, over ten years will have elapsed from the start of the lead ship program before the five production ships will join USS Pegasus to make up the planned six-ship squadron.

Pointing out the span of time for developing PHM-class hydrofoils, a system involving new technologies, new design criteria and new equipment innovations, is not intended to be critical. The application of additional resources could have reduced the elapsed time, but the extent of the reduction cannot be known. The point to be made is that the design and development phases have been

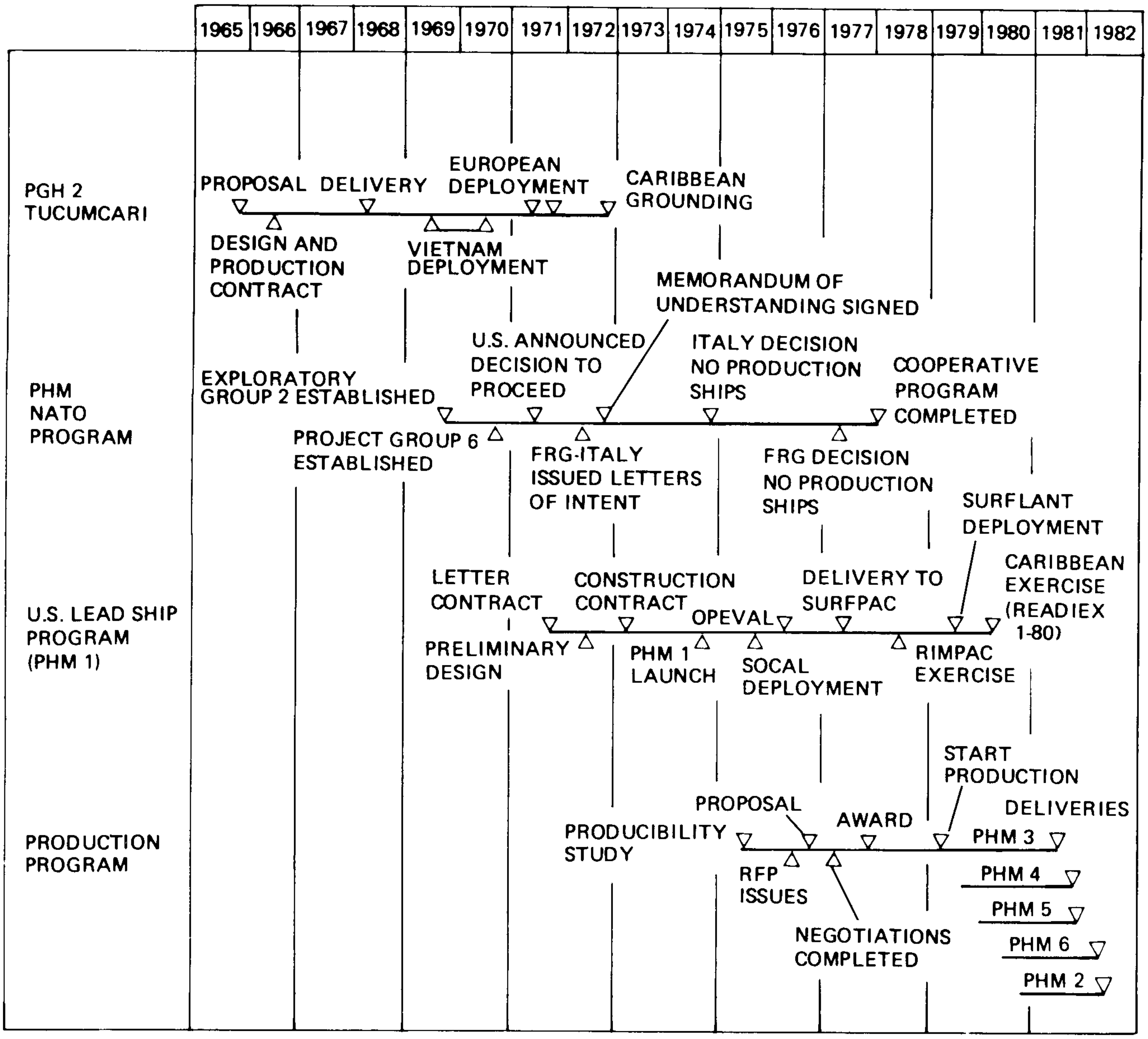


Figure 1. Major Events Leading to NATO PHM Program and Operational PHM Squadron

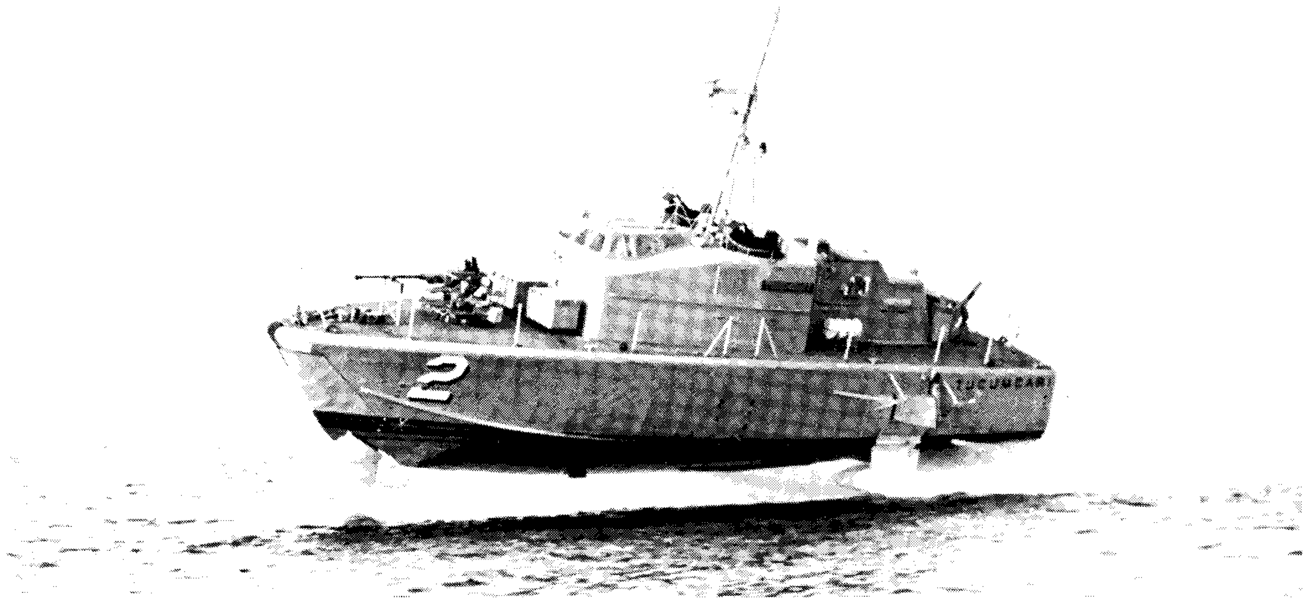


Figure 2. PGH 2 Tucumcari

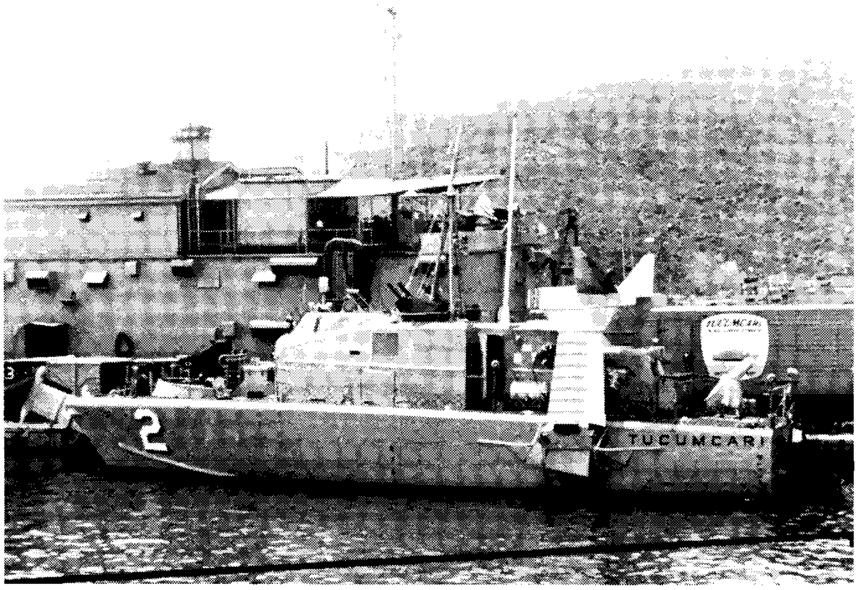


Figure 3. PGH 2 Tucumcari Foil System (Retracted)

successfully achieved and the time to accomplish this is the same or shorter than for other naval ship systems.

Figure 1 also shows the major events for PGH 2, Tucumcari. Because Tucumcari was the basis for the PHM design, a brief review of its design features and operational history is in order to see where the principal features impacted the PHM design.

PGH 2, Tucumcari

The PGH program to develop a hydrofoil gunboat was initiated in late 1965. Two ships were authorized, based on a performance specification. Grumman was awarded a contract for PGH 1, Flagstaff, and Boeing for PGH 2, Tucumcari. The resulting designs were significantly different. As the result of the evaluation of these two ships in trials in the United States and service in Vietnam, the features of Tucumcari, figure 2, were chosen as requirements for the NATO PHM program, reference 1.

Tucumcari is best recognized for its water-jet propulsion system. Propulsion was provided by a Rolls-Royce Proteus turbine driving directly a two-impeller double-suction centrifugal pump. Boeing chose this pump design for its extreme simplicity and minimum number of moving parts. It had an aluminum housing and rotor assembly with a stainless steel drive shaft. After 5 years of operation, the pump remained in essentially the same condition as when installed. There was no evidence of corrosion, erosion, or cavitation damage.

The PGH 2 incorporated a unique foil system, figure 3. The principal features were a canard foil configuration; trailing edge flap control on all foils; a steerable forward strut (rudder); and an Automatic Control System for roll stability, altitude control, ride quality control and banked, fully coordinated turning. The canard configuration where about one-third of the dynamic lift of the ship is supported on the single foil forward and two-thirds on the two foils aft has been conclusively demonstrated to provide superior roll and directional stability and control at all times. This becomes extremely critical in very heavy seas where the possibility exists for broaching the forward foil in large waves.

