Some Special Problems in Surface Effect Ships

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An engineering analysis of the captured air bubble, surface effect ship concept identified developmental task areas in structural design, seal design, sidewall design, and propulsion and their relationships to the mission, ship arrangements, ship performance, and stability and seakeeping. No specific block to technical feasibility was uncovered. The SES can operate at or near the air-sea interface at speeds significantly above those for operational displacement-hulled vessels. It may require, however, a signficant range/payload capability, economical operation, small turning radius, survivability in severe storms, a mission profile with diverse operational requirements, life of many years with low maintenance, or unusual seakindliness during normal operation. Operations analyses suggest an island-hopping procedure similar to that of aircraft. Structural weight is critical. Inflatable flexible seals offer possible control advantages. Sidewalls, when designed for significant buoyancy, present a nontrivial hydrodynamic design problem. A planform suggested by Hydronautics Inc., offers a promising solution to potential cavitation problems. High over-all propulsion efficiency is a major requirement.

Introduction

SUCCESSFUL design of the captured air bubble (CAB), surface effect ship (SES) depends upon detailed knowledge of many characteristics. Preliminary studies show that obtaining an optimum design is a complex problem with a number of variables. This paper deals with some design aspects which are largely unique to SES and, in particular, CAB. Some problems appear readily solvable whereas others are related to elusive factors such as human creativity, current and projected level of technical development, cost of advancing technology, and the associated risks involved.

The desired characteristics for CAB include seakeeping qualities and survivability under exceptional circumstances, stability and controllability, versatility and flexibility of utilization, and economy of operation. Economy of operation is influenced by lift-to-drag ratio, propulsive efficiency, maintainability, reliability, useful load fraction, range requirements, etc. In the final analysis, it is economy, expressed in military terms as cost effectiveness or in commercial terms as cost per ton-mile, that decides success or failure. All the other desired characteristics are attainable if economy is sacrificed. For example, controllability can be achieved by introducing control surfaces and thereby increasing drag, or survivability by increasing structural weight and thereby reducing load fraction.

This paper deals with some of the important SES parameters that influence the characteristics of the ship, and reveals some unique problems in the design and analysis of the SES and its major subsystems. Reference 1 is recommended for further reading.

Configuration

The general ship arrangement and shape are shown in Fig. 1. Rigid sidewalls project down from the sides of the main hull and deflectable seals transverse the bow and stern. These appendages are normally in contact with the water and, together with the bottom of the hull, form the bubble cavity. Air for the bubble is supplied by blowers (typically, the pressure required is greater than the ram air pressure). Main engine exhaust is an alternate means of pressuration. This configuration is for waterjet propulsion, but alternate means are considered later. The length of bubble L_B, breadth of bubble B_B, and height of hull H_H are indicated in the sketch. L_B and B_B combine with the bubble pressure P_B to give the design parameters L_B/B_B and P_B/L_B. The relative planform geometry associated with these parameters is shown in Fig. 2, and Fig. 3 provides an absolute meaning of these parameters.

Figure 2 applies to a 4000-ton ship and values of L_B, B_B, and P_B are given for ranges of L_B/B_B and P_B/L_B. As an example, with $L/B = 2$ and $P/L = 1$, bubble length is 262 ft, bubble breadth is 131 ft, and, from the dashed line, bubble pressure is 262 psf. The planform geometry can be visualized directly by the rectangle formed by the zero ordinate, zero abscissa, and the orthogonal lines connecting the design point to the axes. Limitations on these dimensions are imposed by stability, volume, and over-all beam.

Structures

With performance characteristics resembling an airplane, the weight of the SES structure is of great significance, and conventional ship design practices need to be reconsidered to an extent that is not now clear. As an example, the structural safety criteria, which include design safety factors and specifications on the amount of damage the ship can sustain and still survive, may be considered. Comparing the structural safety criteria of ships and airplanes suggests an intermediate specification which allows economical operation of the SES with suitable survivability and lifetime.

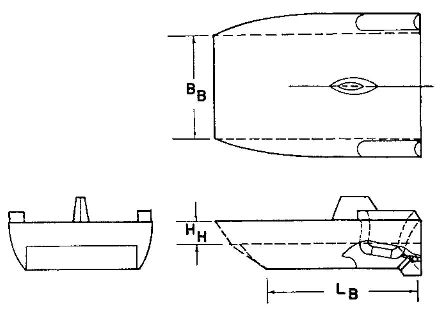

Fig. 1 Basic configuration.

