The Quest for Speed at Sea

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This paper highlights the past, present, and future of the quest for speed at sea. It outlines the development of technologies and concepts to increase the speed of naval vehicles. Although commercial applications of high-speed marine craft flourish, the focus here is on high speed in naval missions.

A historical context details significant attempts to increase ship speed, highlighting Carderock Division's many contributions. The primary focus is after World War II, when the U.S. Navy began to seriously consider the value of proposed concepts for planing craft, multihulls, hydrofoils, hovercraft, and hybrids.

A discussion of current high-speed ship technologies follows, with an overview of limits and advantages, plus a review of operational experience. Costs of development, acquisition, and operations are weighed, followed by a summary of high-speed naval vehicles' potential.

Introduction

For more than two hundred years, numerous efforts strove to increase the speed of waterborne craft for both military and commercial applications. Increased speed of naval vehicles was called for in the vision of the Navy's future set forth by the Chief of Naval Operations (CNO), Admiral Vern Clark, in "Sea Power 21." In a recent conference on "Sea Power 21," the CNO addressed the quality of "persistence." In that particular context, he was referring to "persistence of combat capability," but he could have used the term just as appropriately to refer to the "persistence of technological effort" described in this paper. Persistence in the quest for speed has involved hundreds if not thousands of scientists and engineers over many decades dedicated to developing new ship and vehicle technology to give the Navy credible high-speed options.

In the following sections, we highlight various approaches to the quest for speed at sea and identify individuals who made advances toward this goal possible. We need to understand the past to baseline our knowledge. A discussion of technological limitations and advancements, operational experience, and cost effectiveness of speed follows.

Numerous concepts employed in this quest appear in a timeline at the bottom of each page, divided in 20-year periods. They include planing craft, multihulls, hydrofoil ships and craft, hovercraft, and hybrids. Most of the efforts to increase speed involve getting the hull out of the water. Figure 1, the so-called Sustension Triangle, shows the lift forces raising the hulls above, or partially above, the water surface.

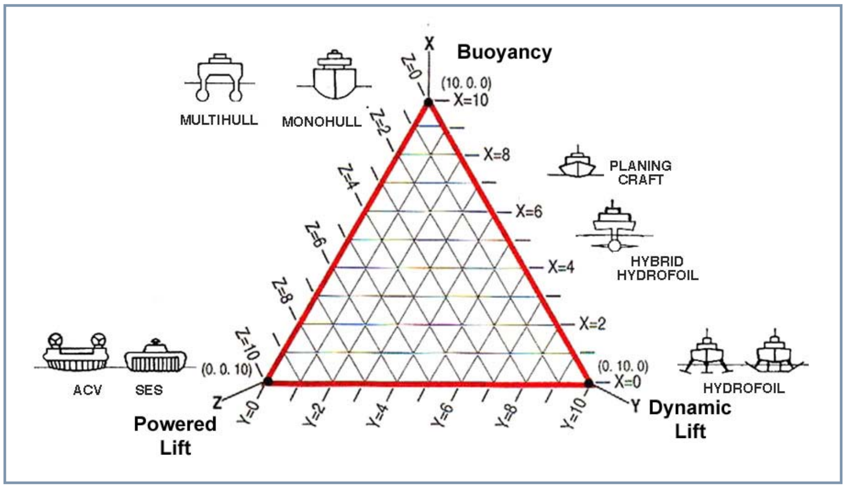


Figure 1. Sustention Triangle.

How High-Speed Ships and Craft Advanced

Here we discuss significant craft and concepts that advanced the quest for speed at sea over decades up to the present. We also identify key individuals who contributed to these advances.

Planing Craft Development

The planing hullform is perhaps the oldest, simplest, and most extensively employed member of the family of modern marine vehicles. As noted by Dr. Daniel Savitsky,[1] modern planing hulls are designed to avoid the so-called "hump" problems, demonstrate good behavior in a seaway, have substantial useful load fractions, and have a potential for growth to displacements up to 1,000 tons or more. These attributes establish planing hulls as effective members of naval units. In the period 1970 to 1983, 327 fast attack units and 1,471 patrol craft were constructed and exported worldwide. Their excellent cost-effectiveness ratio, simplicity of operation, miniaturized electronics, and relatively heavy firepower attract the attention of many navies, particularly those operating in restricted waters. The modern planing hull now has better seakeeping characteristics with little sacrifice in calm water performance.

In the mid-1970s, the U.S. Navy undertook an advanced planing hull research program aimed at improving seakeeping while retaining as much speed as possible and improving the lift-to-drag ratio of the hull through the mid-speed range. This research led to the development of the high length-to-beam ratio, high beam loading, double chine, and moderate dead rise hull that met all of the requirements of good seakeeping and good lifting efficiency. This prototype hull, in a development led by Jerry Gore at Carderock, was designated the Costal Patrol Interdiction Craft (CPIC-X). It became the U.S. benchmark design that met the conflicting demands for the best compromise of high speed and sea kindliness in one hullform with minimum cost and complexity.

Unfortunately, the aggressive and successful planing hull research program initiated in the early 1970s subsided in the late 1970s, when the U.S. Navy decided to emphasize acquisition of large combatants capable of transiting the world's oceans. With this philosophy, problems can arise when we need to engage in limited warfare in areas where the larger ships cannot operate close to shore, or in the inner harbors or rivers.

Since 1990, Donald L. Blount and Associates, Inc. (DLBA) has specialized in the design, testing, and construction of motor yachts, commercial ferries, and military vessels. Blount began his career in the Carderock Planing Craft Branch. In 1992, the motor yacht *Destriero*, designed by DBLA, captured the international speed record during an unrefueled passage from New York to England. This 67-m vessel, which averaged a speed of 53.1 knots in the crossing, is powered by two LM-1500 gas turbines, and is capable of a speed of 65 knots.

With the current new interest in the U.S. Navy's Littoral Combat Ship (LCS) program, the advanced state of planing ship technology represented by *Destriero* is of interest as a candidate design for LCS. Don Blount is currently a member of the Lockheed Martin LCS Team that selected the Sea Blade ship concept that builds on the hydrodynamic lineage of the *Destriero.*

Multihull Ships

The principal advantages of most multihulls are their greater deck area for a given length, excellent transverse stability, and potential for reduced wave-making resistance in the high-speed range for displacement ships. These attributes make the catamaran well suited to carrying low-density cargo, for example as ferries. However, catamaran hulls are prone to pitching, and the cross structure can be subject to large wave impact forces in rough seas.

The concept of a multihull buoyantly supported vessel was demonstrated at least a thousand years ago by Polynesian seafarers. The first known catamaran in the Western world was a sailboat built in England in 1660. Beginning in the early 1800s, a sizeable number of steam paddle wheel-powered catamaran ferryboats and river craft were built there and in the U.S.[2]

Efforts to solve the seakeeping and ride comfort problems led, in the 1960s, to the small-waterplane-area twin-hull (SWATH) ship configuration. Although the SWATH ship is an important development with a number of desirable features, it is not currently considered a high-speed concept and is not covered in this paper.

Catamarans

During the past decade, the catamaran concept has been employed mainly for commercial passenger transport. Since 1980, over 200 small high-speed catamaran ferries were built, mainly in Australia, Norway, and Sweden.

The seakeeping of the catamaran is mixed. The high transverse stability gives rise to pitch and roll at natural frequencies that are near each other. These frequencies, in turn, yield motions that feel more coupled than do those of the monohull. This effect has been described as a corkscrew

motion, involving combined roll, pitch, and yaw. In the design process, knowledge of wave statistics for the actual operating area is vital. Model seakeeping testing in a facility that can generate a reliable representation of wave environment is also important for developing a successful design.

Because of their effect on the resulting accelerations on board a vehicle in a given seaway, the vessel's natural periods of pitch, heave, and roll are vital design parameters to consider. If any of the vessel's natural periods are close to the wave encounter periods expected, the synchronism can lead to amplified motion responses.

A design feature that demands thorough evaluation is the shape and position above the still water level of the increasingly commonly used cross-structure center hull. In addition to affecting vertical motions and accelerations, this geometric feature, if designed carefully, can improve resistance performance in waves.

Semi-SWATH

A semi-Small-Waterplane-Area Twin Hull (SWATH) ship is a combination of a SWATH ship in the forward half and a conventional catamaran in the stern half. The combination results in vehicles with nearly equal seakeeping to a regular SWATH ship, but with superior speed/powering performance. The semi-SWATH ship concept also allows the integration of waterjet propulsion, by far the preferred choice for high-speed ferries. The catamaran-like aft sections are more suitable for machinery arrangement and especially for integrating waterjet propulsion. Like SWATH ships, semi-SWATH ships offer a great deal of arrangeable deck space and exhibit low resistance up to fairly high speeds (40+ knots).[3]

The first and largest semi-SWATH ship in operation is the *Stena* HSS 1500 with a displacement of about 4,000 tons. Other Semi-SWATH passenger vessels are *Stena* HSS 900, and *Seajet* 250. Although not quite as sensitive as SWATH ships, semi-SWATH ships are still somewhat sensitive to overloading and trim. The small waterplane of the forward section makes them more susceptible, in particular, to changes in forward trim.

In 1966, Carderock Division began a multi-year program of catamaran hydrodynamic and structural technology development to support the design of the ASR 21-class of submarine rescue ships. By 1969, this development led to further in-house investigations of larger catamarans as air-capable ships or small aircraft carriers.

Wave-Piercing Catamarans

The increasing need for high-speed marine transport, coupled with the fact that passengers often experience discomfort in open ocean or exposed routes on conventional catamarans, created a need that the wave-piercer was developed to fill. Again, this hullform has twin hulls, but they are long and slender with minimal freeboard and little buoyancy in the bow section. This configuration allows the bows to cut or pierce the waves, reducing the tendency of the vehicle to contour, thus providing lower pitch motions and accelerations, while carrying similar deadweight.[3]

The wave-piercing catamaran started in the early 1980s, with the development INCAT 28 m being the first to operate on a commercial route. Several companies have since developed their own approach to this type of design. One of the more famous wave-piercers is CONDOR II INCAT 78 m.

CONDOR II reduces heave and pitch motions and accelerations while in bow seas. Due to the twin hulls and the separation between them, the vehicle has good inherent intact and damage stability. Large useable deck area results from separation of hulls that are still large enough aft to allow integration of waterjet propulsion and suitability for machinery arrangements.

Due to the slenderness ratio of the hulls, these vehicles are fairly efficient, and numerous operating vehicles provide good statistics regarding operational characteristics. Construction is more difficult than conventional catamarans due to structural complexity of the forward hulls. The wide beam of wave-piercer catamarans is also an issue where ports are not designed to harbor such vehicles. Wave-piercer catamarans may also experience lateral jerky motions in beam seas.

Trimarans

A trimaran is a multihulled vehicle with three hulls supported by hydrostatic and hydrodynamic lift. There are two approaches to making a trimaran. The first approach is to have a very slender center hull supported by two outboard hulls that are smaller in both beam and length. The second approach is to have longer outboard hulls and a shorter center hull forward.[3]

While trimarans have existed for centuries, only recently has interest arisen in pursuing them as viable options for ferry and military applications. The appearance in 1988 of the *Ilan Voyager* aroused interest in this concept. As of late, various defense departments investigated the use of a displacement trimaran hull form for frigates and corvette-size warships, the latest of which is the Royal Navy *Triton* demonstration trimaran. This ship has an overall length of

105 m, a beam overall of 20 m, and a displacement of about 1,200 metric tons.

The attributes of trimaran hullforms include good hydrodynamic efficiency, allowing higher speed with lower installed power, adequate intact and damage stability characteristics, large usable deck area, good seakeeping qualities, and good directional stability. However, they are structurally complex due to cross structures connecting the outer hulls, and the lack of design experience entails some risk. Also, the maneuvering characteristics of these hullforms are relatively poor, unless the outer hulls are large enough to accommodate individual propulsion units.

During the late 1980s, the U.S. Navy performed a series of model tests at Carderock to investigate a variant of the O'Neill Hullform that exploited the wave cancellation between the center body, the center surface-piercing strut, and the two outer hulls. Reference 4 discusses this hull form and points out that significant reductions in net total wavemaking resistance can be achieved at cruising speeds above 24 knots. The resulting powering advantage of the Wave Cancellation Multihull can be substantial. For example, for a 4,300-ton ship at a speed of 30 knots, the savings in effective horsepower (EHP) is between 22 and 28 percent compared to the O'Neill Hullform and SWATH VII configurations. Reference 4 also shows data comparing several monohulls and the Wave Cancellation Multihull concept.

Hydrofoil Ships and Craft

One of the earliest efforts to lift the hull from the water was by use of underwater wing-like lifting surfaces called hydrofoils. These foils, like aircraft wings, follow the Bernoulli principle. Air and water flowing over the curved upper surface must move faster than that flowing beneath. This change in the flow pattern results in low pressure on the top surface and high pressure on the bottom surface. At a given speed, the forces generated lift the hull out of the water.

The Early Years

The first hydrofoil craft was the product of an accident in 1861. Thomas William Moy, an Englishman, studied the aerodynamics of wings by observing the vortices they created. He attached wings to his craft and tested it in the Surrey Canal. To his surprise it rose from the water and, unintentionally, he discovered hydrofoils.

