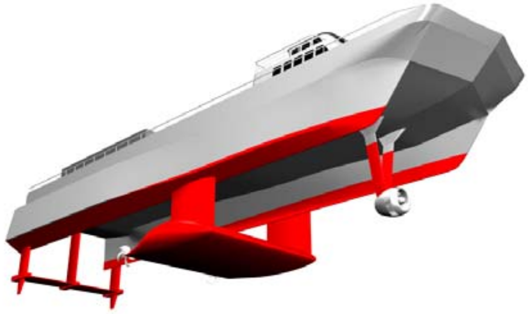
Design and Manufacture of a 2100 Horsepower Electric Podded Propulsion System

Christopher M. Waaler, Visitor, General Dynamics Bath Iron Works, **Michael A. Quadrini,** Visitor, General Dynamics Electric Boat Corporation, **Todd J. Peltzer, P.E.,** Associate Member, Navatek, Ltd.



ABSTRACT

Electric propulsion systems provide numerous advantages to a ship designer including increased power flexibility and design flexibility. Commercial cruise liners have capitalized on the advantages of electric podded propulsion and it is now entering the military marketplace. A program, sponsored by the Office of Naval Research, entitled the Advanced Hull Form Inshore Demonstrator (AHFID) is demonstrating the technical feasibility and producibility of a rim-driven, permanent magnet motor in a propulsion pod. The AHFID program demonstrates a complete electric podded propulsion system, from prime mover to propulsion motor, aboard a converted surface effect ship to evaluate the performance of a rim-driven propulsor in the areas of efficiency, reliability, noise and electromagnetism. This paper will discuss the design, fabrication and anticipated testing of this advanced propulsion system.

NOMENCLATURE

AHFID	Advanced Hull Form Inshore Demonstrator
ALE	Allowable Loads Envelope
EDCE	Electric Drive Control Electronics
GFE	Government Furnished Equipment
GTG	Gas Turbine Generator
HYSWAC	Hybrid Small Waterplane Area Craft
J	Advance Coefficient
LDV	Laser Doppler Velocimetry
LOP	Local Operating Panel
NRL	Navy Research Laboratory
NSWCCD	Naval Surface Warfare Center Carderock Division
ONR	Office of Naval Research
PCC	Propulsion Control Console
PWM	Pulse-Width Modulated
RDP	Rim-Driven Propulsor Pod
ROP	Remote Operating Panel
SES	Surface Effect Ship
SOE	Safe Operating Envelope

INTRODUCTION

In January 2000, then Secretary of the Navy, Richard Danzig, heralded a new era for the U.S. Navy. He announced that the next U.S. Navy surface combatant would have an electric propulsion system. This decision opened up new opportunities for ship designers that had not been available for U.S. warship design since electric propulsion was abandoned by the U.S. Navy before World War II in favor of mechanical shafting and gear trains. The commercial community, particularly cruise ships, embraced electric propulsion many years before this announcement and is enjoying its advantages today.

An electric propulsion system facilitates the replacement of traditional mechanical shaft driven propellers with propulsion pods powered by electric motors. Traditionally these are wound field synchronous motors controlled by cycloconverters. One disadvantage of this arrangement is that as the shaft horsepower of these motors is increased to the necessary levels of a combatant, the volume and weight of the system and motor become too costly for the advantages they provide. Technical advances in the area of rare earth permanent magnets and power conditioning, however, have resulted in the development of high power permanent magnet motors and solid state motor drive units. The permanent magnets can replace the electrical coils on the rotor of the motor and eliminate the need to create the armature electromagnetic field through the transfer of electricity to the rotor thereby allowing for the creation of high torque and power dense systems.

Significant changes, such as the transformation of a warship's propulsion system, are understandably received with some skepticism in the Navy technical community. Before these new technologies can be employed on the ships designed to go into harm’s way, they must be tested and proven. They must demonstrate reliability and performance not only in controlled laboratory environments, but also at sea.

Within this paradigm of test and demonstration, General Dynamics has designed a permanent magnet, rim-driven propulsor pod (RDP), which is a ducted propulsor with the propulsive motor stator integral with the duct, controlled by a pulse-width modulated (PWM) motor drive system (patents pending to General Dynamics Electric Boat). In an Office of Naval Research (ONR) program entitled Advanced Hull Form Inshore Demonstrator (AHFID), General Dynamics' Bath Iron Works and Electric Boat, teamed with Pacific Marine and Supply Company and the University of Maine, have designed and are building a 2100 horsepower RDP that will be demonstrated at sea in 2003. The system will be placed aboard an out of service Navy Surface Effect Ship that will be reconfigured into an advanced hull form called the HYbrid Small Waterplane Area Craft (HYSWAC). The AHFID podded propulsion system will provide additional thrust to the vessel's main propulsion system. A gas turbine generator generates power and power conditioning is accomplished via a motor drive, which are both located in enclosures on the after deck. The RDP will be suspended from the forward section of the HYSWAC via a steel "V"-shaped strut. The system is powered through a four-level, series-parallel, PWM motor drive unit isolated from the 530 VAC turbine generator set via input transformers and commercial switchgear. Through this system, the AHFID program will provide the hardware and risk mitigation experience necessary to assist the Navy in its shift to a new propulsion system technology.

ADVANTAGES OF ELECTRIC PODDED PROPULSION

The advantages of electric propulsion systems have been expounded upon frequently over the last few years. In addition to the numerous advantages provided by electric propulsion in general, vessels built with propulsion pods have several advantages over their mechanical gear, shafted propulsion counterparts. Specifically:

- **Increased Manufacturing Flexibility** - The critical alignment process of the propulsion shaft dictates that most vessels must be built around the propulsion train. This stipulates the fabrication path and drives the initial build schedule. It limits the amount of modularity that can be inserted into the erection units thereby increasing the overall build time. Electric propulsion pods can be built prior to or in parallel with the hull erection sequence and installed at any convenient point in the schedule.
- **Increased Leverage of Commercial Technology** - Fewer and fewer commercial vessels require the precise machining of a military-grade reduction gear. This shifts the cost burden solely onto the military acquisition community. Electric drive eliminates the reduction gear and this sole dependency on the military budget. Electric propulsion pods have found favor in the cruise industry providing the military the opportunity to leverage the

development costs and risk mitigation already borne by the commercial market. Many of the electric propulsion components (e.g., power electronics) are common to the commercial power industry as well. Spare part support and logistical infrastructure costs can be shared between both entities.

