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# The Sea Shadow

## THE AUTHORS

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**Richard G. Paquette** *received a B.S.E. degree in Mechanical / Electrical Engineering from General Motors Institute in 1972 and an M.S. in Naval Architecture & Marine Engineering from the University of Michigan in 1977. From 1967 through 1976 he held a variety of engineering and management positions at General Motors, primarily in the plant engineering and noise control areas. After graduate school he spent a year at Ingalls Shipbuilding performing engineering for nuclear submarine overhauls. Since 1978 he has worked for Lockheed Missiles & Space Co in a variety of technical and management assignments on advanced ship and subsurface programs. He was Chief Engineer during the original construction and operation of the Sea Shadow and returned as the Lockheed Program Manager for the current efforts.*

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## ABSTRACT

**The Sea Shadow, designed, built and tested during the mid 1980's, represents the application of several advanced ship technologies. The Sea Shadow was recently reactivated and has been undergoing additional testing at Santa Cruz Island and in San Francisco Bay.**

**This paper provides a top level description of the ship and ship systems, is supported by photos & sketches, and alludes to the types of data and experience base which exists. The presentation of the paper includes video of the exterior and interior of the ship, of ship systems, and of at-sea operations.**

## BACKGROUND

In the mid 1980's, the US Navy, Advanced Research Projects Agency (ARPA) and Lockheed Missiles & Space Company (LMSC) collaborated on an effort to design, build, and test an advanced surface ship utilizing a SWATH (Small Water Plane Area Twin Hull) hull form and incorporating several advanced technologies. These include ship control, structures, automation for reduced manning, seakeeping, and signature control. The purpose of the craft was to evaluate the performance and applicability of these technologies to future naval vessels. The Sea Shadow was designed and constructed at Redwood City, California within a 27-month period. The ship was built inside the Hughes Mining Barge (HMB-1), which also serves as a field test support platform. The Sea Shadow was recently reactivated, publicly disclosed on April 11, 1993, and has been undergoing additional testing at Santa Cruz Island and in San Francisco Bay (Figure 1, August 1993).

Figure 1. Sea Shadow in San Francisco Bay

## SHIP DESIGN

### Design Philosophy and Criteria

The effectiveness of the Sea shadow as a demonstrator of advanced technologies for application to future Navy vessels was enhanced by the design and construction philosophy selected at the outset as follows:

The craft should be of appropriate size to allow scale up of results.

Design features such as frame spacing, bulkhead penetrations, ventilation systems, stability and safety criteria; etc, that is, all details where possible, should be standard US Navy practice. Materials must be those generally available, workable and applied on US Navy ships.

The craft should be constructed with those skills and processes normally found in the shipyard environment.

Operationally, the craft must be able to perform in sea states appropriate for fully demonstrating the SWATH technology and associate structure; that is, high sea states for this size ship.

The craft must be easily maintained and logistically supportable with minimum training.

That is, create an extremely robust marine vehicle and only push the envelope were required.

The ship design was based on the following specifications in order of priority:

- General Specifications for Ships of the US Navy
- United States Coast Guard Regulations (CFR)
- American Bureau of Shipping Rules

Hull structure, damage stability, and vital operational and safety systems were designed in accordance with US Navy requirements, while less critical items were designed to commercial ship standards.

One area where standard practices were not followed was in the selection of the engineering team, both at Lockheed and in the Navy labs. Effort was spent during the original design and construction effort, and also the follow on reactivation effort, to select a design team with a willingness and ability to provide continuity to the program. Individuals with design, construction, test, and at-sea operational experience were selected. The obvious enhancement to communications, and ability to do concurrent efforts, paid off in efficiency and reduced costs and schedule. This paid off again later when test data was being taken, reviewed in-situ, and improvements in the test taking efforts were incorporated, literally, underway.

**General Characteristics**

Sea Shadow is unlike conventional SWATH ships in that it is of "A" Frame configuration; that is, the struts are canted at an angle to the vertical. Three views of the ship are shown in Figure 2 and the principle dimensions are presented in Table 1.

The "A" frame configuration was driven by a variety of program criteria. Figure 3 depicts the results of model tank tests performed as part of an ID project exploring heave performance for strut angle versus wave period.

| | |
|---|---|
| Displacement | 560 LT. |
| Overall Length | 164 Ft |
| Beam, Maximum | 68 Ft |
| Draft | 14.5 Ft |
| Lower Hull Dia, Max | 10 Ft |
| Upper Hull Clearance | 8 Ft |
| Propulsion | Diesel Electric |
| Sea State | |
| Operate | SS-4 |
| Survive | SS-5 |
| Range* | 1000NM @ 10 Kt |
| Payload Capability | 51 LT. |

* Required range; tank volume accomodates 2250 NM

**Table 1. Sea Shadow Principle Characteristics**

This series of tests shows the significant reduction of ship motions for the 45° selected strut angle in the wave periods and sea states of interest for this size ship. The hydrodynamic mechanism exhibited by canted struts is due to an increase in the added mass and damping coefficients. The result is that Sea Shadow has motions in a seaway equivalent to a 4000 to 5000 LT 'H' Frame SWATH. [1]

