THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
74 Trinity Place, New York, N Y. 10006
Advance copy of paper to be presented at the Annual Meeting, New York, N. Y., November 13–15, 1975

no. 11

The Domain of the Surface-Effect Ship

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The development of the surface-effect ship is traced from its inception to the present day, and its accomplishments and problems are discussed. The SES is compared with other advanced marine craft from all aspects of design and operation. It is determined that the SES is the only advanced craft that does not suffer from either size or speed limitations. The variation of speed and ride characteristics in a sea state are explored to develop the probable operating domain of the SES. Continued subsystem development in seals, propulsion, lift, and structural systems is discussed and estimates are made of improved operating efficiencies that could result. Specific applications in both naval and commercial service are reviewed. The values of direct operating costs associated with a wide range of operations are presented. These substantiate the competitive status of SES. It is concluded that the SES has a good operating potential for designs of varying length/beam ratio.

Operational problems and accomplishments

History of SES operations

SURFACE-EFFECT SHIP (SES) development was started in the United States in 1961, sponsored by the U.S. Navy, and it has progressed steadily through the 1960's and 1970's. Early investigation with testcraft such as the XR-1 (Fig. 1) encouraged more extensive development utilizing the 100-ton class SES 100A and 100B (Figs. 2 and 3). The latter were designed to examine a broader operating envelope and to provide a basis for design of larger transoceanic ships. The XR-5, a high length/beam ratio SES testcraft (Fig. 4), designed to cruise at speeds below hump, has demonstrated a broader operating potential of SES. At the present time the focal point of the Navy SES program is the 2200-ton testcraft. This is in accordance with the basic plan depicted in Fig. 5 [1].[3]

Significant contributions to SES development have also derived from operations of the commercial HM-2 (Fig. 6) and amphibious air cushion vehicles (ACV's), particularly the 160-ton SR.N4 (Fig. 7). The following paragraphs briefly trace the development of the SES and summarize the significant accomplishments and progress milestones achieved in design, performance, and operating reliability.

The XR-1 was the first of a series of SES manned testcraft and was launched in May 1963. This craft has been a workhorse in successfully demonstrating a large number of advances in SES technology over the last twelve years and has been modified to incorporate many different test configurations (Fig. 8) [2]. Initially the XR-1 was designed with 52 ft overall length and a cushion length-to-beam ratio of 3.5. Propulsion was provided by a Continental J69-T-29 jet engine and the lift system comprised a 110-hp gasoline engine driving two 24-in-dia axial-flow fans supplying cushion air. The fore-and-aft seals on the original craft were of fixed plywood. Following shakedown tests, an afterburning General Electric XJ-85 jet engine (2400-lb maximum thrust) was installed and with this configuration the XR-1 achieved speeds of 60 knots in calm water. Further modifications were made in 1963 which included fitting rigid articulating seals and a T53-L-3 turboshaft engine with an air propeller capable of producing up to 3400 lb of thrust.

The XR-1 was modified to the XR-1A in 1965 with a significant increase in beam. The XR-1A configuration incorporated what is now considered a more conventional cushion length/beam ratio of 2.5 and the addition of pneumatically stabilized articulating seals and ventral fins. This modification enabled the craft to operate successfully in rough seas up to sea state 3 conditions.

In 1969 the XR-1A was converted to waterjet propulsion, powered by two T53-L-7A Avco Lycoming engines, and renamed XR-1B. The sidehulls had been extensively modified to accept the semiflush inlets for the waterjets.

The modification to flexible stay-stiffened membrane bow and stern seals systems was undertaken in 1973, updating the craft to the XR-1C configuration. The incorporation of fully articulating flexible seals was aimed at improving ride quality and lowering drag in rough sea conditions. Concurrent with the seal system change, extensive modifications were also made to the lift air supply system to allow evaluation of seal response under varying air supply conditions. The XR-1C was also utilized to obtain structural impact loads data by adding a redesigned bow structure appropriately instrumented to record wave impact loads in rough-sea operations.

Testing has been successfully completed on the XR-1C configuration and the data are being employed to support the design of larger SES. In 1975 the XR-1 was again extensively modified and, as the XR-1D, incorporated many features representative of the current SES technology, including variable-geometry lift fans, planing seals, heave attenuation valves, and variable-geometry waterjet inlets.

Encouraged by the early results of the XR-1 testcraft and other scale-model tests, the U. S. Navy decided that before

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For presentation at the Annual Meeting, New York, N. Y., November 13–15, 1975, of THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS.

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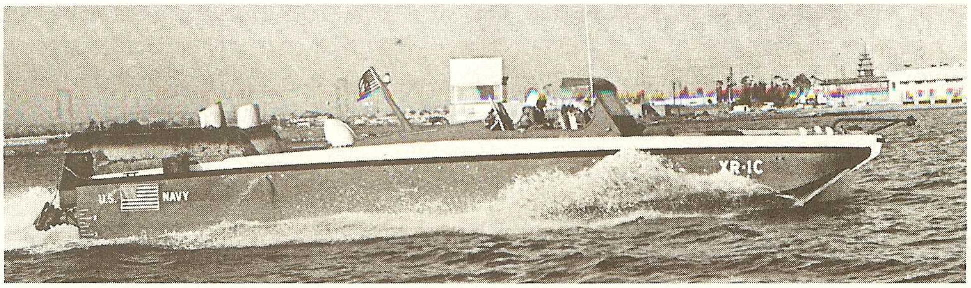


Fig. 1 XR-1C

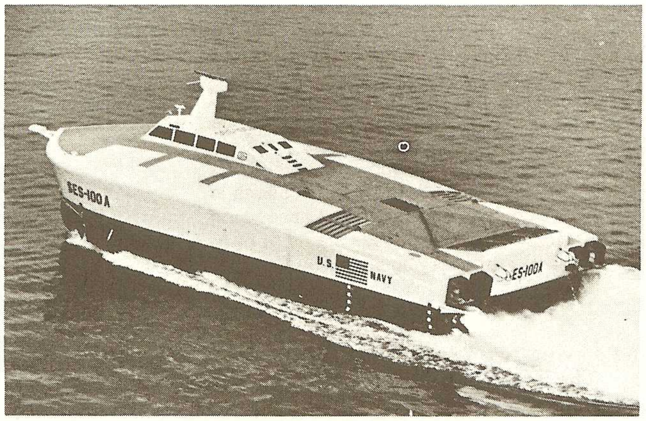


Fig. 2 SES-100A

Fig. 3 SES-100B

proceeding to transoceanic-size craft, larger manned testcraft would be required to further demonstrate the operational characteristics of the SES. Early in 1969, following several concept studies and a design competition, the Navy awarded contracts to Aerojet-General (SES 100A) and Bell Aerospace (SES 100B) for the design and construction of 100-ton SES testcraft that would have the capability of attaining speeds in excess of 80 knots. The designs of the SES 100A and SES 100B were purposely different with respect to hull configuration, lift, propulsion, and control systems to obtain a broad base of subsystem and component evaluation. The basic design characteristics of the two testcraft are listed in Table 1.

During 1972 both 100-ton testcraft became operational, and the Navy's test and evaluation programs will be continued into 1976. The significant results from the tests conducted to date have been confirmation of the predicted performance envelopes with respect to speed, ride quality, maneuverability, and structural loads. Subsystem testing of seals, life fans, waterjet and propeller propulsion, and heave attenuation systems has also provided important data which are now being utilized in the design of larger SES. The SES 100A has demonstrated the performance of both flush and pod waterjet inlets.

Table 1 Leading particulars, SES 100A and 100B testcraft

LEADING PARTICULARS	SES 100A	SES 100B
Overall length	82 ft	78 ft
Overall beam	42 ft	35 ft
Overall height	23 ft	20 ft-3 in.
Cushion height	6 ft	6 ft-2 in.
Bow seal	Bag and multi-membrane	Bag and fingers
Stern seal	Bag and planing surface	Triple lobe
Propulsion	Waterjets	2 to 3½-ft-dia Super-cavitating propellers
Lift fans	3 axial	8 Centrifugal
Power plants	Integrated lift and propulsion by 4 AVCO Lycoming TF 35 gas turbines	
lift:		3 UALC ST6J-70 marine gas turbines
propulsion:		3 P&W FT 12A-6 marine gas turbines
total shp:	14,000	14,400
Steering		
primary:	Waterjet nozzles	Rudders and ventral fins
alternate:	Hydrofoils—React through CG	Variable-pitch propeller blades
Crew	4 Crew + 6 observers	4 Crew + 6 observers

Meanwhile in September 1973 the Navy launched the first high length/beam SES testcraft, the XR-5. The craft has a gross weight of 3.3 tons, an overall hull length of 45 ft, and a cushion length/beam of 6.5. In the subhump operational mode for which it is designed, the XR-5 has attained speeds up to 25 knots in calm water and has been tested in waves up to 2½ ft high. The XR-5 test program was completed successfully in 1974.

The Hovermarine HM.2 has been the only sidewall craft developed that has successfully entered the commercial market. The HM.2 is primarily a passenger-carrying short-haul craft capable of 35-knot speed in sheltered waterways. To date, over 30 craft are in operation. The craft has been steadily improved with respect to reliability and performance since 1968. Improvements to the bow seal were made after the craft exhibited plow-in tendencies in choppy water. Continual improvements in corrosion-resistant machinery designs and electrical installations have resulted from operational experience in the SES environment. The

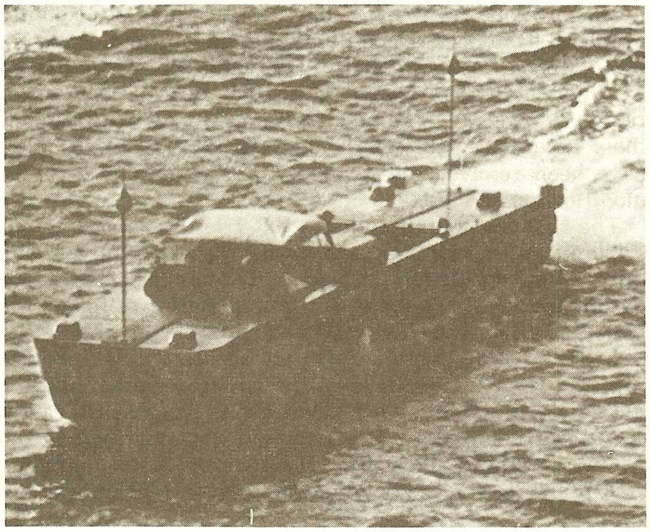


Fig. 4 XR-5

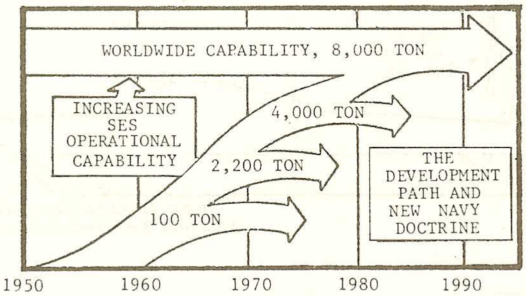


Fig. 5 Evolution of the SES

U. S. Navy, as part of its SES research program, has utilized the HM.2 to increase the understanding of SES ride quality over a broader range of parameters.

SES performance

Improvements in SES performance since the early 1960's parallels the significant developments in the technology of subsystems, including lift, propulsion, and seals. Although the early XR-1 tests were limited to calm water, they served to validate analytical and model test results of over-hump operation, providing a basis for confidence in the developing analytical predictive techniques. The XR-1A provided the first insights into the problems of habitability and ship motions in rough water when the craft was tested in conditions approaching sea state 3. It was confirmed during these trials that improvements in the lift system design would be desirable to reduce ship motions and accelerations in very rough water. Further, to maintain high speeds in open-sea conditions, seal and sidewall drags would have to be reduced. The approach used in the design of the SES 100A and 100B testcraft reflected significant improvements. Flexible seal designs for both craft were employed to improve both seal drag and wave response. The 100A was designed with a heave alleviation system to improve ride quality. This system essentially provided an effective means of smoothing the transient wave-induced cushion over-pressures by venting air overboard (Fig. 9) [4]. The figure shows that the vertical accelerations of the SES 100A were reduced by 50 to 70 percent when the heave attenuation system was employed. These results have provided encouragement for further development to improve the ride quality. The SES 100B was designed with a versatile lift-air supply system to study the airflow distribution effects. Extensive rough-water testing has been accomplished, providing data on SES capabilities, ride quality, and structural loads and design criteria. The data from the 100A and B tests have shown good agreement with analytical predictions and model tow-tank test results.

