Captured Air Bubble (CAB) Vehicle Progress Report

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The Captured Air Bubble (CAB) is a sidewall air cushion vehicle (ACV), a high-speed waterborne craft that is inherently nonamphibious. Some general vehicle comparisons are shown, as well as parametric results pointing to the need for large multi-thousand-ton surface effect ships (SES) to fulfill transoceanic requirements. Then comparisons of theoretical drag predictions and experimental CAB drag data are made, in smooth water and in straight-ahead waves. Because the CAB has large structural members, the sidewalls, in direct contact with the water, there is a unique opportunity for the utilization of high-speed water propulsion systems. A comparison of air propeller and waterjet propulsion systems is then made. The waterjet shows significant efficiency advantages, particularly for the medium "hump" speeds, and this in turn allows CAB vehicles to have a higher specific loading for a given installed power. There is a structural advantage to this higher specific loading, but a slight power disadvantage. A sample tradeoff is then made to indicate profitable design trends.

General Vehicle Comparison

THERE are two principal contenders for the high-speed surface effect ship (SES) class of vehicle. The first is the full-peripheral skirted hovercraft developed by the British; the second is the sidewall captured air bubble (CAB) vehicle which has received a less extensive in-house Navy development. For intermediate speeds, in large sizes there is also an interest in high length/beam ratio air cushion vehicles (ACV's). The term "surface effect ship" (SES) was first used several years ago by the Maritime Administration, in studies performed by them. As used here, SES simply implies a "large" or "ship" size ACV, regardless of specific configuration.

Figure 1 shows an artist's concept of a 4000-ton SES propelled by a waterjet propulsion system. The specific configuration shown in neither the full-peripheral skirted ACV nor the full-sidewall ACV, but a hybrid of the two, with skirts extending around to the aft portion of the vehicle.

Development of the full-peripheral skirted hovercraft or full-peripheral skirted ACV (Fig. 2) has occurred within the last 10 years, principally in Britain. The most significant design trend in the last four to five years has been the introduction of flexible trunks or skirts; this feature has allowed a reduction in the so-called "daylight gap," the distance between the water and the soft structure, and an increase in the distance between the water and the hard structure. These craft are likely to be amphibious, that is, to have over-the-beach capability, and, further, they are likely to be associated with air propulsion systems. The national program in the United Kingdom for about 10 years, together with commercial incentive, has brought this craft to an amazingly advanced state of development for this time period.

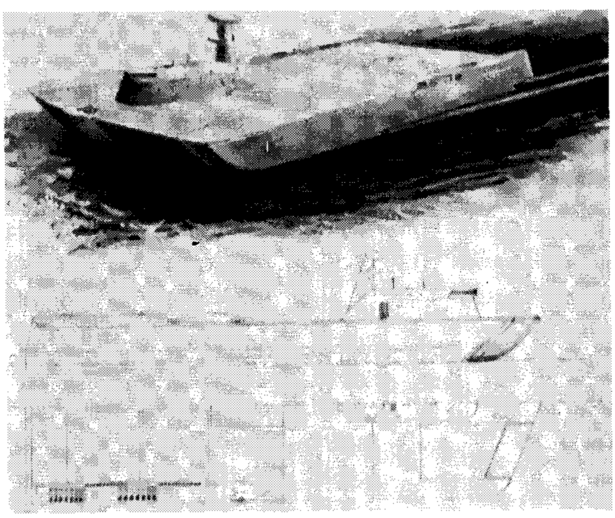

Fig. 1 Artist's concept of 4000-ton surface effect ship (SES).

Like the full-peripheral hovercraft, the captured air bubble or CAB sidewall craft (Fig. 3) is supported on a pressurized region of air beneath the craft. This pressure region is retained by sidewalls and mechanical or fabric seals fore and aft. In this case, the fan power is likely to be less than in the full-peripheral hovercraft case, but in both classes of vehicles there is a potential for sea-state alleviation, that is, a potential for an essential platforming action in which the body of the vehicle moves along relatively straight and level, with a very highly dynamic performance of the fore and aft seals. This platforming action occurs when operating in short waves and/or at high speeds, so that the frequency of wave encounter is high. In very long waves, and especially at slower speeds, the craft will contour the waves. A second characteristic of the CAB class of vehicle is a potential for utilizing the sidewall volume to install propulsion and machinery systems of the water propulsion type. Because of its sidewalls, the CAB is not amphibious. Water-propulsion systems may show propulsive efficiency advantages, but their use restricts the craft to water operation, although running half up on a beach would be possible with proper seal and sidewall design, such as that shown in Fig. 1.