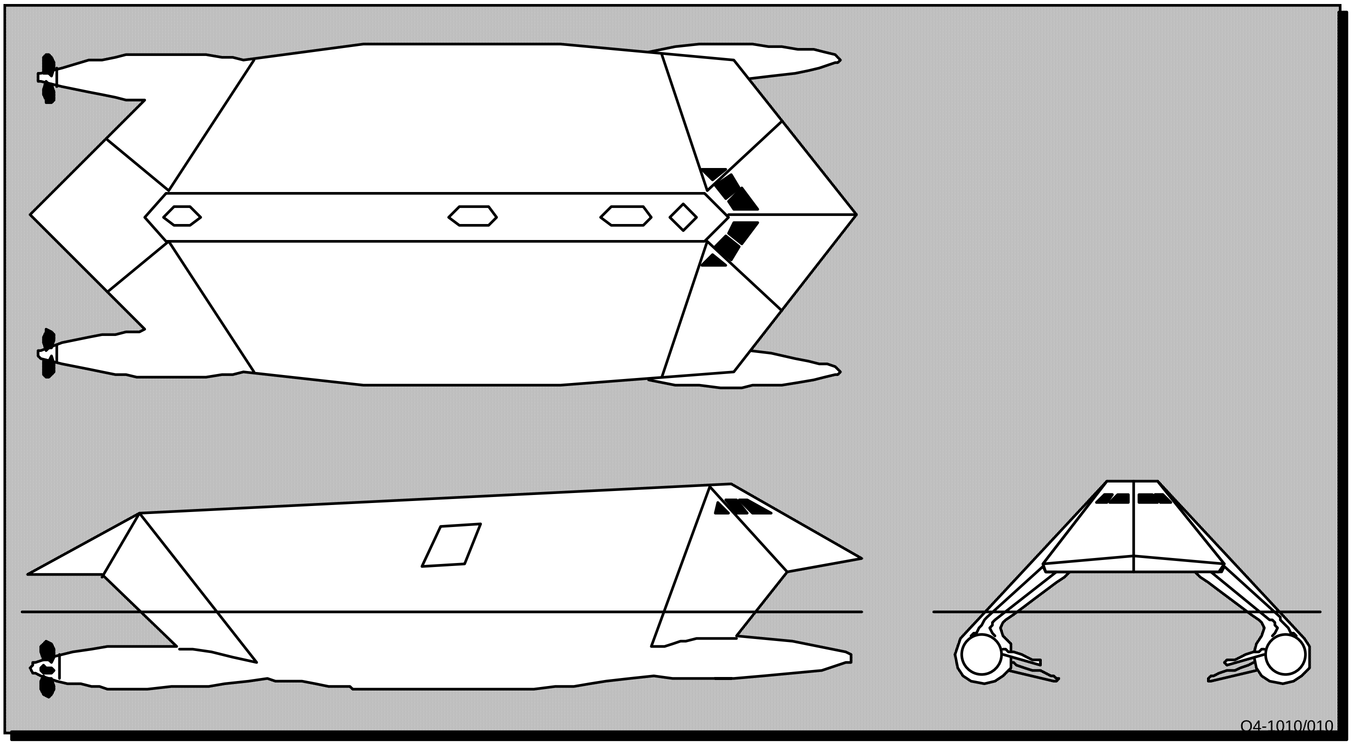

**Figure 2. Sea Shadow**

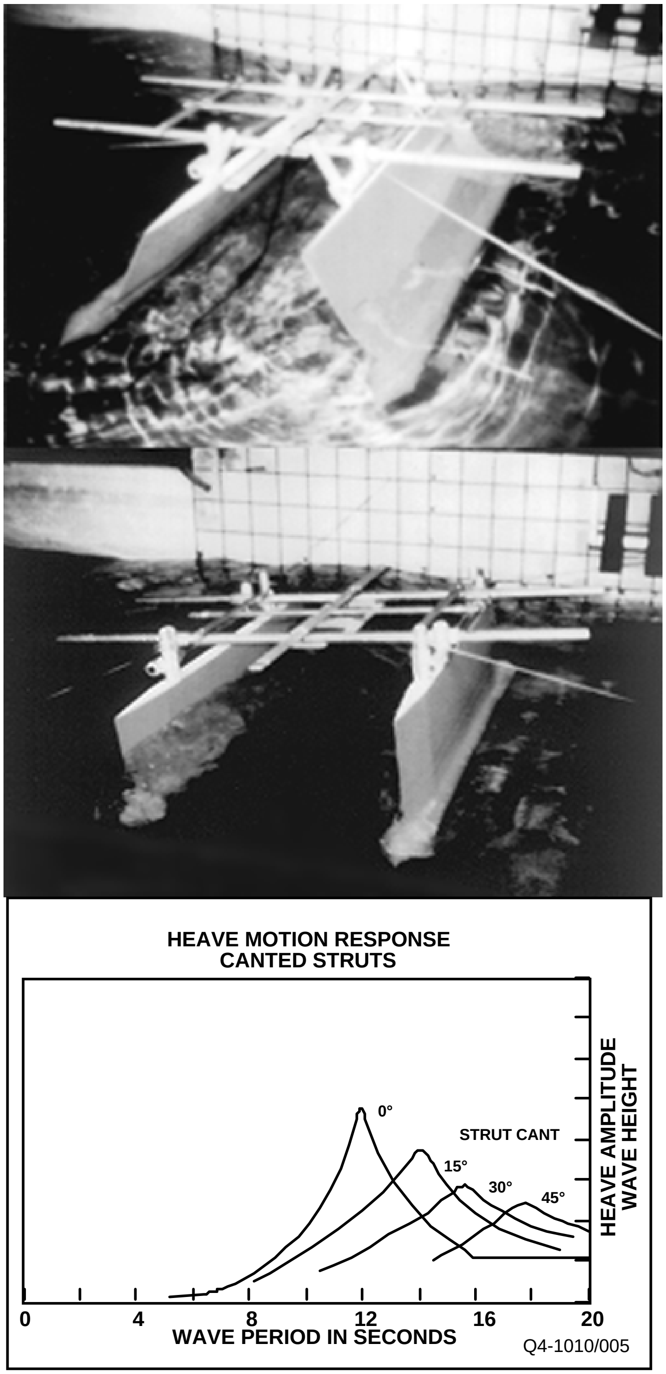

**Figure 3. SWATH "A" frame tests; strut angle vs heave response**

Additionally, the Sea Shadow contains three unique inventions developed and patented by Lockheed which have contributed to the exceptional sea keeping performance.

In addition to canting, the strut leading and trailing edges are cambered in section profile to minimize resistance, sinkage and trim while underway.

SWATH ships exhibit a characteristic pitch down moment as the submerged lower hulls ride parallel to the surface. In the Sea Shadow the lower hulls were tilted bow up in the plane of the struts. This change provides an upward moment that increases high speed stability. This pitch up also reduced resistance and increases propeller immersion aft to minimize cavitation and occurrence of ventilation in a seaway. The struts are also "toed" outward further reducing sinkage and trim, normally common to SWATH ships, over the entire speed range. A further advantage of the "toed" out struts is that, in combination with the desired lines of the upper hull, the ship is deeper forward where two decks are desired for arrangement purposes. The added height provides sufficient headroom for two full decks forward of the engine room.

Another feature is the control surfaces. The Sea Shadow has forward and after fins that, in addition to being actively used for seakeeping, are used differentially for steering. Fins are mounted on the inboard side of the lower hulls as shown in Figures 2 and 4. The forward fins (canards) are mounted approximately 15 degrees below horizontal and can rotate +/- 27 degrees. The aft fins (stabilizers) are similar to the canards, but 50% larger in area.

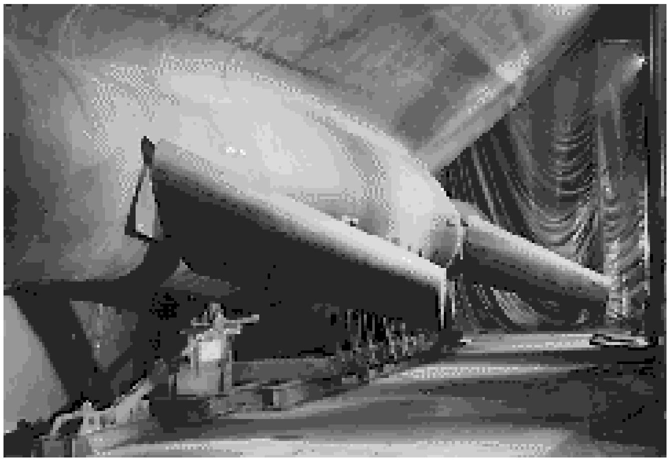

**Figure 4. Starboard Lower Hull; Canard and Stabilizer Fins**

The stabilizers provide excellent turn control and eliminate the need for conventional rudders; an extremely significant departure. Not only does it reduce the number of ship systems, but it also eliminates the structural difficulty of mounting a rudder aft of the propeller. Without a rudder aft, the lower hull may be elongated as appropriate for provision of additional buoyancy aft and restoration of ship hydrodynamic balance. That is, the center of buoyancy of the lower hull is made close (longitudinally) to that of the waterplane. Because of cleanliness of flow in front of the propeller, there is also the bonus of a significant improvement in propeller efficiency. This design, in principle, was subsequently incorporated on the US Navy T-AGOS 19 and 23 SWATHs. [2] [3]

In a SWATH configuration the lower hulls can be shaped to minimize wave drag at a chosen speed by favorable interference between struts and hulls. The configuration of the Sea Shadow lower hulls incorporate modest 'Coke Bottle' shaping to minimize resistance.

**Stability**

The Sea Shadow was designed to meet or exceed the requirements of DDS 079-1; Design Data Sheet, Stability and Buoyancy of US Naval Surface Ships. The following stability criteria were used:

**Intact stability**
- beam wind and rolling due to waves
- crowding of personnel to one side
- high speed turn
- topside icing

**Damage stability**
- two adjacent compartments flooded
- initial heel less than 20 degrees
- counterflood to reduce heel to less than 15 degrees in 10 minutes
- final static heeled/trimmed waterline below wet deck

**General Arrangements**

The inboard profile of the Sea Shadow is depicted in Figure 5. The arrangement is fairly typical with bridge, living spaces, electronics and auxiliary machinery spaces forward. Amidships are the generator and switchboard spaces. Aft of the machinery spaces is the payload space, Figure 6, which was sized to accommodate a variety of test equipment. Currently the equipment used to measure and record ship motions and structural loads data is mounted in this space. An auxiliary machinery space aft of the payload space provides clean power, air conditioning, and chilled water for any equipment, berthing, or other combination of payload space uses. Additionally, there are significant unused volumes in the lower hulls and upper hull aft. The only unusual arrangement feature is the aft location of the anchor which was done to free up prime real estate forward.

The struts contain fuel and ballast tankage and access to the lower hulls.