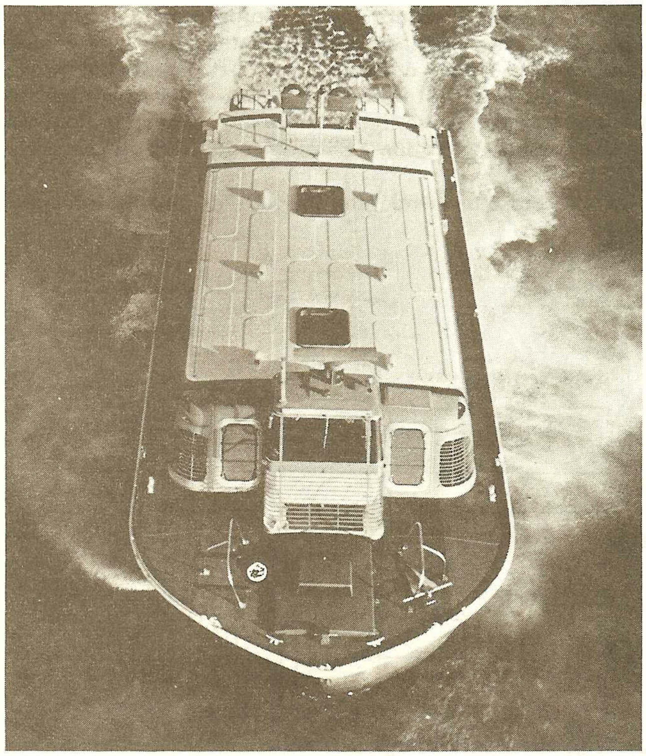


Fig. 6 HM-2

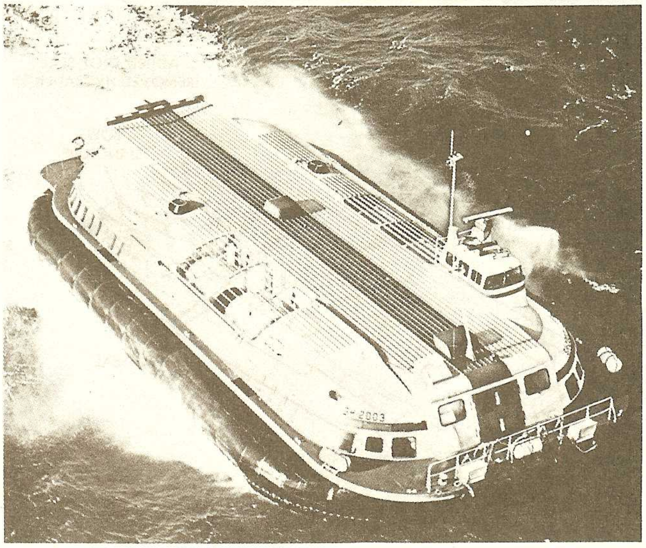
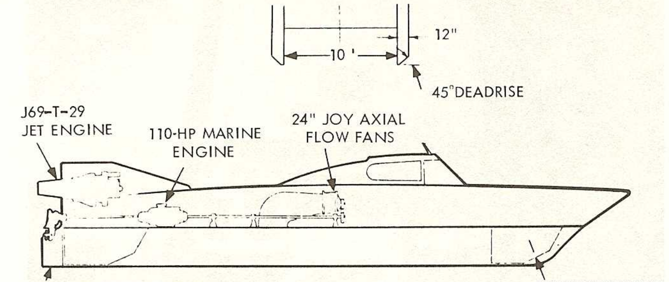


Fig. 7 SR.N4

Over the past 12 years the speed versus sea state envelope of SES operating experience has progressively expanded (Fig. 10). The first-generation SES, the XR-1 and HM.2, achieved low-speed operations in 3-ft significant wave height and a speed of 40 knots in calm-water operations in the mid-1960's. These figures were approximately doubled by the second-generation SES 100A and 100B in the early 1970's.

In the course of developing the SES, its maximum operational envelope has been explored. In doing so, stability problems have been encountered, the most severe occurring when, during the early trials in 1964, the XR-1 overturned. During seal design experiments in 1973, the SES 100A experienced a plow-in. The phenomena associated with each of these experiences are clearly understood and the problems have been resolved and overcome by systematic analysis, modification and tests.

The first configuration of the XR-1 testcraft became unstable in roll during a turn to starboard, at a relatively low speed of approximately 36 knots. The testcraft heeled out of the turn, venting bubble air from the starboard side of the bow seal. The bow seal collapsed, causing the craft to go bow-down while continuing in an outboard roll until she flipped over. In this incident the bow seal design and the marginal roll stability were identified as the primary causes of disaster. The craft was retrieved and modified to the XR-1A configuration. Modifications included reducing L/B by increasing the beam of the cushion by five feet and



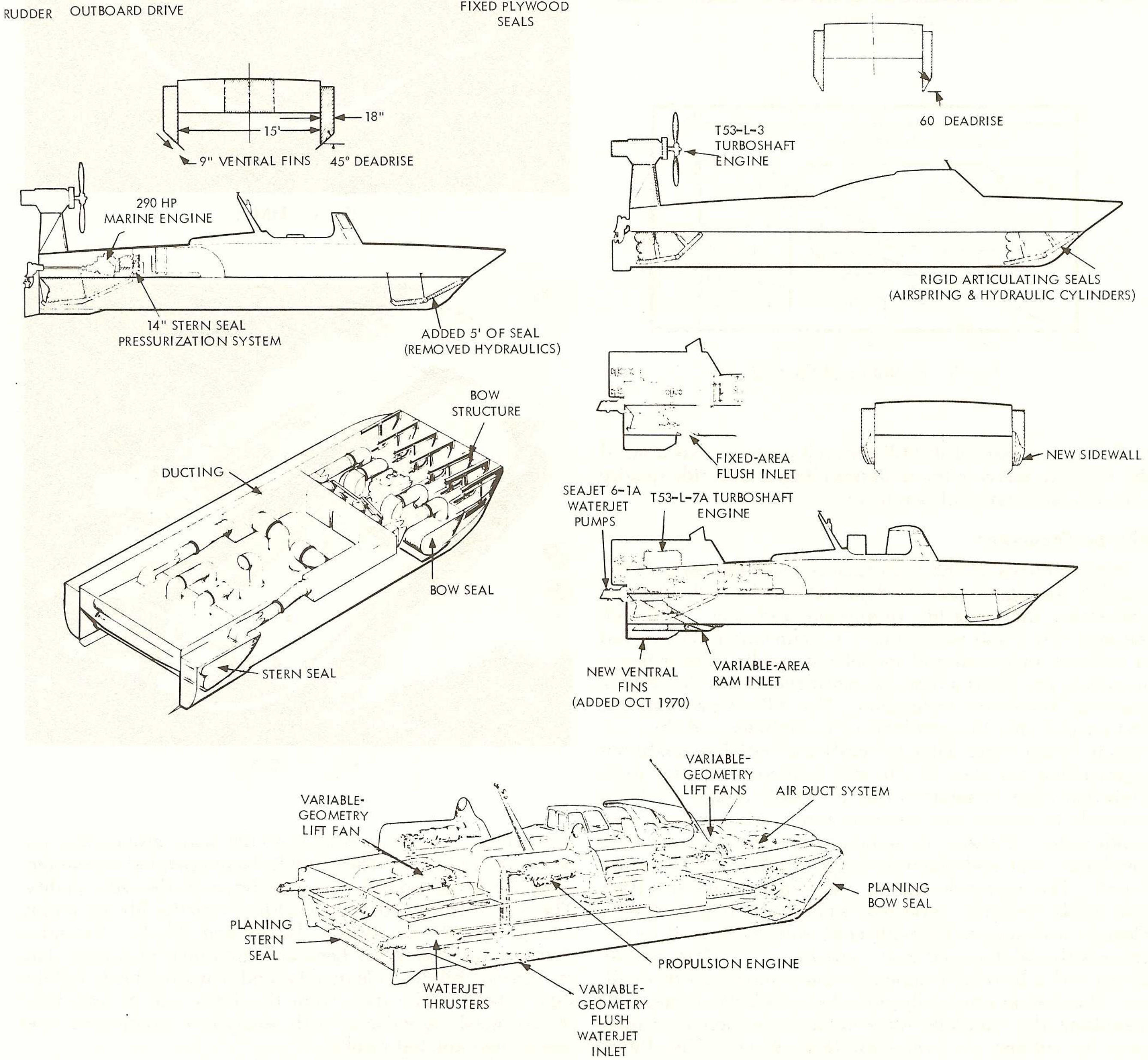


Fig. 8 XR-1 configurations

reducing the sidehull deadrise angle from 60 to 45 deg. To increase stability during turns, and to maintain an inboard rolling action, ventral fins were attached to the sidehulls at the stern. These modifications were tested for more than 150 hr both in smooth and rough water during 1967. During all maneuvers the XR-1A exhibited excellent handling characteristics, essentially validating the design changes.

The SES 100A plowed-in while operating in calm seas at a speed of approximately 60 knots. The plow-in was characteristic of many such incidents which occurred on the HM.2 and on ACV's such as the SR.N6. A pitch-down attitude caused high drag forces on the bow skirt and a rearward movement of the cushion center of pressure, resulting in pitch instability, a severe bow-down trim, and rapid deceleration as hydrodynamic contact with the hull was made. At the time of the plow-in on the SES 100A, the craft was operating with a simple membrane bow seal, incorporated to determine the efficiency of lightweight seals and to allow the craft to operate on shakedown machinery runs. The bow seal specifically designed for the 100A was undergoing extensive modifications at this time. The plow-in resulted in nothing more than rapid deceleration, and the craft was swiftly put back into operation. The SES 100A has since been fitted with an improved bow seal design which has been operated at speeds up to 76 knots, and in waves up to sea state 3, without incident.

Reliability

During any technology development a basis for predicting reliability is difficult to obtain from testcraft data. This is due to the inevitable developmental nature of many subsystems and the frequent changes made for maximum acquisition of data. The SES testcraft have suffered machinery problems, but in all cases the reliability has progressively improved.

Of the subsystems utilized on the SES, only the cushion seals do not have a lengthy developmental history, having been developed specifically for SES and ACV. The SES technology development has been fortunate in being paralleled by commercial ACV craft which have undergone extensive operations accumulating thousands of hours of data with relatively few major changes in configuration. The SR.N4, five of which have operated on a daily basis between Britain and France for many years, has provided the SES technology development with much needed data relative to seal life [5]. The seal life of the SR.N4 has increased progressively through improvements of materials and seal configurations (Fig. 11). The effects of seal wear on SR.N4 performance are presented in Fig. 12, which shows that as the fingers wear down a reduction in speed of several knots is experienced. It is also worthy of note that less than 3 percent of the maintenance cancellations in the SR.N4 operations in 1973 were due to seal problems.

Much of the basis for SES seal design derives from ACV operations. The thirteen years of ACV seals development have seen considerable improvements both in design and in the quality of material. New materials have been developed specifically for ACV skirts and new bonding techniques introduced. Easily replaceable sections of the skirt have been designed to reduce replacement costs. Initially some damage to the skirt system resulted from the use of chains for restraint purposes; these have now almost entirely been eliminated.

