History of Key Technologies

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Development of the Bell Halter 110 SES

John B. Chaplin
Bell Aerospace Textron / Bell Halter Inc., New Orleans, La.

I. Introduction

A MAJOR U.S. Navy development effort is the surface effect ship (SES) program which began in the late 1960's. The result has been the fabrication and development of two successful 100-ton test craft and the acquisition of an extensive data bank of technology, test information, design criteria, and ship designs that have enabled a logical progression into the eventual development of a large surface effect ship (LSES) for the Navy. The Bell design, the SES-100B, established speed records, proved the design of advanced propeller concepts, and supplied a vast amount of technical data in support of the Navy's LSES program.

In the last quarter of 1976, the three-year competition in a design program for an LSES was concluded by the Navy. Rohr Industries of San Diego, California, was awarded a contract to continue the development and begin construction of an LSES.

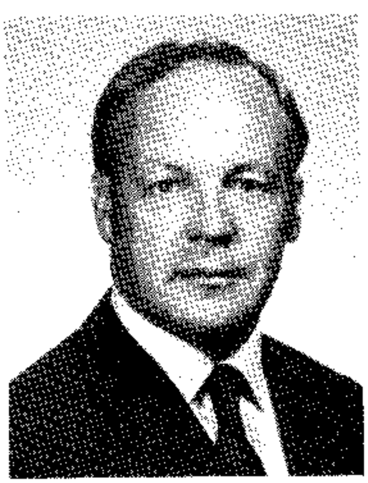
An assessment of Bell's position in January 1977, after the award of the 3KSES contract, indicated a strong engineering base of air cushion technology and advanced marine systems capability. This capability was backed up by a parent company, Textron Inc., with a continuing conviction in SES's and air cushion vehicles (ACV's) and a willingness to commit resources. Therefore, a decision was made to maintain both SES's and ACV's as major products of Bell, to rapidly find an alternate market, and to make the necessary investment to ensure the most rapid development of the optimum SES for that market.

Bell's New Orleans' Operations is located in the heart of the offshore marine industry, embracing both fabricators and operators. This has provided the company with a first-hand view of changing requirements and existing in-service equipment. Each year, petroleum exploration and production progresses farther offshore, not only in the Gulf of Mexico, but worldwide, indicating a potential need for higher-speed craft with better seakeeping characteristics. The application of SES technology appeared to offer a potential solution.

With the increasing range requirements, the crewboat operators were well aware of the requirement for increased speed beyond the capability of their existing conventional planing hull boats. But for these boats of 85–125-ft length, a considerable increase in power was required to increase the calm water speed from the 25–30-knot range to a 35–40-knot speed range. In addition, the hard ride of these hulls in the seas frequently encountered in the Gulf of Mexico would severely limit the ability to use the speed available from extra power.

A parameter that illustrates the increased power requirement with planing hulls of this size range is the ratio of the installed power to the product of the calm water speed and the gross weight of the boat. This term, hp/ton-knot, is obviously not a complete assessment of the capability and merit of the boat. Many other factors, such as the payload and fuel fraction, seakeeping, and first cost and life-cycle cost, are equally important.

Figure 1 shows a plot of existing boat data and a line that represents an approximate lower limit of hp/ton-knot with speed. This data is limited to existing operational planing boats, which are viable alternates for operation in the offshore industry today. Hydrofoils, as shown in Fig. 1, do offer an improvement over the planing boats, but the crewboat operators have shown little interest due to the limited operational speed ranges, the draft off foil, and the cost. A comparison of the SES capability, as demonstrated by operational and test craft, is also shown in Fig. 1. It is a competitive craft.



Mr. Chaplin's 30 years of engineering experience in the aircraft and marine industries, 26 of which were related to ACV/SES, is marked by his early work in ACV/SES research and development. Mr. Chaplin's association with ACV's dates back to 1957–1962, when as Head of the Wind Tunnel and Dynamics Research Department with Saunder Roe Company, he was responsible for the conceptual design, development, and trials of the SR.N1 Hovercraft and the aerodynamic research of the SR.N2 program. He was a member of the crew of the SR.N1 during its first crossing of the English Channel in 1959. His British Hovercraft experience also includes employment with the Folland Division of Hawker Siddeley, from 1960 to 1962, as Chief Hovercraft Development Engineer. He also served as Chairman of the U.K. Hovercraft Operational Panel from 1960 to 1962, under the auspices of British Air Registration Board and Ministry of Transportation. He has been a member of SNAME Panel MS-1 (high-speed surface craft) since 1962, and served as a member of the AIAA Technical Committee on Marine Systems from 1968 to 1970. Mr. Chaplin joined Bell Aerospace Textron in 1962 and was named Program Director, Surface Effect Vehicles. In 1969, with the company transfer of military ACV/SES activity to New Orleans, he was appointed Director, Engineering, New Orleans Operations. In July 1981, Mr. Chaplin was appointed Vice President, Engineering of the New Orleans Operations. He has directed and has been technically involved in all of Bell ACV/SES activities during this period, including the SK-3 (Carabao), SKMR-1, SK-5, SES-100B, AALC JEFF(B), 2KSES, Voyageur, Viking, the U.S. Army LACV-30 programs and the Bell Halter 110-foot Demonstration Boat. Mr. Chaplins's honors include, in 1969, a Medal of Recognition from the French government commemorating the crew of the first hovercraft English Channel crossing in 1959; and in 1979, a Certificate of Honour from the U.K. Hovercraft Society for valuable and pioneering contribution to the development of the Hovercraft industry.

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EDITOR'S NOTE: This manuscript was invited as a History of Key Technologies paper as part of AIAA's 50th Anniversary celebration. It is not meant to be a comprehensive survey of the field, represents solely the author's own recollection of events at the time, and is based upon his own experience. The subject of this paper is especially significant inasmuch as it recounts the transfer of a military system technology to commercial use. Although this has been done in other disciplines, it is an unusual occurrence in marine technology.

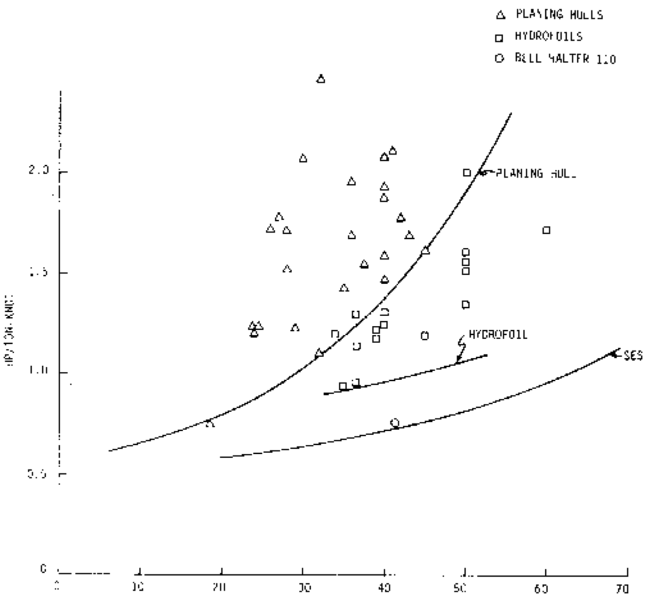

Fig. 1 Hp/ton-knot vs speed for high-performance marine craft.

Using the technology available, it was within the SES technologies to offer a 100-ft boat with an 80-knot calm water speed, good seakeeping capability. A mission analysis study clearly showed the superior productivity of the high-speed SES, and the cost savings, due to reduction in high-paid crew time and loss of exploration rig time, more than offset the higher initial and life-cycle cost. The SES was without doubt the super crewboat.

The response from the operators was immediate and negative. It quickly became evident that the sophistication of the plus-80-knot craft had no place in the offshore market. Gas turbines and other excellent but high-technology systems were seen to 1) lead to high first and maintenance costs, 2) require increased training of personnel, and 3) have poor reliability with the limited maintenance capability available.

Furthermore, the notion of operating at 80 knots was impractical. Seas are rarely sufficiently calm to attain such a speed, and the high cost could not promise commensurate compensation in productivity under all the year-round conditions.

The operators emphasized the need for versatile boats capable of carrying out many of the missions required in the oil fields, rather than high-speed boats with only a primary mission capability and limited flexibility. What was really wanted was a low-risk investment; a new boat that offered a modest gain in performance, with minimum difference in characteristics and systems from their present boats; a boat existing crews could understand, operate, and maintain, and which could be introduced into a fleet alongside conventional craft using existing organization, facilities, and logistics support. They required evolution rather than revolution. There was no doubt that the operators were seriously interested in the application and potential of SES crewboats, and that a rational design based more on their requirements and limitations would be a viable product.

During this early investigative period, it became apparent that Halter Marine, Inc., of New Orleans was also interested, and was convinced of the potential of SES for crewboat applications. Halter is the world's largest builder of offshore supply vessels, having delivered over 1000 craft for worldwide use (more than 45 craft were delivered last year), and clearly dominates the American workboat and marine equipment industry.

For the introduction of an operational SES, Bell Aerospace Textron and Halter Marine, Inc., formed Bell-Halter, a joint venture, which has now been incorporated as Bell Halter Inc.

Table 1 Bell Halter 110-ft demonstration boat design specifications

Dimensions		
Length		110 ft
Beam		39 ft
Height (on-cushion)		28 ft
Height (off-cushion)		22 ft, 7 in.
Leading particulars		
Gross tonnage		Under 100 register tons
Maximum displacement		138 L-tons
Normal displacement		107 L-tons
Light ship		80 L-tons
Maximum deckload		49 L-tons
Fuel (normal)		3100 gal
Crew		4
Machinery		
Propulsion:	Two 16V-149TI Detroit Diesel engines	
	Two 42-in. subcavitating fixed-pitch propellers	
Lift system[a]:	Two 8V-92TI Detroit Diesel engines	
	Two 40.2-in.-diam lift fans	
Performance		
Cruise speed (on-cushion)		SS 0–40 knots
		SS 3–33 knots
Cruise speed (off-cushion)		SS 0–19 knots
		SS 3–15 knots
Range		
SS 3		500 n. mi.

[a] Includes electrical generation.

II. The Rational Approach

Paper designs of every conceivable new form of high-speed craft always exist in great profusion, and it was, therefore, a key objective to have at the earliest possible time a fully operational demonstration boat.

The starting points had to be known technology, established principles and data, and analytical techniques applied to a new set of basic requirements. Meetings were held with experienced boat operators to review the application and suitability of SES's. Through these discussions, Bell Halter evolved design criteria and objectives in terms of reliability, simplicity, economics, and compatibility with operational maintenance and personnel aspects. Also, as a result of these discussions, requirements were established regarding high sea-state performance, off-cushion capability, and stability in the stationkeeping mode.

The conclusion reached was that a 110-ft SES demonstration boat, the Bell Halter 110 (BH 110), could be constructed that would offer a significant increase in performance over the planing hull at a modest increase in cost. A top level specification (Table 1) was developed. The selected market dictated that the following ground rules be applied.

1) The craft had to be reliable, have high availability, and use systems that were readily obtainable and easily maintainable and repairable.

2) The hull construction had to be in accordance with standard marine aluminum boat practice and fully compatible with both the manufacturing capabilities of a typical shipyard and the maintenance capabilities available in the offshore industry.