While the location of the roll authority (forward in conventional or airplane while aft in canard configuration) is not particularly significant for operations in calm seas where the foils are always submerged and fully wetted, it becomes very critical in rough seas. In the case of a forward foil broach, the difference in response between canard and conventional can be dramatic. The forward foil broach on a canard configuration results in no rolling moment. The forward foil broach of a conventional configuration can result in severe rolling. The steerable forward strut adds to the controllability of the canard arrangement foilborne and provides desirable steering forces when the ship is hullborne. Tucumcari could safely operate foilborne in rough water at least one sea state number greater than the slightly larger PGH 1, Flagstaff, with its airplane foil configuration.

An Automatic Control System (ACS) is provided for continuous dynamic control of the ship during takeoff, landing and all foilborne operation. The requirement for an ACS is established at the outset by the fully submerged foil configuration which trades inherent roll stability for superior riding qualities in sea conditions. In addition to providing ship roll stability, the ACS controlled the ship height above the water surface, caused banking in turns and reduced ship motions caused by waves. Automatic foilborne control was based on the concept of "feedback" control. Ship attitudes, rates, and accelerations were sensed and compared with desired values. The differences were processed by an electronic control computer and became electrical commands to hydraulic servo actuators. The actuators moved mechanical linkages to position the control surfaces, causing the ship to respond so as to minimize those differences.

Foilborne turns were accomplished in a banked (coordinated) fashion. This caused the centripetal force required in turns to be provided predominantly by the lift capability of the fully submerged foils rather than by side forces from the struts. Turn coordination enhanced crew comfort during high rate turns because the accelerations due to turning were felt primarily as slightly greater forces normal to the deck rather than as large lateral forces. Fully coordinated, rough water turns were accomplished in relatively steady fashion in spite of variations of the wetted areas on the struts.

After service in Vietnam, Tucumcari toured Europe for the NATO navies in 1971. Jane's Surface Skimmers stated, "The vessel which has contributed most to winning over NATO navies (to hydrofoils) is undoubtedly the Boeing Tucumcari." Upon its return to the United States, it was placed in service with the Atlantic Fleet amphibious forces. In November 1972, during night operations in the Caribbean, it ran upon a reef while operating foilborne. Although the ship was repairable, the cost of repairs was not considered warranted in view of the imminence of the PHM, which would incorporate many of its unique features. It has been removed from the records of active ships and has been dissected for engineering knowledge of its components.

PHM DESIGN AND DEVELOPMENT

Boeing's immediate task in late 1971 - early 1972 was to determine the feasibility of designing a NATO PHM so as to meet the performance goals of the three participating governments, the United States, the Federal Republic of Germany and Italy. The objective was examined from the standpoint of three alternatives for mission suite, in particular the surface-to-surface missiles. (The U.S. Navy, of course, was interested in installing Harpoon missiles, FRG desired Exocet and Italy was interested in Teseo). The feasibility baseline design and parametric studies were to provide the data and alternatives which would allow the participating governments to knowledgeably select the major and primary performance and configuration characteristics to be incorporated into what was called the "NATO PHM Standard Design". Baseline ship cost estimates, by element, were also developed in order 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 of 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 NATO PHM 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 PHM 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. It represents a significant first in U.S. shipbuilding experience.

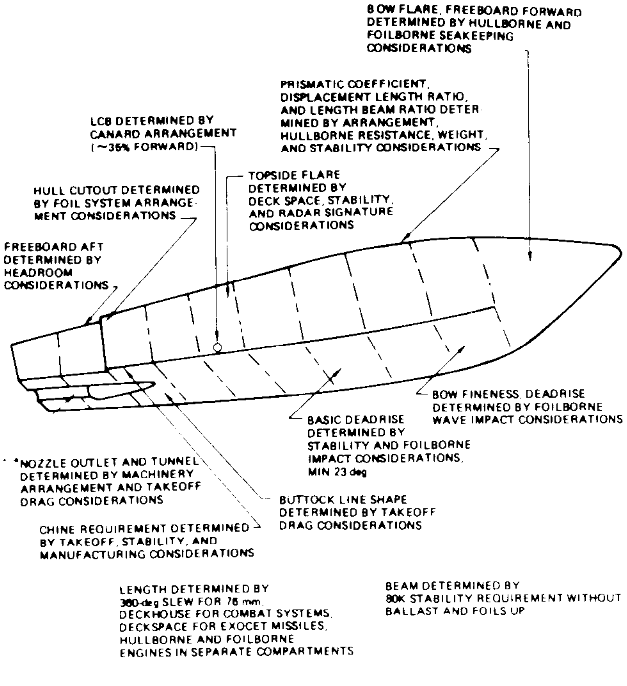
Some of the principal systems will now be discussed including the rationale for their selection. It is of interest, in some cases, to compare the feasibility baseline ship with the final design for PHM 1 to see where changes occurred and why.

Hull Lines

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 considerations determining the resulting hull shape are illustrated by figure 4.

The resulting length overall and maximum beam for the feasibility baseline design were 39.5 meters and 8.4 meters, respectively. This hull accommodated the LM2500 gas turbine for foilborne propulsion. Minor refinements in equipment and arrangements finally resulted in a slightly longer hull. PHM 1 and the production series have a length overall of 40.5 meters and a beam of 8.6 meters.

The hull, at all times, was designed as an all-welded structure fabricated primarily from 5456 aluminum alloy.



*PHM 1 design differs from feasibility baseline design

Figure 4. PHM Feasibility Baseline Hull Design Considerations

The canard foil system arrangement, as described for Tucumcari, was a given from the outset of the program (see figure 5). The forward foil/strut system has always been a steerable tee configuration which stows ahead of the bow in the retracted position identical to Tucumcari. The aft foil system was configured as a structural bent rather than individual tee foils. This resulted in greater structural and hydrodynamic efficiency but necessitated retracting the system 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.

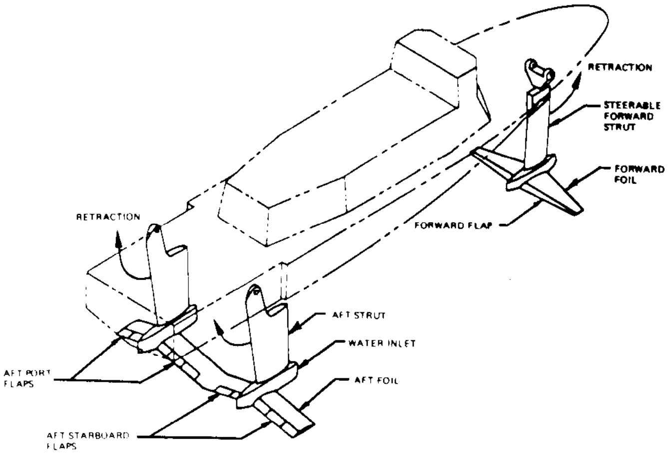


Figure 5. Foil System Arrangement

The feasibility baseline configuration resulted in a distribution of foil area of 32 percent forward and 68 percent aft. This has not changed much even as other systems have changed drastically. For example, the production series has foils arranged with 31.8 percent of the total foil area forward and 68.2 percent aft.

The length of the struts, chosen to allow foilborne operation in 5-meter waves, has changed very little from inception in 1971 to production today. For example, the forward strut is 7.5 meters from pivot to foil chord plane (3.66 meters from keel to foil chord plane). The basic material chosen for the foils and struts was 17-4PH, a martensitic, precipitation-hardening stainless steel. HY 130 low alloy steel had been an active candidate for foils and struts even beyond the baseline feasibility design conclusion. Although recognized to have better field weld repair characteristics, specific corrosion fatigue properties without reliance on coatings remained an unknown.

During extensive operation of PHM 1, USS Pegasus, and after thousands of operating hours on Boeing JETFOILS, considerable data became available on the loads encountered by hydrofoils in rough water. This caused a complete change in the design load criteria for the foil system. As a result, a significant increase in foil operational life is expected on the production ship. This is described later under Producibility Study.

Propulsion

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 consisted of a single AVCO TF 25A gas turbine engine driving a controllable, reversible-pitch propeller through a Veebox.

Since the foilborne system involved the 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.

Foilborne Engine

General Electric's LM500 engine was not a qualified marine engine at the outset of the PHM program and it was estimated that appreciable cost would be involved to accomplish its qualification. Other engine considerations at the time were GE's 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 production. On the other hand, the LM2500, while more costly, was a second generation engine with a substantially higher turbine inlet compression ratio and 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 U.S. Navy gas turbine engines in the fleet (used in both the DD 963-class and the FFG 7-class ships). Also, the selection allows considerable growth in the PHM-class if the full power capability of the LM2500 is eventually utilized. PHM 1 uses 16,200 Hp (metric) from the engine, PHM production ships use 17,000 Hp, and a full growth potential to 30,000 Hp is possible in the future. The gearbox would require complete redesign to absorb this eventual power.

Foilborne Propulsor

The choice of the single engine, mounted on ship centerline, narrowed the selection of waterjet pump to a single or a twin pump consideration. The twin pump system required a power train system which included gearboxes, flexible couplings and shafting spanning the beam of the ship. This configuration was 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. Rocketdyne responded with a mixed flow, single stage pump; Aerojet responded with a mixed flow, two stage pump; and Byron Jackson (Tucumcari supplier), with a double-impeller, centrifugal pump. In the end, Aerojet Liquid Rocket Co. became the foilborne propulsor supplier after all considerations of risk, cost and performance. The foilborne propulsor has been very successful with no changes in performance but with some changes in materials and fabrication techniques between PHM 1 and the production ship. Today, Aerojet has suggested that the foilborne propulsor, in growth considerations, can be used to nearly 30,000 Hp with no change in envelope, no change in weight, and only minor changes in impeller materials.

Foilborne Gearbox

The foilborne gearbox on PHM 1 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 geartooth strength resulted in decreased tooth bending and contact stresses; 4) all fixed splines were removed; and 5) all main gear elements were made integral with their shafts.

Hullborne Propulsion

The feasibility baseline design, using two centrifugal foilborne propulsors, caused the hullborne system to be a single, centerline installation. Gas turbines and diesels were considered for the hullborne prime mover. The diesel, a Mercedes Benz 873, was selected because the hullborne endurance requirement could not be met by the gas turbine with its high fuel consumption.