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Table 1 Relative structural weights for compression panels

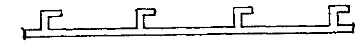
Material \ Panel Construction	Single Skin Stiffened	Sandwich	Relative Cost Factor
Ti 6AL-4V		.26	(10)
181 Glass Reinforced Epoxy		.28	(.6)
17-7 PH		.29	(2)
7075-T6 Clad		.30	(1)
5456-H343		.46	(1)
181 Glass Reinforced Epoxy	.52		
7075-T6	.53		
5086-H34		.54	
5456-H343	.59		
5086-H34	.65		
Ti 6AL-4V	.70		
17-7 PH	.99		
HY-130	1.00		
HY-80	1.06		
200 Maraging	1.10		

Possible structural materials appear to be high-strength steel, stainless steel, aluminum, titanium, and composites. Of these, aluminum alloys and glass-reinforced plastic (GRP) composites appear particularly attractive. The 7000 series aluminum alloys are preferred on a strength basis. However, weldability, corrosion resistance, and stress corrosion cracking susceptibility are poor for 7075, 7079, and 7179 alloys. The 7039 and X7106 alloys hold the greatest current promise; both may be readily welded to themselves and to 5000 series alloys. For sidewalls, 5083 and 5086 alloys are acceptable. Above the waterline (e.g., main hull) 6061 alloys may be suitable. 181 GRP holds exceptional promise if structural designs can be used which are technically beyond current fiberglass shipbuilding procedures. A problem with GRP composites is panel fatigue strength under repeated impact. Another is low modulus of elasticity. These problems, however, do not appear insoluble.

Weight/strength properties of candidate materials have been investigated for the ship's plating. The compressive and shear stresses in the sidewall and hull plating require thin sheet panels over a large portion of the ship. These panels would then be limited in design strength because of buckling. Slamming forces, particularly in the forward areas of the ship, provide design criteria for panel bending. Optimization, therefore, involves stiffener and frame sizes and spacings, as well as thickness of the panel skin. In general, the optimum stress for single-skin panel construction is much lower than yield stress, whereas double-skin (sandwich) construction would be optimum near the compressive yield of the facing material.

Each type of panel construction must be optimized separately before comparisons can be made. Possible types to consider are

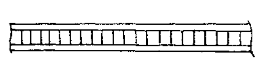
1) Single-skin stiffened panels:

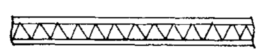
a) Sheet—strinter 

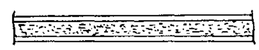
b) Sheet—corrugated 

c) Integrally stiffened 

2) Double-skin panels:

a) Box core or honeycomb core sandwich 

b) Truss core, or corrugated sandwich 

c) Foam core sandwich 

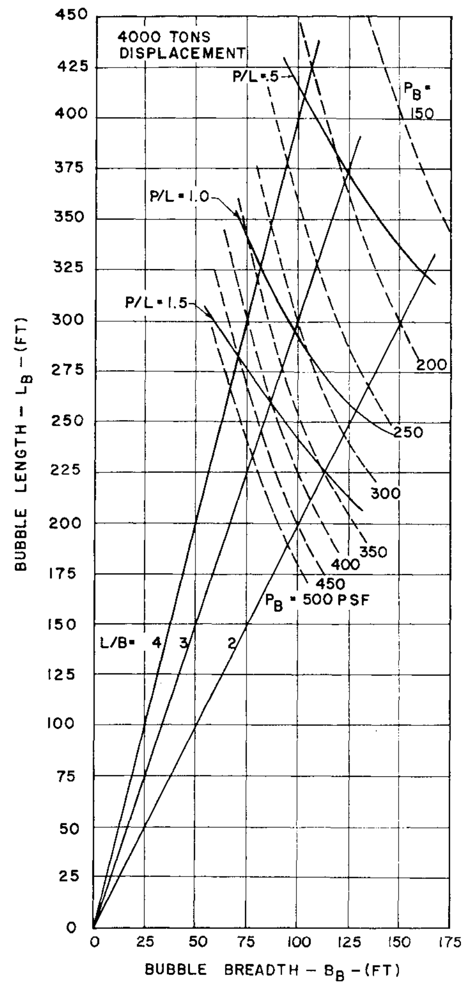


Fig. 2 Geometric identities.

For materials evaluation, preliminary weight/strength calculations were made for a simple stiffened panel and for a sandwich design. Relative weights for panels constructed of various materials are shown in Table 1, using an HY-130 stiffened skin design as reference. Sandwich construction is the lightest with GRP and aluminum alloys the most promising. Sandwich construction using titanium alloy is the most efficient, but cost may be prohibitive and it appears that the optimum facings will be too thin to resist puncture or other damage. This is also true for the 17-7PH stainless steel sandwich design.

Broadening the scope of the structural design, representative considerations will include design criteria parameters, configuration parameters, loading parameters, and structural design variables. The variables of primary concern in this paper are L_B/B_B and P_B/L_B. Hull depth is also considered for its effect on structural weight and drag.

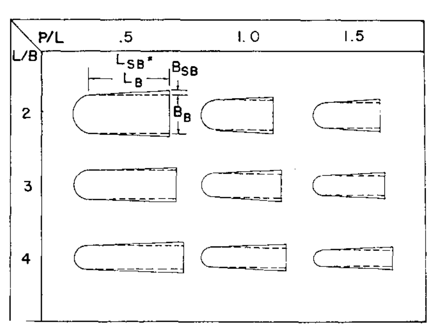


Fig. 3 Relative planform.