Main failures of ACV and SES seals are confined to the fingers. The ACV operates over both land and water, and this amphibious operation has a different and more severe effect on the wear of seals. The SES operates solely over water. Operation over open water causes high-frequency

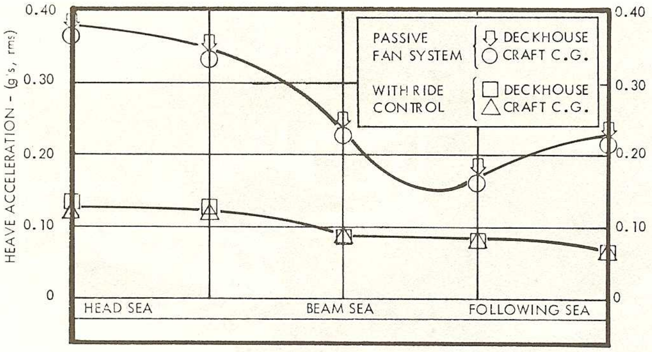


Fig. 9 SES-100A heave alleviation

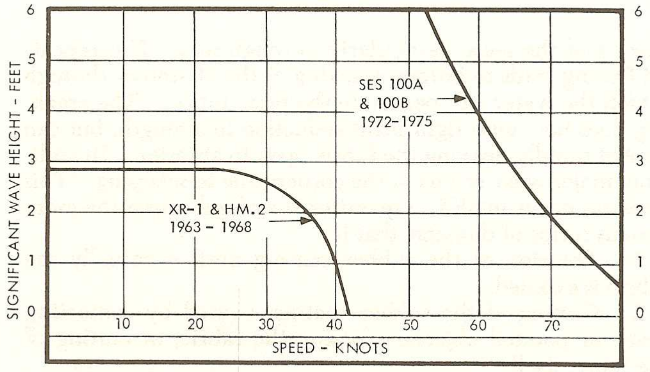


Fig. 10 SES operating envelope expansion

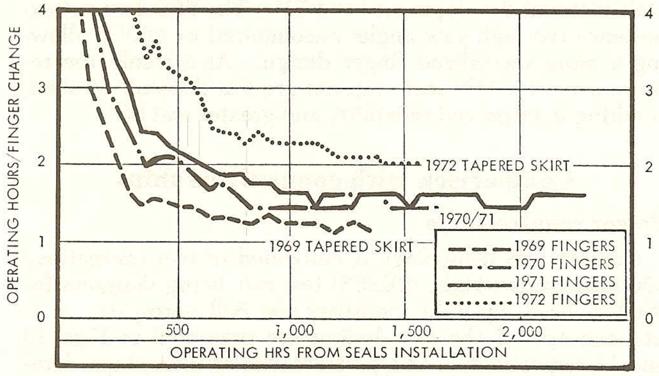


Fig. 11 SR.N4 seals evolution

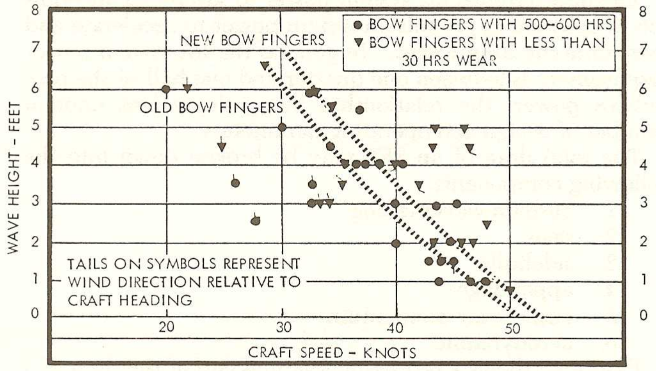


Fig. 12 Effect of seal wear on SR.N4 performance

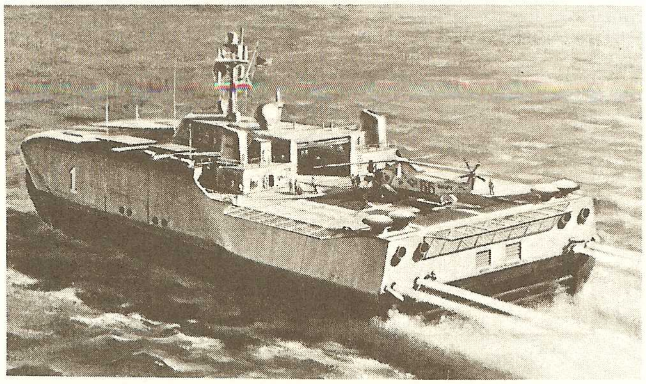


Fig. 13 Rohr's concept of U. S. Navy 2000-ton SES

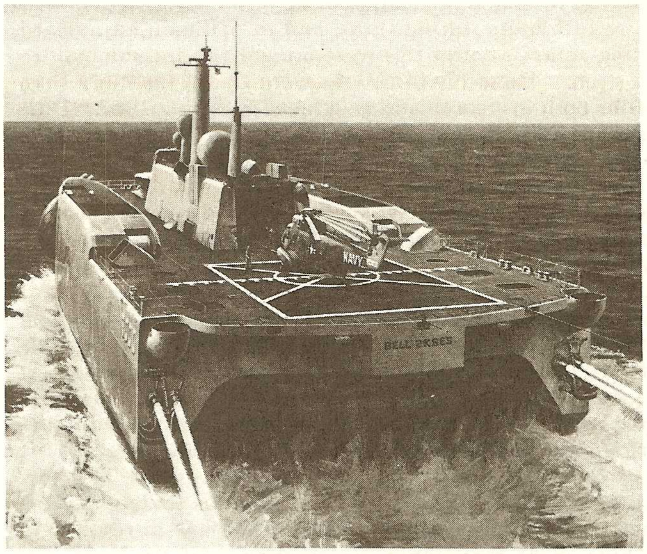


Fig. 14 Bell's concept of U. S. Navy 2000-ton SES

flexing of the seals, particularly in rough seas. This repeated flexing leads to fatigue cracking of the elastomer through which the water can penetrate the basic fabric. The cracking does not cause significant reduction in strength, but can spread rapidly, leaving the fabric open to abrasion. In addition, major wear occurs at the corners due to scooping. This does not occur in SES. Operation over land causes the more serious forms of damage, that is:

1. Abrasion of the rubber coating until eventually the fabric is exposed.
2. Cutting of the rubber coating, caused by contacting sharp or pointed objects, exposing the fabric, or cutting of the fabric itself.

The seals damage incurred over land can lead to more serious damage during subsequent operation over water, and alternate land and water operation magnifies the problem of seals material development for ACV. The SES does not experience the high yaw angles encountered in ACV's, allowing a more specialized finger design. As a result, the requirements for SES seal material are less difficult to meet, resulting in improved reliability and greater seal life.

Comparison with competitive ships

Power requirements

Current SES technology is embodied in two competitive 2200-ton gross weight (2KSES) testcraft being designed for the U.S. Navy by Rohr Industries and Bell Aerospace. Artists' concepts of the two designs are presented in Figs. 13 and 14 respectively. The performance of these ships, demonstrated by numerous subscale and subsystem tests, is used as a basis for the SES data prepared for this section of the paper.

The SES requires lift system power to sustain its air cushion in addition to propulsion system power to accelerate and overcome the drag forces. In general the lift system power requirement is between one quarter and one half of the propulsive power, the relationship being dependent upon a number of design and operating parameters.

The total drag of an SES may be broken down into the following components:

1. cushion wavemaking
2. seals
3. sidehulls
4. appendages
5. cushion air momentum
6. aerodynamic

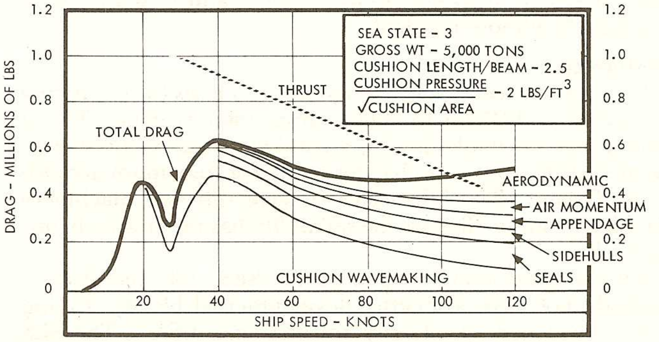


Fig. 15 SES drag breakdown

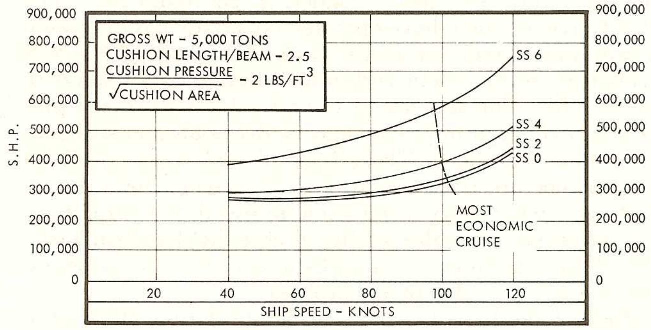


Fig. 16 SES power requirements

Figure 15 shows a representative makeup of the drag of a 5000-ton SES in sea state 3, consistent with the present status of SES technology. The figure shows that the two main considerations in propelling an SES are to provide adequate thrust/drag to accelerate through the hump, which is about 40 knots for this ship, in addition to overcoming the drag at the design cruise speed. For the particular design considered, the lift/drag is about 24 at cruise speeds of 80 to 100 knots, not allowing for the power consumed by the lift system. Above hump, the total power requirement of the lift and propulsion systems increases with speed and sea state (Fig. 16). To operate at 80 knots in sea state 3, the 5000-ton SES requires 340,000 shp, or 68 shp per ton of gross weight.

The loss of speed with sea state for a fixed installed power can be deduced from the figure.

Figure 16 shows the speed for most economic cruise, that is, minimum power/speed, at each sea state. The reduction in speed for most economic cruise from calm water to sea state 6 operation is seen to be only about 5 knots, assuming the availability of adequate power. This implies that the SES should cruise at its maximum speed in the higher sea stress, consistent with satisfactory ride quality and adequate structural strength.

To determine the relative power requirements of the candidate high-speed marine craft, it is instructive to compare the installed power of existing craft (Fig. 17). The nondimensional parameter

$$\frac{\text{Installed power, shp}}{\text{Gross weight, tons} \times \text{max speed, knots}}$$

is plotted in terms of craft gross weight. The figure shows that many testcraft do not have any significant trend, probably because the installed power selected is generally more dependent upon engine availability or test requirements than maximum efficiency. Fewer operational craft are more representative of the most efficient operation for each type of high-speed marine craft, but as these crafts have differences both in design conditions and development status, again a direct comparison cannot be conclusive.

An approach that should provide a more representative review of advanced ships in the application of the most representative current technology of each to a common set of operating conditions. In Fig. 18 a 1000-ton gross weight ship of each type of configuration operating in sea state 3 is considered, with the exception of the planing hull. For the latter a gross weight limitation of 300 tons is assumed, above which the structural loads are prohibitive. A high length/beam SES is shown in the figure in addition to one having a low value. The same specific power parameter

$$\frac{\text{Installed power, shp}}{\text{Gross weight, tons} \times \text{speed, knots}}$$

is presented in the figure in terms of design speed. The figure shows that the best cruise speeds for the competitive ships are as follows:

High *L/B* SES	70 to 100 knots
Low *L/B* SES	25 to 50 knots
Hydrofoil	35 to 45 knots
SWATH	20 to 30 knots
ACV	60 to 80 knots
Planning hull	55 to 65 knots*

* Note that the planning hull could not operate at the above speeds in sea state 3 due to the excessive motions and structural loads; its maximum speed would normally be between 35 and 45 knots.