Later, after the selection of the single foilborne propulsor, the hullborne system changed to a twin system. Twelve candidate hullborne systems were quickly reduced to three principal considerations. 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 usage of PHM. Also, early in the program, it was desired to find some potential FRG equipment suppliers to increase the European content in the ship. The choice of diesel has proven to be excellent. The only change from lead ship to production has 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 CP propeller was based on least cost, best availability, simplicity, direct access for maintenance, and very low underwater damage vulnerability because of the propulsor being entirely within the hull. While the hullborne waterjet has considerably lower propulsive efficiency than the propeller at the desired cruise speeds of under 11 knots, the performance attributes (endurance, reversing and steering) have always been more than required.

Electric Plant

The 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 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 choice of gas turbines for the ship service power units (SSPU) was made because the initial emphasis was on the high speed, short duration foilborne missions. The higher fuel consumption of the gas turbines caused no undue penalty on endurance. On the other hand, there were severe space limitations in the machinery spaces below the main deck. Originally both units were located below. Later in the PHM 1 design, one of the auxiliary machinery spaces was moved to the aft compartment in the deckhouse, but the decision of gas turbine versus diesel for this SSPU was not re-examined. One growth consideration for a future alteration of PHM is to change this particular unit to a diesel. The one ton weight penalty of the diesel installation does not negate its better fuel consumption which still results in a foilborne range improvement of 3 percent and a hullborne range improvement of between 30 and 120 percent, depending on ship speed.

The selection of the voltage and frequency for the a.c. power system involved a long and arduous process during PHM's design and development. Boeing's airplane experience favored the four-wire "Wye" system at 120/208 volts. Also, 400 Hz frequency resulted in smaller, 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 volts, 60 Hz. The final system chosen for PHM 1 and for production was a delta three-wire, 450-volt, 400 Hz system. This decision has been a mixed blessing. The long run benefits will be good.

First, the weight and size of 400 Hz equipment has been lighter and smaller. The two Westinghouse 200 kW (250 kVA) 450-volt, 3-phase, 400 Hz generators have proven to be very reliable. Problems have arisen in PHM 1 with attaining the reliability goals in some of the 400 Hz power users which were redesigned from conventional marine 60 Hz equipment, e.g., the centrifugal pumps in the seawater distribution system. Another problem area has been the solid-state frequency converters which are used to convert 400 Hz to 60 Hz. On PHM 1, frequency converter failures have necessitated removal of the entire unit for repair. These units weigh over 400 pounds and are cumbersome to remove. On the production ship, a significant effort has been made to improve frequency converter reliability and to enable fault detection and maintenance actions to be made at the "card" level.

Hydraulic and Automatic Control Systems

These two systems are worthy of mention because: 1) they have proven extremely reliable and functionally well-suited for the PHM, 2) they combine proven aircraft system equipment applications with unique hydrofoil equipment applications, and 3) they are essential to all operations foilborne, hullborne and docking.

The hydraulic systems operate at a standard 3,000 psi (20.68 MN/m^2) constant pressure. Proven aircraft hardware mostly from the Boeing 747 was used where possible. The hydraulic pumps, tube fittings, tubing material, and filters are all taken directly from the 747.

Because the hydraulic systems are crucial to both foilborne and hullborne operation the design employs multiple levels of redundancy to assure continued operation in the event of system failures or battle damage. Four separate systems supply the required power to the various hydraulic equipment users which include the foilborne and hullborne control actuators, strut retraction and lock actuators, bow thruster, anchor windlass, and emergency fuel pump. Systems No. 1 and No. 2 supply equipment in the forward part of the ship while systems No. 3 and No. 4 supply the aft part. Two separate supply systems feed each user, with provisions included to transfer (shuttle) the user from its primary supply to its alternate supply in the event of loss of primary supply pressure. In the case of the foilborne control and hullborne steering actuators, an automatic shuttle valve was specifically developed for PHM which rapidly transfers the user actuator from a failed supply to the alternate, thus assuring continued safe foilborne operation.

PHM pioneered the use of a new hydraulic fluid, MIL-H-83282, a synthetic hydrocarbon. This new fluid provides a much greater resistance to fire and explosion than the old standby, MIL-H-5606. At the same time it overcomes the serious shortcomings of phosphate ester-base fluids which have proven to be incompatible with the salt water environment.

The hydraulic users on PHM, contrasted to the supply equipment, were for the most part specifically designed and developed for PHM. The four foilborne control actuators, the hullborne steering actuator, two 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 PHM Automatic Control System (ACS) derived much of its basic approach from the earlier PGH 2, Tucumcari, and PCH 1, High Point, control system designs, major technology advances as well as considerable electronic equipment obsolscence had occurred during the intervening years. At the same time, PHM 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.

Functionally the foilborne control system provides continuous automatic control of the ship during takeoff, landing, and all foilborne operation. Pitch, roll, and height feedback loops provide automatic stabilization of the inherently unstable ship. The ship is automatically trimmed in pitch over the entire operating envelope, and roll trim is accomplished by helm inputs. To steer the ship the helmsman simply turns the helm and the ACS automatically provides a coordinated turn with turn rate being proportional to the helm angle. The ship employs the fully swiveled forward strut for foilborne steering, and an inverted "W" foil aft which enhances directional stability and maneuverability. Trailing edge flaps on all the foils are actuated by hydraulic ram actuators to provide the necessary control force.

In order to meet the stringent ride quality requirements, acceleration feedback is provided to the forward and aft flaps. A heading hold system was developed to satisfy long term steering and navigation relief requirements. Duality in sensors, power supplies, electronics and hydraulic actuators was incorporated to meet the foilborne safety requirements. An automatic failure detection system and an auto land system were incorporated for the same safety reasons. Dual tandem actuators were incorporated for the aft flap actuation to eliminate the possibility of a failure resulting in a hard over roll command.

The control system consists of 31 separate assemblies that are distributed throughout the ship. These assemblies include gyroscopes, accelerometers, height sensors, power supplies, computer assemblies, hydraulic servo actuators and pilot house control and display panels. Where possible off-the-shelf, qualified equipment was selected. Gyros, accelerometers, and some power condition equipment fell in this category. The remaining assemblies were designed specifically for PHM. The electronics systems employ all solid state equipment with frequent use of integrated circuit modules such as operational amplifiers and multipliers.

All the control system equipment was subjected to rigorous environmental and life testing. The height sensor installation in the bow was even tested in an iceing tunnel to validate the operability in freezing and near freezing temperatures.

To satisfy the operational reliability and maintenance requirements, the control system assemblies were designed to be interchangeable and an automatic self-test system was developed. The self-test system can verify the operational readiness of the ACS and fault isolate out-of-tolerance conditions to the individual shipboard replaceable assembly. The self-test system is a hybrid system, with all test logic, test parameters, and tolerances handled by digital equipment. The test outputs and ship system measurements are analog since the ACS itself is analog.

Only one significant development problem arose after installation of the ACS on the ship, that being the coupling of electromagnetic noise and shipboard acoustical noises into the height sensors. These problems were solved by minor redesign in the height sensors which effectively immunized the sensor from the noise sources.

On the production ships the only significant changes made to the ACS were the rerouting of cables to accommodate shipboard structural changes and minor redesign of the hydraulic actuators to accomplish cost savings.

76 mm Gun

The 76 mm gun mounted forward on the ship needs to be mentioned. The feasibility baseline design examined the alternative weapon systems of the three participating governments. One common armament was the 76 mm gun. Originally, it was desired to slew the 76 mm gun 360 degrees with the barrel unelevated. This design goal was dropped after the selection of the LM2500 engine which resulted in larger, more forward machinery spaces and larger air inlet and exhaust ducts. The deckhouse, also sized to accommodate the FRG command and control equipment in the CIC, had to be placed forward on the hull. The 360-degree slew capability was not considered an important requirement. The 76 mm gun can still slew 360 degrees, but there are rather large barrel elevation angles associated with the gun pointed in the aft quadrants.

PHM 3 Series Ship Configuration

To most observers, the configuration of the PHM 3 Series production ship looks identical to the PHM 1. Except for structural simplifications achieved during the Producibility Study which is described in the next section, the arrangement is essentially the same. The command and surveillance equipment items and operator stations in the Command Information Center (CIC) have been rearranged, the wardroom was eliminated allowing enlargement of the crew messroom, and the head facilities were combined eliminating one head and creating a crew storeroom.

Figure 6 shows the exterior arrangement of PHM with the location of mission equipment and armament. Figure 7 lists the general characteristics and principal subsystems. Figure 8 lists the mission equipment. Figure 9 shows the platform deck plan. Figure 10 shows the main deck plan and the 01 level deck plan. Figure 11 shows the inboard profile of the ship.

