

THE NATO PATROL MISSILE HYDROFOIL (PHM) SHIP AND WEAPONS SYSTEMS TECHNICAL EVALUATION PROGRAM

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Introduction

The U.S. Navy has completed the Initial Operational Test and Evaluation (IOT&E) of the NATO Patrol Missile Hydrofoil (PHM). This is the first U.S. Navy ship program to complete all aspects of design, construction, Technical Evaluation and independent Operational Evaluation, as required under DOD Instruction 5000.1, which sets forth the "fly-before-buy" policies required of selected DOD system acquisition programs.

This paper reports upon the PHM test program planning, execution and results, through the completion of Technical Evaluation and discusses those aspects felt to have been of unique benefit in the management of the program. In addition, the major areas of test program and system reliability and the lessons learned are explained as well as an attempt to draw overall conclusions regarding the overall concept of exhaustive prototype testing prior to entering a production program.

The program reported herein has been under the management of the Naval Sea Systems Command, the Navy's system acquisition manager for all new ship construction programs.

The independent 30-day Operational Evaluation of PHM, accomplished under the cognizance of Commander, Operational Test and Evaluation Forces, although successfully completed, is not reported upon in this paper.

I. Program Background

In November 1971, the United States Navy awarded a letter contract to The Boeing Company for feasibility and trade-off studies regarding the size and performance characteristics of a new class of submerged foil military hydrofoil. This ship was to be capable of meeting the differing mission and combat system requirements of Italy, the Federal Republic of Germany (FRG), and the United States. A decision to proceed had been reached the previous month by NATO Project Group 6, in response to the United States' offer to sponsor a program to develop a NATO Patrol Missile Hydrofoil (PHM) capable of meeting a high speed all weather NATO surface warfare mission. Details of these events, the earlier U.S. Navy hydrofoil supporting technology and the early preliminary design effort of the PHM program were reported to the AIAA in Paper 72-796 in July 1972.

The specific objectives of the NATO PHM Design Stage program were to design, develop and test a NATO Standard PHM lead ship and establish a production data package, together with full scale test results, capable of supporting national decisions for a follow-on production

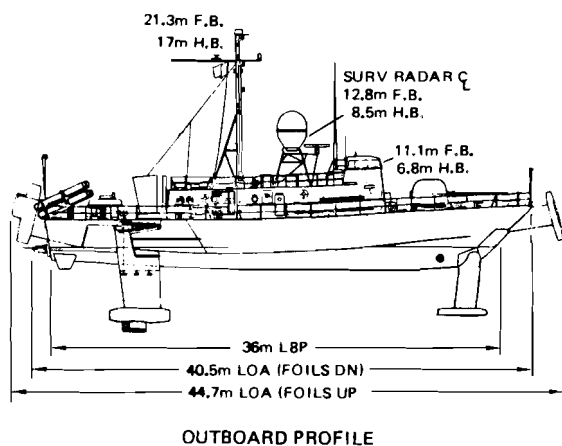
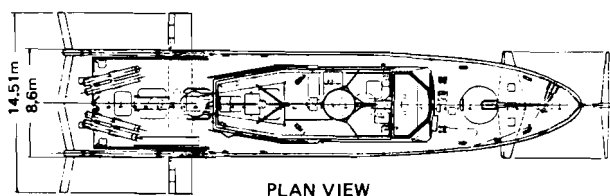


Figure 1. General Arrangements: Plan View and Outboard Profile

program. The PHM Design Stage Memorandum of Understanding (MOU), signed in October 1972, provided for construction and test of (2) U.S. lead ships. In Germany, the progress of the conventional hulled S-143 class fast patrol boat program with its complete land-base and at-sea testing of the same combat system as planned for their PHM has enabled a German decision to determine their entry into PHM production solely on the basis of the tests of the S-143 program combat system and the U.S. lead ship.

Preliminary design of the NATO Standard PHM and U.S. Variant (weapon system) design was completed in December 1972, and a contract for the detail design and construction of (2) U.S. lead ships was awarded in February 1973. The basic ship design is illustrated in Figure 1. Launch of the first lead ship occurred in November 1974, only six weeks behind the original contract date. However, program cost growth forced suspension of work on the second ship in August 1974 and revisions to the planned test program, discussed further below.

II. Test Program Objectives

The PHM program commenced prior to program level implementation of DOD Instruction 5000.1, cornerstone of the "fly-before-buy" prototype testing philosophy now pertaining to all new U.S. weapons systems procurement. The U.S. lead ships were originally conceived of as the first ship of a 30-ship construction program and were funded by Ship Construction, Navy (SCN) appropriations. The test program projected a six-month special underway test period to resolve technical and reliability issues.

However, DODI 5000.1 and the support instructions which followed it in 1972, made it clear that, to meet United States objectives, a more comprehensive weapons system test program would be necessary. Additionally, complete training and operation by a U.S. Navy crew would be required to further enable an "independent" agency's testing of the ship and its logistic support. Consequently, by the fall of 1972, at the time of DOD DSARC II approval of the lead ship program (and authorization of U.S. signing of the PHM Design Stage MOU), a number of changes had occurred:

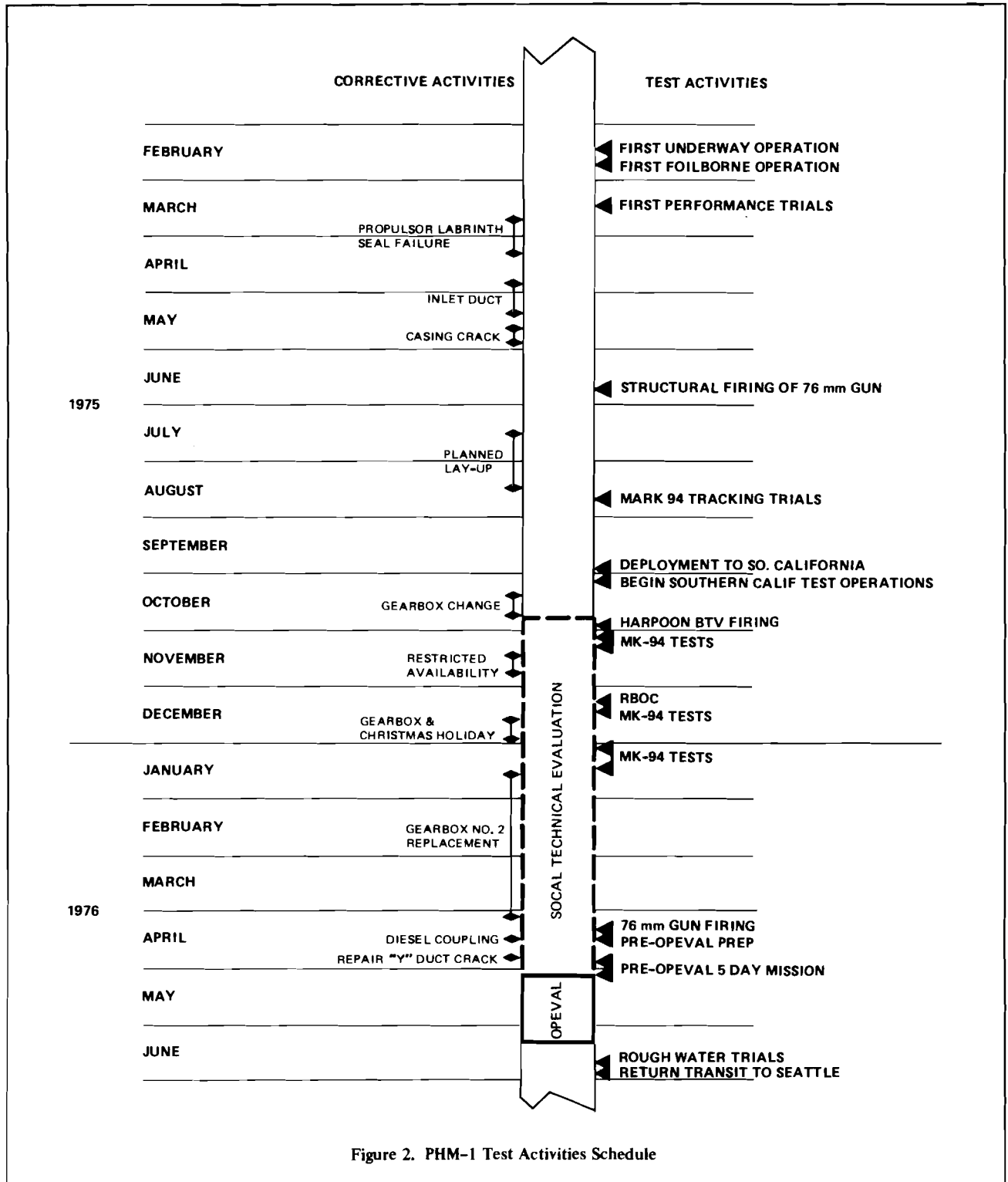
1. The development program was transferred from SCN to RDT&E funding by the Congress.
2. The Navy crews were to be fully trained and integrated into the test program.
3. The first lead ship would perform the tests necessary to establish resolution of platform related issues; the second would address weapons system evaluation.
4. A total of 90 days of Initial Operational Testing and Evaluation (IOT&E) would be accomplished between the two ships, including a 30-day independent Operational Evaluation (OPEVAL) by Commander, Operational Test and Evaluation Forces (COMPOTEVFOR) on the second ship. Later, suspension of PHM-2 construction due to fund shortages, plus early test completion and delivery of the Dutch MK-94 Fire Control System, caused revision

of the test program so as to be performed entirely with PHM-1. The final structure and schedule of this program is illustrated in Figure 2. Its primary objective was the accomplishment of all testing, technical problems resolution, reliability and maintainability assessment, and operational evaluation necessary to support a production decision by the government.

III. Test Program Concepts

The PHM test program included certain innovative concepts considered to have been integral to its success. Primary features were:

1. A separate, comprehensive test requirements section to the contract primary performance specification (Called the Ship Systems Requirement



document (SSR), which sets forth the basic requirements for all verification performance demonstrations by the contractor.

2. A thoroughly detailed supporting Test and Evaluation Plan, which identified all levels of projected systems qualification tests, quality assurance tests, factory, dockside and underway tests and foilborne calm and rough water tests. This plan also distinguished between Contractor's initial "Engineering" Trials and specification compliance "Performance" Trials.

3. Establishment, early in the detail design and construction phase, of a Navy On-site T&E Representative (NOSR). The NOSR was delegated under the contract authority to mutually resolve methods of lower level performance demonstration or qualification compliance and given approval authority on all levels of test plans, procedures, and reports.

4. Incentivization of contractor achievement of performance specifications.

5. Utilization of past experienced hydrofoil personnel in all planning aspects of the PHM T&E program, through Ship Project Directives with other naval activities in the case of the Government and through hiring or internal transfer by the contractor.

6. Completion of U.S. Navy classroom and sub-

systems training prior to ship launch, establishment of an integrated U.S. Navy/Contractor trials crew effective the first day of underway operations, and replacement of balance of contractor's trial personnel (except for ship master) as soon as Navy counterparts completed underway qualifications.

7. Early activation and incorporation into trials support and assumption of preventative and corrective maintenance responsibility by the U.S. Navy Interim Mobile Support Group (IMSG).

8. Placement of a Senior Project Management Representative on-scene for the duration of the underway test program.

9. Accomplishment of all DSARC III Production Decision required testing while maintaining the ship in a predelivery status; i.e., under the cognizance of the Navy Project Manager.

The result of these features has been an extremely orderly well-documented test program, almost entirely managed on-scene, having no delays due to "decision" flow, documentation development, lack of adequate training, personnel or material support. In addition, the Navy Project Manager has retained throughout his needed authority to respond with funds and other major decisions to meet program contingencies.

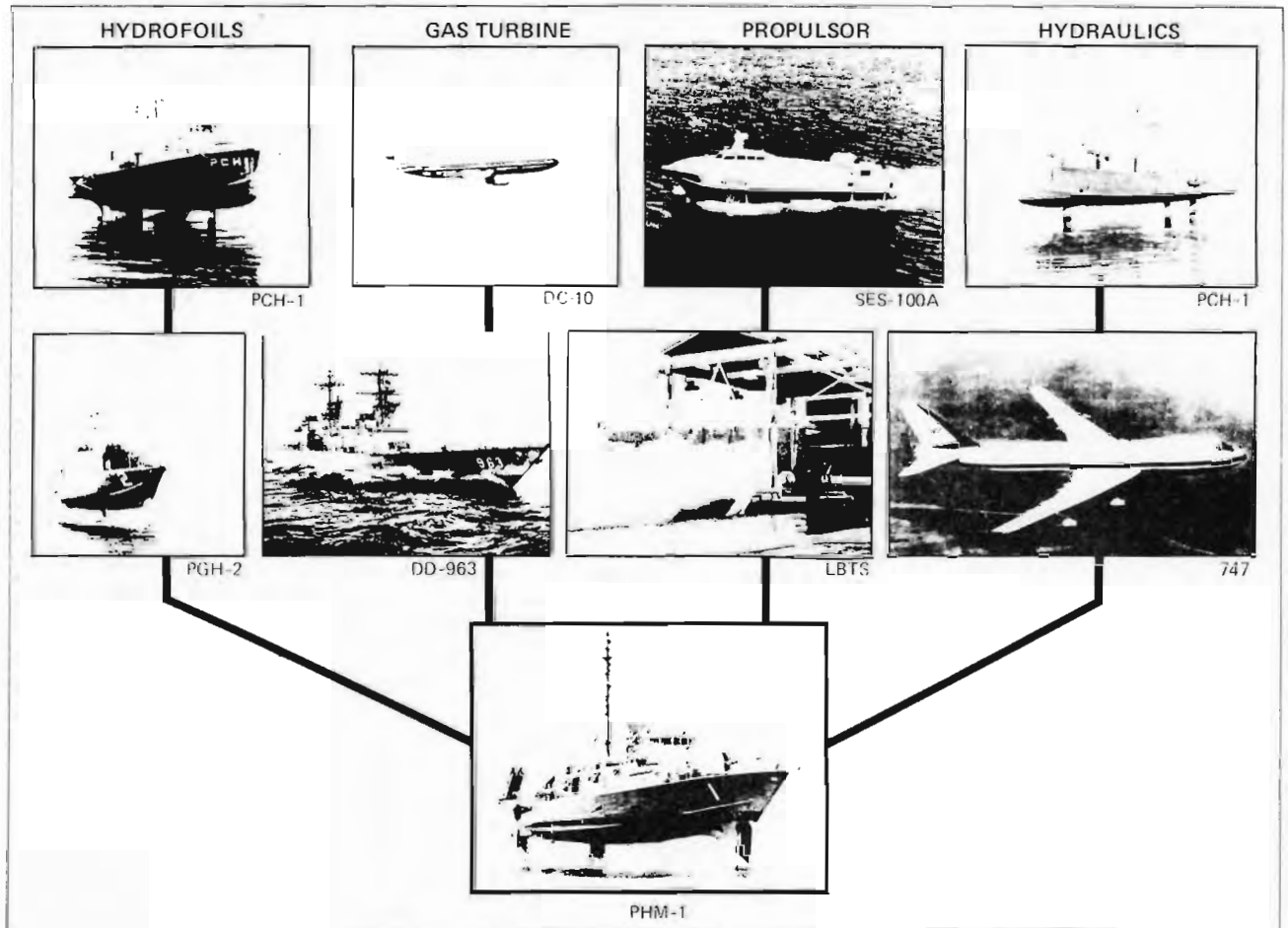


Figure 3. PHM-1 Platform Systems

IV. Equipment/System Qualification Test Program

Contractor Furnished Equipment

Under the PHM contract, component and systems tests were established which ranged from development testing at the design or component level to total system checkouts at the completion of factory installation. In addition, 13 major contractor furnished items were designated as "Critical Items." Critical items, identified in Table I, were: "models, components, subsystems, and systems determined to be crucial to PHM attaining successful and reliable performance. These were items which (were) nonstandard, involved technical risk, lacked complete definition at the program initiation, or were developmental or unique in PHM application." The major history of the PHM primary systems and key design features are illustrated in Figure 3. During the Preliminary Design Phase of PHM (Phase I), certain critical items were subjected to developmental tests, utilizing scale models and/or component prototypes to evaluate alternative design concepts and verify the equipment or concepts selected.