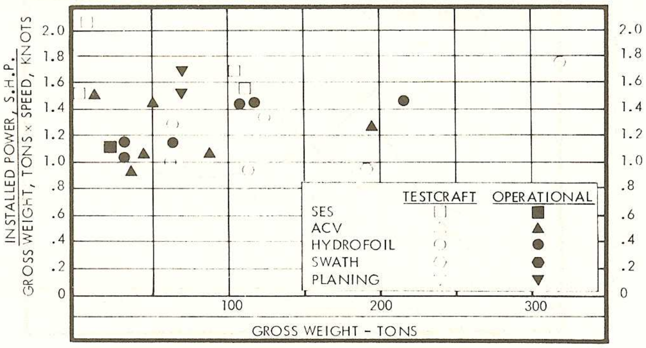


Fig. 17 Installed power of existing craft

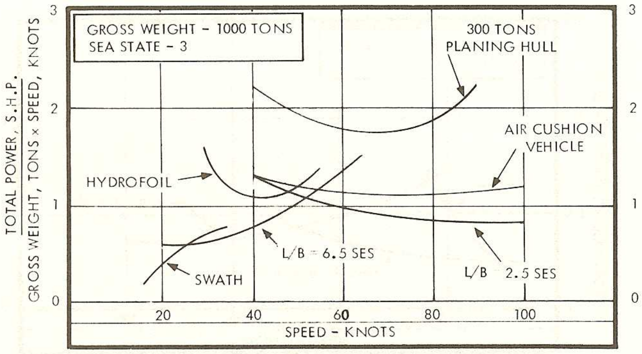


Fig. 18 Specific power comparison—1000 tons

Table 2 Comparative shp/ton gross weight for 1000-ton ships

	CRUISE SPEED, knots		
	30	50	80
Low *L/B* SES	. . .	49	68
High *L/B* SES	18	47	. . .
Hydrofoil	48	57	. . .
SWATH	70	. . .	. . .
ACV	. . .	58	88
Planing hull (300 tons)	. . .	93	148

The most efficient operations, in terms of minimum specific power, are achieved by the SWATH up to 30 knots, the high *L/B* SES from 30 to 50 knots, and the low *L/B* SES above 50 knots. It should be noted that the hydrofoil craft is a strong competitor at smaller sizes due to its ability to operate at speed better than any other surface craft of its size. At 1000 tons it is marginally competitive at 45 to 50 knots cruise speed, at which speed range the preferred selection would probably be based on other factors. The ACV is close to being competitive between 50 and 60 knots, but the planing hull is unsuitable for any operation for which specific power is a significant factor, such as longer-range applications. The power requirements in terms of shaft horsepower per ton gross weight of the candidate 1000-ton ships at cruise speeds of 30, 50, and 80 knots are given in Table 2.

The specific powers of competitive advanced ships of 2000 and 5000 tons gross weight operating in sea state 3 are presented in Figs. 19 and 20 respectively. The only candidates are the SWATH, the low *L/B* and high *L/B* SES. The hydrofoil and ACV are not included in the comparisons; these craft are considered to have gross weight limitations between 1000 and 1500 tons due to foil structural problems and accommodation of efficient air propellers respectively. The figure shows the SWATH to dominate up to 30 knots, the high *L/B* SES to be best from 30 to 60 knots, and the low *L/B* to be more efficient at speeds greater than 60 knots.

The reduction of maximum speed with increase in sea state is presented in Fig. 21 for each of the 1000-ton gross weight ships. In each case appropriate power is installed to give high cruise performance; hence comparative shape of the curves is the sole consideration. The figure shows that the 1000-ton low *L/B* SES holds its performance well up to sea state 3, above which there is a noticeable reduction in speed. As ship size increases, so does the sea state of this

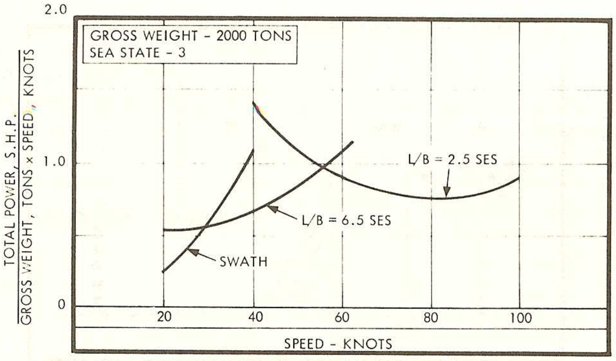


Fig. 19 Specific power comparison—2000 tons

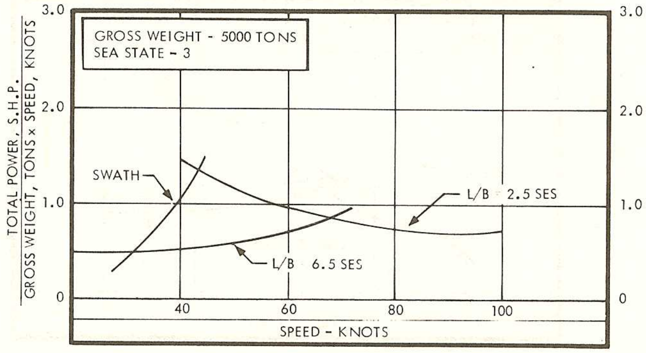


Fig. 20 Specific power comparison—5000 tons

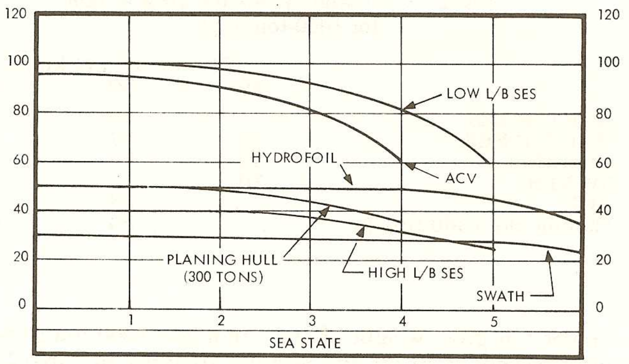


Fig. 21 Comparative operating envelopes of 1000-ton ships

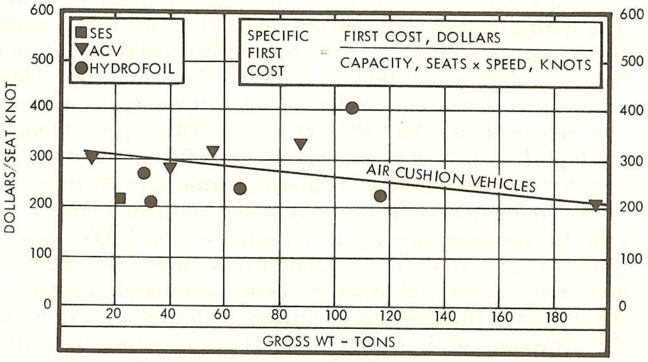


Fig. 22 Specific first cost of existing passenger-carrying craft

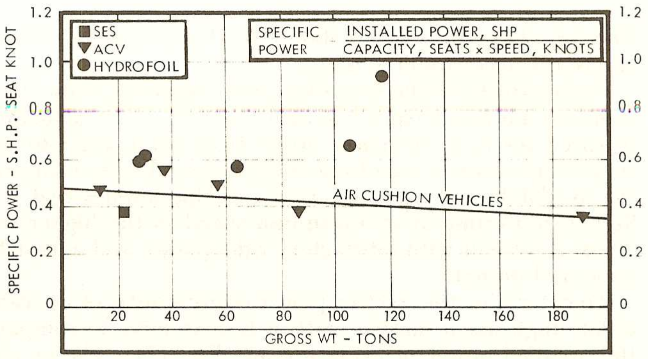


Fig. 23 Specific power of existing passenger-carrying craft

falloff point. The relatively flat drag curve (Fig. 15) causes the speed reduction when the wetted and seal drags due to waves are encountered. The high *L/B* SES, however, with its progressively steepening drag curve, holds its speed capability better in waves, albeit at a reduced level. The ACV starts to appreciably lose performance above sea state 2 due to high seals drag in waves. The planing hull has the greatest degradation of speed with sea state, partly due to its limited size and characteristic of slamming into waves.

Operating economics

The cost of operation is a dominant consideration in craft selection for both naval and commercial applications. Historically, however, there has been far less accuracy displayed in the prediction of ship costs than in ship performance; consequently, estimating the relative operating cost of competitive systems is questionable.

The main factors contributing to the direct operating cost of marine craft are the first cost of the fully equipped hull and the installed power; the latter has dominant effects on both maintenance and fuel costs. As it is not considered practical to attempt a comparison of direct operating costs of existing high-speed craft, it is instructive to compare their first costs and installed powers.

The first cost or the price paid by operators for an existing high-speed passenger-carrying craft is considered in terms of its rate of doing work (Fig. 22). The parameter used

$$\frac{\text{First cost, dollars}}{\text{Capacity, seats} \times \text{speed, knots}}$$

is considered to be most representative of specific cost. The existing hydrofoil craft show considerable scatter and no definite trend. The ACV's have a more significant trend showing reduction in specific cost with increase in gross weight. The sole commercial SES, the HM.2, is seen to have a very competitive specific cost for its size.

The specific powers of the existing craft are presented in Fig. 23. The parameter presented is

$$\frac{\text{Installed power, shp}}{\text{Capacity, seats} \times \text{speed, knots}}$$

As before, the hydrofoil data are inconsistent, with the exception that all the passenger-carrying hydrofoils operating today have higher specific powers than the other craft. Again the ACV's are more consistent and show a reduction in specific power with increase in gross weight. The relatively low specific power of the SES is a key element of its future acceptability as a commercial ship.

The projected direct operating costs of commercial SES utilizing current technology and having gross weights from

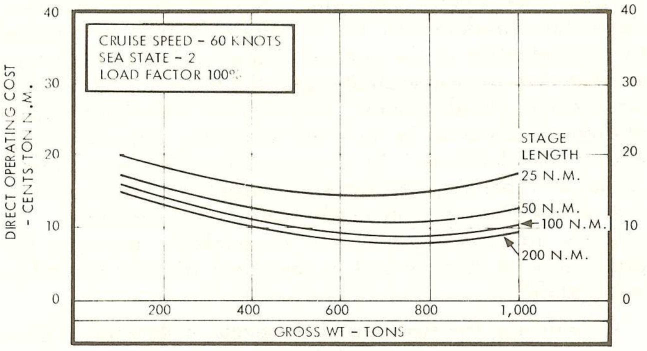


Fig. 24 SES operating cost vs gross weight

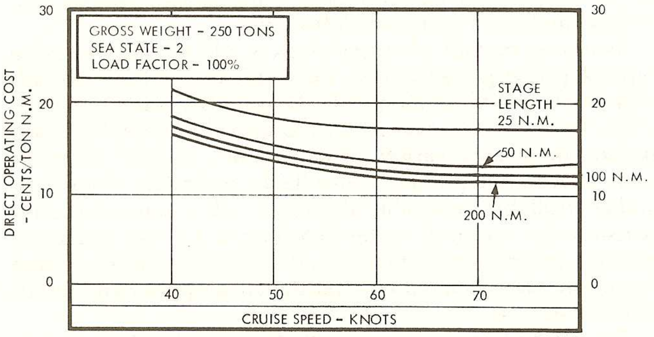


Fig. 25 SES operating cost vs cruise speed

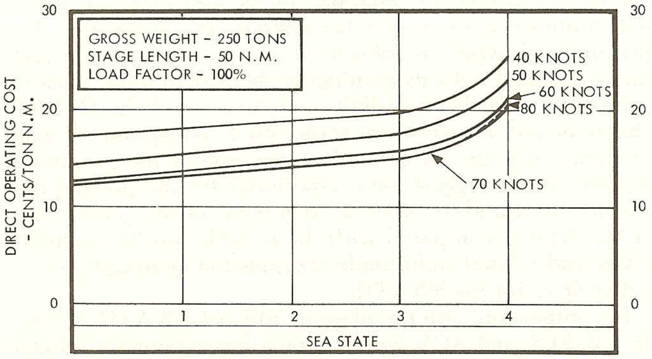


Fig. 26 SES operating cost vs sea state

100 to 1000 tons are given in Figs. 24, 25, and 26. The first costs, installed powers, and design cruise conditions of some of the SES presented in the figures are given in Table 3. The utilizations are given in Table 4.