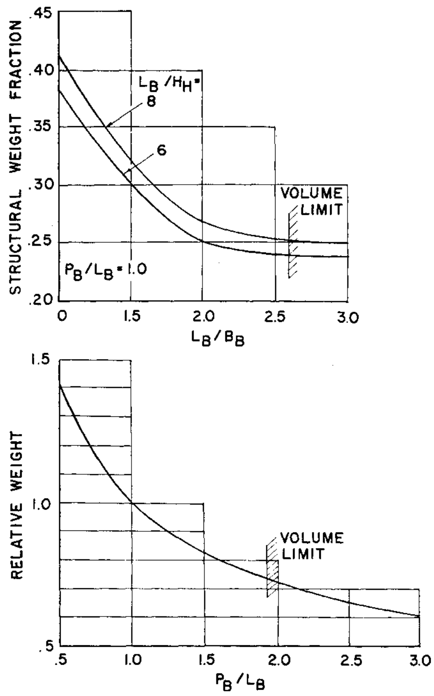


Fig. 4 Weight parameters.

Weight parameters for a 4000-ton CAB constructed of 5086 aluminum alloy are shown in Fig. 4. In preparing such data, a major unknown is the proper bow region slamming load, which has a large effect on the structural weight. Figure 4 was based on approximately 15-psi pressure in the nose plating and results in a weight fraction of about 0.25. This increases to 0.35 if designed for peak slamming pressures of 300 psi. Methods of alleviating effects of wave impact and slamming loads on primary structure, through forward seal or additional shock-absorbing systems, should therefore be investigated further.

Sidewalls

The sidewalls of a CAB, for the most part, give the craft the characteristic mode of behavior which differentiates it from a ground effect machine (GEM) craft. Basically, in CAB, an attempt is made to minimize flow of air in the lateral direction at the cost of adding hydrodynamic drag due to the wetted sidewalls. The seals, of course, deal with the fore and aft flow. Solely from this point of view, the advantages of CAB ships over GEM craft are open to discussion. However, properly designed sidewalls add advantages to CAB ships which are not shared by GEM craft.

For structural reasons, sidewalls cannot be designed as flat thin sheets and even a minimum practical width for a large craft insures that the sidewalls will have a considerable buoyancy when the ship is "off the bubble." Therefore, the additional weight penalty is small in designing the sidewalls to displace the full weight of the ship. These voluminous sidewalls offer some definite advantages. First, as discussed more fully in the section on propulsion, they can accommodate the complete propulsion system, from intake to pumps, at the lowest possible elevation. Second, the sidewalls add flexibility to the mode of operation which may vary from fully flying, with maximum bubble pressure and a minimum of immersed sidewalls, to full displacement with the sidewalls carrying the full weight of the vehicle. This latter involves low-power, low-speed operation with the ability to ride out heavy storms.

Sidewall design offers some serious challenges. At high speeds (70 to 100 knots), cavitation may be a serious threat to sidewall structure. Figure 5 shows a candidate profile. The upper water lines (*WL*) are a modified parabolic shape developed by Hydronautics Inc., and the lower waterlines show aft thickening to accomodate the waterjet propulsion system. Under zero yaw, this shape should be relatively free from cavitation, although yaw will still lead to cavitation of the leading edge. With the ship on bubble at very low speeds, the sterns of the sidewalls, even though they are blunt, should become fully ventilated and, therefore, base drag is practically eliminated. To be investigated are the conditions under which ventilation occurs for various depths of sidewall immersion. If propulsion is by waterjets located at the stern of the sidewalls, the jets will aid in producing ventilation at low speeds.

Another problem, related particularly to the flying mode, although also important for the displacement mode, stems from the relationship between sidewall shape and size and parameters such as controllability, maneuverability, stability, and seakeeping. This must be considered in relation to overall control and stability. The sidewalls play an important role here. For example, with the ship configuration shown, the air bubble does not contribute to stability in roll or pitch. Therefore, this task devolves upon the sidewalls together with the seals, and possibly other appendages may be necessary.

Seals

Providing good fore and aft seals for the SES poses a most challenging task. A brief review of some of the important seal characteristics is given below.

Bubble Leakage

The purpose of the seal is to prevent or limit air leakage fore and aft of the air cushion. Leakage can occur at the interface between sea and seal, between sidewall and seal, between seal elements, and through punctures or faults in the real. Most likely leakage is at the interface between sea and seal which must be closed without introducing undesirable characteristics.

Drag

The seal drag is composed of viscous drag, form drag, wavemaking drag, and spray drag. For most reasonable sea designs the Froude number is so high that the wavemaking drag is small. For many shapes, spray drag can be reduced by adding a ski device at the bottom. Aerodynamic drag of the forward seal is significant and should be considered in evaluating seals with irregular plan view shapes such as scallops.

Dynamic Response (Seal/Hull)

The dynamic response characteristics of the seal and interactions with the ship's motions are perhaps in most serious conflict with the requirement of sealing in the bubble air. It is necessary to compromise between a very stiff spring rate or a highly loaded seal which can keep the gap closed but provides a hard ride to the ship and increases seal drag, and a more flex-

