US Navy Advanced Vehicle Programmes

by

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Abstract

THE objective of this paper is to describe the background and current status of a number of US Navy advanced vehicle programmes. Hydrofoils, hovercraft, SWATH ships, and hybrid vehicles are addressed. Vehicles which are currently operational or under construction are shown and their characteristics are described. Particular reference is made to the unique properties of these advanced vehicles which offer special advantages in their military application.

The Navy is currently conducting an Advanced Naval Vehicle Concepts Evaluation (ANVCE) Study. The assumptions, approach, and present status of this extensive analysis are described. It is anticipated that this two-year effort will provide a sound basis for comparison of relative military worth of these advanced vehicles as well as an assessment of the needs for further development.

The paper concludes with some comments on technology transfer and the status of some commercial exploitation of Navy sponsored technology de~~e~~vlopments.

Introduction

For many years the US Navy has been actively engaged in programmes of investigation and development of a variety of concepts for ships and craft offering the promise of improvements in performance or achievement of capabilities not presently available to the Fleet. In essentially every case, these concepts are not really new but represent new looks at old ideas in the light of new subsystem technology. The advent of the marine gas turbine and associated high performance propulsion system components, light-weight structure and materials, automatic control systems, and a host of other modern technological inventions and innovations make many heretofore impractical concepts an attainable reality. These new vehicle concepts do not come without price, however, and the Navy has had to face the fiscal reality that "performance at any price" can no longer be accepted as an axiom of the research and development business. As a consequence of the continuously rising costs of development and the in-

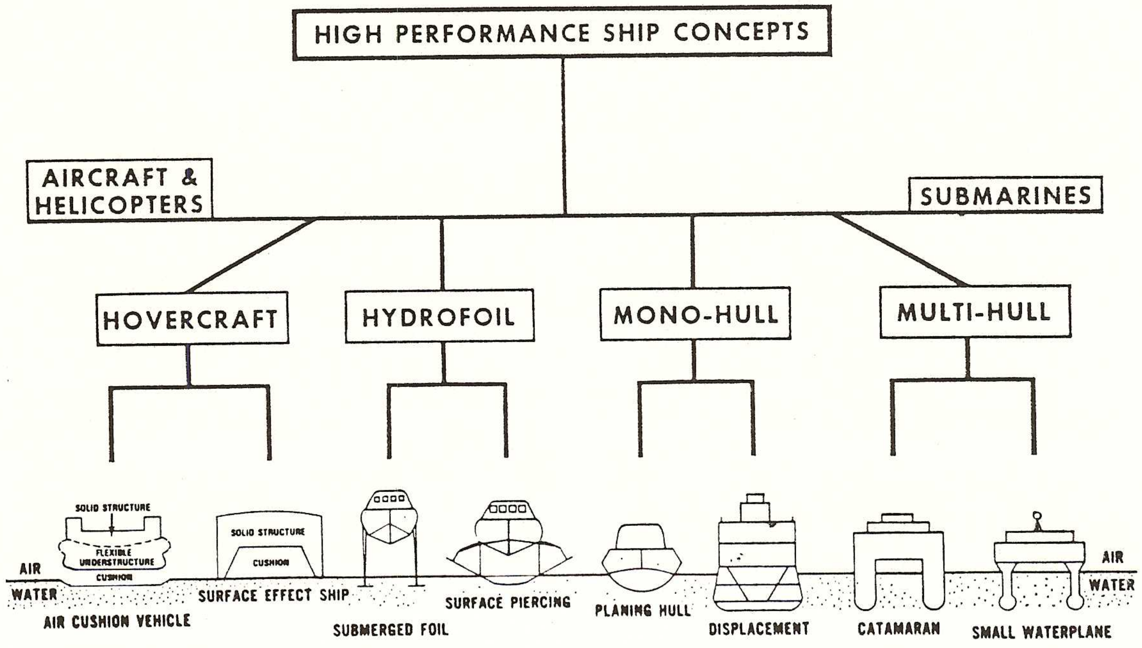
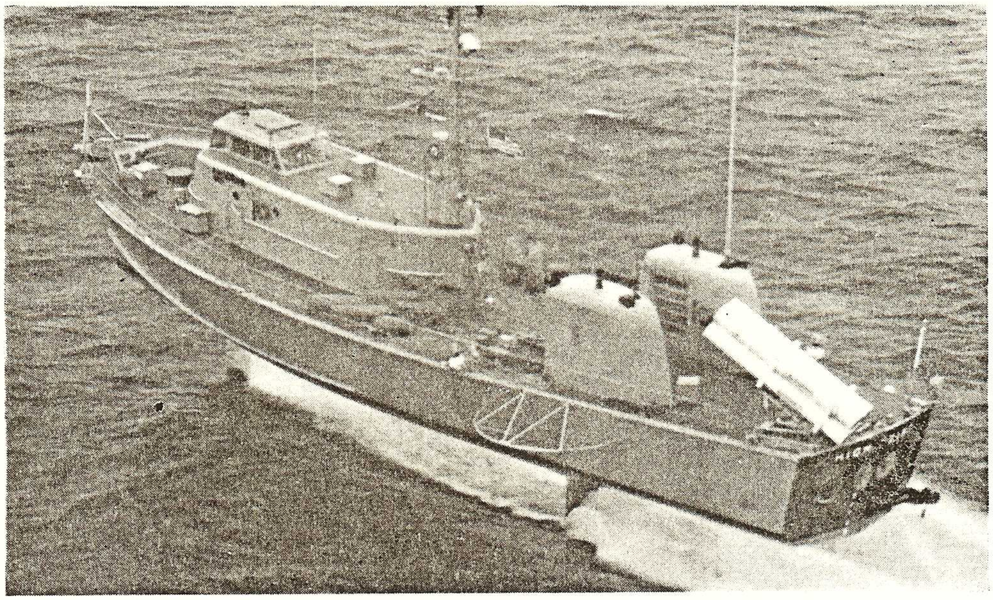


Fig 1 Diagram of Marine Surface Vehicles



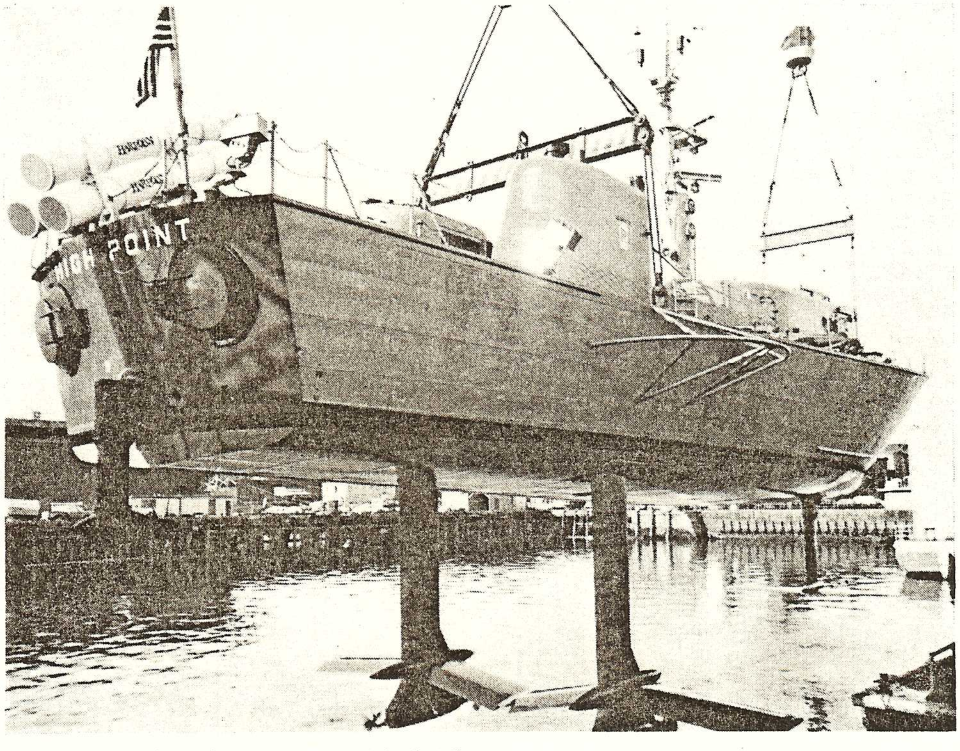


Fig 2 Naval Hydrofoil, HIGH POINT (PCH-1)

creasing number and volume of claimants for the defence dollar, the Navy is under increasing pressure to pursue only those concepts which offer a real payoff in increased military effectiveness. This has led to initiation of the "Advanced Naval Vehicle Concepts Evaluation" whose purpose and status is described in this paper.

The main thrust of the paper is to describe the current status of development of a number of advanced naval surface vehicle programmes which cover a broad spectrum of concepts. The various surface vehicles currently being considered are shown diagrammatically in Figure 1.

The name "hovercraft" was conferred by the recognised inventor of such vehicles in their present-day form, Sir Christopher Cockerell. Many apply this name to all vehicles that are either fully or partially supported by a cushion of air, regardless of whether or not the vehicle is amphibious. The US Navy has adopted the term air cushion vehicle (ACV) for amphibious hovercraft, and the term surface effect ship (SES) for those craft that are non-amphibious, having sidewalls which penetrate the water surface and provide some buoyancy. One exception is the use of the term surface effect vehicles (SEV) applied to the

Arctic SEV programme described herein. It is further noted that the SES is not discussed in this paper since it is the subject of another paper to be presented at this meeting.

Hydrofoils are ships and craft whose weight is supported by lifting surfaces much the same as aircraft wings. These lifting surfaces are either fully submerged or penetrate the air-water interface (surface-piercing). The Navy has explored the merits of each type of hydrofoil system and has concluded that the fully-submerged foil system offers superior characteristics, even though it requires an autopilot control system.

Planing ships and craft continue to offer a number of attractive features not the least of which is relatively low cost. Significant improvements have been made in planing hull forms and these have done much to overcome some of the disadvantage of poor ride quality in rough seas. In a recent development directed toward improved inshore warfare craft, improved hull form, light-weight aluminium structure, gas turbine propulsion, and other technological advances were incorporated in a nominal 100-ton advanced planing craft. This 100-ton craft, designated the Coastal Patrol Interdiction Craft (CPIC) demonstrated new potential for planing ships in rough water rôles.

Continuing across the spectrum of surface vehicle it must be noted that none of these advanced concepts are expected to replace the mono-hull ship in its capability to carry a military or commercial payload. Furthermore, the mono-hull ship can also benefit by application of many of the technological inventions and innovations applied to so-called advanced naval vehicles. This is not without a price, however, and the real payoff of the mono-hull conventional ship is in its economical transport of large payloads.

Finally, we come to the multi-hull ships of which two types are shown. First, there is the conventional catamaran whose hulls are of generally "ship-shape" and the so-called Small Waterplane Area Twin Hull (SWATH) ship, whose hulls are submarine-like.

The Navy's development programmes in hovercraft, hydrofoils, and SWATH ships are described in the following sections. Reference is also made to limited investigations of so-called hybrid vehicles which embody some of the special characteristics of these generic forms.

The following definitions of speed regimes have been used in this paper as suggested in reference 1.

0 to 20 Knots	Low Speed
20 to 40 Knots	Moderate Speed
40 to 60 Knots	High Speed
60 to 80 Knots	Very High Speed
Above 80 Knots	Ultra Speed

Hydrofoils

The Navy's interest in development of hydrofoil ships and craft spans three decades. In 1947 the Office of Naval Research began to sponsor hydrofoil research by industry, university, and government laboratories which included analyses, model experiments, and the design, construction and test of a variety of small developmental craft. One of the more significant test craft produced during the 1950s was *Sea Legs*. This was a 5-ton, 30-knot Chris-Craft hull which was converted by Gibbs and Cox, Inc and the MIT Flight Control Laboratory to demonstrate a fully-submerged, autopilot-controlled foil system. The 300 hours and 8,000 mile foilborne operation of *Sea Legs* over a six-year period conclusively demonstrated the advantages of this type of hydrofoil configuration.

In 1960, after assessment of data derived from *Sea Legs* and the numerous other test craft, the expanding hydrofoil technology base, and the potential offered by such craft in improving naval mission capability, the Bureau of Ships undertook an accelerated programme of hydrofoil development. One of the first steps in this programme was the authorisation of the *High Point* (PCH-1) in the FY 1960 shipbuilding programme.