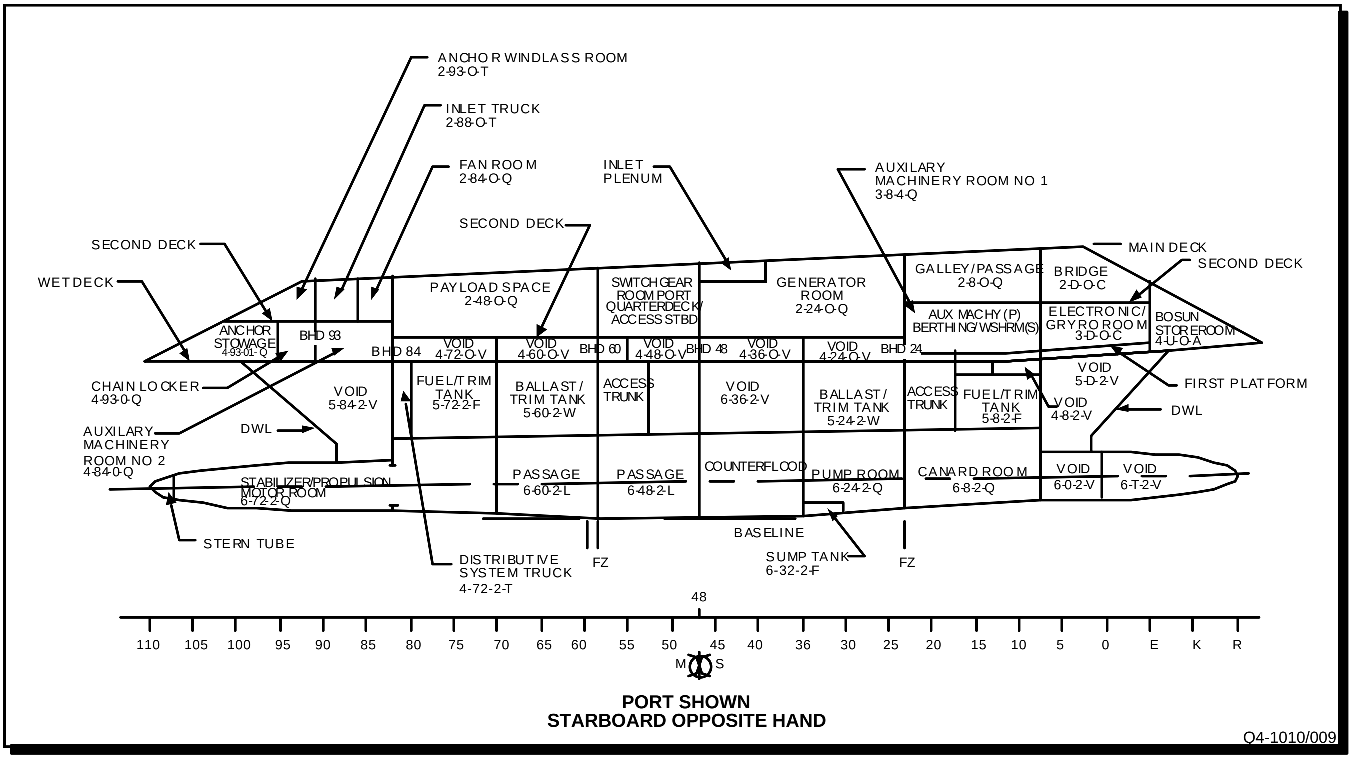

Figure 5. Sea Shadow inboard profile

Figure 6. Payload space

Each lower hull is segregated into eight water tight compartments consisting of a propulsion drive space, fin control rooms, a pump room, a counterflood space, and voids. Access is via watertight trunks which lead from the first platform (forward) or second deck (aft) down the struts.

The shell plating on the underside of the upper hull is referred to as the "wet deck". The diesels, HVAC, and tanks all vent through the wet deck into the "tunnel" area between the struts. All water intakes and overboards are located in the lower hulls below the water line .

| Wt Group | Long Tons | LCG | VCG |
|---|---|---|---|
| Hull Structure | 321.4 | 58.2 | 19.8 |
| Propulsion Plant | 19.2 | 119.5 | 5.8 |
| Electrical Plant | 41.2 | 51.5 | 28.5 |
| Command and Surveillance | 9.1 | 32.0 | 24.8 |
| Auxiliary Systems | 61.1 | 60.8 | 15.5 |
| Outfit and Furnishings | 20.1 | 43.9 | 22.4 |
| Variable Loads | 36.9 | 39.2 | 19.2 |
| Payload capacity | 51.0 | 80.0 | 19.6 |
| Total | 560.0 | 59.9 | 19.6 |

Table 2. Sea Shadow Weight Statement

Access to the ship's interior is through one of three points of entry; the main hatch located amidship on the starboard side which also serves as the quarterdeck and shore connection point: a main deck hatch located forward above the galley area: and a main deck hatch located aft at the auxiliary machinery room. There is a ventilation and combustion air inlet over the generator room and a ventilation inlet at the aft access.

The Sea Shadow weight statement is shown in Table 2. The unusually high percent payload capacity results from meeting the design displacement, without margin, within 0.5%.

## SHIP STRUCTURE

### Hull Description

The major structural elements of the Sea Shadow are the upper hull, the struts, and the lower hulls as shown in the Midship Section, Figure 7. Structural arrangement and sizing of the individual elements is based on the loading distribution determined by finite element analysis.

The main transverse watertight bulkheads, the shell and the bulkhead (second) deck constitute the watertight envelope and subdivision. The watertight bulkheads in the lower hulls, struts and in the upper hull below the bulkhead deck are generally spaced 15 feet apart. Transverse frames consist of deep web frames spaced 7 ft 6 in. apart with two intermittent frames. Ring frames in the lower hulls are on 2 ft 6 in. centers.

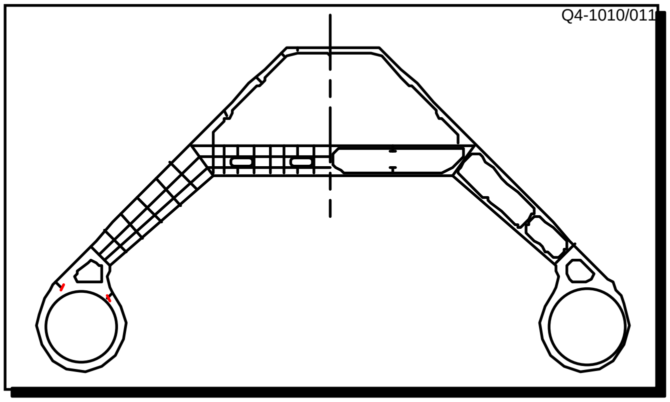

Figure 7. Midship Section

### Design Criteria

The loading conditions are divided into primary and secondary loads. The primary loads are defined as the overall loads which are induced in the structure by the motion of the ship in a seaway. For the Sea Shadow, the maximum values are expressed in terms of a transverse bending moment at the armpit and a corresponding torsional moment. The Sea Shadow is designed to survive in Sea State 5. Numerical values for maximum expected lifetime conditions are shown in Table 3. Secondary loading is defined as the local influence of externally applied forces on a restricted area of the structure. These loads are generally additive to the primary loads.

| | |
|---|---|
| **Primary Loads** | |
| – maximum lifetime bending moment | 7,850 ft-tons |
| – maximum lifetime torsion | 4,300 ft–ton |

| | |
|---|---|
| – maximum lifetime whipping | 4,300 ft–ton |
| – slam pressure | 30 psi (peak) |
| **Secondary loads** | |
| – hydrostatic (operational) | 10 psi max |
| – hydrostatic (max heel) | 16 psi max |
| – hydrostatic (wave impact) | 500 psf max |
| – control surface wave slap | 1,000 psf |
| – secondary bulkheads | 2 psi |
| – wind loading | 100 knots |
| – ice loading | 6 inch thick |
| – deck loads | 100-300 psf |

**Table 3. Primary and Secondary Loads**

Associated with the above loading conditions are 2 stress criteria:

- Primary design stress
- Maximum allowable stress

The primary design stress is based on an empirical criteria which has evolved to ensure the compatibility of the ship's lifetime stress history with the fatigue characteristics of the material. For the Sea Shadow, a maximum stress of 35 ksi in the HY-100 for combined strut bending, torsion and still water bending loads was used. Under the most critical combination of primary and secondary loading, the stress levels are limited to the allowables defined in Section 100a of the General Ship Specification and NAVSEA Structural Design manual. These values are 66.5 ksi for HY-100 and 40 ksi for HSS.

## PROPULSION SYSTEM

The diesel-electric propulsion system provides for a maximum speed of 15 knots, sustained speed of 13 knots, and a cruising speed of 9 knots.