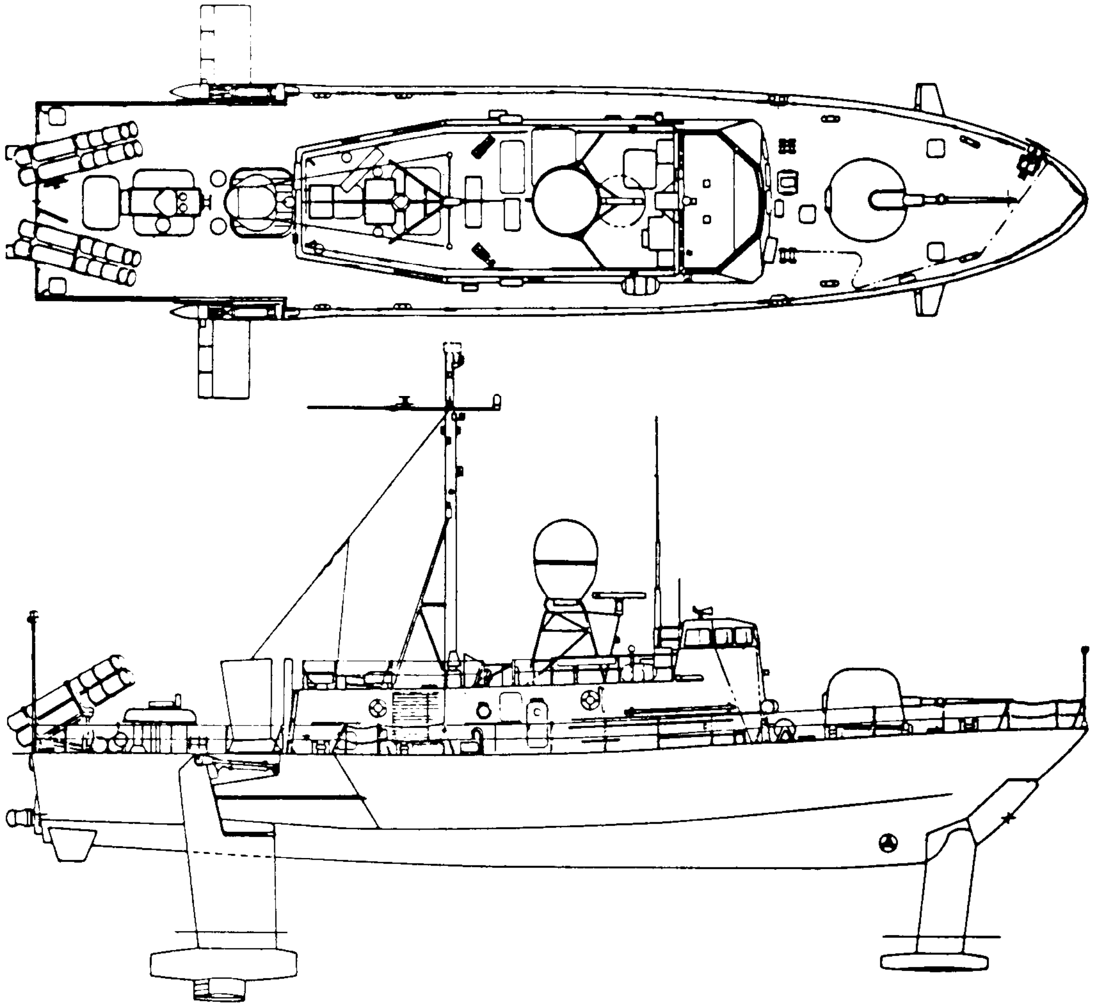


Figure 6. PHM 3 Series Exterior Arrangement

Dimensions:	Length overall, foils down	40.5m
	Beam, main deck	8.6m
	Overall aft foil span	14.5m
	Draft, foils up	1.9m
	Draft, foils down	7.1m
	Height of bridge, hullborne	6.8m
	Height of bridge, foilborne	11.1m
	Full-load displacement	241.3 metric tons
Foilborne propulsion:	(1) General Electric LM2500 gas turbine engine (1) Aerojet Liquid Rocket Company waterjet propulsor	
Hullborne propulsion:	(2) Motoren-und Turbinen-Union (MTU) MB8V331TC81 diesel engines (2) Aerojet Liquid Rocket Company waterjet propulsors with nozzle steering and reverser assemblies	
Electrical:	(2) AiResearch ME831-800 gas turbine engines, each driving one generator rated at 200 kW (250 kVA), 400 Hz, 450V, three phase	
Fuel:	Diesel oil per MIL-F-16884 (NATO F-76) or JP-5 per MIL-J-5624 (NATO F-44)	
Hull:	Welded 5456 aluminum	
Foils and struts:	Welded 17-4PH corrosion-resistant steel	
Accommodations:	24 berths	
Complement:	21 officers and enlisted personnel	
Provisions:	5 days	

Figure 7. PHM 3 Series General Characteristics and Principal Subsystems

Armament:	(1) MK 75 76-mm/62-cal OTO Melara gun (2) Harpoon missile canister launchers (2) MK 135 Mod 0, 4.4-in launchers
Ammunition:	(400) 76-mm rounds (8) Harpoon surface-to-surface missiles, RGM-84A-3 (24) MK 171 Mod 0, chaff cartridges Small arms, ammunition, and pyrotechnics
Command and surveillance:	
Command and control:	(2) AN/SPA-25B displays
Navigation:	(1) AN/SRN-17 OMEGA (1) SMA 3TM20-H radar (1) PL41E gyrocompass and vertical reference (1) UL-100-3 underwater log (1) DE-723D depth sounder (1) Windspeed and direction system (type F) Dead-reckoning tracer
Interior communications:	(1) MCS 2000 intercom, announcing, and alarm system
Exterior communications:	(1) AN/URC-80 vhf transceiver (156-162) (2) AN/ARC-138(V) uhf transceiver (225-400) (2) AN/URC-75(V) hf transceivers (2-30) (1) Radio teletype system
Surveillance:	(1) AIMS MK XII IFF system
Countermeasures:	Rapid bloom offboard chaff ESM (weight, space, power reservations)
Fire control:	MK 92 (Mod 1) gun fire control system Harpoon ship command-launch control set AN/SWG-1(V)