High Point is shown in Figure 2. It was designed by the Bureau of Ships, built by the Boeing Company and delivered to the Navy in October 1963. It was originally intended that the ship would be delivered to the Pacific Fleet for operation by the Mine Force. However, as a result of numerous technical problems arising during early Navy trials, it was recognised that the hydrofoil state-of-the-art was not yet adequate to produce a satisfactory fleet ship with acceptable operational reliability. This led, in 1966, to reassignment of the ship to the newly formed Hydrofoil Special Trials Unit (HYSTU) of the Naval Ship R&D Center (NSRDC). The Center established this unit as a

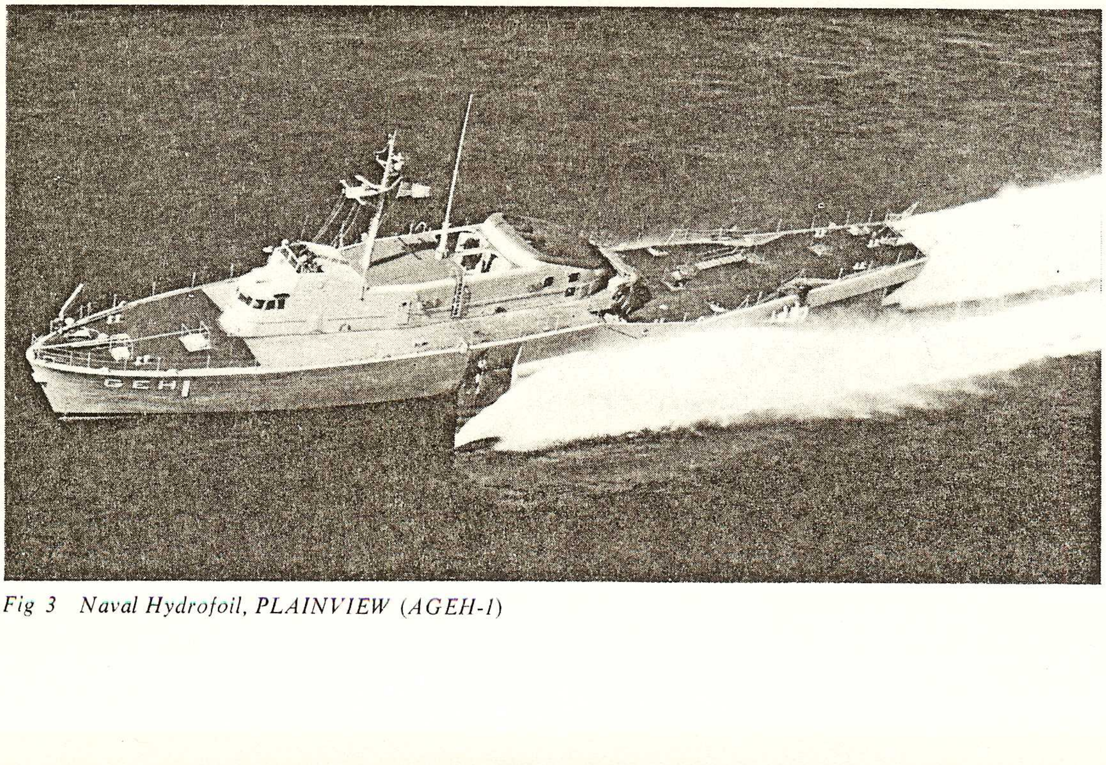


Fig 3 Naval Hydrofoil, PLAINVIEW (AGEH-1)

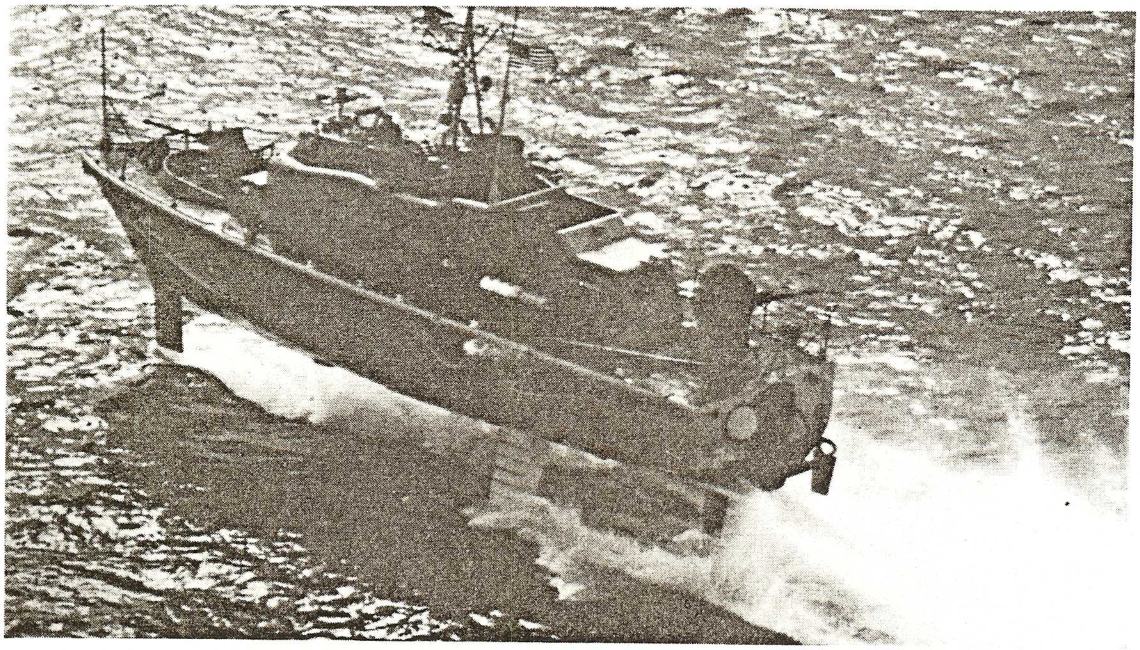


Fig 5   Naval Hydrofoil, TUCUMCARI (PGH-2)

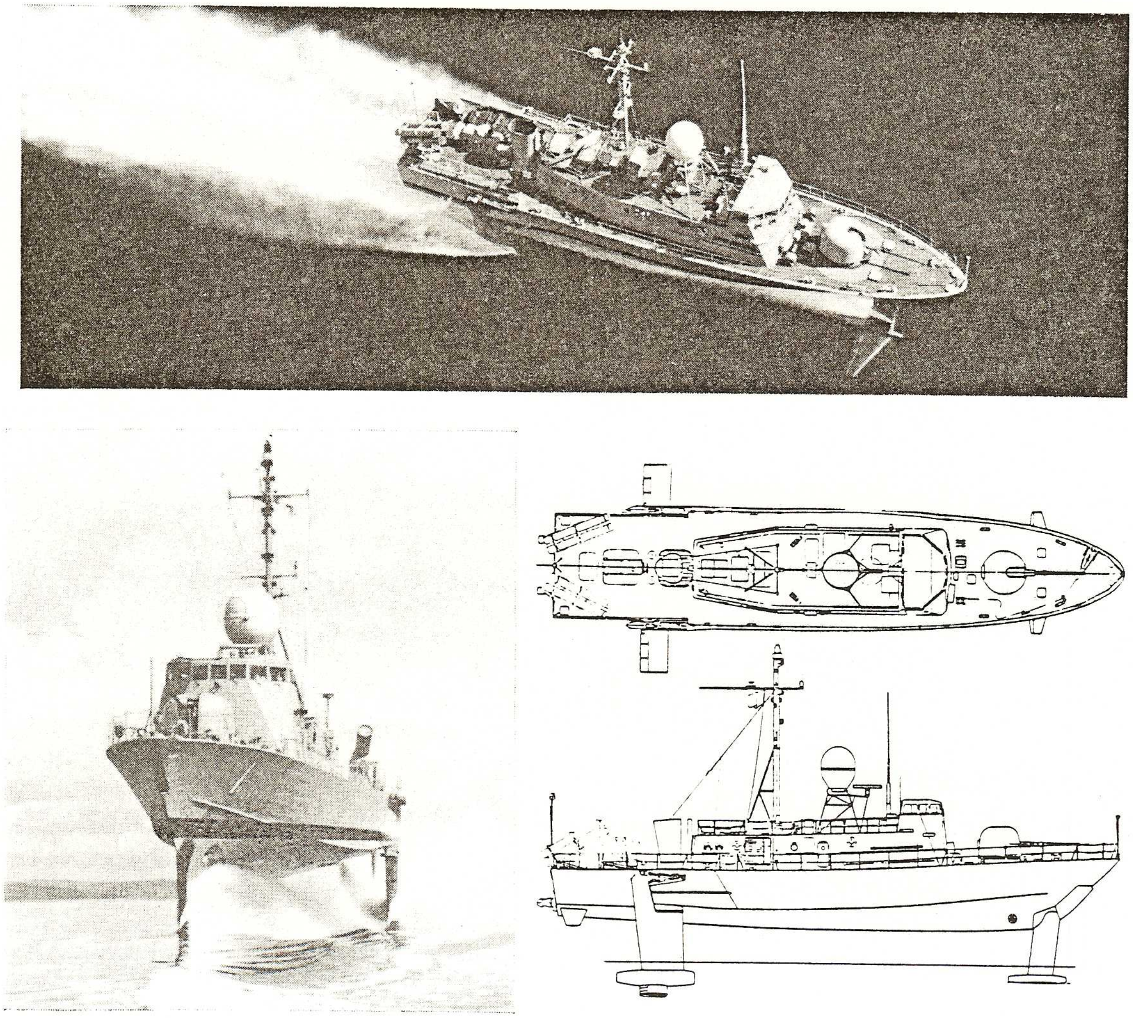


Fig 6   Naval Hydrofoil, PEGASUS (PHM-1)

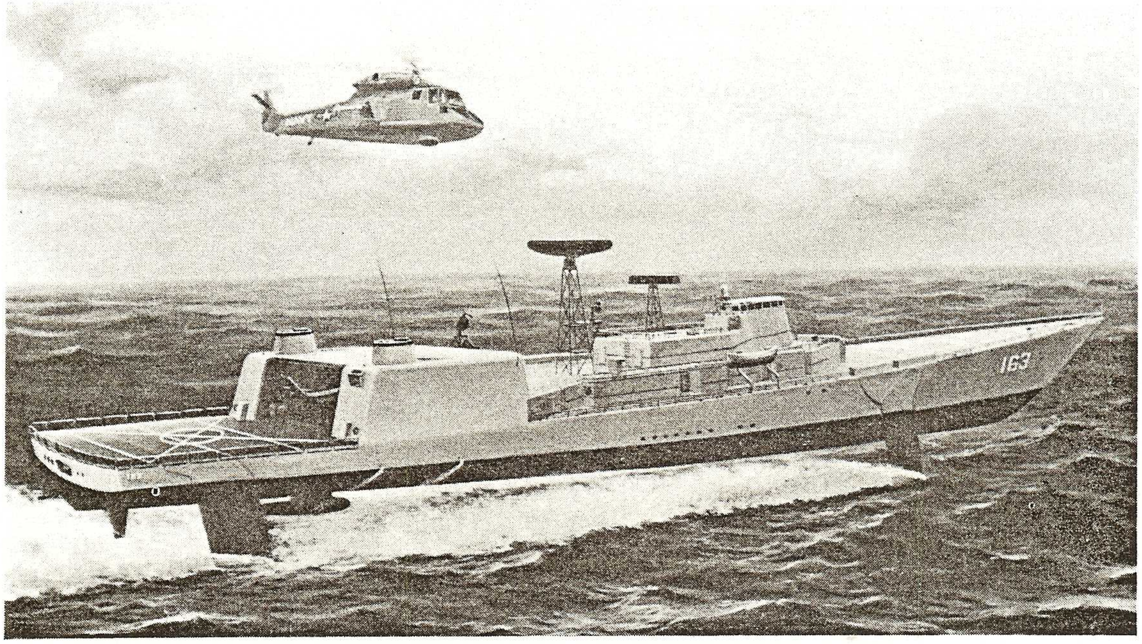


Fig 7 Large Air Capable Hydrofoil Concept

In February 1973, a contract was awarded to Boeing for two lead ships. Launch of the *Pegasus* (PHM-1) occurred in November 1974. The ship is shown in Figure 6 which displays the weapon suite comprising multiple *Harpoon* missile box launchers on the stern, the fire control radar above the pilot house, and the Italian 76 mm OTO Melara rapid fire gun on the bow. During the year following launch the *Pegasus* underwent extensive performance and operational testing in the Seattle area. In September 1975 she made a foilborne transit of 1,200 miles to San Diego where she underwent a seven-month combat systems trials programme in preparation for full operational evaluation (OPEVAL). This final stage of evaluation was successfully completed in June 1976. During this OPEVAL, *Pegasus* demonstrated ship and weapon system performance which is a new milestone in enhanced naval capability.

This essentially brings us to the present and a need to summarise current status and future plans for the Navy's long enduring and many-faceted efforts to add to the Fleet the new mission capabilities offered by hydrofoil ships. *Pegasus,* having completed a post-evaluation refurbishment, has deployed from Seattle to her home base at Long Beach and is assigned to Destroyer Squadron Nine of the Pacific Fleet. After much turbulence in the Congress and the Defense Department, the Navy has been given the go-ahead and funding to proceed with acquisition of five follow-on ships. One will be delivered without a weapons suite and will be used in evaluating the potential of PHM to perform other warfare rôles. As for our NATO partners in this enterprise, many of the original plans appear to be overtaken by events not the least of which has been a significant increase in the expected ship cost. As a result, it can only be said that future participation of Italy and the FRG is not fully established.