In 1909, CAPT Holden C. Richardson USN (Ret), then a young Naval Constructor and an early seaplane designer, sought a solution to landing aircraft on the sea. Inspired by Enrico Forlanini in Italy, who proposed using hydrofoils as landing gear for seaplanes, he fitted a set of submerged foils to a dinghy. While under tow in the Philadelphia river, it lifted from the water and "flew" at a speed of about 6 knots. Richardson's efforts in hydrofoil design continued at least until 1911.

A hydrofoil craft designed and built by the Italian aircraft designer Enrico Forlanini was the first successful such craft manned and motor driven. In 1906, he made test runs of a 1.6-ton craft on Lake Maggiore in Italy. The craft had a 60-HP engine driving two counterrotating air propellers, and reached a top speed of 42.5 mph.

Alexandra Graham Bell and his co-worker and friend F. W. (Casey) Baldwin became interested in hydrofoils as early as 1901. During a world tour, Bell and Baldwin rode Forlanini's boat on Lake Maggiore. On returning to Canada, Bell purchased a license to build and develop the Forlanini ladder-foil system in North America. With Baldwin as designer and engineer and Bell as advisor, they built and tested a number of "hydrodomes." Bell failed to interest the U.S. Navy in the HD-3 and turned his attention to sailboats. With the U.S. entry into the European war, Bell's hopes for hydrofoils revived when the U.S. Navy Department called for proposals to design and build subchasers. However, Bell's offer to build two HD-4 hydrofoil craft for that purpose was rejected. The Navy sent him two 50-HP Renault engines, and design work on an HD-4 continued and incorporated all that had been learned from previous successes and failures. With the Renault engines, the top speed of the HD-4 was only 54 mph, but it performed well with good stability and took waves without difficulty. With Bell's report of the success of these trials, in early 1919 the Navy sent him two 350-HP Liberty engines. Using these engines, on 9 September 1919, HD-4 set a new world's marine speed record of 70.86 mph that stood for the next decade. A year later, Bell got observers from the U.S. Navy and the British Admiralty to watch demonstrations of HD-4. Although all observers made enthusiastic reports, neither country saw fit to place an order. Some felt such a craft was too fragile for naval action at sea.

From 1927 to 1936, Hanns Von Schertel, a young German engineering graduate of the Technical University in Berlin-Charlottenburg, designed eight experimental hydrofoil craft. After several disappointing experiences, he became convinced that the only way to ensure stability of submerged hydrofoils was by use of an automatic lift control and a submerged depth sensor. In the late 1930s, he teamed with Sachsenberg Shipyards in Germany to bid on the German Navy's request for proposals for a hydrofoil craft to be used as a military personnel carrier over short distances. The Schertel/Sachsenberg entry, designated the VS-6, was selected, and several VS-6 models of about 15 tons were built.

Some Military Mission Applications Arise

In 1940, the German Navy gave Schertel a contract to build a 17-ton minelayer that achieved a speed of 47 knots in a seaway. With the beginning of WWII, Germany needed to move tanks from Sicily to North Africa. Against the objections of the Schertel organization, Adolph Hitler, who had decided hydrofoils met this need, specified that work be redirected from the 15-ton VS-6 to a tank carrier. The result was the VS-8, an 80-ton, 105-ft long hydrofoil craft with two 1,830-HP diesel engines. It had an open well aft that could be flooded so that a 20-ton tank could be floated in on a raft. Three were built and one was tested, reaching a speed in excess of 50 knots. Two of the craft were later destroyed on the ways by bombs. The remaining VS-8 ended in grounding.

In 1952, Von Schertel moved to Lucerne, Switzerland, taking with him the technical knowledge gained by two decades of experience. There, he founded Supramar, AG and designed and built the PT-10, a 10-ton, 28-passenger hydrofoil ferry. In 1953, the PT-10 demonstrated the commercial value of hydrofoils operating on Lake Maggiore from Switzerland to Italy. It took 48 minutes for the hydrofoil ferry to cross the lake in contrast to regular ferries that took 3 hours. It could maintain full speed in waves up to 1.5 meters and cope with waves up to 2.5 meters with reduced speed, but still "flying."

The production of hydrofoil craft began in the Soviet Union in 1957. Information from the various Schertel-Sachsenberg hydrofoil craft formed the basis for the Russian passenger craft *Myr* and *Strela*, and the military version of the *Strela*, called the *Pchela*. The Russians also developed their own craft with a semi-submerged foil system for operations in rivers.

In 1966, under a U.S. Navy contract, Supramar built a gas turbine-driven, 4-ton experimental hydrofoil with fully submerged air-controlled foils. It attained a speed of 54 knots tested on Lake Lucerne and the Mediterranean coast. Today, Supramar, AG remains one of the major designers and builders of commercial hydrofoil craft.

Canada Complements U.S. Hydrofoil Program

When Canada emerged from World War II, it had the world's third largest navy, with anti-submarine warfare (ASW) as its sole function. The development of the nuclear submarine posed a severe threat because of its increased underwater endurance and speed. This threat stimulated major efforts in Canadian naval research. The Royal Canadian Navy (RCN) was first to operate anti-submarine helicopters from its destroyers and the first to develop towed variable-depth sonar. A longer-range objective was, however, to regain the advantage of higher surface ship speed in a seaway by the use of hydrofoil ships.

As noted by Michael Curtis Eames,[5] an expert in naval architecture and Senior Scientist at the Naval Research Establishment Atlantic (NRE), located in Dartmouth, Nova Scotia, the hydrofoil program of the Canadian Forces had its origin in the pioneering work of Bell and Baldwin. Their initial aim was to develop the Bell HD-4 hydrofoil potential, leaving the exploitation of research on other promising systems to the United States. In 1951, NRE, now Defence Research Establishment Atlantic (DREA), undertook an extensive hydrofoil craft development program using a number of test craft, including the 7-1/2-ton *Massawippi* (R-100).

An example of U.S. and Canadian cooperation took place during these trials. The theory of supercavitating propellers had just been developed, at what is now the Carderock Division of NSWC, by 24-year-old Marshall Tulin. *Massawippi* was deemed to be an ideal test bed for such a propeller, and one was provided. However, this first propeller collapsed on initial takeoff. Undaunted, the Carderock Project Officer, Dr. William B. Morgan, soon arrived with a second, much stronger propeller and the test was successful.

In 1958, NRE's theoretical work suggested that both Bell and Baldwin had been wrong. It was determined that very different characteristics were required of surface-piercing foils fore and aft. The forward foil had to be responsive to changes in immersion, but insensitive to angles of attack. It had to act like a feeler, setting the ship to the trim required and allowing the stern foil to anticipate the oncoming waves. It must be an inherently inefficient foil system and kept small. Conversely, the aft foil system required a high lift-curve slope, but for lateral stability, it only needed to respond to immersion changes at its ends. It must be inherently efficient, and its behavior enhanced by large span. Thus, they concluded that a bow foil (canard) configuration was essential to achieving good seakeeping ability with reasonable efficiency in a surface-piercing foil system.

Canada and U.S. Focus On ASW

The concept of an ASW hydrofoil ship differs from that of hydrofoil passenger ferries intended to operate continuously at high speed from one harbor to another. The ASW craft is expected to spend most of its operating time in hullborne operation at slow speed. As a result, hullborne seakeeping, endurance, and habitability are of vital concern. Because of the shorter duration of foilborne operation, behavior and reliability in severe weather are more important than extreme efficiency. Even in the foilborne mode, the design priorities differ from those of hydrofoil ferries.

In January 1960, a group of experts from the United States, United Kingdom, and Canada concluded that a hydrofoil ship promised significant improvement in ASW capability. The hydrofoil concept was technically sound, and it complemented the hydrofoil development then underway in the U.S. Navy that involved fully-submerged actively-controlled foil systems. At this point, the Canadian Naval Board recommended proceeding with design and construction of a 200-ton ship, designated the FHE-400 (Fast Hydrofoil Escort).

Hull construction of the FHE-400, designed by DeHavilland Aircraft, was begun at Marine Industries Ltd., Sorel in 1964, and was completed in 1965. The hull was erected upside down to permit maximum use of downhand welding of aluminum, and large sections of the shell were welded as sub-assemblies. Unfortunately, in the final stages of outfitting, in November 1966, a major fire broke out in the engine room during tests of the auxiliary gas turbine. The center of the ship essentially had to be rebuilt. It was not until July 1968 that the ship could be transferred to Halifax on the "slave dock" (a floating barge) that served as her maintenance base.

From September 1968 to July 1971, the ship, christened *Bras-D'Or*, logged 552 hours hullborne and 96 hours foilborne in trials. Regrettably, significant rough-water data were small in number. However, hullborne seakeeping was exceptionally good. Foilborne, under full load, she exceeded her calm water design speed, achieving 63 knots in 3- to 4-ft waves. She took off and landed smoothly, and exhibited good stability and control at all speeds.

In July 1969, with the ship docked to repair persistent foil-system leaks, a large crack was discovered in the lower surface of the center main foil. When the neoprene coating was removed, an extensive network of cracks was found. A new foil element was installed, but in July 1971 this foil also developed severe cracking. Clearly, the use of extremely high yield-strength maraging steel was a major problem due to stress-corrosion cracking.

A decision was made in October 1971 to lay up the ship. However, this decision was not due to the structural problem with the foils, but rather was due to a change in defense policy issued in August 1971. This change in policy assigned priority not to ASW, but to the protection of "sovereignty" and the surveillance of Canadian territory and coastlines. This decision would place the ASW hydrofoil ship behind at least three major procurement programs for the Maritime Command. As a result, on 2 November 1971, the Minister of National Defence announced in the House of Commons: "*A decision has been made by the department to lay up the hydrofoil Bras D'Or for a five-year period.*" Unfortunately, circumstances never occurred to restore the ship to active service and the FHE-400 eventually became a museum display sitting on its slave dock.

The U.S. Navy Begins Exploratory Research Program

During the early 1950s, the U.S. Navy demonstrated various experimental craft.[6] A common remark was "*This is a lot of fun, but what would the Navy ever do with hydrofoils?*" This viewpoint seemed to permeate the entire early history of U.S. Navy hydrofoil development. The Marine Corps' complaint that the speed of approaching the beach had not changed since William the Conqueror headed for a beach in 1066 sparked the Navy's interest in hydrofoil landing craft. As a result, a program began in 1954 to evaluate a hydrofoil-supported landing craft designated the LCVP. A request for proposals (RFP) for an LCVP hydrofoil was released by the Navy. An enthusiastic experimenter with hydrofoil craft, Christopher Hook, joined Bob Johnston, President of Miami Shipbuilding Corporation, to respond to the RFP. To the Navy's surprise, they won the competition. The LCVP was called *Halobates*, named for a sea-going insect with forward-extending feelers. One of the requirements of the design was that the craft be capable of flying in shallowing water. As it approached the beach for a landing, the foils were retractable with diminishing foil depth, with a continuous transition from foilborne to hullborne as the water shoaled. During flight test, *Halobates* reached speeds up to 34 knots in five-foot waves. Its performance was demonstrated over a range of weights from 23,290 to 31,165 pounds. The Navy disagreed with the use of the large feeler arms and considered them quite impractical. Fortunately, a Miami Shipbuilding electronic autopilot was ready to go. A step resistance, on the leading edge of the forward struts, provided a height signal. The Navy also became interested in the use of lightweight gas turbine engines. As a result, when an electronic autopilot was installed in *Halobates*, an AVCO T-53 gas turbine was also installed.

From 1951 to 1954, funds were budgeted to build a 3,500-ton hydrofoil cargo carrier with a destroyer-type hull. The Office of Naval Research (ONR) was given Navy program management responsibility supported by the Bureau of Ships, Bureau of Aeronautics, and NSWC Carderock. The basic research was undertaken by the Hydrofoil Corporation of America, a non-profit organization formed by Dr. Vannevar Bush, President of the Carnegie Institution and scientific advisor to the President of the United States. LCDR Patrick Leehy was designated Project Officer in ONR. CDR Robert Johnston later replaced him. In 1954, it was concluded that the development of a propulsion system for a 3,500-ton hydrofoil might tax the total capability of U.S. industry. On this note, the project was terminated.

A small 5-ton, modified Chris-Craft perhaps did the most to interest the U.S. Navy in the future potential of hydrofoil craft. The craft had its genesis in the 1950s at the naval architecture firm of Gibbs & Cox. They assembled a hydrofoil team headed by Tom Buerman that included Dr. John Breslin, Dr. S.F. Hoerner, L.E. Sutton, and Richard Browne. In 1954, Sutton and Browne were assigned to supervise construction of an autopilot-stabilized test craft that was to become *Sea Legs*. It had a 28.5-ft hull with a 9.0-ft beam, full-load weight of 10,550 lbs. The foils were aluminum with a German section and were arranged in a canard configuration. For the autopilot, Richard Browne started with the basic technology developed by the Draper Laboratory of MIT and assembled a practical working autopilot with 160 vacuum tubes. For the height signal, it utilized a sonic height sensor. The autopilot and height sensor were significant technical advances.

Sea Legs' first flight in 1957 was impressive.[7] The autopilot stabilized the craft in rough seas and it achieved speeds up to 27 knots. After Navy personnel witnessed the trials in the New York area during late 1957 and early 1958, *Sea Legs* got underway to Washington, DC. During the transit in the open ocean, accompanied by the U.S. Navy's PT-812, *Sea Legs* averaged 23 knots in 4 to 5-ft waves. The hydrofoil craft demonstrated seakeeping and performance absolutely impossible for conventional boats of the same, or even larger size. Those aboard reported a dry, comfortable ride, while conditions on the PT-812 were quite different indeed. Three Navy Commanders, William Nicholson, Randolph King, and Kenneth Wilson headed this adventure. When *Sea Legs* arrived in Washington, a number of interested military and government personnel were embarked for further demonstrations. They included the CNO, Admiral Arleigh Burke.