Table I. Critical Items List

1.	Foilborne propulsion engine
2.	Foilborne propulsion gearbox
3.	Foilborne waterjet pump
4.	Waterjet inlet system (foilborne)
5.	Foilborne engine air system configuration
6.	Hullborne propulsion engine
7.	Hullborne propulsion gearbox
8.	Hullborne pump
9.	Automatic control system
10.	Hydrofoils, pods, and struts
11.	Hydraulic actuators (retraction/extension steering, flaps)
12.	Take-off drag and hullborne maneuverability
13.	400Hz generator set (ship service generator set)

Table II defines those items which underwent Phase I developmental testing. Additionally, during Detailed Design and Construction (Phase II), further development tests were performed to qualify components in the induced and/or marine environments defined in the primary performance specification (SSR). The Phase II developmental test program was applied to both critical and noncritical items, identified respectively in Tables III and IV, noncritical items being permitted a variety of alternative means of establishing qualification of the equipment.

Table II - Phase I Development Tests

Baseline hull drag Baseline hull maneuvering Baseline hull seakeeping Verification hull drag Aft foil system	Take off drag and maneuverability
Waterjet inlet system	Hydrofoils, pods, & struts Take off drag and maneuverability
Engine air inlet system Antenna arrangement Shuttle valve	Foilborne waterjet inlet system Hydrofoils, pods, & struts Foilborne engine air system configuration Antenna configuration and GFCS/radar EMC Automatic control system Hydraulic actuators

Alternatives included actual testing of components or equipment and/or analysis of vendor or other service data to determine suitability to the PHM environment. Verification of the Phase II developmental tests for noncritical items was achieved principally through the latter means through use of Certification Data Reports.

**Table III - Critical Items
Phase II Development Tests**

T - Test Q - Prior Qualification/Usage A - Analysis
Component/subsystem
Actuator, aft flap - T Actuator, fwd flap & steering -- T Actuator, strut retract - T ACS control computer - T ACS power supply - T ACS height sensor electronics - T ACS height sensor transducer - T Electric generation system - T Waterjet inlet system - T (foilborne) Foilborne engine air inlet system configuration - T Hydrofoils, pods, & struts - T Take-off drag & maneuverability -- T Antenna configuration & radar EMC - T King post bearing qual. - T Foilborne propulsion engine - Q Hullborne propulsion engine - Q ACS inverter - Q Actuator, hullborne steering - Q Foilborne pump & gearbox - A Hullborne propulsion gearbox - A Hullborne pump - A SSPU - turbine (only) - A Ship service generator set - A (Turbine & electric generation system) ACS control panel - A ACS status panel - A ACS checkout panel - A ACS height sensor thermistor assy - A ACS fwd J-box - A ACS aft J-box - A Accelerometer - A ACS vertical gyro - A ACS yaw rate gyro - A Foilborne trim assembly - A

The next phase of PHM testing, factory tests, commenced with component quality assurance and acceptance testing by the Vendor and concluded with those installed system level tests which were prerequisite to the launch of the ship. This phase of testing included those tests more nearly associated with the ship construction process, such as piping system hydrostatic tests, compartment air testing, and electrical system continuity and functional checks. Such testing conducted prior to ship launch generally fell into four categories: 1) component vendor production acceptance tests to detect manufacturing defects; 2) component receipt tests/inspections to detect defects resulting from shipping; 3) post-installation checks to detect defects from the installation process; and 4) subsystem integration tests to verify component and subsystem functional operation and compatibility. Most of the testing during this phase might be classified as quality assurance in nature. Final systems testing was necessary, however,

**Table IV - Noncritical Items Phase II
Development Tests**

Test Title	
Gyrocompass accuracy & drift rate Seawater pump capacity Bilge pump submersibility Intentionally blank Mobile support van functional Vertical reference accuracy & range Life raft release & inflation Instr. cabling water blocking Anemometer accuracy Speedlog range Voice recorder quality UHF characteristics VHF characteristics HF characteristics Conformance of bell to 33 USC Conformance of whistle to 33 USC ESM performance	Compliance of fuel-water separators to MIL-F-15618F Intentionally blank 250-hour capacity of desalinator and Peak distillate temp. Salt separation panels efficiency Compat. of elect. equip. with ships Operating fluids Shore power overload Nav. radar characteristics Ductwork insulation adequacy Hyd. system fluid temp. Window deicing Organizational level support equip. Env'tl. Emergency fuel pumps submersibility Fuel pre-filter: elements submersibility

to determine wherever practicable, system function and operation and readiness of the ship for launch.

Government Furnished Equipment

The Government Furnished Equipment (GFE) selected for the PHM also underwent extensive qualification programs prior to integration tests and ship launch. Both the Gun Fire Control

System and 76mm Rapid Fire Gun were modifications of foreign weapon development programs by the Dutch and Italians, respectively. The Hollandse Signaal Apparaten (HSA) Gun Fire Control System (U.S. MK-94 GFCS, Designation) employs a unique combination of search and track antennae and signal processing that has been developed over a number of years and had been selected for land based tests in the Federal Republic of Germany (FRG) and installation (as the WM 28) on the FRG

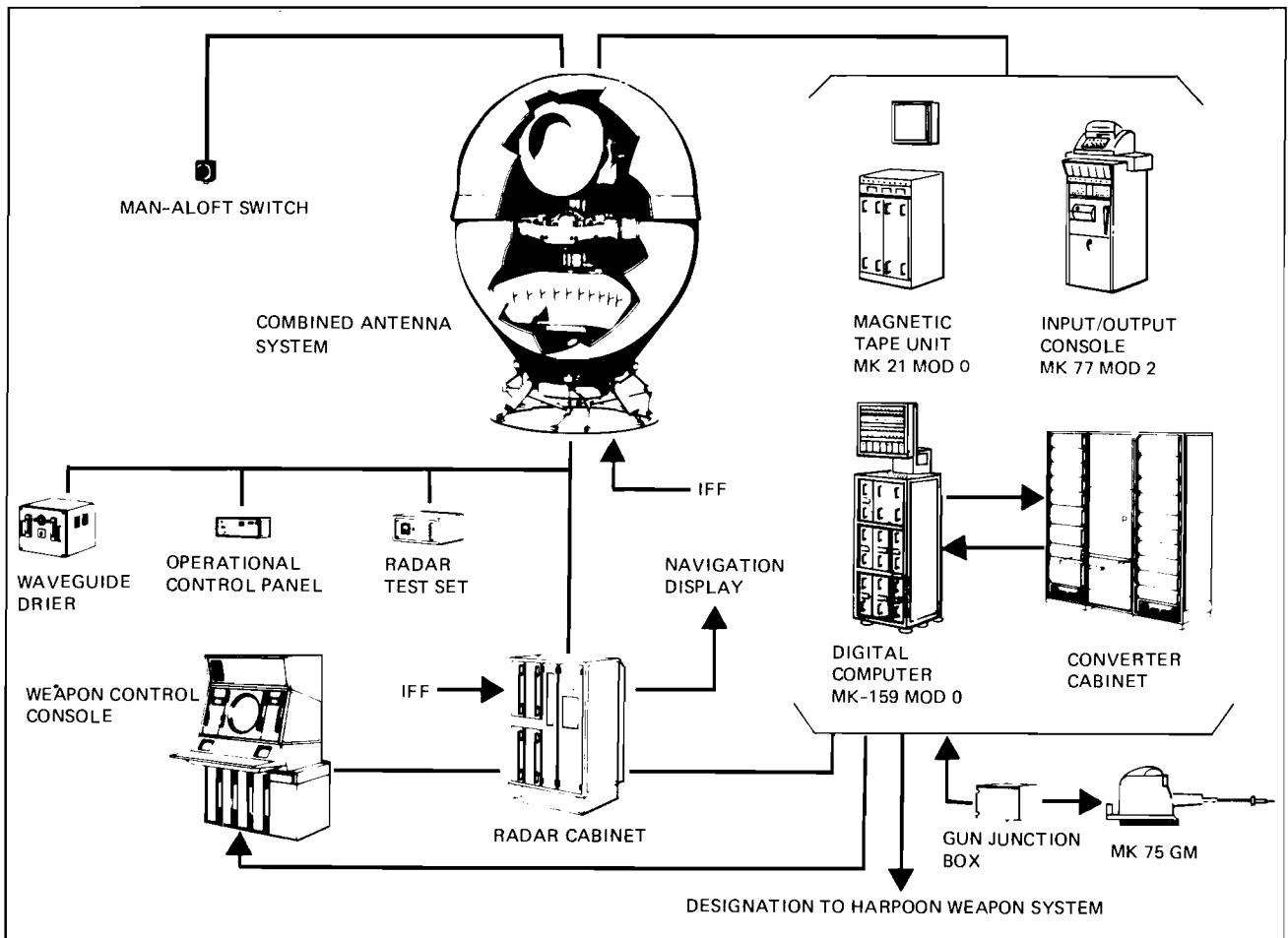


Figure 4. MK-94 (SIGNAAL WM-28) Fire Control System for PHM-1

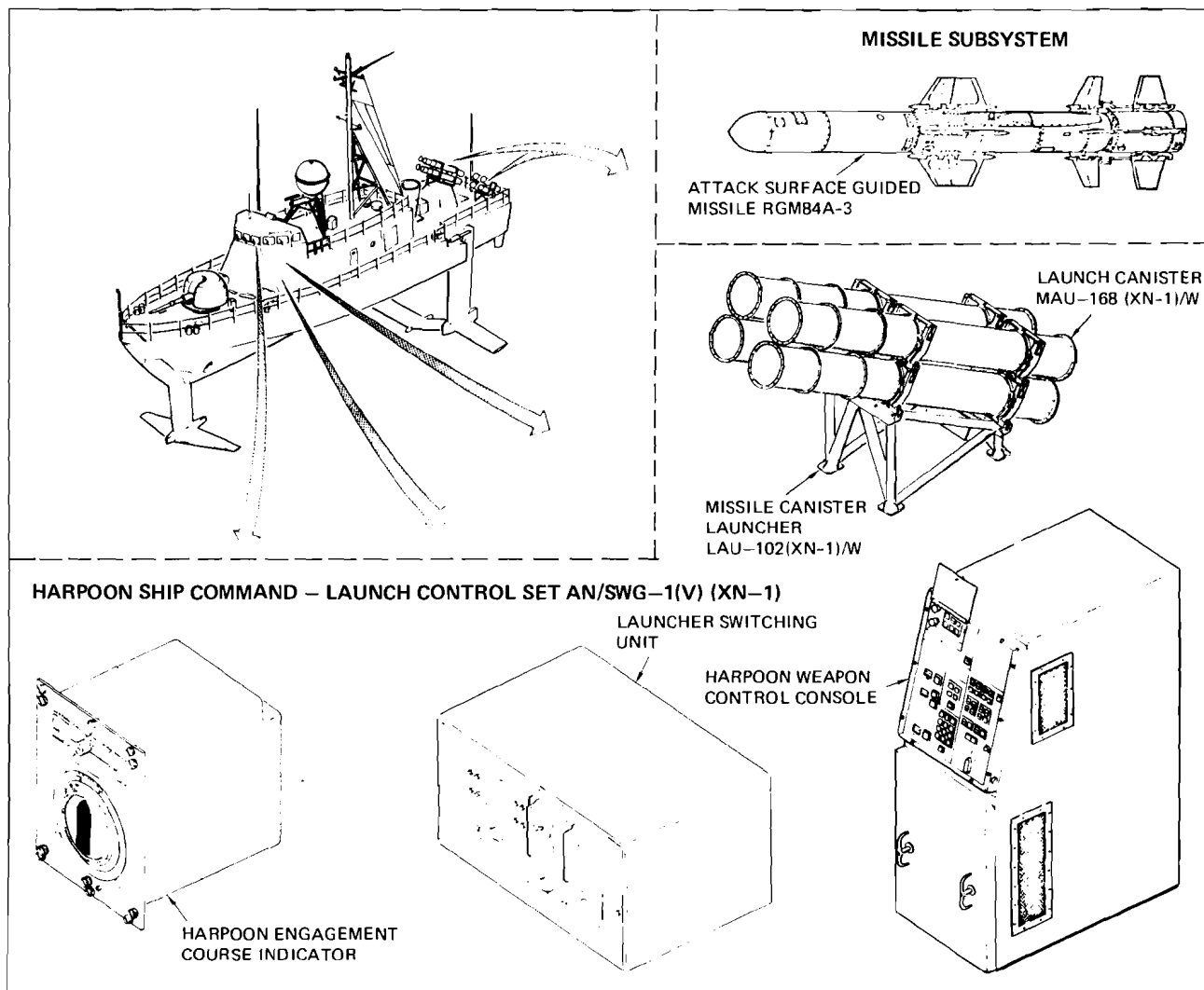


Figure 5. Harpoon System for PHM-1

Navy fast patrol boat S-143 class. (Figure 4) The FRG land based tests were utilized for system qualification and HSA land based tests were utilized for factory acceptance tests of the MK 94 installed in PHM-1. In parallel, the U.S. built version of MK 94 (MK 92 U.S. designation) was built by Sperry and operationally evaluated aboard USS TALBOT (FFG-4) for its suitability for the FFG-7 and PHM production programs. Both MK-94 and MK-92 qualification programs have been successfully completed. The OTO MELARA 76/62 76mm compact gun (U.S. MK 75 designation) has been used by many foreign navies for small ship armament including installation on board the Italian Navy hydrofoil ship SWORDFISH (P420), a variant of the U.S. Navy hydrofoil TUCUMCARI (PGS-2). In order to gain familiarity and qualify the gun prior to licensed production in the U.S., an OTO MELARA built MK 75 was put through a rigorous land based technical evaluation at the Naval Surface Weapons Center, Dahlgren, Virginia. In parallel, another OTO MELARA built MK 75 was placed aboard USS TALBOT for an operational evaluation with the MK-92 GFCS. The MK-75 Qualification program has been successfully completed and the Northern Ordnance Division of FMC has been licensed to build production units.