The propulsion system, shown in Figure 8, is comprised of a 800 HP DC electric motor coupled to the propeller through a 4:1 planetary gear box, a large non-lubricated flex coupling and shafting assembly, a thrust bearing assembly, and propeller shaft with oil-lubricated stern tube bearings. The propellers are three-bladed and of stock design. However, due to the clean inflow, a high level of efficiency and low waterborne noise level is experienced. The entire arrangement is isolation mounted to minimize noise and vibration. The port and starboard propulsion systems are essentially identical.

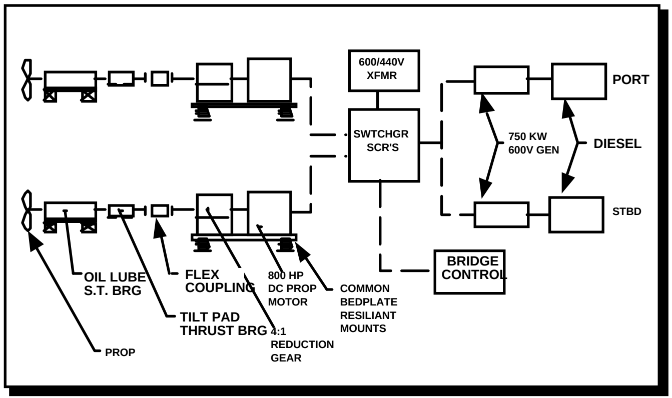

**Figure 8. Sea Shadow power generation and propulsion system**

The propulsion motor is cooled by circulating the compartment air through an air-to-seawater heat exchanger which then ducts upward and directly into the motor. A land-based test site, incorporating all elements in Figure 8, excluding the thrust bearing and propeller but including resilient mounts and propulsion system cooling, was constructed to allow concurrency in ship development and reduce risk. Propulsion power is the main component of ship's electrical load. For this reason, generated voltage was selected as 600 VAC as that proved the most efficient transformation to the 750 VDC required by the selected propulsion motors.

## POWER GENERATION AND DISTRIBUTION

The design criteria for the power generation and distribution system was based on:

- IEEE std 45; 1983
- USCG 259
- General Specifications for Ships of the US Navy
- NEC

There are two diesel generators sets; each consisting of a Detroit Diesel 12v-149TI driving a Kato generator. Each set is capable of providing 750 KW, 600 VAC, of continuous power. An accessory drive mount on the forward end of each engine drives a servo-controlled hydraulic pump which provides hydraulic power for the ship's stabilizers and canards. Each engine generator set is sound isolation mounted to the hull and all connections to the engines are by flexible couplings.

The switch gear provides for independent or parallel operation of the generators and contains two motor control units for power supply to the propulsion motors. The motor control units provide, from the 600V bus, a controlled D.C. output voltage by phase chopping and full wave rectification of the 3 phase voltage. Forward / reverse operation is controlled by reversing the propulsion motor field current. Dynamic braking and power regeneration is employed during deceleration.

The 600 volt bus also provides power to other ship systems via a 600V/480V transformer. Major rotating equipment is powered via forward and aft 480V power load centers. Driven from the 480V bus are two 25 KW MG sets (forward) and one 100 KW MG set (aft) to provide for ship's clean power requirements at 208/120V, 3 phase. The 100 KW MG set is currently unused The 480V bus also provides power, transformed to a 208/120V 3 phase bus, for ship's lighting and other low voltage equipment.

The switchgear operator, via his panel, gives control of all rotating equipment to the bridge where monitoring and control is normally done. In an emergency, the switch gear operator may start and control the diesels, including paralleling, and may control all rotating equipment, including the propulsion motors. As a backup, at each piece of equipment, except for the propulsion motors, there are local controllers.

## AUXILIARY SYSTEMS

Auxiliary systems were built using General Specifications for Ships and USCG specifications as basic design criteria for all critical systems. When applicable, for less critical systems, best commercial marine practice was utilized. The auxiliary systems include:

- Firemain and Auxiliary Sea Water
- Trim and Ballast
- Heating Ventilation and Air Conditioning (HVAC)
- Potable Water
- Fuel Fill and Transfer
- Fire Fighting
- Dewatering
- Hydraulics

Seawater systems combine the firemain and the auxiliary seawater system and is distributed throughout the vessel. It provides pressurized seawater for:

- Fire fighting
- Sea water cooling
- Ballast and deballast
- Emergency dewatering

Four 375 gallon firepumps are provided, two located in each lower hull pump room. Maximum diesel generator, propulsion, and auxiliary cooling loads are met with two pumps running at one time. Pump controls are provided locally as well as at the Engineering Station. System health is monitored remotely at the Engineering Station as well as at numerous local pressure stations.

Trim and ballast system provides the capability to trim/ ballast the ship at rates in excess of 1800 lbs/min (ballasting) and 1600 lbs/min (deballasting).

HVAC systems provide climate control to all electronics equipment locations (bridge, electronics / gyro room, switchgear room), the berthing area and the payload space. The ventilation system is partitioned into three firezones with isolation control accomplished from the Engineering Station. There is 100% redundancy in the four chilled water plant systems that serve the air conditioning systems.

Potable water can be produced using an onboard reverse osmosis plant at a rate of 400 GPD. There is stowage capacity for 400 gallons. Fresh water is distributed to the galley as well as the sanitary facility.

Sea Shadow fueling is done through a semi-automatic control station located at the Engineering Station. Fuel may be transferred to and from any one of the four main fuel tanks as well as the two service tanks located in the diesel generator space. The fuel transfer system may also be used in ship trimming operations.

The ship's fire fighting systems exceed Navy and USCG requirements. A distributed, remotely controlled Halon system, interconnected with the local ventilation system and with audible and visual alarms, is installed in each propulsion motor room, in each pump room, and in the diesel generator space. $CO_2$ and dry chemical fire extinguishers and AFFF systems are located in all appropriate spaces. A USN approved supervised fire alarm panel is located on the bridge with smoke, heat, and CO detectors located throughout the ship.

Four emergency dewatering stations, both remotely and locally controlled, are located in the lower hulls. These can be controlled at the Engineering Station. Additional dewatering capability is provided by submersible (portable) pumps located throughout the ship.

Provisions are made for mooring and towing the ship in up to 40 Kt winds and 2Kt currents. Towing is possible at up to 5 Kts via the forward hatch mooring bitts located on the main deck as well as through a penetration located in the wet deck at the bow.

Redundant pressure compensated hydraulic pumps provide the fluid power for the control surfaces (canards and stabilizers) and opening / closing the main hatch. The 16 gpm, 3000 psi pumps are direct driven off of a power takeoff located on the forward end of each diesel. These pumps are controlled and monitored from the Engineering Station.

Dockside replenishment and servicing is done via interface connections located amidship on the starboard side adjacent to the main access hatch.

## COMMAND & CONTROL

All Sea Shadow systems are designed to provide the highest level of availability while minimizing manning requirements including crew, operations support, and maintenance personnel. To support this requirement, the Sea Shadow's bridge provides sufficient monitoring and control capability to allow operation of the craft with three personnel on duty; captain/helmsman, navigator, and chief engineer. The computer systems operated by these individuals included:

- Motion Control Computer
- Navigation Computer
- Hiper-D Computers
- Engineering /Alarms Computer
- Fuel /Ballast System(s) Computer

For support of the test personnel normally onboard, for extended shift operations, and for safety, a complement of ten to twelve is normally on board.

The Sea Shadow's command and control system architecture was developed (hardware & software) in two years with a 2 1/2 man-level commitment. It was advanced for the time it was originally created; still is by many standards, and retains much of the original hardware. However, the original 8088 computers have been replaced with 486's and the assembler code and Fortran software that was required for speed has been upgraded to C+, which makes field maintenance of software much easier. The systems comprising command and control, the Ship Control System and the Engineering Station, and recent modifications, are described below.

### Ship Control System

The captain/helmsman and navigator man the Motion Control Console, Figure 9, and operate the craft through the Motion Control Computer assisted by the Navigation Computer. The Motion Control ("MC") Computer provides manual and automatic control modes for heading, turn-rate, sea-keeping (pitch and roll control), and speed. Heading is normally controlled by differential stabilizer angle but can be controlled by differential propulsion control. Differential stabilizer angle provides good heading control down to speeds as low as 0.5 Kt. Normally, roll is controlled by differential canard angle and pitch angle by collective canard angle. The Motion control system is very flexible in that canard, stabilizer and propeller system gains, and the ability to cross link the systems through the computer, allows an optimum configuration for meeting heading and ship motion requirements for ambient sea state, current, and wind conditions. The system is configurable underway directly from the helmsman's panel.