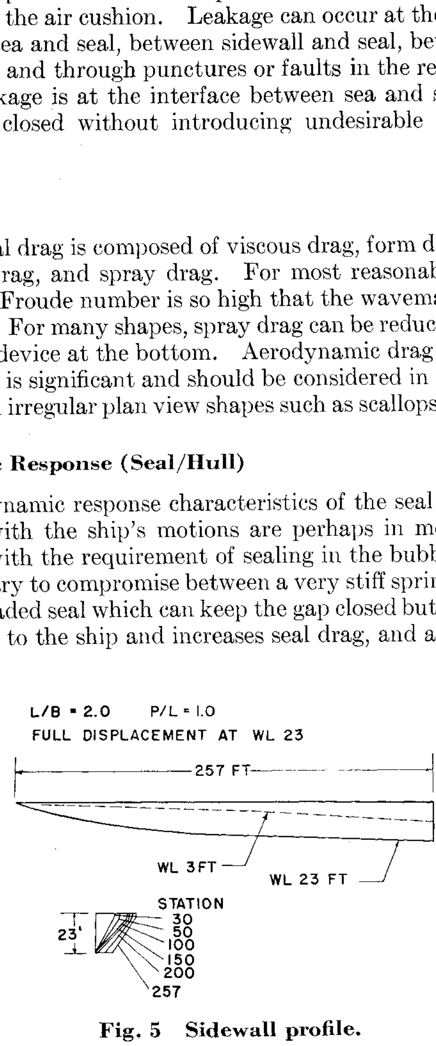


Fig. 5 Sidewall profile.

ible seal which softens the ride but will not have sufficient response to keep the gap closed. (The compromise is similar to the automobile suspension problem.) The accelerations required to follow waves without hopping are readily obtainable. Based upon Cockerell,[2] Fig. 6 shows the magnitude of seal acceleration required to prevent "hop" leakage as a function of wave height and speed. Note the high acceleration requirements associated with low waves which decrease with wave height and ship speed.

Simplicity and Maintainability

Economics suggest simple, easily maintained seals. Seals with replaceable or serviceable segments are particularly desirable. Complex supporting systems (e.g., hydraulic or pneumatic types) are less simple and maintainable.

Damage Resistance and Operational Survivability

Resistance to damage bears significantly upon seal selection. A related consideration is that a partially damaged seal be able to continue operation even though degraded. Damage may be caused by fatigue, cavitation erosion, corrosion, deterioration, and impact with foreign objects.

Controllability and Power Required

Certain seal configurations, through control of buoyancy, extension and spring rate, provide some control in pitch, heave, and roll. The power required to achieve equivalent degrees of control varies somewhat due to variations in the efficiencies and masses involved.

Sensitivity to Bubble Pressure

Related to controllability is the relationship between seal characteristics and cushion pressure which should be known and considered in seal selection, ship stability, and ship operations.

Compatibility with Sidewalls

Two means of joining the front seals to the sidewalls are considered. One is to fair the seal around and smoothly into the sidewall; the other is to bring the seal adjacent to the side of the sidewall so that it is free to respond to wave action. In the latter case, flexible membranes may be used which are fastened to the seal end and the sidewall to give a positive seal at that point.

Motion Independence between Adjacent Sections

To conform to any but unusual wave conditions, some amount of variable seal compliance is required. Each transverse element of the seal meets its own wave form. Ideally, adjacent elements should be independent; however, practicalities of cushion sealing causes some interaction, which, however, can vary significantly between seal concepts.

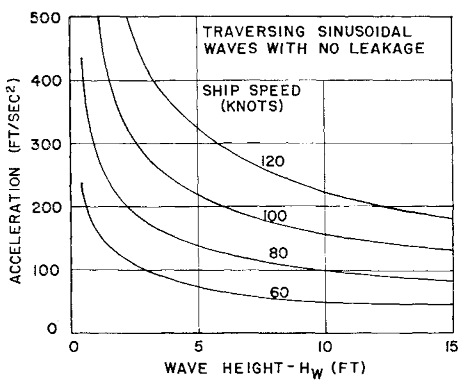


Fig. 6 Seal acceleration requirements.

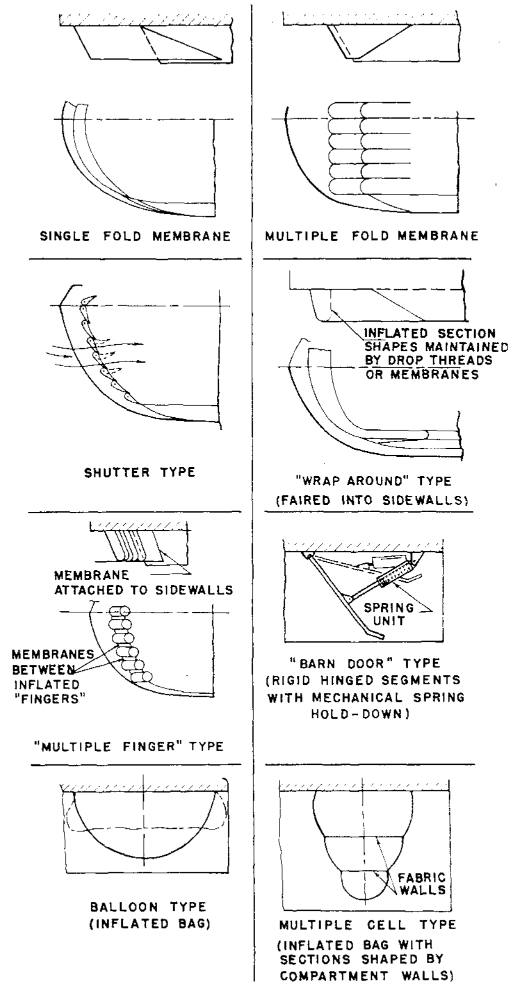


Fig. 7 Seal concepts.