Compared to the full peripheral skirted hovercraft, the CAB has had rather limited development. Most of the work has been done since 1960 and principally within naval laboratories—the Naval Air Development Center, the Naval Air

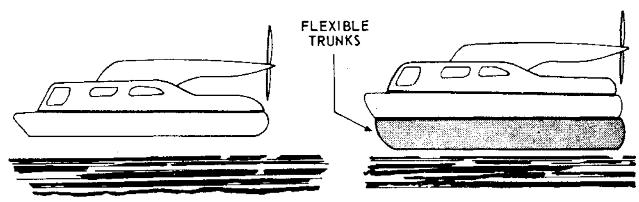

Fig. 2 Hovercraft design trend.

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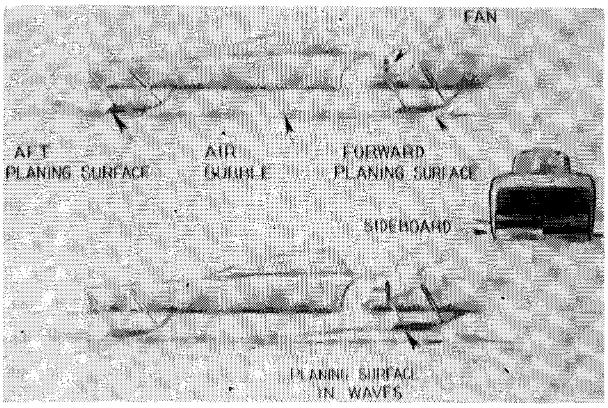


Fig. 3 Captured air bubble (CAB) sidewall air cushion vehicle (ACV).

Engineering Center, and the Naval Ship Research and Development Center (NSRDC) (formerly the David Taylor Model Basin).

In the summer of 1965, NSRDC performed a study of the technical feasibility of future high-speed Navy vehicles. Figure 4, taken from the results of this study, shows a comparison based on the weight-to-power ratio of various overwater vehicles as a function of speed for various weights. It is evident that the air cushion vehicles (ACV's) of both the full-peripheral skirted hovercraft (labeled GEM, i. e., ground effect machine) and the CAB (or sidewall) types show very advantageous (high) vehicle-weight/power characteristics at high speeds (50–100 knots, typically). For example, if speed and weight are held constant (100 knots and 10,000 tons respectively), there is a reduction of 5 to 6 in power required for the ACV relative to the comparable high-speed large displacement hull or ship. The ACV's of both classes show an attractive proximity to the well-known von Karman-Gabrielli line.[1] This is an empirical line drawn between aircraft and ships (ships meet the line about a decade above the upper limit of this chart). The relatively poor performance of craft other than ACV's at high speeds (e. g., 50–150 knots), as measured by their distance from the von Karman-Gabrielli line, has been referred to as the "naval gap." In this general sense, Fig. 4 shows that ACV's have a potential for doing much toward filling this existing high-speed overwater vehicle naval gap.

It is also evident from Fig. 4 that both ACV types show a substantial improvement with vehicle size, even for the calm water conditions given in this plot. Improvement with size would be even more marked in a rough sea.

For the full-peripheral hovercraft or ground effect machine, the daylight clearance was taken to be constant with size; hence the nondimensional daylight clearance was assumed to decrease with size. Some detailed features and limitations of these projections are discussed in Ref. 2.

The projections of Fig. 4 are based on the utilization of air-propellers for the ACV's with propeller areas taken as 20% of the base or cushion areas. Since the completion of the previously discussed study, the subject of high-speed, water-propulsion systems (waterjet and supercavitating propellers) has been investigated more fully. These high-speed, water-propulsion systems show substantial promise over air propellers, at least for the CAB sidewall ACV craft.

Payload fraction as a function of range in nautical miles for a CAB vehicle is shown in Fig. 5. Vehicle gross weight or displacement is treated parametrically from 100 to 20,000 tons, with corresponding vehicle velocities listed. If transatlantic ranges (3000–4000 miles) are required, and it is desired to have reasonable payload fractions of the order of 25–30%, the intersection region in Fig. 5 calls for craft of the 2000- to 5000-ton category.

