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SWATH Evolution: From Ideas to Ships

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SWATH EVOLUTION: FROM IDEAS TO SHIPS

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Abstract

The evolution of the SWATH (Small Waterplane Area Twin-Hull) ship concept is described with special emphasis on how the new ideas were generated, problems solved, and support obtained. The steps leading to the final concept are discussed, together with the methods used to explore and better understand the concept, and how the concept was transformed into an operational prototype. Due to its unusual shape, the 227-ton, 89-ft SSP KAIMALINO prototype has demonstrated motion reductions in waves by factors of four and more relative to conventional monohull ships; this new concept has greatly reduced sea sickness and permitted new vessels to carry out operations at sea which are not possible for conventional ships of the same size.

Introduction

Objectives

The objective of this paper is to present the history of the SWATH concept up through the development of a prototype vessel, and beyond to possible new applications and designs. Emphasis is placed on the people involved, the technical problems, management, milestones, dates, places, and the resulting reports.

SWATH Definition

The acronym "SWATH", like most acronyms, requires further definition since acronyms are seldom explicit. The words "Small Waterplane Area Twin Hull", for example, describe a multitude of vessels since they relate to many kinds of conventional and unconventional catamaran boats including the well-known Hobie Cat sail boats, the Polynesian Proas which have an outrigger, and a wide variety of offshore drilling rigs, in addition to the traditional SWATH vessels. The definition of "SWATH", as used herein, is "a twin-hulled vessel having a small waterplane area, streamlined surface-piercing struts, and twin fully-submerged lower hulls equipped with stabilizing fins". This definition clearly eliminates drilling rigs and catamarans, for example, and yet includes all of the traditional SWATH vessels in operation in the world today.

SSP KAIMALINO

The U.S. Navy's SSP KAIMALINO, launched in 1973, is the world's first SWATH** vessel [1], and is shown in Figure 1. The SSP KAIMALINO*** is an ocean-going vessel consisting of two submerged, parallel, torpedo-like 6.5-ft-diameter hulls, each connected by a pair of streamlined struts to a cross structure supported above the water. Two controllable canard fins are attached near the hull bows, and a full-span stabilizing fin equipped with two control flaps is located near their sterns. The SSP's uniqueness centers on her very low motion in waves, either at rest or underway, large deck area, center well, speed capability, underwater viewing dome, and ability to maintain speed in large waves with very little drag increase. The SSP design was initiated after only one man-year of research followed by a half year of work by several researchers. The SSP design proceeded swiftly; some of the research was done in parallel with the design work. Following the completion of the SSP, many other SWATHs have been built and

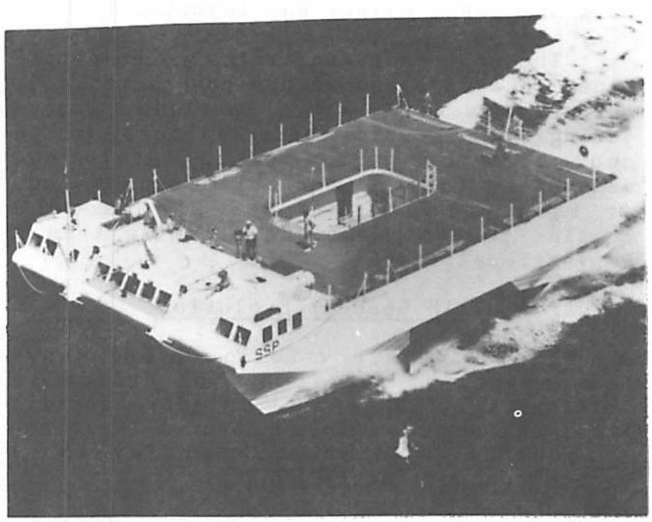

Figure 1. 227-ton SSP KAIMALINO operating in the waters off Hawaii.(U.S.Navy photo)

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** The "SWATH" acronym was introduced some years later but it is used here and elsewhere for clarity.

*** SSP stands for Stable Semi-Submerged Platform, and KAIMALINO is Hawaiian for calm water.

successfully operated in the 12 to 27 knot range having displacements up to 3,500 tons. All of these SWATHs utilize the general stabilizing fin and optional canard fin concepts first introduced by the SSP. SWATH vessels have alternatively been called Semi-Submerged Ships (S^3), Semi-Submerged Catamarans (SSC), and Mod-Cats.

Technical Questions

Some basic questions regarding SWATH are:

(1) Does it do something new and useful?, (2) Is it feasible?, (3) Is it practical?, (4) What are its uses?, (5) How is it designed?, and (6) What are its characteristics? These and other questions will be addressed in this paper.

The design of a SWATH vessel is relatively complex because of the many variables. The geometric design variables include: (1) lower hull length, height, breadth, cross-sectional shape and variation along the hull, depth, and hull spacing, (2) strut location, chordlength, cross-sectional shape and variation along its height, thickness and number of struts per side, (3) cross structure length, beam, height, water clearance, shape, number of decks, (4) sponson length, width, depth, cross-sectional shape and variation along its length, (5) fin locations, number, span, chord, thickness, planform shape, cross-sectional shape and variation along the span, and means of controlling them, and (6) rudder size, shape, location, and number.

The mechanical and structural design variables are similar to those of conventional ships, except for the addition of ballast tanks and pumps, a wider choice of engine locations, addition of an optional fin control system for motion control, a new set of structural load conditions, and a wider choice of deck and cabin shapes and layouts.

The ship characteristics to be determined include speed versus power, payload, motion in waves, natural periods, maneuvering, fin control effectiveness, range and endurance versus fuel, intact and damaged stability, anchoring and towing. It is apparent that a SWATH is more complex to design and to optimize than a conventional vessel.

SWATH Concept Evolution

The SWATH story follows, and shows how invention, research, and design in combination with people, talents, facilities, and organizations produced the operational SSP prototype, and developed technology for future SWATHs.

Personal Background

My invention of the SWATH concept spanned nearly two decades. I was unfamiliar with older concepts that might have been related to the SWATH concept. However, I had degrees in the fields of mechanical, civil, and aerospace engineering from Caltech, USC, and Pennsylvania State University, and I had developed a specialty in the field of underwater vehicle hydrodynamics at NOSC (Naval Ocean Systems Center, but called the Naval Ordnance Test Station at the time). Furthermore, I was interested in new concepts and ideas, and had hobbies that led to the development of the SWATH concept.

One of the hobbies was especially significant; this was the design, construction and testing in the 1950's of new types of outboard-powered hydrofoil boats. My father helped with the construction and testing; together we built and tested twelve different hydrofoil boat configurations.

Early SWATH Concepts

The hydrofoil hobby led to a parallel goal in the early 1950's, which was to develop an alternative to hydrofoils for lifting a hull above the water. I began with ideas to lift a person, rather than a hull, above the water. I sketched many ideas, including two parallel, submerged, streamlined bodies, one attached to each foot. I then modified this "water walker" concept into an idea for lifting hulls by sketching designs which showed two parallel underwater bodies that supported boat hulls, house boats, and other box-like platforms above water. Variations included the use of from one to five underwater bodies. Although the new ideas came at various times of the day, they most often came while I was purposefully trying to sketch such new ideas. Occasionally, I stopped sketching and calculated the displacement and drag to predict the power required for propulsion. I studied many variations in size and shape of the different configurations. The underwater bodies were sometimes equipped with fin appendages, including aft stabilizing fins; occasionally, I added small fins located forward on the bodies. The introduction of stabilizing fins to SWATH ships counteracts the so-called "Munk moment" (a destabilizing hydrodynamic moment acting on bare hulls that tends to turn them broadside to the flow) and provides dynamic pitch stability. Small controllable fins are optionally located forward which I called "canards" (named after similar fins located forward on some aircraft) to aid in motion control and to assist the stabilizing fins in damping motion. These canard fins increase damping of motion, but are destabilizing, so the stabilizing fins must be larger than normal in size.