The PHM primary weapon is a cannister launcher version of the Harpoon surface-to-surface missile built by McDonnell Douglas. It should be noted that the Harpoon system can function as a stand-alone system (Figure 5) or receive target information from the MK 94.

The airborne system is adapted for surface firing by the addition of a booster rocket. Shipboard launch from a ASROC box launcher was tested aboard USS DOWNES (FF 1070). The use of a fixed cannister launcher was first tested aboard the David Taylor Naval Ship Research Development Center's hydrofoil craft HIGH POINT (PCS-1) and later aboard the USS STERRETT (CLG 31) prior to installation and test aboard PEGASUS. The sources of major PHM combat systems and their qualification history is shown in Figure 6.

The PHM is protected by a rapid blooming Off-board CHAFF (RBOC) system of dispensing electromagnetic decoy material. Through developments by the Naval Surface Weapons Center, White Oak, Maryland, a launching system was successfully qualified aboard USS LAFFEY (DD 724).

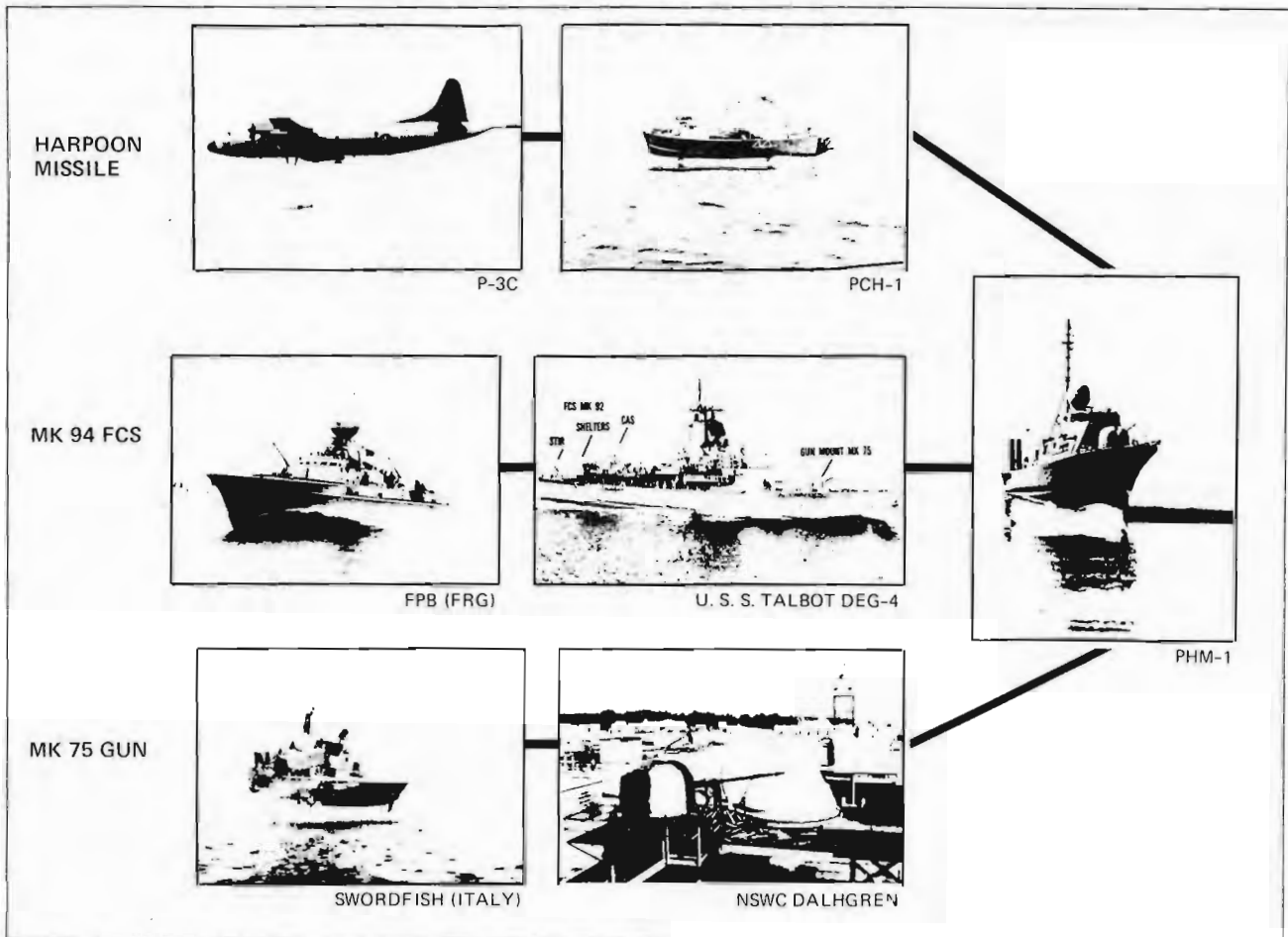


Figure 6. PHM-1 Weapons Systems

The GFE electronic systems, the OMEGA Radio Navigation System built by Northrup and the Interrogation Friend or Foe (IFF) system built by the Naval Electronics System Test and Evaluation Detachment has already been successfully qualified in connection with other vehicle programs. The OMEGA (SRN-17) is an adaptation of a submarine system (BRN-17), and the AIMS MK XII IFF is an airborne system.

The PEGASUS combat system trials program was structured to build on the above qualification programs and prove system integration with the PHM platform.

V. Engineering and Performance Trials (Platform)

Dockside Testing

Commencing with the launch of the ship, the platform trials program was initiated. With only a few exceptions, all engineering evaluations and contract specification compliance tests were conducted subsequent to the start of platform trials. Platform trials were divided into (a) dockside tests and trials, (b) underway tests and trials. Each of the two areas was further divided into engineering trials and performance trials as follows:

Dockside engineering trials (400 series tests)
 Dockside performance trials (500 series tests)

U/W calm water engineering trials (600 series tests)
 U/W calm water performance trials (700 series tests)
 U/W Rough water engineering trials (800 series tests)
 U/W rough water performance trials (900 series tests)

Engineering tests and trials were systems integration tests performed to: 1) assure component and subsystem operability; 2) perform final system adjustments, alignments and calibrations; and 3) to incrementally approach the requirements for contract specification performance verification. Engineering tests and trials served to increase confidence and expand operating regions as well as provide feedback to the systems designers to validate the designs and the components selected to perform the required functions. Engineering tests and trials were not contractually required tests and were not used to demonstrate compliance with contract specifications. As defined in the Test and Evaluation Program Plan, there were 48 individual engineering tests and 44 individual contract performance tests to be completed during the latter stages of construction and the dockside portion of testing.

Underway Tests and Trials

The next and final phase of shipboard testing aboard PHM was the underway tests and trials. As indicated above, these tests and trials were divided into smooth water and rough water trials. Smooth water conditions were generally defined by wave heights less than one-half meter and wind velocity less than 15 knots. The rough water envelope was defined by wave height, wave period and wind speed, as contractually specified in the SSR. As with the dockside tests, the underway engineering trials were intended to accomplish: 1) system and equipment checkout, which cannot be accomplished in the factory or dockside; 2) complete system or equipment calibrations, which cannot be completed dockside; and 3) incrementally approach the requirements for contract specification performance verification. The underway contract performance verification trials were devoted to total system performance and verification of the ship's ability to meet the total ship performance requirements. The rough water trials were a much reduced series of trials intended to validate only the total ship performance in design sea conditions. There were 119 individual tests associated with the underway trials of which 46 were contractually specified performance trials.

VI. Combat System Trials

The PHM Combat System Trials Program was developed by a contractor and Government planning group to provide thorough integration testing of Contractor Furnished Equipment with Government Furnished Equipment and overall integration tests of the Combat System with the hydrofoil platform. Initial component installation "smoke tests" and alignment was performed in the Boeing factory at Renton, Washington, utilizing a team of contractor and Government furnished personnel. Testing moved to dockside after the launching of PEGASUS into Lake Washington on 9 November 1974.

Dockside tests involved activation of all systems prior to underway trials. Preliminary Gun Fire Control System, Gyro System, Surface Search Radar, and Communication Systems tests were performed at the Lake Washington facility prior to the transit voyage to the Boeing facility at Pier 91 on the Seattle waterfront in Puget Sound. The Navigation and Communication Systems were continually operated in support of platform engineering and performance trials in the Seattle area during the spring 1975.

The first major Combat System Trial of the PHM Technical Evaluation (TECHEVAL) occurred on 26 June 1975 to test the MK-75 Gun in various firing modes and attitudes to validate the structural integrity of the platform. (See Figure 7.) During these tests, combat and platform systems were monitored and found to operate satisfactorily in the shock and blast environment of the gun. Magazine loading, ammunition handling, and gun mount safety procedures were validated during the trial.

Starting in August 1975, the MK-94 GFCS was tested for tracking performance. These tests,

extending over eight voyages, utilized the south Whidbey Island area and air squadrons operating out of the Naval Air Station, Whidbey Island. The Naval Ship Weapon System Engineering Station (NSWSES), Port Hueneme, California, provided the test direction and instrumentation for the Combat System Trials. The Operational Test and Evaluation Force (OPTEVFOR) provided operations area and target service coordination support. During the Seattle phase of trials, initial debugging problems were discovered and corrected. These included loose printed circuit cards, improper procedures, and electromagnetic interference (EMI). By this time, the system was fully manned by the prospective crew of the PEGASUS, thus serving also to fulfill necessary hands-on training and deployment readiness requirements.

The Harpoon prototype missiles in cannisters were loaded on 29 September 1975, at the Naval Weapon Center, Bangor, Washington, for the transit to Southern California operating areas. On 30 September 1975, PEGASUS left the Seattle area for a rigorous Combat System Trials program in preparation for the PHM Operational Evaluation (OPEVAL). The Southern California trials involved Fleet Operational Accuracy Check Site (FORACS) tests off San Clemente Island. On 28 October 1975, formal MK-94 GFCS tracking performance trials were resumed utilizing the Pacific Missile Test Center ranges off Pt. Mugu and the continued support by NSWSES and OPTEVFOR. A cannister Harpoon Blast Test Vehicle (BTV) was successfully fired on 29 October 1975, validating the structural, blast, smoke, and temperature compatibility of the Harpoon missile system and the PHM platform. High tempo combat operations were conducted through the winter months to prove the tracking and firing performance against towed and drone air targets and drone surface targets. In this period, the RBOC was launched successfully against targets simulating threats.

Development problems with the Combat System were identified, corrective action taken, and system retest performed to verify system readiness for the PHM OPEVAL. One problem area under estimated in trial planning was the schedule time required to work solutions to EMI. The PHM, because of its small size and resulting high density combat system installation, introduced EMI into various systems in unpredictable ways. Dedicated trial time was required to accomplish EMI identification and resolution. The Naval Electronic Laboratory Center (NELC), San Diego, provided measurement data to aid in the solution to many of the EMI problems. Over the period of May through December 1975, a variety of corrective design features was developed, bringing the ship to satisfactory readiness for the OPEVAL.

A second problem discovered during the at-sea tests was the operational limitation on effective area of surface target gunfire caused by the pointing and firing cut-out cams. Data, analysis, and new cams were developed by NSWD, Dahlgren, Virginia, to upgrade the effective area for the OPEVAL. Difficulties also occurred with the integration of the Electronic Support Measure (ESM) system into the smooth operation of the Combat Information Center (CIC). NELC provided performance measurements and target simulation tests with their Environmental Synthesizer (ENSYN)

equipment. Deficiencies with the PEGASUS ESM equipment and new functional requirements were developed as a result of these trials and may result in a change to ESM equipment installed in the PHM follow-on ships.

The above three problem areas are typical of the nature of combat system integration difficulties and serve to emphasize the importance of at-sea testing with sufficient instrumentation, engineering support, and schedule time to thoroughly understand and resolve all such problems.

The combat system trials were conducted over a span of seven months. Forty-one trial days through the end of TECHEVAL involved 696 rounds of 76mm ammunition expended, 1 Harpoon BTV fired, and 37 rounds of RBOC expended. The MK-94 GFCS met or exceeded its performance criteria in the track-while-scan surface tracking mode and in the air tracking mode. Simultaneous air and surface tracks were tested and system reaction times validated. The hydrofoil systems permitted smooth operation at high speed and rough water;

and, thereby, permitted very stable GFCS operation.

The MK-75 gun demonstrated surface and air shooting accuracy within the required criteria. Accurate rapid fire bursts of 76mm ammunition proved the potent fire power of the PEGASUS. High speed foilborne operation and foils extended hullborne operation provided data to establish excellent interface compatibility and integration between the platform and the gun. All supporting ship systems withstood the shock and blast of the gun without breakdown.

The Harpoon BTV launch while foilborne at over 40 knots (figure 8) proved the successful ship integration of the shipboard cannister launch system and established the marriage of the powerful harpoon tactical cruise missile and the high speed, high sea state, PHM hydrofoil system.

CIC operations exercised target acquisition, assignment and engagement functions to prove the man/machine integration and to validate the



Figure 7. PHM-I Structural Firing

reduced manning concept. Navigation, collision avoidance and CIC to pilot house information functions were exercised during 90 voyages, including 15 overnight voyages, the 1220 n.m. transit from Seattle to San Diego and low visibility operations. CIC trials have demonstrated the integration of the components and have highlighted the need for faster reaction times to support foilborne navigation in restricted or congested waters.