Figure 6 shows speed as a function of gross displacement of the craft for various sea conditions. It is seen that the design-determining condition turns out to be the case of high (State 6) seas. A special importance is attached to the capability to maintain a good speed in a State 6 sea because it is estimated to be the worst sea state that a high-speed ship need ever encounter, making use of modern sea-state forecasting and taking advantage of the more reliable route planning made possible by higher speeds. Moreover, a State 6 sea need be encountered only over short distances, on the order of 100 miles. If a good speed is maintained, it should be practical to drive ahead through the disturbed area at full power in a few hours, without prohibitive fuel burnoff. If a good speed could not be maintained, however, the full-power fuel burnoff would become excessive, and it would be necessary to reduce power and increase transit time to traverse the disturbed area at low speed. If a fixed, above-the-hump speed of 50 knots is taken as a minimum for the condition of a State 6 sea, Fig. 6 shows that a large vehicle of 3000 to 4000 tons is required.

The major problem areas that apply to new vehicle developments in general and to ACV's in particular are resistance (or lift/drag ratio L/D), stability, dynamic loads, structural weight fraction, and propulsion (efficiency and weight and reliability).

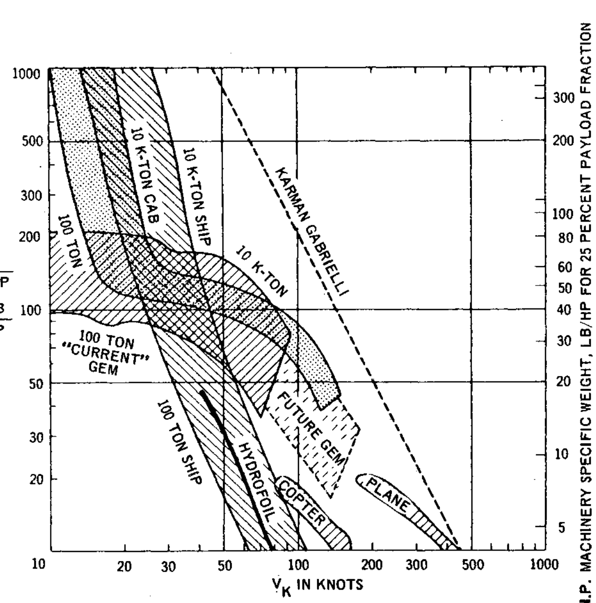


Fig. 4 Gross-weight/power ratio vs speed for various overwater vehicles.

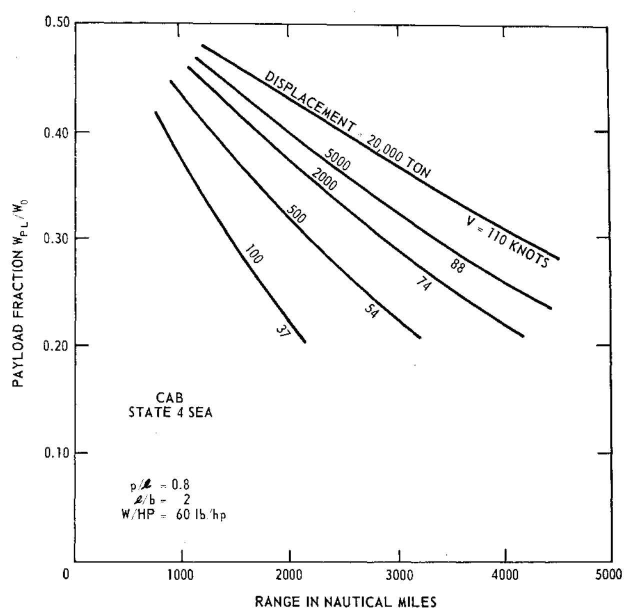


Fig. 5 Payload fraction vs range for various gross weights.

The remainder of this paper deals with specific technical information in two of these areas which was not available in the time frame of the studies that resulted in Figs. 4–6. The two areas are 1) resistance (or L/D) and 2) propulsion. The third topic, stability, is treated in Ref. 3.

Resistance

During 1966, tests of a 12-ft-long model of a 4000-ton CAB sidewall vehicle were conducted at the NSRDC high-speed towing tank at Langley Field, Va.[12] This model is shown as Fig. 7. It has fabric seals forward and mechanical seals aft; both respond very dynamically in waves relative to the body of the craft itself in waves in which the craft is platforming.

Figure 8 shows a significant comparison between theoretical drag-predictive methods and experimental results for smooth water conditions. It considers model drag as a function of model speed and compares a calculated theoretical prediction of drag to experimental values. The experimental points are shown as various shaped dots representing 1–4 blowers. In the 28-fps case (model speed), representing 87 knots for the 4000-ton CAB, the 1-, 2-, 3-, and 4-blower cases represent approximately 5, 10, 15, and 20% of the total vehicle power invested in fan or cushion power. Each blower represents a flow of approximately 350 ft^3/min. A comparison of the theory and experiment is valid only at speeds above the hump. The primary conclusion that can be drawn from Fig. 8 is that there is essential agreement (for smooth-water and with adequate fan power) between the experimental results and the theoretical drag and power predictive methods used in Fig. 4–6.