As expected, the direct operating cost of the SES is reduced with increase in stage length. At higher speeds and greater stage lengths, further improvement in operating costs can be anticipated at gross weights above 500 tons. The case for a larger SES is also dependent upon ride quality or the need to accommodate a particular payload. Up to 70 knots, higher speed means lower operating costs, but this would not be applicable for the limited ferry case with stage lengths below 25 nautical miles. The impact of sea state on operating cost can be very large, as shown in Fig. 26 for SES of 250 tons gross weight.

Reliability

In general, all high-performance ships present, to some degree, a reliability problem of greater magnitude than their conventional counterparts, due to the difference in power density, which is the price paid for the quantum increase in speed. For example, the power density of a modern supertanker is less than 1 shp, and for a modern destroyer about 14 shp, compared with a power density in the order of 80 shp for high-performance ships. Also, the weight-critical nature of the advanced ships demands minimum-weight structural systems which are subjected to the high loadings of high-speed waterborne operations. The additional complexity of particular components of the high-performance ships, such as the foils of hydrofoil craft and the seal installations of SES and ACV, compounds the inherent reliability problem.

A quantified comparison of the reliability characteristics of advanced ships is inconclusive at this time due to the limited and different level of development. A satisfactory quantified reliability evaluation can only be accomplished

Table 3 Basic assumptions of commercial SES operations

Gross weight, tons	100	250	250	250	250	250	250	250	250	500	1000
Payload, tons	30	80	80	80	80	80	80	80	80	200	405
Design speed, knots	60	40	50	60	70	80	60	60	60	60	60
Design sea state	2	2	2	2	2	2	0	3	4	2	2
Installed shp	6,800	12,600	13,000	14,300	16,100	20,400	12,100	16,400	23,900	26,600	53,200
First cost, $M	2.17	4.63	4.69	4.89	5.16	5.78	4.55	5.21	6.36	9.24	17.60

Table 4 Utilization of commercial SES

Gross weight, tons	100	250	250	250	250	250	500	1000
Design speed, knots	60	40	50	60	70	80	60	60
Stage length nautical miles	Annual utilization, hr							
25	1392	1453	1316	1200	1106	1025	975	734
50	1790	1839	1724	1622	1533	1454	1403	1136
100	2078	2117	2040	1960	1901	1839	1791	1555
200	2271	2295	2248	2201	2159	2118	2091	1921

on the basis of specific propulsors, transmission systems, control elements, and materials definition.

Assuming that all advanced ships would employ the same type of prime power source, the reliability of their propulsion plants would be identical. Beyond this basic consideration, however, the evaluation requires the reliability comparison between a variety of candidate propulsor elements such as waterjet pumps, controllable/reversible propellers, and controllable/reversible airscrews. Also, numerical comparisons are required to be determined for the reduction gearing, power line geometry, and other transmission system requirements associated with particular propulsor and installation selections.

The SWATH and planing hull offer an advantage in reliability due to the general simplicity of their hull structures. Between these candidates a statistical analysis would be required to consider the reliability of the hull structure within the framework of a specific operational envelope. The planing hull, which is subject to very severe pressure loadings associated with its planing mode of operation, must be compared with the twin-hull configuration of the SWATH characterized by significant transverse bending and torsional moment loadings. A general comparison of the propulsion systems would suggest some superiority for the planing hull due to the straightforward arrangement of the power train of this type as compared with the possible requirements for offset and related right-angle transmission gearing to a propeller drive for the SWATH.

In comparison with the planing hull and SWATH, the hydrofoil, SES, and ACV would appear less inherently reliable due to the requirements for appended lifting systems and related mechanical installations.

In the hydrofoil craft, the lifting surfaces depend upon highly accurate section geometry and a high-quality surface finish for efficient operation. However, the fundamental operation of the vehicle requires these elements to function close to the air/water interface, in which they are subject to performance degradation resulting from surface damage due to cavitation erosion and floating debris as well as marine growth. Additionally, in submerged-foil configurations, the hydrofoil lifting surfaces are combined with propulsion elements and include electromechanical systems for ship stabilization and for foil retraction. The combination of such systems within underwater appendages, in turn, entails requirements for complex sealing and lubrication provisions. The aggregate system density and limited inspection and maintenance accessibility must necessarily suggest a low reliability rating for these installations.

In the SES and ACV, the lift system includes prime movers, air supply fans, and cushion air containment seals. The seal installations of the SES are significantly less extensive and complex than the ACV, and operate over water only. The inherent reliability of the SES and ACV could be lower than that of less complex ships due to the mechanical nature of the lift system.

It is concluded that in the development of hydrofoil craft, SES, and ACV, maximum consideration to reliability must be given in the selection, design, and installation of the mechanical systems related to these vehicles.

Vulnerability

In general, submerged-body craft (hydrofoils, SWATH) are inherently more vulnerable to damage by striking deadheads and other floating objects than are conventional displacement ships. SES and ACV's possess reduced vulnerability to such objects. In military applications, the high-speed characteristic, the reduced draft, and the small size of the submerged portions will reduce the hit probability of weapons used against these ships. Subordinate to these fundamental considerations, the vulnerability may be assessed by an evaluation of the general characteristics of each type as related to maneuverability, and the influence of particular damage considerations. Additionally, the characteristic of detectability must be included within the scope of vulnerability considerations. In commercial applications, detectability by other ships provides a measure of collision protection and is, therefore, inversely related to vulnerability. In military applications, however, detectability increases the probability of damage and is, therefore, directly related to vulnerability.

Considering the susceptibility aspects of damage, a gross comparison may be accomplished by means of comparative evaluation considering collision with floating objects, and, for military applications, the target area exposed to particular attacking weapons. Due to the high speed and lightweight construction requirements which characterize all of the advanced ships, collision with a major object may result in severe damage, but the candidates do not have comparable submergence of hull and subsystems. The limited basic draft and general absence of underwater appendages and the small wetted hull area of the ACV and SES essentially offer minimized susceptibility to damage from floating objects. The planing hull, although also a shallow-draft vehicle in the planing mode, presents some increase in wetted hull area and, therefore, increased vulnerability to impact damage. The SWATH and hydrofoil craft may be considered to incur increased vulnerability to collision damage due to their increased draft and, particularly in the hydrofoil case, underwater appendages. The functionally critical nature of the appendages of the hydrofoil craft presents a particular concern in this respect. A review of comparative vulnerability, as related military considerations would suggest, minimized vulnerability to torpedo and mine damage for the ACV and SES types due to their underwater geometry, previously discussed, and to their high speed, being greater than that of the torpedo. Also, in relation to basic draft and underwater appendage characteristics, it may be anticipated that the planing hull, hydrofoil and SWATH are, in the order given, increasingly vulnerable to torpedo and mine damage. With respect to airborne weapons, it may be considered that, for functionally equivalent designs, the small differences in the topside geometry resulting from the differences in operational principle have little, if any, significance.

Vulnerability with respect to the effects of damage through collision with floating objects will vary to some degree in relation to the differences in hull geometry and appendages of the various ship types. Ripping-type damage of limited penetration depth but significant longitudinal extent must be anticipated. With ACV's, however, commercial operation has shown that the effect of such damage is in the form of reduced efficiency rather than disablement. With hydrofoil craft, vulnerability to obstacle collision encompasses the lifting foils, propeller-type propulsors or waterjet inlets, steering devices, and related appendages. Since the elevation of the main hull above the water surface provides protection for the primary hull structure, collision with floating objects may be considered to result in loss of operational capability but not jeopardize craft survival. With a planing hull the entire bottom area, together with the underwater appendages, are vulnerable to minor collision, and the risk of damage to the primary hull structure is significant. However, the capability of survival under conditions of severe bottom damage must be provided by means of appropriate design features. Some operational capability is anticipated under conditions of local damage in noncritical areas.

The vulnerability of ACV, SES, and SWATH to collision damage is essentially concentrated in the side hull areas, underwater appendage installations and, with ACV and SES, the seals. Due to the catamaran hull form of these craft, hull structural damage and resulting water ingress can produce a significant list condition which may inhibit operation in the damaged condition. With the incorporation of appropriate design features, survival with extensive sidehull damage can be assured. Also, essentially unimpaired operational capability can be anticipated under conditions of local structural damage outside the critical appendage areas. For advanced ships, the lightweight structure and high machinery density will result in considerable damage from contact explosion with underwater weapons. However, the very shallow draft of SES and the clearance of ACV's reduce the likelihood of such contact. The air cushion of the ACV has demonstated considerable blast attenuation effects, under actual and simulated combat conditions.

As previously noted, detectability in the vulnerability context is desirable in commercial applications because of collision avoidance considerations, but undesirable in military applications for obvious reasons. Detection may occur visually or by means of radar or sonar sensors. Visual or radar detection characteristics are governed generally by planform area and lateral profile area. Sonar detection characteristics are essentially governed by the energy levels of underwater radiated noise and the immersed hull area presented to the listening device.

In general, for ships designed to fulfull identical mission requirements, little difference with respect to visual and radar detectability is anticipated. With respect to passive and active sonar detection, it is anticipated that the SES and ACV types will demonstrate minimum inherent detectability due the limited wetted surface of the hull while in the operational mode and utilizing waterjet or air propeller propulsion systems. Conversely, the SWATH is considered to have maximum inherent detectability characteristics due to the large wetted hull area and the subsurface propulsors. Planing hull and hydrofoil craft are considered to be rated somewhere between these extreme cases.

In summary, the candidate high-performance ships have a variety of vulnerability characteristics, but the detachment of the ship support surface from the water in the case of the SES and the ACV, together with their high speed, gives them a vulnerability edge over their competitors for both naval and commercial operations.

Operating utility

In addition to the speed, range, and ride quality considered, a comparative evaluation of the operational utility of competitive craft must include considerations of payload stowage capability, draft, and maneuvering.

In general, the unique elements of operating utility offered by the high-performance marine craft are high speed and, with hydrofoils, reduced sea-induced ship motions at relatively small size. The general problem with all high-performance vehicles is to provide satisfactory payload and fuel weight fractions within the constraints of given full-load displacement. However, developments to date have demonstrated that, provided lightweight structural systems are utilized together with high-power-density gas turbine prime movers, payload and fuel weight fractions can be provided which are satisfactory for many purposes. Also, investigation has demonstrated that, with payload densities related to passenger transportation and modern military application, the general proportional requirements for structural strength and survivability result in little variation between weight and volumetric limitations. Considering platform utility from the viewpoint of general accessibility for passenger movement or, in military applications, the distribution of weapon systems and for helo operations, the wide planforms of the ACV, SES, and SWATH ships offer significant advantage over the more conventionally shaped planing hull and hydrofoil. Considering draft characteristics, as related to operational utility, an advantage is offered by the amphibious ACV over the other high-performance craft, with the SWATH requiring the greatest water depth.

The hydrofoil and planing hull offer advantages of maneuverability, as their lifting surfaces may be used to provide the required force toward the center of turn. The SWATH, SES, and ACV all require either sideslip or additional hydrodynamic surfaces for turning.

It is anticipated that the SES, ACV, and hydrofoil craft offer superior stopping characteristics to the SWATH and planing hull in that a sharp increase in hydrodynamic drag may be achieved by a deliberate change in the operating mode. This is done by venting the cushion in SES and ACV and feathering the lifting surfaces of the hydrofoil. The SWATH is expected to be the most inferior in this respect.