Adaptability to Wide Size Range

Although a nominal 4000-ton ship has been considered here, ships from below 50 tons to over 20,000 tons are envisioned. The adaptability of the seal to function over a wide range of sizes is thus desirable though not essential. Figure 7 is a sampling of general seal types, each of whose operation is self-evident. Applying the aforementioned criteria to each brings to light some severe shortcomings and limitations.

Propulsion

The selection of the best propulsion system for the SES focuses on marine gas turbine engines for primary power and either water screws, air screws, or waterjet as the thrustors. However, if studies of high-pressure, high-temperature nuclear reactors bear fruit, their horsepower-to-weight ratios will make them very attractive for primary power. The high-speed marine diesel should also be considered. Its major disadvantage is a specific weight nearly ten times that of the gas turbine. In its favor is a currently better thermal efficiency than the gas turbine (by about 50%) which, however, may not be true with the next generation of marine gas turbines. In this application, where weight and efficiency are considered to be critical, the gas turbine appears the most suitable.

In propulsion system selection, it is also necessary to match components and make proper subsystem selections. Then remains the task of sizing and selection in context with over-all ship optimization.

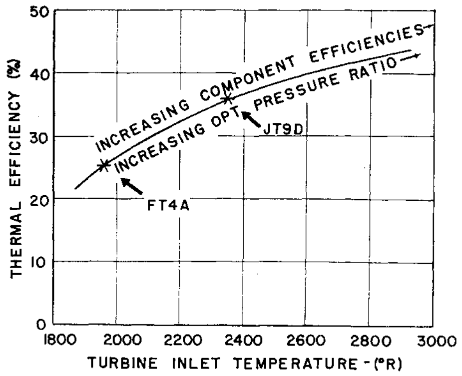


Fig. 8 Engine efficiency.

Within marine gas turbine primary powerplants, there are a number of considerations in selection, improvements, modifications, and installation. For the 4000-ton ship, the Pratt and Whitney FT4 engine is a contemporary example of a highly suitable powerplant. It is an adaptation of the J-75 jet engine with a free power turbine modified for marine applications. Its over-all thermal efficiency is 26% at normal continuous rating with growth potential to 29%. Improvements in the thermal efficiency are suggested by the Pratt and Whitney JT9D turbojet engine developed for the C-5A airplane, which has an over-all thermal efficiency, exclusive of bypass, of 36 to 38%. Thermal efficiency as a function of turbine inlet temperature (compressor power turbine) is shown in Fig. 8, with points for the FT4 and JT9D indicated. To follow the efficiency line shown, assumptions are made with regard to improving component efficiencies and increasing compressor pressure ratios. A consideration which must not be overlooked here is the performance potential of the regenerative cycle gas turbine. Here, penalties in weight, development cost, complexity, reliability, overhaul cost, and installed volume must be compared against its high thermal efficiency. The comparative evaluation of regenerative and nonregenerative cycles presents a challenging problem.

Some interesting free turbine modification possibilities present themselves for specific installations. One possible installation advantage is the ability to separate the gas generator from the free turbine which, in effect, substitutes hot gas ducting for a mechanical drive. An attribute of doing so is the possible elimination of mechanical angle drives.

At common power turbine rotational speeds, a speed reduction gear box is required to match a propeller or a pump. Considerations of changes to the power turbine to match rotational speeds appear appropriate, in spite of development costs, possible added weight, and lowered efficiency.

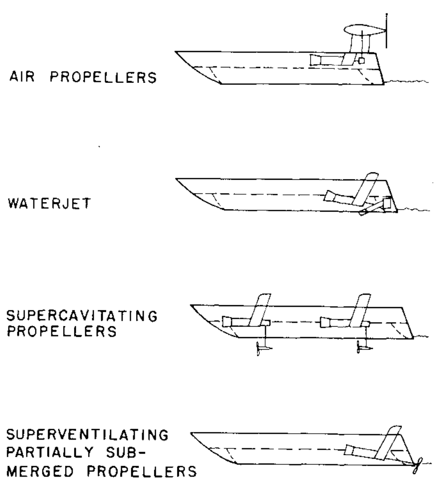


Fig. 9 Basic thruster types.

The installation aspects of locating the engines deep in the sidewalls, taking in air and exhausting the combustion gases, present interesting possibilities. With waterjet propulsion, partially submerged superventilating propellers, and possibly supercavitating propeller, the desire to close-couple the engine and the thruster leads to locating the engines low in the sidewalls. This compromises the design with respect to widening the sidewall and possibly compromising its hydrodynamic characteristics. An additional factor is the amount of accessibility provided and the ease of removal which lead toward widening the sidewalls. Some advantages are realized by installing the engine at an angle to the horizontal. Against doing so are the bearing and lubrication problems and the need, for large angles, of additional development.

Between 70 and 100 knots, recovery of the stagnation air pressure will increase engine performance. Unfortunately, at these speeds white and green water tends to travel in the same direction (relative to the ship) as the air. Eliminating or reducing water intake by changing inlet shape and orientation and including mechanical separators reduces or eliminates the ram recovery. The location of the inlet on the ship and its height has effects on water ingestion. It may be possible to pressurize the main propulsion air intake system from the bubble blowers and use the excess pressure for water separators or filters. There are usually disadvantages to combined systems, however, especially in case of a failure.