The combat systems trials played a major role in establishing readiness for the OPEVAL by also serving as the means by which the PEGASUS crew became fully trained and integrated into a qualified combat team. The combat system of the PEGASUS has met the objectives of the U.S. Navy PHM characteristics and provided the NATO partners in the PHM program assurance that their weapon systems can also be integrated successfully into their respective variant designs.

VII. Reliability and Maintainability

Maintenance Support

A decision was made at the outset of the PHM program to adopt a radically new ship maintenance concept. Experience on earlier Navy hydrofoils

had established that more effective utilization of training, manpower, and shipboard space and weight is possible with separate groups of operating and maintenance personnel, similar to the concept used in aircraft operation and maintenance. This decision coincided closely with other nearly simultaneous Navy policy decisions to undertake limited manning and lo-mix ship maintenance concepts which minimize the number of ship operating personnel and transfer a larger portion of lo-mix ship maintenance responsibilities to dedicated afloat or ashore fleet maintenance groups.

Maintenance decisions applied to PHM involved a major shift of maintenance responsibilities from the organizational (ship's crew) to intermediate (support group) level. During the design, emphasis was placed upon module/component replacement at both organizational and intermediate levels. Major maintenance and/or repair of repairable equipment is to be at either the intermediate or depot level, with a pool of rotatable spares provided to support immediate on-board replacement of failed parts.

A 29-man Interim (Lead Ship) Mobile Support Group (IMSG) was established to support PHM-1 and PHM-2. Pending authorization of the follow-on production program and conversion of the first PHM

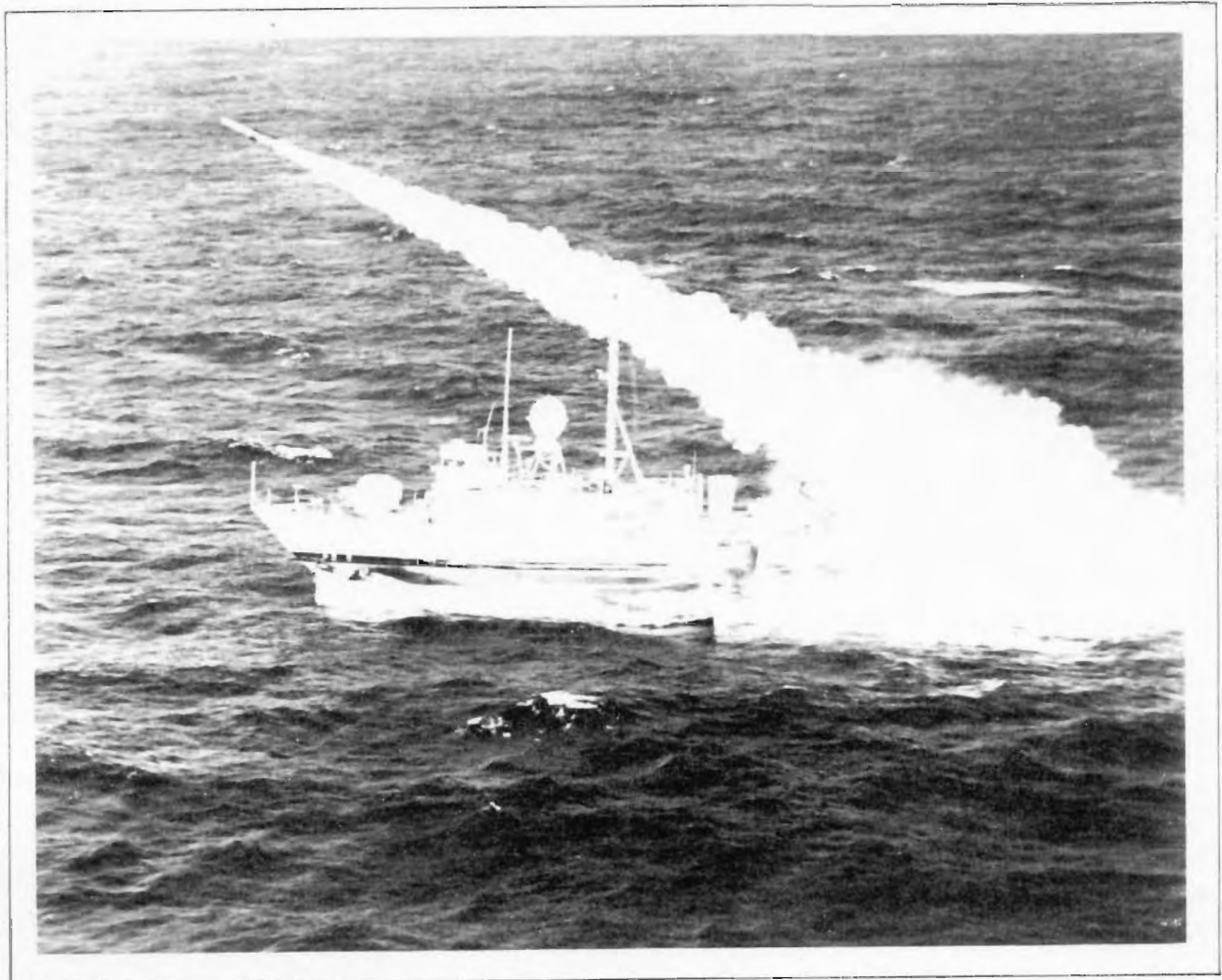


Figure 8. PHM-1 Harpoon Missile Firing

squadron mother ship, it was decided to house the IMSG in a group of mobile container vans, having the required administrative, stowage, maintenance and housekeeping facilities.

During the spring of 1975, during early ship testing and problem resolution, the IMSG accomplished its organization and outfitting of vans. In June 1975, following appropriate agreements by contractor labor organizations, the IMSG assumed preventative maintenance responsibility for all operating ship equipments. In September 1975, shortly prior to deployment to Southern California, the IMSG assumed ship "turn-around" corrective maintenance under a mode of crew training arranged with the contractor. At the time of deployment, the Navy crew was considered to be nearly fully capable of any organizational and intermediate level maintenance not requiring special industrial facility or engineering support.

Following deployment to Southern California for combat systems trials, the IMSG and ship's crew assumed all responsibility for maintenance of the ship. Provisions were made for on-scene depot level supply support by the contractor and utilities and crane services by the port facility (San Diego for first 10 days, Port Hueneme thereafter). Provision was also made for special "Quick Reaction Team" support by contractor personnel should a

technical problem arise where IMSG technical resources or capabilities were felt to be inadequate. Subsequently, during the Operational Evaluation (not reported upon in this paper), all contractor maintenance support was prohibited except for depot level supply functions which correspond to those of a normal fleet activity.

Reliability and Maintainability findings were taken during the above described evolving development, commencing from the time of first ship underway operations in February 1975, through completion of TECHEVAL in May 1976. The findings are discussed in their two major categories: a) major reliability problem areas, and b) overall ship reliability and availability and contract incentive scoring.

Primary Systems Problems Resolution

Main Propulsion System (Pump and Gearbox)

The foilborne propulsor of the PHM illustrated in Figure 9, is composed of a two-stage waterjet pump and gearbox. The gearbox divides the input power into a low speed axial flow inducer stage and a high speed mixed flow impeller stage through concentric output shafts. The pump "pulls" a suction on the water inlets at the aft strut and foil pods at low speeds and operates at positive inlet pres-

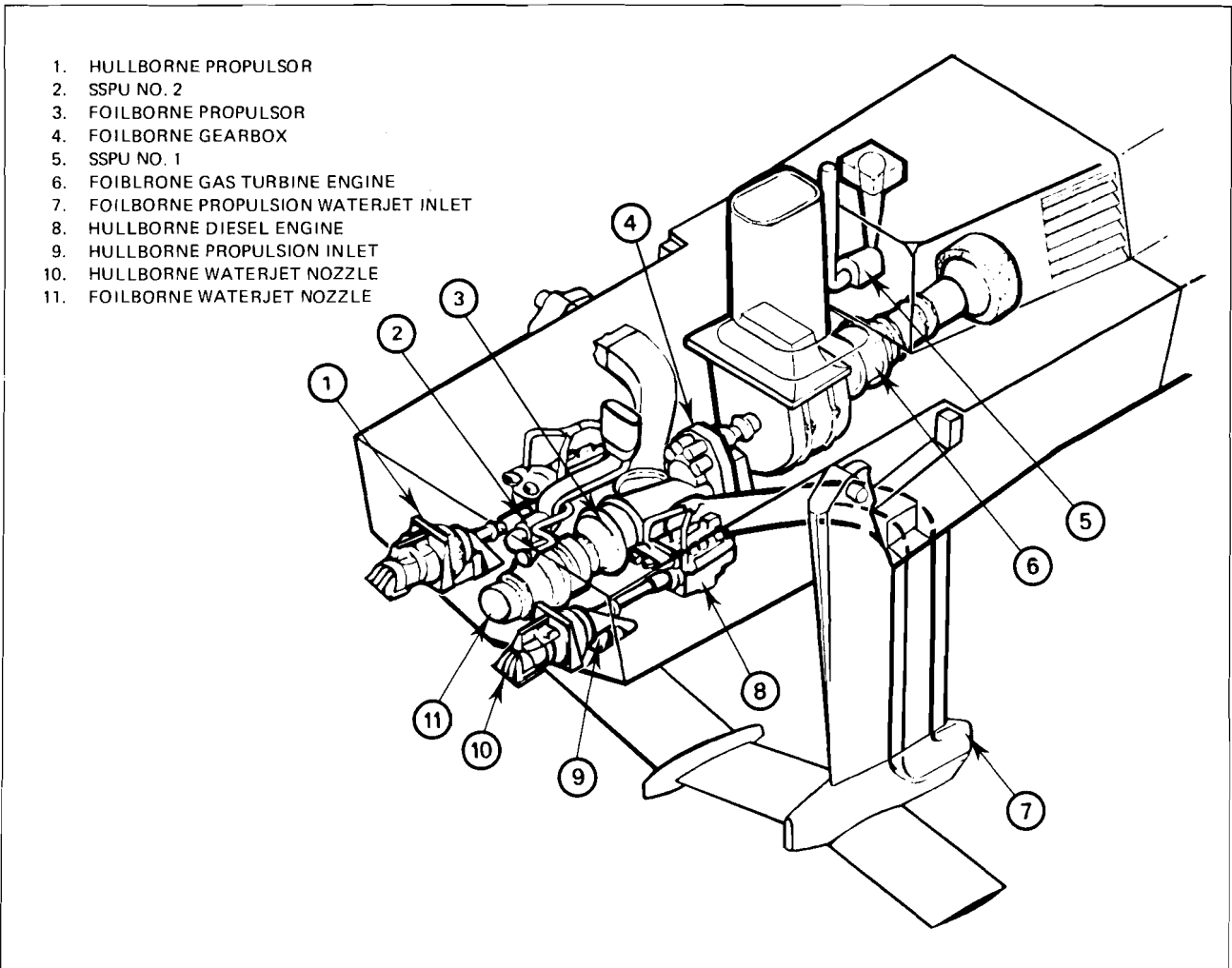


Figure 9. PHM Propulsion System Arrangements

sure at high speeds. The pump receives nominally 16,200 MHP and delivers 21,000 KGF thrust.

Initial problems with the pump included: Failure of the impeller stage labyrinth seal, ingestion of inlet isolation bellows stiffener, failure of the ship's water duct stiffener, improper preload of the bearing pack, and marginal oil supply to bearing races. These problems were corrected by minor modifications to design and procedures.

The major problem with the pump began to show on Voyage 18, following 36 hours' accumulated foilborne time. The cast aluminum inducer stage housing developed an 18-inch axial crack and an 18-inch circumferential crack. The pump had been manufactured with aluminum housings and stator sections and 17 4PH stainless steel rotating shafts and impellers. The salt water corrosion, fatigue, hydraulic environment proved too harsh for the inducer and impeller housings. A temporary "fix" of a wrought aluminum inducer housing was installed in order to sustain continued Puget Sound test program operations until titanium units could be manufactured. The forged titanium inducer and impeller housings installed in August 1975, provided the desired fatigue strength and resistance to cavitation erosion

and gave satisfactory service during the TECHEVAL.

The inlet Y-duct was manufactured by welding pre-formed aluminum pieces. Cracks in the Y-duct developed after 66 accumulated foilborne hours but were small enough to be field weld repaired and not interrupt the test program. Similar cracks occurred at highly stressed junctions in the Y-duct and in ship field modifications to the junction, and welds were sufficient to keep the pump supporting the continuing test program.

Detailed fatigue analysis as a result of the Y-duct failures and strain gage measurements showed that the aluminum Y-duct would have a limited life that might ultimately jeopardize the test program. At the same time, another series of small cracks was discovered after 260 accumulated foilborne hours. The Y-duct was removed (shown in Figure 10), and the inspection confirmed the earlier fatigue predictions of low life. Inspection also showed abnormal corrosion and aggravated cavitation erosion below the static waterline at the exit of the Y-duct. The only readily available alternative was to use the PHM-2 aluminum Y-duct, but to enhance its surface treatment and galvanic isolation in order to increase its expected life. The