- **Increased Maneuverability** - Propulsion pods have proven to be very effective at maneuvering vessels, particularly at low speeds. This can become a critical mission advantage for littoral warfare. The increased maneuverability may reduce or eliminate the need for tug assistance when docking. Some large cruise liner ports have forgone their tug contracts due to lack of use.
- **Increased Efficiency** - Results from testing of propulsion pods have shown they enjoy a significant increase in open water efficiency over conventional designs. In designs similar to the AHFID design, the propulsor efficiency remains high even at high speed. The permanent magnet, radial field motors are extremely efficient. The integration of the motor and the propulsor eliminates the shafting efficiency losses and potentially some of the bearing losses found in conventional shaft driven propulsion systems.

OBJECTIVES OF THE AHFID PROGRAM

Because of the demanding environment of the sea and especially combat at sea, it is imperative that any major advance in technology for the Navy be proven at sea. The fundamental objective of the AHFID program is to design and build a permanent magnet RDP to characterize its performance at sea. By doing this, the program can provide a foundation for additional advances in podded propulsion technology for the U.S. Navy.

Many concerns have been raised regarding the permanent magnet RDP performance in the areas of efficiency, reliability, noise and electromagnetic fields. The quantification of these potential risks is difficult because there is little to no empirical data for this type and size of podded propulsor. The AHFID program will provide the first at-sea testing of a permanent magnet RDP of this size and power level.

To characterize efficiency, two experimental processes will be used to evaluate the AHFID RDP. The first assessment took place in November 2001 at the Naval Surface Warfare Center Carderock Division (NSWCCD) David Taylor Model Basin. A scale model (1:4.375) of the struts and the propulsor (12 inches in diameter) was installed into the towing basin. A rim-driven motor was not installed for this test; instead, a Kempf and Remmers dynamometer drove the unit through a downstream shaft. The thrust was calculated through a load cell system and the propulsor thrust was measured by the shaft dynamometer. This provided the opportunity to compare the data to other propulsors with known performance characteristics.

The second assessment of system efficiency will be conducted with the demonstration-size (72 inches in diameter)) AHFID propulsor operating on the HYSWAC at sea. The power into the propulsor will be determined directly from the input current transformers and voltmeters. The power out of the propulsor relies on accurate measurement of the vessel's speed through the water and the propulsor thrust. Measurement of the propulsor thrust at sea is not simple, however, therefore several methods are being considered. The primary method is through a system of fiber-optic strain gages affixed to the strut and strut-ship interface being developed by the Naval Research Laboratory (NRL) working with the University of Maine. Through computer modeling and small scale testing it is anticipated the thrust vector can be extracted from the applied load set and associated strain response. Alternatively, a set of load cells is being considered for insertion at the strut-ship interface to obtain the thrust value. Finally, a rough estimate of the RDP thrust could be derived from the HYSWAC performance curves or potentially a thrust block mounted on the shafts of the main propulsion system.

As with any new technology, reliability data can only be obtained through the operating time of the equipment and the operating time is based on the amount of funding available. Currently the program budget supports sea trials and limited demonstrations of the podded propulsion system at sea. Therefore in the short term, the AHFID program is focusing on the availability of the propulsion system, i.e., the ability of the AHFID propulsion system to be available for demonstration on short notice.

Due to budget constraints, noise and electromagnetic characterization tests have been deferred; however, the AHFID team continues to pursue several testing opportunities for the RDP. At sea, the team is exploring the use of existing facilities in the Hawaiian operating areas and the use of the Navy's P-3C Orion aircraft.

To build a robust and accurate performance database for permanent magnet RDPs, the AHFID RDP must be evaluated in controlled environments. To accomplish this, the AHFID team is exploring several options. The small-scale model may be tested at the Pennsylvania State University Garfield Thomas Water Tunnel where cavitation can be measured and the hydrodynamic interactions could be mapped through laser doppler velocimetry (LDV). The AHFID RDP may also be tested at the Navy's Large Cavitation Channel (LCC) in Memphis, TN. This would provide the opportunity to fully measure and evaluate the powering characteristics of the combined motor and propulsor and other characteristics in a laboratory setting. The RDP may also be tested at the Navy's research facilities in Bayview, ID where any tunnel wall effects would be eliminated and specialized evaluation apparatus could be employed.

In June 2001, NSWCCD released a report suggesting potential electromagnetic testing opportunities for the AHFID RDP. This proposed testing included in-air measurements during motor and motor drive integrated testing, testing at the new NSWCCD electromagnetic testing facility, and testing in Pearl Harbor, HI with a mobile shallow water range. These tests would populate an empirical database to validate computer modeling and to explore the scaling effects of increasing motor size. Better comprehension of the effects of scaling will aid in more accurate predictions of full-scale podded propulsors for Navy combatants.

PROGRAM CONSTRAINTS

As with any program, the AHFID program is subject to constraints. The AHFID system design was tailored to maximize the research opportunity within these constraints, nonetheless, there are several features of this program that are not optimal.

The AHFID pod is located at the bow of the HYSWAC to maximize the amount of minimally disturbed flow to the propulsor and collect minimally contaminated data. The intent is to provide the best possible environment for capturing physical test conditions and defining appropriate inputs to the prediction methods. This will facilitate comparisons between predicted and at-sea data. This location is significantly different than what might be expected on an actual surface combatant using RDPs for main propulsion. Such an installation would typically involve stern mounting with the RDPs ingesting a very different flow field. While expected to be minimal, the HYSWAC underwater hull configuration will affect the AHFID propulsor performance.

The main HYSWAC hull is approximately 4.5 feet above the waterline when operating at intended drafts. The RDP is intended for operation at a depth of submergence of about 13 feet to the centerline. This requires the “V-strut” configuration to provide needed strength and stiffness with minimum strut drag. Each leg of the “V” is far longer than what is commonly found on commercial liners. This adds significantly to the overall drag of the podded propulsion system.

Additionally, a typical surface combatant usually employs twin propulsors. A single RDP is being employed in the AHFID program to achieve a representative thrust coefficient for one of the twin AHFID pods on a notional surface combatant.

The design for the HYSWAC requires the AHFID propulsor to operate in concert with the main propulsion system. The HYSWAC is the modification of an existing vessel and will not be configured to minimize its noise. On-board noise producing equipment (propulsion plant, auxiliaries, etc.) is not optimal, and the hull form and appendages have not been modified or designed for a testing environment. Also, the HYSWAC electromagnetic characteristics have not been a factor in its design. As a result, the ability to measure any emissions of the RDP at-sea is impaired. As such, the HYSWAC is not the optimum platform to demonstrate all the attributes of the RDP; however, it does provide the most immediate and cost-effective path to demonstrate the RDP technology at-sea, thereby achieving the overarching goal of the AHFID program.