Operating envelopes

Based upon the foregoing considerations, some tentative conclusions may be reached with regard to the probable operating regimes for each of the high-speed marine craft studied. These conclusions, presented in Figs. 27 through 31, are very general in nature and care should be taken in their interpretation. The first four figures present the preferred craft at each speed and sea state combination at gross weights of 100, 500, 2000, and 5000 tons. The selection is generally based upon design constraints, efficiency, ride quality, and utility. Figure 34 shows the anticipated speed versus gross weight operating domain for each of the five types of ships.

The hydrofoil is limited in both size and speed. With current technology, a gross weight limitation between 1000 and 1500 tons seems probable, and a speed limitation between 40 and 50 knots for efficient operation. The excellent ride quality of a modest-size craft at intermediate speeds in a high sea state suggests that the hydrofoil will find a place in the spectrum of high-performance marine craft. Its relatively high cost could be constraining for general commercial operations.

The SWATH has merit in-lower speed operations of up to 30 knots, particularly when very stable platforms are needed. To fully utilize the latter characteristic, the strongest case for the SWATH is in high sea states, which would imply long-range transoceanic operations.

The air cushion vehicle, whose main advantage is its amphibious capability, is the most direct competitor to the SES ship in terms of speed. However in direct competition with the SES, the higher power requirement of the ACV will prohibit its selection. Applications of the ACV will therefore probably be limited to amphibious ones and its size will be constrained in accommodating its air propellers without resorting to inefficient high disk loadings. Any broader use of the ACV could be based upon a need for extensive Arctic operations or overwater speeds above 120 knots, where its air propulsion would become more competitive.

The planing hull will probably be limited to small sizes only, with continued development of the more sophisticated craft. Its simplicity and inferior efficiency suggest short-

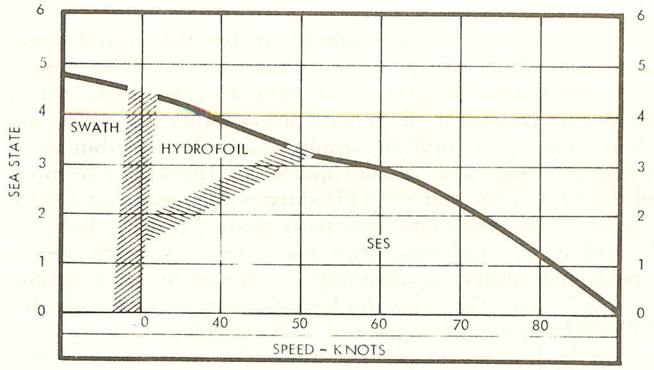


Fig. 27 Operating envelope of preferred ships, 100 tons gross weight

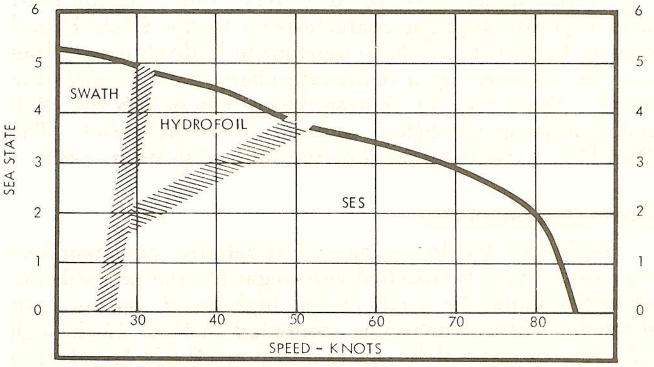


Fig. 28 Operating envelope of preferred ships, 500 tons gross weight

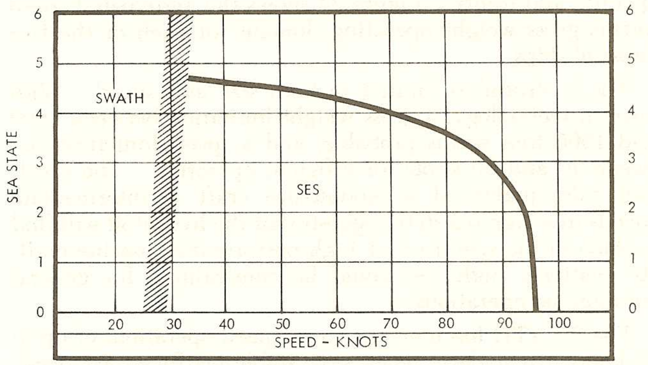


Fig. 29 Operating envelope of preferred ships, 2000 tons gross weight

stage length, small-payload specialized operations at intermediate speeds.

The SES does not suffer from size and speed constraints. Further, because of its superior cushion and propulsor efficiency over the ACV, it promises to have the broadest operating envelope of the high-speed marine candidates, with moderate-speed operations accomplished by SES of high length/beam and high-speed operations by low length/beam craft. Although it does not compete with the SWATH for low speed/high sea state or with the hydrofoil for small size/high sea state operations, the competitive range of the SES extends from small size/medium sea state to large size/open ocean operations.

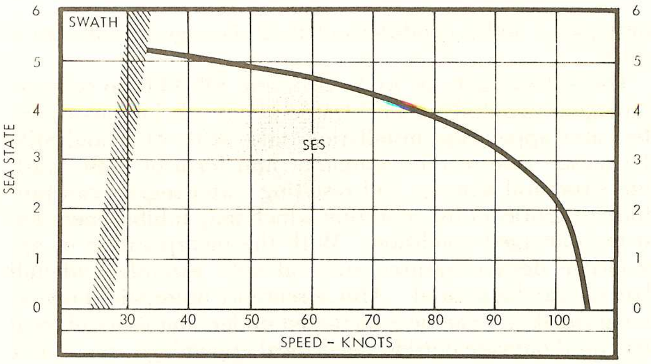


Fig. 30 Operating envelope of preferred ships, 5000 tons gross weight

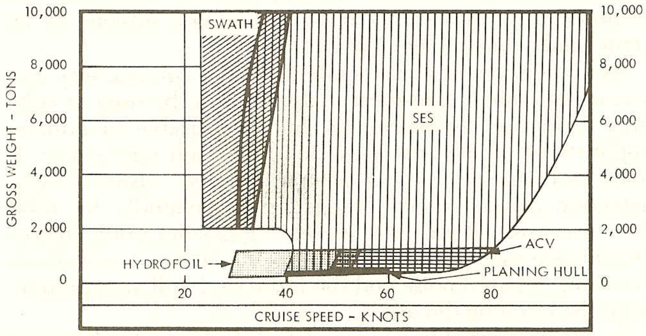


Fig. 31 Probable operating domain of high-speed ships

Future technical developments

Subsystems

To evaluate the operational potential of the SES, consideration should be given to any anticipated improvements in its operating characteristics. The SES is in a relatively early stage of development, with a total of only five testcraft having been constructed. Many significant technical developments are predicted within the next decade, based on current developmental trends. Although few subsystems are unique to the SES, the high-speed overwater environment itself is unique. Consequently the adaptation of components developed for other environments was inevitable in the early development of the SES. Optimization of these components to meet the SES requirements will continue, and substantial improvements in performance, cost, weight, and reliability can be expected. The brief review of the salient items following indicates the considerable potential of this concept.

Seals

The seals offer the greatest potential contribution for improving overall SES performance and reliability. Significant advances have been achieved to date in understanding the role of the bow and stern seals in ship dynamics. From the early testing on the XR-1 utilizing simple fixed plywood seals to maintain the cushion, it was apparent that calm water presented few problems to the SES seal. However, sea conditions markedly deteriorate the craft performance if the seals are unable to respond to waves with minimum drag. The trends in seal designs to date have gone far toward the objective of compliant low-drag operation. The SES 100B bag and finger seal, for example, has shown consistent operational characteristics and performs well

Table 5 Finger material developments required for lightweight flexible material

	EXPECTED INCREASE IN FINGER LIFE, percent
Improved tear strength of base fabric	30
Less degradation of material properties with seawater immersion	20–30
Improved adhesives for material joints	2–5
Improved adhesion of fabric to elastomer	10–20
Improved abrasion resistance of elastomer	50

throughout the operating envelope. Although seal response and drag will continue to be improved, the growth of SES technology and the movement toward transoceanic ships of 2000 tons and up emphasize longevity and reliability. The experiences on SES and ACV in current operation have shown that while seal performance is generally satisfactory, mean times between failure can be considerably improved over current designs. The transoceanic seal must meet high standards of reliability comparable with the other subsystems aboard the SES. To assure the extended life of the seal, continued development of both seal materials and structural design is important. Based upon current ongoing work in these areas, it is possible to predict with some degree of credibility future improvements in seal technology.

A predicted increase in finger life broken down into the separate parameters influencing the longevity of the finger material is given in Table 5. The percentage increases in material life are based on analysis of finger wear of craft in commercial and test operations and ongoing material development work.

Although improvements in all areas are not mutually exclusive, an extrapolation of the improvement over the past ten years is employed for predicting future benefits. Assuming continued development in these areas, an increase of approximately 30 percent in seal life would be a conservative estimate. This alone could account for an increase from 600 to 800 hr of time between finger replacement on SES in current operation, independent of improvements in configuration and structural design. This is equivalent to 15 transatlantic crossings before replacement. Recognizing that the requirements of the transoceanic seal may still exceed even this capability using conventional seal materials (that is, elastomer coated fabrics), seal designs utilizing other materials and configurations are being considered and show great promise. Experiments utilizing planing surface seal concepts developed as a parallel to the finger seal concepts have been very encouraging. This concept employs a hard/semirigid surface at the water interface, in place of the elastomer coated fabric, mounted on an inflated bag. The planing surface can be constructed of several different types of material such as glass-reinforced plastics or fiber composites. This seal could provide increased longevity, reduced maintenance, improved response to waves, and reduced drag. Still further advanced seal designs would utilize inflated structural sections and high-compliance brush ends to provide additional performance advantages.

Propulsion system

Propulsion efficiency may be expressed as

$$\frac{\text{Net thrust} \times \text{speed}}{\text{Shaft power}}$$

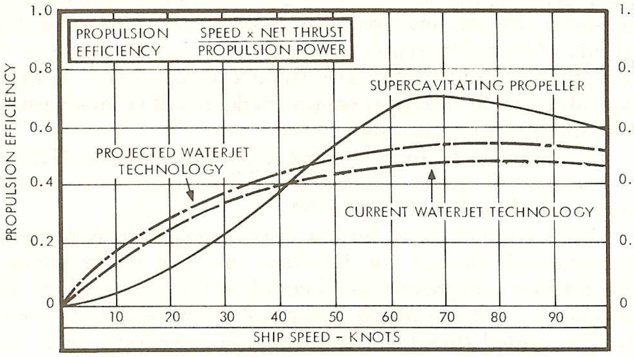


Fig. 32 Propulsion efficiency

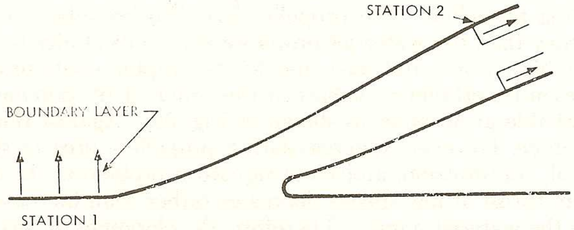


Fig. 33 Flush waterjet inlet boundary-layer control

For comparison purposes, the drag attributed to the installed propulsor is subtracted from the gross thrust to give the net thrust.

At the present time the waterjet is the preferred propulsor for SES. Propulsion efficiency with the current technology is shown in Fig. 32 in terms of ship speed. Selection of the system obtaining this efficiency is derived from tradeoffs related to machinery arrangements, ship weight, and endurance. The propulsion efficiency is a function of the component efficiencies of the jet, inlet, pump, exit nozzle, and power transmission. In order to increase this value, improvement in all or some of the foregoing elements is necessary. Since no significant improvement is expected for transmission and nozzle efficiencies, the remaining areas for improvement in the next decade are jet, inlet, and pump efficiencies.