Figure 9a is a similar comparison for this model in 3.0-in. regular waves (6.5 ft full scale). Again there is an essential agreement between theory and experiment, provided that adequate fan power is present. There is, however, an anomalous effect that begins to appear, i.e., the best experimental points are above the theory at interim speeds, but they are below the theory at the highest speed, 32 fps (model scale) or 100 knots (full scale). The anomalous effect is still present in Fig. 9b, where the best experimental points at high speed are considerably better than predicted.

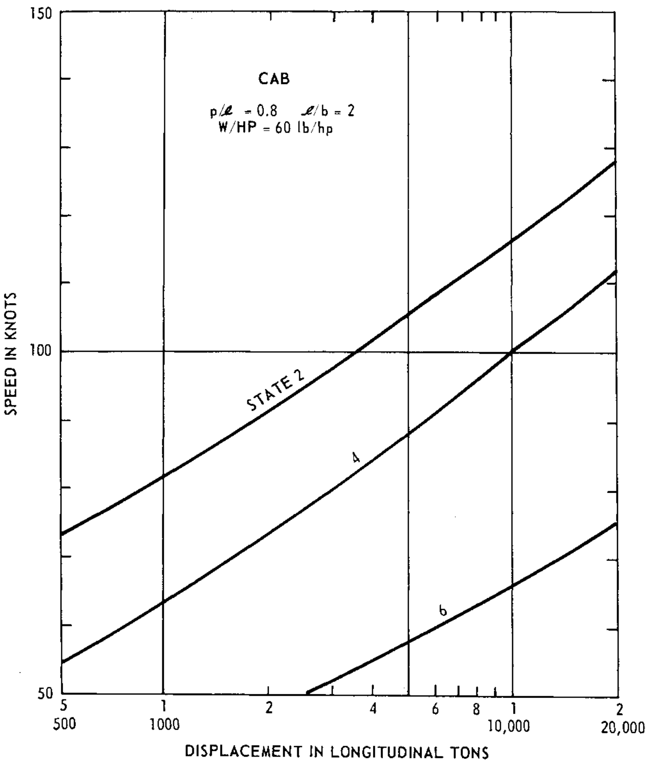


Fig. 6 Speed vs gross weight for various sea states.

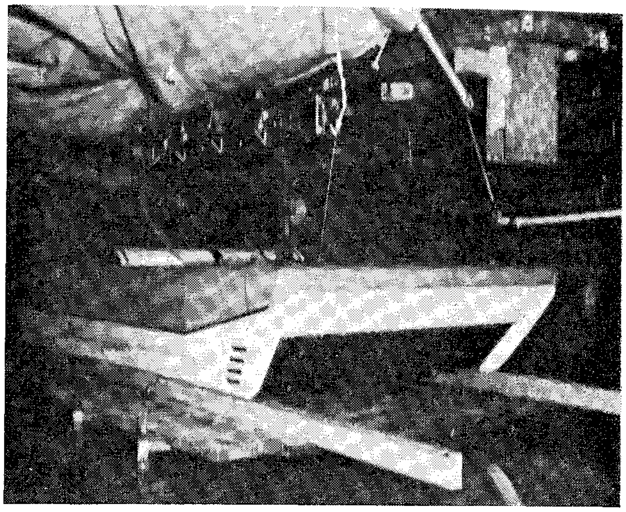


Fig. 7 CAB model (1/27.2 Scale) of a 4000-ton SES.

Propulsion

It was mentioned previously that the amphibious full-peripheral hovercraft would likely have air propellers; these are compatible with overland operation. The CAB, which is not amphibious, has a potential advantage in the use of high-speed, water propulsion systems. The propulsor, gears, and prime mover can be installed, partially or totally, in the sidewalls of the vehicle.

Figure 10 is a picture of a waterjet propulsor, together with a turboshaft engine and associated machinery installed in the sidewalls of a large CAB vehicle. The water is ingested at the bottom of the sidewall into an inlet-diffuser region. From here it moves through the waterjet pump and exits through a nozzle at the rear of the sidewall. It is significant that the duct lengths can be of minimum length with minimum bends; this allows the most favorable over-all duct loss coefficients without prohibitive water weights.