The AHFID program is tailoring the electric propulsion equipment design and layout to facilitate future opportunities. The enclosures housing the power generation equipment are configured to be able to remain on the HYSWAC to support other demonstration projects. In addition, the power generation equipment and motor controllers will be configured in a manner that allows their use in other locations and on other vessels should future testing require alternative sites or platforms.

The outer diameter of the RDP was limited to allow for installation and evaluation in the Navy’s LCC in Memphis, TN. The RDP is a hydrodynamically scaled version of a notional full-scale surface combatant pod, but many motor attributes do not scale linearly. Experience in similar propulsor test programs indicate that the measured efficiency of the AHFID propulsion pod will be less than a geometrically similar pod scaled up to 20 MW as a result of these non-linearities. Therefore, commercial best practices were used to determine the best motor design to fit within the hydrodynamically scaled pod.

The amount of funding, of course, is finite, precluding a great number of tests and analyses that might otherwise be performed to predict and verify the actual performance of the RDP. Budget constraints also impacted the program in other ways. The vessel, a former Navy surface effect ship, the electric generator, and the motor drive units were government-furnished equipment (GFE) to the program. The type of host vessel, the output frequency and voltage of the generator and the configuration of the motor drives would have undoubtedly been different had they been designed for the AHFID system. Thus the system had to be modified to account for and to adapt to these eccentricities.

HOST VESSEL INTEGRATION

Host Vessel

The host vessel for this demonstration is the HYSWAC. This is the U.S. Navy's surface effect ship SES-200 (IX-515) (Figure 1) converted to a small waterplane area configuration using Pacific Marine's patented lifting body technology under a separate program funded by ONR (Figure 2). The principal characteristics of HYSWAC are provided in Table 1.

Figure 1 SES-200 (IX-515)

Figure 2 HYSWAC

AHFID Modifications

A number of significant modifications to HYSWAC's structure and systems are required to accommodate the AHFID system. These include:

- ship-to-strut interface
- fuel system
- electrical system
- seawater system

Additionally, a support structure for the power generation system modules is required on the main deck. Figure 3 shows how the AHFID system will look when installed on HYSWAC.

Table 1 HYSWAC Principal Characteristics

Length	160 ft (48.8 m)
Beam	43 ft (13.1m)
Draft	18.5 ft (5.6m)
$\Delta_{\text{Full Load}}$	340 LT

Ship-Strut Interface

The RDP is attached to the hull by means of a bolted connection. Since the original structure of the SES-200 was not designed to support the weight of the RDP and the struts, nor carry the loads associated with the expected inertial and hydrodynamic forces associated with operating the RDP, it is necessary to add a significant amount of structure to HYSWAC to accommodate these requirements. The weight of the pod and the additional structure added to HYSWAC is balanced by the placement of the modules on the weather deck. The HYSWAC will be capable of operating at its design trim, with or without the AHFID system installed.

Fuel System

The fuel for the power generation system will be supplied from one of the main HYSWAC tanks, which will be isolated from the rest of fuel system. A small day tank located on the main deck will provide positive head to the gas turbine generator (GTG) fuel pump.

Electrical System

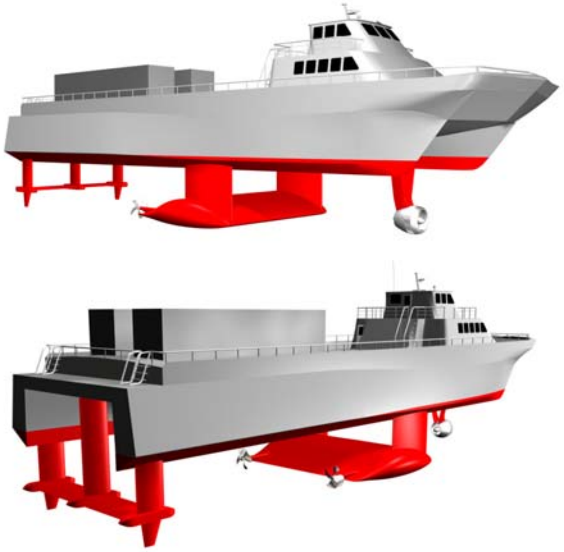
The electrical system for the power generation system requires a single 240-volt, 3-phase connection to provide the power required for the support systems and auxiliary equipment. This power is supplied by the installed generating capacity of HYSWAC.

Seawater System

Seawater is supplied to the power generation system by the installed firemain system on

HYSWAC; seawater return is piped to an overboard discharge.

Figure 3 HYSWAC with AHFID Installed



MODULAR POWER GENERATION/CONDITIONING SYSTEM

The purpose of the modular power generation/conditioning system is to provide the electrical power required to drive the RDP at the proper voltage, current, power factor, and frequency.

The initial design concept called for integration of the power generation/conditioning source within the main engineering spaces of the host vessel. This proved impractical due to the internal subdivision of the host vessel, so a decision was made to modularize the power generation/conditioning equipment and mount the system on the main deck of the host vessel. The use of standard shipping containers to house the equipment was investigated, but this also proved infeasible due to equipment width and stack lengths among other issues and consequently the use of custom-designed enclosures was pursued.

The arrangement of the power generation/conditioning system consists of three major subsystems:

- Power Generation
- Power Conditioning
- Bridge Control and Monitoring

Power Generation System

The power generation module consists of the gas turbine and a generator along with various subsystems with the main purpose of generating electrical power to operate the RDP. This module also possesses several ancillary systems to provide control and monitoring, fault detection/power interruption, and others (cooling water for both the generator and motor drive, and air conditioning/fire detection/suppression, etc.).