On the continuing R&D front, the PCH-1 is being employed to support the PHM programme in the evaluation of new and improved ship subsystems and mission equipment. It is likely that this ship, which has been a mainstay in hydrofoil technology development for many years, will soon reach the end of her illustrious Navy career. Meanwhile, the focus of development is about to shift to consideration of advanced hydrofoils combining the reliability of PHM with the performance in other rôles. A large hydrofoil ocean combatant, which may be in a range of sizes from 700 to 1,500 tons is also a likely candidate for further development. Figure 7 is an artist's rendering of such a ship of the future. The *Plainview* is expected to play a major rôle in this new initiative to be based on the results of the Advanced Naval Vehicle Concepts Evaluation, discussed elsewhere in this paper.

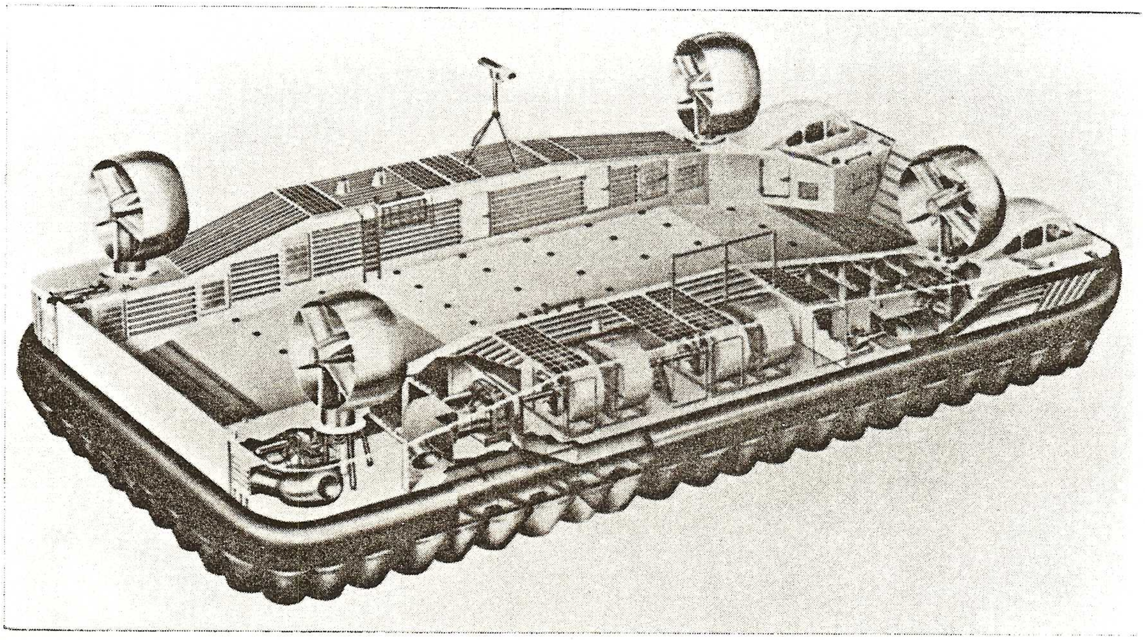
The principal characteristics of the Navy's operational hydrofoil ships and craft are summarised in Table 1. If the reader wishes additional information references 2 and 3 should prove helpful.

TABLE I

CHARACTERISTICS OF U.S. NAVY HYDROFOILS

	PCH-1	AGEH-1	PGH-1	PGH-2	PHM-1
Full Load Displacement (Tons)	126	320	69	58	231
LOA (Ft.)	115	212	74	72	146
Max. Beam (Ft.)	32	40	21.5	19.5	27.6
Draft (Ft.)					
Foils Up	8.6	6.3	4.3	4.4	6.0
Foils Down	19.8	25	13	13	22
Speed (KTS)					
Hullborne	12	13	9	9	11
Foilborne	High*	High*	High*	High*	-
Foil Configuration	CANARD	AIRPLANE	AIRPLANE	CANARD	CANARD
Max. Cont. HP.	6200	28000	3200	3200	18000
Gas Turbine	PROTEUS(2)	LM1500(2)	TYNE	PROTEUS	LM2500
Propulsor	PROPELLER	PROPELLER	PROPELLER	WATERJET	WATERJET

* 40 to 60 knots - See reference 1.



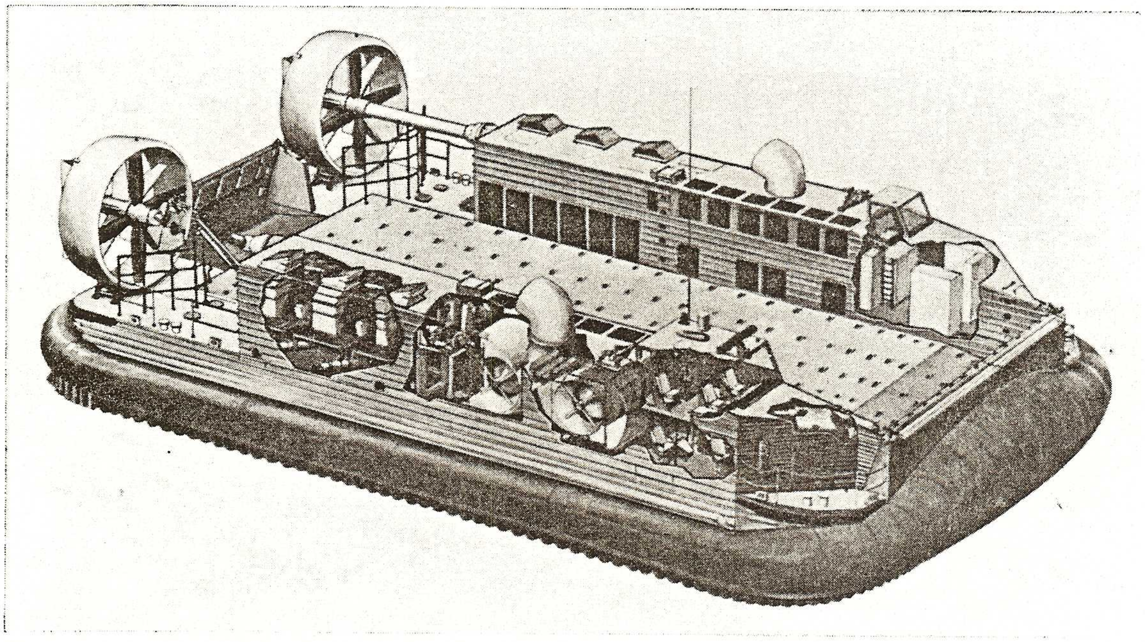


Fig 8 Arrangement of JEFF A and JEFF B Landing Craft

Hovercraft

The US Navy's active interest in hovercraft dates from the early 1960s with a number of research programmes being sponsored by the Office of Naval Research and the Bureau of Ships. In 1963 the Navy acquired the Hydroskimmer (SKMR-1), a nominal 25-ton test craft designed and constructed by Bell Aerospace Company. This was the largest Air Cushion Vehicle in the US at that time and was capable of calm-water speeds up to 70 knots. This successful programme was followed by acquisition and deployment in Vietnam of three Patrol Air Cushion Vehicles (PACV) which were actually conversions of the SRN-5 produced by British Hovercraft Corporation. Experience with these craft demonstrated the value of the ACV's capability to traverse at high speeds a wide variety of unprepared surfaces.

With the issuance, in 1965, of a Navy requirement for improved landing craft, it was natural to include the ACV as one of the leading candidates for this rôle. At the onset, the Amphibious Assault Landing Craft (AALC) Development Programme, directed by the Naval Sea Systems Command, undertook formulation of an extensive computer model to examine various mixes of different landing craft and identify an optimum set to perform the ship-to-shore mission. This study was carried out by Stanford Research Institute and led to the conclusion that ACVs of 30,000 and 120,000 pound payloads merited development as assault landing craft. Funding constraints did not permit developing both sizes simultaneously so the decision was made to concentrate on the larger size craft.

Early in 1970 contracts were let to the Aerojet-General Corporation and Bell Aerospace Company for preliminary

TABLE II

JEFF CRAFT CHARACTERISTICS

	JEFF A	JEFF B
Length (Ft.)	93	87
Beam (Ft.)	48	47
Height (Ft.)	23	23
Gross Weight (Lbs)	340,000	325,000
Cargo Area (Ft^2)	2,100	1,740
Speed (KTS)	50 (SS-2)	50 (SS-2)
Range (NM)	200	200
Slope Cap. (%)	11.5	13
Inst. Power (HP)	16,800	16,800
Engines	6-TF40	6-TF40

designs of an ACV capable of being transported in the well-deck of the LSD or LPD and of carrying a 60-ton payload at 50 knots in sea state 2 through the surf zone and over the beach. Each contractor produced a design in accordance with the Navy specifications but embodying several significantly different technical approaches to major subsystems configurations. As a result, early in 1971 the Navy contracted for the detailed design and construction of a development prototype by each contractor.

The Aerojet Craft (JEFF A) and Bell Craft (JEFF B) configurations are shown in Figure 8 and their characteristics are given in Table II. It is also of interest to note the comparison of planforms and payloads shown in Figure 9. Here the AIST is a Soviet military ACV now in production and the SRN-4 is the cross-channel ferry built by British Hovercraft Corporation (BHC), a new stretched version of which is now under construction. The Bell SK-5 is a military version of the SRN-5 previously mentioned and the SRN-6 is a stretched version of the SRN-5. A military version of the Bell (of Canada) *Voyageur*, designated the LACV, has been purchased by the US Army and has been undergoing tests at Ft Story, Virginia. Finally, the BH-7 is a military ACV produced by BHC, a number of which have been delivered to Iran.

The more important differences between the two design approaches embodied in the JEFF craft are shown in Figure 10. In Figure 11 these underviews of experimental models show that the Bell bag and finger skirt design requires compartmentation of the cushion by stability trunks whereas the Aerojet version with pericell skirts requires no compartmentation.

At this writing, construction of each craft is essentially complete. The JEFF A was constructed by Todd Shipyards, Seattle, Washington and was transported by barge to Aerojet's facility in Tacoma, Washington, for outfitting and test. In Figure 12 the craft is shown before attachment of the skirt. The craft is presently underway on a seagoing barge for delivery to the Experimental Trials Unit of DTNSRDC which is located at Panama City, Florida, as a tenant activity of the Naval Coastal Systems Laboratory.

The JEFF B was constructed by Bell at NASA's Michoud facility in New Orleans, and has been delivered to the Experimental Trials Unit. It is currently undergoing final checkout prior to starting the planned extensive test programme. In Figure 13 the JEFF B is shown at the Panama City facility. In the trials programme, soon to get underway, performance envelopes will be explored and extensive fullscale data will be obtained on structures, machinery, auxiliary systems, control, and motion characteristics in calm and rough seas, through surf zones and overland. Ultimately, a full demonstration of operations in and out of the well-deck of an assault ship will be conducted. Evaluation of these two craft, each of which is expected to meet performance goals, will provide the basis for the specification, design and acquisition of a new class