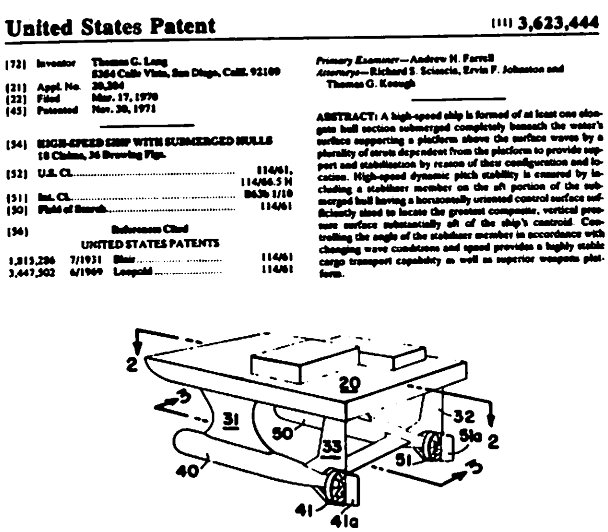
From time to time in the mid and late 1950's, other ideas came to me for supporting hulls above the water. These included boats with ram wings, air cushion vehicles (later called hovercraft and ground effect machines), and surface effect ships (also called captured air bubble craft), having air cushions and sidewalls. Occasionally, I made calculations of lift, drag, power, air pressure, and curtain power to help determine the feasibility of these ideas.

Later SWATH Concepts

During the early 1960's, the ideas for utilizing underwater bodies to lift a hull above water tended to center around two parallel bodies, with occasional sketches showing one submerged body with some type of surface-piercing stabilizing means. The ideas for the SWATH concept crystallized in the early 1960's. Work on the SWATH idea temporarily halted from January 1965 to June 1968 while I earned a Ph.D. degree in Aerospace Engineering under a 2.5-year Navy scholarship. While there, I wrote a thesis on a generalized engineering design procedure [2] which included examples for the design of airplane wings, two- and three-dimensional hydrofoil fins, and submerged vehicles. This design methodology was useful throughout the development of the SWATH concept.

Patents

Figure 2 shows the first of several patents that I own on SWATH vessels. This U.S. Patent #3,623,444 is the first patent (Nov. 30, 1971) which covers all of the features of existing SWATH vessels, including stabilizing fins and optional canard fins. Also, it covers either one or more struts per side. The U.S. Government has license-free use of this patent. I was allowed to retain the commercial rights in view of inventing the basic idea outside of work, and the fact that ship design was not within either the mission of the Center or my work duties at that time.


United States Patent [11] 3,623,444

[72] Inventor Thomas G. Lang, 5364 Calle Vista, San Diego, Calif. 92109
[21] Appl. No. 20,304
[22] Filed Mar. 17, 1970
[45] Patented Nov. 30, 1971

[54] HIGH-SPEED SHIP WITH SUBMERGED HULLS
10 Claims, 36 Drawing Figs.
[52] U.S. Cl. 114/61, 114/66.5 H
[51] Int. Cl. B63b 1/10
[50] Field of Search 114/61

[56] References Cited
UNITED STATES PATENTS
1,815,286 7/1931 Blair 114/61
3,447,502 6/1969 Leopold 114/61

Primary Examiner—Andrew H. Farrell
Attorneys—Richard S. Sciascia, Ervin F. Johnston and Thomas G. Keough

ABSTRACT: A high-speed ship is formed of at least one elongate hull section submerged completely beneath the water's surface supporting a platform above the surface waves by a plurality of struts dependent from the platform to provide support and stabilization by reason of their configuration and location. High-speed dynamic pitch stability is ensured by including a stabilizer member on the aft portion of the submerged hull having a horizontally oriented control surface sufficiently sized to locate the greatest composite, vertical pressure surface substantially aft of the ship's centroid. Controlling the angle of the stabilizer member in accordance with changing wave conditions and speed provides a highly stable cargo transport capability as well as superior weapons platform.

Figure 2. U.S. Patent #3,623,444 on fin-stabilized SWATH vessels which covers one or more struts per side, Nov. 30, 1971.

Other Early SWATH-Like Patents

The earliest SWATH-like patent I have found while searching the U.S. Patent Library is Nelson, 1905 [3]. Although this design has twin submerged lower hulls, the water line is midway up a pair of additional twin upper hulls, so it would not be a SWATH. Faust, 1932 [4] invented a vessel which has four underwater hulls which is somewhat SWATH-like, but still not a SWATH. The earliest patent which comes closest to a SWATH is Creed, 1946 [5] which has twin submerged hulls, and one long strut per side, but no stabilizing fins. Leopold, [6] is very similar to Creed's concept, but his patent claims are more narrow, specifying non-cylindrical (non-circular) lower hull cross sections and at least one concave side on each strut; like Creed, his concept has no stabilizing fins, so it, too, is not a SWATH as defined herein. These patents are illustrated in Reference [7].

The Navy's First SWATH Program

Introduction of the SWATH Concept into the U.S. Navy

After returning in July 1968 from PhD work to my Navy laboratory in California, I was invited to join a design group working on a new type of underwater vehicle. Later in 1968, I was asked by the group to search the literature for a small high-speed mother ship to support the vehicle, and one that would be very stable at high speed in large waves. I could not find an adequate ship. As a consequence, I suggested that the SWATH concept, which I had been working on as a hobby, be used for the mother ship. The group thought this was a good idea, and suggested that I describe this new concept to the laboratory's technical director, Dr. William B. McLean (inventor of the well-known U.S. Navy Sidewinder air-to-air missile).

Dr. McLean was highly supportive of this new concept, especially since he had recommended that the Navy should consist of submarines in combination with small surface ships. The SWATH concept fit nicely into this goal since it would make small ships more feasible because of their reduced motion in waves. However, the mission of NOSC was anti-submarine warfare (ASW) systems, and not the design of ships. Consequently, Dr. McLean asked me for a proposal to study the feasibility of this new concept and how it might effect ASW systems in particular, and Naval systems in general. He immediately accepted the resulting proposal dated 9/30/68, and allocated IED (Independent Exploratory Development) funds to conduct a technical analysis of the SWATH concept.

Technical Analysis Study

The SWATH Technical Analysis Study sponsored by NOSC IED was the first Navy study on SWATH; also, it was the first known study on fin-stabilized SWATH ships. An initial step in the study consisted of sketching various shapes and sizes of SWATH naval ships, together with estimates of their speed and power. Using these results, a nondimensional relationship was developed (using the methodology of [2]) for power as a function of size and speed. This relationship was graphed together with similar relationships developed from published data for monohull ships, submarines, planing boats, hovercraft, and surface effect ships. The results indicated that SWATH vessels were more efficient than other craft in the intermediate speed region between where displacement monohulls and planing monohulls are commonly used.

Another part of the technical analysis was the development of equations for calculating the static roll stability and the natural period in roll. Also developed, was a preliminary analysis of strut stress as a function of the spreading and crowding loads that act on the lower hulls and struts.

PSAC Presentation

Work proceeded rapidly on the new concept. Dr. McLean arranged for me to give a presentation on the SWATH concept to the President's Science Advisory Committee (PSAC) on 11/25/68. The above-mentioned graph was presented among others, together with a discussion of possible naval uses of SWATH. The concept was of considerable interest to the Committee, which recommended that model tests be conducted.

Technical Analysis Report

The technical analysis report was completed in May 1969 [8]. Ref. [1] provides selected excepts. The study summary stated that this new concept shows considerable Navy promise, and that a towing tank test program was being planned in preparation for the design and testing of a man-carrying test craft. This man-carrying test craft evolved into the SSP KAIMALINO. A variety of SWATH naval ship designs and applications were analyzed and proposed in [8]; many of these applications remain viable candidates today.

Early SWATH Model Tests

Earliest Models

As part of my continuing hobby on SWATH, small models were made at home and tested in a bath tub; they exhibited very little motion in waves, and high damping of forced motions. One of the models was towed by hand in calm water on 3/1/69, and demonstrated surprisingly little evidence of wave-making drag.

Model Test Alternatives

I considered various alternatives for Navy-sponsored model tests as early as September, 1968. In a discussion on 9/16/68, Dr. McLean suggested a man-carrying version, instead of a model, that would be made using two torpedo hulls. Calculations later showed that available torpedo hulls were too heavy, so I continued to make calculations on tow tank model alternatives. In April 1969, I proposed a program and cost estimate for tests on a variable-geometry tow tank model to be followed by the development of two progressively-larger man-carrying SWATH test craft.

First SWATH Towing Tank Tests

Early in 1969, information on the SWATH concept was given to the Naval Ship Systems Center in Washington, D.C. (currently called the Naval Sea Systems Command, and referred to herein as NAVSEA) and funding was requested for model tests. The request was turned down, based upon a belief by the Naval Ship Research and Development Center (now called the David Taylor Research Center, DTRC) that the proposed concept would be unstable in pitch. As a result, Dr. McLean funded the model tests under the Center's IED program. The objective was to obtain not only the usual hydrodynamic data, but also motion pictures of the model when free to heave and pitch in order to prove that it was indeed stable. I completed the model design and test plan on July 2, 1969. The model variations included length, beam, hull shape, stabilizing fin size, strut location and thickness, and vertical center of gravity. The test variables included pitch angle, yaw angle, model restraint in heave and pitch, and wind direction. The data included five components of forces and moments, and three components of model motions. Both still and motion pictures were taken.