It is possible to compile a list of inlet design variables and to evaluate configurational compromise, performance, and weight as decision factors. The engine exhaust has considerations similar to those of the inlet.

The basic thruster types considered are depicted in Fig. 9. With the air propeller, the engine can be remotely installed in the hull as shown or directly coupled through a gear reduction box if a nacelle is used. Remote installation has the disadvantage of mechanical complexity with two right angle gear boxes and a long intermediate drive shaft. The thrust axis will produce a negative pitching moment.

A waterjet can be located in the stern of the sidewalls or aft of the main hull with a penalty in inlet duct losses and weight. The greatest uncertainty and potential problem in waterjet development is the water inlet and ducting. Factors in inlet-duct design include weight (including captured water), added drag, pressure recovery, internal and external cavitation, total head losses in the ducting, flow uniformity at the pump intake, and air ingestion. All must be considered over a large speed range, over a large mass flow range, and with engine "out." Conflict exists between these factors and between ship design and some desired inlet characteristics. For instance, an inlet designed for optimum pressure recovery and minimum duct pressure loss may add unduly to ship drag and weight. Studies and test programs, considering all factors, whose objective is an optimum inlet system, are important.

To accommodate a wide range of mass flows at high speed without cavitation, a variable inlet area will probably be required. The alternative of a large radius inlet leading edge will add measurably to the drag. A problem of pump cavita-

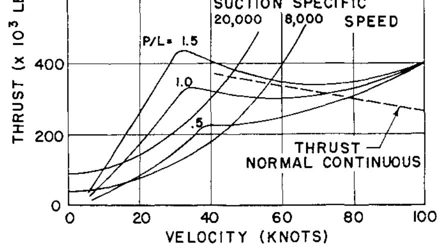


Fig. 10 Thrust available and drag, waterjet propulsion.

tion in waterjet propulsion is depicted in Fig 10. To operate under some conditions without cavitating, it is necessary to limit flow rate and hence thrust. Performance lines of limiting thrust are shown at suction specific speeds of 8,000 and 20,000. (Suction specific speed is a measure of the ability of a pump to operate efficiently under incipient cavitating conditions.) A critical performance region exists just below and around the hump speed. An inability to accelerate past hump speed is, in fact, indicated under several combinations of ships and pumps. The obvious solution of increasing specific suction speed, unfortunately, must also consider the expense of lowered pump efficiency. Operation of the pumps for a short time while cavitating is not uncommon in rocket engines, although pump life is shortened. Alteration of the drag level in the hump region may provide a solution.

Supercavitating propellers show promise on the basis of potential efficiency. With horizontal engines, two right-angle drives are required. Retraction may also be required or desired as indicated by Booz-Allen Applied Research.[3] Blades are subject to cavitation erosion and leading edge fatigue failures, but the design created by the USN David Taylor Model Basin for the Maritime Administration's Dennison hydrofoil ship may have solved the latter problem.

The partially submerged superventilating propeller is relatively new. Here, the low-pressure side of the blade experiences pressures closer to atmospheric than cavitation, resulting in a propeller which is efficient over a wide operating range.

In the CAB configuration, two propellers are installed, one at each bottom aft end of the sidewalls. A ship with eight engines will thus have four engines driving each propeller through shafts, an aggregating gear box, and speed reduction gears. The mechanical problems are at once evident. Also periodic loading of the blades presents problems in blade fatigue, habitability, and ship's structural excitation, although these can be reduced by increasing the number of blades.

To facilitate a "first cut" analysis of different propulsion systems, an over-all efficiency has been established as the ratio of thrust-work-out to fuel-energy-in. At a given speed and power, therefore, this over-all efficiency is inversely proportional to the fuel flow rate. It does not directly include variations in drag associated with the installations. Figure 11 gives the results at 70 knots. The reference turbojet case is for an engine of 42% thermal efficiency without bypass and without afterburning.

Drag

The drag of CAB craft is greatly affected by variations in design, especially bubble geometry and bubble pressure. Much attention has been given to a proper evaluation of this drag. Estimates shown in Figs. 12a–12e have been calculated using a method which is essentially that of Chaplin and Ford.[4] They are based on the following assumptions: 1) the side-

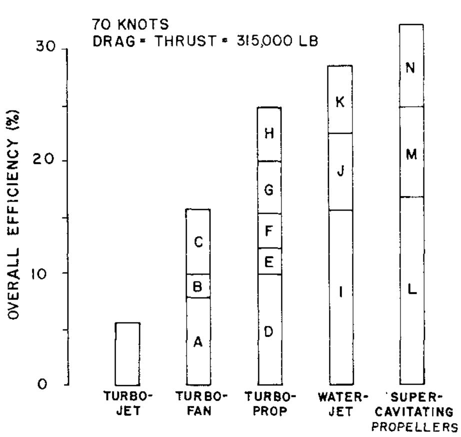


Fig. 11 Over-all propulsion efficiency.