Jet efficiencies, in general, are known to increase with a decreasing pump headrise for a given flow rate. However, higher flow rates require a greater volume of water aboard ship. Waterjet tradeoff studies characteristically optimize for lesser flow rates and higher pump headrises. No significant efficiency increase in this area is projected.

A potential of about 3 percent increase in pump efficiency is predicted, primarily based on improved knowledge of pump internal flows, improved surface finish, and minimizing tip flow leakages.

A promising area for improved performance is the waterjet inlet. Current nominal cruise ram recovery is about 74 percent at cruise speeds with the flush inlet. Ram recovery is defined as the total pressure at the end of the inlet less the freestream static pressure—both quantities divided by the freestream dynamic pressure. Flow losses caused by internal flow diffusion are responsible for much of the loss. Some improvement might be expected with the introduction of boundary-layer control at Stations 1 and 2 of Fig. 33. The boundary-layer removal at Station 1 could be transpirational suction and at station 2 could be tangential slot jet injection. At both these stations, such energization of the boundary layer decreases separation losses and improves static pressure recovery. Improvements in the inlet variable geometry are also anticipated to improve the flow at all ship speeds. Overall increases in ram recovery of the order of 15 percent are being sought with these developments. Utilization of variable nozzle concepts could simplify mechanization and improve reliability.

As a result of the foregoing, an overall propulsion efficiency increase of about 7 percent can be expected at typical cruise speeds as shown in Fig. 32.

Thrust augmentation for a waterjet propulsion system can be achieved through air injection into the water stream. Gas turbine compressor bleed could be the source of the injection air. The resulting two-phase blow condition would provide added thrust by increasing jet velocities. Any potential increase in thrust, in principle, will produce an increase in propulsive efficiency. Many developments in this field are being pursued at the present time.

An alternative to the waterjet propulsor is the supercavitating propeller. The propeller has a higher inherent efficiency than the water-jet propulsor due to its ability to handle high flows and also due to its simpler configuration. Presently, efficiency values in the order of 68 percent are available at 80 knots as shown in Fig. 32. Against this advantage, however, supercavitating propellers present structural, transmission, and noise signature problems. In addition, thrust at low speeds decreases rather than increases, as for the waterjet pump. Therefore, development of this concept will inevitably stress priorities other than performance.

The waterjet system is not optimum for both low-speed and high-speed operation. The pump favors high-speed operation with a resultant sacrifice in fuel consumption at lower speeds. A two-pump system (one with a high head, low flow for high-speed operation and one with a low head, high flow for slow-speed operation) could augment overall system efficiency at the price of complexity.

The concept of the pulse-jet propulsor for operating efficiently at both high and low ship speeds is another possible development. The primary feature of this concept is the variable water flow rate which is adjusted to ship speed to provide maximum efficiency operation at all ship speeds. Similarly, a switch to total ramjet operation similar to the thrust augmentation outlined in the foregoing could reduce the use of rotating machinery at high power levels. Such devices have been successfully tested in the past, but only in small sizes.

Lift system

SES lift system efficiency is defined as

$$\frac{\text{Cushion pressure} \times \text{flow rate to cushion and seals}}{\text{shaft power}}$$

The losses in the lift system include duct friction, bends, area changes, orifices, valves, and lift fans. With current technology, lift system efficiencies range from 60 to 75 percent. Potential design improvements include the following:

1. More responsive stern seal to reduce air escape at stern of ship.
2. Improved duct designs.
3. Improved fan designs, having efficiencies of over 90 percent. Potential improvements include better fan-housing design and the application of flow control methods using Coanda principles such as the jet flap and circulation control devices.

As a result of the foregoing improvements a lift system efficiency of 78 percent is considered attainable.

In addition to improving the lift system efficiency, there is considerable scope in reducing the required flow rate to cushion and seals. According to the scaling laws, flow rate is in proportion to cushion area and the square root of cushion pressure. There is potential reduction in the flow rate by:

1. Reducing the normal leakage beneath the seals and sidewalls.
2. Reducing additional flow rate required to attain an acceptable ride quality in a sea state.

These flow rate reductions may be achieved by better seal design and better fan controls or heave attenuation valves, or both.

From these considerations it is concluded that, with continued development, the ratio

$$\frac{\text{Lift system power, shp}}{\text{Gross weight, tons} \times (\text{cushion pressure, lb/ft}^2)^{1/2}}$$

might well be reduced from its currently attainable value between 1.1 and 1.2 for a 5000-ton SES to about 1.06.

Light ship weight

The structural weight of SES craft as constrained by current technology and economic considerations represents 25 to 30 percent of full load displacement. Also, machinery, auxiliary systems, and other light ship outfit incur a weight fraction in the order of 20 to 25 percent. On this basis, the operating utility of the craft must be evaluated on the basis of 45 to 50 percent weight fraction for fuel and payload weight. Considering future developments, it is anticipated that some reduction in the light ship weight fractions will be provided by technological advances with resulting improvement in the fuel and payload capability. In the machinery area, improved power density will be provided from metallurgical advances and other gas turbine and propulsor-related developments. In the auxiliary systems and other outfitting areas, some weight reduction may be anticipated from the development of improved electrical power generators, air-conditioning plants, and improved methods and material for distributive systems. It is anticipated, however, that the most significant single reduction in light ship weight fraction will result from improved methods of structural analysis, increased understanding of allowable safety factors, improved production techniques, and particularly the economic feasibility of utilizing advanced composite and other ultrahigh-strength materials.

The structural weight fractions just discussed are related to the utilization of modern high-strength marine-grade aluminum alloy materials. Although many materials offering improved performance are presently available, their utilization is constrained by limited experience in large-scale applications in a marine environment and by economic considerations.

The improved performance offered by advanced materials is shown by the strength density comparison in Table 6.

It must be noted, however, that the full utilization of the properties exhibited in Table 6 is constrained by elastic modulus considerations in structural elements which are buckling critical.

Table 6 Candidate SES hull materials

MATERIAL	YIELD STRENGTH/ DENSITY
Aluminum alloy	420,000
HY-130 steel	460,000
Titanium alloy	750,000
Glass-reinforced plastic	820,000
Advanced composite (limited application)	3,900,000

A preliminary study of the influence of the discrete utilization of advanced materials in large ships shows that a reduction in the structural weight in the order of 10 to 12 percent may be reasonably anticipated within the 1980 time frame. This weight reduction represents a reduction in the structural weight fraction to about 23 to 25 percent, depending upon craft performance, hull geometry, and operational environment considerations. On this basis, it may be considered that SES of 5000 tons gross weight will have a fuel-plus-payload weight of about 2800 tons with projected technology developments.

Performance

The two drag components of the SES that can be reduced to the greatest extent over the next decade are the sidehull and seal drags. The latter was discussed earlier, and the drag reductions will be twofold:

1. Reduced contact area, associated with better seal response.
2. Reduced drag coefficient, associated with presenting a better hydrodynamic shape to the water.

Sidehull drag reductions, although less in scope than with seals, can be substantial. Improved hydrodynamic shaping of the sidehull to accommodate the unique flow patterns and requirements for stabilizing forces will be the main source of drag reduction.

The anticipated reductions in ship drag for a representative 5000-ton SES operating in sea state 3 are shown in Fig. 34. The figure shows that a total drag reduction of about 5 percent in the 80 to 100-knot range in sea state 3 is predicted. This improvement would increase the maximum lift/drag to a little over 25. Negligible reduction in hump drag is anticipated.

The projected increases in efficiency of both the propulsion and lift systems, together with the foregoing drag reductions, will result in a significant reduction in the required total installed power (Fig. 35). The figure shows an anticipated reduction in power of about 10 percent for the 5000-ton SES over the cruise speed range.

The projected reductions in installed power and structural fraction, together with lower equipment weight, will result in a substantial reduction in light ship weight. For example, if the projected improvements are attained, the light ship weight of the 5000-ton SES capable of operating at 80 knots in sea state 4 would be reduced by about 150 tons or 3 percent gross weight. The weight saving can be used to carry additional fuel for improved range, additional payload, or a combination of the two (Fig. 36). The figure shows for example that the 5000-ton SES cruising at 100 knots in a sea state 3 could have its operating capability improved from 1000 tons payload and 2670 nautical miles range to 1100 tons payload and 3200 nautical miles range. At the short-range/high-payload edge of the envelope the improvement is small, being mainly due to the light ship weight reduction, but for long range/low-payload, operation, benefit is also obtained from the increased cruise efficiency. The projected 5000-ton SES has a full oceangoing operating capability.

Projected economics

The projected improved operating efficiencies discussed would result in significant reductions in direct operating costs of commercial SES. The latter are presented in Figs. 37, 38, and 39 for a family of craft having gross weights from 100 to 1000 tons. In comparing these direct operating costs with those utilizing current SES technology given in Figs. 24, 25, and 26 respectively, the measure of improvement lies between 6 and 10 percent.

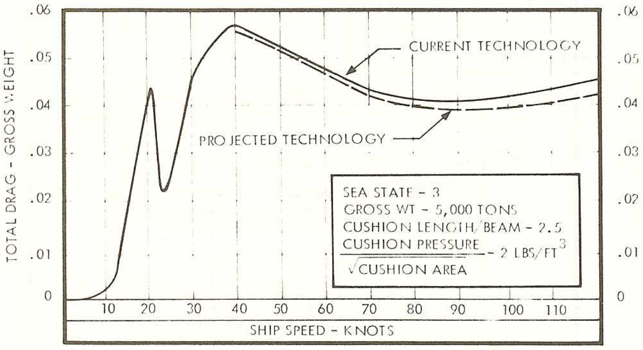


Fig. 34 Projected SES drag projection

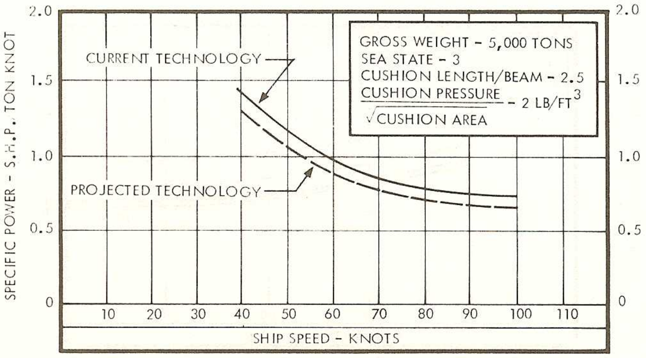


Fig. 35 Projected SES power reduction

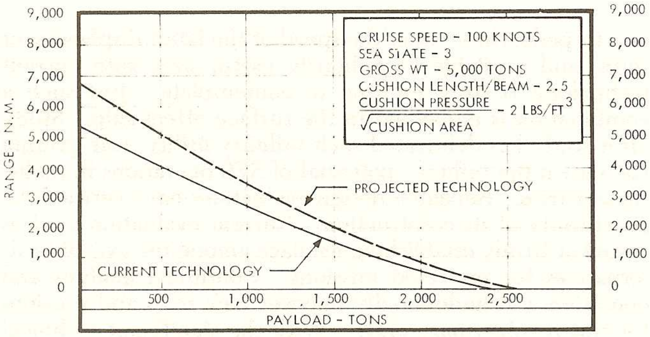


Fig. 36 Projected SES range vs payload

The first costs, installed powers, and design cruise conditions of some of the projected commercial SES studied in preparing Figs. 37, 38, and 39 are given in Table 7.

The reductions in direct operating costs do not change any of the conclusions discussed earlier. The commercial SES studies show competitive operating costs, particularly over the longer stage lengths of 50 nautical miles or more. The optimum size of SES within the scope of this study is any gross weight between 500 and 1000 tons, provided the ride quality is acceptable and a high load factor can be realized. Over the longer stage lengths, a cruise speed of at least 60 knots is required for best operating economics. Rough-water SES operations in sea state 4 or higher are economic with gross weights of 500 tons and greater.