In 1962 and 1963, *Sea Legs* underwent more detailed evaluation by the Carderock Division. It was extensively instrumented and provided at-sea data for future designs. This small boat was the single most important forerunner of the U.S. Navy's decision to get serious about the use of hydrofoil ships and craft in the future Navy fleet. In recognition of its importance, *Sea Legs* is presently on exhibit in the Mariner Museum in Newport News, VA.

The U.S. Navy Gets Serious

With the growing momentum generated by the expanding technology base, and the demonstrated attributes of hydrofoils for naval missions, the Bureau of Ships Preliminary Design Branch began a design study, in late 1957, of hydrofoils for ASW. This study was strongly influenced by Canada's development of the hydrofoil ASW ship FHE-400. In a letter dated 24 January 1958, OPNAV requested BuShips to study a hydrofoil for harbor defense and coastal patrol. Designated the PC(H), when compared to the sub chasers PC(S) and SC, it appeared capable of performing the mission of these patrol craft in a superior manner. As a result, the PC(H) was substituted for the PC(S) and SC in the FY60 shipbuilding program. With the blessing of OPNAV, PC(H) design work continued until March 1959 when the preliminary design was completed. Based on the experience with *Sea Legs*, the selected design was a fully-submerged, autopilot-controlled foil system in a canard configuration. It was thus that the many years of hydrofoil research finally bore fruit with the design and acquisition of what was expected to be the U.S. Navy's first operational hydrofoil ship.

The contract plans and specifications for PCH were turned over to BuShips Code-526, the Mine, Service, and Patrol Craft Branch, otherwise known as the Type Desk. The contract for detailed design and construction was to be bid on a competitive, fixed-price basis. In June 1960, The Boeing Company in Seattle, WA was awarded a contract for a fixed price of $2.08 million to do detailed design and construction. Boeing's research and entry into hydrofoil programs began in 1958 with in-house funding. A Marine Group was formed in 1959 as part of the Aerospace Division. Later it became Boeing Marine Systems. Hull lofting began in the Fall of 1960 at Martinac Shipyard in Tacoma, WA. The ship, designated the PCH-1, was launched in conventional fashion the evening of 17 August 1962, and christened *High Point,* after High Point, NC.

In retrospect, it seems no surprise that the builder's trials, post-delivery tribulations, special performance trials, and final acceptance trials, clearly demonstrated that the ship was not ready, and possibly might never be ready, for delivery to the fleet. This fact was finally recognized, and OPNAV made the decision to transfer the ship to NSWC Carderock to continue development of the technology base for design of naval hydrofoil craft and ships. The following twenty years of the PCH-1 trials, modifications, and exploration of mission applications appear in detail in Reference 8.

In 1961, BuShips initiated the Hydrofoil Accelerated Research Program (HARPY) directed toward bigger, better, and faster hydrofoil ships. James Schuler, Hydrofoil Program Manager, initially directed the program with assistance from Owen Oakley and Ralph Lacey in Code 420. The need for a high-speed test craft to investigate sub-cavitating, ventilated, and super-cavitating foil systems was evident. In June 1961, BuShips awarded a contract to Boeing to design and construct a high-speed test craft that could be highly instrumented and propelled at speeds up to 100 knots. This

craft, named FRESH-1 (Foil Research Hydrofoil), was launched on 8 February 1963. Powered by an aircraft turbine engine on 3 May 1963, it attained a speed of 80 knots. FRESH-1 characteristics and test operations appear in Reference 9. During one of its trial runs, in a turn, the craft became unstable due to foil ventilation and capsized. Fortunately, there were no casualties. As a result of the Navy's decision to delay, CNO Admiral Zumwalt's quest for a 100-knot Navy, FRESH-1 was laid up.

On 10 November 1966, NSWC Carderock established the Hydrofoil Special Trials Unit (HYSTU) as a tenant activity of the Puget Sound Naval Shipyard (PSNS). It was staffed by LCDR Karl Duff, USN as the Officer in Charge, and a number of technical and administrative personnel. The Officer in Charge of HYSTU, and the assigned hydrofoil ships were administratively assigned to CO&D Carderock with local control by COM 13 in Seattle. Civilian personnel were responsible to the Technical Manager of the Hydrofoil Development Program Office at NSWC Carderock.

During the period when PCH-1 was under construction, the Navy contracted with the Grumman Corporation for the design of the 320-ton hydrofoil ship AGEH-1.[10] Lockheed Shipbuilding in Seattle, WA constructed it. The ship, christened *Plainview*, after Plainview, TX and NY, was delivered to the Navy in 1969. At that time it was the largest hydrofoil ship in the world. It was originally planned as an ASW ship and was designed to achieve speeds of 90 to 100 knots. However, due to experiences with other hydrofoils, the decision was made to install only two LM-1500 gas turbines with space available for adding two more, thus limiting the speed to a nominal 50-60 knots. Also, rather than deploying the ship to the fleet, it was assigned to the Carderock Hydrofoil Special Trials Unit for additional R&D trials.

The first U.S. Navy operational hydrofoils delivered to the fleet were the patrol gunboat hydrofoils (PGHs). Two PGHs were built, one by Grumman, *Flagstaff* (PGH-1), and one by Boeing, *Tucumcari* (PGH-2). Although designed and built to the same performance specifications, their configurations were substantially different. PGH-1 was propeller driven and had a conventional foil distribution. PGH-2 was waterjet propelled and had a canard foil system. They were delivered to the Navy in 1968 and both saw service in Vietnam, making them the first U.S. Navy hydrofoils in combat. The operational experience gained with these hydrofoils, particularly the *Tucumcari*, provided the confidence necessary to proceed with the Patrol Hydrofoil Missile (PHM) ship program.

NATO Navies Join Hydrofoil Program

In 1972, three NATO navies formally agreed to proceed with the joint development of a high-speed hydrofoil combatant. A Memorandum of Understanding (MOU) was signed by the United States, Federal Republic of Germany, and Italy. A letter contract was awarded to the Boeing Company for a feasibility study, and the design and construction of two Patrol Combatant Missile (Hydrofoil) Ships.[11] Although the initial contract called for two lead ships, program cost growth in August 1974 forced suspension of the work on the second ship. PHM-2 was later incorporated into the production program. Nearly six years elapsed from the signing of the letter contract for the design and construction of the lead ship, PHM-1, in November 1971. She was commissioned as USS *Pegasus* in July 1977. It was not until 1981 and 1982 that the five additional PHMs joined the PHM-1 to form the desired squadron of six ships. The PHM Squadron was based in Key West, FL and assigned to support the U.S. Coast Guard in intercepting drug smugglers who were using high speed "Cigarette" boats.[11] Their operational experience is described in a following section. To the dismay of the advocates of Naval hydrofoil ships, on 30 July 1993 at the Naval Amphibious Base, Little Creek, VA, the Navy decommissioned the entire Class of PHMs in one day, the first such act in naval history. The ships were in mint condition, had fulfilled all expectations for their performance, and had another 15 years of useful life. The Coast Guard indicated they would be glad to take over the squadron, but the Navy had to provide the operating funds. The Navy refused. In time, except for one of the ships, all others were sold for scrap. Since that time, the Navy has not operated hydrofoil ships.

U.S. Navy Hydrofoil Effort Focused On Design Concepts

Since the mid-1980s, advancement of hydrofoil concepts in the U.S. Navy has been restricted essentially to "paper" studies, although subsystem technologies have continued to advance. Even though currently there are no hydrofoil ships in the U.S. Naval fleet, interest continues in developing the technology and improving the subsystems for these ships. The hydrofoil community, of which Carderock is a major contributor, continues to carry out conceptual studies and feasibility designs of relatively large hydrofoil ships to suit a variety of mission applications. In this respect, a fundamental limitation impacts the growth potential of hydrofoil ships. It is the "square-cube" law that states the lift developed by foils is proportional to their plan form area (the square of a linear dimension), whereas the weight to be supported is proportional to the volume (the cube of a linear dimension). Thus, as the size of the ship

increases, the foils tend to outgrow the hull. Early developers felt that this phenomenon limited hydrofoil ships to relatively small sizes compared to the "blue water" Navy. Smaller size might have been one of the reasons why the Navy earlier had decided to abandon the hydrofoil. However, further design studies show that foil system weight fractions increase only slightly with ship displacement because strut length varies with the design sea state, not ship size. Also, larger foils are structurally more efficient, and advances in materials technology produced significantly lower foil weight fractions.

The largest hydrofoil ships built to date are the 320-ton *Plainview*, and the 420-ton Russian *Bobachka*. In recent years, however, a number of large hydrofoil designs appeared:

- **Corvette Escort** – 615 long tons, length 196 ft, foil span 58 ft
- **DBH** – Developmental (Damn) Big Hydrofoil. Several designs of a nominal 750-ton ship for transoceanic mission, length 173 ft, foil span 60 ft, 50 knots
- **NATO/U.S. Navy Hydrofoil** – 780 tons, length 216 ft, foil span 76 ft
- **Boeing Hydrofoil Ocean Combatant (HOC)** – 1,250 tons, length 200 ft, foil span 70 ft, 50 knots in SS 5
- **Boeing HY-7 (Model 1026-010)** – 970 tons, length 198 ft, foil span 82 ft, 50 knots, 70 knots dash
- **Grumman HYD-2** – 2,400 tons, length 365 ft, foil span 116 ft, 51.5 knots in SS 6

Hovercraft Include Amphibious Craft and Non-Amphibious Ships

Hovercraft offer another way to raise the hull above the water surface by supporting it on a cushion of air. In this section, the term "hovercraft" is used generically to describe both amphibious Air Cushion Vehicles (ACVs) and non-amphibious Surface Effect Ships (SES), which use side hulls to contain the air cushion. These hovercraft are treated in separate sub-sections.

Modern Development Of Air Cushion Vehicles Begins

As early as the 1700s, interest appeared in another way to raise a craft above the surface of the water by lifting it on a cushion of air. Various ideas circulated over the years until 1955 when modern development began. In that year, the English inventor Christopher Cockerell (ultimately knighted for his achievements) developed the first annular jet craft. Built by Saunders-Roe Ltd., now British Hovercraft Corporation (BHC), designed by a team of engineers headed by R. Stanton-Jones, the craft was designated the SR.N1 and was demonstrated on 19 July 1959, near Dover, England. The craft hovered some two feet above the water of the English Channel, traveling up on the land and back out over the water. Cockerell called his invention the "hovercraft." Another English inventor, C. H. Latimer-Needham, decided to try a different design and added a "skirt" to contain the jets of air that allowed the craft to rise higher above the surface. The trials and tribulations of this development are described in Reference 12. In the same period, research occurred in the U.S. along similar lines. Dr. Harvey R. Chaplin, Head of the Carderock Aerodynamics Laboratory, was responsible for most of the basic research on air cushion craft, which began in May 1957.

BH.7, the first of three craft built by BHC specifically for military missions, was launched on 31 October 1969. It had a nominal gross weight of 45 tons and accommodated 70 fully-equipped troops, with a maximum calm water speed of 65 knots.

A significant milestone in air cushion craft resulted when, on 6 April 1978, the BHC Super 4 (a 300-ton stretched version of the 170-ton SR.N4 ferry with a 55-foot section added amidships) was launched. The world's largest hovercraft at that time, it carried 416 passengers and 60 cars over distances up to 150 miles.

In the U.S., almost the entire development of air cushion craft was focused on high speed, high-density craft. In the early 1960s, several companies explored a range of forms including plenum, side hull, recirculation, labyrinth seal, and others. Both ONR and BuShips began studies of military applications. The most successful venture during this period was the BuShips-sponsored SKMR-1, designed and built by Bell Aerospace Textron in 1963. At that time, it was the largest such craft in the U.S., with a gross weight of 22 to 28 tons, depending on the payload, and a calm water speed of 70 knots. It later added 4-foot skirts.

In the mid to late 1960s, the U.S. Army operated three small ACVs designated SK-5s by the supplier, Bell Aerospace. Based on the U.K. SR.N5, they proved to be extremely valuable assets during the Vietnam conflict.

U.S. Army Requires Air Cushion Vehicle (ACV)

With the publication of the TransHydro study in 1973, the Army requirement for an amphibious air cushion lighter was born. By June 1974, a required operational capability (ROC) was approved by the Department of the Army for a 20- to 30-ton payload, 40-knot, fully amphibious air cushion vehicle, designated the Lighter Air Cushion Vehicle, 30-ton payload (LACV-30). In 1975, the Army bought two pro-

totype LACV-30s. They were an adaptation of Bell Aerospace Textron's commercial ACV *Voyageur* with major improvements. Two Pratt & Whitney ST6T-76 twin-pack gas turbine engines, rated at 1,800 SHP, powered them. They each drove three-bladed, 9-foot diameter, Hamilton Standard variable-pitch propellers. Based on the experience with these two prototypes, the Army purchased a total of 26 LACV-30s.