A separate control mode implements a series of heading commands from the navigation computer to follow a track. The navigator plans the track, and inputs a series of waypoints and course changes. For some tests, this consisted of a series of 18 heading changes. In this autocourse mode, the ship will follow the track through the series of heading changes to the accuracy of the navigation system.

**Figure 9. Sea Shadow bridge and Motion Control Console**

Every automatic mode can be overridden by manual control inputs or may be immediately disengaged by a single push-button. Backup electrical controls for fins, and an emergency hand pump, are located at the hydraulic panel next to each fin. Back up control of propulsion motors is at the switchgear. All fin angle and propulsion motor data, both commanded and actual, is recorded to an optical disc for future reference.

### Navigation System

When constructed, the Sea Shadow's primary navigation sensors were a Mk-27 gyrocompass, a vertical reference (pitch/roll) gyro, and a Doppler sonar. A commercial LORAN-C receiver and SATNAV Omega were kept aboard but seldom used during test operations.

Recent test operations involved aircraft and other ships. In order to coordinate their movements safely and efficiently and to gather and record correlating data critical to the tests, the existing navigation system was upgraded with the addition of a compact ring-laser-gyro INU, a differential GPS system (NATS described below) and a dedicated navigational computer; see Figure 13. The original sensors, and their feed through the MC computer, were retained for cost purposes and the sensor data sent from the MC to the navigation computer.

The VME-bus Navigation Computer hosts a custom Kalman filter which polls all navigational sources available, assesses the fidelity of data coming from each one, and provides the best weighted position data to the operator, and the MC computer, including a dead reckoning position if there is a gap in data. Using the Navigation Computer, the navigator enters way-points and course lines on its CRT chart display. A moving chart symbol shows the ship's current position, heading, and recent track on the screen. Distance and time to next waypoint, cross-track error, and course-made-good data, as well as position, heading, course and speed are displayed numerically.

The NATS, Navigation and Telemetry System, consists of six identical Navigation and Telemetry Units (NATUs) each containing a commercial differential GPS, a transceiver, and an MS-DOS computer. Each NATU can stand alone and provide GPS data to the user. In differential mode, each NATU transmits, every second, its own GPS position and velocity and receives the GPS positions and velocities of all other NATUs over the telemetry net. In this mode, the NATS provides very accurate relative position data. For the majority of Sea Shadow testing, a NATU located at a fixed, surveyed location generated and transmitted the differential corrections for the GPS receivers of the other units thus providing very accurate absolute positioning data.

A separate PC, in some cases a laptop, processed data from the NATU and displayed the positions of all NATU equipped ships and aircraft on its screen. As in the Sea Shadow's navigation computer, way points, course-lines, and numerical data blocks could be shown for each ship or aircraft. In the case of the Sea Shadow, the telemetry link also bused the ship INU and Gyro data to off board data collection systems. All data transmitted on the net were recorded to support post-test data analyses.

In the course of test operations, NATUs were installed on a destroyer, a frigate, a USCG 82-ft cutter, a work boat, and two aircraft. Despite wind and current, crewmen quickly became adept at hitting critical waypoints within a few meters and a few seconds of the test's plans. Positioning accuracy is within 2 to 3 meters, and attitude data, including heading, accurate to a milliradian or less.

### Engineering Station

The Engineering Station contains the hardware and software for the Engineer to control and monitor the ship's machinery via the Engineering/Alarms ("A" Computer) and the Fuel/Ballast ("B" Computer) Systems, Figure 10, and additional systems. This station provides for centralized monitoring and control of the ship's operating machinery and includes the following:

- Firemain and Seawater cooling
- Diesel generator control
- Bilge and hatch alarms
- Emergency dewatering
- Propulsion lube oil
- Hydraulic system
- Oily Waste
- Fuel transfer
- Sea water trim and ballast control
- CCTV
- Watertight door control
- Firealarm system
- Overboard valve condition indicators
- Damage control and isolation
- Data recording system

**Figure 10. Sea Shadow; Engineering Station at bridge's aft bulkhead**

Remote Terminal Units (RTUs) are located throughout the ship, Figure 11. RTUs contain solid state relays for control of rotating equipment, valves, etc; signal conditioners for controlling and digitizing data from pressure, temperature, level, speed, valve position and other sensors, an up down data link microprocessor for communicating with the Engineering Station computers, and a local uninteruptable power supply.

As an example, Remote Terminal Unit No. 6 (RTU-6) controls servo-mechanisms and reports the output of sensors in the port-aft lower hull, as follows:

| | |
|---|---|
| Firemain /Aux SW | 4 valve operators<br>1 pressure sensor |
| Propulsion Lube Oil | 2 pump controllers<br>3 pressure sensors<br>3 level indicators<br>3 temperature gauges |

| | |
|---|---|
| Hydraulics | 3 pressure sensors |
| Emergency Dewatering | 2 valves<br>1 pressure sensor |
| Bilge | 4 alarms |
| Damage Control | 2 indicators |

All the functions monitorable and controlled from the Engineering Station are monitorable and controllable locally at the system via motor controllers, manually operable valves, temperature & pressure gauges, etc.

The Engineer always has excellent, timely oversight and control over the overall plant lineup and best information of current system readiness conditions. Time to assess problems is greatly reduced by allowing the engineer to modify his plant lineup and quickly identify and isolate problems. Through the data logger, a running record of all system information is kept to support the engineer in planning upcoming maintenance actions and preventative maintenance requirements and in assessing modifications to systems for improved performance. Logged data is also used for training engineering personnel on equipment lineups for a variety of operating conditions and subsequent sensor indications which may be expected.

The location of the Engineering Station on the bridge provides for good communications of all plant conditions to the helmsman and navigator, and, from the helmsman and navigator to the engineer, system performance requirements for upcoming tests. A summary diagram of the main elements of Sea Shadow's computer control system are shown in Figure 12.

**Hiper-D Control System**

Under ARPA's sponsorship, Sea Shadow's Command and Control system was modified during reactivation to include ARPA's High Performance Distributed (Hiper-D) computer system. The three computers and Ethernet shown to the right of the dashed line in Figure 12 were added. When Hiper-D was turned on, the functions of the A, B, and MC computers were distributed among the three Hiper-D computers, while the A, B, and MC computers themselves performed two-way data transfer only. The following key features were demonstrated:

- Distributed processing for ship control
- Fault tolerance of computer failure while in Hiper-D mode
- Recovery to the ship's original system from a Hiper-D system failure
- Ability to rehost an existing marine control software on a Hiper-D system