Figure 8. Mission Equipment

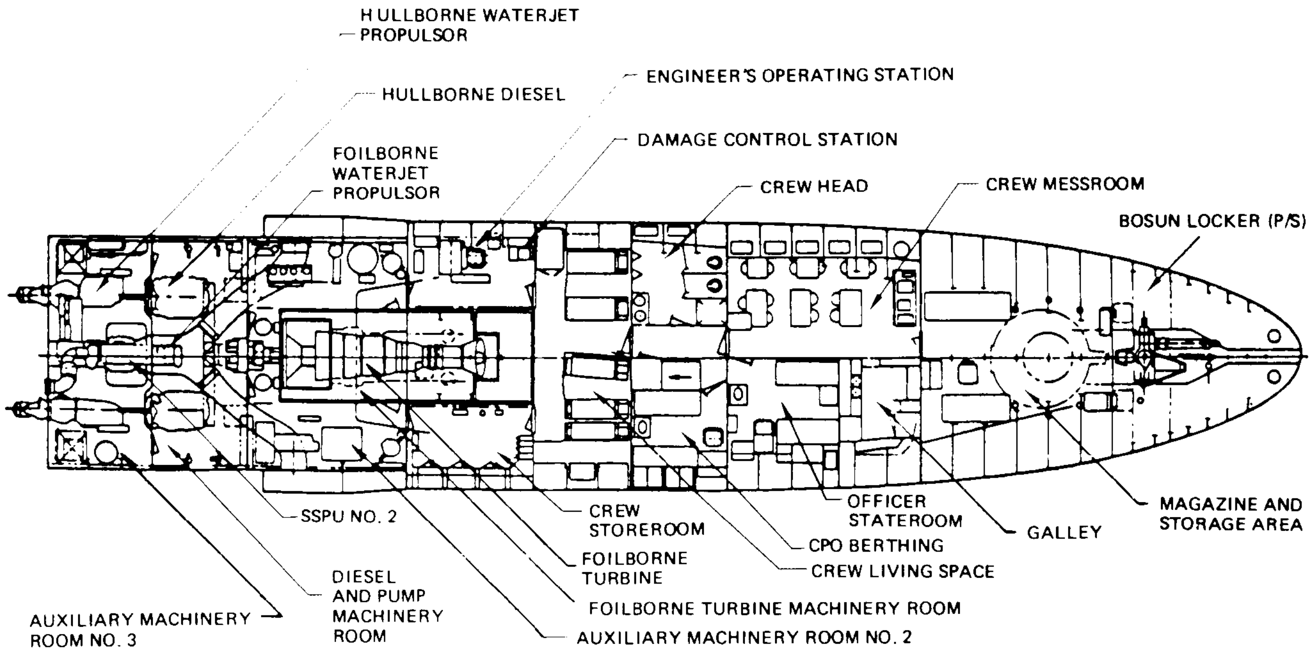


Figure 9. PHM 3 Series Platform Deck

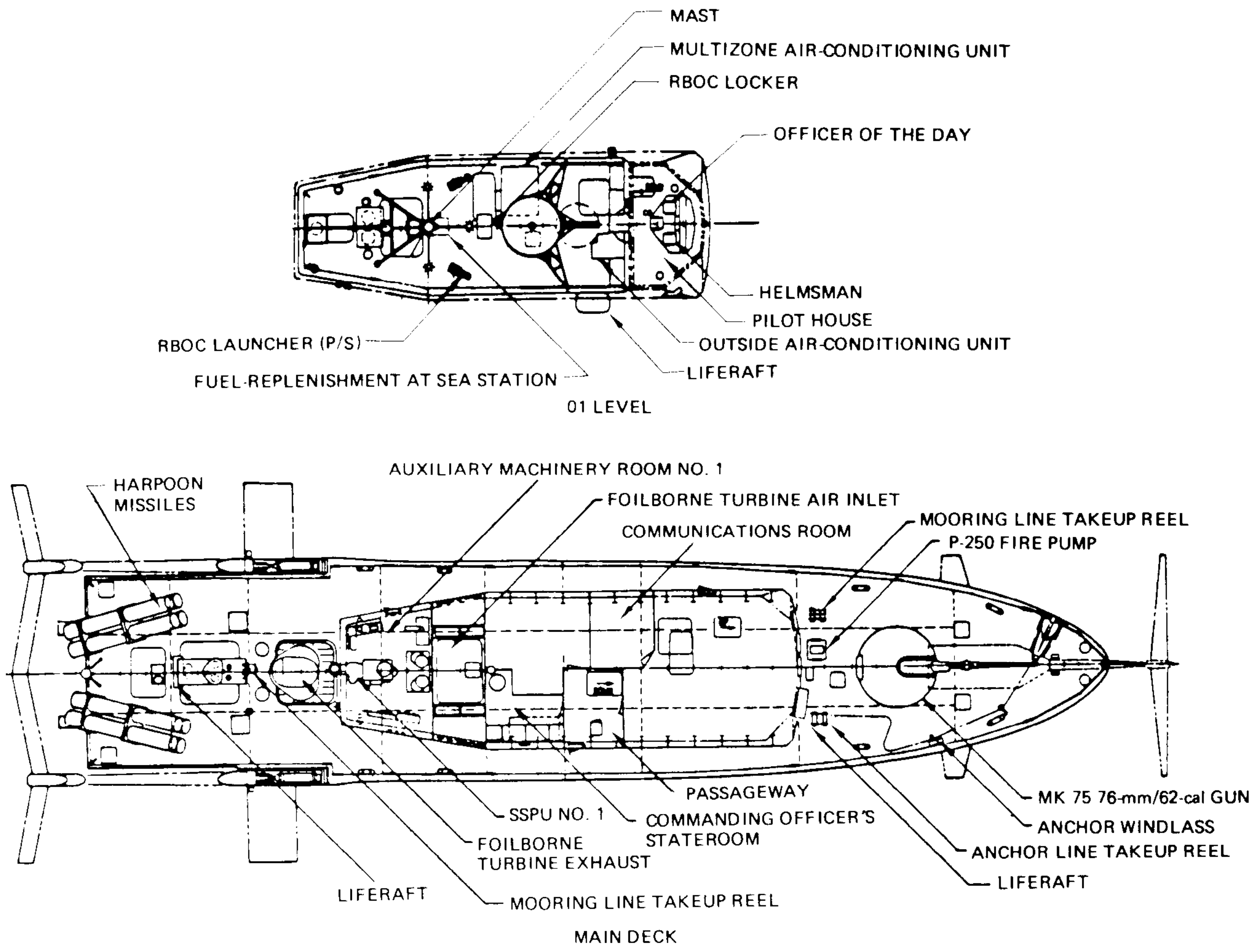


Figure 10. PHM 3 Series Main and 01 Level Deck Plan

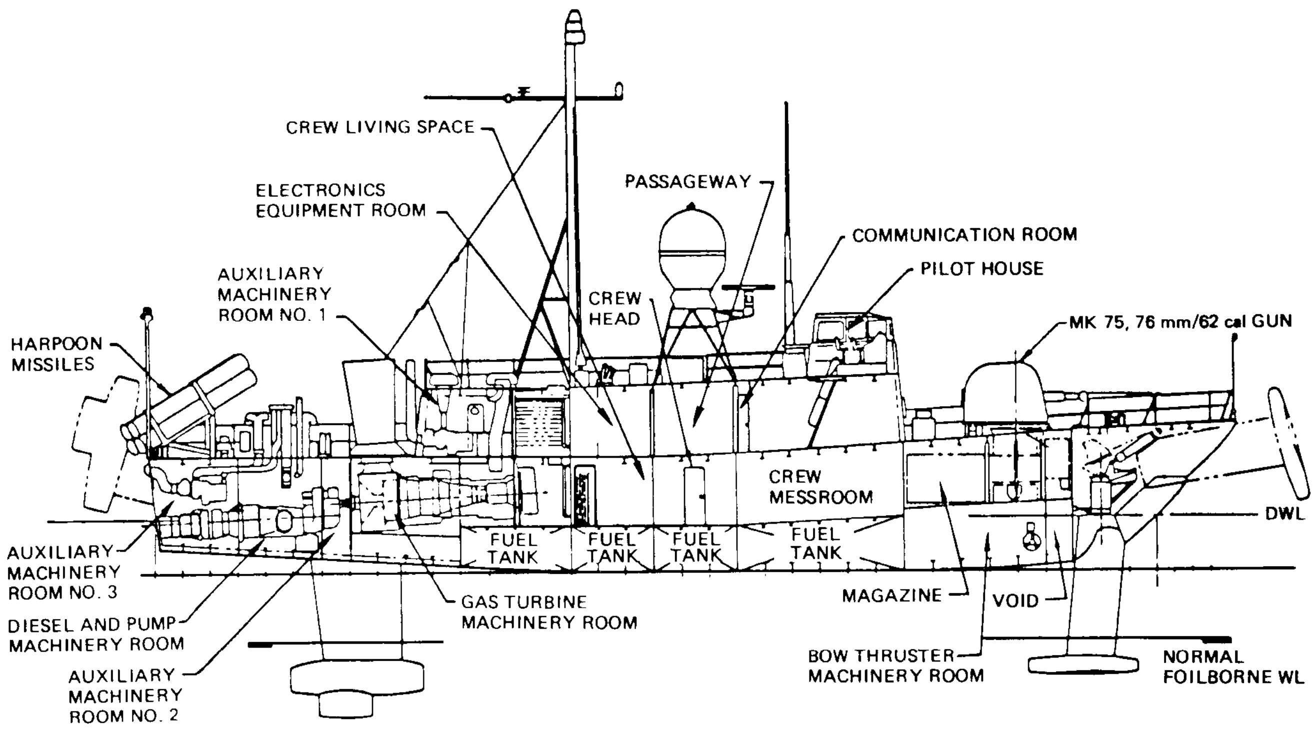


Figure 11. PHM 3 Series Inboard Profile

PRODUCIBILITY STUDY

After the completion of PHM 1 and before the PHM 3 design was started, a producibility study was performed to determine ways to simplify the ship's design in order to reduce construction time, reduce overall welding (a high-cost item) and improve the end product. This study integrated engineering design with advanced construction technology.

In order to best illustrate the changes resulting from this study, a typical transverse watertight midships bulkhead was chosen as a representative example of a hull structural element which was to be redesigned, figure 12.

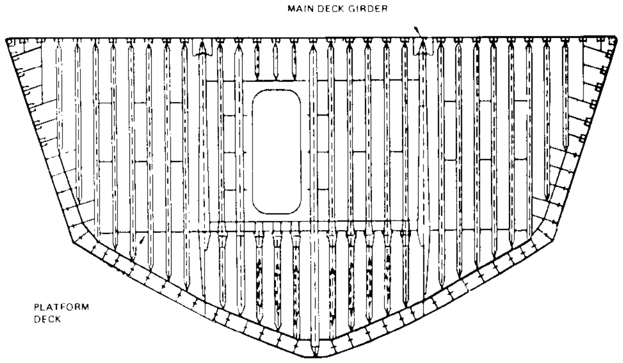


Figure 12. PHM 1 Bulkhead

PHM 1 Hull Design

In order to reduce the amount of welding and the resulting weld distortions, a decision was made at the outset of PHM 1 design to use wide-ribbed extruded panels wherever practical considerations of fabrication and material usage would permit. These panels were used extensively for decks and side shell and were initially intended for use on bulkheads; however, the introduction of large local loads in the bulkheads caused by foilborne wave impacts on the hull bottom made the use of such panels impractical.

In accordance with previous designs, bulkhead and deck stiffeners were intentionally aligned on PHM 1 and watertight collars were provided at the intersection of longitudinal deck and side shell stiffeners and at the bulkhead web. PHM 1 bulkhead stiffeners were designed for structural continuity through the platform deck area.

Accordingly, typical bulkhead construction consisted of "tee" extruded stiffeners welded to plate web. Local reinforcement of bulkhead webs was provided by insert plates butt welded in the plane of the web. Residual stresses caused by welding resulted in excessive distortions at the corners of these insert plates.

Brackets and chocks were added to achieve stiffener continuity which, because of poor weld accessibility caused by low profile and close stiffener spacing, were difficult and costly to install. See comparison of bulkhead stringer configuration, figure 16.

PHM Production Design

The PHM production design resulted from extensive study of PHM 1 design and construction problems. Many parts were used, access to welds was difficult and subsequent fit-up was time-consuming due to weld distortion. The resulting PHM 3 Series bulkhead design is shown in figure 13.

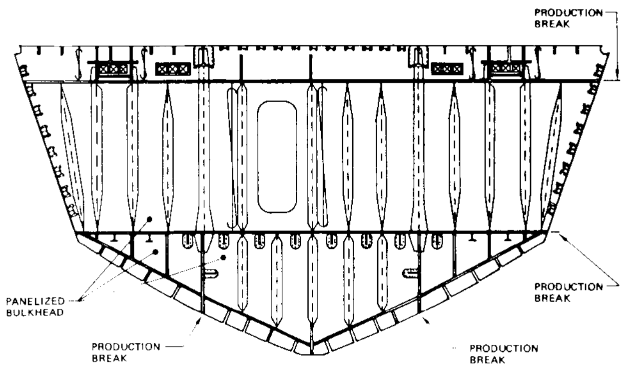


Figure 13. PHM 3 Bulkhead

Key features of the typical bulkhead design include offset stiffeners, snipped stiffeners, thicker skin gage, panelized bulkhead segments, provisions for penetrations and a design integrated with the manufacturing plan.

The termination of bulkhead stiffeners on a beam header at a production break below the main deck simplifies installation and fit-up of the deck module. It also provides for an area in which an orderly arrangement of electrical, hydraulic and piping runs can be made. Production design bulkhead penetrations necessary to accommodate these systems are unencumbered with the presence of bulkhead stiffeners, a more efficient arrangement than on PHM 1. The design provides for a maximum of panelized welding (mechanized welding of stiffening members to the web) of bulkhead segments. One such bulkhead segment is shown in figure 14.

To ensure good fit-up and minimize the need for trimming on installation, panel segments are trimmed to net size by routing after all welding is complete. An increase in the basic bulkhead web gage permits a reduction in the number of bulkhead stiffeners and thus the amount of welding compared with PHM 1.

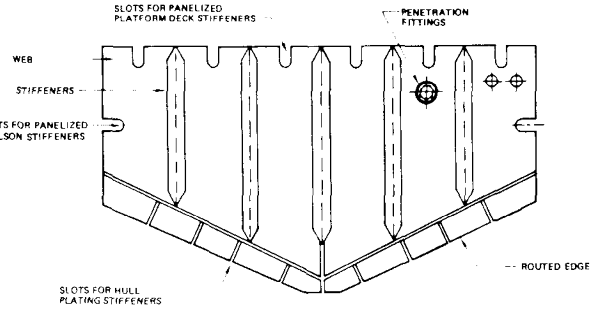


Figure 14. Panelized Bulkhead Segment

Figure 15 is typical of design detail developed to provide simple assembly/subassembly fit-up with a small number of loose parts and maximum access for the welder. Note that the manual alignment of stiffeners above the platform deck is the only fit-up on assembly required with this design. The panelized fuel tank bulkhead segment which is machine profile routed after subassembly welding is a part of the welded lower hull module. Slots are pre-cut in the bulkhead with sufficient clearance to permit easy installation of the platform deck onto the lower hull module. The flat bar longitudinal stiffeners on the platform deck provide for a simple one-piece collar closeout with good welding access. The vertical bulkhead stiffeners are intentionally offset from the platform deck stiffeners in order to accommodate the fit-up detail shown. The bulkhead stiffeners above the platform deck are left unwelded for a short distance on the panelized bulkhead segment to permit manual alignment with stiffeners below the deck prior to final weld closeout. This is in contrast to the fit-on-assembly approach and difficult weld-behind-flanges configuration used on PHM 1. Figure 16 should be examined in order to allow better visualization of the differences in the two bulkhead configurations. The contrast in the two designs is evident when comparing these illustrations. This contrast is even more evident when numerical comparisons are made. For this specific example, the figure 13 bulkhead, there are 75 percent fewer individual parts, a reduction of 58 percent of the length of welds, an estimated 71 percent fewer fabrication manhours and an estimated 68 percent reduction in total cost. All these reductions were gained with a less than a five percent increase in weight.