Although the LACV-30 fulfilled a major need in the Army Logistics Over The Shore (LOTS) requirement, some requirements remained unmet. The transportation of heavy, outsize cargo quickly exceeded the LACV-30 capability. The Army approved a Letter of Agreement for a LAMP-H on 24 May 1982. The LAMP-H was required to transport heavy equipment, LOTS support equipment, the M-1 tank, tracked and wheeled vehicles, 20- and 40-ft containers, and general cargo. In response to these requirements, the Army evaluated four candidate concepts: the Marine Corps LCAC, a modified U.K. SR.N4 ferry, an air cushion barge, and a modified LACV-30.

The Army operated the LACV-30s up until the mid 1990s. Most of these were ultimately turned over to a Native Alaskan corporation that continues to lease them to meet requirements in Alaska.

Navy and Marine Corps Begin LCAC Program

The Landing Craft Air Cushion (LCAC) is a dramatic innovation in modern amphibious warfare technology. It provides the capability to launch an assault from over the horizon, thereby decreasing the risk to ships and personnel and creating uncertainty for the enemy as to where the assault might occur.

In the 1965-1970 period, the U.S. Navy and Marine Corps undertook studies of the application of the air cushion principal to improve amphibious landing craft. Two craft were designed and constructed: the JEFF (A) by Aerojet General Corporation, and the JEFF (B) by Bell Aerospace. In October 1977, Carderock established the Assault Landing Craft Experimental Trials Unit in Panama City, FL for the purpose of testing these two air cushion prototypes. The Jeff (B) was launched on 17 December 1977 and made its first trial run reaching a speed of 42 knots. The Jeff (A) made its first run at Panama City, FL on 17 October 1978.

Based on the results of these trials, Bell Aerospace Textron was awarded a contract in 1981 to begin the production of the Landing Craft Air Cushion (LCAC). These craft are powered by four Avco-Lycoming TF40B gas turbines, each rated at 3,955 SHP (two for propulsion and two for lift). The craft are capable of carrying a 60-ton payload and 75 tons in overload. They can carry a main battle tank, with a range of 200 nautical miles at 40 knots with payload in sea state 2, and 300 nautical miles at 35 knots without payload. Four LCACs can be carried in the LSD 41 class and 3 in the LSD 36 class.

On 29 June 1987, the LCAC was approved for full production. Textron was awarded a contract to deliver 48 craft through FY 1989. Lockheed Shipbuilding was also selected as a second source. As of 1995, 82 LCACs were delivered. The largest deployment of LCACs took place in January 1981 with 4 detachments of 11 craft reported for duty in the Persian Gulf in support of Operation Desert Storm.

As of this date, 92 LCACs have been delivered, and Textron Marine and Land Systems is currently under contract to perform a Service Life Extension Program (SLEP) to extend the craft's life beyond 20 years.

Why Surface Effects Ships (SES)?

Although the Surface Effect Ship (SES) has a number of unique advantages, the principal motivation behind the concept is that the air cushion, which supports the majority of the weight of the craft, significantly reduces the resistance to forward motion at high speed. It also helps to mitigate the effect on craft motions and accelerations when operating in rough seas. Although power is required to create and sustain the air cushion, the reduction in resistance is so large at high speed that the sum of lift and propulsion power is significantly less than that for the equivalent monohull.

SES Development Begins

In 1959, Ted Tattersall in the U.K. initiated development of the first solid sidewall hovercraft, later called the SES. At about the same time in the U.S., a small team led by Allen Ford, at the Naval Air Warfare Research Department of the Naval Air Development Center (NADC), invented a similar concept called the "Captured Air Bubble." This hovercraft had rigid sidewalls that penetrated the water surface and contained an air cushion between them sealed fore and aft with bow and stern seals. Ford claimed that, despite the loss of amphibious capability, the design resulted in a much higher lift-to-drag ratio due to the reduction of air leakage.

The Tattersall team, with the backing of William Denny & Bros., licensees of Hovercraft Development Limited, built the first U.K. 70-foot manned model with a cushion Length-to-Beam (L/B) ratio of 7:1. It had a weight of 5 tons and was powered by two 35-HP Mercury outboard motors. Introduced on 22 June 1961 as the D.1, the craft made 18 knots and lifted the cross-structure above the surface of the water. It was successful enough to lead to the building of the 70-passenger, 20-knot GRP SES D.2 that went into experimental passenger service in 1963.

In the U.S., Allen Ford launched the XR-1 in May 1963. It was 50 feet long, weighed 10 tons, and was propelled by a J-79 jet engine. The craft's Length-to-Beam (L/B) was 3.5 and, with a more powerful J-85 engine, it achieved a speed of 60 knots. In 1965, Ford joined Harvey Chaplin at Carderock. His original design went through eight major modifications leading up to the XR1-E, some 22 years later. Four were built as commercial ferries capable of carrying 70 passengers at a speed of 27 knots, subsequently modified to give a maximum speed of 34 knots.

Although the top speed of early operational SESs was less than 40 knots, the historical thrust was to develop an 80- to 100-knot capability. In 1969, design and construction contracts were awarded to Aerojet General for the SES 100-A and to Bell Aerospace for the SES 100-B test craft. Both of these 100-ton craft were extensively operated, and validated their architectural and engineering technologies and subsequent modifications. The SES 100-B established a sustained speed record of 91.9 knots in a slight chop on Lake Ponchartrain, and also operated at 35 knots in 6- to 8-foot waves. In 1978, the SES 100-A served as a scale model for the design and construction of the Navy's 3,000-ton, 80-knot prototype, called the 3K SES. Unfortunately, the 3K SES program was terminated in December 1979, just three weeks before beginning hull construction and after an expenditure of over $400 million. This termination, based mainly on the lack of a mission for a large prototype, frustrated the thrust for a 100-knot Navy.

The SES-200: Exploring New Geometries

Military applications of SESs required examination of the early geometry. Low L/B ratios and thin side hulls characterized most of the early SESs. They were designed to operate almost exclusively on cushion at high post-primary hump drag speeds. This design proved to be efficient for ferry operation but not for military applications.

In the late 1970s, Bell Aerospace joined with Halter Marine to build the BH-110 SES as a shuttle to serve oil rigs in the Gulf of Mexico. Together they built four of these craft. Unfortunately, the 1970s moratorium on oil drilling in the Gulf resulted in a loss of this market. They tried to find new customers about the time the 3K-SES program was terminated. The focus of Navy SES interest turned to lower technology and somewhat lower speed. Bell Halter developed Coast Guard interest in a small, fast cutter to deal with drug smuggling "Cigarette" boats in the Florida Keys. A cooperative trials program was conducted by the Navy and the Coast Guard using a BH-110 for about a year. This program resulted in sufficient interest for the Navy to acquire one BH-110, and for the Coast Guard to acquire the other three.

In the early 1980s, in order to advance the technology base of high L/B SES craft, the Navy awarded Bell a contract to stretch their BH-110 with a 50-foot extension of the hull. This craft was designated the SES-200, which was about 200-tons displacement. Bell also installed a prototype ride control system. The result of the stretch to a higher L/B ratio gave better seakeeping and a lower operating cost below the primary hump. Special note is made of this craft because of its extensive employment in advancing the SES technology base.

In late 1984, the NAVSEA SES Program Office was disestablished. The SES-200 and the Patuxent River Test Facility were transferred to Carderock in an attempt to keep the SES technology program alive. Jack Offutt was put in charge of the craft's operation, which continued from January 1985 until 1990. Joint trials were run with the Coast Guard and CINCLANTFLT deployments in fleet exercises and as a test platform for live-fire exercises. The craft also made port calls in the Caribbean. It then was deployed to the NATO Special Working Group and was involved with trials for the U.K., France, Spain, Canada, and Norway in the 1984–86 timeframe. After the NATO deployment, the craft was re-engined with high-speed diesels and waterjet pumps, and trials at higher speeds were conducted.

In circa 1990, management responsibility for SES-200 was transferred to the Carderock Combatant Craft Department in Norfolk, VA. The attempt to find additional customers was not successful, and the craft became a liability without funds for maintenance and operation. Discussions of alternatives were held with ONR, and it was decided that the craft could be used for a program at Pacific Marine Navatek in Hawaii, under Steve Loui. They were looking for a way to test lifting body technology on a large scale. SES-200 was given to Loui to modify for a test as a Hydrofoil Small Waterplane Area Catamaran (HYSWAC). The hull was modified to a catamaran with a lifting body. As of this writing, it has been undergoing a hull modification in the shipyard, and tests are expected to begin in the summer of 2003.

SES Design and Construction Expands

In the decade of the 1980s, there was a worldwide expansion in the design, construction, and operation of hundreds of SESs, primarily as commercial ferries with some military applications. Most were relatively small (less than 200 tons) with operating speeds of 25 to 40 knots. The European experience definitely proved the economic feasibility of SES ferries.

In the early 1980s, a contract was awarded to Textron Marine Systems for a number of U.S. Navy GRP SES Mine

Countermeasure Craft (MSH). The contract was terminated before construction of the first craft. At this same time, the Navy also developed the concept of a SES Special Warfare Craft Medium (SWCM). A contract was awarded to Rohr Marine (RMI) but terminated before construction of the first craft. During this period, the technology lead transferred back to Europe, with the SES concept being aggressively pursued for commercial and military applications.

Notably, in 1987, the Swedish Defence Material Administration (FMV) initiated a comprehensive SES R&D program involving a number of Swedish firms and government agencies. This program led to a building contract with Karlskronavarvet AB for the stealth test craft *Testrigg Smyge.* This craft was aimed at evaluation of stealth optimization, new weapons systems, cored GRP construction, the SES concept, and waterjet propulsion for future MCMs and combatant craft. Construction was completed in 1991.

The great proliferation of SES craft up to 1991 is extensively covered in the Lavis and Spaulding paper, Reference 13. Significant developments in SES ships and craft during the last decade are provided by Robert A. Wilson, one of the pioneers on the Carderock SES technical team. He is coholder of six patents relative to SES, and from 1965 to 1980 was Deputy Head of the SES Division in the Aviation and SES Department. He retired from the Carderock Division in 1996. Since then, he has continued to follow worldwide developments of surface effect ships and craft.

Development of SESs is continuing in Scandinavia and Japan. The Swedes and the Norwegians brought along the concepts that resulted in the *HMS Smyge.* It demonstrated the ability of the shape to reduce signatures. Also, the Norwegian Cirrus passenger ferries proved popular in service on the fjords north of the Arctic Circle, and in other areas.

UMO Mandal is using SES technology as the basis for its design and construction of naval vehicles, particularly Mine Countermeasure Vessels (MCMVs) and Fast Patrol Boats (FPBs). The MCMVs are specially fitted for minehunting and minesweeping. The rationale for selecting the SES concept is its lower acoustic and magnetic signatures, higher tolerance of underwater explosions, improved sonar conditions, higher strength-to-weight ratio, shallow draft, precise maneuvering, good seakeeping in heavy weather, high speed and low noise levels, and improved crew comfort compared to other concepts. UMO Mandal is currently building four SES minehunters and five SES minesweepers for the Royal Norwegian Navy.

UMO Mandal's Skjold-Class Fast Patrol Boats are similar in design to the MCMVs, but are smaller and faster. Like the Smyge, the Sjkold-Class capitalizes on the adaptability of the SES's hull and materials used to reduce the radar signature. They have delivered one prototype FPB to the Royal Norwegian Navy and have an option for production of a series of another seven units.

SES development is underway in Japan since the 1970s, with two SES development teams. One team was from the Japan Defense Agency, whose goal was a missile boat; the other team was from the Japanese Ministry of Transportation, whose development target was a cargo carrier. The Ministry of Transportation developed the TSL-A under the Techno Super Liner program. This test platform was named Hisyo. After its initial trials, Hisyo was sold to the Shizuoka Prefecture Office and, after some modifications, used as a ferry boat or in an emergency as a rescue boat. The Japanese Defense Agency built two test platforms named Meguro and Meguro-2.

The positive experience with the TSL-A was its good seaworthiness, giving the Japanese the confidence that a large SES could be used commercially around Japan if its length was over 100 meters. On the other hand, the negative experiences were the difficulty of manufacturing, the maintenance of the large fore and aft seals, and the expensive cost compared to a monohull high-speed ferry with the same capacity. Nevertheless, Mitsui is designing, and plans to construct, a large SES ferry for cars, trucks, and passengers. This ferry is nominally 140 meters long with a displacement greater than 1,000 tons, and cruises at 30-35 knots. Its one-way operating time is expected to be 14 hours including multiple stops. The projected launch date is in 2004.

Is there a future for the SES in the U.S.? U.S. SES commercial derivatives such as the Air Ride Craft, Inc. ferry concept exist. Also, the Navy's current Littoral Combat Ship (LCS) competition states the need for a low-cost, fast, high-endurance, small surface combatant. This competition has produced one SES concept. The National Defense Magazine notes that Raytheon is offering a composite SES, and they have teamed with UMO Mandal to capitalize on their experience. The article notes, "the Skjold design is impressive, despite some risk. Scandinavian countries have been notorious for taking new hullforms and proving them out. Only time will tell if the SES comes back to the country that developed the technology."

Hybrid Hull Forms Offer New Possibilities

Hybrid ship hullforms are those in which total lift in the operating or cruise mode is derived from a combination of buoyancy, air cushion lift, or foil dynamic lift. Hybrid forms offer hydrodynamic efficiency and improved seakeeping characteristics, while retaining the relative simplicity of conventional monohulls and multihulls. Developments in

this arena proceed rapidly; new variations are on the world's drawing boards now. Compared to conventional monohulls and even to the so-called advanced vehicle forms, hybrid ship concepts are relatively new.