3) The craft had to offer speed performance, fuel efficiency, and rough-water seakeeping qualities that were significantly superior to competing planing hulls.

4) The performance and handling qualities in the off-cushion mode had to be attractive.

5) The dimensions of the craft, in particular its beam and draft, had to be compatible with existing harbor facilities.

6) Costs to buy and maintain the craft had to be of overriding importance; therefore, additional machinery and equipment had to be kept to a minimum.

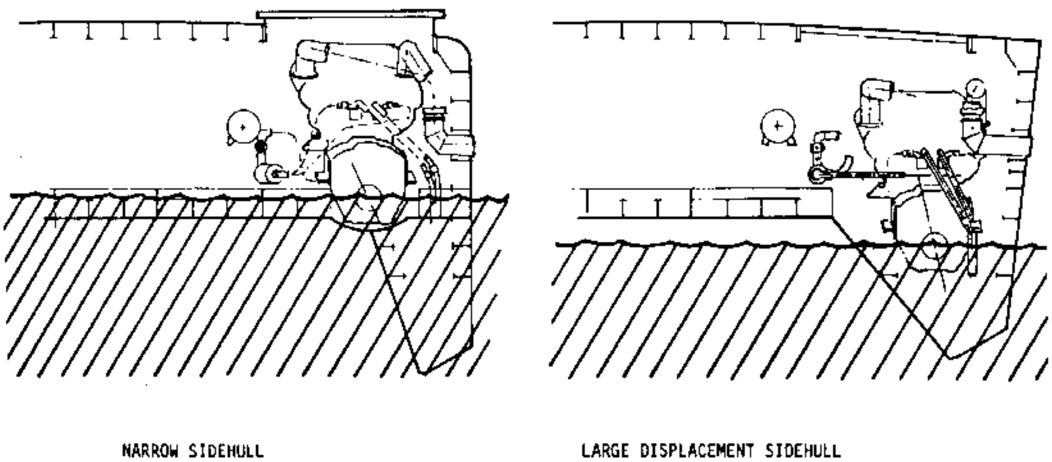

Fig. 2 Sidehull comparison.

As a result of these ground rules, the following key decisions were made early in the program.

1) The design was to use only the fully proven technology. There were to be no requirements for new technical developments.

2) The main power plants for the craft were to be commercially available, proven marine diesels. The propellers were to be standard, subcavitating, fixed-pitch designs.

3) The flexible seals were to be made of proven materials, using simple design and processes selected for optimum life, ease of maintenance, minimum wear, and reliable performance in varying sea states and speeds. The lift fans selected to provide the lift air were to be simple centrifugal fans, directly driven by production diesel engines.

4) All below-deck arrangements and outfitting were to be in accordance with conventional marine practice, using existing materials and equipment.

Although the primary purpose of the Bell Halter program was to develop an operational SES for offshore crewboat applications, it was realized that these successful operations could open up new markets and other high-speed marine applications (e.g., ferrys and patrol boats). For these applications, the potential operators would probably consider more advanced systems.

Therefore, an additional requirement was placed on the design team that the basic hull concept should be compatible with and capable of accepting higher power advanced diesel engines, gas turbine propulsion, variable-pitch and surface-piercing supercavitating propellers, and waterjet propulsion with minimum changes in the basic design. The selection of the aluminum hull construction also provided design flexibility to allow changes in the length of the boat with minimum impact on manufacturing (and hence, the maximum advantage in the learning process), while giving customized design for specific operator requirements.

III. Bell Halter 110 Design

It was apparent from the beginning that no existing SES hull form was capable of meeting all the requirements that were being established, and that some measure of innovation should be pursued in this area. Of particular concern was the requirement to operate efficiently over the full range of speeds and with good efficiency and maneuverability in the off-cushion mode. Minimum drag in the high-speed mode could be achieved with a platform of low length-to-beam (L/B) ratio as used on the SES-100B, while a high L/B craft, such as the XR-5, is superior at lower speeds. However, the narrow beam of the high L/B configuration limits the cushion height, and the key requirement for good rough-water performance could not be met in the size range of interest. A design was selected in which a moderate L/B ratio of approximately 2.5 was combined with a novel sidehull geometry to achieve the desired objectives of balanced performance.

Preliminary design studies quickly indicated that the boat size to meet the operational requirements would be about 100 ft in length. The operators of conventional crewboats also strongly recommended that a hull length of at least 100 ft would be necessary to cope with the typical Gulf of Mexico winter seas. For this size of SES, the only suitable main engine was the General Motors (GM) Detroit Diesel 16V-149TI rated at 1335 hp for crewboat operations. A final configuration optimization based on this engine led to the selection of a hull length of 110 ft.

In the development of the high-speed SES for the Navy, the emphasis on speeds of 80–100 knots for a 3000-ton ship required a minimum wetted area of the sidehull and a minimum size of the aft appendages (i.e., rudders and fins) needed to provide adequate directional stability. The solutions to this problem were not simple. In one case, a design team selected partial-length sidehulls that required a complex, three-dimensional bag and finger bow seal. Another design approach was to use a full-length sidehull with a two-dimensional bow seal. Both approaches used thin sidehulls. Neither of these designs provided the balanced performance considered essential for the basic mission requirements of the BH 110.

The SES-100B Navy test craft, built and designed by Bell, has been the most successful high-speed SES and, although this craft had a small displacement sidehull, it did incorporate the concept of the low-deadrise planing sidehulls to provide adequate directional and roll stability combined with a high-efficiency, high-speed hull form. Thus, it was an obvious decision to base the development of the Bell Halter large displacement sidehull on this considerable background of experience and technical data.

To provide optimum operation over the full speed range for the BH 110 design, it was considered essential that in the low-speed, off-cushion mode there should be sufficient displacement in the sidehulls so that the main center hull would float clear of the water, thus avoiding the barge-like, low-speed characteristics of craft that use thinner, low displacement sidehulls. The large displacement sidehulls offer an additional advantage from the standpoint of machinery arrangements. Figure 2 shows cross sections of the narrow and large displacement sidehulls that illustrate the previously mentioned advantages. The lower engine location, that is possible with the high displacement sidehull configuration, simplifies the propeller shaft installation. The shaft can be fully contained within the sidehull and, for a given shaft inclination angle, the shaft length can be reduced. The lower, more aft location of the engine, which is then possible, is favorable from the standpoint of both the vertical and longitudinal center of gravity location.

The significant reduction in wetted area, when operating in the hullborne mode with the center of the main hull clear of the water, provides both increased hullborne speed and a low-speed range which matches the high-speed range.

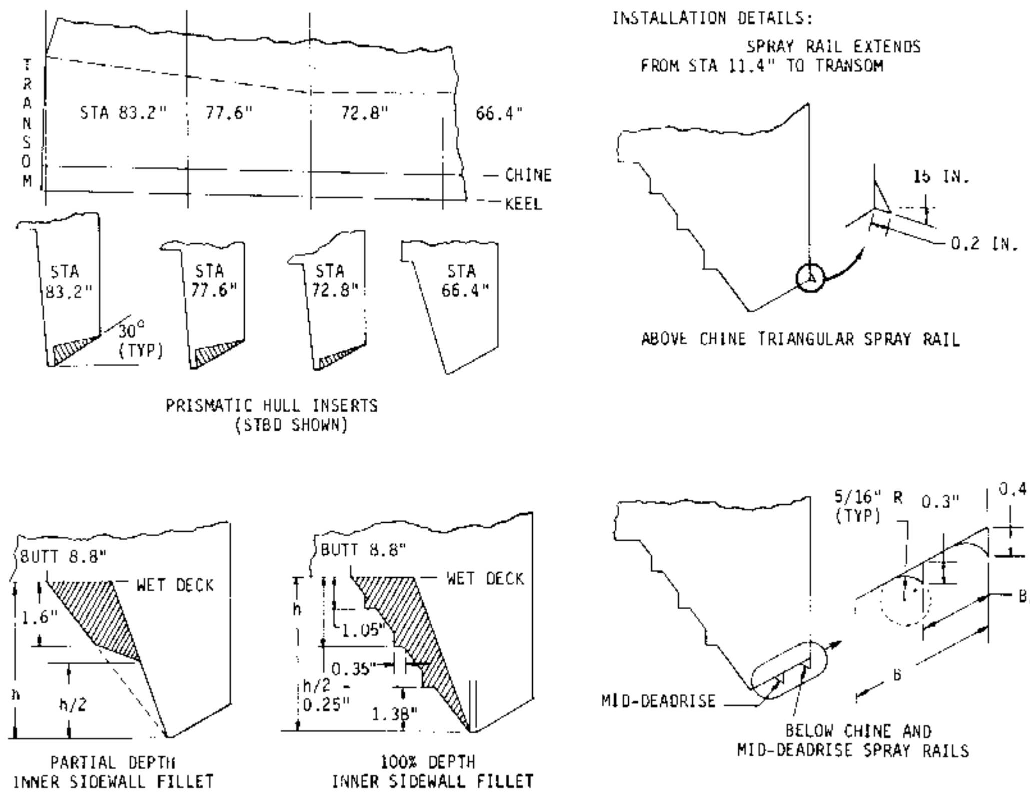

Fig. 3 Sidehull variation evaluated in tow tank tests.

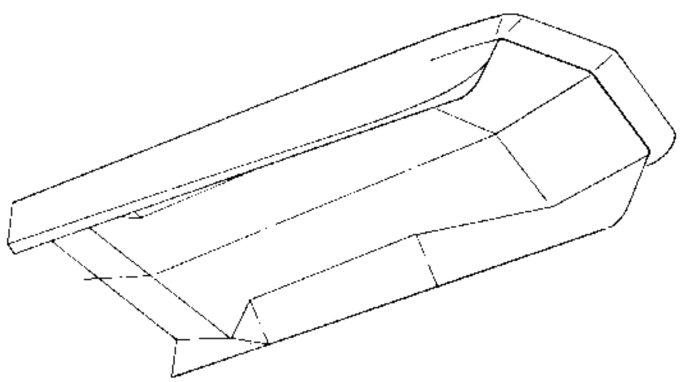

Fig. 4 BH 110 sidehull arrangement.

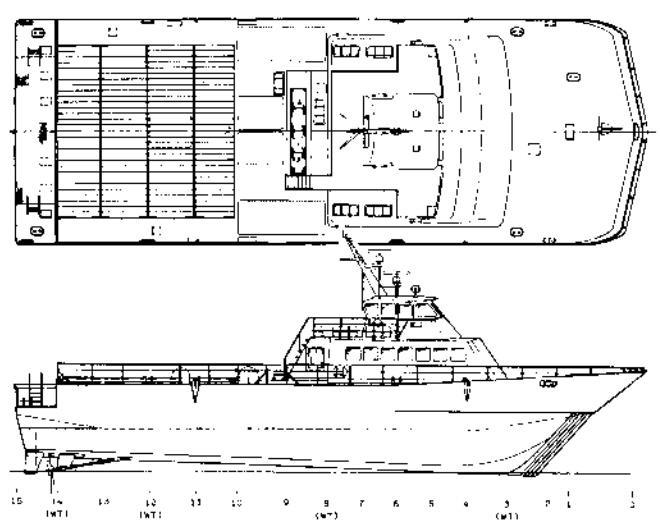

Fig. 5 Bell Halter 110-ft (BH 110) demonstration boat.