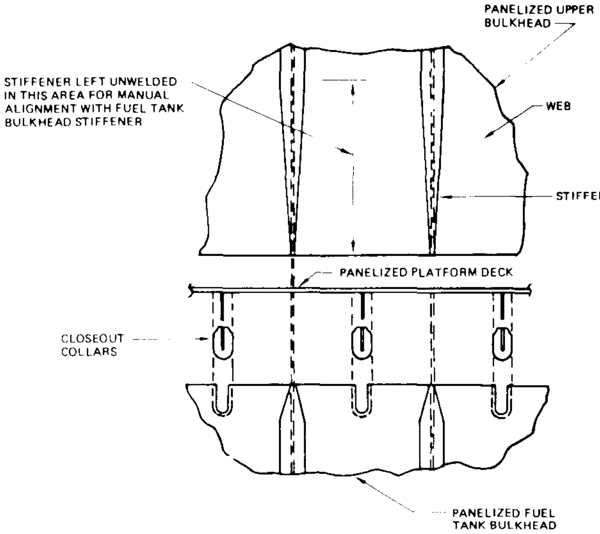


Figure 15. Typical Bulkhead Design Detail

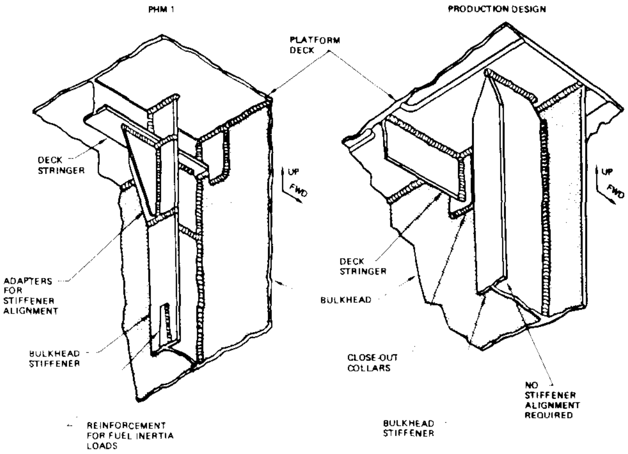


Figure 16. Comparison of Bulkhead Stringer Configuration

Examining the results of the study for the entire hull shows a 49 percent reduction of individual parts, a 59 percent decrease in total weld length and a 720 percent increase in the use of mechanized welding. The estimated hull weight reduction was about nine percent. Therefore the additional engineering effort (cost) did accomplish its objective; a simplification in design, a reduction in production cost, and an improved end product.

Early in the operational life of PHM 1, cracks appeared in the skins of the foils. Detailed investigations showed that material fatigue was the major source of failure. Detailed fatigue load spectra were obtained from full-scale ship trials, tests were conducted to determine material fatigue properties and a detailed design resulting in significantly lower stresses and smoothing of stress concentrations was completed. This design along with the study of its producibility resulted in totally new foil and strut structure. The foil structure is created from large thick billets, Numerical Control (NC) machined for interior contour with welded upper skins. This eliminated most welds from the lower surface of the foil which is the predominate tension surface. The skin welds in the upper skins were located in order to improve their weldability and inspectability. The foil section was also changed from a NACA 16-206.5 to NACA 16-306.5, an increase in camber. The differences in the structural configurations are shown in figure 17.

The same kinds of manufacturing improvements such as fewer individual parts, less weld length and increased mechanized welding were investigated in the strut and foil design. The use of Electron Beam (EB) welding for heavy gage steel structure (foil billets), and Plasma Arc welding for high rate straight line weld in medium gage structure were identified as construction simplifying, cost effective measures. The result of this study was a less complex but heavier foil system, although much of the weight change can be attributed to the upgrading in the system's strength and fatigue capability.

This study was conducted at a time when the knowledge of the PHM 1 design and construction problems were still fresh in mind, thereby taking advantage of recent "lessons learned".

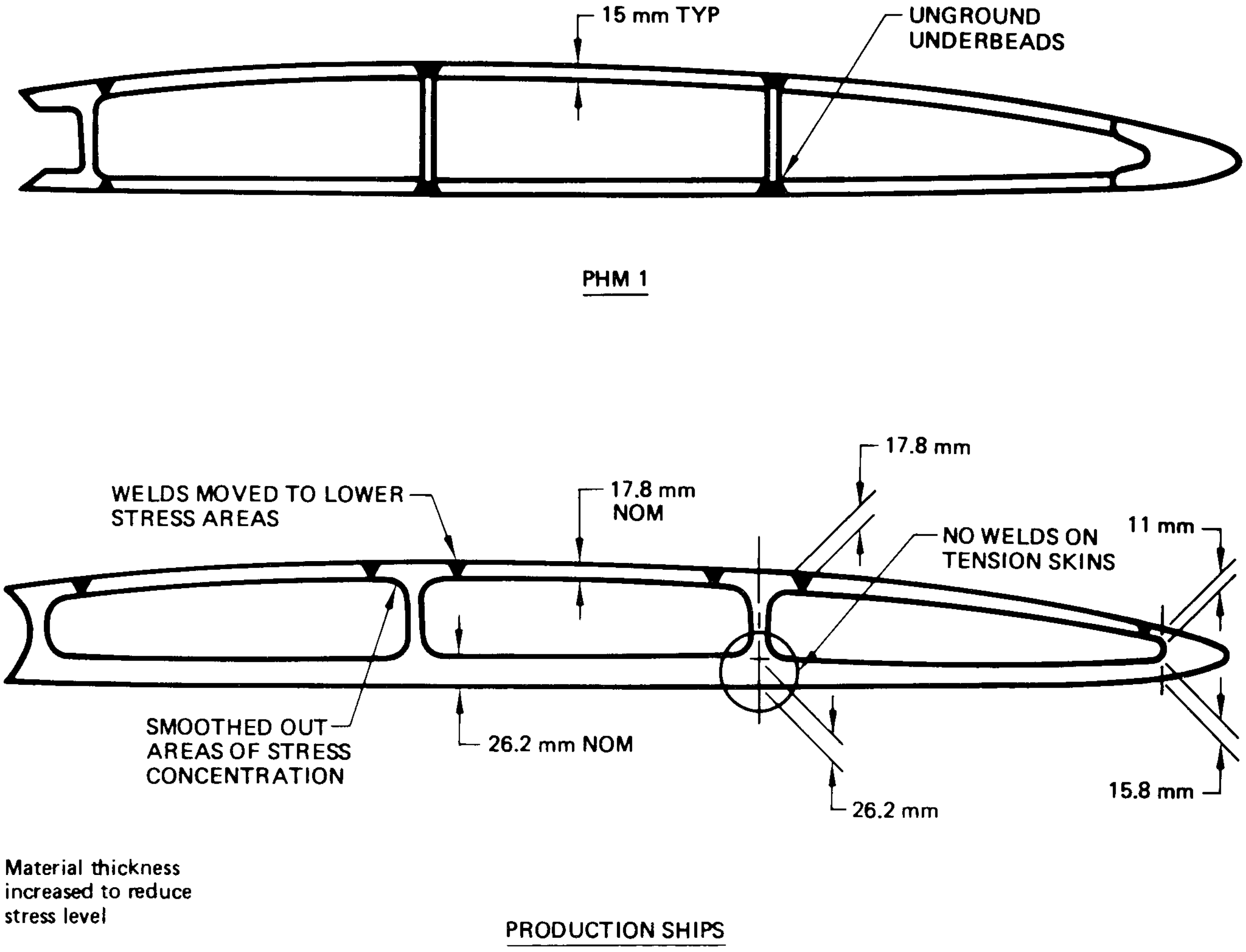


Figure 17. Comparisons in BL4500 Aft Foil Configuration

PHM PRODUCTION

The producibility study, as previously discussed, was performed to determine ways which would facilitiate the PHM production. Methods such as modular construction which are commonly used in aircraft manufacture were investigated and incorporated into the production plan. Work was divided into functional areas (metal cutting, welding, machining, tube bending, assembly, etc.) to improve the efficiency of the work force and to support the modular construction plan. A master assembly sequence and schedule was created, tooling was designed and produced, materials purchased and shop orders were written. These shop orders provided a list of drawings required, the tools (jigs or fixtures) to be used, parts and materials required, the step by step sequence to be used in performing the work package, quality control procedures and inspections required, and a start and end date as well as an estimate of the time to complete the package. Shop orders describe work packages which can usually be accomplished in about 2 hours, but may require as little as 30 minutes or as much as 8 hours or more.

With the above functions accomplished the actual PHM construction was begun. The following paragraphs further discuss the program and schedule, the assembly sequence and the tools and fixtures used in the PHM production program.

Production Assembly Sequence and Schedule

The schedule, figure 1 depicting the major events leading to deployment of a U.S. Navy operational squadron, ends with delivery of five PHMs. Figures 18, 19 and 20 depict the assembly sequence and tie it to the actual PHM 3 schedule.

Assembly Sequence

The operations in each tool and tool position are shown to give the reader an appreciation for the complexity of the assembly sequence and of the state of completion at each stage of assembly. In order to depict the sequence in a less complex manner, only representative operations and tools are shown in figure 18. Several things should be noted. 1) Parts to be welded are positioned in such a manner that welding is predominately accomplished in the down-hand, vertical or horizontal positions. 2) Where possible, automatic machines are used to weld long joints. 3) Electron Beam (EB) welding is used, where the part size permits, to join thick steel parts in a single pass. These methods help to assure higher quality welds. 4) Equipment and systems installation and the testing of the systems and ship compartments are conducted continuously throughout the entire process. This enables rework of faulty construction or replacement of faulty equipment at a time when they are most accessible. It also reduces the time involved in the final tightness, completion and acceptance tests.

Schedule

Now that the assembly sequence is in mind, figures 19 and 20 tie that sequence with a schedule. Although all component assembly sequences are not shown, representative data is presented to allow the reader to acquire a feeling for the relative time involved in each operation and therefore the complexity of those operations.