A computer program has been established on waterjets[4–8] as well as air propellers; vehicle drag and power characteristics are included.[9,10] Air propellers and waterjets can now be com-

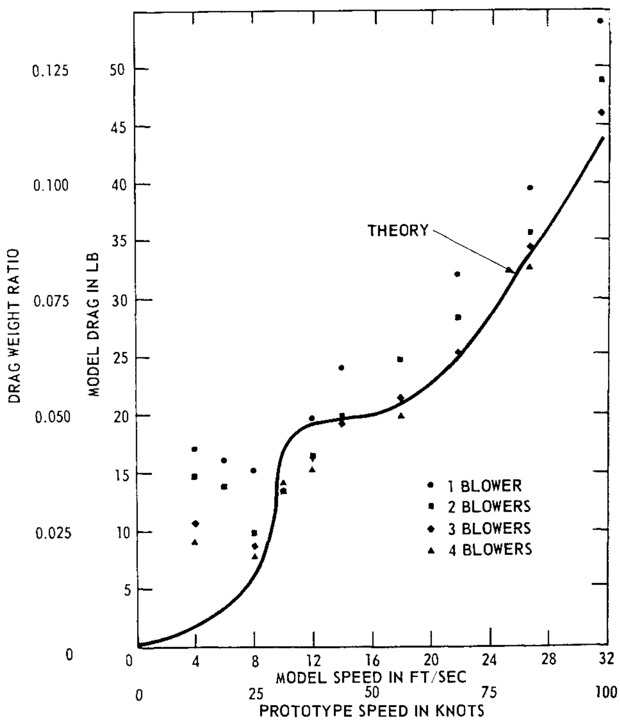
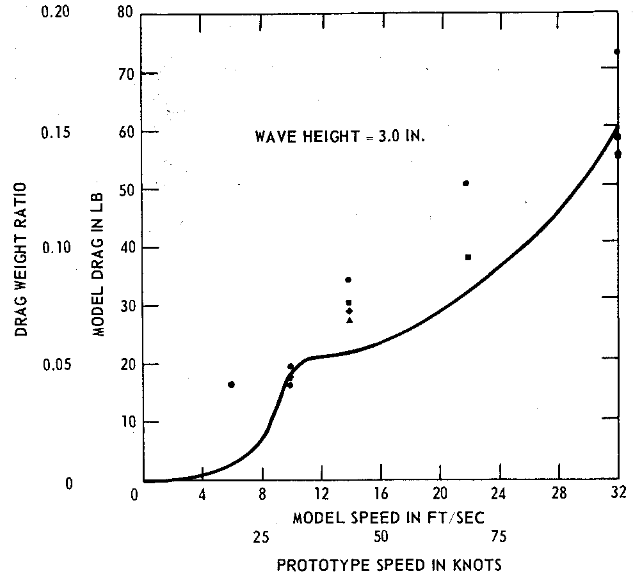
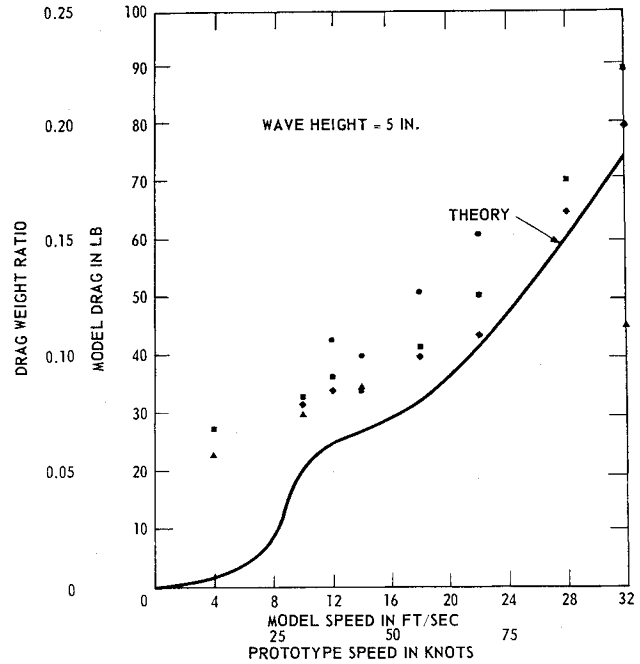


Fig. 8 Model drag results in smooth water.



a)



b)

Fig. 9 Model drag results in waves.