About 500 test runs were conducted during August and September, 1969 (Figure 3) with the assistance of H.V.L.Patrick of NOSC. The results showed that the stabilizing fins were indeed needed to prevent pitch instability at moderate to high speeds. Also, a greater longitudinal spacing between struts reduced pitch motion in following waves. Good motion characteristics in beam waves and winds occurred when the transverse metacentric height was between 0.5 and 1.0 hull diameter (i.e. about 8% to 16% of the beam). Comparative tests with a conventional ship model showed that the SWATH concept greatly reduced motion in waves.

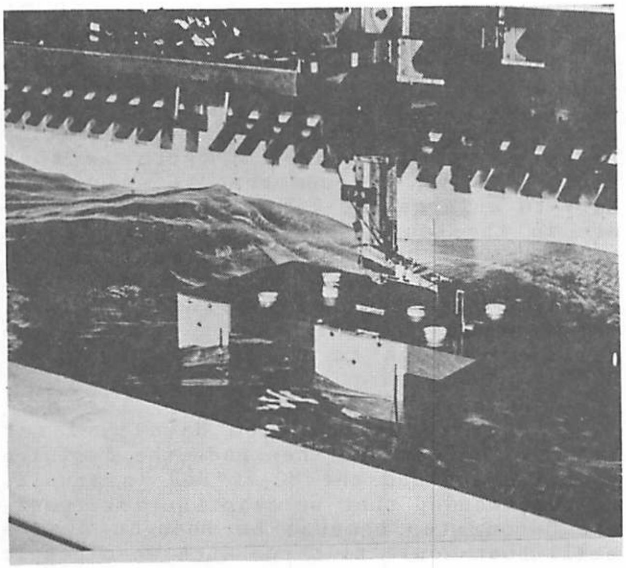


Figure 3. First tank tests of a SWATH model, conducted in the 315-ft Convair/General Dynamics towing tank in San Diego, Ca, August 1969. (U.S. Navy photo)

First SWATH Feasibility Study

Sponsorship

Later in 1969 I again visited NAVSEA, and took along model data and motion pictures that verified the stability of SWATH vessels. This time there was greater interest, but still no funding. As a consequence, I approached NAVAIR (Naval Air Systems Command), ONR (Office of Naval Research), and DARPA (Defense Advanced Research Projects Agency). Interest was high, especially by R. Krida in NAVAIR who saw the potential as a carrier for helicopters, V/STOL, RPV's, missiles, and Naval aircraft. He was the first to provide outside funding; it was to be used for a Naval Feasibility Study on SWATH to support air systems. Following his support, I was able to obtain funding from J. Smith and CDR R. Hanford in ONR to study technical questions related to SWATH dynamics, propulsion, and structures. This sponsorship led to another group in ONR, headed by CDR S. Gordon, which supplied funding for a detailed analysis of the SWATH towing tank data. DARPA was also interested, but not to the extent of sponsorship. With this funding in hand, I went back to J. Haines in NAVSEA who now agreed to sponsor a generalized SWATH ship feasibility study.

Since each sponsor was interested in different aspects, we integrated the effort into a single comprehensive Naval Feasibility Study. This is probably one of the few times that a feasibility study has been sponsored jointly by NAVAIR, ONR, and NAVSEA.

Project Personnel

Work on the Naval Feasibility Study began in January 1970. There were many questions to answer, so I obtained the part-time assistance of several NOSC personnel. These included P.D. Burke for the structural analysis, J.L. Wham and R.M. Anderson to explore the sonar potential of SWATH Navy ships, W.J. Sturgeon (Jakus Associates) who made the concept drawings, and R. LaMoglia who gathered background material for the systems analysis. I was able to hire D.T. Higdon to explore SWATH ship motions and automatic control. P.L. Warnshuis transferred into this fledgling group to lead the operational utility study, and H.E. Karig transferred in for the propulsion system analysis. These latter personnel formed the beginning of the Advanced Concepts Group that I led for the next eight years until retiring in 1978 (the Group worked not only on the SWATH ship concept, but many other types of new Naval vehicles, ideas, and systems). Other NOSC personnel who provided ideas and reviewed our reports were W. Hicks, D. Colladay, R. Sulit, J. Avery, and D. Schultz.

Feasibility Study Results

The feasibility study was completed in September 1970, and a seven-part report was published [9]. This report concluded that the SWATH concept was technically feasible in all respects, and that many potential Naval applications existed. Chief among the recommended SWATH applications were its use for basing aircraft and missiles, sonar and anti-submarine warfare, patrol, mine detection, oceanic research, submarine rescue, and hospital ships.

Burke made good progress on structural ideas and estimated the structural weight of all-steel and all-aluminum SWATHs as a function of vessel displacement [9, Part IV]. Higdon analyzed the loads and motions in waves for general SWATH ships, including the effects of automatic control [9, Part III]. He showed that very little motion would result in waves, and that automatic control would further reduce motion by a factor of two or more. Karig developed generalized propulsion system weights for SWATH ships as a function of power level for diesels, turbines, and combinations thereof [9, Part V]. He also showed that the power plants could be located in the lower hulls. Warnshuis [9, Part VII] developed a generalized mathematical model for determining SWATH ship performance, based upon information developed in other parts of [9]. He also included the option of towing a fuel pod to extend range, and recommended many types of applications for SWATH ships. Wham and Anderson covered the sonar potential of SWATH ships [9, Part VI], showing that great potential exists relative to conventional monohulls, which led to the idea of replaceable bow domes for the SSP. My contribution was to summarize the overall study and present an analysis of the SWATH model tank tests [9, Parts I and II].

Development of the SSP KAIMALINO, the First SWATH

SSP History

In December 1986, I presented a paper [1] on the history of the SSP at the Winter Annual ASME meeting as the result of a request by Dr. J.D. Stachiw (NOSC) and his wife, Dr. J. L. Stachiw who were affiliated with the historical section of this society. Parts of this present paper were abstracted from that reference. Details on the SSP design are presented in [1] and [10].

Early SSP Designs and Proposals

Returning to the 1968 and 1969 period, I proposed on 5/28/69 the construction of a 1-ton manned SWATH to be followed by the preliminary design of a 20-ton SSP having clear acrylic bow domes on the lower hulls for underwater viewing. (Although the acronym for SSP was not yet coined, it will be used from here on to denote the designs which evolved into the final SSP design.)

Later, Dr. McLean asked me to propose a larger SSP than 25 tons to follow the 3-ton boat development; preferably one that could be used at NOSC San Diego for supporting the NOSC CURV (an undersea tethered Controlled Unmanned Recovery Vehicle). As a consequence, I made design calculations for a 50-ft SSP for oceanic research which had two 5-ft diameter clear acrylic bow domes. This proposal was received with great interest by Dr. J.S. Lawson, the Director of Naval Laboratories (DNL) when Dr. McLean and I visited him on 1/14/70. He seemed to be our best hope for sponsorship since a NavSea representative told me somewhat later on 3/19/70 that a 50-ft SSP development was premature and that recent tests on a ModCat model (SWATH-like design without fins) at DTRC indicated that a small 50-ft SWATH would swamp in the ocean.

In March 1970 Dr. McLean asked me to travel to the NOSC Hawaii laboratory to visit J.D. Hightower (JDH) who was managing the RUWS program (a tethered Remote Undersea Work System vehicle, a larger and deeper-diving version of the CURV). The goal was to explore the possibility of using the 50-ft SSP at NOSC Hawaii to support the RUWS instead of basing it at NOSC San Diego to support the CURV. Also, I was asked to explore the possibility of enlisting the aid of JDH in having the vessel built in Hawaii, if it was desirable to use it there. I briefed JDH in Hawaii on March 30-31, showed him SWATH films and slides, and gave him copies of our SWATH work including an outline of a 50-ft SSP development plan. He liked the idea of using the SSP to support RUWS, and suggested that a center well be included in the SSP to lower the RUWS into the ocean. Having made previous calculations on the structure, I readily agreed since a 4-strut SWATH configuration requires no structural members in that region. Also, I found that it was necessary to enlarge the SSP in order to operate in the rough seas around Hawaii, and to support the RUWS. The next day in Hawaii, I made the necessary calculations and laid out the design of an 80-ft SSP. Many aspects of this 80-ft SSP design carried through to the final design of SSP.