Applications

Naval applications

The potential of a surface ship capable of twice the speed

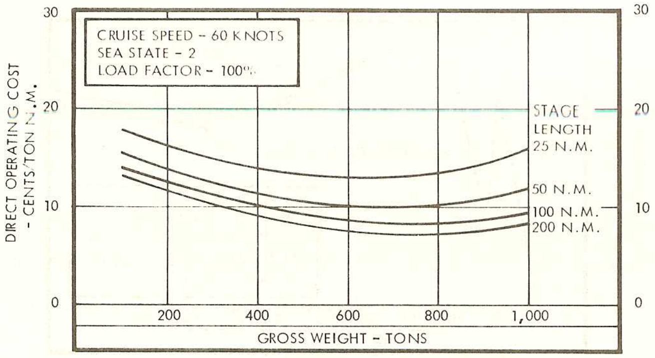


Fig. 37 Projected SES operating cost vs gross weight

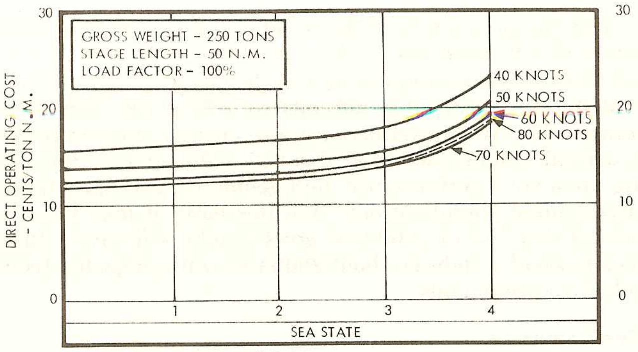


Fig. 39 Projected SES operating cost vs sea state

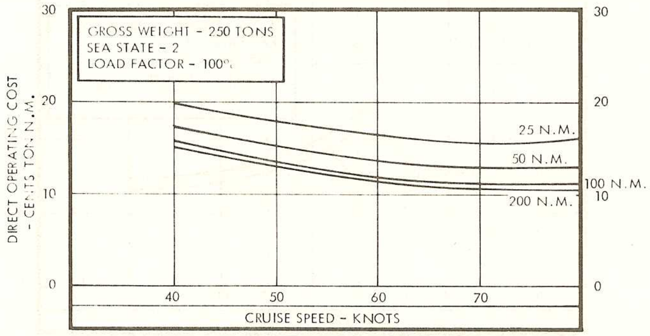


Fig. 38 Projected operating cost vs cruise speed

of a torpedo, three times the speed of the latest displacement ships, and available in militarily useful sizes with current technology is truly exciting to contemplate. Just such a combination is embodied in the surface effect ship. Study after study has delineated such military utility; war gaming has shown the military potential of SES operations in realistic scenarios. Repeated design evaluations have verified the practicality of its construction. Current evaluation work is aimed at firmly establishing its place among the available alternatives for projected missions. Continued analysis and operation will undoubtedly uncover new roles and missions for this revolutionary craft. With the significant technical advances and verifications achieved to date and a conservative assessment of improvements forseen for the near term, as presented in this paper, ships for various missions can be envisioned. In order to avoid problems of classification, reference to specific weapons and sensors will not be made. In some cases, the weapons and sensors for the application are not presently being developed, but all are considered feasible.

The prime missions of today's Navy are strategic deterrence, projection of power ashore, naval presence, and sea control. Only the surface ship offers capability in all of these areas. However, the great emphasis placed on the development of other vehicles during the past 30 years has left the surface ship at a speed and operational disadvantage inconsistent with its potential.

To realize this potential, the best available technology must be employed. Primarily what is needed is speed; the surface effect ship can provide this speed without sacrifice of operational utility. In the following paragraphs, the SES is examined in each of the cited roles.

The strategic deterrent role requires the largest and most unique displacement ships. In order to be able to perform an effective strategic strike, the ship must be capable of carrying and launching either long-range aircraft, large ballistic missiles, or cruise missiles similar to the now obsolete Matador and Mace weapon systems. In the case of surface effect ship, this would require vessels in the over-5000-ton class; these probably could not be initiated until smaller, transoceanic SES are evaluated. Further, this mission is now adequately covered by a combination of SSBN's and aircraft carriers. In view of this, it is not expected that SES would be used in the offensive mode for strategic deterrence. It would, rather, be more effective to employ it as a counter-offensive weapon. For this application, the role of the SES would be surveillance and quick reaction antisubmarine, anti-SLBM operations to counter preemptive strikes. For this purpose, antisubmarine weapons are available today and the launching of SLBM's would be sufficient provocation to initiate counter-offensive tactics. The anti-SLBM system is yet to be developed.

In the projection of power-ashore role, SES provides the Navy with the ability to react quickly over long distances to a remote area. For strategic resupply of high-value cargoes, an all-SES convoy would have markedly reduced vulnerability to submarine attack. Utilizing remotely piloted vehicles, the SES could provide both convoy and landing surveillance for amphibious forces.

Table 7 Basic assumptions for projected commercial SES

Gross weight, tons	100	250	250	250	250	250	250	250	250	500	1000
Payload, tons	30	80	80	80	80	80	80	80	80	200	405
Design speed, knots	60	40	50	60	70	80	60	60	60	60	60
Design sea state	2	2	2	2	2	2	0	3	4	2	2
Installed shp	6,200	11,600	11,800	13,000	14,700	18,600	11,000	15,000	21,700	24,200	48,400
First cost, $M	2.07	4.47	4.52	4.68	4.95	5.54	4.36	5.00	6.03	8.93	17.00

Naval presence is both the most nebulous and, possibly, the most useful mission assigned to the Navy in peacetime. Dating back to the days of gunboat diplomacy in the 1800's it has been a method of deterring potential enemy action and enhancing an ally's position. Admiral Zumwalt stated in a speech earlier this year that one of the most significant factors in forcing the decision by Israel to release the Egyptian Third Army was the superiority of the Russian Navy in the Mediterranean. Were we able to deploy a significant force of antiship missile-equipped SES, a different posture is evident. This could have been accomplished with continental U.S.-based ships in less than 2½ days, including refueling once at sea.

The final mission, and the one finding the most immediate application with currently sized SES in the 2000-ton class, is that of sea control. The U.S. economy is structured upon a high-quantity, multiple-commodity trade basis. With the exception of foodstuffs and coal, major raw materials are significant import items. Leading these imports in criticality in time of conflict are petroleum products. For this reason, long vulnerable sea lanes must be maintained open and convoys protected from marauding submarines.

It is in the convoy protection role that the speed advantage of the SES over the submarine proves its value. The submarine, which must come to the convoy, can no longer engage and disengage at will. Once detected, this option will now lie wholly with the SES. By operating its own helicopters (which is currently planned for the 2000-ton class), it can attack multiple threats. It can act as a refueling ship for helicopters based on convoy ships, greatly extending their range and effectiveness. The SES can employ sprint-and-drift tactics to search out and destroy attacking submarines while permitting the convoy to advance at its maximum possible speed.

Its quick reaction time; relative invulnerability to torpedoes and mines; reduced susceptability to missile attack due to high-speed maneuverability; and its ability to loiter, either on or off cushion, combine to provide potential improved effectiveness in all remaining sea control tasks currently assigned to surface combatants of similar size. Studies have clearly shown this advantage. It only remains for the first ships to verify it in practical operation with the fleet.

Commercial applications

Two commercial applications are immediately seen for surface effect ships:

1. High-speed ferries capable of carrying passengers and cars.
2. Utility craft for offshore oil rig servicing.

The predicted scope of these two operations is given in Table 7.

Using the data shown in Fig. 37, it is readily apparent that small SES of less than 200-tons gross weight do not offer nearly the same economies as the 400-ton craft. Likewise, any SES operating at stage lengths of 25 miles or less cannot fully reap the benefits of its high speeds. Commercial ferry SES operations, therefore, will be successful only on routes where travel time is an important factor and the stage length is long enough to take advantage of the craft's speed capabilities. Some of the early history of ACV development bears this out. Many of the smaller-craft operations were short lived. The only really successful large-scale application is the SR.N4 operation across the English Channel where appropriate speed, payload, and turnaround characteristics can be demonstrated.

Since the inception of offshore oil drilling, industry activity has gradually moved away from the shoreline to more distant locations offshore in search for oil. Simultaneously, the craft which supply these platforms and rigs have undergone evolutionary changes, growing larger, faster, and more sophisticated as the distance offshore increases.

Table 8 Predicted scope of commercial SES operations

	PASSENGER FERRIES	OFFSHORE UTILITY
Gross weight, tons	100 to 500	100 to 200
Payload	Passengers and cars	High-priority cargo
Routes, nautical miles	25 to 200	50 to 200
Location	High population densities	Offshore drilling areas
Speed, knots	50 to 80	50 to 80
Sea state	Up to sea state 4	Up to sea state 4

There are basically two types of cargo which must be transported to these platforms: high priority, which includes passengers, food, specialized tools, service company equipment, etc.; and regular cargo, which includes drilling mud, cement, water, and pipe. Two types of vessels have evolved to serve these needs. A 100-ft aluminum planing hull capable of carrying 70 passengers and 20 tons of deck cargo at 20 knots was developed for the high-priority market. The bulk cargo is generally carried by a 200-ft steel displacement boat capable of carrying about 1000 tons of cargo. Because of the increasing distance offshore, the 20-knot aluminum craft is used less to transfer crews. This task has been largely taken over by helicopters. The planing hull still makes daily high-priority cargo runs.

Today, many drilling rigs are operating some 150 to 200 miles offshore in the Gulf of Mexico. The 100-ft supply boat is reaching the limits of its capability. In some cases 10 to 12-hr one-way trips are required to send high-priority items to the drilling rigs. These rigs cost some $25,000 to $35,000 per day to operate and any downtime is extremely costly. An obvious need exists for a new craft to make the daily high-priority cargo trips to these platforms. SES craft are believed to be excellent candidates. Because of the payload requirements of 50 to 100 tons or more, an SES in excess of 200 but less than 400 tons gross weight would be required. This craft would be able to demonstrate optimum economics because of the long routes and daily trip requirements.

Table 8 shows that the offshore oil operations are expected to be with SES of a relatively narrow range of ship designs based upon the known high-priority cargo requirements of existing platforms. The commercial ferry size range is a wider band, for payloads of 50 to 250 tons would be able to demonstrate the full economic benefits and meet the needs of the passenger routes. One interesting point is that a craft of 50 to 100 tons payload capable of 50 to 80 knots would satisfy both applications.

Conclusion

Based upon the present status of its technology, the surface effect ship is expected to be prominent in high-speed marine operations. The requirement for high-speed marine craft, which has stimulated the development of the many types of craft discussed in this paper, is undisputed for both naval and commercial operations. Of the candidate surface marine systems considered herein, each is limited either in speed, size, or both, with the exception of the SES.

Full-scale operations have demonstrated both the performance and reliability of the advanced design features of the

SES. Further developments during the next decade should ensure improved cost effectiveness.

The anticipated lower cruise speed for economic SES operations is about 35 knots, where it is bounded by SWATH and displacement ships. Larger SES of intermediate speed will be of the high length/beam configuration. Smaller SES will not be in direct competition with hydrofoil craft and planing hulls due to the difference in speed range. The largest potential of the SES, however, appears to be in large-payload, high-speed open-sea operations, for which there is no direct competition in sight.

Acknowledgment

The authors wish to thank the U. S. Navy and Rohr Industries for permission to publish this paper. The surface effect ship data contained herein are largely based upon results from the U. S. Navy Surface Effect Ships Program under the direction of Captain Carl Boyd, USN, whose encouragement is appreciated. All opinions expressed, however including the conclusions given with regard to the projected operating domains of the competitive advanced ships, are strictly those of the authors.

Particular thanks are expressed to the many colleagues in the U. S. Navy and Rohr Industries who have provided numerous valuable inputs and criticisms to the paper.

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