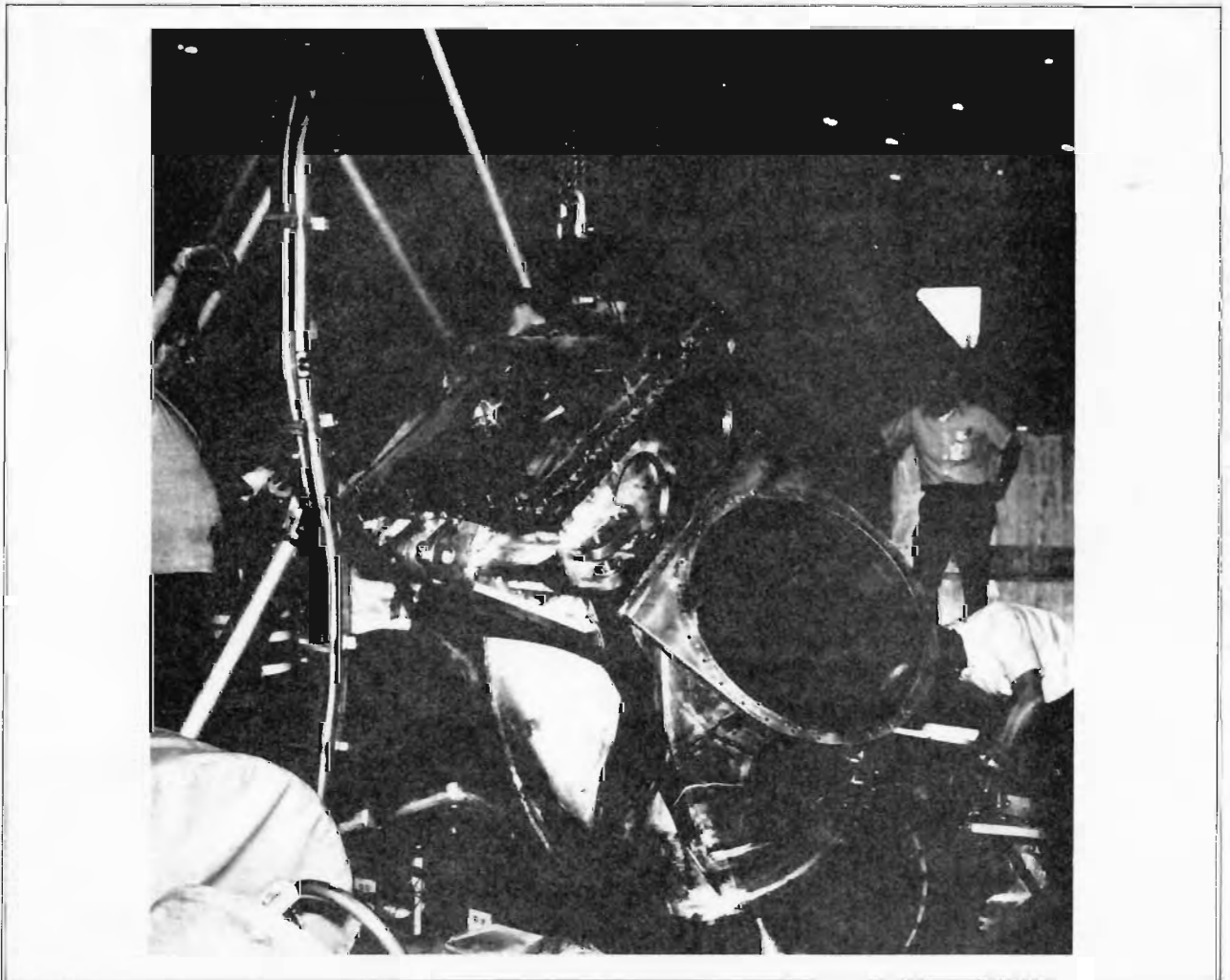


Figure 10. Removal of PHM-1 Main Propulsion Y-Duct

surface treatment involved: a) shot peening, b) etching the shot residue, c) zinc flame spraying, and d) coating with an epoxy system. The attachment electrical isolation washers and sleeves of mylar tape were replaced by a fiberglass reinforced material to prevent breakdown due to the material extruding with time under load. This Y-duct served satisfactorily to support ship operations through completion of OPEVAL in June 1976. However, nickel alloys, stainless steels, and titanium are candidate materials for the production PHM Y-ducts to provide an improved capacity to withstand the harsh hydrodynamic and stress environment and assure that production pumps will have adequate life.

After 185 accumulated foilborne hours, the original (Mod 0) propulsor gearbox developed excessive vibrations that aborted a trial mission. The unit was removed by ship's force at Port Hueneme and PHM-2's identical (Mod 0) gearbox was installed to support testing. Inspection of the failed gearbox revealed excessive fretting between the splines of shafts and gears, to an extent that they no longer fully supported their pinion gear. In addition, the high bending load caused a fatigue crack in the high speed pinion shaft resulting in the observed vibration. A Mod 1 design was developed to provide better piloting of the pinions on their splines and a tighter interference fit to prevent fretting.

The replacement Mod 1 gearbox had run only 15 hours foilborne, when a routine inspection showed two low speed pinion teeth had broken off. The PEGASUS was layed up for approximately three months awaiting failure analysis redesign and the modification and manufacturing of replacement parts. Detailed failure analysis by a team of gear experts from Boeing Marine Systems, Boeing Vertol, Aerojet Liquid Rockets, Sier Bath, Western Gear, Naval Ship Engineering Center, Hyattsville, and Philadelphia, discovered three major problem areas. The Mod 0 gearbox probably failed for the same fundamental problems as the Mod 1 box, but they were masked by the fretting of the loose spline fit. The lead angles of many gear teeth in the Mod 1 gearbox were found to be out of tolerance when mounted on their shaft splines. The gearshaft alignment was out of tolerance because of gearbox bearing bore misalignment, bearing carrier distortion, and bearing concentricity tolerance. An analysis showed that the vector sum of gear mesh forces on the built-up bolted bull ring gears caused sufficient deflection to abnormally load the gear mesh at the apex, the site of crack initiation of the failed teeth. Because of limited time, it was not possible to completely redesign and build a production model gearbox to continue the lead ship trials program. Hence, in the ensuing modification, such features as the splined pinion and bolted bull gear remained as long term risks. However, the Mod 2 gearbox did have a number of design improvements. Misalignments and tolerances were corrected. The bull gear rings were reoriented so that the gear loads opposed each other and thus reduced deflection, and the low speed pinion retaining nut was modified to provide a through bolt to resist the separating loads on the pinion helices.

Hullborne Propulsion System

Primary hullborne propulsion is provided by two

Mercedes diesel engines coupled through reduction gears and Zurn flexible couplings to Aerojet waterjet propulsors. (See Figure 9) During the first year of ship operations, there were several failures in this system. After approximately 50 hours of operation, the starboard clutch failed due to shearing of the pressure plate bolts. The bolt failure was identified as a fatigue problem. Bolts were replaced by larger size and the clutch pressure plate was modified. No further casualties in the clutch area have been experienced during an additional 1350 hours of operation.

After 389 hours of operation, the Jurid flexible coupling contained within the starboard transmission and the propulsor and the bearings in the transmission. After 537 operating hours, an identical casualty occurred on the port hullborne unit. New or modified design Jurid couplings were not available to correct the deficiency in this area, so the transmissions were rebuilt using new Jurid couplings of the original design. After 288 hours on the port unit and 337 hours on the starboard unit, the Jurid couplings again failed. Alternative older type Jurid couplings with approximately 15 years' service in other applications were available and installed. As of this writing, the replacement Jurid couplings appear completely successful. Additionally, the Zurn flexible couplings are being modified to allow larger internal clearances and will be evaluated when available.

Ship Service Power Units

PHM has been outfitted with two identical Ship Service Power Units (SSPU's). Each SSPU consists of a Garret Airesearch ME 831-800 Gas turbine prime mover with an accompanying gearbox and turbine accessories. The driven equipment consists of: 1) a Westinghouse 400 Hz. 250 KVA generator; 2) two ABEX hydraulic pumps; and 3) an Airesearch Load Compressor which provides starting air for the foilborne turbine. To date, the PHM has not experienced an in-ship failure of the gas turbine prime mover. There has been one failure of a gearbox, which was caused by a lube oil spray nozzle vibrating loose, which, in turn, caused a change in the spray pattern and subsequent gear failure.

The ship has experienced several failures of the SSPU driven equipment. These failures may be summarized as follows:

a. LM-2500 Air Start Load Compressors: Each SSPU experienced a failure of the load compressor during the starting cycle of the LM-2500. The problem was traced to failure of the aluminum torque converter within the load compressor. The torque converter was changed to steel parts, and the problem has not recurred.

b. Generator Control Unit: Early in the dockside and underway testing of the ship, several failures of the generator control units were experienced. Correction required design modifications in the control circuitry and was accomplished by the suppliers. The ship has experienced only one subsequent failure which was traced to an electronic component failure within the unit.

c. SSPU Starters: During the first six months of underway testing of PHM, six failures of the SSPU starters were experienced. The problem was

eventually traced to a high inrush current to the starters during the start cycle. Modifications were incorporated, which limited initial current inrush to a level which was acceptable to the starter, and the problem has not recurred. This problem is considered typical of difficulties which may be created by failing to make proper design review of "off-the-shelf" equipment adaptation. In this case, the truck starter system adapted to the SSPU was interfaced with totally different power supply and load characteristics without corresponding design provisions--so the difficulties were, in retrospect, not a surprise.

d. Low Lube Oil Pressure: While operating in Southern California, the ship experienced several inadvertent trips of SSPU #2 due to low lube oil pressure. This problem was traced to oil slosh in the sump and insufficient time delay in the tripping circuitry. Modifications were incorporated in the tripping circuitry by the vendor and the problem has not recurred.

e. SSPU #1 Inadvertent Trips: During testing of the weapons system, several inadvertent trips of SSPU #1 were experienced. The problem was traced to insufficient shock isolation of the SSPU local control panel. The local control panel shock mounts were modified to provide proper isolation, and problem has not recurred.

The majority of the problems associated with the SSPU's was associated with the driven equipment. Most of these problems were discovered and corrected within the first 200 operating hours of the units. With more than 2,200 cumulative operating hours to date, the SSPU's have proven to be extremely reliable units. The ship operators have been extremely pleased with the high reliability and instant availability of the units. Figure 11 provides the failure history of the SSPU's and their driven equipment.

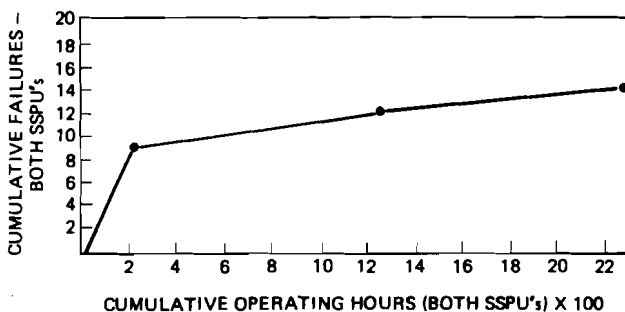


Figure 11. Failure History Ship Service Power Units

Struts and Foils

The PHM strut and foil system is composed of welded 17-4 stainless steel pieces. The port and starboard foil panels of the aft foil system are bolted together at the ship's center line. The aft foil system is bolted to the port and starboard struts to form an inverted "Pi" assembly, which mounts on retraction trunnions to the ship. The aft struts and pods serve as the water duct inlets to the foilborne pump, and each port and starboard foil panel receives its flap control from a control rod that is in the strut trailing edge fairing. The forward foil is bolted to the steerable forward strut to form an inverted

"Tee" assembly, which mounts via a ring post in a retraction yoke to the ship. Flap actuation is similar to the aft struts. Steering actuation is accomplished by a cylinder working between the yoke and a king post bell crank.

During construction, the heat treatment for the welded 17-4 PH material was an initial problem. The Naval Ship Engineering Center, Hyattsville (NAVSEC), the Naval Ship Engineering Center, Hyattsville (NAVSEC), The Naval Research Laboratory (NRL), and the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) supported a trade-off analysis between direct aged and solution treated furnace profiles as they effect distortion of the panel and the fracture toughness of the weld. The PHM-1 struts and foils were direct aged heat treated only.

The PHM-2 forward foil was solution treated prior to aging, and subsequent production panels will similarly be solution tested to improve the fracture toughness of the weldment.

An important design feature incorporated into the forward strut steering system is a foil tip debris impact energy absorber. Hydrofoil trials conducted at the Hydrofoil Special Trials Unit (HYSTU) on the research hydrofoils HIGHPOINT (PCH-1) and PLAINVIEW (AGEH-1) indicated a need for particularly large debris (such as 3-4 ft. dia. logs), of restricting the impact energy that reaches the steering system in order to prevent steering break-away and subsequent loss of position control of the strut. A mechanism with series bolts designed to absorb the impact torsional energy through shearing was developed by NSRDC and the contractor. The full scale absorber was successfully tested at a land based test site and is now an integral part of the PHM-1 and the production design.

Early performance trials with PHM-1 indicated higher than predicted drag. A step-by-step drag reduction program was initiated that improved both "top-end-speed" and endurance. The first action taken was to fair the leading edges of the aft strut lower stiffeners with "bullet" noses. Additional steps led to fairing both leading and trailing edges of all stiffeners. The production design was developed to remove these stiffeners and to stiffen the strut with thicker skins.

The second step taken was to reduce the surface roughness from predominantly 5µm RMS to less than 2.5 µm RMS. All surfaces of production units will be polished to less than 2.5 µm RMS to maintain hydrodynamic efficiency and to inhibit surface corrosion.

The third step taken was to improve hydrodynamic lines of the strut and foil pods by the addition of pod extensions.

During the Seattle phase of testing, observations of the forward foil indicated higher than predicted occurrence of cavitation. Review of the contour data for the PHM-1 forward foil and the PHM-2 forward foil showed that the PHM-2 foil was built closer to design contour and should reduce cavitation drag and increase lift effectiveness. As a fourth step, the PHM-1 forward foil was replaced by PHM-2 foil and drag improvements verified in test.

As a result of a heat treat furnace minor accident, the PHM-2 foil had a distorted tip and a slight twist angle tip to tip. The cavitation limits caused by the twist and tip distortion prevent optimum trimming of ship pitch and forward and after-foil incidence angle. A fifth step was taken in Southern California to flame straighten the twist and distortion. The flame straightening technique utilizes the local application of heat by a torch under controlled temperature, heat rate, position and direction of travel to straighten foil distortion. The flame straightened foil reduced cavitation, improved lift effectiveness, and permitted the retrimming of the ship.

During the trials program, cavitation on the aft (inboard of the struts) foil panels was observed. Review of the contour data and refinement of both forward foil down wash prediction and cavitation "bucket" prediction show that significant improvement in cavitation reduction and drag reduction will be achieved in the production panels by minor modifications to design. Production manufacturing tolerances on contour, surface roughness and assembly fit-up have been established to limit the build-up of errors that effect cavitation, drag and life effectiveness in order to assure hydrodynamic performance in the production ships.

The camber of the foils will be slightly increased to increase their capacity to life without cavitation when manufactured to the production tolerance.

Detailed analysis has developed a new understanding of the downwash effect at the aft foil from the forward foil wake. The differential incidence angle of the inboard aft foil panels relative to the outboard aft foil panels has been decreased to 1 degree in order to improve its angle of attack with the forward foil downwash. The margin to cavitation and lift saturation of the aft outboard panels remain higher than inboard panels in order to maintain roll control authority by the outboard panels when lift limits are reached inboard in high sea states or in extreme maneuvers.

The PHM-1 has provided the vital full scale observations and data analysis in a real environment required for production engineering. These observations and analysis have focused the production engineering effort onto refinements to the strut and foil design necessary to assure that production PHM's meet their performance requirements when built with acceptable manufacturing techniques and tolerances.

Ship Service Pumps

With the exception of one hydraulically driven emergency fuel pump and ABEX pumps which supply the ship's hydraulic power, all other pumps providing ship services are electrically driven pumps. Due to the fact that the primary ship's service electrical power is 400 Hz, the pump motors on all of the ship service pumps are 400 Hz motors. Table V lists the system application, supplier and number of pumps used aboard PHM.