After returning from Hawaii, I met with Dr. McLean who then made the decision to build and use the 80-ft SSP in Hawaii. He recommended that we skip the intermediate 3-ton step because he thought such a small boat would tilt too much when people moved around; also, he thought that it would introduce an unnecessary delay in the program. I then suggested that we substitute a 5-ft radio-controlled model for it, and he readily agreed.

Later, in order to expedite the program, JDH and I agreed that the SSP, if funded, would be a joint program between us wherein I would be responsible for all of the SWATH-related design aspects and associated work in San Diego, and he would be responsible for the structural and mechanical design in Hawaii, and for getting it built there.

SSP Sponsorship

Work at San Diego and Hawaii on a proposal for the 80-ft SSP began on 3/31/70. During a trip on 4/15/70 to Washington, D.C. to present progress reports of our SWATH Naval Feasibility Study, I laid the groundwork for presenting the SSP proposal. On the same trip, the DNL suggested a joint effort between NOSC and DTRC for 12-ft model tests.

On 5/18/70 I arranged eleven different appointments for JDH and me to present the new SSP proposal; these included NAVMAT, NAVSEA, OPNAV, DARPA, NAVAIR, NAVOCEAN, and DTRC. As a result, Dr. Lawson (DNL in NAVMAT) agreed to provide $250K, and Krida in NAVAIR, with the support of Admiral Davies, agreed to provide an equal amount. Admiral J. Langille (then a captain in DNL's office) was a great help by convincing NAVSEA to also agree to match DNL's funding. On 6/5/70, Captain C.B. Bishop (Commanding Officer of NOSC), sent an official letter to NAVMAT proposing that DNL act as the SSP Program Manager in the joint DNL/NAVAIR/NAVSEA program, which he did.

SSP Technical Plan

We were clearly at the leading edge of SWATH technology since there was no previous outside technical literature on SWATH to draw upon. We had to work from basic physical principles and conventional ship technology. We were planning a giant step in going from 5-ft towed model tests to an 80-ft operational vehicle. The risks were enhanced because the SWATH effort had been only a 1-man program for a year, augmented by several other people at NOSC for an additional half year. Seldom has a major Navy development proceeded so quickly.

Early focus was placed on the selected critical issues of drag, static stability, dynamic stability, structure, and propulsion. To reduce risk, the aid of the specialists already working on the SWATH Naval Feasibility Study was enlisted. Also, although the SSP was designed to be inherently stable, an automatic control system was planned to not only further reduce the already low motions, but to reduce risk in the case of unanticipated dynamic problems. A radio-controlled model was unorthodox, but it was felt that it would serve to explore certain types of dynamic behavior that could not be investigated with towed models or theory.

JDH wisely chose later in 1970 to contract a group of naval architects at the Pearl Harbor Naval Shipyard (PHNS) to do the majority of the structural and mechanical design, and to prepare all of the SWATH contract drawings. At NOSC Hawaii, A.T. Strickland became the technical assistant to Hightower, G. Wilkins was a consultant, and H.O. Porter assisted in program management. NOSC Hawaii proposed to build the SSP on their grounds with the help of contractors.

At NOSC San Diego, I designed the SSP configuration, planned the model tests, coordinated with NOSC Hawaii and managed the work on dynamic analysis and automatic control design, hydrodynamic loads, model test analyses, main and auxiliary propulsion systems, additional proposed uses of the SSP, sonar installations, acrylic bow dome design, and structural concepts.

SSP Technical Work

To stimulate outside interest, I gave the first SWATH paper (unpublished) on 5/5/70 at an AIAA/NAVY meeting at Newport, RI. During the next two months, I updated the SSP configuration and estimated the power for the 150-ton, 23 knot SSP, and increased the overall length to about its final length of 89 ft.

In Hawaii, JDH managed the overall program, and was successful in obtaining additional funding from DNL since the estimated cost had increased. Strickland determined the auxiliary power requirements, made initial calculations on strut stress, estimated vessel component weights and centers with the help of H.Chalmers, and managed the work of the naval architects at PHNS who began 7/1/70. The intended construction site for the SSP was changed on 11/12/70 from NOSC to the Pearl Harbor Naval Shipyard.

In San Diego, I designed the 5-ft radio-controlled model (Figure 4), and awarded a contract to the Convair Towing Tank to build and test it. C.R. Nisewanger joined our Advanced Concepts Group to aid in the model tests, to maintain and modify the model, and to help in the SSP design. The SSP model performed well in tank tests during October, 1970 and exhibited no dynamic problems. It responded nicely to flap, canard, rudder, and motor commands. It banked into turns without roll control, and maintained a straight course with only one propeller operating with only a small rudder deflection. On 8/24/70 at DNL's suggestion, NAVSEA officially requested DTRC to verify the final NOSC SSP design by constructing and testing a 12-ft model.

During September I improved the methodology for predicting SWATH drag and power [9,Part I]. Also, I conducted an analysis of canard effectiveness which verified the selected size, predicted the roll, heave, and pitch natural periods, and estimated the side force and strut moment. On 8/21/70 in a memo to JDH, I suggested that aluminum be used for the cross structure and struts, and that the lower hulls be made of steel; the latter resulted from inputs from both J. Stachiw (NOSC) and P. Burke.

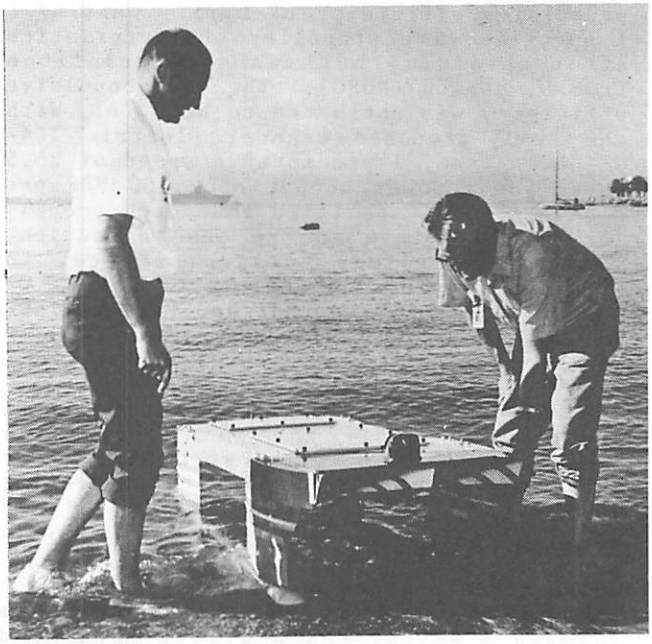


Figure 4. Five-foot, 6-channel, radio-controlled model of the KAIMALINO being prepared for tests in San Diego Bay by D.T. Higdon (left) and C.R. Nisewanger (right). (U.S. Navy photograph)

I laid out a new drawing of the SSP scaled down to the 12-ft model size, and delivered it to DTRC on 10/22/70. On the same trip, I distributed our final reports to the sponsors of our 7-part SWATH Naval Feasibility Study; this report was distributed rather widely throughout the Navy, universities, and industry. On 12/11/70 Higdon completed his calculations on control surface hinge moments and loads, and specified their maximum deflections. Also, he had completed numerous computer analyses by this time on SWATH motion and motion reduction using various control system logics [11,12, and 13]. His estimate of SSP side loads on 6/8/70 was later found to be reasonably close when compared with model test results. He also verified that the SSP should be stable in yaw. D. Endicott (NOSC) [14] conducted experiments to verify the estimated canard hinge moment.

Tests on the 12-ft model began at DTRC on 3/22/71, and were run around the clock. J. Fein and C. Pritchett of DTRC conducted the tests. (Fein later conducted and wrote most of the SSP motions trials and reports.) At that time, I was able to hire R.B. Chapman (who had just gotten his Ph.D. from Caltech) so he, Higdon, and I attended the model tests, sometimes separately, and sometimes together. On 6/2/71 Chapman and I completed a detailed analysis of the 12-ft model drag results, included corrections for one data reduction error, for various model anomalies, and for a change made in the SSP aft struts following the 12-ft model tests [15]. The result was an estimate of 2,050 SHP per side at 25 knots using a propulsive efficiency of 0.75. On 6/4/71 I specified the propeller characteristics after obtaining hull wake calculations from D. Nelson (NOSC). The new propulsive efficiency was estimated to be 0.77. With the newly-proposed General Electric T64-GE-6B engines, I predicted a speed of 25.5 knots for a power output of 2,150 SHP per side. Also, I specified that each propeller should rotate in the same direction, contrary to normal marine practice, in order to reduce cost and spare parts. On 10/22/71 I requested that underwater viewports be placed in the struts and above the propellers to later observe them.