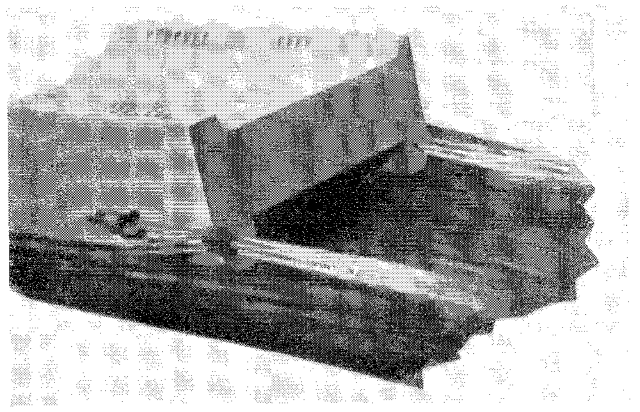


Fig. 10 Waterjet propulsion installation in a CAB sidewall.

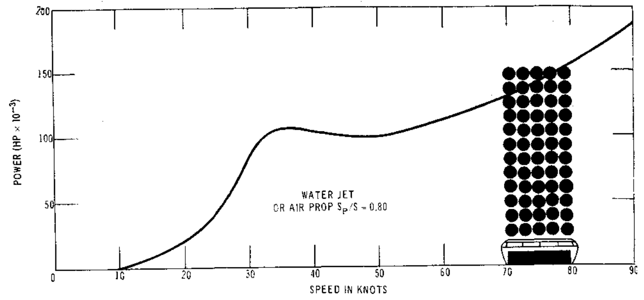


Fig. 11 Power vs speed for waterjet and for large air propeller array.

pared based on results of this program for a 4000-ton CAB vehicle.

Figure 11 shows shaft power vs speed, where the shaft power depends both on the vehicle drag characteristics as a function of speed and on the propulsive efficiency. This plot applies to waterjet propulsion of the type shown in Fig. 10 enclosed within the sidewalls. The same power results can be obtained for air propellers; but in this case, the propeller area must be absurdly large, 80% of the base or cushion area of the craft.

If more reasonable, but still large propeller areas are accepted (20% of base area), it can be seen from Fig. 12 that higher shaft powers are required because of lowered propulsive efficiencies. The efficiency drop is caused by the lowered air mass flow rate.

If more practical air propeller areas are considered (5% of the base area) as shown in Fig. 13 the propulsive efficiency loss is severe and results in high values of required shaft power. Roughly, a factor of 2 in installed power required is shown in Fig. 13, 150,000 shaft horsepower for the waterjet vs 300,000 shaft horsepower for an air propeller of 5% propeller-to-base-area ratio. This difference is of paramount importance in large craft with long required ranges.

Propulsion considerations are not independent; they interact with the choice of vehicle characteristics. For example, if the vehicle specific loading (weight/cushion-area) increases, there is a likelihood of a reduction in structural-weight fraction, which can then be invested in payload or in fuel to increase range. But the upper value of vehicle specific loading is controlled by the wave-making drag at the hump speed and the propulsive efficiency at the hump speed (for a given installed power).

Figure 14 shows structural weight fraction as a function of the pressure-to-length ratio (p/L). The pressure p is essentially the specific loading (weight/cushion-area). This plot shows that there is, in fact, a substantial potential savings in the structural weight fraction for high (p/L) values; the value 0.8 is typical of the present state-of-the-art and 1.5 is a possible projection. The exact downward trend of Fig. 14 is subject to further definition of loads and designs; however, the principal conclusions of the subsequent tradeoff argument will be relatively insensitive to the exact finalized shape of Fig. 14.

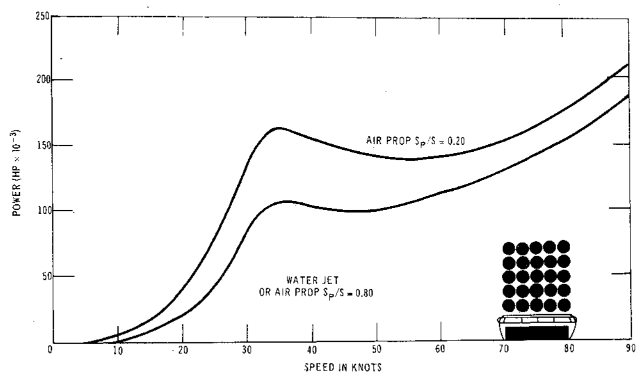


Fig. 12 Power vs speed for smaller air propeller array.