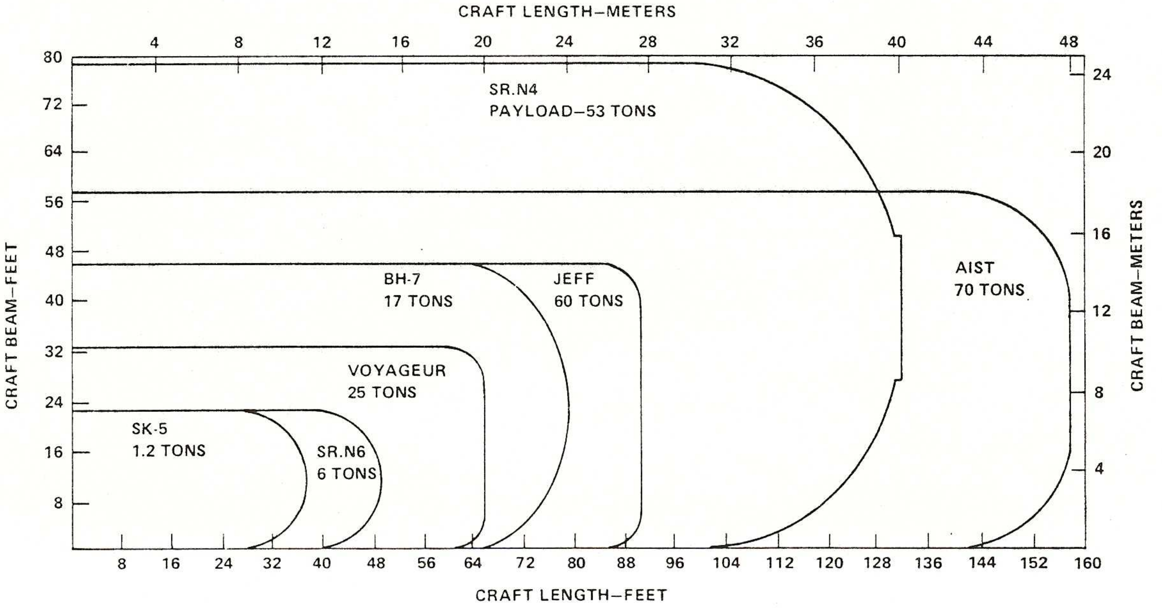
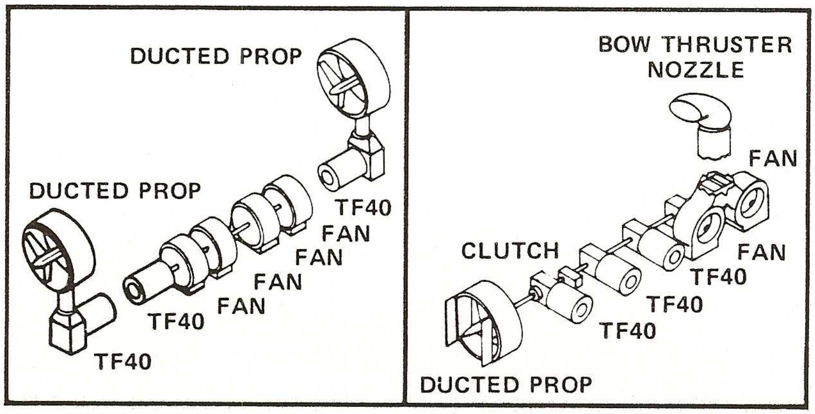
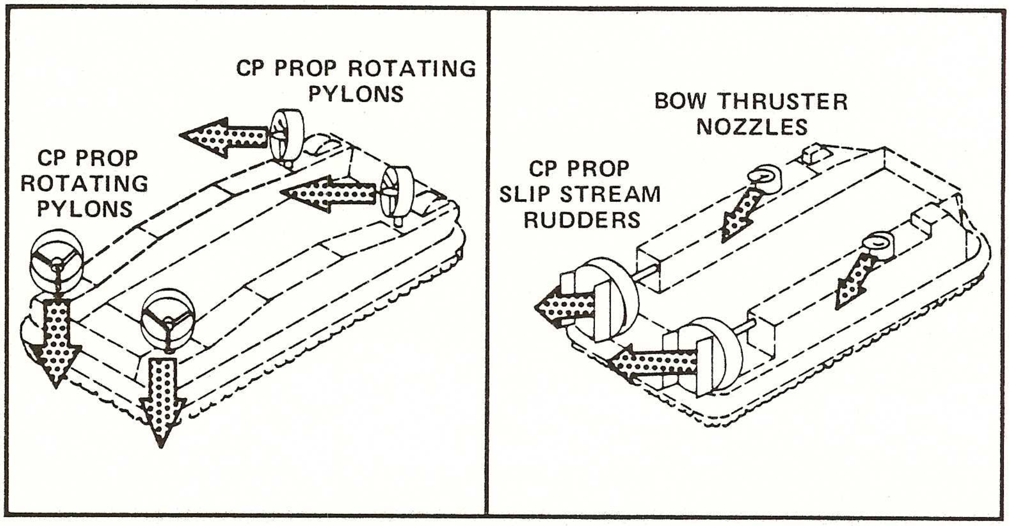


Fig 9 ACV Planform Comparisons



POWERING CONCEPT LIFT/PROPULSION MACHINERY ARRANGEMENT

SEPARATED ON JEFF (A) INTEGRATED ON JEFF (B)



ALTERNATIVE CONTROL SYSTEM CONCEPTS

ROTATING PYLONS ON JEFF (A) THRUSTERS/RUDDERS ON JEFF (B)

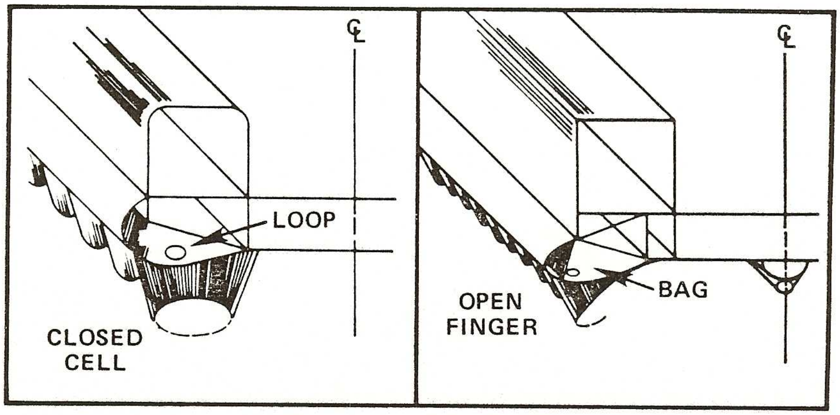
Fig 10a Comparison of Machinery and Control

of air cushion landing craft. Reference 4 provides considerably more detail on the AALC craft characteristics and the planned evaluation programme.

With the increased interest in the potential offered by the air cushion vehicles, in 1968, the Defense Advanced Research Projects Agency (ARPA) undertook a broad study of ACV miltary applications and concluded that these craft offer a significant capability to traverse the various types of surfaces found in the Arctic region. They are particularly attractive because their low-foot-print pressure permits traversing the tundra and permafrost without causing the kind of damage caused by other vehicles. The multi-terrain attributes of these craft and the increasing interest in our Arctic presence led ARPA, in 1970, to initiate a separate programme to develop the technology base for application of ACVs in the Arctic. This effort was designated the Arctic Surface Effect Vehicle (SEV) Development Programme to distinguish it from the Navy's other ongoing ACV development. Because of their already heavy involvement in ACV technology, ARPA sought and received the Navy acceptance of programme responsibility.

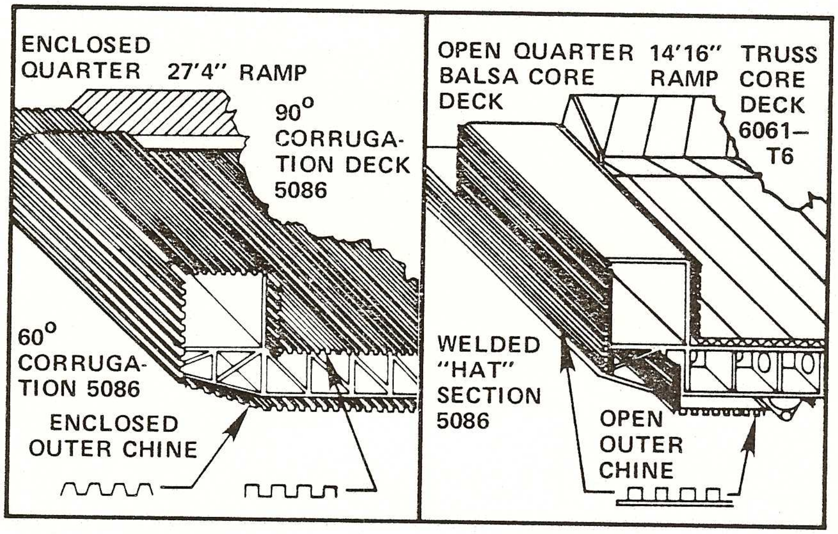
Under the technical direction of DTNSRDC, with participation by the US Army's Cold Regions Research and Engineering Laboratory (CRREL), and the Applied Physics

SKIRT SYSTEM AIR CUSHION FLEXIBLE UNDERSTRUCTURE



JEFF (A) USES PERICELLS JEFF (B) USES FINGER SKIRTS

ALTERNATIVE STRUCTURAL APPROACHES



JEFF (A) JEFF (B)

Fig 10b Comparison of Skirts and Structures

Laboratory of John Hopkins University (APL/JHU), the programme undertook to:

> "develop the technology required to exploit the Arctic military potential offered by the Surface Effect Vehicle."

The initial goals for the Arctic SEV characteristics were established as follows:

Gross Weight	1,000 tons
Payload	300 tons
Range	3,000 n miles
Maximum Speed	150 knots
Endurance	60 days

Phase I of the programme was directed toward development of the technology base related specifically to Arctic vehicles and included the following major task areas:

- * Definition of the Arctic environment
- * Parametric analysis and trade-off studies of vehicle concepts
- * Investigation and development of critical subsystems, including skirts, structure, life support, obstacle avoidance, and navigation equipment
- * Establishment of criteria for design
- * Preliminary design and analysis of several vehicle configurations and sizes

During the summer of 1971 an extensive test programme was conducted in the vicinity of Point Barrow, Alaska. Using a refurbished SK-5 (PACV), Figure 14, operated by the Coast Guard, data was obtained under a variety of conditions including operation over the ice pack, the open

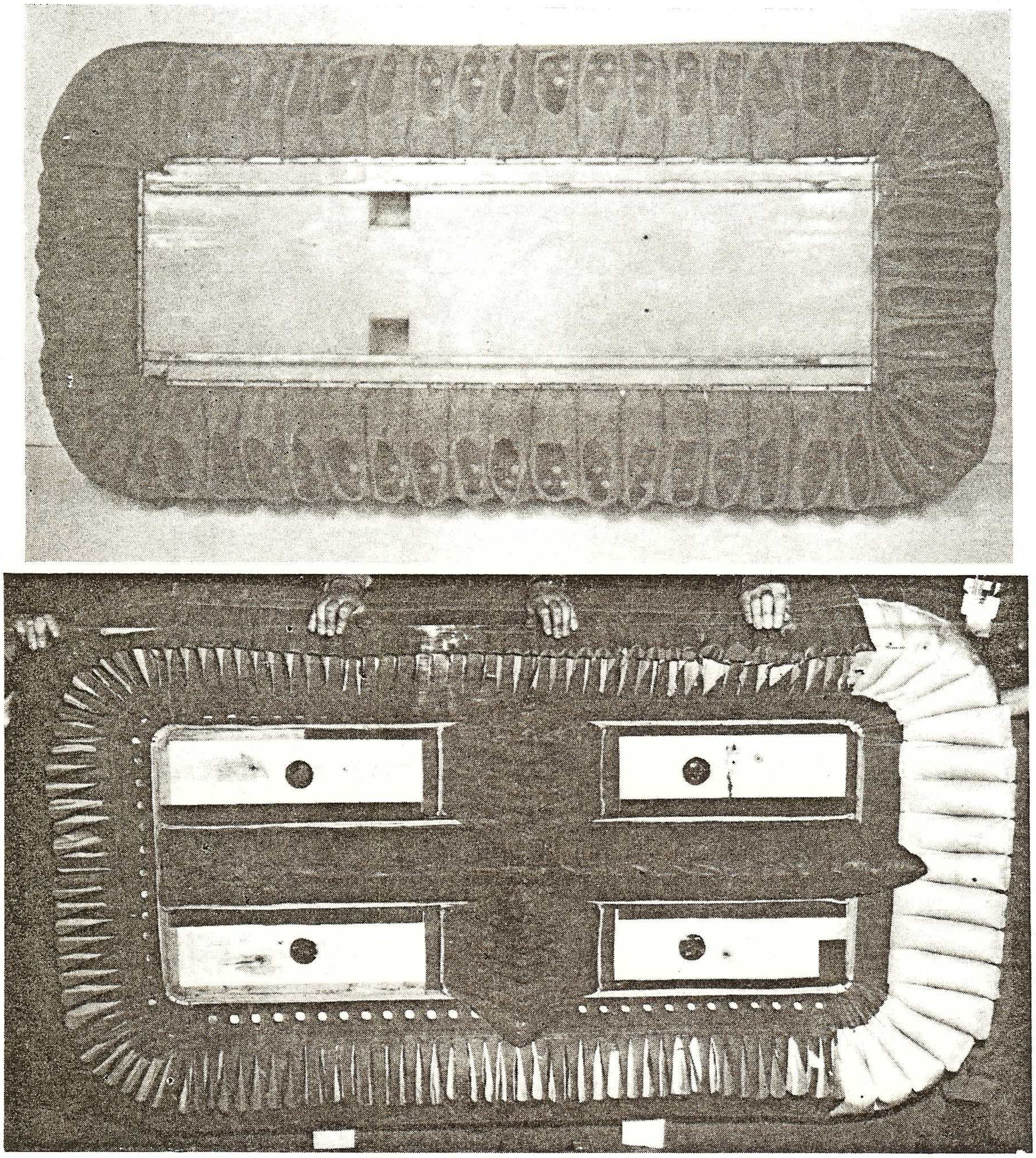


Fig 11 Aerojet Pericell and Bell Bag and Finger Skirt Systems

sea, and the tundra. These operations confirmed the great facility of these craft to traverse all types of terrain including their ability to traverse obstacles of near skirt height.