Gas Turbine Generator

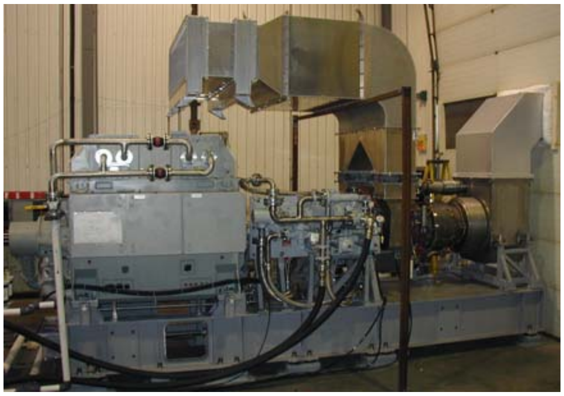
The GTG is an integrated unit with all major components mounted on a common base plate. The GTG is comprised of a gas turbine, a gearbox, and a generator, with associated ancillary equipment, as shown in Figure 4. The common base plate is resiliently mounted inside the power generation module.

The prime mover is a Vericor (formerly Allied Signal) TF-40 gas turbine (15,400 RPM), a marine adapted, two-shaft, direct-coupled design. The power turbine is capable of 3 MW output. The gas producer turbine drives the compressor and accessories mounted on the integral gas turbine gearbox. The unit is mounted and cantilevered to the generator gearbox. Modular design permits removal of most sections without disturbing power turbine alignment. Fuel is vessel-supplied diesel fuel and functions as the gas turbine lubricating oil cooling medium. The lubricating oil system is self-contained to the engine. Inlet ductwork will enter the top of the GTG module and will have moisture separating, foreign object exclusion, and silencing provisions. The exhaust ductwork will exit the top of the GTG module and will incorporate a silencer.

The gearbox is an epicyclic design and has an input speed of 15,400 RPM and an output speed of 7,000 RPM. A gear-driven lubricating oil pump is the primary pump for the generator and gearbox and is supplemented with a motor-driven pre-lubricating pump mounted elsewhere on the base plate. The gearbox output coupling is a diaphragm-type coupling.

The GFE generator is rated at 3 MW; however, only 2 MW are required for this application. The generator is three-phase delta connected with a 530 VAC, 350 Hz regulated output voltage. It is a six-pole wound field synchronous machine with a design speed of 7,000 RPM. Loads on the four, three-phase delta windings are transformers with three-phase rectified secondaries and are balanced three-phase loads. The generator power leads exit the top of the generator housing. Twelve current transformers are provided in the generator for current monitoring by the switchgear. The generator lubrication oil system is common with that of the reduction gear and the main sump is mounted within the base plate and the cooler is mounted on the base plate. The generator has two integral air coolers mounted above the stator.

Figure 4 Gas Turbine Generator Set



The electric plant monitoring and control system provides all monitoring and control functions required by the engine-mounted auxiliaries, separate auxiliaries, and the entire electric plant. The electric plant monitoring and control for the gas turbine generator and the electric plant is comprised of the electronic control unit (ECU), the local operating panel programmable logic controller, located within the power generation module, and the remote operating panel (ROP), located on the bridge.

Switchgear

The switchgear (switchboard) is a key component in the delivery of 530VAC, 350Hz electrical propulsion power from the four winding generator to the electrical propulsion motor drive input transformers. There are four electrically isolated, three phase, generator windings, each having 530VAC line to line terminal voltage at 350Hz. This power is supplied from each of the four generator windings through four electrically isolated sections of the switchboard to four motor drive transformer module primaries. The switchboard provides the means to protect, control, and monitor this electrical power distribution system. The switchboard is comprised of four electrically isolated vertical sections with a common ground bus between all four sections. Each vertical section is split into a top and bottom section. The top section houses the control and monitoring equipment and the bottom section houses the circuit breakers and power cable terminations. Terminations for power cable connections are provided in the rear bottom of each switchboard section.

Auxiliary Support Systems

The principal auxiliary support systems include fresh water cooling for the generator and for the motor drive electronics; seawater cooling to remove the heat from the fresh water cooling system; ventilation and air conditioning; electrical power distribution; lighting; and fire protection.

Power Conditioning System

The power conditioning system, housed in a separate module, consists of a motor drive cabinet that conditions the power developed by the power generation module prior to delivery to the RDP. This module also possesses several ancillary systems that provide grounding resistance, air conditioning, and cooling water.

Motor Drive

The motor drive is a 3-phase, 4-level, single-circuit motor drive utilizing modular input isolation transformers. The motor drive consists of four 475kVA input transformers, twelve 150kW power modules, three output filters, one motor drive cabinet, one transformer cabinet, one electric drive control electronics (EDCE), and one motor drive control station. The entire motor drive, with the exception of the control station, will be co-located in a single module. The motor drive is rated at 2,400HP at $3.3kV_{L-L}$ with a maximum output frequency of 120Hz. The motor drive is designed to produce high quality output voltage and current waveforms with an overall efficiency of greater than 97% (including input transformer losses). The motor control system is capable of seamlessly transitioning between control of either motor torque or motor RPM, and provides active limiting of motor speed, torque or power. High speed data logging of motor drive parameters is available at the EDCE, while lower bandwidth data logging is performed automatically at the propulsion control console (see below).

Bridge Control and Monitoring

Primary operation and monitoring of the AHFID equipment occurs on the bridge. Both the power generation and power conditioning systems have control and monitoring instrumentation located on the bridge. The power generation system is controlled and monitored via the ROP, also called the electric plant monitoring and control (EPM&C) station and the power conditioning system via the propulsion control console (PCC) which provides ultimate control of the RDP.

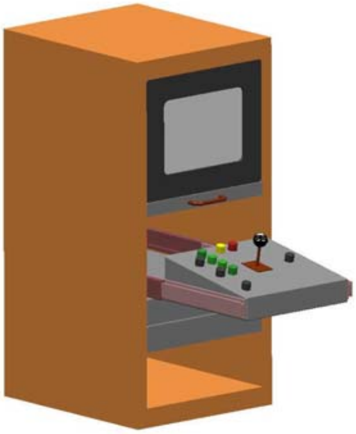
Electric Plant Monitoring and Control

The EPM&C station provides remote operator interface with the gas turbine, gearbox, generator, switchboard metering and relays, and electric plant auxiliaries.

Propulsion Control Console

The PCC provides control of the AHFID system, acting as a throttle for the output of the RDP. Figure 5 shows an illustration of the PCC. The PCC provides a graphical user interface (GUI) which provides both graphic and numerical displays of motor speed, torque, power, and current. The GUI also displays all mode and state changes, and warnings/faults in an event log that can be saved to document a particular test and to allow gross correlation of data logs to a series of events. The PCC provides a desktop control panel with pushbutton switches, illuminated indicators, a torque throttle, and an RPM adjustment potentiometer as the primary motor control interface.