A considerable gap in time occurred between the early studies of hybrid ship forms at Carderock in the 1970s and the proliferation of hybrid commercial vehicle designs. Early U.S. Navy studies were oriented toward military applications that included a full range of missions using various size ships from small patrol craft to 4,000-ton frigates. The technology matured through analytical studies, feasibility designs, computer simulations, and model tests in developing, as an example, the Hydrofoil Small Waterplane Area Ship (HYSWAS) hull form. The concept provides considerable potential improvement over current small monohulls in terms of maximum speed, motions in rough water, and range at high speed. Compared to the conventional hydrofoil, with a fully-submerged foil system, the hybrid hydrofoil concept has the potential for considerable range improvement as a tradeoff for very high-speed capabilities. A 12-ton, 27-ft HYSWAS vessel called *Quest* was a key element in the demonstration of the technology. The craft had exceptional seakeeping performance and demonstrated superior motions through six-foot seas at 30 knots. Also, the Japanese (Kawasaki), Techno-Superliner (TSL-F) prototype, a variant of HYSWAS, having a displacement of 45 tons, a length of 56 ft, and a beam of 20 ft, was successfully tested. Another variation of HYSWAS was a ferry design by E. Mohr that employed two side floaters connected to the superstructure by hydraulically operated, telescoping pistons. This feature is used to minimize the draft of the vessel when hullborne.

Other hybrid forms include the Hydrofoil Catamaran (HYCAT), the Hydrofoil-Supported Catamaran (HYSUCAT), the Hypercat by Mitsui, the Catafoil by the University of Stellenbocsch, and the Hitachi Superjet-30. Other designs include basically catamaran hulls with foils supporting a portion of the full-load weight of the vessel when at operating speeds, while the hulls continue to support the vessel with their buoyancy. However, International Catamaran Designs Pty Ltd introduced a *Trifoil* concept. This hybrid form uses a foil system combined with a trimaran hull. More recently, Techman of Norway and Island Engineering have designed, built, and tested a demonstrator vehicle employing a trimaran hull and fully-submerged foil system. In this hull form, the outer two hulls are clear of the free surface, whereas the center hull remains partially buoyant in the operating mode.

Many variations to the hybrid ship theme exist, and we must appreciate that no single design or arrangement is best. The naval architect must deal with the requirements—whether they are military or commercial. If shallow draft and modestly rough water are to be encountered, some of the hybrids described above are more appropriate than others. If relatively deep draft, compared to other AMVs and monohulls, can be tolerated, and open-ocean rough-water tolerance is a must, then the designs featuring single or double lower hulls with fully submerged foils appear to be more promising in overall performance. As we enter the 21st century, the question is—to what degree and at what pace will naval ships adopt this technology? Commercial interests are leading the way in this field, and the U.S. Navy may end up with a case of reverse, dual-use technology transfer.

Current Boundaries and Limitations to High-Speed Ships

With the above background on high-speed ships and craft, we must examine their limits and how these limits may be extended. We can discuss boundaries and limits to the quest for speed in terms of first principle mathematical relationships. As seen in the equations in the following section, first principles are expressed in terms of hydrodynamic, fuel, propulsion, and structural weight efficiencies.

Improvements in these efficiencies, through advancements in technology, can provide a basis for the Navy to accelerate its quest for speed and mission effectiveness in small-to-medium-size ships. Improvements in hullforms can lead to ships with higher lift-to-drag (L/D) ratios at high speed. Improvements in prime mover performance (lower specific fuel consumption), and higher propulsion efficiency, combined with improved hydromechanics, can allow higher speeds and greater range at high speed to be achieved more economically. Advances in materials and automatic control systems can reduce ship empty weight, improve motions and, at the same time, reduce costs.

How Do We Measure Ship Efficiencies?

Basic mission requirements are usually specified by an operator in terms of speed, range, and payload. The designer is then faced with the challenge of satisfying these specifications and examining tradeoffs in the process. Without even discussing the form of the ship hull, a frame of reference for the exploration of fast, high-performance ships can be established by resorting to "first principles" of vehicle performance:

- Hydrodynamic efficiency is measured in terms of L/D ratio, a non-dimensional value.
- Fuel efficiency is given in terms of specific fuel consumption (sfc).
- Propulsion and structural weight efficiencies are

expressed in terms of weight fractions based on total ship weight.

These parameters are imbedded in two basic relationships that describe performance of marine vehicles. One is an expression relating shaft-horsepower per ton of full-load displacement (SHP/W) to speed, propulsive coefficient (PC), Effective Horsepower/Shaft Horsepower (propulsive efficiency), and lift-to-drag ratio (hydrodynamic efficiency):

$$SHP/W = 6.87*V/(PC*L/D)$$

Range is another fundamental performance measure, and relationship depends on fuel weight fraction, speed, power-to-weight ratio, and specific fuel consumption (sfc engine fuel consumption efficiency):

$$R = 2240*(W_f/W)*V/(P/W)*sfc$$

Where:
P = Power in shaft horsepower
W = Ship total weight in long tons
V = Ship speed in knots
PC = Propulsive coefficient of the propulsion system
L = Total lift of ship systems in long tons
D = Total drag of ship in long tons
R = Range in nautical miles
W_f = Propulsion system fuel weight in long tons
sfc = Specific fuel consumption of propulsion system in lb/hphr

Calculations can be made over a spectrum of ship speeds, range, lift-to-drag ratio, and SHP/Ton, among other parameters. Note that payload does not enter into these relationships. Payload is the value that remains after the designer determines the ship empty weight, and satisfies the speed and range requirements, which in turn defines fuel load.

The major options for achieving high speed in a seaway follow:

- **Hydrodynamic Efficiency:** Lifting the hull out of the water either completely or partially, wave cancellation with multiple hulls, motion control, hydrodynamic planing, and friction drag reduction techniques to achieve higher lift-to-drag values.
- **Fuel Efficiency:** Diesel engines, gas turbine engine variants including Inter-Cooled Recuperative (ICR), and fuel cells.
- **Propulsion Efficiency:** High performance propellers, water-jets, pump-jets, podded propulsors, and electric drive.
- **Structural Weight Efficiency:** Light-weight/high-strength aluminum, high-strength steel, composites, and sandwich construction.

Hullform Efficiency Compared

First, how do the various hull forms designed over the years compare in efficiency? Many approaches attempted this comparison; two are discussed here.

As far back as 1950, Theodore von Karman and G. Gabrielli published a famous paper "What Price Speed?".[14] Their answer to the question posed by the paper title addressed power required to achieve a given speed. A price is paid for power: the cost of the power system; the cost of the ship to accommodate the power; the cost of delivering the power to propel the ship; and the cost of feeding the power system. They had collected a vast amount of data on vehicles ranging from bicycles to fighter aircraft. Information was displayed on several charts, one type of which is shown in Figure 2.

Note that the impact of large tankers and supersonic aircraft has shifted the 1950 limit line in Figure 2 to the right. The 1970 limit line and various vehicle envelopes form a triangular region that constitutes a gap in marine and aircraft technology. The significance of this gap is that it appears difficult to penetrate this region. Only through improved efficiencies can designers find a way to develop AMVs that allow them to enter this domain.

Figure 2 shows curves representing the minimum specific power (that is, installed horsepower divided by gross weight, or SHP/W) as a function of maximum speed for various types of marine vehicles, ships, and aircraft. Less efficient vehicles of any given type lie to the left of the curves, but none of the proven designs lie to the right of the corresponding envelope. Also shown are lines of constant effective L/D (or PC*L/D).

More recently, a term called Transport Factor (TF) has been introduced by Colen Kennell in several papers.[15, 16] Transport Factor is a non-dimensional relationship between the weight, design speed, and installed power of a vehicle:

$$TF = K_1 *W/(SHP_{TI}/K_2*V)$$

Where SHP_{TI} = Total Installed Power, K_1 and K_2 are factors to accommodate units.

The Transport Factor (TF) concept, shown in Figure 3, provides insights into the interaction of some of the fundamental parameters in the assessment of high-speed ships and craft. The various parametric relationships link ship weight, speed, range, cargo capacity, installed power, and fuel efficiency to assess vehicle and subsystem alternatives.

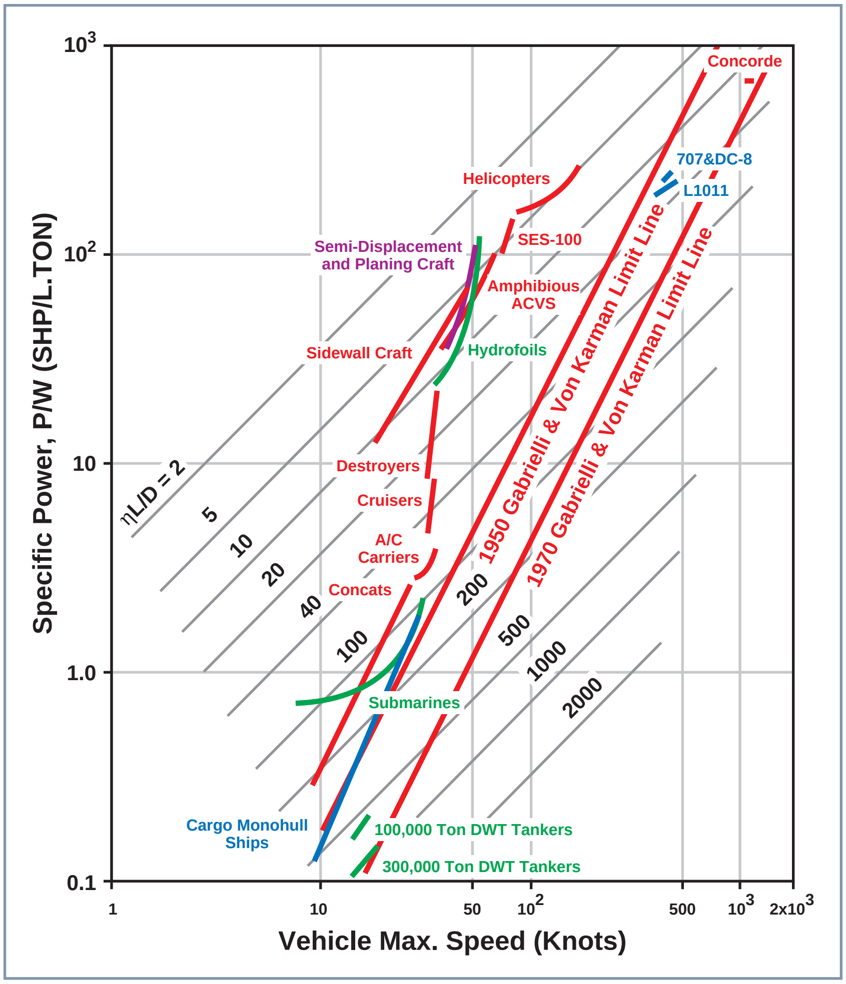


Figure 2. Specific power, P/W, versus calm water speed for various vehicles.

The concept emphasizes overall design attributes of the ship rather than precise performance characteristics. While Transport Factor analysis seems applicable to all types of vehicles at all speeds, the focus of Kennell's work has been on large ships capable of transporting large cargoes over trans-oceanic distances at speeds of 30-100 knots. Data for other types of vehicles have been included to provide perspective.

Transport Factor (TF) is a non-dimensional relationship between the weight, design speed, and installed power of a vehicle. It has similarities to other parameters used to assess different types of vehicles. The two most closely related are those pointed out above, generally known as Transport Efficiency (TE), or SHP/ton, and the lift-to-drag ratio (L/D). Transport Efficiency is generally used to relate the sum of a vehicle's installed propulsion and auxiliary power to its weight and maximum speed. On the other hand, Transport Factor uses design speed (for example, sustained speed and service speed) rather than maximum speed. TF includes only the sum of installed propulsion power and lift power for dynamically supported vehicles while excluding power for hotel loads. Hotel load power is generally small compared to propulsion power for high-speed vehicles, but becomes more significant as speed decreases.

The significance of this plot is that it provides an upper boundary, or sense of physical limitation, of today's technology. How far this boundary can be lifted, by applying the various improvements in efficiency, remains to be seen.

Kennell's approach to this subject differs from that of Gabrielli and von Karman. They used TE for a large number of vehicles to establish minimum power requirements for each type of vehicle over a range of speeds. Transport Factor data can be similarly analyzed to produce a similar result. A more useful insight into design and technological issues associated with different vehicles can be obtained by separating TF into three components, namely ship, cargo, and fuel. In Reference 15, Kennell elaborates on these elements of Transport Factor.

Technology Advancements

Subsequent to the technical effort of the Carderock Division and the Advanced Marine Vehicle (AMV) community in its quest for speed during the 1970s and 1980s, considerable progress occurred in the categories of hullforms and ship subsystems. We briefly describe this progress here to provide the reader with a sense of the potential for these elements to contribute to high-speed ship technology.