The BH 110 hull form draws upon the technology base established by the successful SES-100B and refined through a series of tow tank tests. The final hull lines were arrived at by selecting those design characteristics of the various models tested that would optimize on-cushion performance and assure good stability. Compared with the SES-100B, the hull form of the BH 110 differs in the following respects.

1) The sidehulls extend almost the full length of the cushion in order to simplify the design of the bow seal. A correspondingly larger rudder is used to maintain directional stability at bow-down attitudes.

2) The cushion depth is tapered from approximately 7.5 ft at the bow to 5 ft at the stern. This feature was incorporated to enhance the rough-water performance and seakeeping qualities of the boat.

3) The inner face of the sidehulls is inclined to the vertical amidships, with smaller angles towards the bow and stern. This feature was incorporated to improve the lateral stability of the boat, increase sidehull buoyancy, and provide additional space for propulsion machinery installation.

The main development task was to obtain a sidehull configuration which would provide the required displacement and volume, maintain a maximum cushion area, and yet not give too large a drag increase for the high-speed, cushionborne mode. At the same time, the inner wall of the sidehulls of the bow and stern would have to be near vertical to allow the unimpeded movement of the flexible seals.

Systematic tow tank tests were carried out with progressive increases in the sidehull thickness, some of which are shown in Fig. 3. The final configuration selected is shown in Fig. 4. The fine entry shape at the bow of the inner sidehull is similar to the configuration of the highly successful German E boats. It avoids the generation of a large wake inside the cushion, which would have resulted in increased wetting and probably would have interfered with the satisfactory operation of the stern seal. The abrupt change of section at the stern of the inner sidehull and the sharp step is typical of the configuration of flying boat steps, and it ensures that the flow separates from the sidehull at this point.

One of the most interesting achievements of this development was that the drag of the final large displacement sidehull was virtually unchanged from that of the original narrow sidehull for sea states 0–5 at all speeds above hump. In addition, there was a definite indication that at hump transition speeds, the increased buoyancy of the sidehulls, particularly in the higher sea states, gave a significant reduction in hump drag.

Because of the inner sidewall slope, the flow has a tendency to ride up the surface and increase wetting. This results in increased drag, which can be eliminated by using spray rails as shown in Fig. 3. The spray rails also improve the roll stability of the craft by reducing the sidehull wetting above the chine

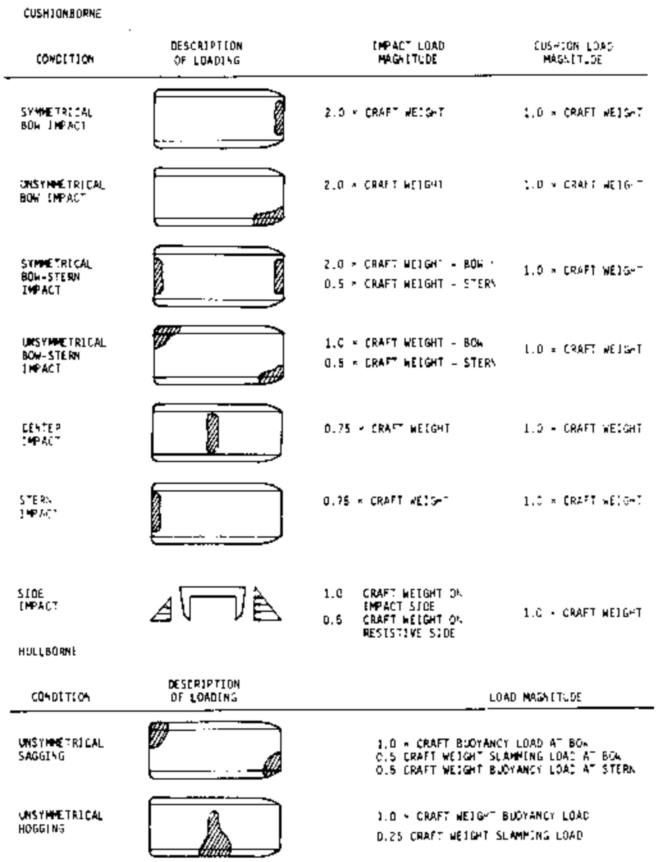

Fig. 6 Hull loading conditions.

and, therefore, reducing the above-chine sideforce on the leading sidehull (when in a turn).

The BH 110 demonstration boat outboard profile and general arrangement is shown in Fig. 5. The forward deckhouse provides spacious seating for 40–60 passengers, while the aft deck provides adequate space for the required cargo.

A major design consideration was the determination of the requirements to meet the United States Coast Guard (USCG) regulations and to ensure that the boat was admeasured at less than 100 tons. The New Orleans USCG District, although greatly overloaded by the requirements to support the conventional shipbuilding programs, gave excellent support and guidance. One of the first design changes associated with the USCG regulations was in the relocation of the tonnage deck. If the main deck had been selected as the tonnage deck, then the tonnage volume would have been well over 100 tons. However, by stopping the main deck level some 7 ft forward of the transom and continuing the second deck aft of this point, the second deck was then considered to be the tonnage deck and the boat admeasured under 100 tons.

IV. Structure

Structural design criteria was evolved from a number of sources, again, in close cooperation with the USCG. For the areas of the hull, which are similar to conventional aluminum planing hulls, typical planing hull criteria have been used. Values for wet-deck design pressures have been taken from model- and full-scale testing programs carried out by the David W. Taylor Naval Ship Research and Development Center over many years, and modified by recent experience gained with the SES-100B. Loadings used to design the hull girder are a combination of conventional hogging and sagging conditions supplemented by bow, midships, and stern impact loadings, which have been based on prior SES and ACV experience. One of the unconventional loading aspects of the SES results from its relatively large beam. This requires consideration of impact loadings which are off center and, therefore, produce significant torsional loads in the hull. Figure 6 summarizes the hull loading criteria and Fig. 7 summarizes the pressure criteria used for the BH 110.

An extensive model test program was conducted, primarily to generate performance and stability data. These tests also provided information on impact loads and data for the selection of the speed-vs-wave-height design envelope.

Since the hull was to be fabricated in 5086 aluminum alloy using commercial welding techniques, the working stress

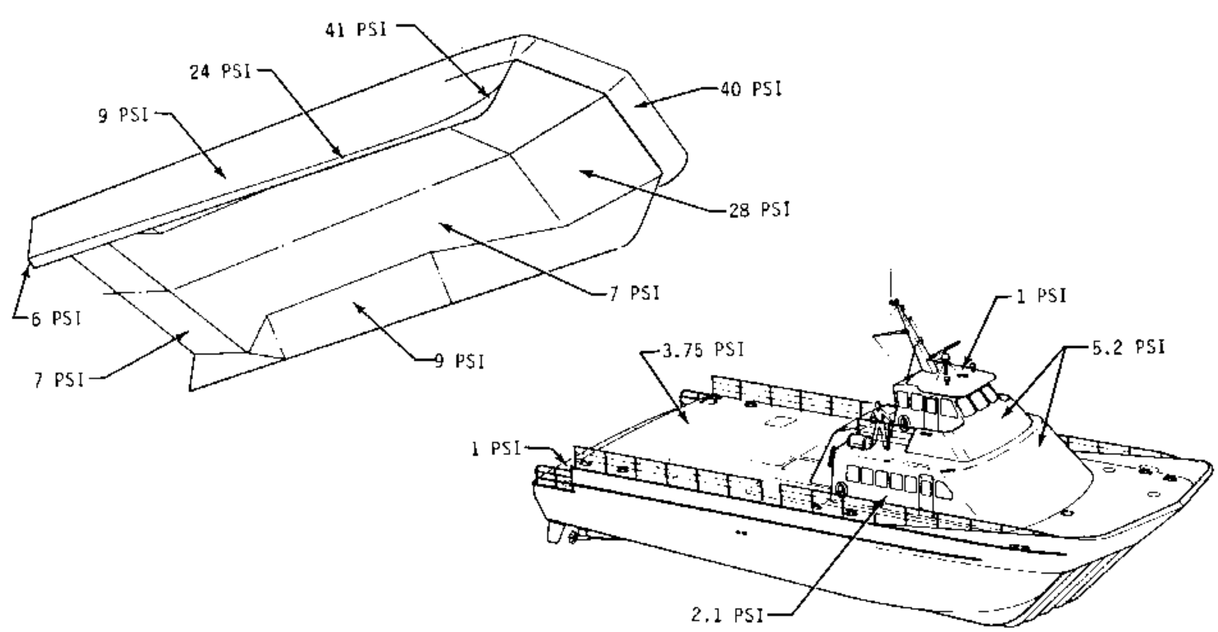

Fig. 7 Hull design pressures.

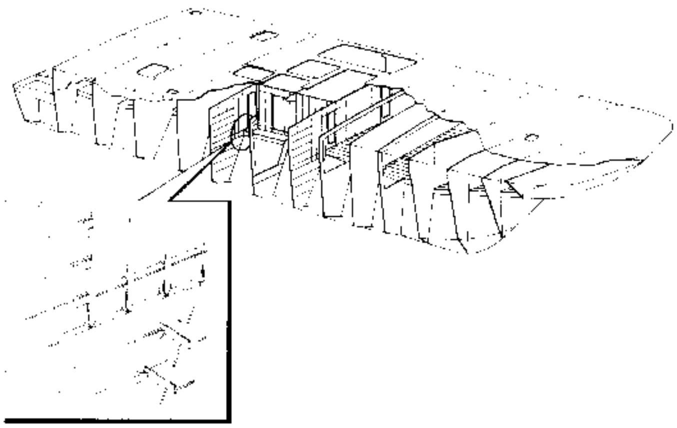

Fig. 8 Structural arrangement of the BH 110.

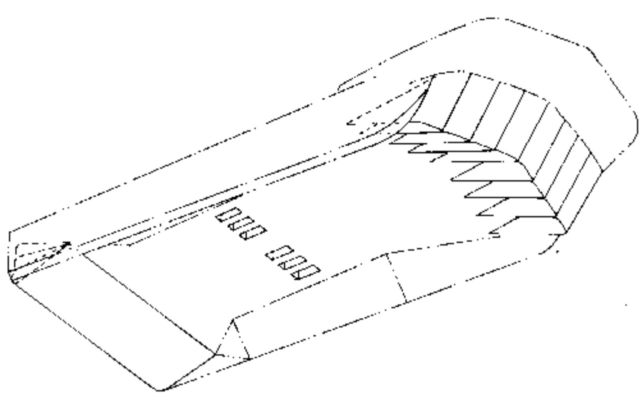

Fig. 9 BH 110 seal system.

levels were also selected on the basis of commercial aluminum crewboat practice, and allowable stress of 14,000 psi was used in conjunction with maximum working loads. This was reduced 9500 psi, the endurance limit of the material in the welded condition in high fatigue areas such as the bottom plating of the sidehull bow. The allowable stresses were also limited in structural areas subjected to compression loadings by stability considerations. The craft has been certified by the USCG. Because of the unconventional design and the effort to minimize structure weight in many areas, a comprehensive load stress analysis was submitted to support the certification.