Figure 5 Propulsion Control Console



STRUTS

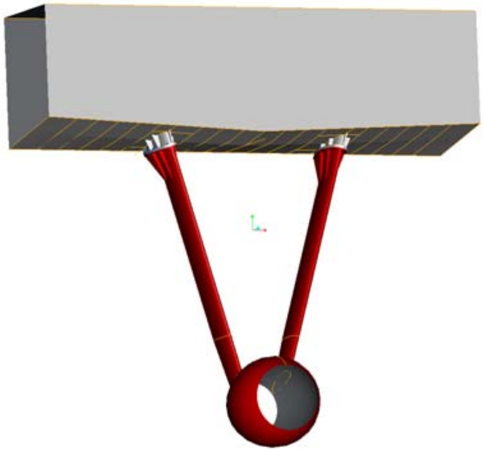
The strut system (Figure 6) is designed to meet four objectives. First, it transmits the thrust produced by the RDP to the HYSWAC. Secondly, it houses both the power cables and the instrumentation wiring for the RDP. Thirdly, it provides a medium by which the strain response to the propulsor thrust can be measured. Finally, it provides a conduction path to electrically bond the RDP motor to the motor drive unit.

The struts are a design compromise to minimize the wetted area of the struts, yet provide the required strength and stiffness. The struts have a NACA 0020 cross section with a 34-inch chord. The resulting high aspect ratio necessitates the use of high strength steel to withstand both the thrust force when the RDP is operating and the drag force when the RDP is not operating and the vessel is operating at high speed. Computational fluid dynamic analyses were conducted to define the hydrodynamic contour of the strut transition to the RDP aft duct.

The RDP after duct is made of nickel-aluminum-bronze. The HYSWAC hull is made of aluminum. To avoid bi-metallic welding of these two critical joints, the struts are designed with bolted connections both at the pod and at the ship interface. Significant structural reinforcement is necessary inside the hull to accommodate the large stresses and moments anticipated at the ship-strut interface. To facilitate the connection at the ship, the struts are knuckled inward (not shown in figure) near the interface to provide a mating surface parallel to the vessel's baseline.

The side plate of the struts will be thermally or mechanically formed to the NACA contour and will contain internal web plates for stiffness and to retain the geometry. The leading and trailing edges will be machined from bar stock. The inner void of the struts will remain dry.

Figure 6 Strut Assembly

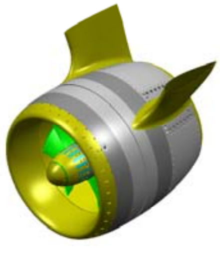


The thrust measurement system is comprised of several fiber-optic Bragg grating point sensors distributed at optimum locations over the strut assembly. A strain calibration matrix can be developed that can resolve the resultant forces and moments into their individual contributions. From this, the thrust vector can be extracted. To validate this methodology, the finite element model of the strut, with strain sensors in appropriate locations, is placed under various anticipated load conditions. The thrust load was then obtained from the strain response of the model and preliminary results indicate agreement within seven percent of the applied thrust load. Further validation of the methodology will occur by instrumenting and applying known forces to the small-scale strut and pod used for hydrodynamic testing of the propulsor. Once the strut system is installed on the ship, the thrust measurement system will be calibrated by placing known forces on the struts while the vessel is in drydock.

RIM-DRIVEN PROPULSOR POD

The RDP is a ducted propulsor with the propulsive motor stator integral with the duct as shown in Figure 7. The motor stator is protected from the environment by the duct and through a composite can. The motor stator features copper windings and laminated steel plates that transmit torque to the motor rotor through a rotating electromagnetic field. The motor rotor, which houses magnets and laminated steel plates, is structurally attached to the rim of the propulsor rotor. The propulsor rotor spins freely about a fixed shaft and generates (80%) the RDP thrust. The shaft is stationary, serving as a positioning device and to transmit thrust through a thrust plate and fixed shaft to the hydrodynamic/structural propulsor stator. The propulsor stator serves as the structural connection between the propulsor rotor, the shaft, and the RDP hydrodynamically shaped duct. The propulsor stator blades also remove the swirl induced by the propulsor rotor blade rotation. The resultant torque on the stator blades is approximately 95% of the propulsor rotor torque, acting in an opposite direction.

Figure 7 Rim-Driven Propulsor Pod



The demonstration unit is capable of operating at a maximum continuous rating of 1948 horsepower at a rotor speed of 307 revolutions per minute (RPM), and 24.6 knots. At this operating condition, the unit develops 33,350 ft-lbs of torque and 17,049 lbs of thrust. As previously discussed, the RDP will be utilized as a thruster and will be operated in coordination with the primary propulsion system. The unit will be attached in a fixed position at the bow of the vessel and be operated nominally at a 10-foot immersion (i.e., the top of the duct exterior is 10 feet below the surface of the water), dependent upon sea state.