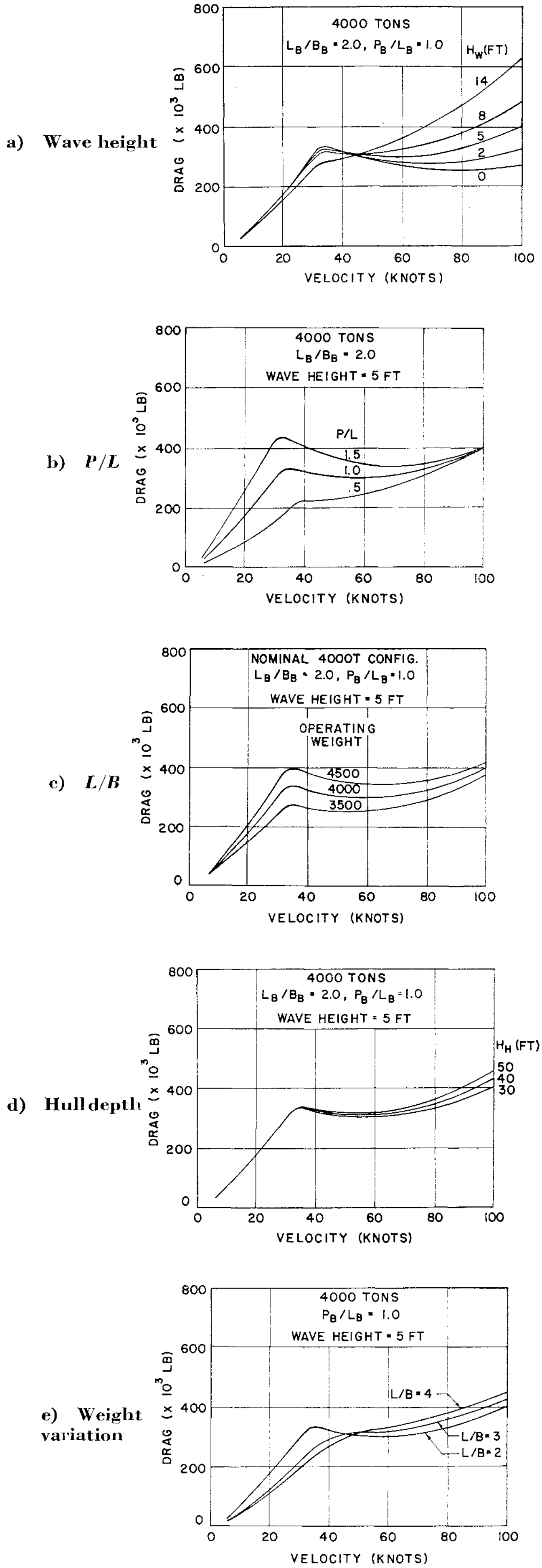


Fig. 12 Drag curves.

Table 2 Route analysis for selected ports

Selected routes	Block distance, naut miles	Block time, hrs (wave height = 5 ft, V_0 = 85 knots)	Payload, tons (5 ft)	$W_p{}^a/T_B$ (5 ft)	Block time, hrs (wave height = 20 ft, V_0 = 60 knots)	Payload, tons (20 ft)	$W_p{}^a/T_B$ (20 ft)
From SFO to Saigon	6878	80.92			114.63		
Via: Wake	7459	89.76	645	7.18	126.32		
Guam-Midway	7397	91.02	1118	12.28	127.28	583	4.58
Guam-Wake-Honolulu	7733	96.98	1342	13.84	134.88	901	6.68
From SFO to Tan Shui (Taiwan)	5611	66.01	57	0.86	93.52		
Via: Midway	5779	69.99	1018	14.54	98.32	443	4.51
Wake-Midway	6226	77.25	1118	14.47	107.77	583	5.41
Wake-Honolulu	6495	80.41	1298	16.14	112.25	838	7.47
Guam-Wake-Honolulu	6934	87.58	1342	15.32	121.57	1039	8.55
From N.Y. to Bremen	3614	42.52	740	17.40	60.23	49	0.82
Via: Plymouth	3636	44.78	993	22.18	62.60	407	6.50
Azores	3913	48.04	1436	29.89	65.22	1035	15.87
From N.Y. to Said	5105	60.06	55	0.65	85.03		
Via: Gibraltar	5105	62.06	939	15.13	87.03	331	3.80
Gibraltar-Azores	5125	64.29	1436	22.34	89.42	1035	11.57
From N.Y. to Capetown	6801	80.01			113.35		
Via: Luanda-Porto Grande	7286	89.72	1077	12.00	125.43	525	4.19
Ascension-Porto Grande	7290	89.76	1077	12.00	125.50	525	4.19
Ascension-Georgetown	7384	90.87	1133	12.46	127.07	604	5.76

[a] W_p = payload, T_B = block time, W_p/T_B = average productivity in tons per hour.

wall submergence is just sufficient to prevent bubble leakage, 2) the trim angle of the sidewall is equal to the arc tangent of the bubble drag-to-lift ratio, 3) bubble pressure is adjusted to compensate for the buoyancy of the immersed portion of the sidewall, 4) the aerodynamic lift and seal lift is 5% of the total lift, 5) the aerodynamic drag coefficient of the hull above the waterline, C_D, equals 0.5 (this is for a well-streamlined SES), and 6) the momentum and energy penalty associated with the bubble air is neglected.