Figure 8 shows the structural arrangement of the BH 110. The hull is an all-welded structure of 5086-H116 aluminum plate, extrusion, and flat bar. The 5086 aluminum was selected because of its recognized corrosion resistance in salt water, its ductility and ease of repair by welding, and because of its general acceptance by the commercial users of craft of this type. Similarly, the all-welded construction has the benefit of complete watertightness and extensive, successful past experience.

While the materials and fabrication methods used for the hull follow standard marine practice for small aluminum boats, some minor deviations were necessary in the sizing and spacing of the structural elements. Two factors unique to this craft are involved. The first of these is the catamaran-type configuration that results in increased transverse bending moments from loads on the sidehulls. The typical frames of conventional small boats are not suitable for this type of loading and, in general, full-depth bulkheads must be used. Because of internal accommodation requirements, such bulkheads must be spaced between 8 and 12 ft, rather than the more typical 30–36 in. frame spacing.

The structure consists of transverse bulkheads at spacing between 8 and 12 ft, longitudinal T-section stiffeners at spacings of 18 in., and external plating. Plating is generally 3/16- and ¼-in. thick, with greater thickness in the bow region and

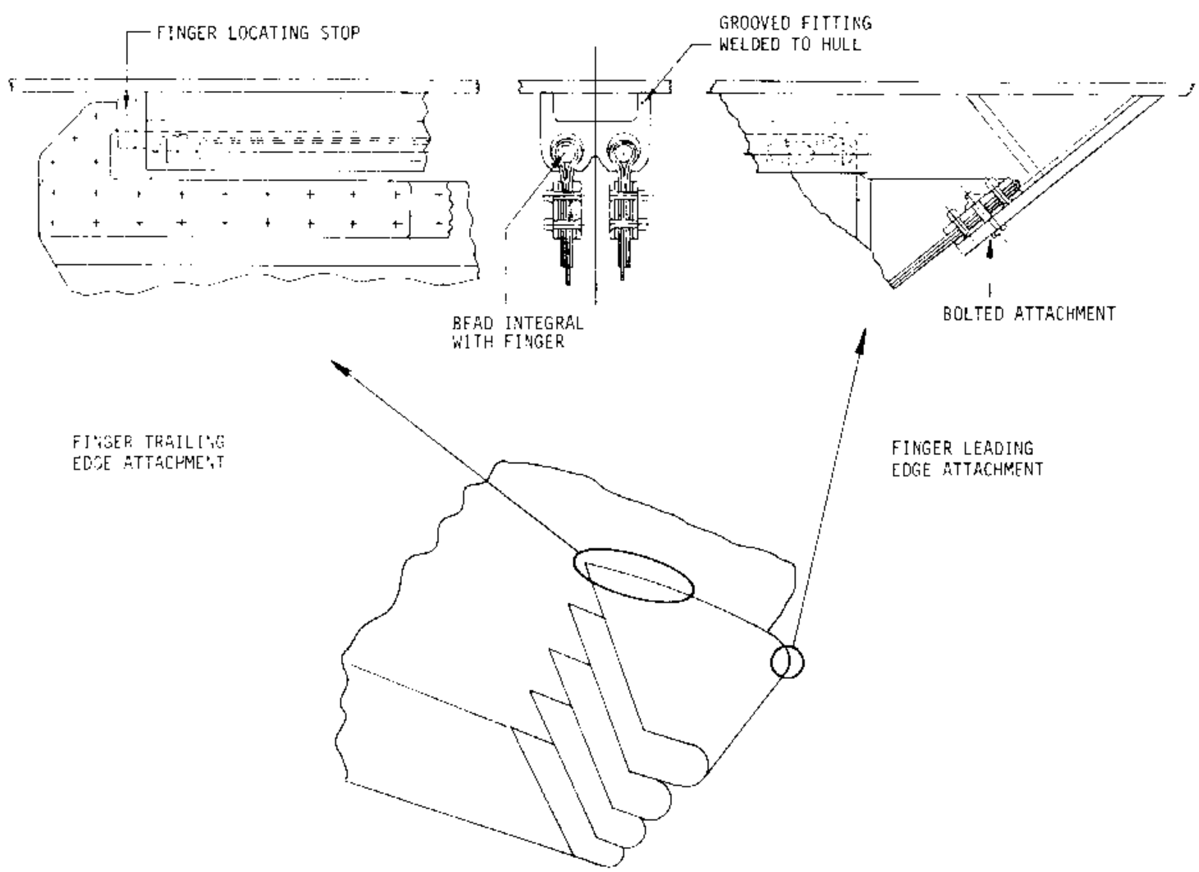

Fig. 10 Bow seal details.

Table 2 BH 110 hullborne stability characteristics

	Displacement		
	310,000 lb	240,000 lb	188,915 lb
Longitudinal metacentric height above baseline (KM_L), ft	192.0	142.5	163.0
Transverse metacentric height above baseline (KM_T), ft	73.7	71.7	82.5
Longitudinal center of buoyancy (LCB) from amidships, ft fwd	0.81	1.28	1.90
Longitudinal center of flotation (LCF) from amidships, ft aft	0.1	1.11	1.03
Vertical center of buoyancy (KB) above baseline, ft	5.21	4.6	4.1
Tons per inch immersion (TPI), L-ton	4.81	2.40	2.25
Moment to trim 1 in. (MTI), ft L-ton	23.3	13.3	12.1
Draft to keel aft perpendicular, ft	4.9	4.06	3.25
Freeboard to cross structure aft perpendicular, ft	1.97	2.81	3.62
Freeboard to deck aft perpendicular, ft	3.55	4.39	5.2
Maximum draft to keel	7.9	7.06	6.25
Freeboard to cross structure at forward perpendicular, ft	1.7	2.54	3.35
Freeboard to main deck at forward perpendicular, ft	7.47	8.31	9.12
Free surface correction[a] longitudinal, ft	0.22	0.28	0.35
Free surface correction[a] transverse, ft	0.18	0.23	0.29

[a] Fuel, potable water, and waste water tanks assumed to be 50% filled.

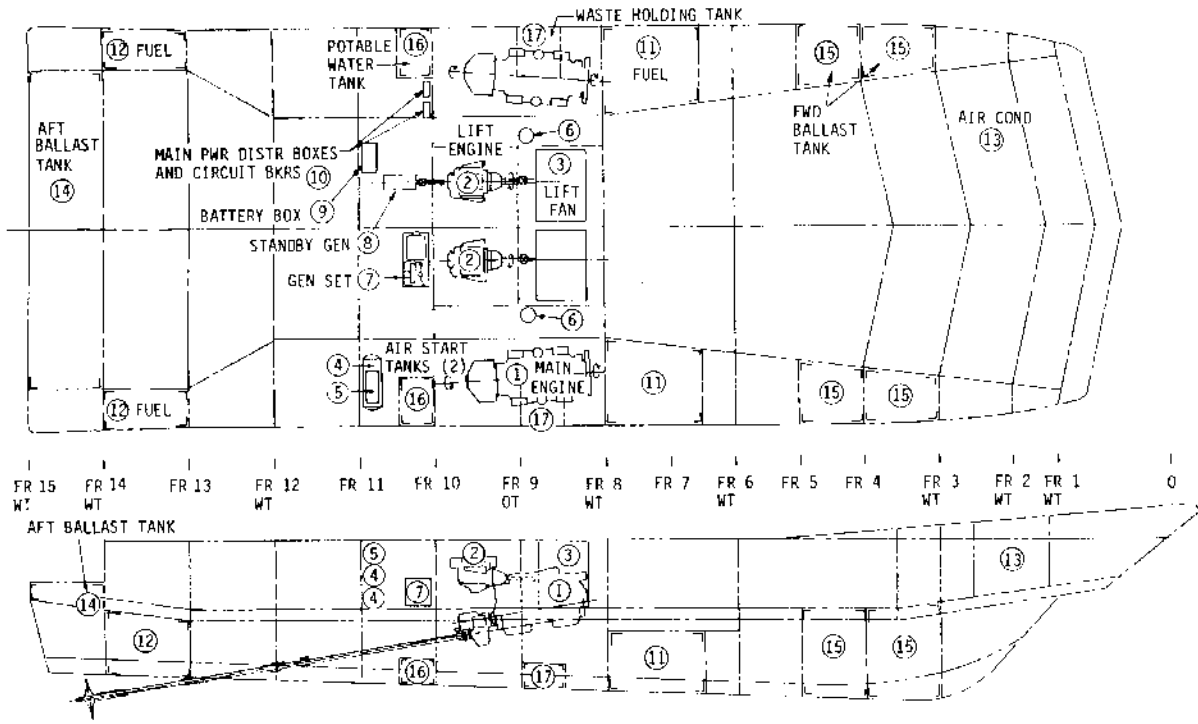

Fig. 11 General arrangement of lift and propulsion machinery on BH 110.

at the bottom of the sidehulls where pressures are high. Longitudinal stiffeners are extruded T-sections, except where deep stiffeners are used at the wet deck. All stiffeners are attached to the bulkheads at the bulkhead stiffeners, with appropriate gussets and chocks to avoid buckling under the reactions to the pressure loadings. Transverse bulkheads are ⅛-in.-thick plate with vertical T-section stiffeners at 18-in. spacing and heavy plate cap members to carry transverse bending moments. The bulkheads extend down into the sidehulls. Watertight bulkheads are provided with watertight doors and nonwatertight bulkheads with openings, as required for access. Reinforcements are provided around these openings. Hatches are provided in the main deck, particularly for engine and lift fan installation and removal, and for stowage of cargo below decks. An opening is also provided for lift air inlet to the lift fans. All deck openings are reinforced and are generally aligned to minimize structural discontinuities. A substantial bow structure of closely spaced frames supports the bow plating and, similarly, at the bottom of the sidehulls closely spaced frames between bulkheads support the bottom plate.

V. Flexible Seal System

The seal system (Fig. 9) is based on the SES-100B proven configuration, but has been simplified to minimize the initial cost and facilitate maintenance in the field.

The bow seal (see Fig. 9) consists of eight fingers, each the full height of the cushion and each consisting of a single loop of rubber-coated fabric with a simple attachment to the wet deck, permitting easy removal. The stern seal (see Fig. 9) consists of three loops of rubber-coated fabric extending across the cushion. End caps are fitted, but no internal fabric structures are used. No particular wear has been observed on this seal on the SES-100B at the end caps under conditions of very high-speed operation (over 70 knots), although repairable damage has occurred infrequently. Conservatively, a life of 3000 h is again assumed with end cap repair every 250 h, although the much lower speed of the 110-ft boat makes this type of damage very unlikely.

To facilitate the maintenance of the seal system, careful attention was placed during the design to the method of attachment. Repairs or replacement of both the bow and stern seals can be made with the boat in the water; dry docking will not be required. The stern seal is attached by a simple system of bolts and backing plates, and the complete bag can be attached or removed in a few hours. For the bow seal, each finger is attached by sliding the two integral beads at the top edges of the finger into a special extrusion welded to the lower surface of the center hull (Fig. 10). The finger is pulled forward until the locating stops at the tail contact the end of the extrusion. The attachment is then completed by installing the bolts of the upper finger leading edge.