During the course of dockside and underway testing, several problems were discovered with some of the pumps as used in the PHM application. The majority of the problems was confined to the

salt water cooling pumps and the pumps used in the bilge dewatering, waste water, and chilled water systems. Table VI provides a brief summary of the problems and corrective action.

Table V
PHM Ship Service Pumps

	System	Pump supplier	Number
1.	Salt water cooling and firemain	Roper	5
2.	Waste water	Prosser	4
3.	Bilge water	Prosser	6
4.	Chilled water	Prosser	2
5.	Fresh water	Task	2
6.	Aux. lube oil	Prosser	2
7.	Turbine wash	Prosser	
8.	Fuel pumps (AC)	Task	4
9.	Fuel pumps (DC)	Task	2
10.	Macerator pumps	Gat	3
11.	Sludge pump	Gat	1

Modifications incorporated in the salt water cooling pumps have been highly successful. The majority of these pump failures was associated with pump water burn-out due to wet windings. During the first seven months of ship operations, 31 pump failures were recorded. During the next seven-month increment of operations, only an additional five failures were recorded.

Table VI
PHM Ship Service Pump Problem Summary

Pump	Problem	Solution
Salt water pumps	1) Pump impeller blade - failure at root	Material change and increase in root thickness and radius
	2) Pump motor winding failure due to wetting down	Covers installed to prevent wetting down. Windings encup pumps are not submersible pumps.
	3) Pump bearing failure due to inadequate or improper lubricant	Lubricant type changed and bearings repacked.
Waste, chilled and bilge water pumps	1) Pump failure due to improper seal between pump and motor	Modification to seal and motor case to allow positive pressure against same incorporated.
	2) Pump failure due to opening of internal thermal fuse.	Investigation in progress. Possible modification to fuse access.

Although there are five applications of Prosser pumps in the ship, three of these applications have accounted for the majority of the pump

failures. To date, there have been 30 pump failures associated with the bilge dewatering, waste water, and chilled water systems. The vendor has been conducting failure analysis and developing pump seal, bearing and fuzing modifications to increase the reliability and maintainability of these pumps. As of this writing, however, modified pumps have not been received and tested in the ship.

f. 400/60Hz Static Converters

In order to provide 60Hz power for some of the hotel and combat systems loads, the PHM is equipped with three 20 KVA 400Hz to 60Hz static converters. The ship's normal electrical load requires that two of the three installed converters be on line with the remaining converter being the back-up converter. During the underway test period of PEGASUS, the back-up converter was used as the primary power source for the special instrumentation which was installed for platform and combat systems testing. A total of six 400Hz/60Hz converters were provided under the contract. For purposes of this discussion, only those converters which have been used aboard the ship are considered. As of this writing, the high time converter has achieved some 8,000 hours' operating time aboard the ship. The unit, which was used for qualification testing at the vendor, has never been operated aboard the ship. To date, there have been 28 failures of the converters aboard the ship, and the total operating time of the converters has reached 25,300 hours. This equates to a cumulative average operating time between failures of approximately 900 hours. Figure 12a provides graphic illustration of the failure history of the converters aboard the ship, while figure 12b provides an illustration of the trend of average operating hours between shipboard failures.

It should be noted that during the first six months that the ship was deployed to Southern California, 12,000 operating hours were accrued on the converters with five failures. This equates to an improved average operating time between failures of 2400 hours since deployment.

The causes of the 400Hz/60Hz static converter failures aboard PHM can be classified as:
 1) component failures, 2) failures due to inadequate manufacturing quality control and, 3) interface incompatibilities with input and/or output loads. Each of these failure areas can be summarized as follows:

1) Component Failure - The failed components, which have been identified to be the primary failures of the equipment, are the light emitting diode/silicone controlled rectifier, the commutating capacitor, the snubber circuit capacitor, the zener diode, and the input transformer. Analyses of the failed components have revealed deficiencies in the component design and/or component manufacturing process. The vendor has proposed to replace each of these deficient components with an improved version and to include burn-in to reduce any infant mortality.

2) Manufacturing quality control - The quality control problems which were found to cause the equipment failure, are the cold solder

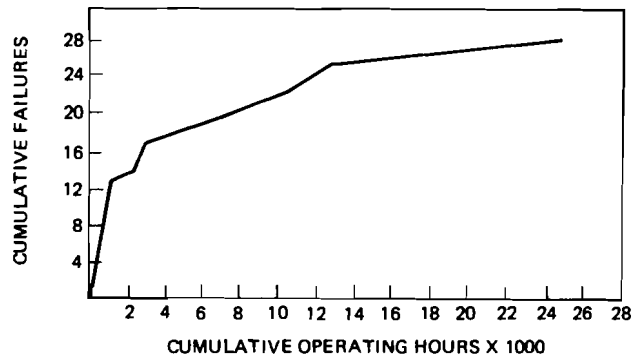


Figure 12a. 400 Hz/60 Hz Static Converter Failure History

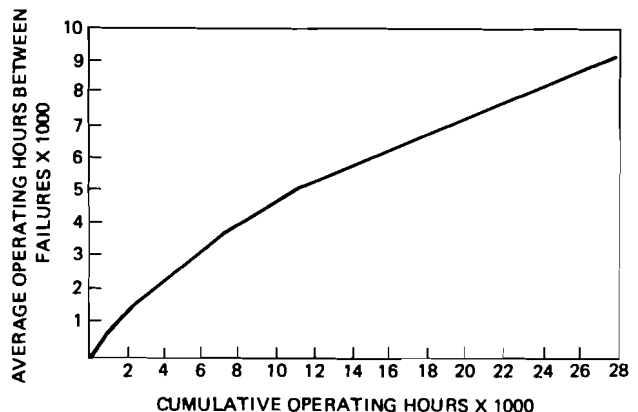


Figure 12b. 400 Hz/60 Hz Converter Operating Hours Between Failures

joints, the loose PC board connectors, and the in-line splicing of conductors. The vendor has proposed improved manufacturing processes which are: (a) to use flow soldering method, (b) to use more reliable connectors, and (c) to eliminate the in-line splicing.

3) Interface incompatibility - The interface incompatibility problems have not been positively identified. However, it is believed that failures under this category were caused by: (a) input undervoltage cycling, (b) "sympathetic switch-through," and (c) EMI from external sources. Since the vendor could only simulate the input undervoltage but not the undervoltage cycling, the undervoltage (without cycling) simulation test at the vendor has not caused any frequency converter failures. Undervoltage as a cause of frequency converter failure has not been established. The input 400Hz line fuses have been replaced with circuit breakers in an attempt to provide a faster and orderly shutdown of the frequency converter when input overcurrent occurs under the input undervoltage condition. Further interface compatibility testing is in progress aboard ship as this paper is published. Beyond this, additional plans to test or to analyze the switch-through or the EMI problems will probably be deferred until such time as a PHM production contract is awarded.

It may be noted that the majority of difficulties discussed for all the above systems

was associated with the particular application and environmentally interface characteristics of each system. Hence, they were not revealed until integrated into the ship and tested at sea. The importance of at-sea testing to a thorough understanding of all development and application problems of new systems cannot be overemphasized.

Overall Ship Reliability and Availability Assessment

Although the time of award of the PHM lead ship contract preceded most of the government's current procurement reliability instructions for new ship contracts, concern at that time over this issue was already intense due to the radically new type of ship and integrated equipment involved, the new type of maintenance concept, NATO implications, and the recognition of deficient reliability performance in many recent DOD acquisitions. It became evident early, however, that the program could not afford a classical aerospace reliability qualification program (i.e., where sufficient testing is performed prior to major construction to validate reliability allocations of all replaceable components). It was also recognized that incentivizing the contractor in this area would be difficult, especially if measurement depended upon tracking the accumulated time lines of all the many hundreds of ship's equipment which enter into an overall ship reliability determination. It was decided, therefore, that a "lumped parameter" approach would be undertaken, provided that a sufficiently structured and statistically supportable model of target reliability and availability could be established.

Three areas were decided upon as representing the major objectives to be incentivized:

- (a) The performance without interruption throughout ship mission of all mission critical functions.
(RELIABILITY)
- (b) The high availability throughout ship mission (either through high reliability or easy repair/replacement) of all important ship's equipment.
(AVAILABILITY)
- (c) The successful demonstration of each ship contract performance characteristic on the first attempt.
(PERFORMANCE SUCCESS)

A NAVSEC computer model of the PHM Preliminary (Contract) Design, used earlier in mission profile reliability predictions, was employed to project expected success of the above RELIABILITY and AVAILABILITY parameters for an average eight-hour test mission. This duration was expected to represent the normal PHM daily underway test operations through contract delivery. A matrix of (50) mission critical reliability functions was established for the RELIABILITY predictions. A second matrix of over 600 equipments was used for the AVAILABILITY predictions. Computer model results showed that probability of completing

an eight-hour mission without failure in either RELIABILITY or AVAILABILITY exceed 90 percent. On this basis, incentive negotiations and cooperative computer model studies were entered into with the prime contractor.

The following is a summary of those technical incentives which were agreed to during Underway Tests which were to be performed under the contract.

RELIABILITY: PHM reliability of mission essential functions as defined under the contract. A failure of any predesignated mission essential function, no matter what the duration of the failed state, was to be scored a trial-day failure. For reliability measurement, 50 mission critical functions were identified to be scored on a daily basis.

AVAILABILITY: Operational availability of all items of installed equipment required to satisfy the mission essential functions. These were to be fully operable at the end of each predeclared trials day. A trial day success would be scored if all equipments, as defined, were operational at the end of each predeclared trials day. A total of 613 individual items of equipment were identified to be scored on a daily basis.

PERFORMANCE SUCCESS: Percentage of PHM Performance Trials Agenda items complete on first attempt. Exclusions would include agenda items rerun due to weather, instrumentation problems, or other phenomenon having no relationship to the ability of the ship to perform the agenda items in question.

A series of operating rules for PHM systems and equipments was established for all tests and trials conducted for purposes of scoring under the Technical Incentives of the contract. These operating conditions were established as targets which are summarized below:

- a. Operating Hours - The PHM equipment and systems and alternates, for incentives scoring, were expected to be operated for a maximum number of hours during each trials day.
- b. Operating Loads - Insofar as is possible, the equipments and systems were to be operated in a loaded condition during the trials period.
- c. Cumulative Operating Hours and Cycles - The cumulative ship underway time was expected to be approximately 600 hours prior to delivery. The following operations projected minimum levels of operational use in the quantity indicated during underway operations.
 1. Foilborne hours - 250.
 2. Strut extensions - 64, and retractions - 64.
 3. Cold battery starts of each diesel - 8.

4. Operating hours of each ship service turbine - 285.
5. Main turbine starts - 64.
6. Diesel engine starts - 60 each engine (additional to 3 above).

Additionally, a series of general scoring rules was established for use of the RMC incentives. These general rules may be summarized as follows:

- a. The scoring was based on a sample of the first 40 trials days, scored for incentive purposes.
- b. The duration of a trials day was to be measured from the time of last line taken-in (underway) to the time of the first line over (moored).
- c. No failures were to be scored in any category for the following causes:
 1. Failure of government furnished equipment, test equipment, or support: These were to be scored as no-score.
 2. Secondary failures: These were to be scored as successes for the secondary failed equipment if its failure were clearly secondary; i.e., a direct consequence of a prior failure or other failure.
- d. A trials day was to be between 4 and 12 hours in duration, and nominally planned for 8 hours. For purposes of establishing the sample base for RELIABILITY and AVAILABILITY, the average trials day over the whole sample base was to be no less than 7.5 hours.
- e. Provided that a failure leads to a subsequent correction by redesign of hardware or by modification of procedures, the associated failure score may be deleted if approved by the project manager.

On this basis, the resulting technical incentive plan for performance over the first 40 contractor performance trials is depicted in Figures 13 through 16. As mentioned above, the scoring procedures established under the contract provide for elimination from the scoring results, any failures which, by agreement of the Navy Project Manager, is proven to have been due to a design deficiency or procedural error which is subsequently corrected by the contractor. In such a case, the applicable failures are to be ruled "no-score"; and additional scoring trials are to be conducted, necessary to complete the data base of 40 trials. At the time of this writing, prior to deletion of any "no-score" data, RELIABILITY results are shown in Figure 13. Correction of deficiencies in the main propulsion system and automatic control system, responsible for most of the failure scores, is expected to raise performance into the incentive scoring area prior to ship delivery.

Reliability Incentives Performance
(50 Subsystems)

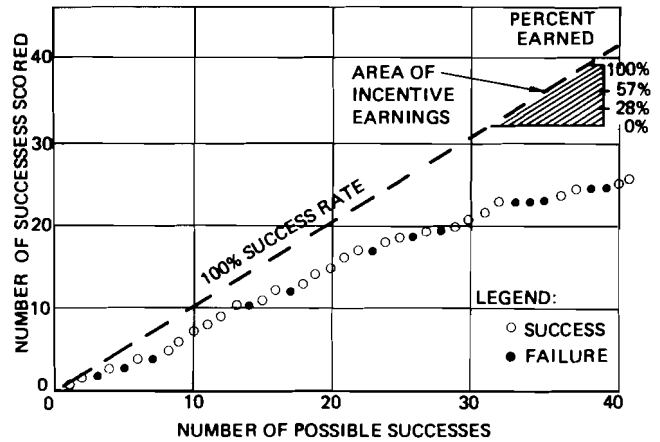


Figure 13. PHM-1 Ship Reliability Scoring Performance (Interim)

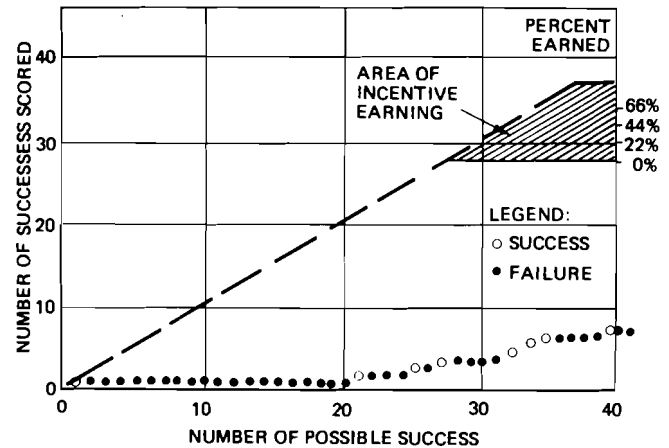


Figure 14. PHM-1 Equipment Availability Scoring Performance

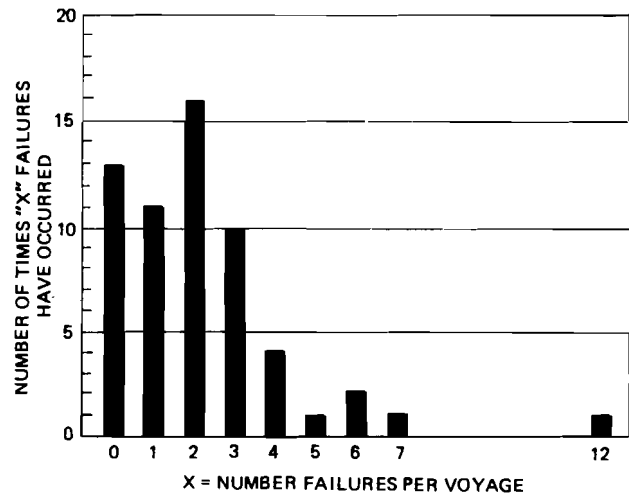


Figure 15. PHM-1 Equipment Availability Failure Distribution

Scoring in AVAILABILITY has demonstrated that an average of two to three equipments of those in the scoring matrix are down (inoperative) at the end of each voyage. In retrospect, this is not a surprising conclusion; and it appears that the incentive targets may have been somewhat severe. The AVAILABILITY scoring results are shown in Figure 14. Distribution of the number of failed equipments on each scoring voyage is shown in Figure 15.