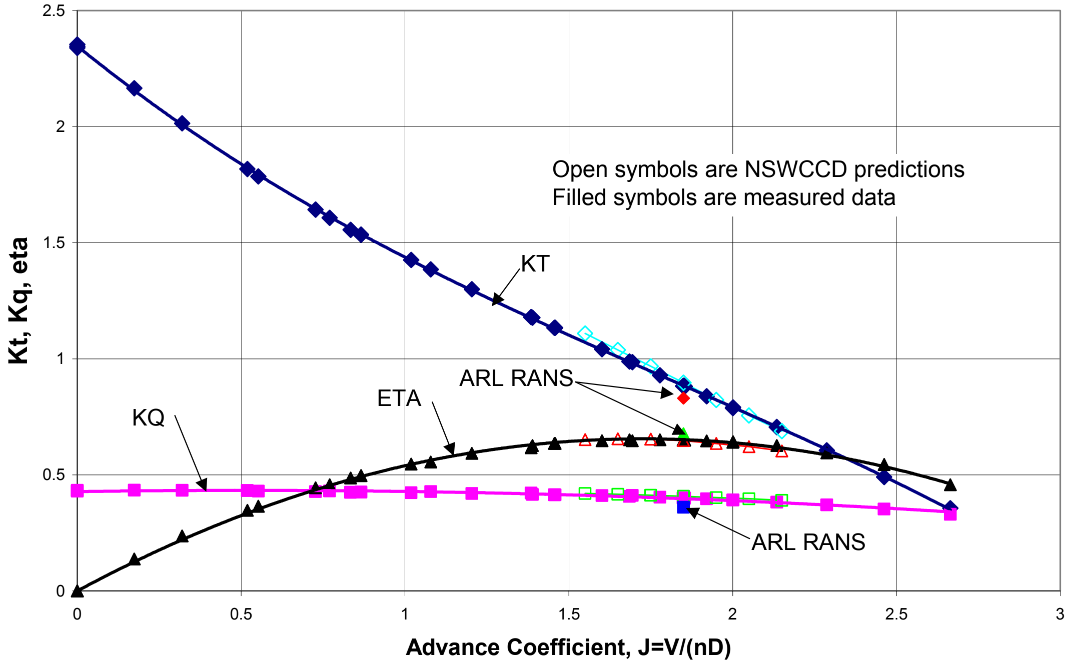
Hydrodynamic Design

The primary hydrodynamic design objective was to achieve an overall efficiency (including motor and bearings) greater than 63 percent while precluding damaging cavitation. As with all designs, constraints (e.g., funding, size, operability, etc.) are invoked to ensure that the end product is suitable for the given application. In the case of the AHFID RDP, the following constraints were invoked:

- The outer diameter was limited to approximately 72 inches to ensure that the unit could be tested in the future in the Navy's Large Cavitation Channel.
- The overall hydrodynamic arrangement was non-optimized to support integration of the motor stator. The AHFID motor stator was uncharacteristically thick due to the electric drive power generation/conditioning system and the means by which the motor would be manufactured.
- The RDP would be non-azimuthing.
- The RDP design point was for ship speeds above 25 knots to ensure conditions were adequate to investigate certain features of the unit.

The lead hydrodynamic design organization (The Applied Research Laboratory Pennsylvania State University (ARL/PSU)) utilized commercial two-dimensional and three-dimensional design and analysis tools to develop the RDP hydrodynamic geometry. Specific attention was paid to ensure that the appropriate mass flow was attained, losses were minimized in the rotor rim to motor stator gap region and that the blades were not overloaded. Once an acceptable hydrodynamic geometry was developed and it was determined that the motor could be arranged to fit within the geometry, the design was frozen for final predictions to be conducted and small, model-scale, test hardware was manufactured. Upon completion of model manufacture and after disclosure of performance predictions, the unit was tested for open water performance in the NSWCCD David Taylor Model Basin tow tank facility.

Figure 8 Results of Scale Model Tow Tank Testing



Small Model Scale Testing

The first series of tests were conducted in uniform flow for the full AHFID configuration including the RDP and the V strut. The RDP was submerged to a depth consistent with that expected, when the demonstration scale is mounted to the HYSWAC. Rotor, stator duct and strut forces and moments on the model were measured at various advance coefficients (J). An advanced coefficient of zero results from maximum torque at the bollard condition, when the carriage speed through the water is zero, to rotor locked conditions at zero RPM. This series of first quadrant data was measured both at zero degrees pitch and yaw and again at a pitch angle of 6.5 degrees, propulsor nose up.

The subsequent series of tests included conducting Reynolds number sensitivity tests to determine effects on the various propulsor coefficients by varying carriage speed and shaft speeds while maintaining the design advance coefficient of 1.85. This was followed by a flow visualization evaluation where paint was applied to the outside of the RDP duct and struts as well as the duct interior and blade surfaces. Different colors of paint were used on each surface to assist in distinguishing the contributions from each. The testing concluded by measuring the drag produced by the strut assembly alone without the rotor, duct or stator present. The RDP, including the strut transition piece, was replaced by a hydrodynamically shaped piece of a short length, including end caps. Carriage speeds corresponding to the Froude-scaled RDP open water speeds were measured.

The results of the testing are shown in Figure 8. The RDP exhibited a relatively flat efficiency curve as is characteristic of ducted propulsors. At the design J of 1.85, the hydrodynamic open water efficiency (without struts) was found to be about 65 percent at model scale. This is expected to increase to at least 66 percent at the demonstration size due to reduced skin friction at higher Reynolds number.

According to the data, the measured thrust and torque values are higher than the original design values. The design motor torque limit is reached before the power limit. Two conclusions may be drawn from these results. From a ship design perspective, the design thrust can be obtained at a lower RPM and a higher efficiency than predicted. From a hydrodynamic analyst's perspective, however, the design codes did not accurately predict the measured torque and thrust values of the small-scale RDP.

From the tow tank results, the expected performance of the demonstration-scale RDP can be calculated. By maintaining the design advance coefficient, the expected motor torque limit will be achieved at 307 RPM and 24.6 knots achieving 109 percent of the design thrust. The struts are expected to contribute approximately 6 percent of drag. The RDP is predicted to provide (excluding the strut drag) a maximum of 16,800 lbf net thrust at 306 RPM - which is the design motor torque limit - at 24.5 knots with an open water efficiency of 66 percent.

Motor Design/Manufacture

The motor was designed in conjunction with the hydrodynamic design of the RDP since the motor is an integral portion of the pod. Development of the motor design required several iterations of both electrical and mechanical conceptual evaluations to obtain a motor design that would fit into the hydrodynamic shape of the RDP. The final motor electromagnetic design allows for the use of non-metallic stator and rotor canning. The overall electrical characteristics of the design are provided in Table 2.

Table 2 Motor Electrical Characteristics

Efficiency	97.7%
Frequency (Hz)	97.5
Voltage (VAC)	3300
Phases	3
Poles	36

The motor is comprised of two major parts: the stator and the rotor. The stator assembly contains the wound electrical core inside a hydrodynamically contoured frame. The wound electrical core is made up of pressed laminations of electrical steel and copper windings. The contoured frame has been shaped in accordance with the hydrodynamic design of the RDP and is bolted in a cantilever fashion to the main structure of the RDP. The wound electrical core is sealed from the seawater environment by the stator frame and the non-metallic stator can. The stator can is comprised of various layers of fiberglass and filler material that creates a durable watertight barrier against the sea. The weight of the complete stator assembly is approximately 9,780 lbs.

The motor rotor assembly consists of 36 pressed laminations of electrical steel pieces fastened to the rotor hub. Between the pole pieces are 36 rows of neodymium iron boron magnets, which are permanently magnetized. The magnets are held in place by a wedge that fits into grooves on either side of the pole piece. The rotor hub is a nickel aluminum bronze cylinder. The finished rotor assembly is attached to the rim of the propulsor. The motor rotor assembly (Electric Boat patent pending) weighs approximately 2,025 lbs.