VI. Machinery

The main propulsion engines selected for the demonstration boat are two Detroit Diesel 16V-149TI marine diesels, which have a maximum rating of 1600 hp at 1900 rpm and a crewboat rating of 1335 hp. These engines drive two 42-in.-diam, three-bladed, fixed-pitch, fully submerged, subcavitating propellers through inclined shafts. Two Reintjes gearboxes provide a 2:1 speed reduction between the engine and the propellers. The gearboxes also include an integral clutch and provide opposite propeller shaft rotation.

Two Detroit Diesel 8V-92TI marine diesel engines drive the two 40.2-in.-diam centrifugal fans which supply the lift air to the cushion. Figure 11 shows the general arrangement of the lift and propulsion machinery for the demonstration boat.

The electrical machinery includes a diesel-driven generator unit and a standby generator driven off the port lift engine. The primary unit is a GM 3-71 65-kW unit providing 110-V ac power. The standby generator is a KATO KMAAG 14 40-kW generator clutch driven off the port lift engine.

The diesel machinery used in the demonstration boat are rugged marine units that have been proven in coastal and offshore vessels. They provide long periods between overhauls when operated within their ratings. They also provide low specific fuel consumption (sfc), thus permitting economical operation over a wide range of operating speeds.

VII. Stability and Maneuvering

Buoyancy characteristics of SES configurations are generally very satisfactory, because the hull is less dense in terms of weight per cubic foot of volume than either conventional displacement hulls or planing hulls. The relatively wide beam, in comparison to the length and the displacement of the sidehulls, contributes significantly to the roll righting moments and, as a result, hullborne stability characteristics are generally very acceptable. The high displacement sidehulls of the Bell Halter demonstration boat provide a further contribution to the buoyancy and stability characteristics of the typical SES. Table 2 shows the hullborne characteristics of the BH 110 for three gross weight conditions. At 310,000-lb displacement, the center section of the main hull is in contact with the water, and the maximum keel draft is 7.9 ft. For this displacement condition, the longitudinal and transverse metacentric heights above the baseline are 192 and 73.7 ft, respectively. The reserve buoyancy at a displacement of 240,000 lb is 720%.

The arrangement of hull compartmentation was selected so as to ensure that all stability requirements were met for a one-compartment flooding situation, and this was verified by computer analysis.

From the standpoint of cushionborne stability criteria, the demonstration boat was designed to exhibit inherent stability about all axes so that no stability augmentation devices would be required for safe operation at any speed or sea state condition.

It was required that pitch and roll restoring moments increase continuously with increasing angle from the nominal running trim. Damping in pitch and roll was to be such that any disturbance would reduce to less than one-half amplitude in one cycle. Sufficient positive directional stability was to be provided over the feasible range of operating pitch attitudes so that after any yaw disturbance the boat would be restored to a condition of zero-yaw rate and zero sideslip. Also, the roll moments induced by sideslip were to be such that the craft would roll into the turn produced by the sideslip.

Model tests were performed on the demonstration boat configuration to verify the cushionborne pitch and roll stability of the craft and to measure the directional stability characteristics. The rudders were then sized to provide the required directional stability. The full-scale tests have confirmed that the demonstration boat meets the stability criteria.

Criteria established for failure mode operation were as follows. The boat was to be able to proceed in either the off-cushion or on-cushion modes with the propulsion system on either side inoperative. Rudder power was to be adequate so that a turn of 0.5 deg/s could be maintained away from the dead engine. In addition, the craft was to be able to safely survive any single failure of the propulsion, lift, or steering systems. These failure mode criteria were addressed during rudder size selection to ensure that the turning moments available were adequate to counter moments when one engine is out.

The primary control for performing high-speed turns is the helmsman's wheel, which operates the two rudders located in the slipstream of the fully submerged propellers. The turn performance of the demonstration boat at a speed of 32 knots (37 mph) is shown in Fig. 12. At a typical rudder deflection of 15 deg, a yaw rate of 3.7 deg is developed. This rudder deflection produces sideslip and roll angles on the order of 8 and 4.5 deg, respectively, and results in a turning radius of 800 ft. The maximum rudder deflection available is ± 30 deg. This range was provided primarily to provide the desired turning performance at the lower speeds and for countering the thrust moments produced when one engine is out.

A secondary control for turning is the differential thrust that can be produced by differential application of the propulsion engine throttles. This control is most appropriate for turning at low speeds when the rudder effectiveness is reduced. The propulsion system reduction gearbox includes provision for reversing propeller rotational direction. This provides powerful control moments at very low speeds for close quarter maneuvering, such as for docking operations. The excellent maneuverability of the demonstration boat has been verified during many full-scale operations.

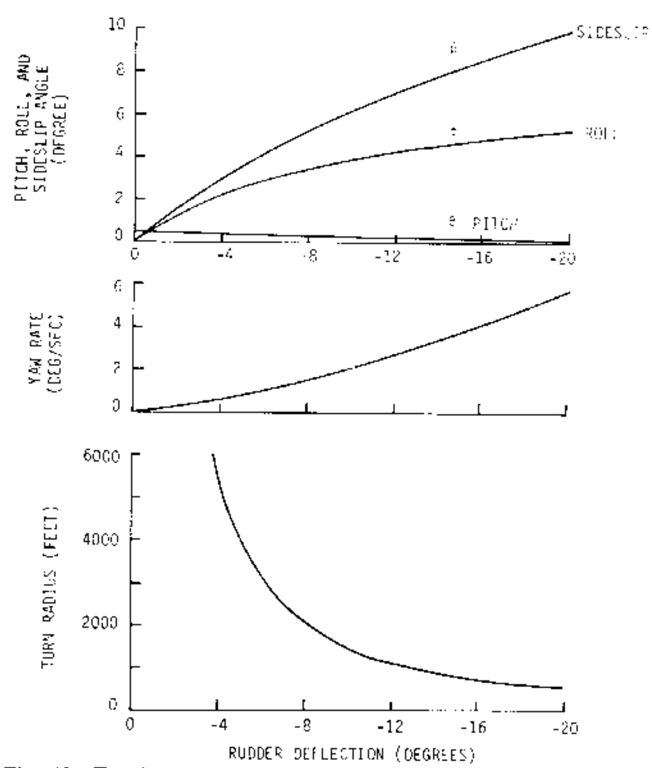

Fig. 12 Turning characteristics vs rudder deflection: velocity = 32 knots, full load displacement, $L_{cg} = 0.2$ ft aft, calm water.

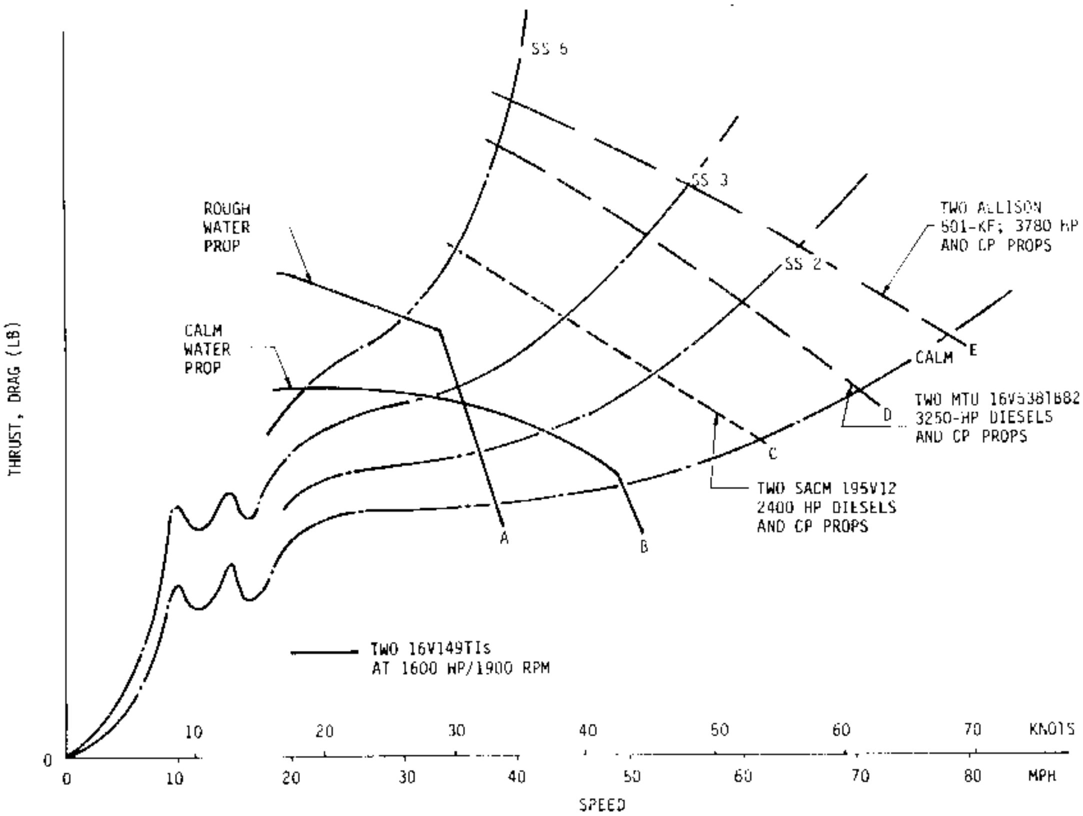

Fig. 13 BH 110 thrust and drag vs speed.

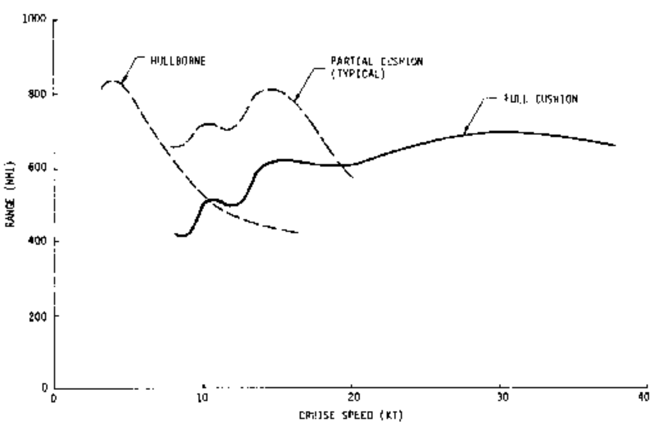

Fig. 14 BH 110 range performance.

VIII. Performance

Drag-vs-speed curves for the BH 110 are shown in Fig. 13 and thrust-vs-speed curves for different engine and propeller combinations are shown superimposed on these drag curves. Curve B represents the thrust curve for the BH 110 demonstration boat configuration, which uses two 16V-149TI Detroit Diesel engines and a 3.5-ft-diam fixed-pitch (pitch-to-diameter ratio = 1.4) subcavitating propeller optimized for low sea state operation. Increased thrust could be obtained at the higher sea states if lower pitch ($P/D = 1.2$) propellers were used (curve A), and controllable-pitch propellers could provide approximately optimum thrust over the entire speed range. Performance growth capability is provided by the installation of larger diesel engines, such as SACM 195 12V's, MTU 16V-838's, and gas turbines, with controllable-pitch propellers or waterjets. As stated earlier, cost was a primary consideration and, since the crew boat requirements could easily be met with the Detroit Diesel engines and fixed-pitch propeller, this selection was made.