During the course of Phase I, it became clear that the original goals for vehicle characteristics were not only too ambitious but such characteristics were not necessary to satisfy envisaged requirements. Accordingly, the following modified goals were adopted:

	Medium Size	*Large Size*
Gross Weight (tons)	150	500
Payload (tons)	30	50
Range (nautical miles)	500	800
Maximum Speed (knots)	60	70
Endurance (days)	2	14

Here, it may be noted that the medium size was influenced by the comparable size of the JEFF craft whose detailed designs were already available.

In light of these new goals and new data being generated by the broad spectrum of technology development, contracts were let to Bell and Aerojet to prepare preliminary designs of a 150-ton nominal size ACV suitable for Arctic operation. A third contract was let to Boeing for the conceptual design of a nominal 500-ton Arctic SEV. Photographs of small-scale display models of those designs are shown in Figure 15. The large white object prominently mounted on each superstructure is the obstacle-avoidance radar conceived by APL/JHU. Internal arrangement drawings of the three concepts are shown in Figures 16, 17 and 18.

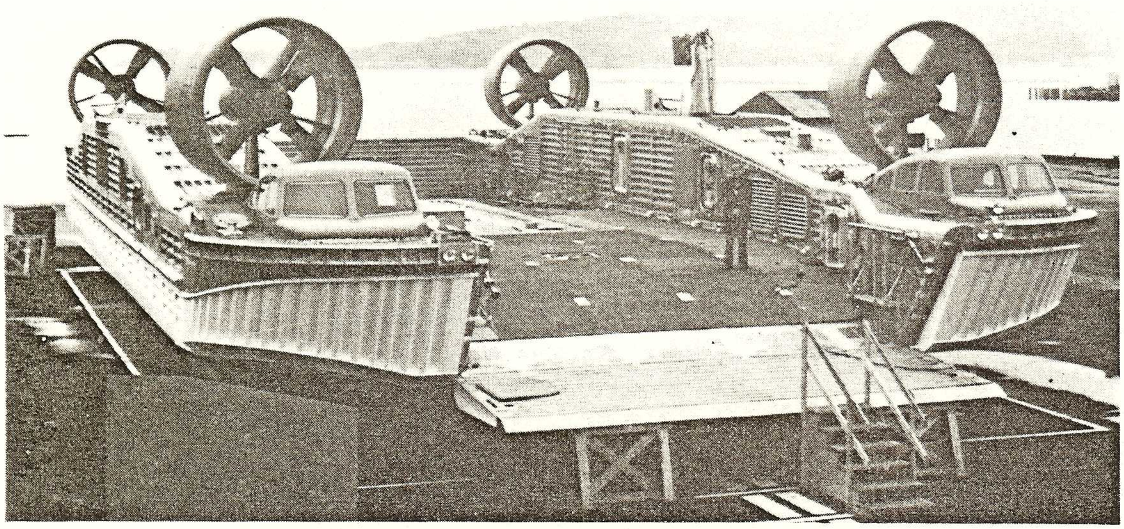
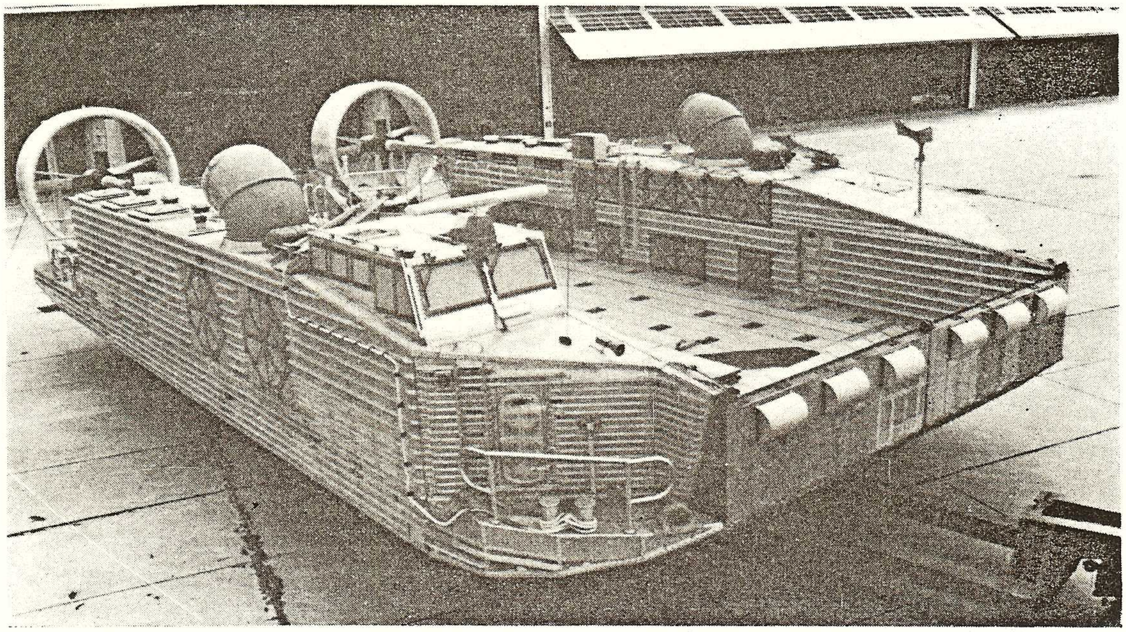


Fig 12
JEFF A
before
skirt
attachment

Fig 13
JEFF B
before
skirt
attachment



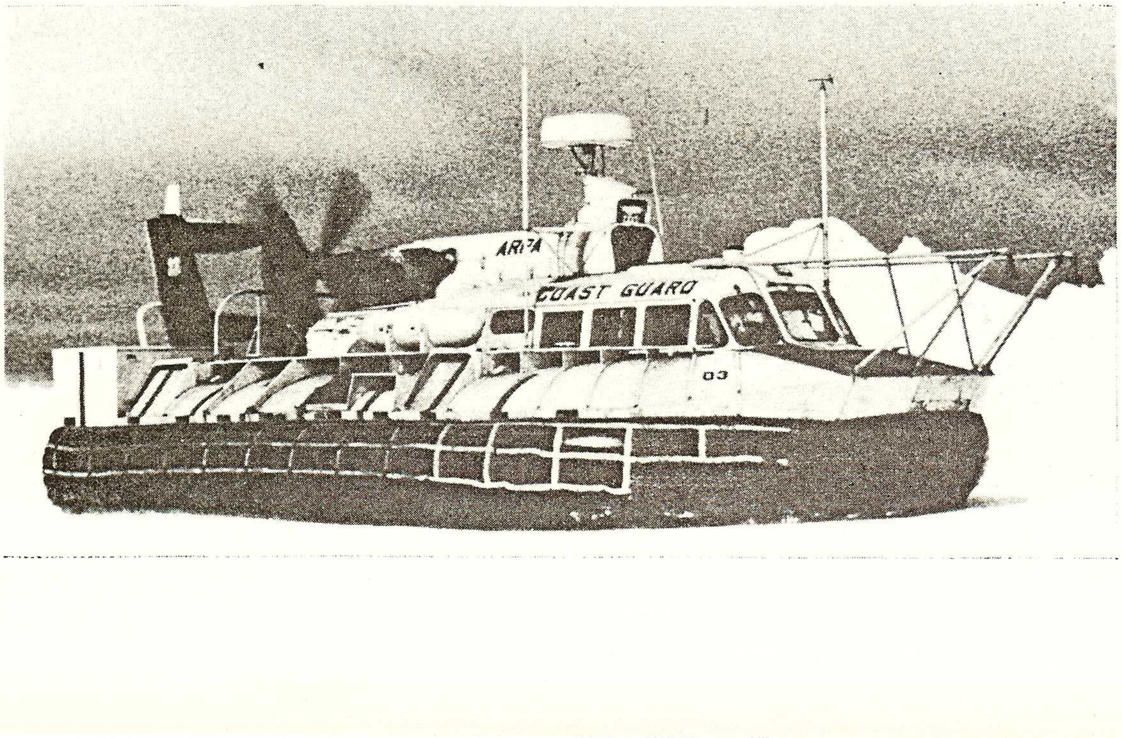


Fig 14
Patrol Air
Cushion Vehicle
in Arctic
(PACV)

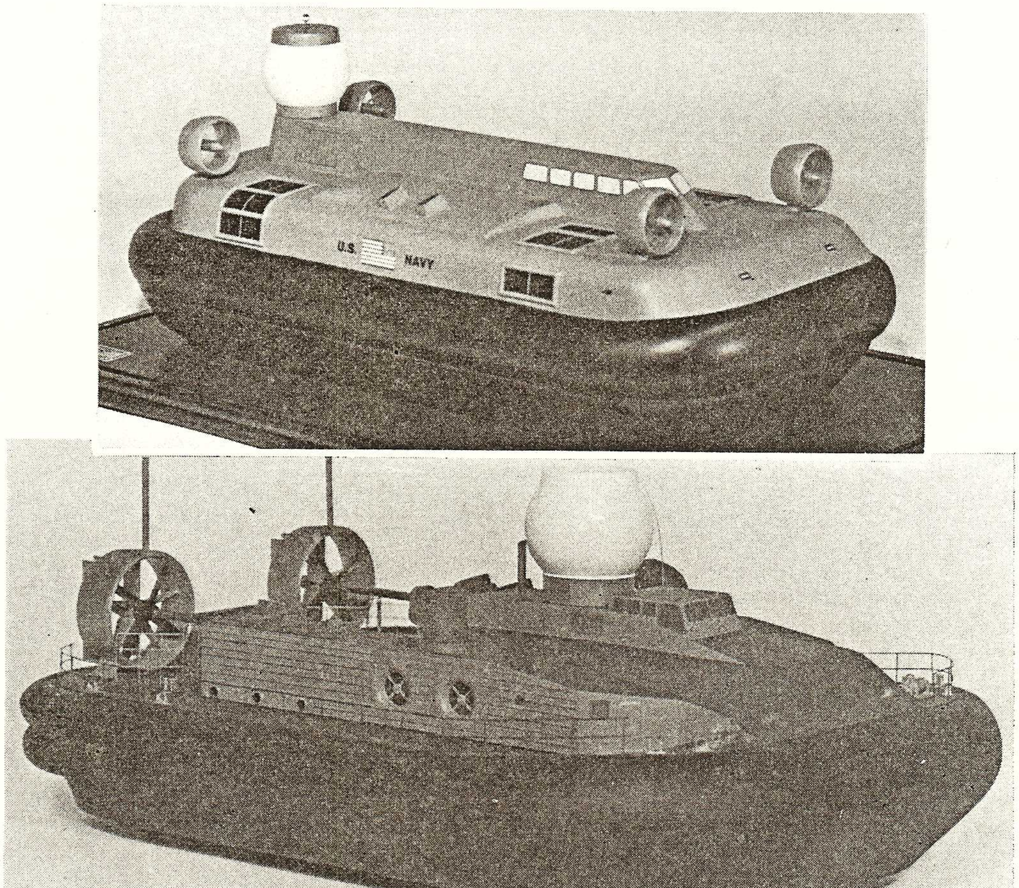


Fig 15 Arctic SEV models of 150-ton Aerojet, 150-ton Bell, and 500-ton Boeing Concepts