Performance Predictions

The motor performance predictions are derived primarily from electrical and electromagnetic evaluations performed as part of the motor design process. A combination of proprietary fast running motor design computer programs, two and three dimensional commercially available electromagnetic finite element analysis (EMFEA) computer programs, coupled with Electric Boat proprietary post processors, and hand calculations where needed to cross-check output from computer programs for electrical design of the motor. The primary motor electrical design tool used for fast iterative evaluation of motor topologies is PMCAD. This program was developed for design of permanent magnet motors and is based on classical equations, but modified to incorporate nuances associated with permanent magnet motors of the embedded magnet type and test data from these types of motor designs. Two and three-dimensional versions of commercially available software (MAGSOFT), in combination with Electric Boat developed EMFEA post processors, were used as the primary EMFEA tools. With the combination of design analysis tools and post processors, past permanent magnet design predictions of electromagnetic performance have typically been within 1-2 percent of actual measured values.

Bearings

The RDP possesses seawater lubricated radial and thrust bearings to transmit loads from the propulsor rotor to the stationary support structure. The radial bearings are capable of supporting the propulsor rotor's weight as well as the additional hydrodynamic vertical or side loads, while allowing the rotor to rotate freely with low friction and wear. The thrust bearings are capable of transmitting forward and aft propulsive thrust or drag forces from the propulsor rotor to the stationary support structure. The thrust bearings also allow the rotor to rotate freely with low friction and wear.

Table 3 Anticipated Operating Profile

Rotor Speed (RPM)	Duration (hrs)	Maximum Forward Thrust (lbs)	Maximum Aft Thrust (lbs)
77	1,110	1,170	550
128	3,530	3,140	1,490
172	2,030	5,710	2,740
220	880	9,310	4,380
259	330	12,980	6,180
293	120	16,500	7,820

The projected operating profile for the RDP is based on an 8000 hour operating life. The distribution of these hours versus speed is given in Table 3 along with the corresponding maximum thrust load at each speed.

The radial bearing design consists of two 10-inch long bearings located within the propulsor rotor hub bore. The two bearings were spaced as far apart as possible within the constraints of the design to aid in rotor stability. The bearings rotate with the propulsor rotor hub on a stationary stub shaft. This is reversed from typical propulsor or strut bearing designs where a shaft rotates within a stationary bearing. The stub shaft is cantilevered from its support points in the aft pod structure. Each 10-inch bearing length provides a length to diameter (L/D) ratio slightly above 1.0. The radial bearing material is Thordon SXL, which is molded into two full 360-degree cylinders, each 10 inches in length. The bearing design is similar to a partial arc bearing in that a smooth shaft surface bears against an uninterrupted non-metallic bearing surface. Partial arc bearing designs can be found in many commercial stern tubes and strut bearings. The entire area of the bearing wear surface will be smooth (no axial or circumferential grooves) to provide an uninterrupted surface upon which a hydrodynamic wedge can be developed and sustained. Seawater will be used to cool the bearing and flush debris out of the bearing to shaft annulus. Cooling water is designed to flow from the high pressure side of the propulsor rotor through the aft thrust bearing, forward through the radial bearings, and exit through the forward thrust bearing into the low pressure side of the propulsor rotor. Axial grooves (channels) will be machined into the port and starboard sides of the shaft to allow a location for debris to be flushed out.

Forward Thrust Bearing

The propulsor rotor hub transmits forward propulsive thrust to the pod structure via the forward thrust bearing. The thrust bearing design consists of a set of non-metallic segmented thrust pads. These pads are rigidly attached to a base ring that is then attached to and rotates with the propulsor rotor hub. A corrosion and wear resistant metal thrust plate is connected to the stationary shaft. The forward thrust bearing's segmented thrust pads rotate and bear against the stationary thrust plate. Water that has circulated through the radial bearings exits the pod through the spaces between the rotating pads in the forward thrust bearing. The bearing operates on self-forming hydrodynamic pockets of seawater between the thrust plate and each thrust bearing pad. The maximum steady state thrust load produces an average bearing pressure of approximately 210 psi.

Aft Thrust Bearing

The aft thrust bearing is similar in design to the forward thrust bearing and transmits propulsive thrust (or drag from an unpowered rotor) in the astern direction from the propulsor rotor hub to the pod structure. The aft thrust bearing is identical to and is completely interchangeable with the forward thrust bearing. The aft thrust bearing is stationary and is fixed to the pod structure. It bears against a thrust runner that is attached to and rotates with the propeller rotor hub. The aft thrust bearing is primarily designed to handle transients in loading of the propulsor rotor and to handle drag forces from an unpowered rotor, either secured or windmilling. The aft thrust bearing is sized to transmit a maximum load that produces an average bearing pressure of approximately 105 psi (approximately 50 percent of the ahead thrust).

Structural Design

The structural design was based on conventional commercial practices to ensure that a robust unit would be developed with minimal redesign. Materials were selected based on corrosion resistance to the seawater environment, strength and manufacturability. Nickel –aluminum bronze is employed in the blade rows and aft duct. Various grades of steel are specified in duct and strut components that provide increased strength, but require a protective paint coating. The shaft is fabricated from monel. All fasteners are specified as corrosion resistant.

Upon completion of the hydrodynamic and overall subsystem arrangements, engineering best practices were utilized and sensitivity studies performed to determine locations based on propulsor stator arrangement. Once the structures were finalized, the design was frozen and it was agreed that restrictions on the ship would be invoked to limit loading on the pod to a specified safety factor.

TESTING

Small Scale Testing

Tow tank testing of a scale model of the AHFID RDP was conducted at NSWCCD as described above.

Integrated Testing

Integrated no-load testing of the motor and motor drive unit will occur at the Electric Boat

Quonset Point, RI facility. Prior to this testing, the motor drive will be tested through closed loop motor control to a load bank. This will validate the motor drive harmonic performance and thermal performance. Following this testing, the RDP will be installed in a floor mounted test fixture and the motor drive will be operated in closed loop control at no load. The motor drive software and hardware, the bridge control hardware and software, and the RDP hardware will all be integrated. This will provide an opportunity to verify the proper operation of the EDCE algorithm, the RDP encoder, the EDCE, and generally ensure the motor and motor drive are communicating appropriately. This will also provide the opportunity to validate the motor design data.

Additional testing at this stage is desirable to ensure proper operation of the motor and motor drive unit prior to complete system testing dockside and at sea. However, other similar motor and motor drive testing has provided sufficient experience to allow the motor and motor drive to be shipped to Hawaii for installation and subsequent sea trials with minimal land-based integrated testing.