Table 3 Range performance of BH 110 powered by two 16V-149TI Detroit Diesel engines

Sea state	Boat displacement	Max range, n.mi.
Calm	Normal[a]	698
	Full[b]	1360
2	Normal	670
	Full	1230
3	Normal	500
	Full	920

[a] Normal displacement = 107 long tons.
[b] Capacity fuel displacement – 116 long tons.

The calm water range capability of the BH 110 demonstration boat is presented in Fig. 14 for a full load displacement of 240,000 lb and a normal fuel load of 22,000 lb. Tankage is provided for a maximum fuel load of 39,000 lb, for which these ranges are increased by approximately 75%. In the full-cushion operating mode, the relatively constant range characteristic of speeds above hump is primarily due to the efficiency of the propellers and the fact that the diesel sfc at partial power remains relatively low. The large displacement sidehulls give efficient operation at low speeds in the hull-borne mode while at the midspeed range; operation on partial cushion gives the maximum range by achieving the optimum fuel flow to the lift engines.

Table 3 shows the range capability of the BH 110 as a function of displacement and sea state. Because sea state 3 has been selected as the design condition, there is only a small reduction in range and cruise speed between calm water and sea state 3 operation.

IX. BH 110 Construction

Construction of the BH 110 was accomplished in Halter Marine's Chalmette, Louisiana, yard. This facility specializes

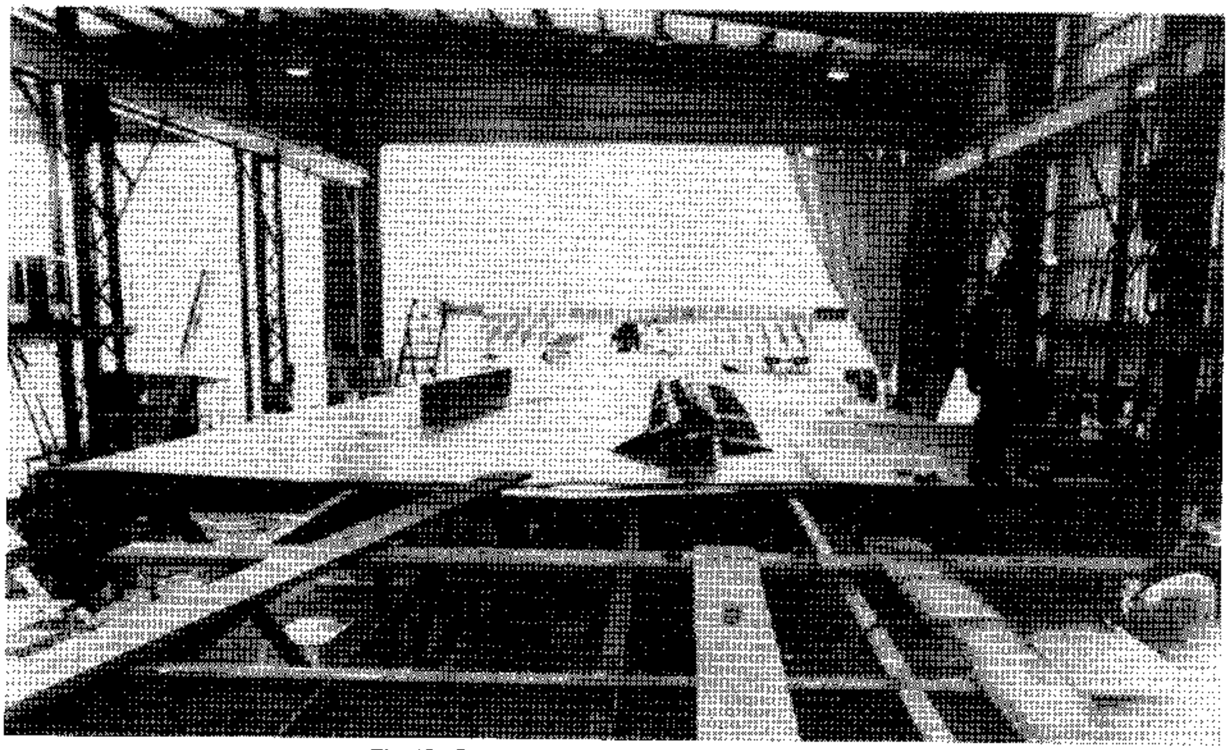

Fig. 15 BH 110 construction—flat wet deck buildup.

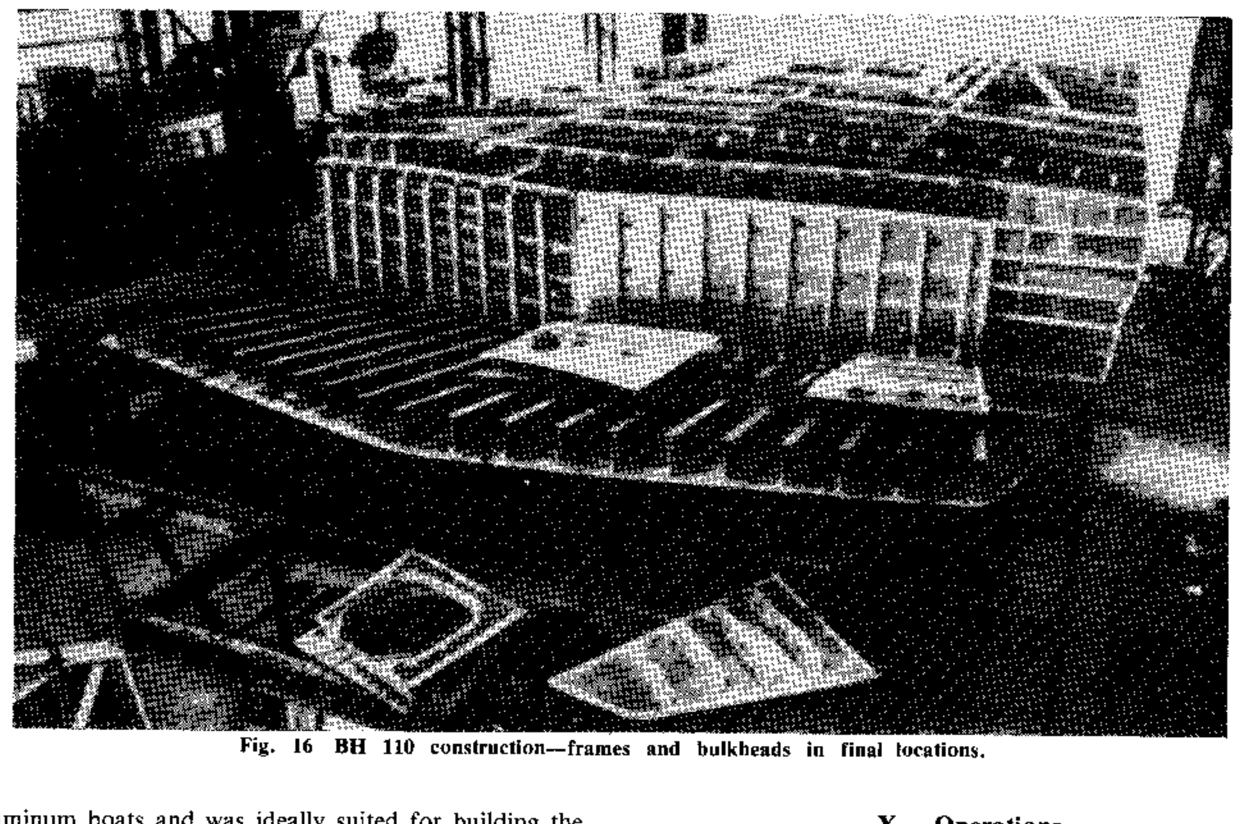

Fig. 16 BH 110 construction—frames and bulkheads in final locations.

in aluminum boats and was ideally suited for building the demonstration boat. The flat wet deck buildup on the construction rig is shown in Fig. 15. Figure 16 shows virtually all hull frames and bulkheads in their final locations. Frames and bulkheads were made up in subassemblies and installed in the hull. Approximately 8 months after construction began, the completed hull was launched in late October 1978. Figure 17 shows the interior of the main passenger deckhouse.

Upon completion of outfitting, the BH 110 began sea trials in late December 1978, and quickly validated almost all performance goals. Figure 18 shows at-sea operations of the boat in the Gulf of Mexico.

X. Operations

The design, construction, and sea trials spanned a period of two years. Figure 19 shows the time sequencing of the major program activities. The BH 110 received its USCG certificate on February 26, 1979. To move from a design concept to a certificated vessel in 24 months, particularly for the unique hull form of an SES, was attainable only through the fullest cooperation of the USCG.

The demonstration program began early in 1979 and included many marketing demonstrations in the coastal waters near New Orleans. Visitors representing the offshore in-

Fig. 17 Interior of the BH 110 main passenger deckhouse.

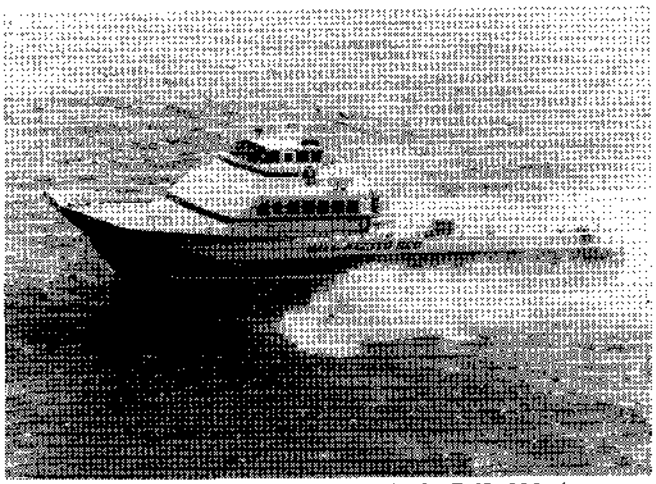

Fig. 18 BH 110 operations at sea in the Gulf of Mexico.

dustry, ferryboat operators, and many foreign countries have been favorably impressed by the BH 110. The BH 110 was also used in actual offshore operations to establish user confidence in underway and rig-side performance. Figure 20 shows the boat stern-to a rig in the Gulf of Mexico. The following comments were made by experienced crewboat captains regarding the BH 110. "Excellent seakeeping at all headings." "Holds course in all seas." "Boat handles seas up to 12 feet with minimum need for helmsman action." "Confident boat could operate in 20-foot seas." The captains were all extremely impressed with the excellent maneuvering characteristics of the BH 110. Its broad beam results in much more conventional control capability than is provided by a conventional hull, both at speed and rigside.

The most outstanding features of the boat, as viewed by potential users, are the large open-deck and below-deck volume, excellent maneuverability, high performance, good seakeeping characteristics and performance in rough seas, and the fact that standard marine equipment is used and is readily accessible.