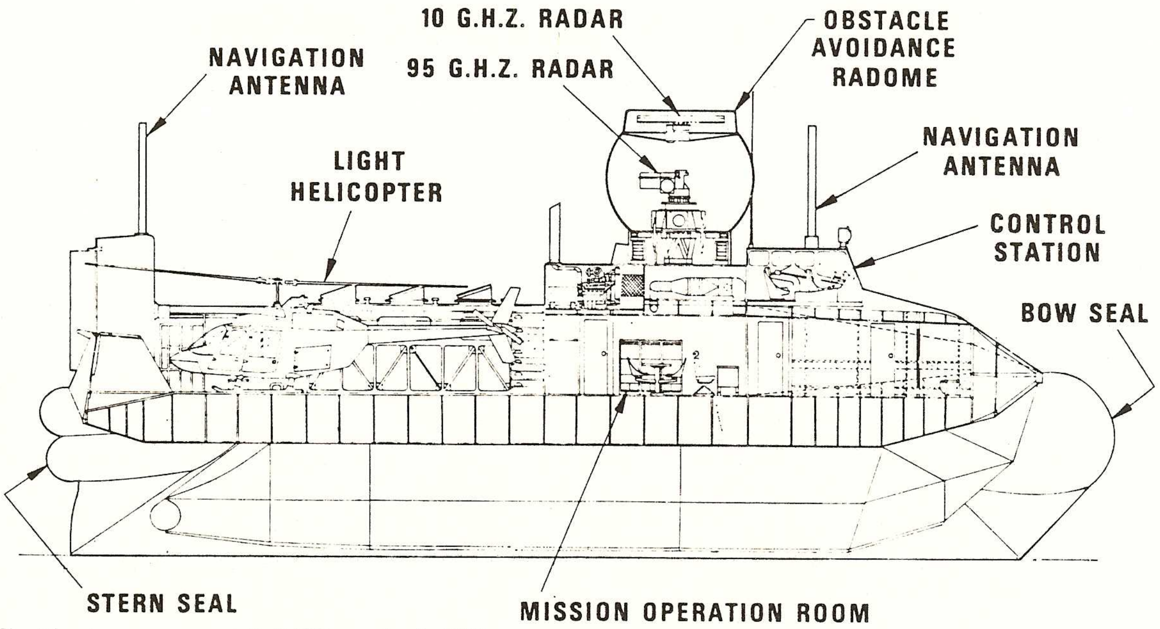


Fig 16 Arrangement of Bell 150-ton Arctic SEV

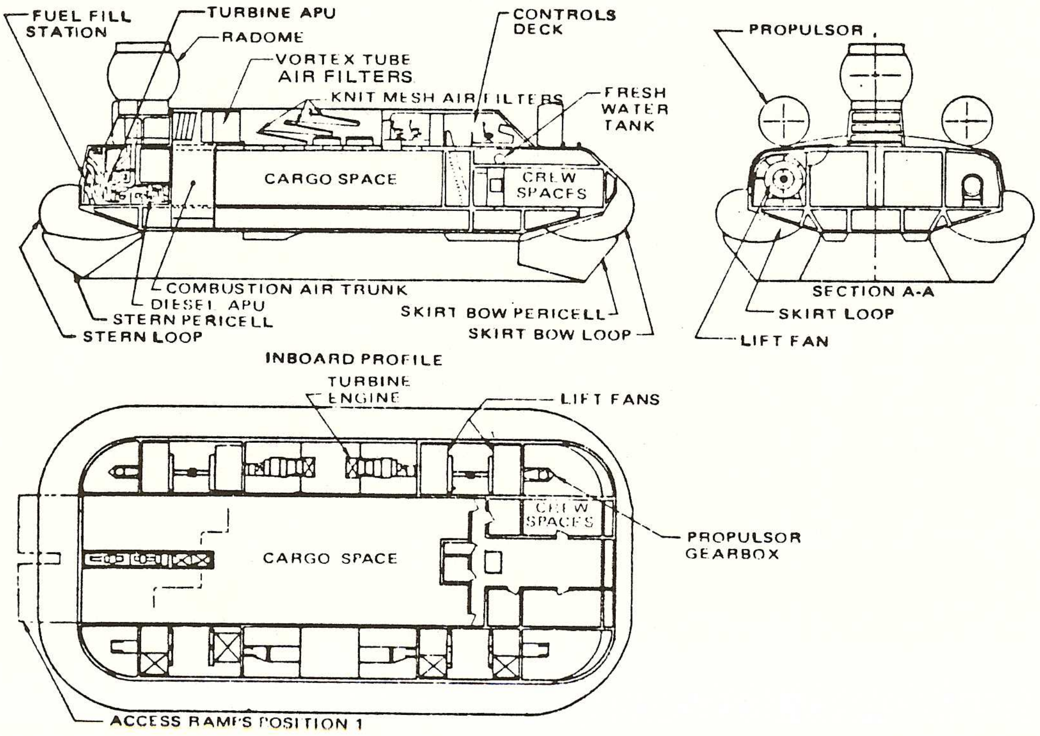


Fig 17 Arrangement of Aerojet 150-ton Arctic SEV

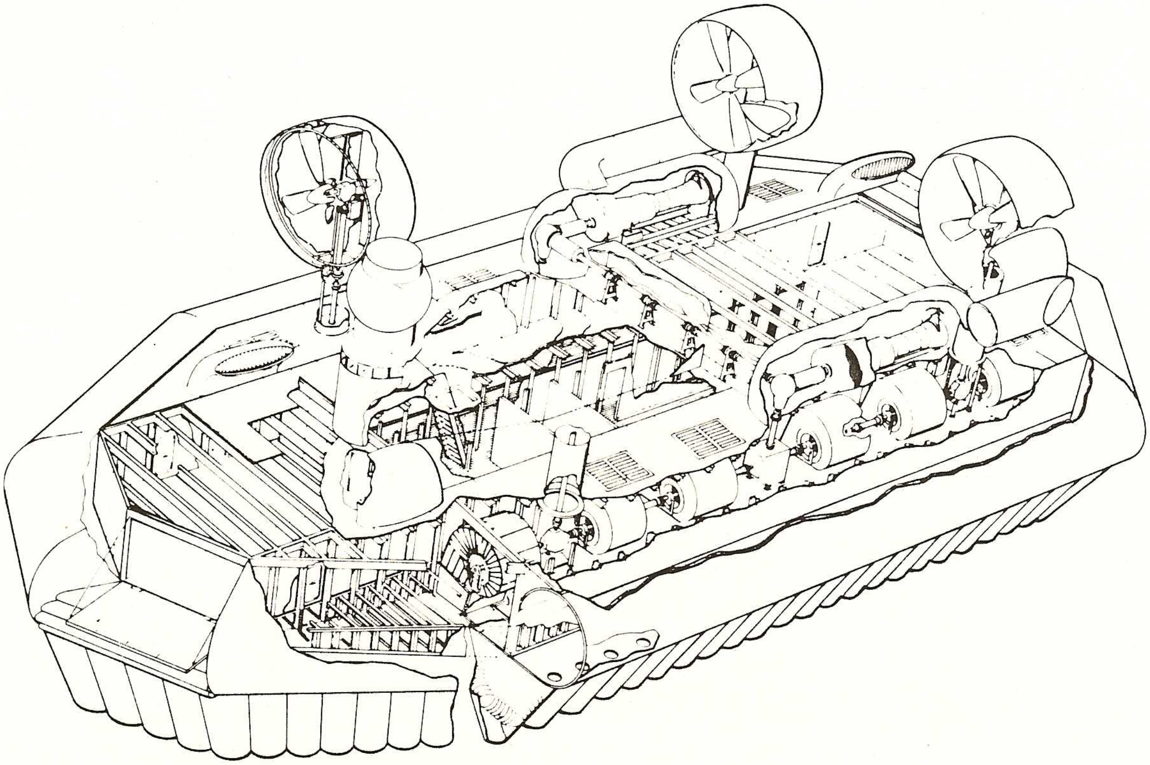


Fig 18 Arrangement of Boeing 500-ton Arctic SEV

It was the original intent of the programme to follow Phase I with the design, construction and evaluation of a developmental prototype to be operated under actual Arctic conditions. ARPA had anticipated that one or more of the military services would join in supporting such a venture. By 1974, however, as the Phase I effort drew to a close, no such interest on the part of the services had materialised. Further, there was no clear mission requirement calling for such a vehicle to be developed. As a result, ARPA decided to terminate the programme with full documentation of the extensive technology developments and design studies. All the work of the programme was summarised and published in a two-volume summary report, reference 5. Contained therein is a wealth of data

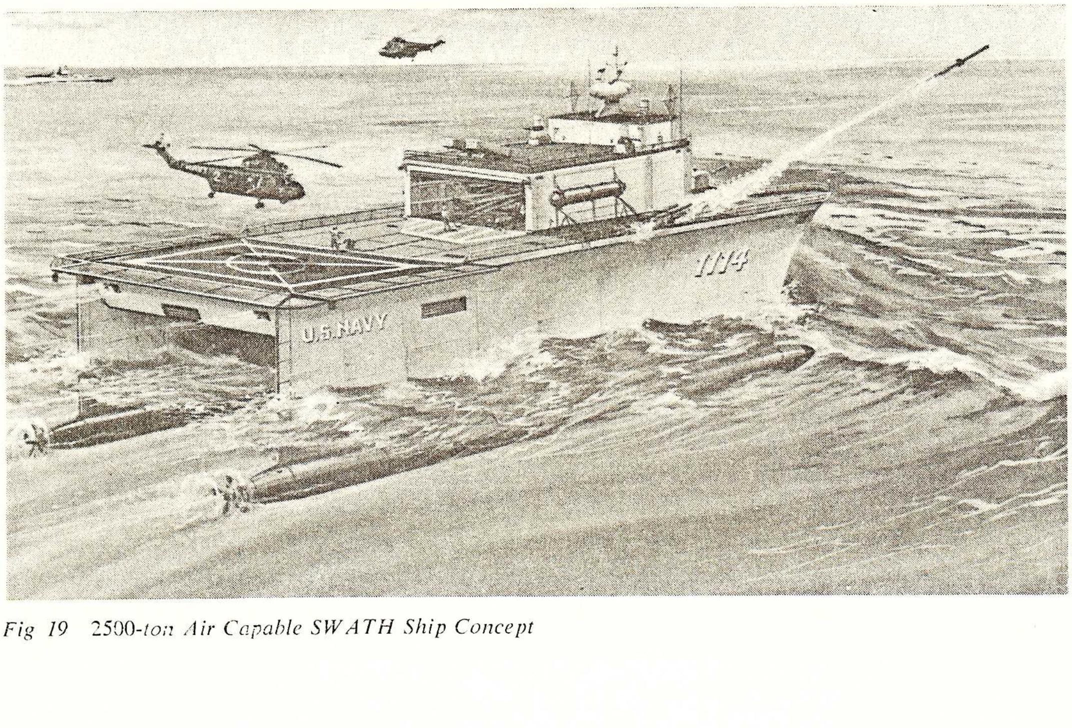


Fig 19 2500-ton Air Capable SWATH Ship Concept

Fig 20 SSP KAIMALINO with Helo

and numerous additional references to other material covering definition of the Arctic terrain and environment; the technology of SEV subsystems and system design; and the development of navigation, communication and obstacle avoidance systems. As an additional source of information for those who wish to delve deeper into the complete spectrum of ACV technology reference 6 by Mantle is recommended as the most comprehensive and up-to-date publication on the current "state-of-the-art".

SWATH Ships

The acronym SWATH, standing for Small Waterplane Area Twin-Hull Ship, was selected by the Navy to distinguish this member of the catamaran family from other forms with twin ship-like hulls. The name was almost abandoned soon after being coined when it was discovered that the acronym also stood for Shallow Water Absorbent Trash Harvester, a craft of considerably less lofty purpose. In time, this confusion has been overcome, however, and the SWATH ship has been recognised as a promising advanced naval vehicle configuration.

The SWATH concept features two fully-submerged, submarine-like, demi-hulls connected to an above-water, box-like bridging structure by one or more relatively thin struts attached to each demi-hull. Figure 19 depicts an artist's rendering of a nominal 2,500-ton air-capable SWATH ship. It is not a new idea, having been proposed in the form of various basic patents going back to the 1800s. However, as with many other advanced naval vehicles concepts, there has been no significant exploitation of the idea until relatively recently. In the late 1960s the advantages offered by SWATH ships began to generate considerable