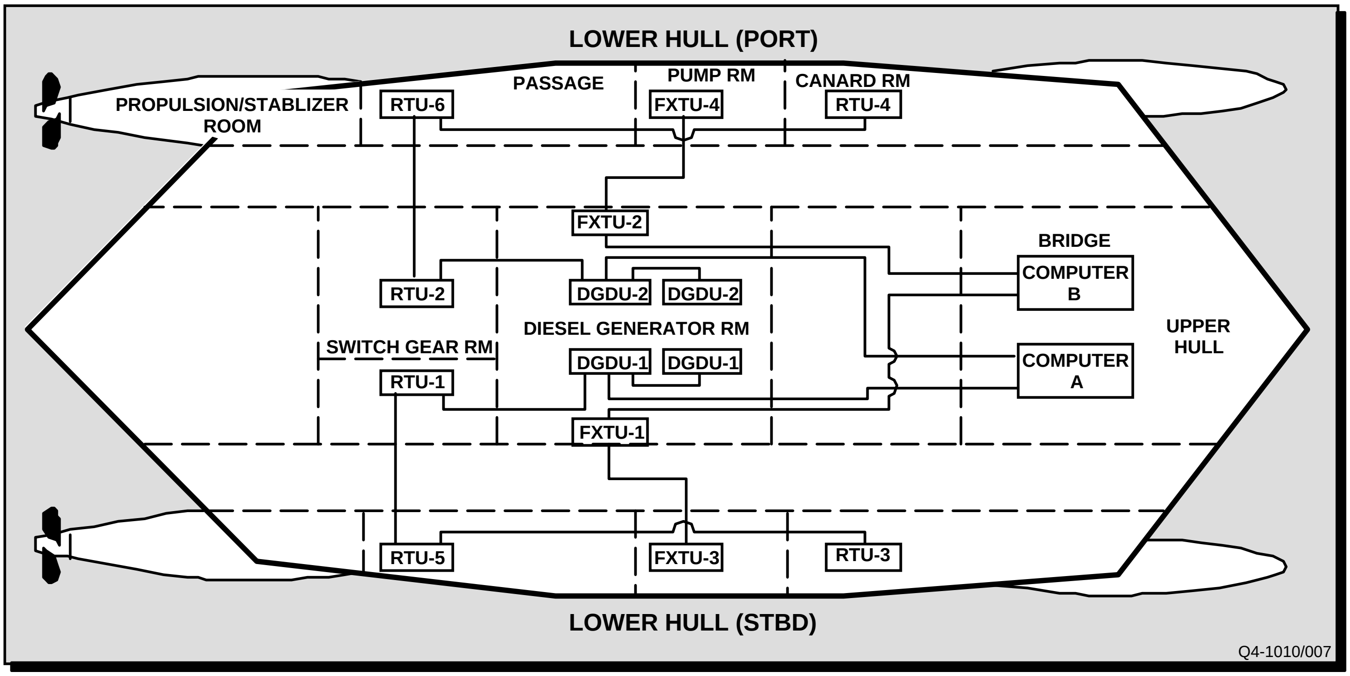

**Figure 11. Sea Shadow Ship Control System - Engineering Station communication link to RTUs (Remote Terminal Units) throughout the ship**

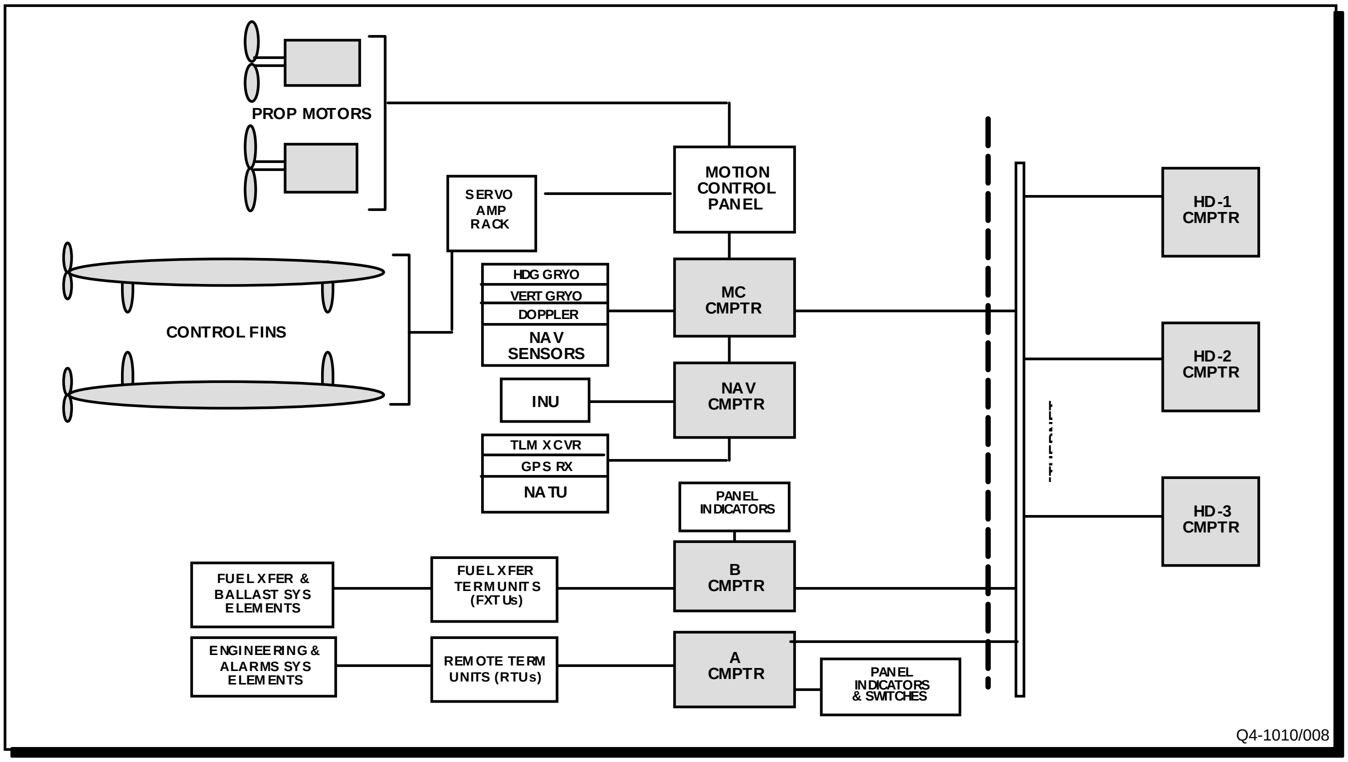

**Figure 12. Sea Shadow Ship Control System, showing baseline system (left) and modifications to incorporate High Performance-Distributed (Hiper-D) Computer system (right).**

### Internal Communications

There are three independent systems for internal voice communications. A two-channel commercial marine intercom system (21-MC) for normal use, a general announcement system (1-MC), and for emergency use a sound-powered phone system. The latter two systems connect every man-accessible space. In addition, a closed circuit television system permits remote monitoring of the propulsion motor, stabilizer, canard, auxiliary machinery and generator rooms from the bridge, galley, and electronics rooms with display at the Engineering Station.

### External Communications

Sea Shadow is equipped with a UHF antenna that serves the primary external communications equipment. Connected to it via a 4-port tunable coupler are WSC-3 and ARC-128 transceivers for clear voice, secure voice, telemetry (from the NATU), and Link 11 Navy Tactical Data System.

In addition, a standard marine VHF and a cellular telephone, with externally mounted antennas, act as backups.

## SHIP DESIGN & CONSTRUCTION

The Sea Shadow was designed and built in just under 27 months at Lockheed Missiles & Space Company's Redwood City facility on the south end of San Francisco Bay. The site combines engineering and analysis, machine shop and metal forming equipment, internal and external welding pads, 480' of pier frontage , and a floating dry dock; the Hughes Mining Barge, HMB-1. The construction approach was based on the following elements:

- Concurrency of design, construction and system test phases.
- Sea Shadow assembly inside the HMB-1 floating drydock.
- Process development and validation by the Module Prototype Project prior to welding modules constructed of thin HY-100 plate
- Modular hull construction based on fabrication of structural units at four facilities throughout the country and at Redwood City.
- Integrated land based testing of generators, switch gear and total propulsion system prior to installation.
- Full scale bridge mockup to develop and test Ship Control and Engineering Station hardware and software prior to integration with the ship.

The Sea Shadow structure was designed for modular construction. Due to schedule requirements the sections were built in a number of shipyards and steel fabrication facilities. A construction fixture was erected in the HMB and a series of benchmarks was established by use of laser surveying equipment. Measurement of barge deformation due to tidal changes was measured and accounted for. Hull sections were landed on the fixture in the HMB and were outfitted prior to joining the adjacent modules. Even though one engineer and one QA inspector were tasked with traveling from yard to yard to control and inspect module dimensions, there still was concern that there may be offsets at module joints from different yards that would exceed the construction tolerances. To guard against this, modules were landed with a gap of about one foot between adjacent components. In making the welded joints, two joints were actually made and some fairing could be accomplished if required.