In February 1980, the Bell Halter 110 successfully made a voyage from New Orleans to Norfolk, Virginia. Several stages of this journey were made in typical east coast bad weather with seas of 8–12 ft. The SES demonstrated excellent seakeeping and high-speed capability in these seas. One impressive operation, particularly to the engineers on board, was the rounding of Cape Hatteras at night in a freshening northeasterly gale. At Norfolk, the U.S. Coast Guard, with the help of the U.S. Navy, carried out a one-month evaluation program to determine the capabilities and effectiveness of the boat in typical Coast Guard missions. The conclusions of this program were that the SES could effectively carry out all of the required Coast Guard missions and that it would be an excellent patrol boat offering speed, seakeeping, and payload capability superior to their existing 83- and 95-ft patrol boats. Two important conclusions were that, in addition to these operational improvements, the SES would 1) use only the same amount of fuel per nautical mile at 25–30 knots as the 95-ft patrol boat used at 15 knots and 2) require only the same size crew as the 95-ft patrol boat with no new skill requirements. In other words, the SES could be directly substituted into the

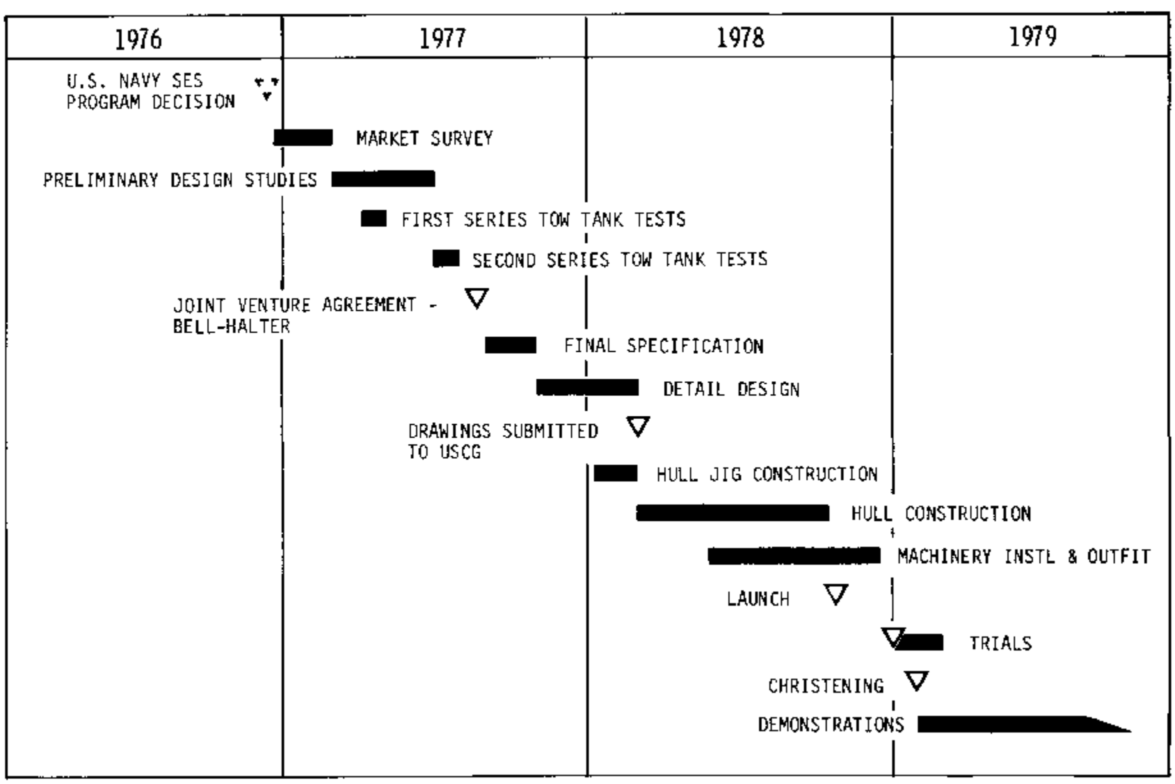

Fig. 19 BH 110 program schedule.

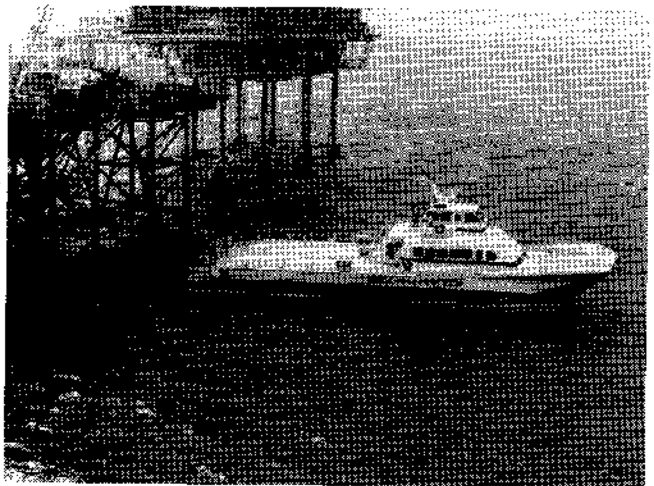

Fig. 20 BH 110 offshore operations.

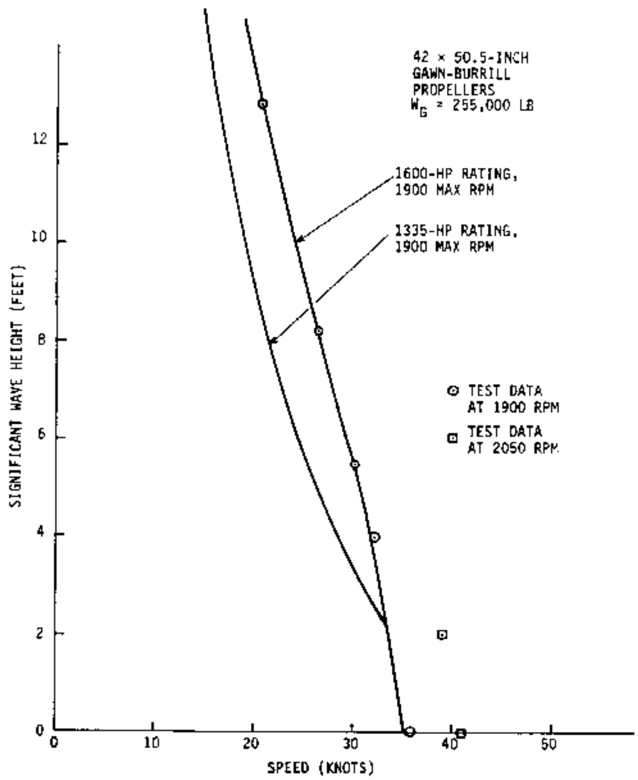

Fig. 21 BH 110 sea state vs speed envelope.

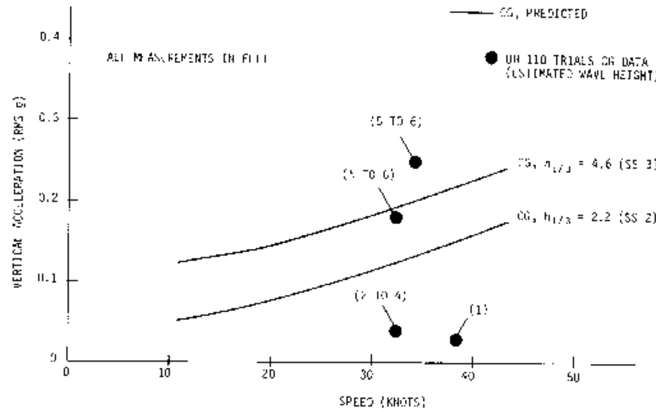

Fig. 22 Ride characteristics of BH 110—comparison of trials data with predictions.

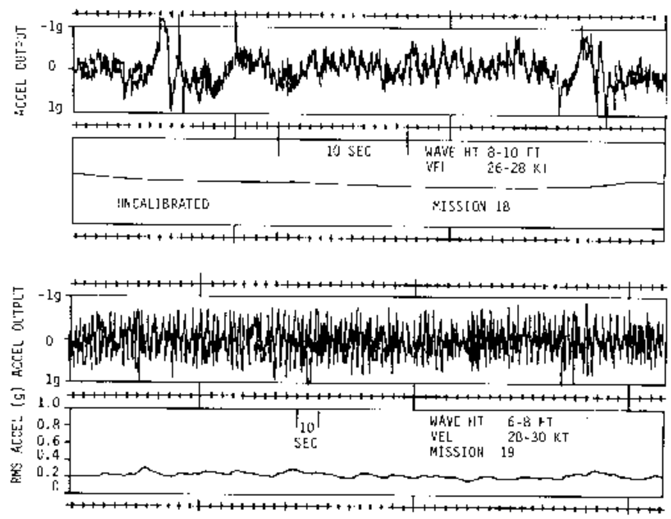

Fig. 23 Acceleration time histories.

present U.S. Coast Guard patrol operations and replace the 95-ft patrol boat, with no impact on what are today two of the most important factors in the Coast Guard budget—fuel and manning.

XI. Test Results

Figure 21 shows the relationship between wave height and craft speed for the BH 110 demonstration boat. The solid lines shown in the figure represent the predicted performance for the engines rated at 1600 hp and at 1335 hp at 1900 rpm maximum continuous. As indicated by the circle data points, actual test data validated the predicted performance. Operating the engines at a higher speed (2050 rpm) increases craft speed by approximately 5 knots.

It is significant to note that the reduction in speed with increasing sea state is quite gradual for the 1600-hp rating. This effect is largely due to the propeller characteristics and represents an rpm limit. The more rapid falloff in speed vs sea state of the 1335-hp rating curve above a 2-ft wave height is due to a true power limit and not an rpm limit. Nevertheless, the BH 110 is nominally a 37-knot boat with a plus-40-knot capability.

Instrumentation was also used to gather motions data while operating in heavy seas. Figure 22 shows vertical acceleration as a function of craft speed for several sea state conditions. The data points shown in the figure represent actual data obtained during sea trials. The measured data is either close to the estimated acceleration (based on tow tank test data) or is somewhat more favorable. Figure 23 shows accelerometer signals for two speed/sea state conditions. The larger seas show occasional spikes in acceleration which exceeded 1*g*, while acceleration in the 6- to 8-ft seas were typically $\pm 0.6g$. It should be noted that throughout these missions, hull slam was not experienced. Although a comprehensive set of acceleration and motion data has not been collected, it does confirm the subjective evaluation of experienced crewboat captains. The SES offers a dramatic improvement in ride.

Technical experience in the structural area has, to date, centered around two main activities: 1) a program to measure structural loads and pressures in order to confirm the structural criteria; and 2) a program to investigate structural fatigue cracking, which has occurred at the aft end of the hull, and to understand propeller-induced vibration, a major contributor to the fatigue damage.

To study loads and pressures produced in high waves, the hull has been instrumented with accelerometers, strain gages, and a cushion pressure sensor. Five accelerometers located at the bow, stern, and c.g., in combination with a measurement of cushion pressure, permit impact loads producing either pitch, roll, or heave to be determined using some assumptions

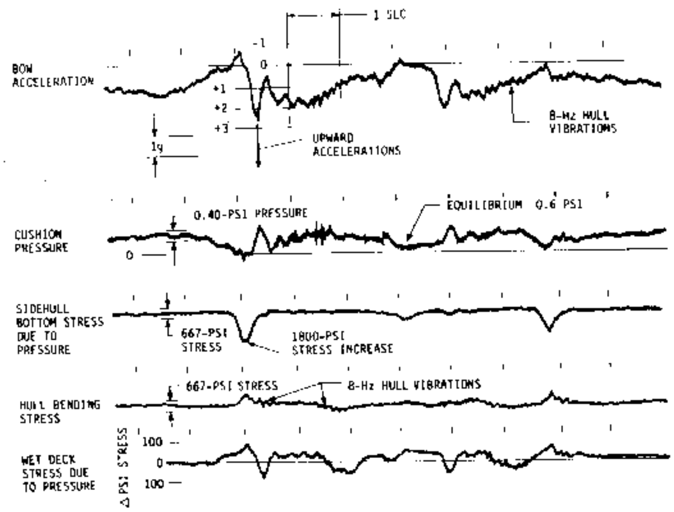

Fig. 24 Structural data: 28 knots, 10- to 12-ft seas.