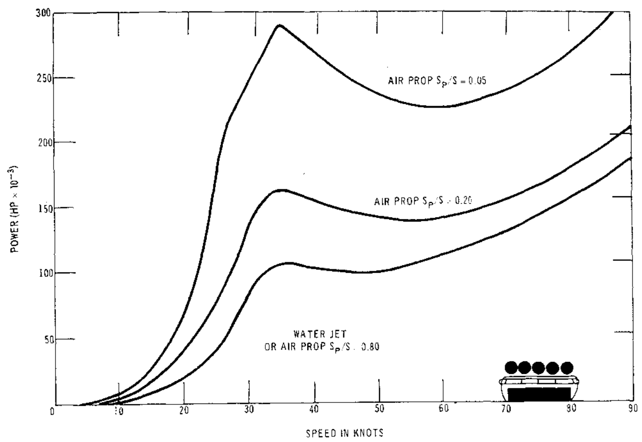


Fig. 13 Power vs speed for small air propeller array.

Figure 15 shows power calculations for a 4000-ton CAB as a function of speed, with (p/L) a parameter. For each value of (p/L), a high- and a low-sea-state condition is calculated (States 2 and 6). Because highly efficient waterjet propulsor systems are utilized, the powers at the hump speeds (30–40 knots) are low for (p/L) of 0.8. Figure 13 shows that the greatest power advantage for an efficient propulsion system is at and near hump speed. For a (p/L) of 1.5, 150,000 shaft horsepower at hump speeds is not exceeded. This power value is somewhat arbitrarily selected; however, the

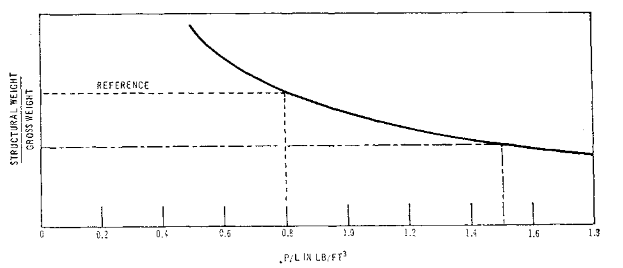


Fig. 14 Structural weight fraction vs pressure/length ratio.

argument to be made is a relative one, and (p/L) values of 0.8 and 1.5 will be used.

For the low sea state, the cruise velocities are nearly equal (about 85 knots) for both (p/L) values; for the high-sea-state case, the velocity for a (p/L) of 1.5 is only about 3 knots lower than for a (p/L) of 0.8. By going to (p/L) of 1.5, however, we gain significantly in payload or fuel load (Fig. 14).

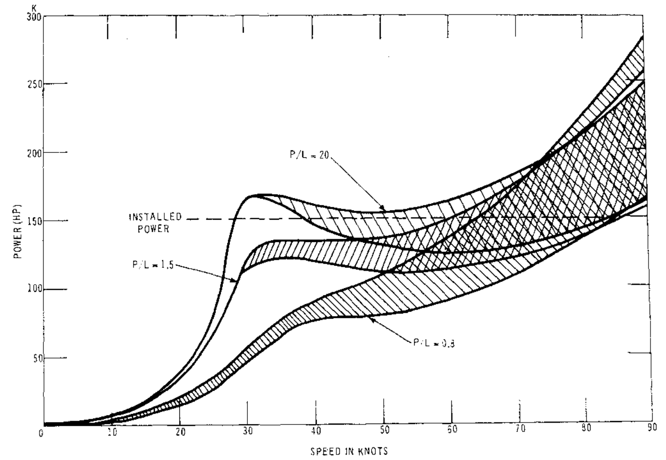


Fig. 15 Power vs speed for several pressure/length ratios over a range of wave heights.

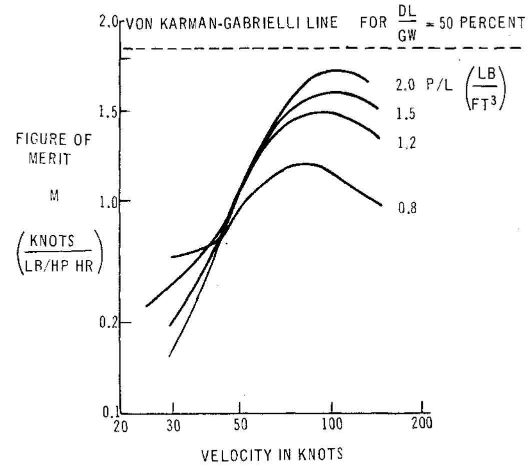


Fig. 16 Figure of merit vs speed for several pressure/length ratios.