The contractor has been quite successful in demonstrating required contract performance of the ship or its systems on the first demonstration attempt, achieving an average success rate of 96 percent to date. This is illustrated against his target incentive in Figure 16.

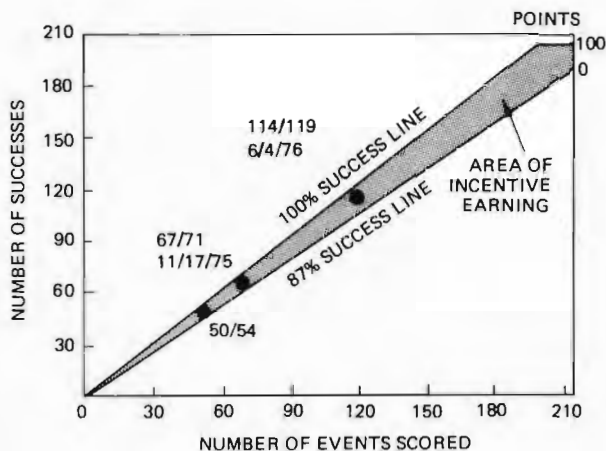


Figure 16. PHM-1 Specification Performance Success Scoring

VIII. OPERATIONS SUMMARY

Figures 17 through 19 summarize the operating data accumulated by PHM-1 during its first year of operation. Figures 17a and 17b illustrate the profile of trials days, underway and foilborne operating hours experienced by PEGASUS and compare them with the corresponding predicted profiles prepared in December 1974, approximately two months prior to ship's first underway voyage. Several observations may be drawn:

Except for period of time when PHM-1 was inoperative due to main propulsion system failures, the ship succeeded in accomplishing underway trials, underway and foilborne operations at almost exactly the rates anticipated. That is, except for the main propulsor the projected rate of trials of three voyages per week, eight underway hours per day and approximately 40 percent of foilborne time was fully supported by the maturity of the ship and integration and reliability of the ship and its combat systems. In fact, every operating profile "flat spot" (i.e., period of non-operation) of greater than one week during the first year of operations was attributable to difficulties in the main propulsion system. This includes the major planned maintenance period of July-early August 1975, where the major work item was installation of propulsion systems components and materials, and the Christmas holidays, 1975, where the main propulsion gearbox was exchanged.

The conclusion is that although the program suffered severely from failure to have an adequately qualified propulsion system prior to ship launch, the maturity of the applied hydrofoil technology, selection of combat systems, management of systems integration, and the test program planning are all fully vindicated.

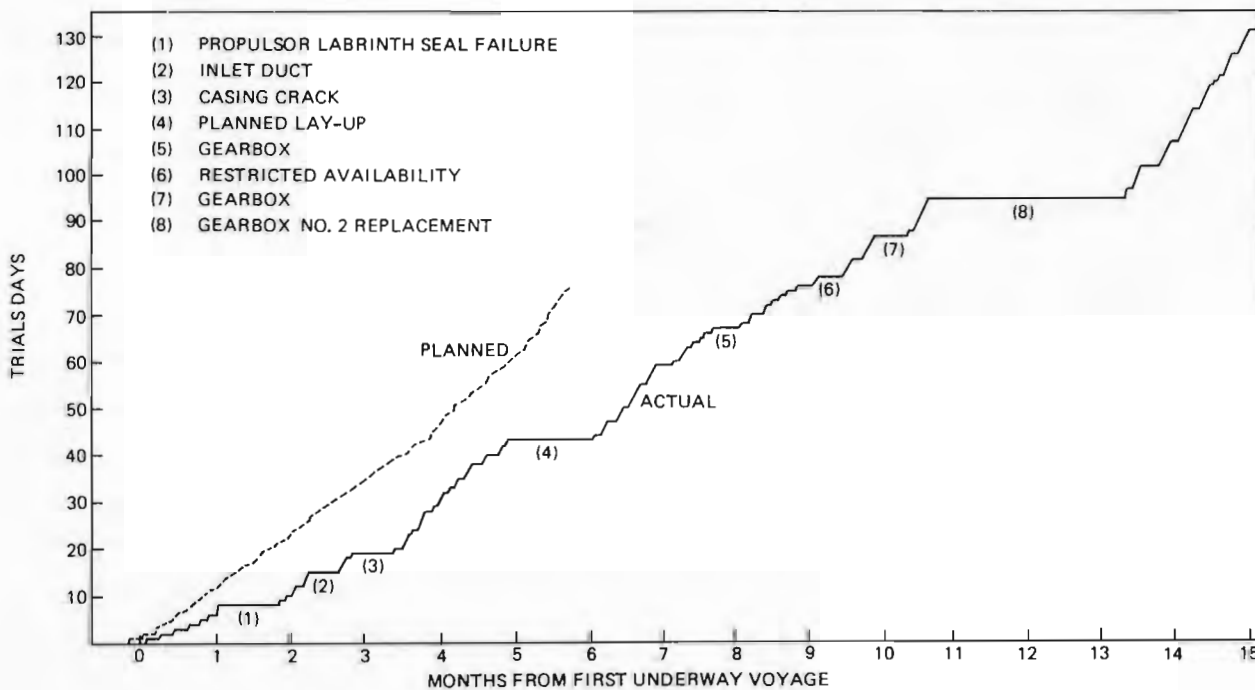


Figure 17a. PHM-1 Operating Profile

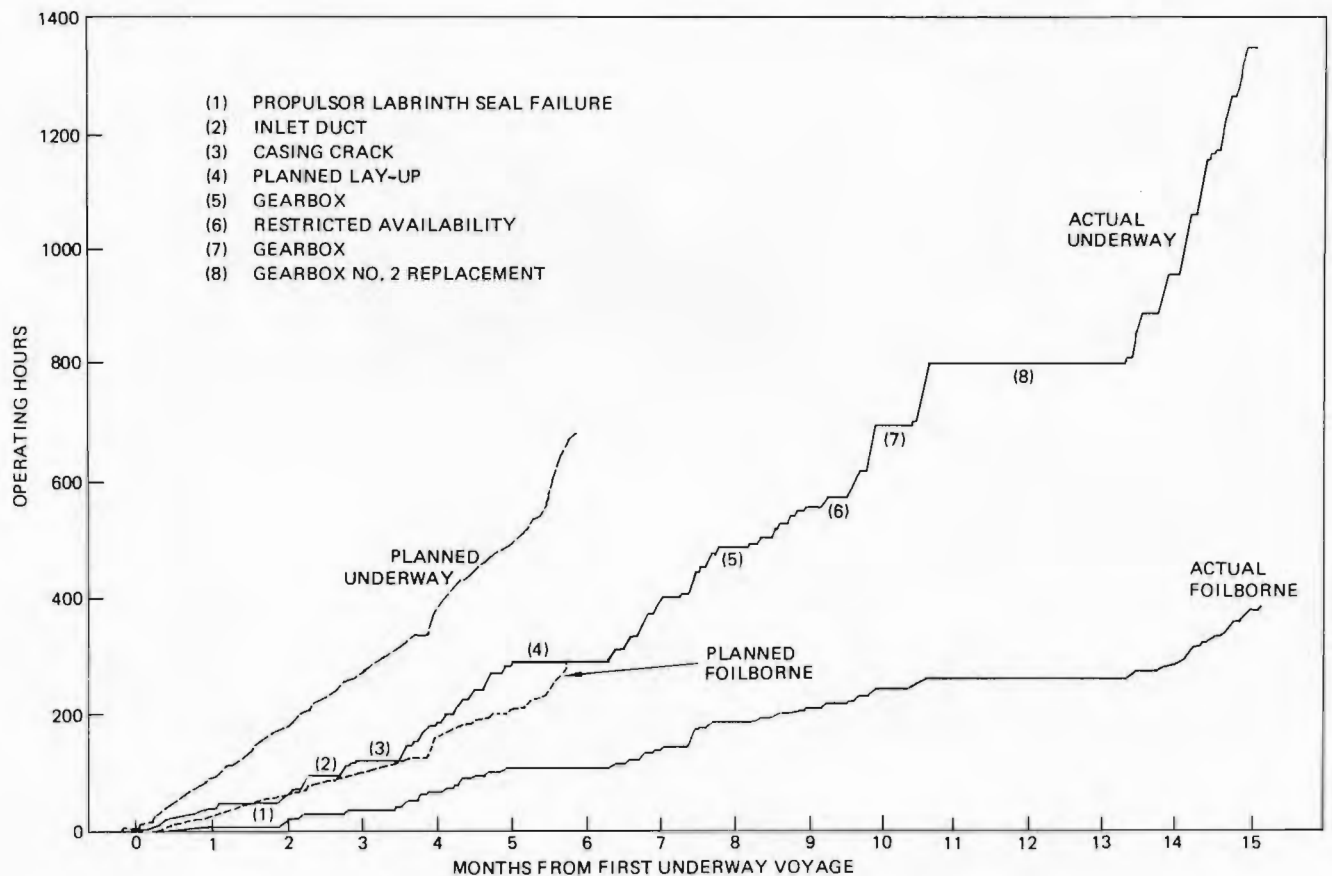


Figure 17b. PHM-1 Operating Profile

Table VII and Figure 18 illustrate the cumulative equipment time and Navy crew operating experience, respectively, which existed at the conclusion of PHM Technical Evaluation. Together with the prior figures, this data is illustrative of the effort necessary to bring a ship of this type to the point where it is ready to certify

readiness for an independent Operational Evaluation. Especially important in the case of PHM was the early integration of Navy crew members into all aspects of operation and maintenance, thus placing them on the same "maturity" curve as the ship and equipment, and enabling simultaneous certification of each as

Table VII. Cumulative Equipment Operating Time, PHM-1

	FEB*	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN
FOILBORNE ENGINE	2.09	22.51	54.28	74.25	150:17	173.55	184:15	237:31	305	337	399	429
HULLBORNE ENGINE-P	32.02	71.24	114.58	155.36	239:17	299.08	324:31	407:55	481	534	654	765
HULLBORNE ENGINE-S	28.24	62.66	108.45	147.18	231:16	288.45	313:59	396:37	455	499	578	686
SSPU NO. 1	49.45	117.86	202.38	287.21	421:13	476.28	593:59	735:59	778	864	1024	1098
SSPU NO. 2	42.37	88.78	151.27	228.19	370:51	428.57	463:01	519:56	615	691	831	975
STATIC CONV NO. 1	178.80	332.20	2342.3	2930.6	3339.7	3971.2	4165.8	4725	5468	6023	6767	7247
STATIC CONV NO. 2	1128.40	1233.70	2032.4	2917.7	3381.0	3783.5	3913.7	4510	5124	5461	6205	6577
STATIC CONV NO. 3	1000.40	1605.30	1653.7	2375.1	2815.2	3438.8	3680.6	3997	4676	5226	5598	5790
MK 94 GFCS	20.00	20.00	80.00	148.0	238.7	482.9	505.2	640.4	740	884	950	1143

* HOURS SINCE LAUNCH 9 NOV 1974

soon as ship material reliability was sufficiently established.

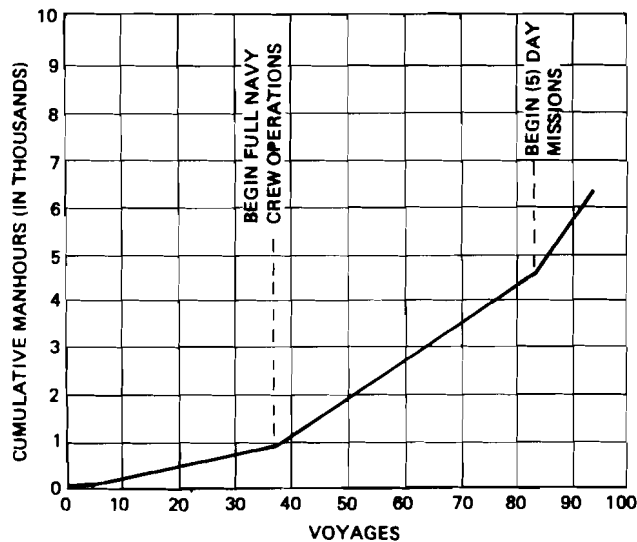


Figure 18. PHM-1 Cumulative Navy Crew Operating Experience

Comparative PHM-1 and earlier hydrofoil first-year operating experience is illustrated in Figure 19. This demonstrates clearly the remarkable reliability and pace of operations of PHM-1 during its first year despite the continuing interruption of main propulsion system problems and the much greater complexity of the PHM combat systems, test program, crew integration and deployment schedule compared to earlier hydrofoil programs.