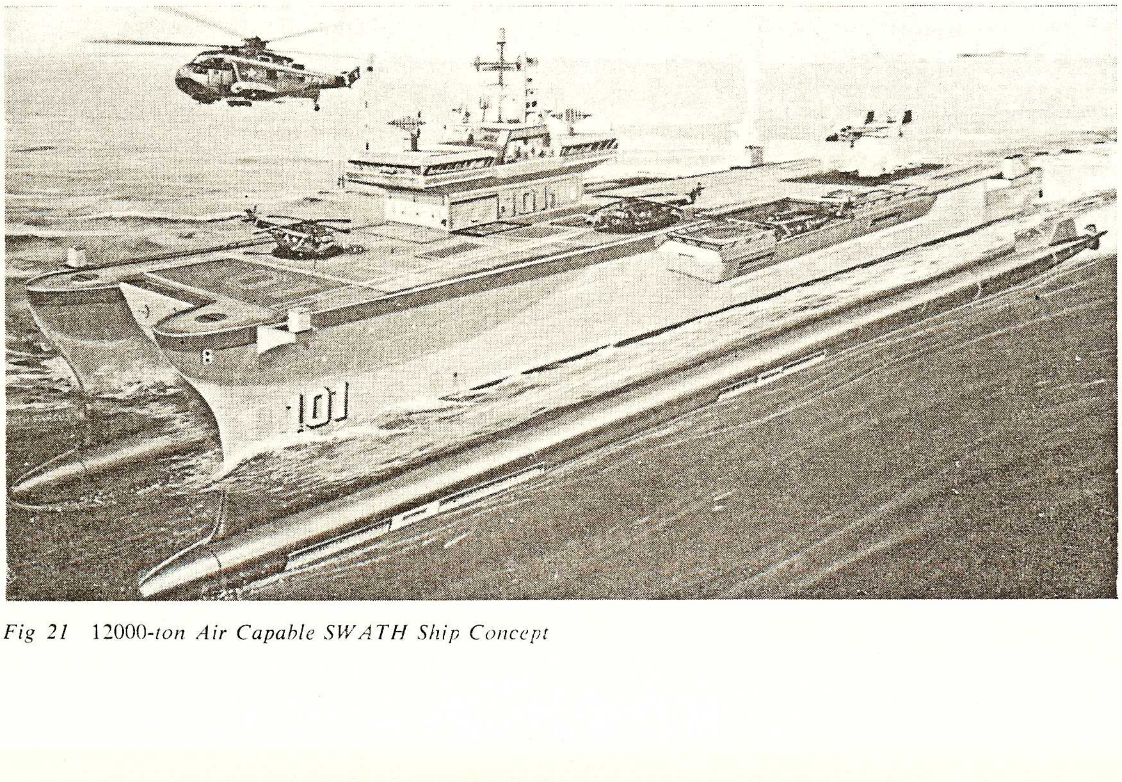


Fig 21 12000-*ton Air Capable SWATH Ship Concept*

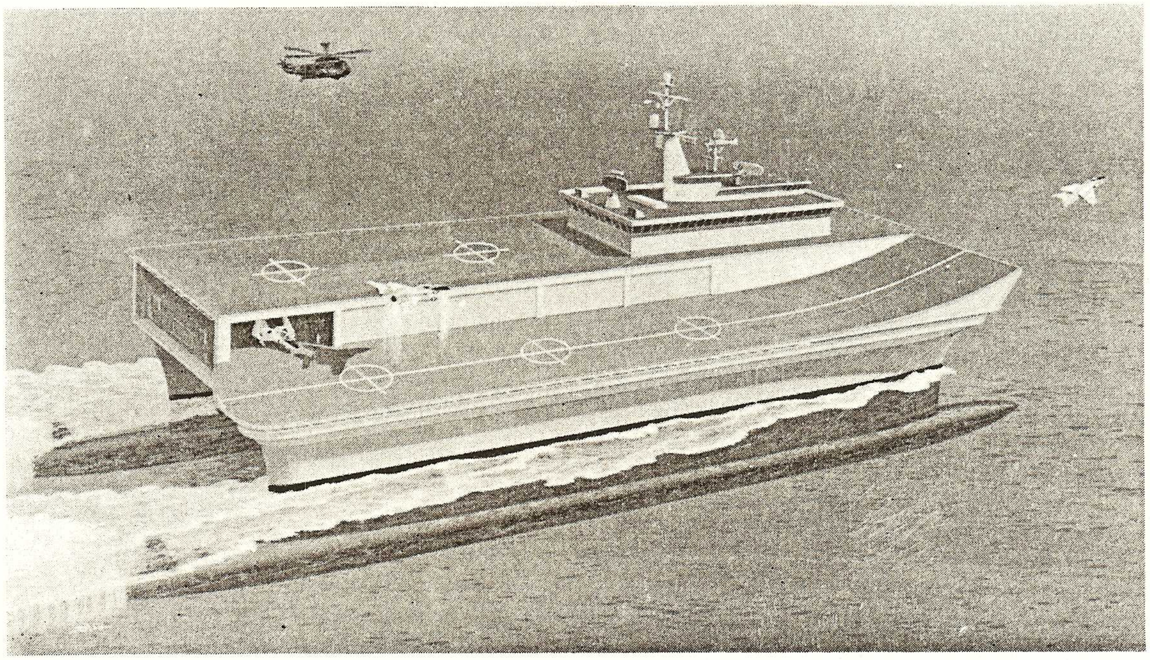


Fig 22 7000-ton Air Capable SWATH Ship Concept

interest in both the military and commercial applications of this ship configuration. These advantages include excellent platform steadiness in rough seas, the maintenance of speed in a seaway, large useable deck area, and the volume efficiency of the main structure. During this period Litton Industries, with its TRISEC concept, the Naval Undersea Center (NUC), with its Semi-Submerged Ship (S^3), and the Naval Ship R&D Center with a number of model configurations were all actively engaged in establishing a basis for design of such ships and confirming their utility for naval application. In 1973 the Naval Material Command sponsored a laboratory programme to establish a firm technology base adequate to proceed with acquisition of a large developmental prototype. NAVMAT also supported the design and construction of a 190-ton SWATH workboat for use by NUC at its Hawaii laboratory. This craft, designated the SSP *Kaimalino,* is shown in Figure 20. It was constructed by the Coast Guard Yard at Curtis Bay and has the following characteristics:

Overall length	88.3 feet
Beam	49.7 feet
Maximum draft	15.3 feet
Installed power	4,000 hp (two 2,000-hp gas turbines)
Maximum Speed	25 knots

In 1975 direction of SWATH development was assigned to the Naval Sea Systems Command. Since that time the Navy has continued to expand the understanding of structural, hydrodynamic, and performance aspects of SWATH design through laboratory experiments and analyses. Technical trials have also been conducted with the SSP during which extensive data on structure, control, motion, and other performance factors have been gathered. Of particular note was the conduct of more than 80 landings and take-offs of a LAMPS, SH-3 helicopter under various conditions of speed, wind over the deck, and sea state. The pilots flying these qualification tests were most enthusiastic about the excellent characteristics of this craft and noted that it could only be compared to an aircraft carrier in its qualities as a helicopter platform. The steadiness and controllability of the craft in rough seas has also been adequately demonstrated to a large number of observers who have ridden it in recent months.

Another important part of the current effort is being carried out by the Naval Ship Engineering Center where a number of designs have been developed to support selection of the more promising applications for the SWATH concept. These designs have ranged from a nominal 2,500-ton size for applications such as a mine countermeasure ship, an escort, or Coast Guard support ship, all air capable, to large VSTOL-carrying ships ranging up to as much as 45,000 tons. Artist's renderings of 7,000-ton and 12,000-ton air capable SWATH concepts are shown in Figures 21 and 22. For sizes up to about 2,000 tons construction of aluminium is desirable and may be necessary to achieve an acceptable payload fraction. Above about 2,000 tons, steel can be used and the cost of construction should not differ substantially from that of conventional monohulls of equal displacement.

Although the SWATH ship does offer some significant advantages over monohull ships there are also disadvantages that must be recognised. For a given displacement it is clear that a SWATH ship will have a greater draft than a monohull. This can be off-set somewhat by ballast control but still will limit larger sizes in the use of some harbour facilities. Also, another natural consequence of reducing the waterplane area is an increase in sensitivity to changes in disposable load. Here again, ballast control can serve to off-set this effect. Further, it is expected that adequate control of SWATH ships may require some form of active control surfaces on the demi-hulls. Finally, although their reduced response to the seaway permits maintaining significantly higher speeds in rough waters than comparable monohulls, the calm water drag of SWATH is greater as a result of significantly greater wetted surface.

At this time it may be stated that it seems clear that the SWATH ship is a concept whose time has come. There seems little question that in the very near future the Navy will identify a firm requirement for which a SWATH ship will offer superior performance and utility. This will also give added momentum to the already considerable interest in commercial applications of this novel and promising new ship type. Those who wish to explore further the technical and design aspects of SWATH ships will find references 7 and 8 useful sources of information.

Hybrids

If one considers that, to sustain them, hydrofoils depend on dynamic lift, hovercraft on powered static lift, and conventional ships on buoyancy, it is natural to think of possible combinations which might offer particularly attractive vehicle characteristics. A hybrid marine vehicle is one which embodies more than one source of sustention over a major portion of its operating regime. For the past several years the Navy has been engaged in a relatively modest effort to examine the properties of the spectrum of hybrid marine vehicles. For example, various combinations of foils and air cushions, foils and buoyancy, air cushions and buoyancy, have been examined analytically using basic data derived from the parent vehicle types. In some cases, where there appears to be particular promise in a given configuration, more detailed studies have been made which have included preliminary concept designs and even some model experiments to verify performance predictions.

One of the more promising hybrid concepts which has evolved from this work is the so-called HYSWAS or Hydrofoil Small Waterplane Area Ship. As shown in Figure 23 a HYSWAS represents a combination of the SWATH ship concept with a single demi-hull and a fully-submerged hydrofoil which, underway, helps to unload the main hull and raise it above the water surface. HYSWAS appears to offer a number of potential advantages such as:

* Speeds up to 40 or 50 knots in rough seas
* Efficient operation at both low and high speed
* Good range characteristics
* Good useful load fraction
* Flexibility in general arrangement

Parametric analyses have been made covering a range of displacements from 500 to 3,000 tons, ratios of length-to-diameter of the demi-hull from 12 to 20, and variations of proportions of dynamic lift from 20 to 40%. Even more detailed studies have focused on a nominal 2,000-ton displacement HYSWAS as a basis for comparison to other advanced vehicles being developed. Figure 24 is an artist's rendering of a 2,000-ton HYSWAS with air capability.

TABLE III

CHARACTERISTICS OF 2000-TON HYSWAS CONCEPT

Full Load Displacement	2000 tons
Design Buoyancy	1400 tons
Dynamic Lift	600 tons
Lower Hull Length	257 ft.
Lower Hull Diameter	15.4 ft.
Strut Chord	180 ft.
Strut Height	19.7 ft.
Main Foil Area	850 $ft.^2$
Main Foil Span (tip to tip)	87 ft.
Aft Foil Area	270 $ft.^2$
Aft Foil Span (tip to tip)	40 ft.
Upper Hull Length	234 ft.
Upper Hull Beam (max.)	78.8 ft.
Hullborne Draft	35.1 ft.
Foilborne Draft (design)	23.1 ft.

The principal characteristics of such a vehicle with 70% buoyancy and 30% dynamic lift are given in Table III. This proportion of sustension forces appears to offer good hydrodynamic qualities for a broad range of operating

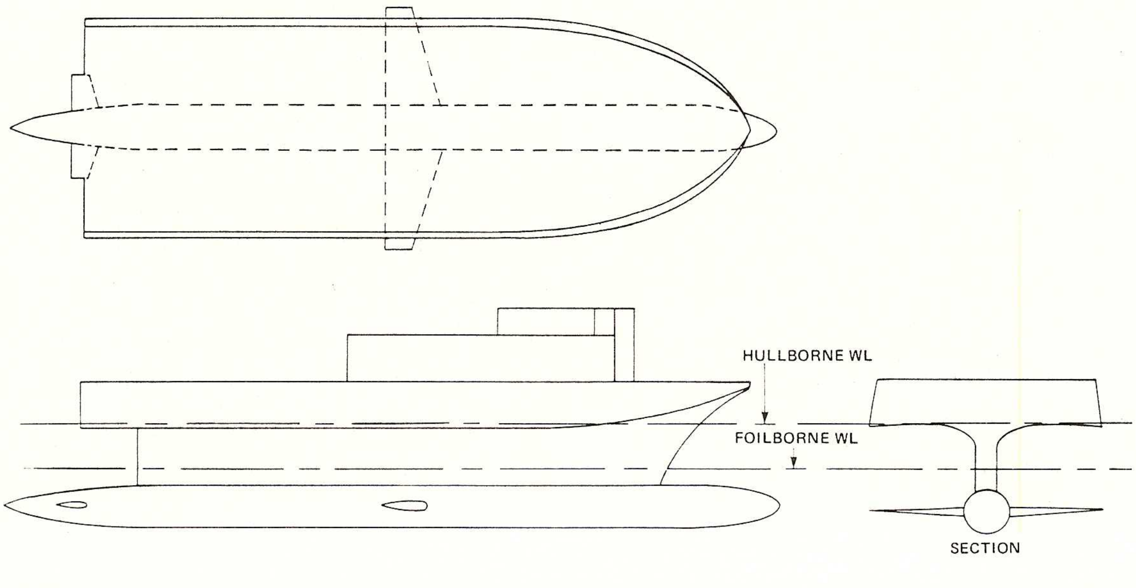


Fig 23 Sketch of HYSWAS Concept

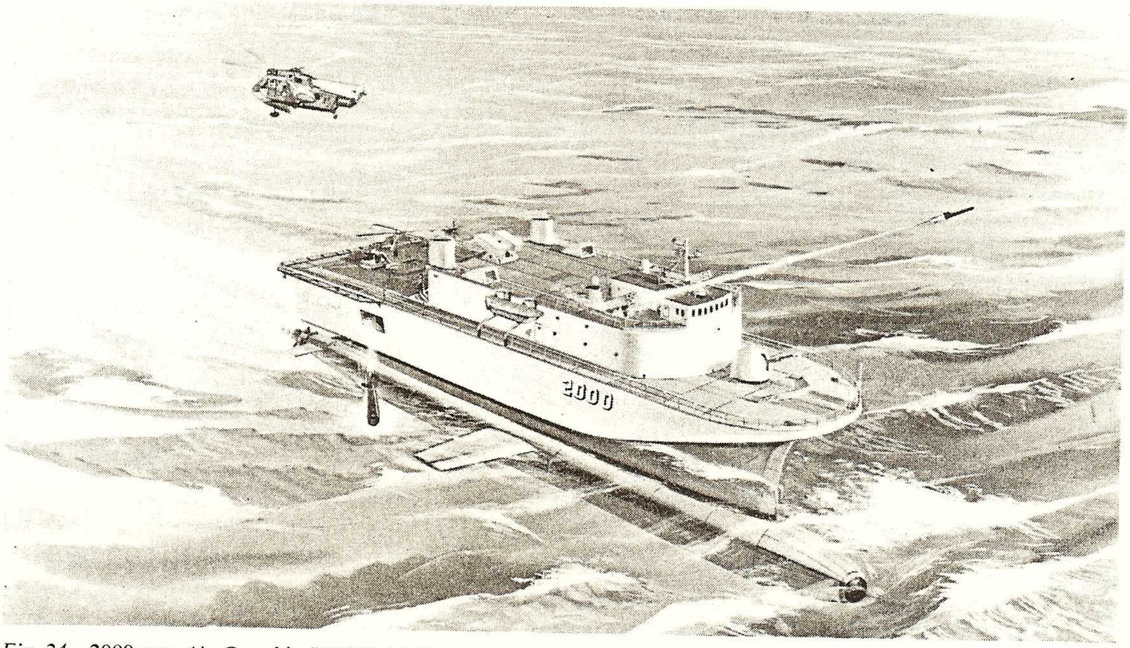


Fig 24 2000-ton Air Capable HYSWAS Concept

speeds. This design concept is all aluminium and arranged to accommodate a crew of 188, two LAMPS-size helicopters, and a formidable weapons system of guns, missiles, and torpedoes. The main propulsion consists of two LM 2500 (25,0000 hp) gas turbines located in the upper hull. A Z-drive transmits power through the strut to a contra-rotating planetary reduction gear and fixed-pitch, contra-rotating propellers in the demi-hull. Auxiliary propulsion is provided for operation at low speeds hullborne.