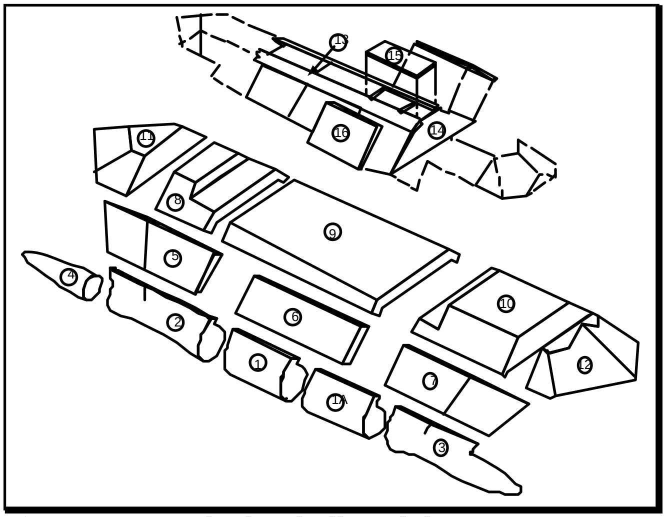

**Figure 13. Sea Shadow hull modules**

The first Section landed, 15 months before going to sea, was section 1 shown in Figure 13. The lower hull sections were placed in the HMB but initially were not aligned so as to permit installation of machinery prior to welding the sections together. After the three center upper hull modules were in place, the bulkheads were erected and the long main deck edge stringers were put in place. The alignment of these was critical to meeting the tolerance in all the upper hull shell plating and the main deck.

The last sections to be landed were the struts, which were not put in until the lower hulls were aligned and welded together, Figure 14. While the struts were being erected, the upper hull was resting on the construction fixture and the lower hulls were resting on timers set up on the deck of the HMB. After the struts were welded, the lower hulls were jacked up to put the total ship weight on the blocks. The construction fixture was then removed. Prior to going to sea for the first time the ship was landed on rubber doughnut docking blocks which have been routinely used ever since.

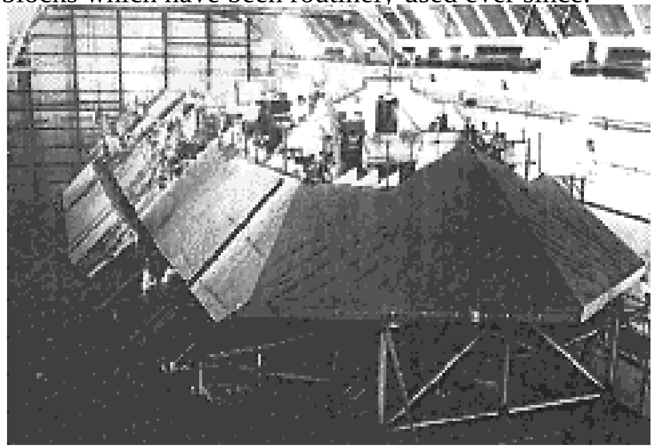

**Figure 14. Sea Shadow hull module fixturing inside the HMB-1, Redwood City CA**

During this period a number of tests were conducted to verify the adequacy of the design and construction. In one of these, the strut armpits were extensively strain-gauged and large hydraulic jacks were used to simulate the heaviest at-sea loads the ship might see. The actual stresses compared very favorably with the predicted stresses.

**Module Prototype Project**

The objective of the Module Prototype Project was to determine if the Sea Shadow module joint design, selected high strength, thin steel materials, and close tolerance requirements, were compatible with standard shipyard practices in a normal environment. An additional objective was to identify production

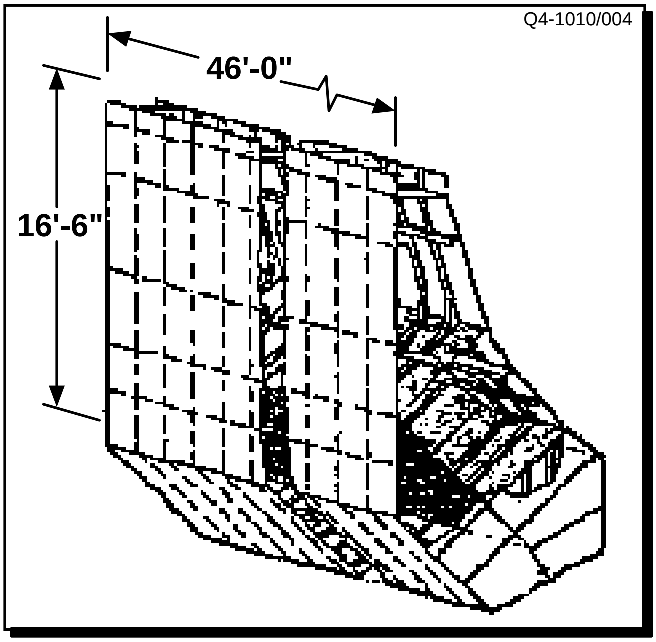

**Figure 15. Module Prototype Project test module**

procedures and techniques, time estimates and cost factors for Sea Shadow module fabrication. To serve this purpose, a sample portion of the Sea Shadow hull, including all challenging aspects required for the final structure, was designed at Redwood City and then built at Lockheed Shipbuilding.

The final Module Prototype assembled structure, consisting of four modules, is shown in Figure 15. The structure was primarily HY-100 plate with HSS stiffeners, complied with NAVSHIPS 0900-000-1000, and generally satisfied Section 074 of the LSD-41 Class Specification then being built in the Seattle Shipyard. The final report addressed such items as producibility instructions, distortion control, weld procedures, jigs, erection sequence and quality assurance. The processes and techniques developed under the Module Prototype Project established that the Sea Shadow structural design, including required tolerances, could be achieved by a shipyard or steel fabricator.

## Bridge Development

The details of the methods used to design and build the Sea shadow in such a short period would be the subject of an expanded discussion. In this paper, we briefly mentioned the propulsion system land based test and the modular approach to the structure. A short discussion of how one of the most innovative elements of the Sea Shadow was developed is warranted here.

The main body of the design engineering team at Redwood City worked in what, at the time, was an unheated and uncooled warehouse on a concrete pad. On the same concrete pad next to the drafting area was erected a foam core mockup of the bridge, Figure 16. This mockup was used to display structural details to shipfitters and to develop the Ship Control panel and Engineering Station. This mockup was also used to finalize operator habitability aspects including ability to observe and operate all console features easily, ability to layout and use charts and logs, and the ability to see out the windows. All hardware and software for the Ship Control system and Engineering Station were developed, integrated, and fully tested in this mockup.. Once the basic size and other aspects of the bridge were confirmed from the mockup, construction of the actual bridge outer structure began and continued concurrently with integration of hardware in the mockup. Figure 17 shows the condition of the actual bridge, shown receiving part of the shell structure, just 65 days prior to dock trials.

In addition, the Sea Shadow, a radically new hull form at the time, was initially required to conduct all launch and recoveries from the HMB-1 during the dark of night. A simulator was created that allowed the helmsman to operate the propulsion control throttles while observing, through the computer display, what he would be seeing (mostly the few lights on the HMB-1), at three angles through the bridge windows. The simulator modeled Sea Shadow heading, speed and seakeeping response to throttle setting, sea state and wind conditions, and modeled moored HMB-1 pitch, roll and yaw in the same conditions. Through this simulator, Sea shadow launch and recovery operations from the HMB-1 were practiced.

**Figure 16. Sea Shadow; Bridge mockup**

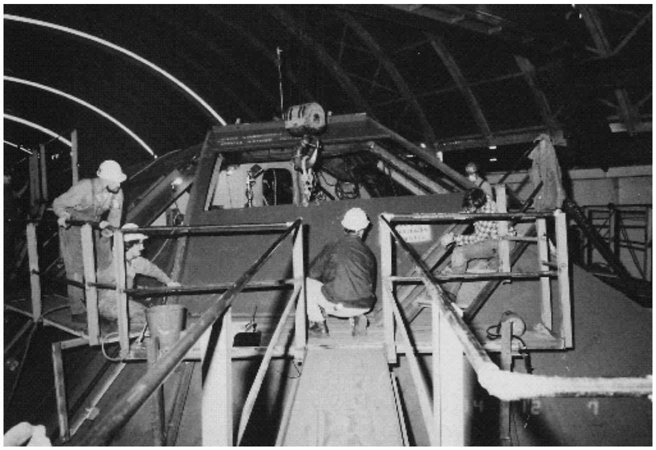

**Figure 17. Sea Shadow; Bridge during construction**

## Hughes Mining Barge (HMB-1)

The HMB-1, shown in Figures 18 and 19, is a 324 foot long, 107 foot beam, 5800 ton displacement floating drydock constructed in the early 1970's as a fully submergible system. During late 1982 and early 1983, the HMB-1 was reactivated and modified to support the construction and testing of the Sea Shadow. The roof and a 15 ton overhead bridge crane were reinstalled, catwalks were added and the assembly tool was fabricated on the well deck of the barge to support modular construction. Near the end of construction,