Hullforms

The Advanced Naval Vehicles Concept Evaluation (ANVCE) study in the 1970s,[17] produced many AMV concept designs. For instance, hydrofoil designs ranged in sizes up to 2,400 tons and speeds to 70 knots. While these concepts explored the envelope of AMV feasibility, they did so using the technology of the 1970s. A conventional hydrofoil larger than about 1,500 tons in the near future is unlikely;

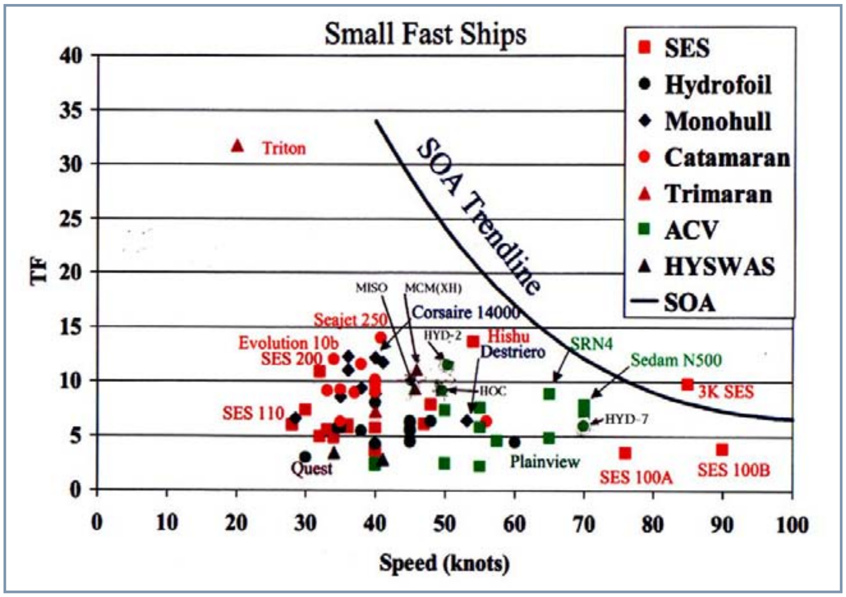


Figure 3. Transport factor versus speed for a variety of AMVs and ships.

however, hybrid hydrofoils of much greater displacement might be feasible. Although AMVs in the 70-knot regime are possible, speeds of 50 to 55 knots are more reasonable for the near future.

Figure 4 shows the relationship of the various major AMVs and the relative benefits derived from each compared to conventional displacement monohull ships.

Subsequent to the ANVCE study, another comprehensive study performed by NATO explored a host of AMVs.[18] The eight nations of the NATO Naval Armaments Group (NNAG), Special Working Group 6 (SWG 6), consisted of Canada, France, Germany, Italy, Norway, Spain, United Kingdom, and the United States. SWG 6 carried out studies to provide recommendations by which nations can decide upon their future involvement in NATO applications of Advanced Naval Vehicle (ANV) technology.

SWG 6 work on this particular project began in 1984 with the development of Outline NATO Staff Targets (ONSTs) for Hydrofoils, Surface Effect Ships (SES), and Small-Waterplane-Area Twin-Hull (SWATH) ships. Each ONST called for a multi-mission capability with emphasis on the Anti-Submarine Warfare (ASW) role. The objective was to assess the feasibility of increasing the operational capabilities of NATO Naval Forces by augmenting existing and planned forces with new platforms capable of operating at high speed and/or maintaining high mission capability through improved seakeeping under all sea conditions.

SWG 6 developed seven designs to a pre-feasibility level of detail and assessed their military value, affordability, and technical feasibility. The development needs for each were identified. SWG 6 concluded that the program had the potential of significantly increasing the combat cost-effectiveness of NATO forces entering service after the year 2000.

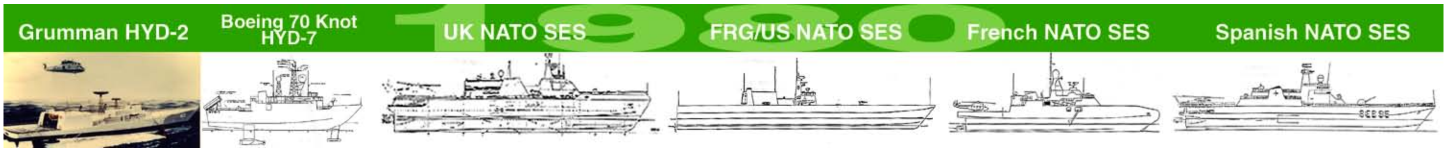
Advanced Marine Vehicles are sensitive to weight, power, and fuel efficiency. Most of these vehicles require, or their performance is enhanced by, an automatic control system. Both Navy and commercial technology development have advanced in these areas.

Structures/Materials

There have been even more dramatic advancements in lightweight composite construction. In its infancy in the 1970s, lightweight composite construction is now quite mature. AMV hulls were traditionally constructed of 5456-series aluminum to minimize weight. The yachting industry advanced the art of lightweight aluminum fabrication. New, higher-strength, stiffer alloys were developed. Composites offer not only light weight, but also opportunities to increase strength or stiffness. These characteristics can be of great benefit for all AMVs, but particularly for large hydrofoils whose hull girder is essentially supported at two points. Foils are an integral part of control systems for a wide variety of AMV applications. Relative to the technology of the early 1970s, newer, higher-strength, more easily fabricated steels offer the opportunity to construct struts and foils, not only for hydrofoils, but for motion control systems, at much less cost and lighter weight. Encapsulation systems can surround a structural element with a urethane airfoil shape. This technique allows much lower fabrication cost, better corrosion resistance, resistance to damage, and easier repair ability. Alternatively, better coatings protect struts and foils from corrosion.

Hydromechanics

Hydromechanics design tools advanced both for commercial and naval purposes. The AMV community now has the opportunity to design various hull forms, and examine a myriad of alternative shapes to determine minimum resistance. These design tools also apply to customized foil shapes for cavitation-free and minimum drag operation. Alternate control schemes, such as circulation control, can allow lighter weight, lower cost, and less complicated flight and steering control mechanics.



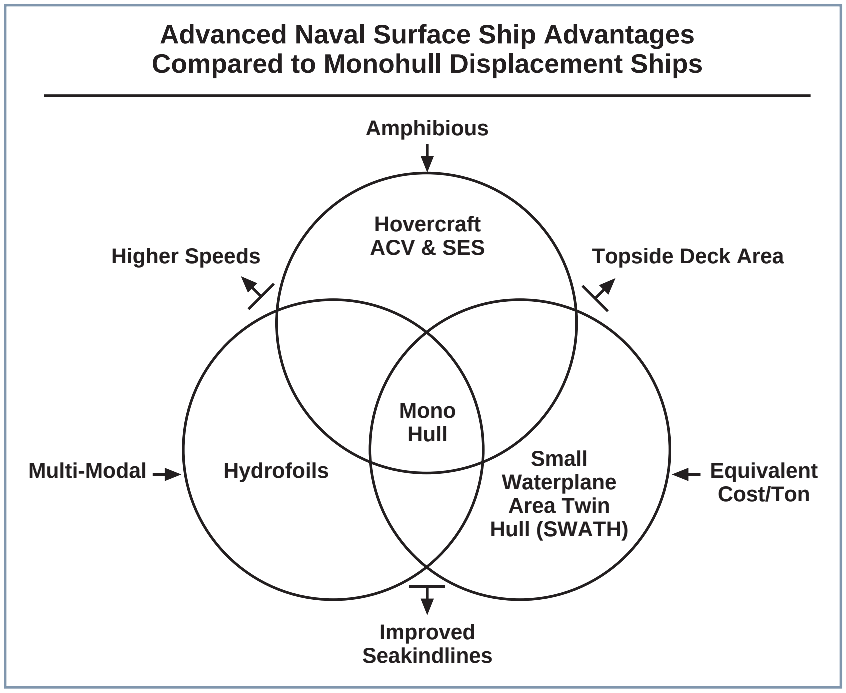


Figure 4. Advanced marine vehicle relationships.

During the past 10 to 15 years, catamaran hulls were employed by many builders, not only in the conventional sense, but also for commercial hydrofoils. The catamaran hull offers the foil designer a higher aspect ratio with a corresponding improvement in the lift-to-drag ratio. The recent interest in commercial catamarans by the Navy suggests that catamaran, or other multihull forms, might gain acceptance for naval missions.

Although the quest for friction drag reduction (FDR) goes back many decades, reducing this element of ship drag continues to be one of the hydrodynamicist's major goals. Over the years, numerous techniques such as micro-bubbles, polymers, air films, highly water repellent or Super Water Repellent (SWR) coatings, magneto-hydrodynamics, and probably others were the subjects of laboratory experiments. However, successful applications to full-scale ships were few, if any. Nevertheless DARPA, through the use of computational techniques, believes that modeling capability can allow researchers to run full-scale experiments on a computer. This capability can provide a basis for discovering techniques that bring optimum results. This technology can most likely succeed and result in a major contribution to greater hydrodynamic efficiency for future higher-speed AMVs.

Automatic Controls

Major advances in automatic control technology were made. Ride control systems for hovercraft continued to be improved over the last several decades. Also, although the PHM hydrofoils had an analog control system, which occupied a compartment of its own on the ship, now a digital control system can be built that fits in a laptop. Furthermore, the use of hydrofoils in ride control systems resulted in the development of much more efficient and effective algorithms for control. This challenging component of foil design for application to all AMVs was simplified greatly. Additionally, a corresponding decrease in control system cost and weight occurred.

Propulsion

Advances in naval gas turbine technology have fostered steady increases in propulsion efficiency over the last 30 years. Diesel technology has also improved during this time frame. Each is lighter weight, more power-dense, and more fuel-efficient. Gas turbines have now advanced to a degree where they may be advantageous over diesels in high power applications. Gas turbines are much more common in the Navy today than they were in the 1970s. The choice of prime movers, however, depends on a specific set of mission requirements and concepts for operations.

Propulsion system technology also advanced. Very large waterjets were developed for commercial applications. They are now much lighter, more efficient, and more reliable. Developments in podded propulsion systems and improvements in propeller efficiency make propeller propulsion considerably more efficient. Contrarotating propulsors are now commercially available for high-speed vehicles and can be scaled up to the power levels required for naval AMVs. Relative to the PHM-class waterjets, propulsive efficiency gains of more than 15 percent can result using modern propulsion technology. AMVs, and particularly hydrofoils, can also benefit from the investment made by the Navy in podded propulsors and electric drive systems. For air cushion vehicles, air propulsion has improved with the introduction of lighter weight materials. The High Speed Sealift Innovation Center project at NSWC Carderock addressed the technologies associated with a number of large (4,000 tons and greater) sealift ship concepts. Its Technology

Development Plan (TDP) is a key reference for future work on large high-speed ships.

Weapon Systems

Of all the improved subsystems that continue to progress subsequent to the AMVs of the 1980s, advancements in weapons, and the combat systems directing them are the most dramatic. Weapon lethality, as recently demonstrated during Operation Iraqi Freedom, is impressive in terms of accuracy, range, and power. Today, long-range pinpoint-targeting accuracy is the norm. When applied to ships, these capabilities, combined with the high-speed maneuverability of some AMVs, become a valuable mission asset.

High-speed ships also provide improved platforms for launch and recovery of Unmanned Air Vehicles (UAVs) because they can minimize the speed differential between the platform and unmanned vehicles.

Mission Applications of Speed

In documenting the quest for speed at sea, we examined the development of various vehicle types, the technologies that enable them, and their limitations and relative advantages. However, it is their mission suitability, effectiveness, and costs that, in the final analysis, determine their utility as a deployed fleet asset. So, in this section, we briefly examine the operational experience for U.S. fleet-deployed vehicles and compare the operational characteristics and tradeoffs among vehicle types. Finally, we briefly summarize the issues associated with the costs of development, acquisition, and operations.

Since the fall of the Berlin wall, the mission and vision of the Navy evolved from a blue-water, war-at-sea focus recounted in "*Maritime Strategy*" (1986), through a littoral emphasis articulated in "*...From the Sea*" (1992) and "*Forward...from the Sea*" (1994), to a broadened strategy in which naval forces are fully integrated into global joint operations – "*Sea Power 21*" (2002).[19] A new element of this strategy is the development of the Littoral Combat Ship (LCS). As articulated by the CNO, Admiral Vern Clark, in *"Sea Power 21,"* the "*stealthy and lethal Littoral Combat Ship will add new dimensions to our ability to counter enemy submarines, small craft and mines. Designed to be smaller and faster than any current U.S. warship, they will have the maneuverability and signature reduction to take the fight to the enemy.*" Admiral Elmo Zumwalt, a former CNO, articulated similar goals when he recalled the focus of the PHM program he started in 1970: "*Our concept was to achieve a small, high-performance, small radar cross section, high-speed, all weather capability with sufficient armament to deal with likely threats. Our planned use was to achieve presence in the smaller seas, i.e. Adriatic, Aegean, Gulf of Sidra, Red Sea, Persian Gulf, Arabian Sea, Pacific Rim areas and the Baltic and Black Sea.*"[20] In both cases, the Navy needs an alternative for using high-value assets for low-end missions. For the 29-year period ending 1999, almost 60 percent of missions conducted by ships were low-end missions.

While many of the high-speed vehicle types described above have been in existence for many years, we have limited experience in their application in actual naval missions. Of the high-speed concepts, only the hydrofoil, the air cushion vehicle, and the planing craft were operationally deployed. However, two extensive studies were conducted providing insight into the tradeoffs, value, and limitations of each concept: the Advanced Naval Vehicle Concept Evaluation (ANVCE) conducted in the United States from 1975 to 1979, and the NATO assessment of Advanced Naval Vehicles performed by the NATO Naval Armament Group's Special Working Group 6 (SWG 6) from 1984 to 1987.[21, 22] These two studies provide a comprehensive and balanced assessment framework, and along with the limited operational experience, provide insight into the naval utility of speed. We review here the experience, trends, and tradeoffs illustrated in the two studies as they relate to the use of speed and vehicle tradeoffs.