Around March 1971, NAVAIR offered to design and supply the main propulsion system for the SSP. The work was led by W.E. Simmons of the Naval Air Engineering Center (NAEC). Simmons proposed that we use the above-mentioned General Electric turbines. Due to their size, he recommended that the engines be placed in the cross structure, and drive the propellers through a 4-tier chain drive. Detailed drawings of the propulsion system were completed around August 1971.

NOSC Hawaii continued to integrate the efforts of the different design teams, report to the sponsors on overall progress, assist in various aspects of the structural and mechanical design, keep track of the overall weight and center of gravity, help obtain the necessary funding to complete the SSP design, and arrange for construction at Pearl Harbor. Work on the detailed design of the SWATH proceeded rapidly at PHNS where the design team had been increased to 10 personnel working 10 hours a day, 6 days a week.

SSP Construction

Several months were lost in contracting for the construction of the SSP because PHNS doubled their cost estimate at the last minute causing us to look elsewhere for construction. The final draft of the SSP drawings and specifications was completed by PHNS personnel on 3/10/72. Dr. R.A. Frosch (Assistant Secretary of the Navy for R and D) suggested that the USCG be considered for SSP construction. As a result, construction of the SSP began at the USCG Yard at Curtis Bay, MD. in June 1972. Porter was responsible for construction. Strickland was stationed at the Yard to monitor the first half of construction, and W. Mazzoni (NOSC) the second half. Shortly after construction began, P.V.H. Serrell (NOSC San Diego contractor) reviewed all of the structural drawings. He found several regions where changes were needed; fortunately, these changes were incorporated prior to construction of the parts involved. The SSP construction (Figure 5) proceeded quickly, and on schedule; the SSP was launched on 3/7/73, and first operated in Chesapeake Bay in October 1973. The SSP was tested at its design speed of 25 knots in November 1973.

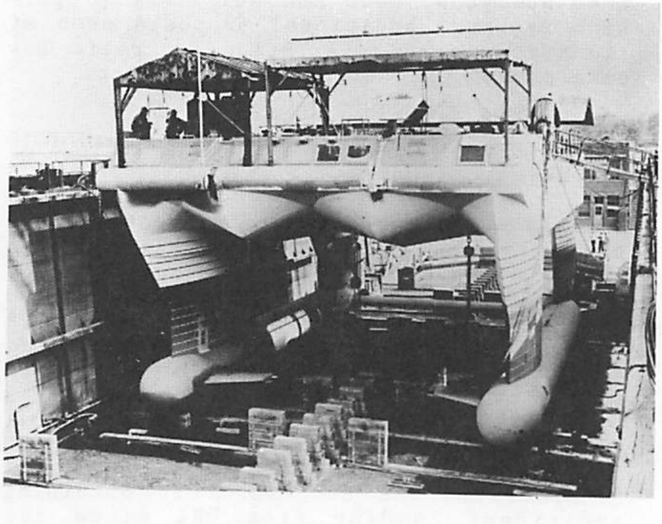


Figure 5. SSP KAIMALINO under construction in the spring of 1973 at the U.S. Coast Guard yard at Curtis Bay, Maryland. (U.S. Navy photograph)

SSP Trials

On 3/4/72 Higdon completed calculations on the SSP trim attitude as a function of speed, based upon the 12 ft model test results. In October 1972 Serrell designed a loading device that was used to simulate the hydrodynamic spreading loads acting on the critical structural stresses. During September and October 1973 a series of tests was conducted by Bedore and Chapman on the 5-ft radio-controlled model in the Lockheed Tow Basin (previously owned by Convair) in San Diego to measure impact pressures [16].

Following a trials plan outline we issued the first draft of a detailed comprehensive SSP trials plan in September 1972, and a "minimum" trials plan on 12/12/72. Plans for a short set of SSP "Mapping Trials" were developed on 1/8/74; the purpose was to obtain sufficient data to map the SSP power and control surface settings as a function of speed, propeller pitch, and other variables so the SSP could begin sea trials with the proper settings. On 3/26/73 DTRC issued an outline of a new sea trials test plan that relied heavily on ours.

On 2/13/74 S. Hawkins (SWATH Program Manager at DTRC selected by NAVSEA) agreed with Dr. McLean that all final reports on the SSP tests by DTRC would be approved by both NOSC and DTRC prior to issuance. Also, the raw data would be shared. I was then asked by Dr. McLean to approve all such test reports for NOSC.

The SSP mapping trails were successfully completed on 2/19-20/74 in Chesapeake Bay near Annapolis, MD. On 2/28/74, in the initial stages of the DTRC sea trial program, a shaft in the upper part of one chain drive failed due to stress concentration at a sharp-edged keyway. DTRC was very helpful in exploring the cause. Following modifications of the chain drive system, the SSP was transported to NOSC Hawaii in February 1975 for use as a NOSC range support vessel. In November 1974 McCartney, with the assistance of R.A. Wiley (NOSC) and Nisewanger, completed the design of the SSP auxiliary propulsion system [17].

In May 1974 we were asked by NOSC Hawaii to increase the SSP displacement to provide more payload. On 12/31/74 Bedore, R. Wernli (NOSC), and I designed "add-on" blisters for the lower-hull midsections to provide 30 tons more displacement and which actually reduced drag at speeds up to 16 knots because of special "hull shaping" derived by using wavemaking drag theory developed by Chapman [18]. Several years later these blisters were replaced with larger ones by NOSC Hawaii that increased the displacement to the current 227LT.

On 7/15/75 DTRC began sea trials on the SSP in Hawaii. We assisted in test planning, participated in the trials, analyzed the results, and compared results with model tests. A large number of reports resulted, all of which are referenced in [1]. Fein of DTRC was of great help, and wrote most of the reports on SSP seakeeping. The findings correlated reasonably well with model tests and predictions.

An acrylic dome was installed at the bow of the port lower hull late in 1975. This hemispherical dome was designed by J.D. Stachiw of NOSC [19]; it is 6-in thick, 6.5-ft in diameter and weighs 5,000 lbs. At the time, it was the world's largest acrylic casting. This dome permitted two or three observers to look out underwater; with the SSP underway the view is spectacular.

Our primary sponsor, Dr. Lawson, requested that the automatic control system not be installed on the SSP for about a year. His purpose was to demonstrate that the vessel was inherently stable, and had low motion characteristics, even without motion control. Higdon later designed, constructed, and installed the automatic control system on the SSP in late 1975 [20]. The new system operated well, and further reduced the already-small SSP motions when underway. The final SSP characteristics and design are presented in [1] and [10].

SSP Operational Experiences

During April and May 1978 the USCG, with Navy assistance, conducted comparative side-by-side motion tests on the 89-ft SSP, a 95-ft USCG patrol boat, and a 378-ft USCG cutter in the Molokai Channel off Oahu. The results showed that the SSP had the least motion in waves. All of the 18 USCG test personnel got seasick aboard the patrol boat, while there was almost no incidence of sea sickness aboard the SSP or the large cutter [21,22,23]. The difference in length between the SSP and the cutter was a factor of 4.

Hightower and R.L. Seiple [24] describe the operational experiences of the SSP KAIMALINO in supporting a wide variety of tasks in the ocean off Hawaii. The authors stated that the SSP has performed operations in waves that monohull ships twenty times her displacement were unable to accomplish.

On 3/7-11/83 tests were conducted by a joint USCG/Navy team to explore a SWATH's buoy-tending capabilities. The 89-ft SSP was compared in side-by-side tests with a 180-ft USCG buoy tender. Both vessels were very maneuverable, but the SSP was found to have a far superior seakeeping ability [25]; the average roll of the USCG tender was 16 times that of the SSP in beam seas.

In a memo on 6/21/76 Dr. McLean reported that he had the opportunity to participate in the use of the SSP during the past week to photograph porpoises underway and to study sharks while at anchor. He stated that the low vessel motions in waves, when either underway or at rest, would spoil anyone relative to the use of conventional craft. Even at rest in large waves and 35 knot winds, the SWATH rode for hours at anchor with little perceptible motion; also, the hunting of conventional vessels at anchor was not apparent with the SSP.

In September 1976 the Naval Air Test Center and the USCG explored the helicopter-handling characteristics of the SSP during a series of over 80 landings and takeoffs. A cover was placed over the SSP well. The SSP performed dramatically better than much larger Navy ships [26, 27]. Pilots called the SSP stability characteristics in waves "unprecedented".