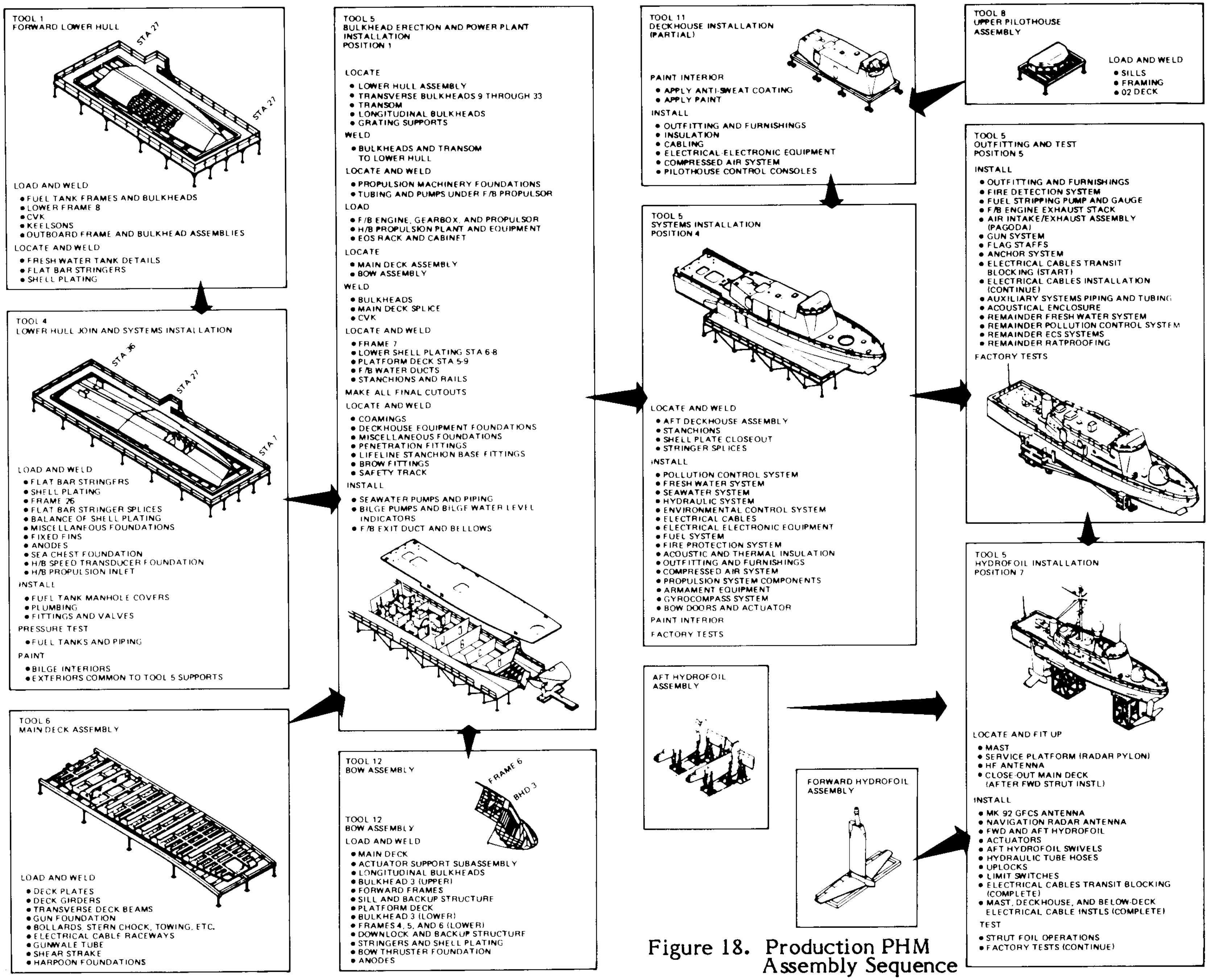


Figure 18. Production PHM Assembly Sequence

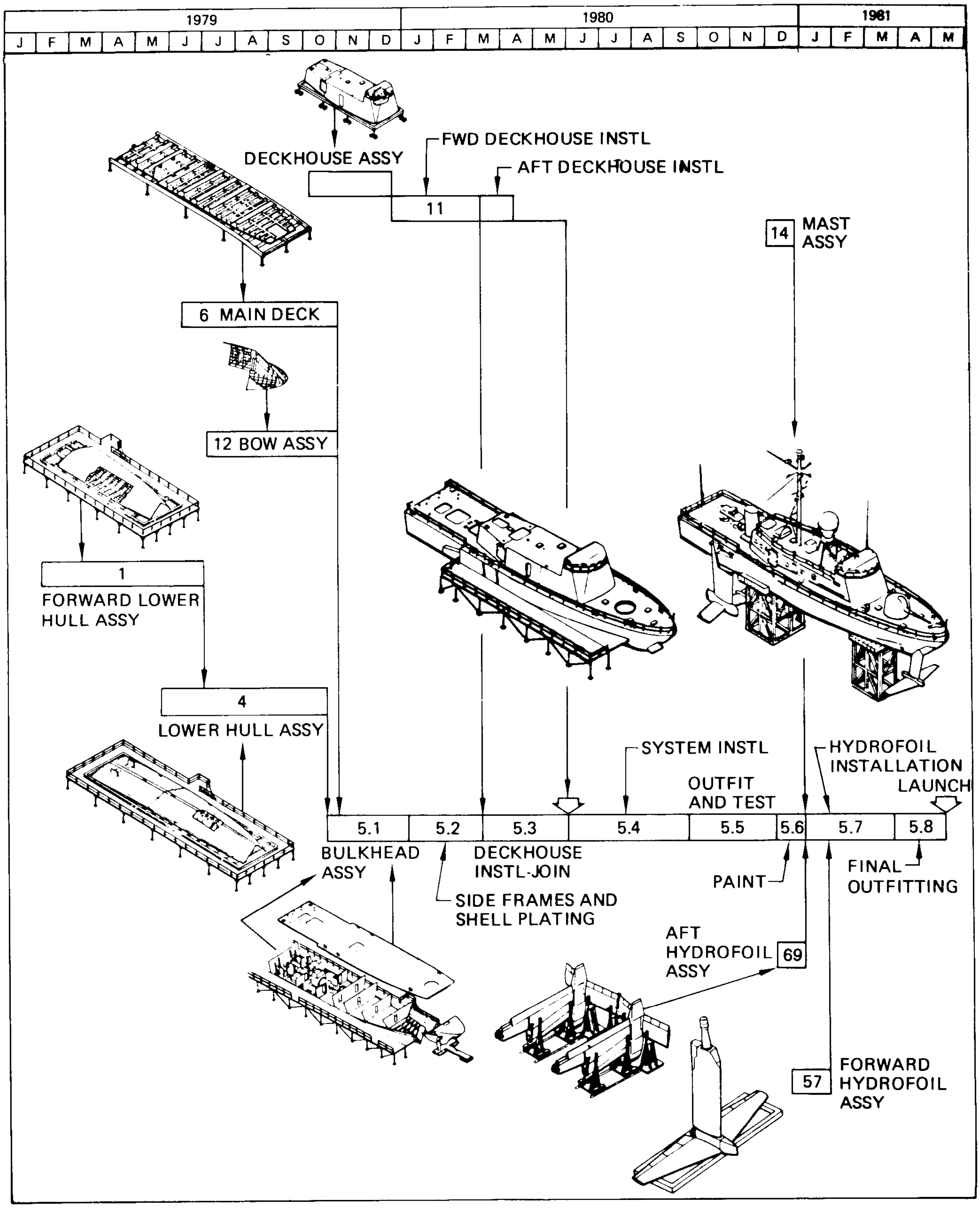


Figure 19. PHM Production Assembly Schedule

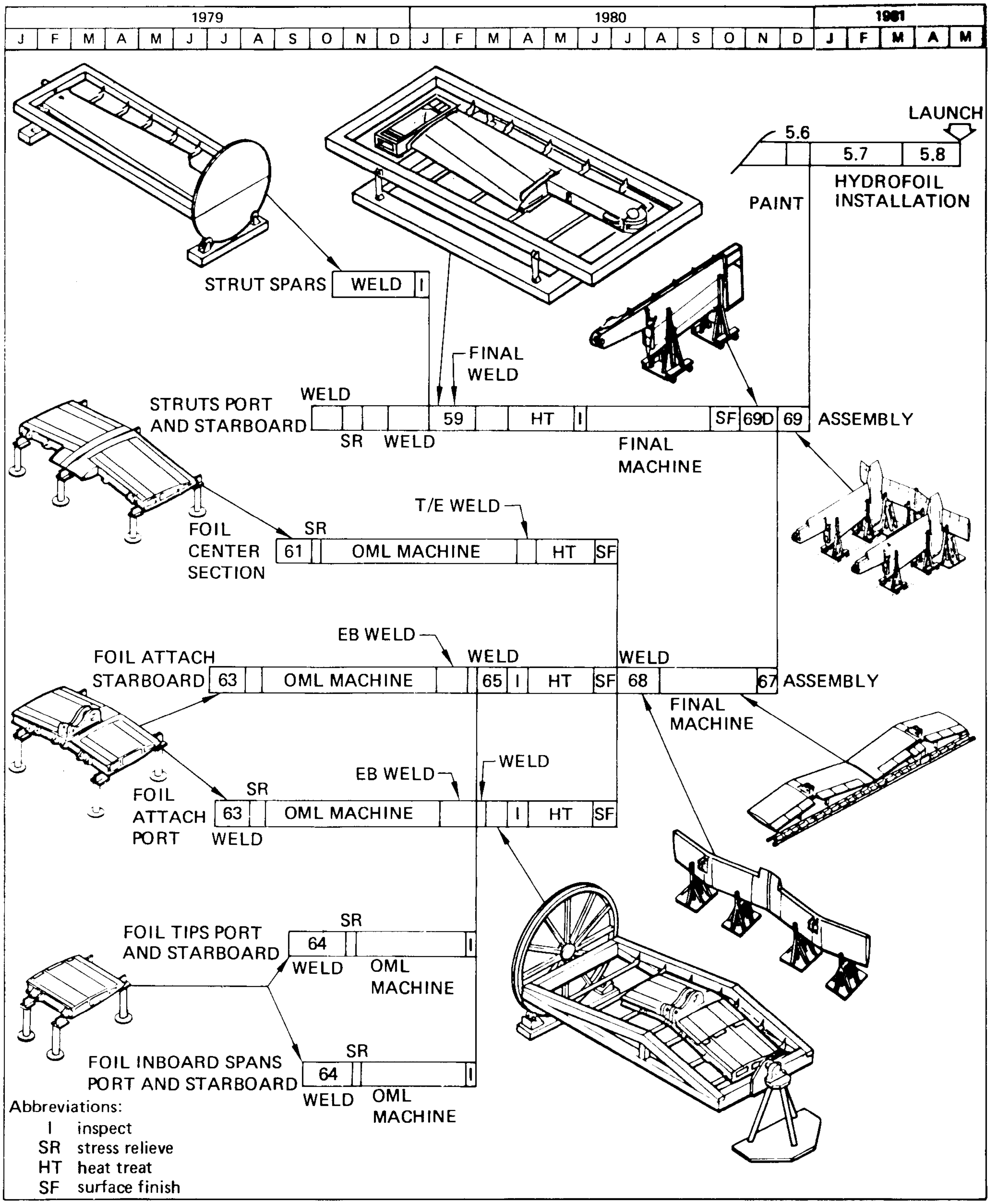


Figure 20. PHM 3 Aft Strut and Foil Production Assembly Schedule

Learning

One of the major advantages to the modular concept of fabrication is that it gives the workman a chance to improve his capabilities to perform a job. The shop orders mentioned earlier define the jobs to be done and the sequence in which they are to be done. They do not tell the workman specifically how to do the job. The workman will initially produce a fully acceptable part but not necessarily in an efficient manner. After a few repetitions he will have "learned" the job procedure, will have the right tools in hand, and will perform the job in the most efficient manner. This learning process of repeating a job or performing similar jobs reduces the manhour expenditure, shortens the second and subsequent unit schedule and results in reduced cost. A standard used in estimating is called the "learning curve." The learning curve states that each time the production quantity doubles (i.e., 1, 2, 4, 8, 16, etc.), the manhour expenditure per unit will be a given fraction (or percentage) of the manhours needed to produce a unit in the preceeding quantity. As an example, it was originally estimated that the manufacture of the lower hull, Tool 4, would follow a 75 percent learning curve, figure 21. During definition of the work sequence, the Methods group in Industrial Engineering predicted the learning rate would be 75 percent to build Unit 2, but would then improve to a 70 percent rate. In fact, the actual "learning curve" experienced between units 1 thru 4 in Tool 4 has been much better than the initial prediction. These data are shown on figure 21.