Operational Experience

Of the three deployed concepts, PHM, LCAC, and PC, the LCAC and the PC are still operationally deployed. Experience shows that successful operational deployment involves not only the ability to effectively perform assigned naval missions, but also integration into the Navy's logistics and support infrastructure.

Patrol Hydrofoil Missile (PHM)

The basic concept of the PHM was to operate offensively against major surface combatants and other surface craft to conduct surveillance, screening, and special operations. When measured against other ships, the PHM used its top speed and employed its weapons in heavy seas that severely limited the effectiveness of any of the larger conventional ships. After numerous delays and changes, the squadron of six PHMs was homeported in Key West, Florida. This decision was driven by a desire to show a "presence" in the Caribbean and support the U.S. Coast Guard in the counter-drug mission. In the operational period from 1977 to the decommissioning of the squadron in 1993, the following observations were made:[23, 24]

- The six PHMs, representing about 3 percent of the U.S. Navy, accounted for 26-29 percent of all surface Navy drug seizures over the ten-year period ending in 1993. The street value of the drugs seized by PHMs amounted to $1.1B, or 5 times the cost to operate the PHM Squadron over that period of time.
- From March 1983 to February 1987, the PHM Squadron amassed over 4,400 days underway with a voyage reliability rate of 97 percent.
- Three of the PHMs achieved 100-percent availability in a 90-day forward deployment to Grenada, ending in May 1987.
- The PHM Squadron staff, six ships, and their Mobile Logistic Support Group evolved to a personnel requirement in 1992 of 43 officers and 362 enlisted. This number is roughly equivalent to the crew aboard a destroyer-size ship.
- The PHMs actually cost about $3M per ship per year to operate, about 1/3 the cost of a FFG-7, or 1/5 the cost of a Spruance-class destroyer.

Landing Craft Air Cushion (LCAC)

The LCAC is an air cushion craft designed for transporting, ship-to-shore, personnel, weapons, equipment, and cargo of the assault elements of the Marine Air-Ground Task Force. They are capable of carrying heavy payloads (60-75 tons), such as an M-1 tank, at speeds in excess of 40 knots to the shore and across the beach. This unique combination of high speed and all-terrain capability is a dramatic innovation in modern amphibious warfare technology. The LCAC enables launching assaults from points over the horizon, thereby decreasing risk to ships and personnel, and it creates a greater uncertainty in the enemy's mind. Starting in 1987, the Navy acquired 92 LCACs to date and has conducted operations around the world, including the Arctic. The largest deployment of LCACs took place in January 1991 with four detachments consisting of eleven craft in support of Operation Desert Storm. The LCAC, which is deployable on six different classes of Navy amphibious ships, can reach more than 70 percent of the world's coastlines, compared to only 17 percent with conventional landing craft.

Cyclone-Class Coastal Patrol Ship (PC-1)

The primary mission of these ships is coastal patrol and interdiction surveillance, an important aspect of the Navy's littoral strategy. These 35-knot craft are able to transport small SEAL teams and their specialized delivery craft, or Coast Guard boarding teams, for counter-drug inspections and homeland-security operations. The *USS Cyclone* (PC-1) was commissioned in August 1993 and transferred to the U.S. Coast Guard in August 2000. Of the thirteen remaining craft, nine operate out of Little Creek, Virginia, and four out of the Naval Amphibious Base, Coronado at San Diego, CA. They have limited endurance for their size. These Navy vessels, slated for decommissioning in 2002, after September 11, will remain active in support of homeland security tasks. One of the craft, PC-14, was modified with a stern ramp permitting launch and recovery of a Naval Special Warfare RIB (Reinforced Inflatable Boat) while underway, an important LCS capability. The PC-14 also incorporates reduced radar, electro-optic, and infrared signatures.

Operational Characteristics and Tradeoffs

The two studies mentioned above, ANVCE and the NATO SWG 6 assessments, represent an important framework for comparing operational and ship characteristics tradeoffs. The ANVCE study considered nine generic concepts that generated 23-point designs using common criteria and payloads. The NATO study considered three generic concepts and generated seven-point designs also using common criteria and payloads. The resulting performance attributes of each concept were then compared and assessed by a team of experts. The following concept characteristics, taken from both studies, are provided to illustrate the operational limitations and advantages of the use of speed at sea as they might relate to the LCS:

- Overall speed comparison
- Days per year of sustained operations at speed
- High and low speeds operability in a seaway
- Range capability versus speed
- Mission payload weight trends

• Overall Speed Comparison

While maximum speed in calm water is an important design parameter, for military operations the speed in rough water may be a more significant measure. Figure 5, from Reference 22, shows a comparison of the predicted maximum, continuous, calm water-speeds of the point designs considered in the NATO study. Also assessed is the annual average maximum speed sustained in the North Atlantic. The concepts are ordered by the sustained speed in rough water and include a U.S. hydrofoil, Spanish SES, French SES, U.S./German SES, Canadian hydrofoil (surface-piercing configuration), U.K. SES, and a SWATH ship. A NATO frigate design (NFR 90), and the FFG-7 are included for comparison.

- **Days Per Year of Sustained Operations at Speed**

Speed, combined with limitations of weapons systems and crew effectiveness, measures the operational availability of a vehicle as an effective weapons system. The NATO studies assessed the operational availability (days per year) as a function of speed of each concept in the same North Atlantic environment, as illustrated in Figure 6. These calculations include the operational limitations of each concept type such as foil borne broaching, pitch angles > 3 degrees, and significant vertical accelerations at the bridge. For most of the year, the SESs and the hydrofoils have a clear sustained advantage over the monohulls (FFG-7 and NFR 90).

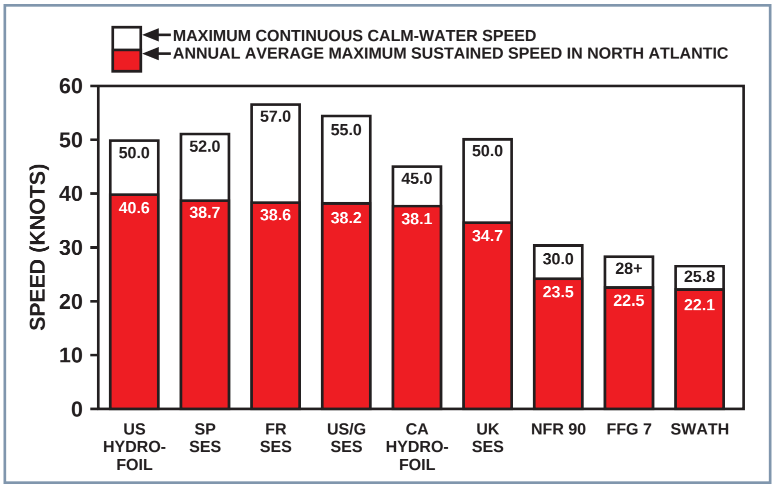


Figure 5. Comparison of speed capability.

- **High and Low Speed Operability in a Seaway**

The LCS is anticipated to operate in a sprint-and-drift mode for many of its operations, so low-speed operability is also important. The PHM-1, in a 12-day exercise off Hawaii called RIMPAC-78,[25] accumulated over 167 underway hours with 65 percent at low speed and an average speed-of-advance of 21.14 knots. The NATO study examined the operability at high and low speeds of the point designs in the northern North Atlantic in winter. Figure 7 illustrates the results of that assessment.

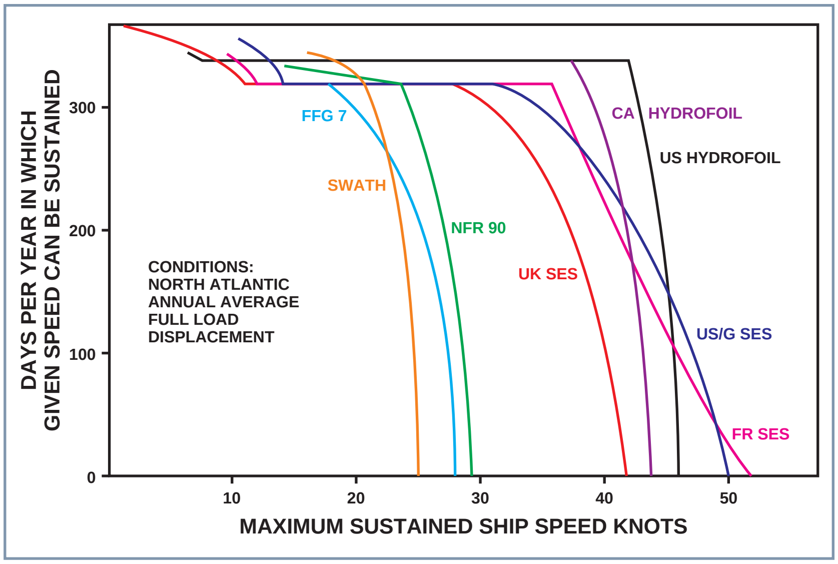


Figure 6. Days per year versus maximum sustained speed for NATO ANVs.

- **Range Capability Versus Speed**

Efficient multi-mode operation at high and low speeds is an important design consideration for the LCS. Figure 8 shows the predicted distance covered per ton of fuel for each LCS point design as a function of speed. The data show that the range of the SES and the hydrofoil can be extended considerably by resorting to hullborne operation. In comparison, the range of the SWATH ship and the FFG-7 can increase range only slightly by reducing speed.

- **Mission Payload Weight Trends**

Figure 9 shows the mission payload weight as a function of full-load displacement for the point designs in both the ANVCE and NATO studies. The NATO study observed: "*All the Point Designs carry considerably less mission-related payload than their respective baseline monohulls. The SES and the Hydrofoil Point Designs have smaller payloads because of their smaller size. Their payload weight fraction, however, is consistent with those of comparable monohulls. The SWATH ship, however, has a payload which is some 42% below the trend line established on the basis of full-load displacement.*"

Cost of Speed

In the final analysis, cost may be the most important determinant in deploying high-speed ships at sea. Is the cost worth the additional flexibility and mission effectiveness offered by the higher speeds? A cost assessment is the focus

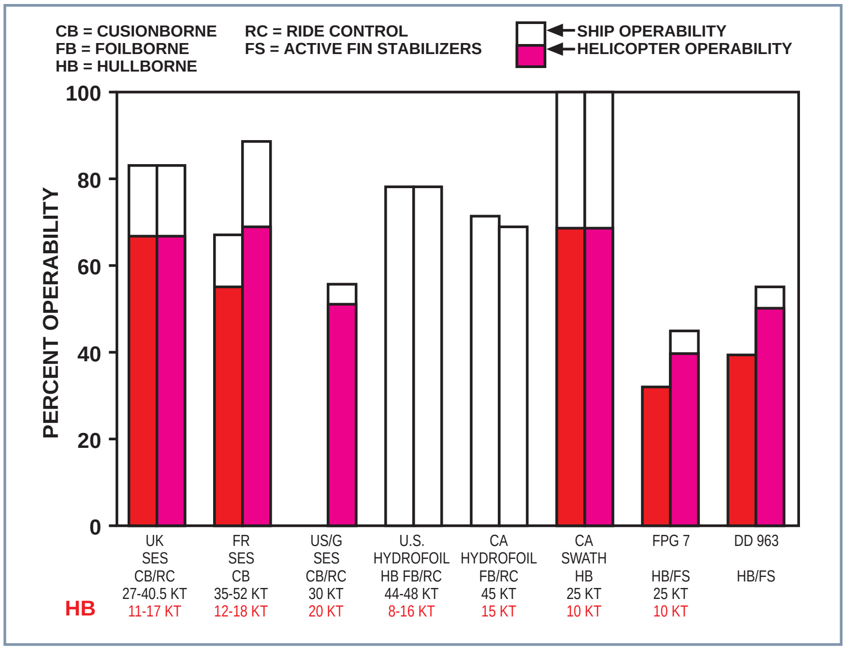


Figure 7. Comparison of percentage operability at high and low speed in Area 1 of N. Atlantic in winter.

of the two comprehensive studies mentioned above. Both establish a set of common standards and payloads that permits a more consistent cost-estimating methodology.

Vehicle Technology Development Costs

An aspect of cost not always discussed is the cost of developing the vehicle technology itself. This cost includes the basic and exploratory research (6.1 and 6.2) in the Navy's RDT&E accounting method, the advanced development (6.3) which examines and demonstrates total system technologies, the engineering development (6.4) devoted to pre-acquisition research on a specific configuration, and the actual ship construction costs, Ship Construction, Navy (SCN). The hydrofoil concept has the most complete history of these costs, starting in 1949 and ending in 1980 with the final SCN and RDT&E appropriations. This program resulted in two research vehicles (PCH-1 and AGEH-1) and eight operational vehicles (PGH-1 and 2, and six PHMs). The proportions of the total cost over the thirty-year research program and fleet deployment are

• Basic Research & Exploratory Develop.(6.1+6.2)	3.0%
• Advanced Development (6.3)	17.8%
• Engineering Development (6.4)	15.5%
• Ship Construction, Navy (SCN)	63.7%

Laying the technical foundation of a vehicle technology (6.1 to 6.3) represented about one-fifth of the total concept development cost resulting in a fleet deployable concept.