In February 1985 the National Science Foundation and ONR sponsored four test cruises aboard the SSP. Sixteen participants from three universities conducted nine scientific projects, each an extension of their current work [28]. R. Dinsmore, (Woods Hole Oceanographic Institution) made the arrangements for the test cruises. This reference stated: "During one storm, participants that usually got seasick did not. Beakers, portable computer terminals, coffee cups, etc., placed on smooth tables did not shift or spill. Instrument deployments and recoveries were made over the side and through the center well with greater ease than on a much larger monohull. Without exception, the participants were enthusiastic about the SWATH concept, and intend to use SWATHs."

I was surprised and gratified to receive in 1976 the Lockheed-Sponsored Eighth Annual Marine Technology Society's Award for Ocean Science and Engineering sponsored by Lockheed. The award was based upon my contributions to the development of the SSP KAIMALINO.

NOSC Advanced Concepts Group

Composition of the Group

As mentioned earlier, the SWATH program at NOSC was the stimulus that started the Advanced Concepts Group. The objective in organizing the Group was to collect different specialists into a single group to develop new concepts for the U.S. Navy.

The Group grew from the original four in 1970 to over twenty, and stabilized at around fifteen. About two-thirds of the Group had Ph.D. degrees, but some had no college degree. Several members joined the Group right out of college after spending one year in the New Professional training program at NOSC.

Operation of the Group

By conducting brainstorming sessions and developing an Advanced Concept Writeup format, many new naval concepts including SWATH-related applications were developed. Also, by being in the same physical area, individuals in the Group tended to discuss their new ideas with others. Since about 8 to 10 different specialties were represented, a member could generally find someone nearby who could answer questions that arose, or contribute to a new idea.

The SWATH and SSP funding was sufficient to start the Group, but was not a steady source of funding. The new ideas generated by Group members led to sufficient additional funding that the Group was always self-supporting. Support came from NAVSEA, NAVAIR, ONR, MARINE CORPS, DARPA, NOSC IR/IED, and other Navy Laboratories.

When projects became too large for Group members alone, help was generally available from others at NOSC, from nearby University students, other Navy Laboratories and Government agencies, consultants and contractors. Many models were built, and experiments conducted in our shop and three small laboratories. Also, we had use of the main NOSC shop and water tunnel.

Group Projects

Typically, each person in the Group was responsible for one or more projects, and would assist other Group members in their projects. This worked well in view of the interdisciplinary nature of the personnel.

In addition to the SWATH and SSP work, the Group conducted research, analyses, model tests, and sometimes prototype development, concurrently on such projects as: single-hulled semi-submerged ship concepts (S^4), towed pods, unmanned spar buoy helicopter, closed cycle undersea propulsion, advanced electric propulsion systems, laser holography to determine propeller elasticity, disk turbines, polymer transducers, torpedo drag reduction by suction, porous materials research, laser doppler velocimeter for water tunnel tests, new torpedo and submerged vehicle concepts, advanced surface and air vehicle concepts, and the systems analysis of various advanced naval concepts.

SWATH Technology Development

SWATH Drag

Much was learned about SWATH drag from the first set of model tests reported in [9, Part II] in 1970. I developed a methodology for calculating the frictional, form and wind drag of SWATH vessels, but had only crude methods for estimating the wavemaking and spray drag components. The methodology for friction and form drag was based on using the actual component Reynolds numbers, over-velocity effect, and form drag for each vessel component, and then including the interference drag between each component. In contrast, the standard ship approach was to merely calculate the total wetted surface area, use the Reynolds number based on ship length to get a drag coefficient and then add a "correlation factor" of 0.0005 to roughly make the calculated value agree with experiment.

I later conducted some experiments in the Free Surface Water Tunnel at Caltech on surface-piercing struts which aided in exploring spray drag; also, experiments on the use of spray rails showed how to reduce this type of drag. Chapman later conducted more-detailed experiments on spray drag at Caltech, and developed equations in 1971 for predicting this source of drag [29].

A major step forward was the development of a complete drag prediction methodology made by Chapman [18] in Nov. 1972 when he developed the theory for predicting wavemaking, wind and spray drag, added to my earlier viscous drag methodology. To verify the accuracy of his new theory, he conducted a large number of tank tests on the drag of separate struts and hulls, and combinations thereof [30], and found excellent correlation. Later, he and R.L. Wernli (NOSC) modified the associated computer program and documented it [31]. Since then, excellent agreement with experimental drag has been found with 4-strut SWATH model tests, and reasonably good agreement with 2-strut SWATH model tests.

SWATH Dynamics and Motion

Higdon extended his early theory on SWATH dynamics and motion, and wrote several papers. He was the first to develop methodology for SWATH dynamics and automatic control [20 and 32], prediction of SWATH side loads [5 and 33], and sizing SWATH fins [34]; he also led other work on control surface design by M.G. Harris [35], and wrote a joint paper on SWATH dynamics with me [36].

Chapman, in 1974, was the first to study and develop the theory for sinkage and trim of SWATH vessels [37]. In 1977, Sturgeon [38] (Computer Sciences Corporation) graphed motion picture data taken by NOSC of two SWATH models at rest in beam seas in the Convair tank, each with about the same displacement and transverse metacentric height, but one had one strut per side, and the other had two struts per side. The results showed that the motions were significantly lower for the two-strut-per-side model, and in some waves, a factor of three lower.

SWATH Structure

Burke provided considerable insight to the structural design of SWATH ships [9, Part IV]. Since Serrell had reviewed all of the SSP structural drawings, we contracted him to determine the weight saved by constructing the SSP totally of aluminum [39]. The weight saving amounted to around 35 LT, and this would translate into increased payload; however, the SSP cost would have significantly increased. Thus, a tradeoff exists between size, cost, structural material, payload, and performance; this tradeoff is best resolved for each individual design case. In general, however, all-aluminum construction, rather than steel, is required for SWATH ships if maximum performance is desired. Construction of both aluminum and steel, like the SSP, is a good alternative, and all steel appears best for large ships where cost is critical, and for lower-performance SWATHs. Fiberglass and composites show promise for the smaller SWATH vessels, although aluminum currently tends to be favored.

SWATH Model Tests

Valuable SWATH information has been obtained from model tests, some of which have already been discussed. The NOSC model tests on SWATH have provided information on drag, static and dynamic stability, controllability, maneuvering, towing, anchoring, motion in wind and waves, water impact, addition of large sonar domes and hull blisters, spray drag, wavemaking drag, fin and rudder design, impact alleviation, hinge moments, sinkage and trim, and operation with one propeller disabled and with flooding due to damage. A number of the references already cited describe these tests, and a paper was presented in 1974 on the use of radio-controlled models to explore new concepts [40].

Towed Pods

In 1973, Warnshuis [41] introduced the idea of towing pods behind SWATH ships. These pods could contain fuel, sensors, weapons and other items. By towing fuel, for example, a small SWATH could have the range of a large ship. By towing sensors or weapons, it could have the payload of a much larger ship. His analysis showed that when towing pods, speed is reduced, but not as much as one might think, even if the pods were a sizable fraction of the SWATH displacement.

Bedore [42] conducted model tests on towed pods using the SSP radio-controlled model, and showed that the concept is feasible if certain design parameters are chosen correctly. Serrell [43] designed a pod that contained a fold-out device for offloading a container ship when a port is unavailable. In 1974, Warnshuis summarized experimental work on towed pods, and proposed several future designs and experiments [44].

SWATH Characteristics

I presented several papers on general SWATH design and characteristics. The first published paper was presented in 1971 at an ASME meeting [45], followed by another published in the Naval Engineers Journal [46], a third paper with Higdon [47] at an AIAA/SNAME/NAVY meeting in 1972, and a fourth [48] which was presented in 1972 at an ONR-sponsored symposium in Paris.

Later papers on general SWATH design were presented at an AIAA/SNAME Conference in 1978 relating to its Naval potential [7], and at a 1985 RINA-sponsored conference in London with Sloggett [49] in 1985 where SWATH is compared with other types of ships and advanced marine craft. In 1988, Sloggett and I [50] presented a paper in Australia at a meeting sponsored by The Institute of Marine Engineers (London) which compares SWATH powering in waves with other types of marine craft, showing that SWATHs excel over all other types of surface craft in the higher sea states, except for high-speed hydrofoil boats.