Modeling the electrical system and its associated controls is an integral part of the testing. Past experience indicates that validation of these models are key to the successful implementation of the propulsion system aboard HYSWAC. A one-line diagram model of the components being tested is being developed. The control system is simulated using MATLAB and the electrical networks are modeled using SABER. The two models were combined and the plant model compensated for the control system model. The control system was then implemented into the system software followed by integration of the software and hardware. This approach allows the hardware and software to be qualified in a simulation/stimulation environment before final validation in the delivered configuration.

Sea Trials

No model testing of the HYSWAC will occur prior to sea trials. The HYSWAC will have an active advanced ride control system that will mitigate the effects of the roll and pitch in a seaway. The operating characteristics of the vessel with the underhull foils, including the effective horsepower curve and maneuvering characteristics, have been estimated based on an amalgamation of experience with similar vessels and the SES-200B itself. The AHFID RDP and strut designs were based on these estimates and assumptions were made based on expected HYSWAC performance. The AHFID system design was completed prior to the HYSWAC design, therefore the design philosophy for the AHFID system was predicated on constraining the HYSWAC vessel to these assumptions. HYSWAC sea trials, which are scheduled to occur prior to AHFID sea trials, will include sufficient information to develop a safe operating envelope (SOE) from the RDP ALE for the vessel and to provide a check of the thrust measurement system of the main propulsion system before AHFID and the supporting equipment is installed. This testing will include maneuvering and seakeeping (roll, pitch) in a variety of sea and wind conditions. Once the AHFID system is installed, the HYSWAC will only operate within the limits of the SOE.

The fundamental parameters to be measured at sea are availability and efficiency. The measurement of the availability of the AHFID system will be qualitative in nature. The system is both operational and available for demonstration when called upon or it is not. A reliability database will be built as the operational time proceeds.

The measurement of propulsor system efficiency will begin with a bollard pull with the RDP operated through a set of shaft speeds. A towing dynamometer will be inserted on a cable between the vessel and the bollard to validate the readings from the calibrated strut thrust measurement system through a range of expected axial loads. The bollard testing will not provide any information regarding the potential coupling of loads that would be expected from side loads at sea.

At-sea, a series of measurements will be conducted with the RDP operating at the design advance coefficient. The combination of RPM of the propulsor and speed of the vessel will be varied up to the maximum motor torque limit. The AHFID RDP will be brought to the test RPM, then the HYSWAC's main propulsion system will bring the ship to the test speed. Measurements of the forces on the struts will be taken and the thrust of the propulsor will be computed from these measurements for the efficiency calculations. The vessel will be performing an extended racetrack maneuver to provide long straight runs from which to average the force values and provide a more accurate measurement of thrust and efficiency. The long straight test runs will also provide an opportunity to evaluate the thermal stability of the motor and motor drive. Off-design measurements will be obtained as will reverse RPM tests to more fully characterize the RDP performance and determine the deceleration that can be expected from AHFID-like units.

There are a number of differences between the model scale and demonstration scale units that may impact the propulsor's performance at-sea. These include manufacturing tolerances, minor changes in the strut geometry, a non-uniform gap around the demonstration-scale propulsor rim, and a relatively shorter propulsor rim length on the demonstration-scale RDP. This shorter rim length is expected to decrease the rim drag and torque, thereby increasing the efficiency at the design point. There is also a significant bio-fouling concern when operating in the warm Hawaiian waters.

Most scale model testing is done with models that are geometrically similar to their full-scale counterparts with a constant scale factor. Model tests are also generally conducted at the same Froude number as the full scale trials. This allows prediction of full-scale hydrodynamic results through scaling by the Reynolds number. The predictions of demonstration-scale AHFID RDP performance from the scale model (1:4.375) testing will be obtained in this manner. As described previously, however, scaling to full scale becomes more complex because the thickness-to-chord ratio of the demonstration-scale is substantially larger than what is necessary for an 18 MW, 16-foot diameter propulsor. Due to this non-geometrically similar relationship, the effects of the propulsor duct will not scale directly with Reynolds number and the full-scale predictions require other data sources.

CONCLUSION

The results of the small-scale tow tank testing of the AHFID RDP indicate that the improved efficiency goals of rim-driven podded propulsors can be achieved. General Dynamics has also conducted tow tank testing of configurations similar to the AHFID RDP, but they were geometrically scaled from an 18MW design (i.e., the duct that houses the motor stator is thinner than the AHFID RDP when reduced to small scale). The results of these tests provide credibility to predictions of achieving greater than 70 percent efficiency from full-scale rim-driven podded propulsors. The AHFID program will demonstrate that such propulsors can be designed and manufactured to achieve these efficiency goals without sacrificing reliability. The AHFID program provides the advanced propulsion system hardware that will become the foundation for future developments in podded propulsion for the U.S. Navy. It has been designed to allow for a complete characterization of permanent magnet, rim-driven propulsor powering noise and electromagnetic performance. It will test the RDP performance in the demanding environment of the sea and will be available for subsequent testing in other controlled environments.

The Navy is beginning to embrace electric propulsion and recognize the advantages that it provides. The AHFID program is a near-term opportunity for the Navy to mitigate the development risk associated with the next advancement in naval propulsion, podded propulsors.

ACKNOWLEDGEMENTS

The authors recognize the success of this program is dependent on the efforts of many talented people at the contributing organizations. Regrettably we cannot acknowledge all of them individually. We would like to acknowledge the following individuals for their exceptional support: Gary Jebsen and Paul Rispin of the Office of Naval Research, Dan Sheridan of DJS Associates, Scott Forney, Don Thompson, Rick Kaye, Dan Kane, Spyro Pappas, Al Franco, Charles Knight, Jack Chapman, Jen Panosky and Piet Van Dine of Electric Boat, Jim Baskerville, David Forrest and Michelle Comtois of Bath Iron Works, Steven Loui and Gary Shimozono of Pacific Marine, John Koskie of the University of Maine, Ed Robinson and Jon Eaton of the Pennsylvania State University, and Michael Todd of the Naval Research Laboratory, Stuart Jessop, Jerry Sikora, Ken Remmers of the Naval Surface Warfare Center Carderock Division.

REFERENCE

Anderson, K.J. et al, February 2002. Advanced Hull Form Inshore Demonstrator Model Strut and Propulsor Performance in Uniform Flow. NSWCCD Technical Report No. NSWCCD-50-TR-2002/012