Figure 12a is for a ship of nominal $L_B/B_B = 2$ and $P_B/L_B = 1$. The curves show the effect of wave height, particularly at high speeds due to the larger wetted area at the sidewalls. At lower speeds drag reduces with wave height. The paradox is due to the complicated relationship between bubble lift, sidewall lift, bubble drag (wave drag), and sidewall (viscous) drag.

Figure 12b shows the effect of varying pressure-to-length ratio P_B/L_B. This ratio has the most noticeable effect on the hump drags at 30 to 40 knots where the drag is predominantly bubble wave drag. With increasing speeds, differences in drag decrease until at 80 to 100 knots there is little difference at various ratios of P_B/L_B. Lower values of P_B/L_B are preferable because drag at any increase of speed is always lower over the whole speed range up to 100 knots. However, referring to Fig. 2, it is seen that lower bubble pressures are associated with larger dimensions, lower ship structural densities, ineffective use of available volume, and heavier structural elements for a given total all-up weight. The choice then apparently is between small efficient craft with high hump drags (with associated problems of hump cavitation, etc.) and larger less efficient craft with lower hump drags. Preliminary studies indicate that it may be possible to combine the best features of these two.

Figure 12e shows the effect upon drag of varying length-to-beam ratio L_B/B_B. For values of L_B/B_B considered, this parameter does not affect the drag as significantly as does P_B/L_B.

Figure 12d shows the variation of aerodynamic drag with the depth of the main hull. This is useful in determining the "best" hull depth, when used in conjunction with other hull-depth criteria such as structural weight, stability of the vessel, and cargo volume requirements.

Figure 12c shows the effect on drag of varying operating weight for a configuration designed for 4000-ton operation. The most noticeable effect occurs at hump speeds which lessen as speed increases.

Some interesting features emerge when lift-to-drag ratios are calculated for different operating weights. Considering first the speeds for minimum L/D in the flying mode (best cruise speeds), the best cruise speed increases markedly with increased weight so that on a typical mission the ship can be maintained at best cruise speed by decelerating as fuel is consumed and the vessel lightens. The actual minimum L/D values decrease by approximately 4% for a weight change from 3500 to 4500 tons. At 80 knots there is a 10% increase in L/D and at 100 knots an 18% increase. (These values may be considerably different for other configurations.)

The curves shown in the aforementioned figures indicate the relative effects that various parameters have upon drag. However, a number of uncertainties currently limit accurate estimates of absolute values of drag. There is, as always, the question of scaling (due to viscous effects) from data obtained for experiments with small-sized models. The estimation of viscous drag of the sidewall in the presence of waves is only approximate because of lack of knowledge of boundary-layer build-up as the wave sweeps the sidewall. Seal drag estimates are taken from trunk estimates for ground effect machines. Relative characteristics might be quite different, however, especially under large wave deflections when the seal's contribution to drag will be large. A valid estimate of aerodynamic drag is probably dominated by the contribution of the front seal/bow and the bases, and these are a strong function of specific shape in the proximity of the ocean. Addition of an equivalent drag to allow for the blower system is important (frequently guessed to be 10% of total drag), although the very nature of the CAB SES lays open the question of the blower requirement. Hopefully, leakage and, hence, blower power might be low enough under some sea conditions to add negligibly to the over-all power required.

Route Analysis

In typical ship operation with conventional hulls, nonstop routes are established between the ports of origin and destination. The SES, as compared to a conventional ship, has an L/D approximately one tenth as large and a thrust specific fuel consumption about two times as large. The obvious implication is that for the SES the versatility of nonstop operations is severely curtailed. This ship has, in fact, range characteristics more nearly like those of an airplane. That strategically located refueling stops will be desirable is a natural result of this evaluation.

An analysis has been undertaken to quantitatively evaluate specific routes and possible refueling bases in order to determine reasonably correct nonstop range requirements for the SES so that meaningfull tradeoff analyses can be made.

Five specific and representative terminal port groups were selected and missions were analyzed for these routes, considering both nonstop and intermediate refueling stop operation. A 4000-ton ship was postulated with a total useful load fraction of 0.60 allocated to fuel or payload in any proportion. A nominal condition with a significant wave height of 5 ft and a cruise speed of 85 knots was selected. An extreme condition with a significant wave height of 20 ft and a cruise speed of 60 knots was added to check conclusions. The information generated is shown in Table 2.

The block distance shows that addition of intermediate refueling stops undesirably increases the total distance covered. Block times were computed assuming short 2-hr refuelings. Ship's payloads which resulted from the analysis (including 10% fuel reserve) are shown in the third column. They are established by the longest port-to-port distance, including refueling stops. The payload-flow parameter, payload/block time, is shown in the next column. It includes compensation for the disutility of longer block distances and layover times for refueling stops. From Table 2 it may be readily seen that great increases in payload and consequent decrease in cost per ton-mile is achieved in spite of an increase in block time between port of origin and port of destination. Of equal importance, the calculations show that the longest leg of the most productive route to the ports examined is 2400 naut miles in the Pacific and 2800 naut miles in the Atlantic. These figures significantly affect over-all design of the vessel by reducing the range requirement heretofore assumed to be 3500 to 4000 naut miles.

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