SWATH Ship Applications

First SWATH Ship Conceptual Design Study

The first SWATH ship design study was completed by the NOSC Advanced Concepts Group on 4/3/71, and issued in report form in September 1971 [51]. This ship was to be a 3000-ton multipurpose SWATH (Figure 6) having a modular payload and a range of 3,000 miles at 35 knots with a near-level ride through Sea State 6 using an automatic control system. It was to be powered by two GE LM2500 gas turbines located in the lower hulls. To minimize its weight and maximize its performance, it was to be constructed entirely of aluminum (a steel ship could not approach this performance, although it would be more resistant to combat damage).

The designers and report co-authors included Chapman, Higdon, Burke, Stachiw, Karig, Wham, Anderson, Warnshuis, W.L. Hastings, M.R. Halling, and myself, all of NOSC San Diego. Valuable outside assistance was received from the Boeing Co. (automatic controls), Alcoa (aluminum structure), Litton Systems (gas turbine propulsion system, and others.

Model tests and theory provided a drag coefficient (based on volume) of 0.0481, including a roughness allowance; this value permits a speed of 35 knots at 50,000 engine horsepower for the 3000 ton SWATH. Data from a Rand Corporation report on naval ships provided the weight allocation for the auxiliary systems, electric power, command and communications, and outfitting. A set of defensive weapons was selected. A basic ship's crew of 150 was selected, augmented by a

Figure 6. Display model of a 3,000-ton SWATH with members of NOSC management and the Advanced Concepts Group (From Left to Right: Nisewanger, Chapman, Baldwin, Karig, Bishop, Clifton, Lang, McLean, Warnshuis, Sturgeon). (U.S. Navy photo taken in 1972)

mission-associated crew which ranged up to 110, depending on the type of payload. The structural weight ratio for aluminum was calculated to be 0.40. Sturgeon provided the modular subsystems design and general layouts, the manning selection [52], and a world port and dry docking study [53].

The payload and associated personnel, fuel, and weapons totaled 546 tons. Alternative missions included: carrier escort, V/STOL carrier, ASW, weapons ship, air defense, patrol and surveillance, logistic support, oceanic research, and medical support. We were unable to find sponsorship in the Navy for this vessel, and NavSea was not interested in pursuing it, so the idea went into hibernation.

Subsequent work by NOSC and others have verified that the basic assumptions and theory used for this rather advanced SWATH were reasonable. In 1974, Sturgeon [54] conducted a comprehensive study on modular means of outfitting this 3,000-ton SWATH design, which verified its selective outfitting flexibility and potential for being mass produced. In 1973, U.W. Hird [55] (Jakus Assoc.) updated the drydock study, and M. Sorenson (NOSC) updated the hull shape [56]. In 1973, Serrell [57] conducted a detailed preliminary-design of the structure, whose shape was slightly modified hydrodynamically, and estimated a structural fraction of 0.333; this result suggests that the original 3,000-ton design with a structural fraction of 0.40 was conservative. Apparently, the idea was ahead of its time.

P. Mantle [58] studied the time taken by the U.S. Navy to build its first operational vessel following the first concept prototype (such as th SSP), and the average time is 22 years. This means that the most probable date for the first Navy SWATH to become operational would be 1995. The schedule currently calls for this first SWATH ship, the 3500 ton TAGOS-19, to be completed in 1991, which would beat the average by 4 years, if completed on time.

500 Ton SWATH Design

During 1973, the Advanced Concepts Group conducted a comprehensive study on a 500 ton multipurpose SWATH designed for naval use. Data showed that its seakindliness would be equivalent to about a 10,000 ton monohull. Calculations showed that it could attain a speed of 36 knots with turbines, which would place it in the high-speed class for displacement naval ships. It would have a fuel and payload capacity of 135 tons. Consequently, it would have all of the characteristics of a large naval ship except payload and range; and it was even given those, in a sense. The design included five side-by-side recesses placed in the main deck, just aft of the primary forward strut structure, which would house five 8 x 8 x 20 ft quick-change containers. Consequently, instead of providing it with a multipurpose mission system, such as on a large ship, it could be quickly outfitted for one of a variety of missions such that a set of these 500 ton ships would have the mission capability of a single, and very much larger, ship. To provide the range of a large ship, Warnshuis suggested towing a fuel pod. Thus, several of these small 500 ton SWATHs would provide the capability of a much-larger naval ship at a fraction of the target value and cost per ship, and also provide considerable flexibility in use and mass-production potential.

Although most of the Advanced Concepts Group participated in the design, the system design was lead by Warnshuis. Reports were written by Sturgeon and U.W. Hird [59] on the general arrangement and features; Burke [60], J.Smith [61], and Serrell [62] on the structure and on propulsion and structural tradeoffs [63]; N.Estabrook (NOSC) [64] on hull shape using Chapman's program; B.Dunne (Ship Systems Inc.) [65] on survivability; Alpers (Naval Weapons Center on modular payloads [66]; L.Bollinger and Feher (General Aircraft Corp.) [67] on air applications; R.Bedore (NOSC) [68] on fuel pod tests; and Warnshuis [69] on the program summary and mission applications.

Parts of this and other SWATH ship application studies were sponsored by NOSC IED with the approval of Dr. Wm. B. McLean, W. Hicks, or E. Cooper.

SWATH Mission Studies

In addition to the mission studies conducted as part of the 3,000 ton and 500 ton SWATH design studies, Warnshuis and Sturgeon in 1972 [70] conducted the first comprehensive study on SWATH airbasing, which included a variety of creative concepts and arrangement layouts. In 1976, various unusual naval logistic applications utilizing SWATH and S^4 (Single-Hulled Semi-Submerged Ship) concepts were presented by Warnshuis [71]. In 1974, some new ideas on mission use, general arrangement, and future studies on SWATH were presented by Warnshuis [72], as were some novel ideas on the use of SWATH for sonar [73], and for undersea surveillance in 1974 [74].

Other SWATH Developments

DTRC and NAVSEA SWATH Work

Following the introduction of SWATH into the U.S. Navy by NOSC, the David Taylor Research Center advanced the state of the art by conducting a very large number of theoretical studies and model tests on SWATH, and completed many design studies both in conjunction with, and in addition to other design studies by NAVSEA. Much of this SWATH work is summarized by S. Hawkins and T.Sarchin [75], G. Kerr, T. Anderson, and C.Kennell [76], J.L. Gore [77] and C.M. Lee [78]. Interestingly, all models tested at DTRC until the fall of 1973 were similar to the Creed concept [5], and were therefore not SWATHs, as defined herein, since they did not have stabilizing fins. A recent report by K.K.McCreight [79] nicely summarizes the work on SWATH seaworthiness at DTRC.

Japanese SWATH Vessels

Mitsui has become the world's leader in SWATH vessel development. Following a visit to NOSC in 1970, Dr. Narita initiated a SWATH program at Mitsui that lead to the 1977 construction of the MARINE ACE (a 20 ton version of the SSP), 343 ton SEAGULL (1979), 236 ton KOTOZAKI (1980), 3500 ton KAIYO (1894), 15m MARINE WAVE (1985), and 15m SUN MARINA (1987). Mitsubishi constructed the 239 ton OHTORI in 1980. A summary of the Mitsui work is presented by T. Mabuchi, Y. Kunitake, and H.Nakamura [80].

U.S. SWATH Vessels

A small manned SWATH model was developed by F. Marbury at Litton Industries in 1971 which started as a SWATH without stabilizing fins, but ended as a true SWATH with fins. Following construction of the Navy's SSP KAIMALINO in 1973, other operational SWATHs built in the U.S. were the: (1) 19m SUAVE LINO (owned by Leonard Friedman and donated to the winning Stars and Stripes 12-meter sailboat team as their tender and renamed the BETSY) constructed by the Poole Boat Co. in 1981, (2) 22m CHUBASCO [81] constructed in 1987 by James Betts Enterprises under contract and design by SWATH Ocean Systems, Inc., (3) 18m HALCYON [82] designed and built by RMI Inc. (later bought by SWATH Ocean Systems, and sold to the U.S. Army Corps of Engineers in 1988), and (4) 24m CHARWIN built by St. Augustine Trawlers Inc. and converted by C. Rains into a SWATH in 1988 by the addition of stabilizing fins. The SUAVE LINO, CHUBASCO, and HALCYON were all covered by a patent license under my SWATH U.S. Patent #3,623,444.

A major new development is the Navy's new class of SWATH towed-array surveillance vessels, the first of which is the 3,500 ton T-AGOS 19 which is under construction at McDermott Marine, and due for delivery in 1991. Five follow-on SWATH vessels are planned by the Navy.