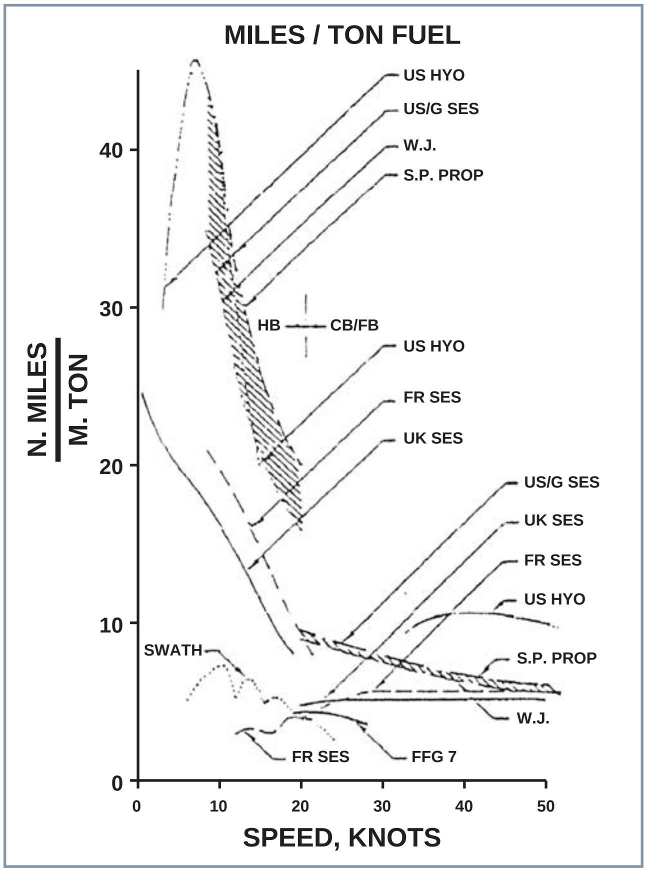


Figure 8. Comparison of range per unit of fuel.

Acquisition Costs

Acquisition costs are related to speed as well as vehicle size. As mentioned before, the ANVCE Study examined 23 different point designs and applied a common cost-estimating methodology to all designs. Figure 10, taken from Reference 26, is compiled for two classes of ships, a 3,000-ton and a 1,000-ton displacement class. The absolute values are ratios of the FFG-7 costs. Peter Mantle, the Technical Director of the ANVCE study, states: "*The cost of going faster increases almost linearly until the dynamic (lift) vehicles come into play (i.e., hydrofoils, air cushion vehicles, and surface effect ships), at which time speed comes relatively easily and cheap. However, it will be noticed that the cost of such vehicles over a conventional warship (FFG-7) is greater than 2:1*".[27]

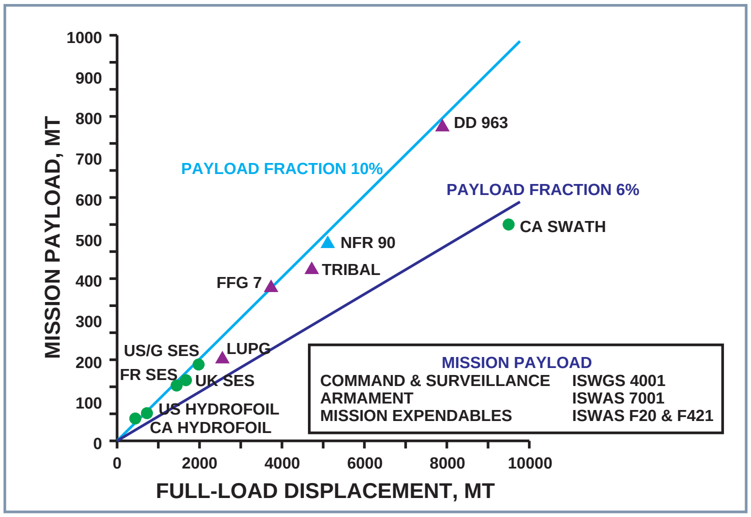


Figure 9. Comparison of mission payload.

Operating and Support Costs

Operating and support costs range from 52 percent to 69 percent of the total life-cycle cost, which includes development, acquisition, and operating and support costs. The NATO SWG 6 study examined operating and support (O&S) costs for the six advanced ship point designs. Lifetime O&S costs consisted of the following cost elements: direct personnel, operations (less fuel), fuel, direct maintenance and modernization, recurring investment, and indirect costs. Table 1 compares the proportions of the annualized O&S cost per ship for an average of the four SES designs, and an average of the two hydrofoil designs compared to the FFG-7.

Although size and payload differ significantly, the higher-speed vehicle requires a smaller crew than the FFGs, most probably due to an increase in ship automation. However, the percentage of the annual O&S cost in terms of fuel significantly increases.

Summary

A serious question remains: after all this scientific and technical development – why does the Navy not have higher-speed ships? The answer is as complicated as the technologies required to increase speed at sea. The quest for higher-speed ships competes for a share of limited fiscal resources. In addition, because Navy culture and career incentives prefer larger ships with larger crews, it is perceived that we must modify the Navy's support and logistic infrastructure to accommodate such new technologies. These changes constitute major disincentives. Despite these disincentives, several high-speed vehicles have already found their way into naval service. The most notable example for the U.S. Navy is the Landing Craft Air Cushion (LCAC). The LCAC is an ideal means of transporting troops and heavy equipment from a standoff position many miles from shore, through the littoral, across beaches and marshes to solid ground, and farther inland. It would seem, however, that high-speed ships are not yet fully integrated into the Navy's current strategic and tactical thinking.

As the nature of the threats to the United States and other major maritime powers changes in the 21st century, the long-recognized technical advantages of high-speed and shallow-draft, air-cushion vehicles are likely to receive even greater attention. With the emphasis in the U.S. Navy's new vision on littoral warfare expressed in "Sea Power 21," and the new role of the Department of Defense in dealing with asymmetric threats posed by terrorists, rogue states, and criminals who use the high seas, it may well be that the time for higher speed ships has arrived. If so, the Carderock Division will, as it has in the past, be an integral part of the persistence in developing the technology necessary to continue the quest for speed at sea.

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Table 1. Annualized O&S Cost

	% of Annualized O&S Cost		
O&S Cost Categories	Avg. SES	Avg. HYD	FFG-7
• Direct Personnel	19%	17%	32%
• Operations (less fuel)	13%	14%	14%
• Fuel	37%	21%	17%
• Direct Maintenance and Modernization	25%	39%	31%
• Recurring Investment	4%	7%	4%
• Indirect Costs	2%	2%	2%

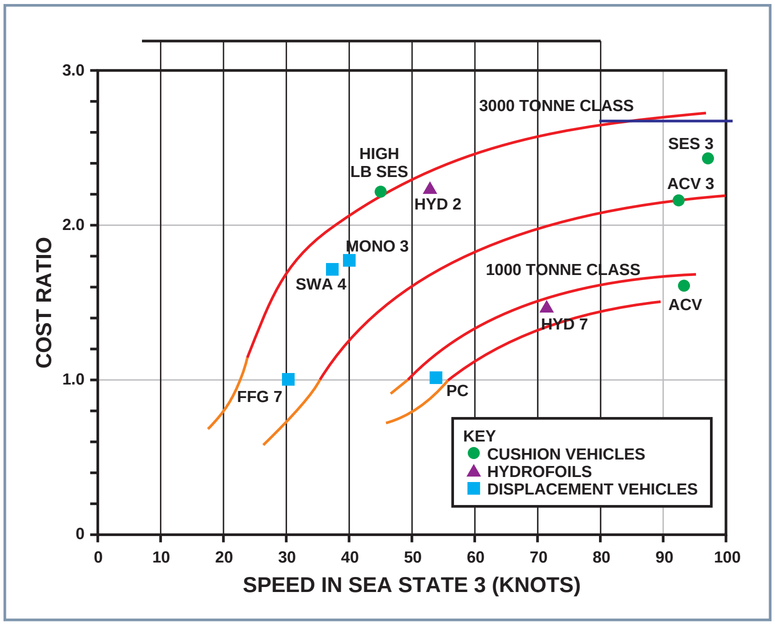

Figure 10. The cost of speed.

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*Note: Most references are available from the website of the International Hydrofoil Society. They are also available on AMV compact discs that are available from the IHS for a small fee.

Dennis J. Clark *worked at the Carderock Division of the Naval Surface Warfare Center for nearly 40 years in a wide variety of positions prior to his retirement in January 2003. He has been Director of Strategic Planning, Assistant Technical Director, Head of the Costing and Design Systems Office, Deputy Head of the Advanced Concepts Office, Manager of Systems Integration in the Advanced Hydrofoil Development Office, and lead structural researcher for the Hydrofoil Office. He is a charter member of International Hydrofoil Society and throughout his career he has supported the development of advanced vehicles through a number of activities: developed the Advanced Ship Data Bank (currently containing over 15,000 documents on advanced vehicles); led the development of a total ship early stage design tool called ASSET (Advanced Surface Ship Evaluation Tool) for a variety of ship types (surface combatants, hydrofoils, SWATH ships, and tri-hull concepts); led the development of cost estimating capability for advanced technology and vehicles; and promoted innovation through a number of venues by serving as chairman of Carderock's Invention Evaluation Board for the last ten years, promoting the development of Carderock's Innovation Center, and functioning as ONR's lead researcher on the Concept Assessment of Platforms and Systems task. Mr. Clark is an engineering graduate of City College of New York and has completed graduate work toward an MBA at George Washington University.*

William M. Ellsworth *P.E. graduated from the University of Iowa in 1948 with an M.S. in Mechanical Engineering, majoring in Fluid Mechanics. Upon graduation, he joined the David Taylor Model Basin Hydromechanics Laboratory as a Project Engineer. Over the next ten years, he completed course work for a Ph.D. in Aeronautical Engineering and held various positions in the Hydromechanics Laboratory, ending as the Head of the Towing Problems Branch.*

He left DTMB in 1958 and joined the newly formed Systems Engineering Division of Pneumo Dynamics Corp. as Head of Marine Engineering. He held various positions over the next six years ending up as Division General Manager and Corporate Vice President.

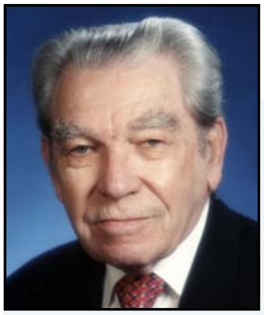
In 1964, at the invitation of Dr. William E. Cummins, Head of the Hydromechanics Laboratory, he returned to the David Taylor R&D Center as Head of the Hydrofoil Technical Development Program. In 1969, he was appointed Associate Technical Director for Systems Development, and Head of the newly created Systems Development Department, initially as GM-17, and later as an ES-4 in the Senior Executive Service. He was responsible for the development of advanced naval vehicles including hydrofoil craft, air cushion craft, amphibious assault craft, Small-Waterplane Twin-Hull (SWATH) ships, advanced submarine concepts, mobile ocean bases, and shipboard material handling and transfer systems.

He retired from federal service in January 1983 and joined Engineering & Science Associates (ESA), a small group of consultants, as Vice President. Over the next ten years, he provided consulting services in marine systems and advanced naval vehicles to a variety of government, academic, and commercial activities. He wrote a book on the Navy's experimental hydrofoil Highpoint (PCH-1) entitled "Twenty Foilborne Years." He also assisted Dr. Rodney Carlisle in the writing of the 100-year history of the David Taylor Research Center, entitled "Where the Fleet Begins," and served as the co-chairman of the Editorial Advisory Board.

When ESA disbanded in 1994, he formed Ellsworth Engineering as a sole-proprietorship and continued to provide consulting services to government and industry up to the present time.

He received the David Taylor Medal in 1967, the Navy Civilian Service Award in 1972, the ASNE Gold Medal in 1974 as Naval Engineer of the year, the Navy Distinguished Civilian Service Award in 1980, and the Senior Executive Service Meritorious Presidential Rank Award in 1980.

He is currently a Fellow and Life Member of ASME, a life member of ASNE, a member of the U.S. Naval Institute, and a licensed Professional Engineer in the State of Maryland.



John R. Meyer *holds B.Ae.E. and M.Ae.E. degrees in Aeronautical Engineering from Rensselaer Polytechnic Institute, and has done additional graduate work in the same field at the Massachusetts Institute of Technology. He joined the Naval Surface Warfare Center, Carderock Division (NSWCCD) in 1971, was associated with Advanced Naval Vehicles in the Advanced Concepts Office, and then served as Manager of Hydrofoil Technology in the Hydrofoil Group of the Ship Systems Integration and Programs Departments. He has authored many NSWCCD reports, American Institute of Aeronautics and Astronautics, and American Society of Naval Engineers papers on the subject of hydrofoils and hybrid marine vehicles. He retired from the Center in 1997 and has been active as a consultant in this field. Among other projects, he has been working on a project for the NSWCCD involving the Planing HYSWAS Integrated Mode (PHIN) Unmanned Surface Vehicle.*

He currently serves as President of the International Hydrofoil Society. Prior to employment at NSWCCD, he held several research and development, long range planning, and engineering management positions with Boeing-Vertol, Trans-Sonics Inc., Air Force Cambridge Research Center, and the Aero-Elastic Laboratory at M.I.T.