To evaluate the tradeoff implicit here, a tentatively selected figure of merit M was used. It has many of the terms of the Breguet range equation, and expresses proximity to the von Karman-Gabrielli line (Fig. 4). It is proportional to dispos-

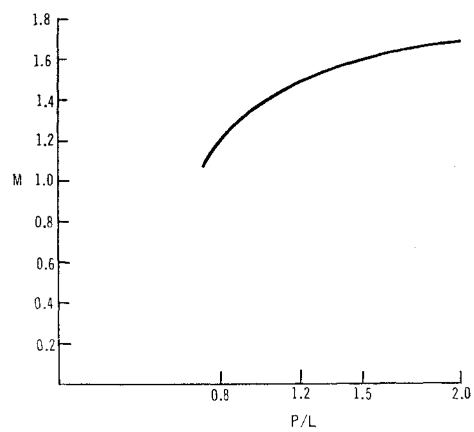


Fig. 17 Maximum figure of merit vs pressure/length ratio.

able-load fraction (DL/GW), that is, fuel plus payload fraction, and inversely proportional to specific fuel consumption (SFC), which expresses powerplant efficiency. The

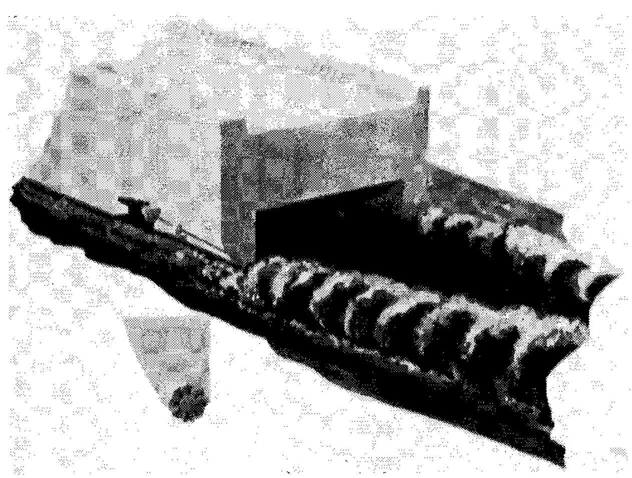


Fig. 18 Semisubmerged supercavitating propeller installation in a CAB sidewall.

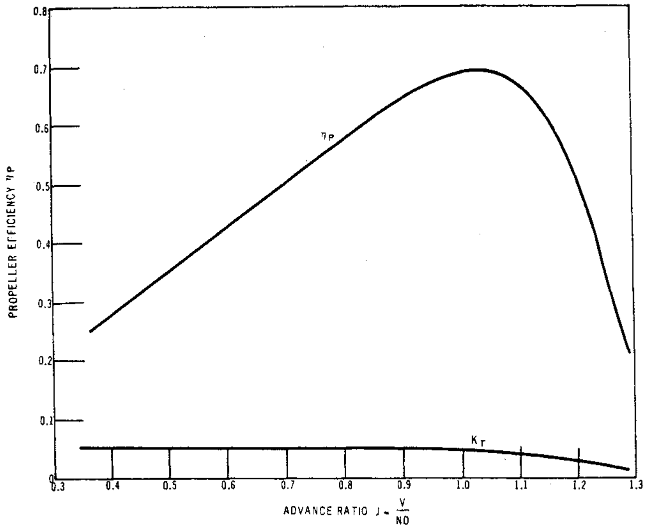


Fig. 19 Propeller efficiency vs advance ratio for a semi-submerged supercavitating propeller model.

terms are defined as follows:

range = $K(WV/P)[1/(SFC)] \ln (W_i/W_f)$
range = $K(L/D)[1/(SFC)] \ln (W_i/W_f)$
W_i = initial weight
W_f = final weight after fuel burnoff
SFC = specific fuel consumption
P = power
W = weight
V = velocity (V_K in knots)
K = constant
GW = gross weight
M = figure of merit = $(WV_K/P)[1/(SFC)](DL/GW)V_k$

This figure of merit M is plotted in Figs. 16 and 17. These figures confirm that the trend to high (p/L) values is a profitable one. For this reason, it is concluded that the ACV field will probably trend to higher (p/L) values, typically from 0.8 1.5, particularly in sidewall CAB craft where efficient waterjet systems can be utilized.

A second class of propulsion to be considered is a partially immersed supercavitating propeller (see Fig. 18). An advantage of such an installation in a CAB sidewall is that there are no shafts or large pods in the water; the shafts and machinery can be contained within the sidewall.

Figure 19 shows early test results of propeller efficiency as a function of advance ratio.[11] The value of the maximum propeller efficiency is encouragingly high, as high, in fact, as a fully immersed supercavitating propeller, exclusive of shaft or pod losses of the fully immersed propeller.

The availability of these promising possibilities for high-speed water propulsion of CAB vehicles, waterjets, and partially immersed supercavitating propellers raises the probability for the successful development of an efficient high-speed water propulsion system for CAB vehicles.

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