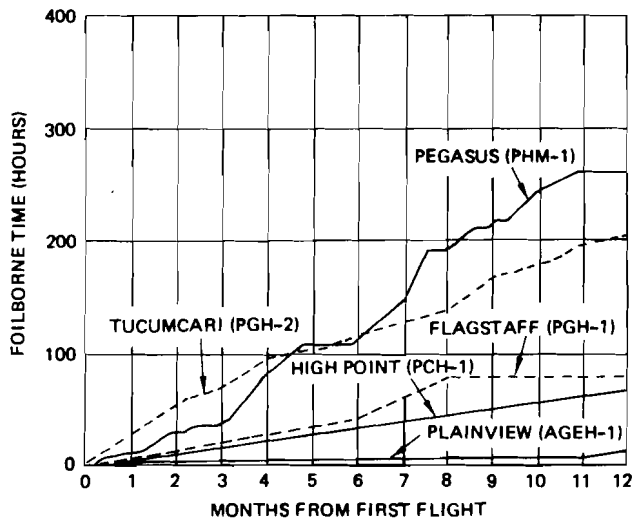


Figure 19. First Year Comparison of PHM-1 and Other U.S. Navy Hydrofoils

Table VIII summarizes and compares the first year of PHM-1 operations with that of an average U.S. Pacific fleet destroyer. The operations during the nine months of deployment to Southern California are also shown. The enhanced area coverage capability of PHM is evident. When considered in the context of initial ship investment, costs of crew manning, and operating costs per mile, the efficiency of PHM utilization for a certain portion of the present-day destroyer mission is especially evident.

Table VIII. Comparison of PHM-1 First Year Experience With Average Pacific Fleet Destroyer

	1976 (avg year) destroyer	PHM-1 (first year)*	PHM-1 9 month (SOCAL deployment)
1. Underway (average of 30 ships)		Underway 803 hours	Underway 965 hours
a. Deployed	890 hours		
b. CONUS	275 hours		
Total	1,165 hours		
2. Average underway speed	12 kts**	Average underway speed 18.6 kts	Average underway speed 17.8 kts
3. Distance traveled	13,980 nmi	Distance 14,958 nmi traveled	Distance 17,194 nmi traveled

*11 Months from first underway voyage

**a. COMSURFPAC OPS

b. Janes Fighting Ships 1974-75 (DDG 37, DD931, DD FRAM, FF 1040 Classes)

IX. T&E Lessons Learned

In retrospect, the PHM-1 T&E program has provided some lessons that should be passed on to future total ship test programs.

First and foremost is the need to get the right people involved early so that the number of surprises and misunderstandings can be kept small as the test program begins.

As was noted in the test program concepts section, one of the primary features of the PHM-1 T&E program involved the bringing together of experienced people early for test planning not only for the Navy but also for the contractor. This action is considered to be one of the major strengths of the PHM program. The early involvement between the development agency and OPTEVFOR (commencing in January 1972) in trials planning and objective setting also proved invaluable despite the extensive negotiations required to establish the first total ship implementation of DOD Instruction 5000.1. Concurrence in bounding the amount of testing and eliminating redundant testing during the OPEVAL was a key cost saving. The management support in securing test ranges, fleet, and target service priorities is another key cost saving function of OPTEVFOR.

The early integration of the prospective Navy crew members for ship operation and maintenance with the contractor's trials crew provides an important and effective hands-on training program, early operational viewpoint feedback into the correction of defects and the production design, as well as a significant operating cost saving. The PHM-1 T&E program has demonstrated the work ability of the legal, contractual, and procedural agreements to permit a smooth integration of Navy operation of a contractor owned ship.

The second area is the need to set the right test objectives for those high power level components that represent significant scaling up of already existing hardware. The large

uncertainties for these scaled-up components should be frankly recognized and test requirements established to reduce these uncertainties early in the test program. Risk analysis should be made available to the decision process controlling such test programs. However, without understanding by review authorities that such a conservative approach is necessary in establishing a thorough test program, a program could be forced ill-advisedly into reflecting even well-founded optimism into inadequate test programs. For example, the PHM-1 test program provides clear evidence that there is no effective substitute for extensive testing of "first article" high power gearboxes.

Another important question for test programs of high power components is the trade-off between land based testing and shipboard testing. The risk of building an effective land based test site for large component testing should be carefully considered. Many of the developmental problems and solutions for PHM-1 could only have been discovered through at-sea fully integrated testing. The artificialities of the land based test site and difficulties with its construction can represent large schedule and funding risks and may introduce site dependent problems with the test article, as well. However, many component performance parameters become difficult to measure when integrated into the total ship test programs. Furthermore, many of the extreme conditions are difficult to test at sea, thus necessitating land based testing.

Therefore, a balanced program may involve both selective performance and verification and extreme condition testing at a land based test site and early integration testing at sea in the real environment.

As the test program unfolds and difficulties with component qualification progress are faced, decisions regarding continued component qualification testing versus at-sea testing are required. In the case of the PHM program, the decision to support early ship launch and start of at-sea PHM testing was the key to a full understanding of the main propulsion system problems, as well as earliest completion of other vital testing and problem resolution required for the production decision.

The third area is a collection of lessons related to the formal turn over of the test ship for OPERATIONAL EVALUATION (OPEVAL).

In order to build the requisite mutual confidence in the ship by crew, program manager, and OPNAV sponsor, a test program with sufficient budget and schedule is required. It is felt that the approximately 1,000 hours of underway operations required to certify PHM readiness for OPEVAL are representative of requirements for future advanced ship types of similar technical maturity. The 1,000 hours can be achieved in approximately 15 months provided the necessary support items are well planned.

The objective of the OPEVAL must be well understood before a declaration of readiness for the OPEVAL can be established by the program. If, for example, the objectives include self-sustained operational mission demonstrations,

then such self-sustained operations must be demonstrated to the program manager's satisfaction before OPEVAL readiness is certified. Test planning should reserve adequate schedule and funding budgets for these readiness demonstrations.

Recognizing the Navy-wide attention focused upon such issues as OPEVAL readiness certification, it is also important to have appropriate procedures for approaching such a milestone. The PHM-1 readiness certification was successfully handled by an increasingly formal process starting with informal discussions 60 days prior, draft certification 30 days prior, certification letter 14 days prior, and an on-scene formal review with confirming message 7 days prior to commencement of OPEVAL.

The major logistics support element essential to PHM success was the availability of whole subsystem replacement units that permitted continued ship operation while failure analysis and modifications were being made. The accessibility for removal of major components designed into PHM, illustrated in Figure 10, was an important feature that secured the demonstrated high availability of the PHM for testing. In the case of the PHM program, although the specific use of PHM-2 as a redundant system and program assurance device was not possible as planned, its systems spares and back-up parts use for PHM-1 served the program in essentially that fashion and proved vital to the program's success.

X. Conclusions

The DSARC process, as it became understood in the early 1970s, showed prospects of improved control on acquisition decision making based upon actual test result milestones. It offered the potential benefit of improved stability to program development. Based upon early program milestone decisions and the convictions presumably represented, it could be anticipated that sufficient discipline would apply to sustaining programs through attainment of their next planned milestone(s). The question now exists, "How has DODI 5000.1 and the DSARC process affected ship acquisition programs such as PHM?" In the case of PHM, the following conclusions can be drawn:

1. Building and testing entire lead ships and integrated weapons systems under RDT&E funding (one of the implementing features of DODI 5000.1) is a nearly unworkable concept. The requirement to depend upon annual appropriations over the life of the design, construction and test program, and the resultant planning, programming, and continued defense effort requires inordinate pre-occupation of the program manager's resources and energy. This is very debilitating to the overall effectiveness of his financial planning and management. RDT&E appropriations, when enacted, remain particularly subject to limited apportionment, conditional release, and reprogramming to other programs. Changes in funding requirements are almost impossible to execute in any reasonable time frame, and any annual reprogramming in excess of \$2M (a very small percent of annual expenditure rate) requires approval of the four major congressional committees (Armed Services and Appropriations). The conclusion drawn is that RDT&E funding

should be limited to Phase I levels of design, systems development, and qualification aspects of ship development only, and that ship construction and testing should be SCN funded.

2. The extended duration of a "drawing board to test completion" lead ship program is so great that it becomes subject to extreme variations in political support. With changes every three or so years in the DOD and Navy Secretariat, the CNO and nearly all the supporting staff positions, a program can blow from hot to cold between DSARC milestones. Thus, the PHM follow ship program has shrunk from 28 ships to 5 ships; and at one point during the PHM OPEVAL, a key test activity toward which the Navy had been pointing for over four years, the House Appropriations Committee actually cut out all PHM follow ships from prior year appropriations!

3. The PHM follow ships will definitely benefit in reliability from the extensive testing and problem resolution effort performed on PHM-1, especially in the main propulsion system. In addition, the accomplishment of producibility design improvements subsequent to completion of PHM-1 has also reduced the projected costs of follow ships. However, there has been significant

cost increase to the follow ship program caused by the deferral of ordering any follow procurement until completion of all lead ship IOT&E testing. Despite the exhaustive validation test effort, however, production ship performance and operational characteristics have not been significantly affected by the extended lead ship test program.

4. The extension of time associated with exhaustive resolution of problems has made it very difficult to coordinate the interests of other participating governments, in the case of PHM. Nonrecurring cost shares have continued to increase, and top level decisions in the other governments have been delayed and complicated by the same changing political factors that have affected the U.S. program. Finally, the requirement to design, build, and operationally test one PHM ship prior to ordering even long lead materials for follow ships has placed about a four-year extension into the availability of PHM ships to the fleet. The U.S. Navy has demonstrated thoroughly the 1971 technology upon which the program was undertaken. Yet, it will be 1982 before the U.S. Navy has its first six-ship squadron of PHMs. When the production contract is awarded, the contractor will have to completely retrain about 95 percent of his production force, the lead ship production



Figure 20a. Rough Water Trials

personnel having been released to other programs or laid off over two years ago. While there is no basis for doubting necessity of the basic DSARC concept, the time, cost, and fleet modernization penalties that we are now paying for the current method of implementation appear to be excessive. There must be a better method of assuring reliability and operational utility of new ship weapons systems.

From the PHM experience of trying to interpret the DSARC process for a total ship program for the first time, some alternate approaches seem apparent. Since total ship programs have relatively small numbers of units with fairly large unit costs, the "all or nothing" step at DSARC III may be too large a transient for the acquisition system to be able to accommodate and afford. It may be necessary on such large decisions to break this step into two steps. Such an approach would refocus the objective of IOT&E to provide the test base of only the key systems that drive the effectiveness of the ship and provide the basis for DSARC release of long lead production procurement. This approach would concentrate the IOT&E resources on the elements that are critical for a production decision and leave the

refinement and grooming of the remainder for a follow on test and evaluation (FOT&E) program. FOT&E would then no longer be an open ended program but rather would concentrate on much of the refinement of evaluation and design modification necessary for the final production design and start of construction. Such a procedure could save two years and associated costs in the production of follow ships. In cases where large numbers of units may be involved, a pilot line production decision, such as is employed in missiles and aircraft acquisition programs, could be employed. There are undoubtedly other alternatives. The challenge before us is to find some disciplined process that provides the fleet with a timely capability to meet its commitments.

PEGASUS will soon join the fleet. The planned 30-day OPEVAL was completed in 32 days in May and June 1976. The OPTEVFOR REPORT is in preparation for the production decision process. A very successful rough water trials program in design sea state (Figure 20) was completed in June 1976. Rough water data is being reduced and will be reported in the future.

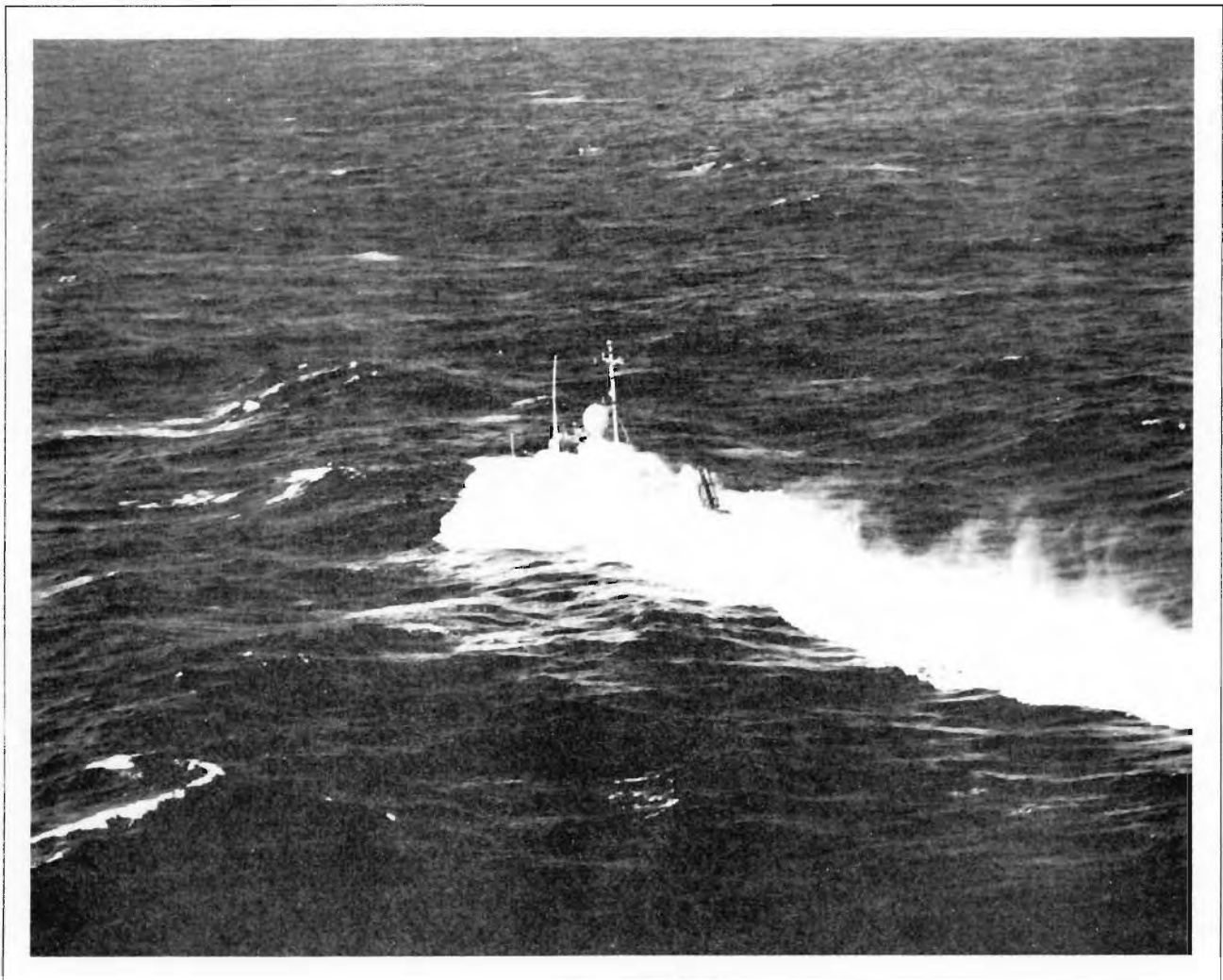


Figure 20b. Rough Water Trials