Other SWATH Developments

Many other countries are interested in SWATH, and are actively planning construction. This interest is evidenced by the many SWATH papers given at two international RINA-sponsored conferences "SWATH and Multi-Hulled Vessels" held in London in 1985, and again in 1988. C.V. Betts [83] presented an excellent review of world-wide SWATH developments, and lists references to the more recent work on SWATH. There are now several hundred references on SWATH.

The Future

SWATH is most applicable when people, aircraft, RPV's, or low-density payloads are to be carried, and especially where the motion of other types of vessels prevents them from carrying out their missions. Possible future naval, university and commercial applications are presented in [84-87]. Figure (7) is an artist's rendering of a 64 ft multipurpose SWATH designed by the author's Semi-Submerged Ship Corporation (SSSCO) for sportfishing or day cruising, and which can be outfitted for many other uses such as range support. Figure (8) shows an artist's conception of a 247-ft SWATH oceanographic research vessel [88] designed by SSSCO and sponsored by the Woods Hole Oceanographic Institution. Similar versions could be used for the Navy T-AGOS mission, seismic surveys, diving support, or cruise ships as shown in Figure (9). A proposed 150-ft SWATH oceanographic research ship is illustrated in Figure (10). These are but a few of the many types of SWATH vessels that we may see developed in the future.

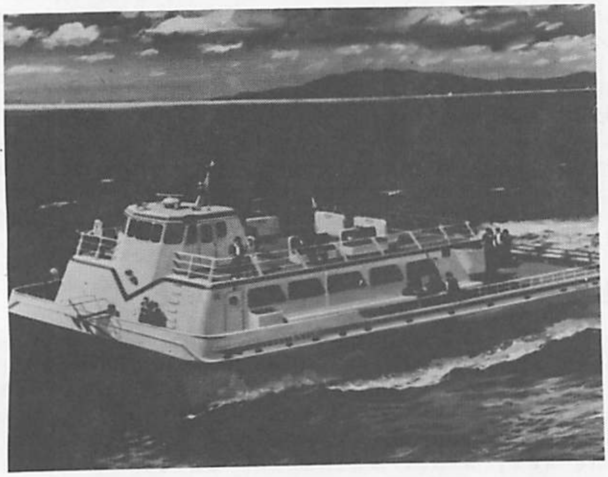


Figure 7. Artist's rendering of SSSCO's 64-ft multiple-purpose SWATH design, shown outfitted for one of many possible applications.

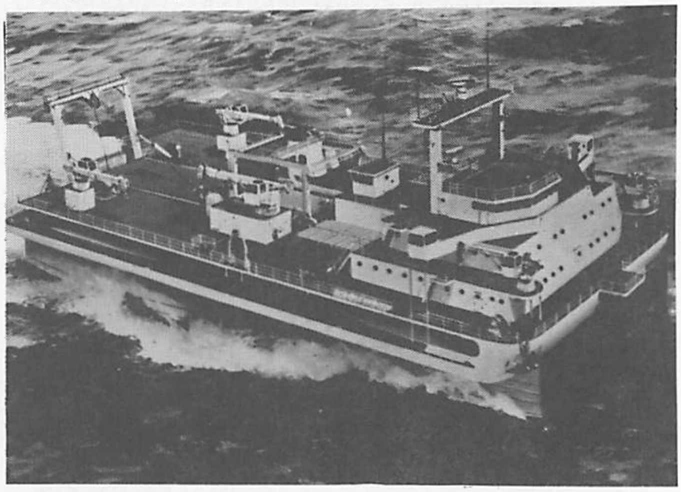


Figure 8. Artist's rendering of SSSCO's 247-ft SWATH oceanographic research vessel design.

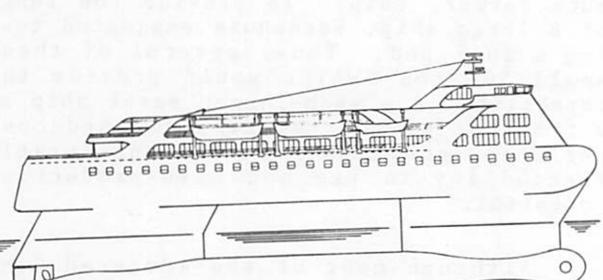


Figure 9. Sketch of a proposed SSSCO 2500-ton SWATH cruise ship.

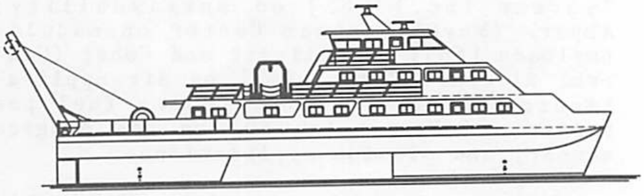


Figure 10. Profile of a proposed SSSCO 150-ft SWATH oceanic research ship..

Conclusions

The SWATH vessel, SSP KAIMALINO, resulted from a combination of design, research and invention made possible by the efforts of many people, talents, and facilities. The path to success was far from direct since many hurdles were encountered, both technical and otherwise. Also, there was no technical literature on the subject to draw upon when the design work began.

The SSP program proceeded quickly relative to most Navy ship programs. The actual design work started after one year as a one-man project plus another half year as a several-man program at the Naval Ocean Systems Center. The overall period for the design and construction of the SSP, was about three and one-half years.

The NOSC Advanced Concepts Group conducted a considerable number of SWATH model tests, research and design studies; they introduced the SWATH concept to the U.S. Navy and conducted the first Navy SWATH project. The Advanced Concepts Group was responsible for many "firsts" in SWATH. These are listed in Table I.

The SSP has been successful not only for its intended purpose as a range support craft for the Navy, but for leading the way for many other SWATH developments at NOSC and other Navy laboratories, and at many other organizations around the world. Several hundreds of reports on SWATH research, design, and development have been published following the initiation of SWATH work at NOSC. Stimulated by the SSP, The Mitsui Company in Japan, with the help of the Japanese government, has become the world leaders in SWATH vessel development; however, the U.S. is catching up. Many other countries in the world have conducted studies on SWATH, and a number of new SWATH construction projects are in the planning stage.

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TABLE I. SWATH MILESTONES ESTABLISHED BY NOSC PERSONNEL

1952-1964	Development of the SWATH concept.
Oct. 1968	First U.S. Navy program on SWATH.
Nov. 1968	SWATH presentation to President's Scientific Advisory Comm.
Mar. 1969	First SWATH model test.
May 1969	First SWATH Technical Analysis Report.
May 1969	First in a series of SSP designs.
Aug. 1969	First SWATH towing tank tests.
Jan. 1970	First SWATH sponsorship by NAVAIR, ONR, and NAVSEA.
Mar. 1970	NOSC San Diego/NOSC Hawaii work began on the SSP.
May 1970	First paper on SWATH (AIAA-NAVY meeting, unpublished).
July 1970	First outside funding obtained for the SSP.
Sept.1970	First comprehensive SWATH concept feasibility study.
Oct. 1970	First SWATH Radio-Controlled model tests.
Mar. 1971	SSP configuration finalized.
June 1971	First report on the calculation of SWATH side loads.
Aug. 1971	First report on SWATH dynamic analysis and motions.
Sept.1971	First report on a large SWATH design, 3000 LT.
Sept.1971	First report on SWATH spray drag.
Oct. 1971	First SWATH world port and dry dock report.
Nov. 1971	First published paper on the SWATH concept.
Mar. 1972	Final SSP drawings completed.
June 1972	Construction began on the SSP (Curtis Bay USCG yard)
July 1972	First report on SWATH fin sizing.
Aug. 1972	First overseas paper on the SWATH concept.
Sept.1972	First report on SWATH ship airbasing.
Oct. 1972	First report on the structural design of a SWATH.
Nov. 1972	First report on a complete SWATH drag methodology.
June 1973	First report on towed pods using SWATH ships.
Aug. 1973	First report on a small SWATH ship design,500 LT.
Oct. 1973	First operation of a SWATH ship (SSP).
Nov. 1973	First report on SWATH ships for supporting sonar systems.
Nov. 1973	First model tests on SWATH-towed pods.
Feb. 1974	First report on SWATH sinkage and trim theory.
June 1974	First report on SWATH modular mission systems.
July 1975	First sea trials on a SWATH (SSP).
Late 1975	First acrylic dome on a SWATH.
Late 1975	First automatic control system on a SWATH.
Aug. 1975	First report on SWATH ships for undersea surveillance.
Mar. 1976	First report on the logistic applications of SWATH ships.
Sept.1976	First helicopter landings on a SWATH.
Apr. 1978	First report on SWATH automatic control systems.
May 1978	First side-by-side motion tests of a SWATH and monohull ships.

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