Investigations of hybrid vehicle forms have not been carried to a point where firm conclusions can be reached regarding their potential for future application. Inherent disadvantages must be clearly weighed against advantages and this requires considerably more hard data than is currently available. Nevertheless, there does appear to be some real future payoff in seeking to capitalise on combinations of the desired characteristics of some of the present advanced vehicles while at the same time avoiding some of their inherent penalties. At this stage, as an example, HYSWAS appears to be a particularly promising candidate for further investigation. Reference 9 provides more detailed information on this hybrid ship concept.

Navy Study

As the numbers of potentially useful concepts for new naval vehicles have multiplied and costs of development have increased, more and more questions have been raised regarding their relative merits in application to naval missions. This situation led, in late 1975, to the initiation of a broad evaluation under the direction of the Chief of Naval Operations. The effort, designated the Advanced Naval Vehicle Concepts Evaluation (ANVCE), is still underway and not expected to be completed before early 1978. It encompasses hydrofoils, surface effect ships, air cushion vehicles, SWATH ships, planing ships, wing-in-ground effect (WIG) vehicles, lighter-than-air craft, sea-loiter aircraft, and air-loiter aircraft. Conventional and advanced monohull ships are also included as a baseline for comparison. The study is divided into six major phases, the first four of which essentially have been completed.

Phase one addressed the specifications of a number of realistic scenarios wherein the various vehicles of interest might be expected to find application. In phase two there was a comprehensive assessment of the technological state-of-the-art underlying each vehicle concept and identification of critical gaps in the technology. In parallel with this phase, phase three addressed the formulation of an acquisition and life-cycle cost model. Phase four was directed toward overcoming the identified technology gaps by conduct of some critical experiments and further analytical studies, thus providing an acceptable technology base for vehicle comparison. In other words, an attempt was made to bring the risks in vehicle assessment into some reasonable balance.

Clearly, the wide range in the level of maturity of the technology underlying the various concepts prohibited full parity in this regard. The paucity of real data for some of the aircraft concepts was, for example, difficult to overcome within available time and funding. Phase four also addressed itself to the need for realistic design concepts including combat suites compatible with platform characteristics. A number of "point designs" were developed for each vehicle, in a range of sizes, each drawing from an approved list of weapon and sensor systems those equipments considered most suitable for a given mission application. This, in effect, permitted each vehicle "advocate" to "take his best shot" at a scenario where his vehicle offered potential utility.

Phase five of ANVCE has, not surprisingly, proved to be the most troublesome. Here, an attempt is being made to combine in a comprehensive computer model the vehicle costs and performance characteristics to assess their relative military worth in carrying out the postulated naval mission. As might be expected, this is a formidable task. Incorporation of those vehicles' characteristics in a realistic environment involves extremely complex mathematical modelling. On the other hand, attempts to simplify the model can easily lead to elimination of the very attributes which created interest in a concept in the first place.

Once a basis for assessing the relative military worth of these advanced vehicles is established, the final phase of ANVCE will be ready to make recommendations for future vehicle development. Anticipation of this guidance has had considerable impact in slowing the pace of many current development efforts and results are anxiously awaited by the various vehicle advocates.

In the meantime, however, the evaluation has already produced a number of tangible benefits. At the onset it was recognised that there was great need for standardisation of terminology and nomenclature. As a result, a number of working papers were produced that established a consistent basis for comparison of performance characteristics. Consistency was also brought about in the definitions of various design margins.

The opportunity to make a comprehensive assessment of current technology and identify critical gaps was in itself adequate justification for much of the effort. There are also a number of deficiencies which have been brought into better focus and which require further attention. Most notable of these is the whole issue of how to define "ride-quality". This is a matter not only of concern to the military but also to the operator of commercial marine vehicles. If the surface of the sea were always calm there would be little interest in many of these advanced marine vehicles. The sea surface is seldom calm, however, and the ability to operate economically in rough seas at reasonable and even very high speeds is a performance characteristic much sought after. The description of the sea surface, the motions of a platform in the seaway, and the effects of these motions on ship performance, human and equipment performance, are all involved in the formulation of rational criteria for comparing the relative merits of various vehicles. Much progress has been made in this area but there is much yet to be accomplished. For example, the question of how to quantitatively relate the motions of a vehicle to the performance of human operators is still far from resolved. Certainly ANVCE has called much needed attention to many such issues and will, hopefully, stimulate increased effort to resolve these fundamental questions.

Technology Transfer

The development of Advanced Naval Vehicles for the US Navy has been the cause as well as the beneficiary of a massive and multi-dimensional technology transfer effort. The advanced technologies in structures, materials, propulsion and other subsystems provided the basis for the Navy to establish programmes. These programmes continue to provide a focus for developing new technology in platforms and payloads which is flowing back into commercial applications.

In the case of the development of advanced marine vehicles, the great bulk of the technology base already resides in industry because it has been developed in partnership with industry.

Aerospace firms such as Boeing and Grumman have long been involved in contracts supporting the Navy's expansion of the hydrofoil technology base. They, in turn have applied this knowledge to pursue commercial applications. Boeing has produced the *Jetfoil*, discussed in a separate paper, which they have marketed around the world. Grumman also has actively pursued the commercial hydrofoil market and is currently negotiating with Israel for purchase of a stretched version of the *Flagstaff*.

In the case of hovercraft, much of today's technology was developed through British government and industry efforts. In the US currently it is fair to say that a major portion of the technology resides with industry even though the Navy has been a major sponsor of hovercraft research and development. Here also major industrial firms such as Bell Aerospace, a licensee of British hovercraft, and Bell's Canadian subsidiary are actively pursuing the commercial market for the air cushion vehicle.

There is another aspect of technology transfer which should also be addressed and that is the transfer or translation of research and development results into criteria which may be used by the designer of production hardware. The problems of form, language, and process involved in providing the hardware designer and the contract specification writer with the data and tools they need is often not given enough attention by the development community. It is not nearly enough to hand over a five-foot shelf of technical reports as the finished product. This was a somewhat painful lesson learned in the Navy's hydrofoil development programme where the infusion of basic technology into the design community met with considerable difficulty. It was soon realised that it was necessary to distill from the voluminous data base, the essential criteria for design and to clearly document the rationales supporting the myriad of design trade-off decisions which had been made. It was also recognised that there needed to be a specialised computerised data repository to permit ready access to the available data base and to categorise these data in accordance with their relevance and validity. This led to the creation of what is now known as the Advanced Ship Data Management System maintained by the Naval Ship R&D Center. This computerised working tool provides interactive access to reports, working papers, experimental results and other data for Navy and qualified contractor personnel actively working in the development and design of advanced surface vehicles.

As a mechanism to provide tools to the designer it was also recognised that there was need for a general specification to provide the detailed foundation for specification of a particular ship. This has been instituted in the case of hydrofoils and a 19-volume GENSPEC is currently in preparation by teams of government and contractor technical personnel. It is expected that this will provide the model for other vehicles such as the hovercraft, thereby facilitating their progress into the stage of production hardware acquisition.

Participation in conferences such as this meeting is also an important part of solving the problems of technology transfer. A recent meeting of the Canadian Aeronautics and Space Institute on Air Cushion Technology was a good example. A parochial interest in Naval Air Cushion Vehicles can be both broadened and deepened by noting the uses which are being studied and developed. Commercial and sports vehicles are obviously related development, but the Canadians are using the Air Cushion Concept for non-self-propelled barges for river crossing and also for ice-breaking.

The technologies which have been developed for use in these advanced vehicles have broad commercial application. The need for reduced weight has led to adapting some advanced design and weight control techniques used in aircraft and space programmes to marine vehicles. Computer-aided design, aluminium and plastic materials for hulls and piping, marinisation of gas turbines derived from aircraft engines, high speed reduction gearing, and more efficient electrical and hydraulic systems are a few examples. The premium on weight reduction and cost reduction has also led to emphasis on reduced manning which, in turn, has re-emphasised reliability and ease of maintenance as major design considerations. Special new materials such as HY-130 steel for hydrofoil struts and foils as well as the whole technology of flexible understructures have been developed specifically for advanced marine vehicles.

There are always problems when bringing new technology out of the laboratory and into the open oceans. Premature exposure can be fatal to new ideas. However, some of these new ship concepts have matured enough to be ready to enter the competition of the real world. We talk about problems because the advantages which these concepts offer are not free. Better performance may cost more money. Whether the cost is reasonable depends largely on the recognition of the values as well as understanding of which old ideas are no longer valid.

In the early days of hovercraft, for example, the large power needed to provide a reasonable air gap was a major concern. Another problem was stability while cushionborne. Both of these problems changed drastically with the invention of flexible understructures, cushion dividers and pericells. The lift problem shifted to the reliability, maintainability and vulnerability of the skirts as well as shapes and fabrication techniques to improve performance and reduce cost. As these problems have been solved the problems of efficient fans and air distribution systems are receiving greater attention.

Sidewalls were introduced to reduce cushion air leakage with rigid, and later, flexible seals at the bow and stern. The sidewalls provide a convenient location for propulsion systems on large vehicles. Cavitation and structural loadings due to wave impacts then appear as problems. Careful design, smooth skins and model testing to confirm predicted loads and motions provide reasonable answers to these problems.

Manoeuvrability in terms of course keeping and turning ing radius is very different for air cushion vehicles, surface effect ships, hydrofoils and SWATH ships as compared to conventional monohull displacement ships and high-speed planing hulls. Sidewalls can provide directional stability if they are located aft. Air cushion vehicles, with air propulsion, tend to use aerodynamic control surfaces. The traditional problems of static and dynamic stability are magnified when higher speeds require quick reaction. Powerful computer programmes have been developed and are being verified by full-scale experience. This technology is well in hand. In fact, the US Navy has developed and demonstrated the Hydrofoil Universal Digital Autopilot which has been used to control the very different configurations of the PCH and AGEH.

As the major problems of size, speed and configuration have been solved, the technological emphasis has begun to move from "proof of fundamentals" to "optimisation of subsystems". This shift of emphasis is notable in many areas ranging from foil and strut shapes for hydrofoils to the welded hydraulic system and HY-130 steel tail strut/foil on AGEH.

Many of the problems which occupied our attention just a few years ago are now in hand. For example, the question of canard versus airplane or tandem foil configurations is now clearly seen to be a matter of arrangement and balance rather than an issue of fundamental hydrodynamic performance of hydrofoils. The question of single strut compared to twin struts on SWATH ships seems to be in the same category.

The fact that many of these advanced vehicles operate for long periods of time at high speed in rough seas has stimulated research and development on seakindliness. This has been accompanied by greater emphasis on how to provide smoother riding qualities to reduce the risk of structural damage to the ship and to prevent degradation of the cargo and crew performance.

One example of the wide interest in these advanced craft is the recent publication of an "Advanced Surface Craft Economic Model", Reference 10, by the Society of Naval Architects and Marine Engineers. This model can be used to compare advanced and conventional craft in a simple fashion before deciding whether they might be used advantageously in commercial services.

This paper must end on a note of caution. The advantages and limitations of these advanced concepts have been discussed. These concepts should be used where their advantages pay off and where their inherent limitations are recognised. The enthusiasm of the advocates should not be allowed to be the foundation for misapplications. The advantages of these concepts are real and proven. The limitations are known and require careful consideration. Successful application will lead to broader usage, more feedback and further refinement of Advanced Marine Vehicles for use in Commercial Marine Transport Systems.

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