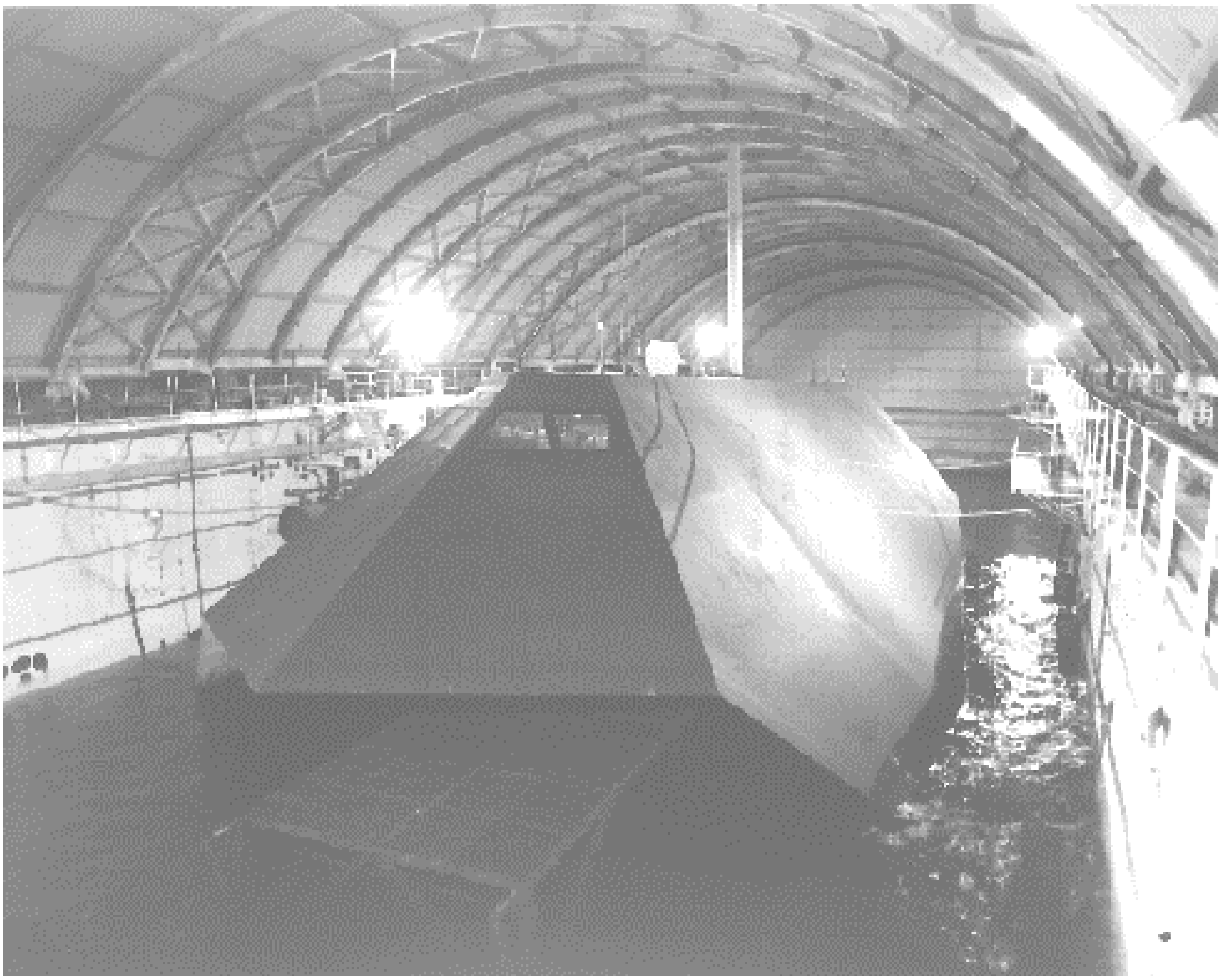

**Figure 18. Sea Shadow Moored Inside the HMB 1**

the steel wall at the aft end of the barge was replaced with a vertically opening "megadoor". The 76 foot wide, 72 foot high steel reinforced fabric door is normally closed except during ship deployments . The roof, consisting of 6 moveable and two fixed aluminum telescoping sections, provides a large clear vertical opening into the barge. The roof sections were retracted as required for module and equipment loading.

During Sea Shadow dock trials, an inclining experiment was performed. Because of the narrow main deck, a longitudinal inclining was performed instead of the traditional transverse inclining. Dock trials and the inclining were conducted in the Redwood City area by flooding down the HMB-1 and checking the ship systems. The current HMB-1 / Sea Shadow configuration allows all ship systems to be operated and tested in the "dry".

**Figure 19. HMB-1, Hughes Mining Barge**

Following construction completion, the HMB-1 served as the field test support platform and covered drydock for the Sea Shadow. The barge provides shore power, hydraulics system flushing, replenishment fuel, spares storage, and staging of logistics and personnel. Normal operation is to tow the HMB-1 to a test site, moor or dock the barge, ballast the barge down from it's nominal 8 foot draft to 42 foot to float the Sea Shadow, raise the megadoor, release the mooring lines, and back out the ship under its own power. The HMB-1 has proven to be a valuable construction and test support asset. While it continues to house the Sea Shadow, the ship can operate from a conventional pier.

## OPERATIONS

Following completion of construction in the mid-80's, the Sea Shadow was taken to Santa Cruz Island for testing. Due to security requirements, all tests were conducted on a closed range at night. Excellent maneuvering capabilities and many other aspects of the success of the design were confirmed. Elements of the program have been applied to other craft including the T-AGOS 19 and DDG-51.

After the Sea Shadow's recent reactivation, additional tests were conducted in April, August, October and November of 1993. These tests were performed during day and night and included extended, open ocean periods. The variations in time of year and time of day at locations throughout the Channel Islands and Point Conception area provided analysts with data for a wide range of environmental conditions.

During the open ocean tests the Sea Shadow conducted operations in conditions up to a fully developed Sea State 5; the original design requirement for survival. The craft was fully instrumented and operated during a series of Sea State 3-4 test exercises previous to sea state 5 exposure. Maximum stresses seen at sea state 5, in the most highly stressed areas of the ship, were low and correlated to the levels predicted by the finite element model. During the at-sea tests, an instrumentation system very similar to that utilized on the T-AGOS 19 tests was installed. This system measured and recorded data from approximately 50 strain gauges, along with ship motions and relative wave height data. A buoy was also deployed in the area to determine the characteristics of the sea state. Comparative performance data was collected on the Sea Shadow, a destroyer, a frigate and a USCG cutter during the tests.

Sea Shadow performed as expected based on results of computer predictions and model tests both in seakeeping and in its structural strength.

During one open ocean operation, the Sea Shadow remained at sea for 73 hours and traveled 519 nautical miles in the process of finding and operating in the highest sea states available. The 24 personnel on board included ship's crew, scientists and test personnel. This crew of 24 shared 12 bunks and one head with two WC and one shower. Test crew personnel (coed), though working long hours, experienced little motion induced fatigue on the Sea Shadow, especially when compared to the fatigue of the personnel on the USCG cutter.

The high caliber of technologists, analysts, test conductors, operators and support personnel teamed for the recent Sea Shadow Program tests represented a wide range of Navy Lab, ARPA, and industry organizations. The test database is extensive, of very high quality, and covers all ship systems, seakeeping and structural performance, and signature aspects for a reduced observable SWATH ship.

During testing, the Sea Shadow has achieved its design goal of providing a robust platform capable of demonstrating fully many advanced technologies. That the craft was designed and built in only 27 months, and performed so well, is a credit to the many men and women, at all levels, from Government and Industry who had the vision, capability, and dedication for this effort.

## ACKNOWLEDGMENTS

The authors are most grateful to the US Navy and to Lockheed Missiles & Space, Company Inc. for permission to present this paper.

The giant leap of faith demonstrated by the Sea Shadow would not have been possible without the vision of pioneers and promoters of the value of advanced technology to US fighting forces such as Secretary William Perry, VADM (Ret) Reynolds, and the late ADM A. J. Whittle III. There have been many who have contributed to the successes of this project over the years and, although they can not all be attributed, we hope that this first discussion will provide some recognition of the challenges met.

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