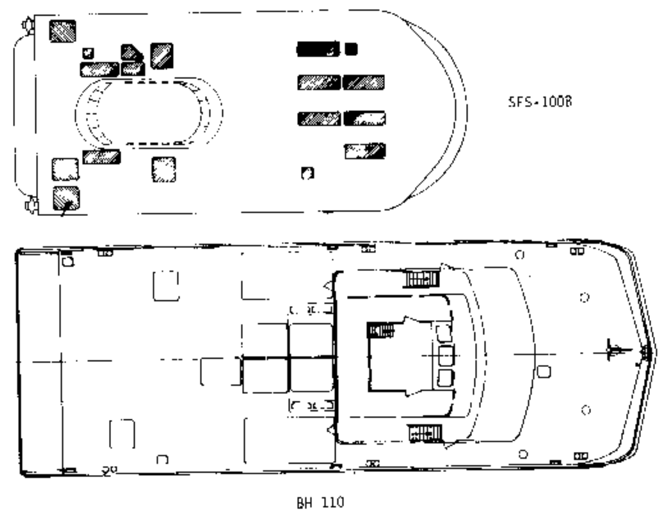

Fig. 25 Planform comparison of the SES-100B (top) and BH 110 (bottom).

about the load center of pressure. Twenty-two strain gages, with additional backup units, have been located on the wet deck bottom plating, at the bow and stern, and on the sidehull bottom plating in the bow region. These strain gages are arranged so that an average pressure over an area of stiffened plating can be measured by combining the strain data with analysis of strains as a function of pressure. It is considered both more practical and more valuable to the structural designer to measure pressures in this manner than to install pressure sensors and measure very localized pressure peaks.

Two structural test missions have been conducted under rough-water conditions during which loads and strains were measured. The conditions have included head seas with waves of 8–12 ft, with occasional waves to 14 ft, and speeds of approximately 26–28 knots. During these operations, accelerations at the bow approaching 3g have been experienced, but there has been no significant wet deck slamming. The plating stresses did not exceed 2000 psi, as compared to an allowable stress of 14,000 psi, and stresses in the hull girder due to bending did not exceed 2000 psi.

A typical sample of data from some of the sensors is shown in Fig. 24. This data is very typical of wave encounters throughout the rough sea measurements conducted to date. Each encounter begins with a loss of cushion pressure as a wave trough passes beneath the craft, in combination with a modest stern impact from the preceding wave peak. The result is a negative acceleration at the bow. Evidence of sidehull bottom impact as the craft falls is seen in Fig. 24, but the resulting load from this impact is small.

The principal restoring forces that produce the high positive accelerations result from a buildup of cushion pressure as the bow of the craft descends and the bow seal contacts the water, sealing the cushion. The hull vibratory response to the loads can be seen in the hull bending trace. The stress in the wet deck bow stiffening shown at the bottom of Fig. 24 matches very closely the cushion pressure trace, indicating that a wet deck impact was not involved in this particular sequence.

XII. Program Assessment

The Bell Halter development has been a successful program for the demonstration of cost-effective SES's. One of the major problems in introducing a new system or craft is the inability to close the gap between the technology drive and the operational need. In most cases, where the new system represents a fairly radical development, it is necessary to provide the potential operator with a prototype or demonstration unit which can be operated and evaluated within the existing overall system. This will determine whether it is of any value and, if so, what design changes will be required. Unfortunately, in order to survive in the competitive research funding

Table 4 Comparison of installed power and performance

	BH 110	SES-100B
Propulsion power, hp	3200	12,160
Lift power, hp	570	1260
Total power, hp	3770	13,420
Maximum speed, knots	40	90+
Efficiency, hp/ton-knots	0.88	1.75

environment of industry or government, any new idea must have its performance potential prognosticated to the highest limit (a challenge which is also not unattractive to engineers).

It is interesting to compare the Bell Halter 110-ft demonstration boat program with the SES-100B program in which Bell was a principal participant. Figure 25 shows the plan views of these craft.

It must be clearly understood that there are significant basic differences between these programs, and this comparison is not intended in any way to be a relative grading or assessment of these programs. Rather, the purpose is to show how some of the differences, although justified for each program, have a dramatic effect on the program cost and schedule. Some considerations will also be suggested for future programs.

The BH 110 required significantly lower costs and less time spent from concept to first operations than the SES-100B craft. The main factors that influenced these cost differences concern fundamental aspects of the specific programs, including the program and technical objectives and goals, the level of risk reduction during the design and construction, the number of individuals and organizations involved in the design decision-making process, and the level of configuration control.

The establishment of the principal technical objectives and goals has a dramatic effect on the program time and cost. Table 4 compares the speed requirements of the craft with the installed power. The SES-100B propulsion power limit is due to the high-speed requirement. But, it is not just the level of power requirement that influences the cost. The need to package and install the engines, transmissions, propulsors, and support systems within the craft, for example, adds to the complexity and cost. It is important to note that the SES-100B was intended as a high-speed test craft to probe the limits of SES technology, while the BH 110 is fundamentally a commercial vehicle.

There is no doubt that the SES-100B is an outstanding research vehicle; and its performance and, particularly, its record speed of over 90 knots have done much to help the SES program survive. But putting aside political considerations and considering only the technical objectives, some interesting questions are raised.

The two basic technical requirements for the SES-100B were 1) to be a Froude scale model of a 2000-ton SES, and 2) to be capable of carrying out tests in nonscaling technical areas such as high-speed surface erosion at the intended speed for the 2000-ton SES, i.e., 80–100 knots. In considering the complexity and costs of the SES-100B, there is no doubt that it was the second of these objectives that dominated. Yet in terms of the technical requirements for the second objective, hardly any of the defined areas turned out to be critical, and of the data that was provided by the SES-100B, much could have been obtained from test rigs and laboratory research.

It is not the intention of this paper to present an argument about the SES program selection of the importance of speed, the political justifications of the program, or that this may not be important in future programs. However, there is no doubt that for a future test craft the limitation of the required performance envelope, particularly if the craft is a scale model, could reduce the cost significantly.

It may also be true that we in the technical community help to create some of the high program costs when we strive to justify new programs and advocate our own concepts over competitive systems, or compete for limited research funding or contracts. Sometimes it even seems that a goal is to demonstrate to the world the brilliance of our own capability and technology. We are part of the process of setting demanding technical goals. Certainly, there is a role for research vehicles, but the requirements of an operational fleet or commercial craft should be determined by the anticipated application, not by the ambition of technology.

In the BH 110 program, the decision was made to build an SES well within the state of the art and with a performance which, while only modest in terms of the SES technology capabilities, was considered adequate to achieve the overall objectives.

The reduction of program and technical risks in many of today's programs has assumed major importance. These become a contractual requirement on many government vehicle development programs. For craft that are to be procured for operational or fleet services, it is certainly logical to provide expenditures in the early part of the program to avoid the much greater costs of multiple occurrences of a problem in service. But it is too easy for this requirement for risk-reduction programs to become routine and to be imposed on all programs as a standard procedure, regardless of whether the programs are really justified. For example, in a program to design and build a single craft, it could be more cost effective in many cases to take some calculated risk and be prepared to correct problems after the craft is operated. This, by no means, suggests a carefree or cavalier approach.

In the BH 110 program, the rational approach was to take some risk. In the career-oriented environment in which we operate, risk-reduction can serve the purpose of avoiding exposure to an unforgiving management attitude toward errors or mistakes, rather than optimizing the true cost effectiveness of a program. In this age of conservatism, we may have lost the ability to take risks, and it could be that we need logical risk-taking programs and education, instead of risk-reduction programs and manuals.

In the design and development of an advanced craft, there are very few engineering decisions that have only one unique and adequate solution. Most often, there are several. Consequently, time and effort are expended when there are a number of people or organizations involved in the decision-making, debating the final selection of one of these solutions. Each individual brings to the process his own bias and preference, but the final solution is frequently no better than any of the other potential solutions. The time and cost involved in engineering and design is proportional to the number involved in the decision-making.

For the Bell Halter program, competent individuals were selected and made responsible for many of the key decisions. Once these decisions were made, they were accepted and implemented. A minimum of management review was required, and the primary involvement of management was in the initial selection of the competent decision-makers, rather than in continuous and detailed review of the decisions.

The requirement for the detailed definition of the design of the boat is one of the major causes of cost. Again, it can be argued that there should be standardization, interchangeability, and a reasonable degree of configuration control for fleet operational craft. However, for a single-craft program or for commercial operations, such configuration control is unnecessary and expensive. The requirement to dimension and design every detail of a craft on engineering drawings, and to state specifications and every procedure to be used in manufacturing will greatly increase the cost of engineering and design.

In the SES-100B program, there was a considerable degree of configuration control and over 1000 drawings were made. For the BH 110, 60 single-sheet drawings were made. Obviously, there were many other factors that influenced the number and type of drawings, but there is no doubt that the configuration control was one key element.

The effect of tight configuration control on the program cost will continue through manufacturing by expanding the quality control requirements, and will necessitate many manufacturing actions or engineering dispositions when the craft built does not meet the detailed configuration requirements.

XIII. Conclusions

The Bell Halter 110 SES program has demonstrated that the SES technology developed under the sponsorship of the U.S. Navy over the last decade can be successfully applied to moderate-cost SES's, using commercial marine construction to provide a cost-effective and competitive high-speed advanced marine system. Bell Halter Inc., as a result of the favorable demonstration programs with the first boat, has invested in the production of the Bell Halter 110 Mark II. The first four boats have already been sold, with the first boat already delivered and in commercial service in the Mexican Pemex oil fields. The U.S. Navy program to build a 3000-ton SES, the award of which in 1976 to Rohr Industries was the cause of Bell embarking on the Bell Halter SES program, has unfortunately been canceled.

However, there is now interest in the U.S. Navy in the potential and the cost-effectiveness of the Bell Halter SES approach, and the fact that an SES speed of 50 knots, rather than the 100 knots, may bring such significant cost reductions in the ship procurement, operation, and manning to offset the less significant reduction in mission effectiveness.

In 1980, the U.S. Navy SES program changed its objectives from a high-technology 100-knot SES to the 50-knot fuel-efficient concepts and, as a first step in this new program, purchased the Bell Halter 110-ft boat. This boat is presently being modified to provide accommodations in a patrol boat mode and will first be evaluated by the U.S. Navy and the U.S. Coast Guard for a six-month period in this configuration. After this program, the hull will be cut in half and a 50-ft-plug extension added to convert the 110 into the SES 200, a high length-to-beam boat.

During the early days of the Bell Halter 110 program, there was much discussion on the selection of a name for the craft. Such names as Dash Boat, Rapid Boat, Speed Boat, and many others were considered. In looking back today, a more appropriate name for that first vessel might have been Phoenix.