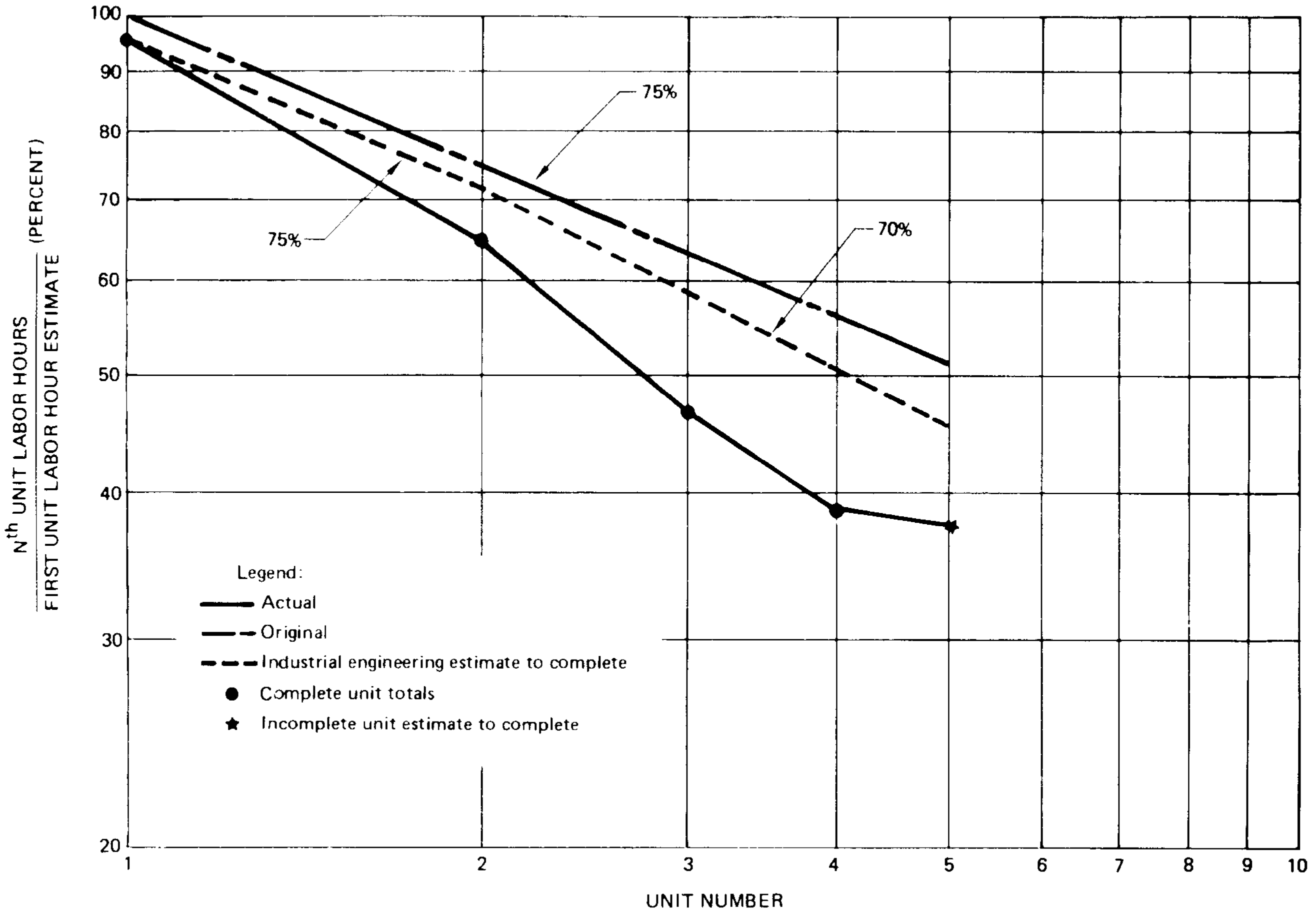


Figure 21. Tool Number 4 Learning Curve

Learning

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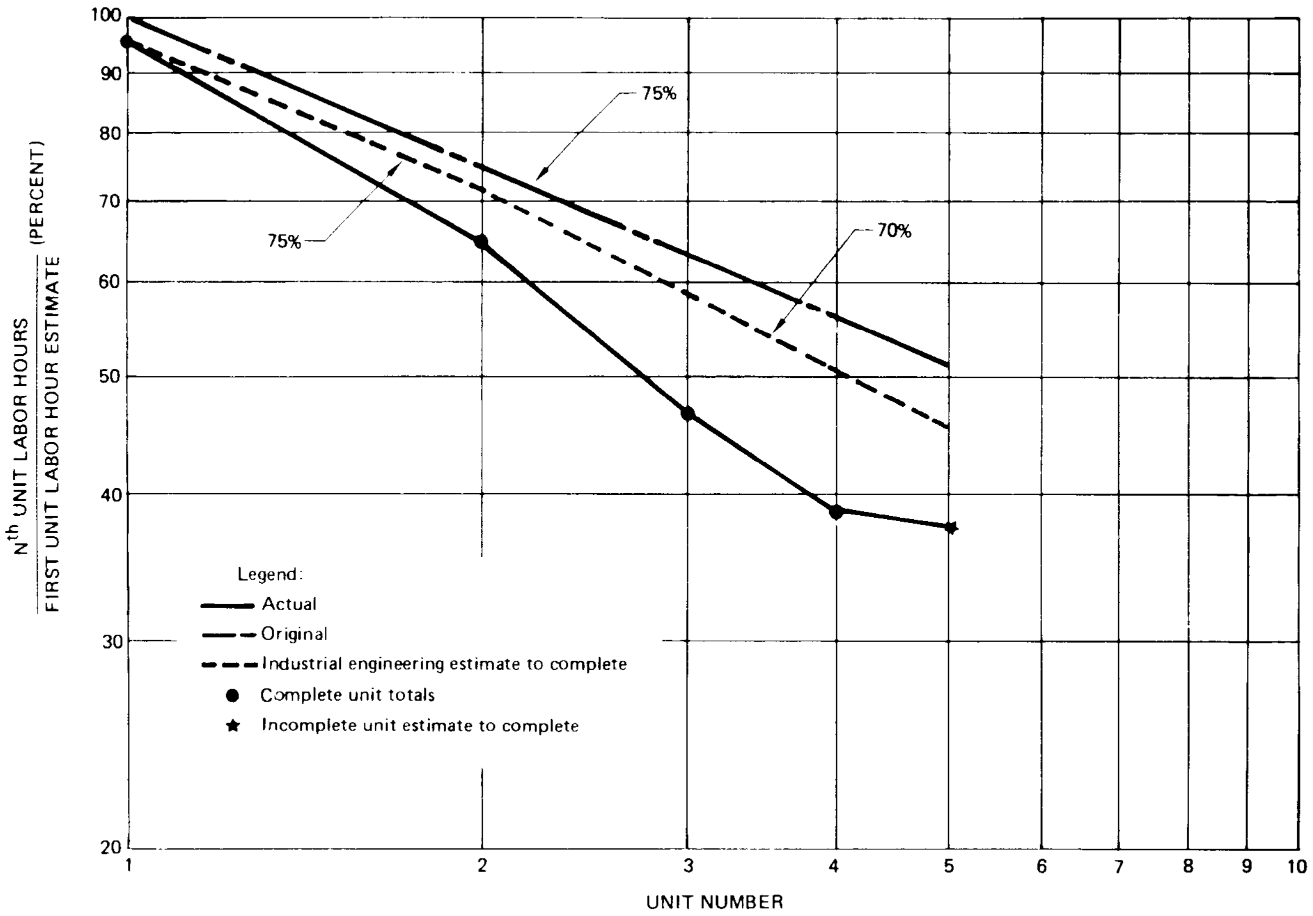

Figure 21. Tool Number 4 Learning Curve

Figure 22. Boeing Marine Systems Hydrofoil Production Facility

SUMMARY

PHM is a well developed and tested ship system. Lessons learned from both construction and operation of the lead ship, USS Pegasus, have been incorporated into the production ship design. Many elements of the ship have been specifically designed to facilitate production. Detail manufacturing planning, tooling, and production management systems consistent with efficient rate production have been completed. Progression of four ship sets through the major tool positions has demonstrated the effectiveness of the production design and process, and production learning has been achieved. Figure 22 shows the factory floor with assemblies at all stages of completion.

While this document does not address specific roles and missions for PHM, operational experience to date verifies it is a highly effective surface warfare ship. Studies show the role of PHM can be extended to include ASW and mine countermeasures by adapting equipment presently available or in development and taking advantage of the growth potential included in the ship design.

The attributes of PHM as an operational unit combined with the quality, cost and near-term availability resulting from the series production approach described here provide an effective fighting ship capable of meeting the many needs of the world's navies.

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