Feasibility Study of a Hybrid Airship Operating in Ground Effect

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A hybrid airship is developed in the context of an all-cargo aircraft operating in ground effect for increased performance. The concept is proposed for the transportation of containerized freight on the transatlantic route from New York to London. A performance and economic algorithm has been developed to compare the hybrid and conventional airship designs. A parametric study has been performed that covered vehicle gross weights from 250 to 4000 tons. The metric used for comparing the two designs was the potential profit for a year's operation. Results of the study show that the hybrid has a higher annual profit up to a gross weight of about 1500 tons. A 1000-ton hybrid, offering a 43% higher annual profit over the conventional airship, is selected as a feasible design point for future development.

Introduction

THERE are presently two modes of transocean bulk cargo transportation in operation. These are the containership, which carries up to 2000 containers at a speed of 30 knots, and the air freighter (Boeing 747-F), which carries up to 14 containers at 450 knots. An examination of the transport efficiency of these vehicles shows a large "transport gap" between the two, over which no vehicles presently operate in the context of transocean cargo transportation. The rigid airship offers a natural solution to this transport gap; however, it does not become efficient until large sizes are considered. A new hybrid airship concept is proposed, which appears to provide a natural transition between the aircraft and the conventional airship. By extending the concept to include operation in ground effect (G.E.) above the ocean's surface, the performance of the hybrid (G.E.) airship is enhanced further. The hybrid (G.E.) airship concept is proposed as a dedicated intermodal cargo transport for transocean operation.

Concept Description

Vehicle Configuration

The hybrid airship concept presented (Fig. 1) embodies three separate aerospace technologies which include: 1) use of partial aerostatic lift, 2) lifting body aerodynamics, and 3) ground effect (G.E.) augmented lift. The bend of the technologies into the hybrid (G.E.) airship concept presented results in significantly improved performance in terms of transport efficiency.

A low-aspect-ratio wing with strakes is blended into a rigid airship hull in combination with forward canard control surfaces. Low wing structural weight is achieved through the use of the low-aspect-ratio wing, which in turn may be used because of operation in ground effect. The wing strakes increase the wing stall margin ($C_{L\max}$) and move the aerodynamic center forward. The forward canards provide pitch trim control over the flight envelope. The aft wing position allows the placement of the engines and propulsors aft in the hull for increased propulsive efficiency. The vertical stabilizers are mounted on the wing tips to serve also as wingtip vortex diffusers or "winglets."[2] These winglets serve to reduce induced drag.

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The volume of helium which must be enclosed in order to provide the required aerostatic lift results in a fuselage size which is larger in proportion to the aerodynamic lifting surface than that which is encountered in conventional aircraft design. Lifting-body technology currently being developed for the Space Shuttle[2] provides an excellent data base for developing high lift/drag ratio lifting-body configurations.

The airship hull has been reshaped from a conventional circular into the rectangular cross section to reduce the

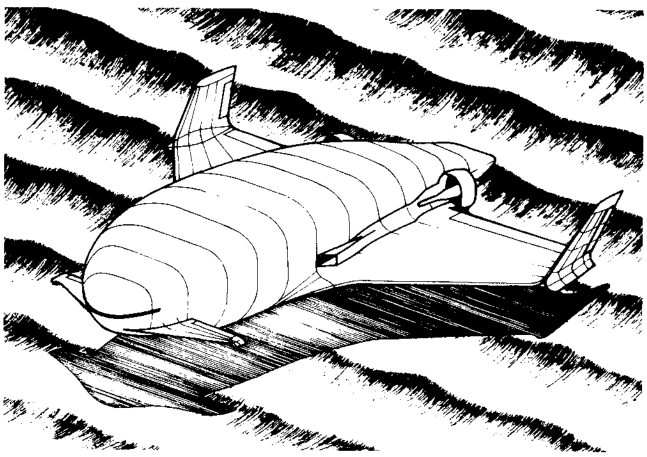


Fig. 1 Hybrid (G.E.) airship concept.

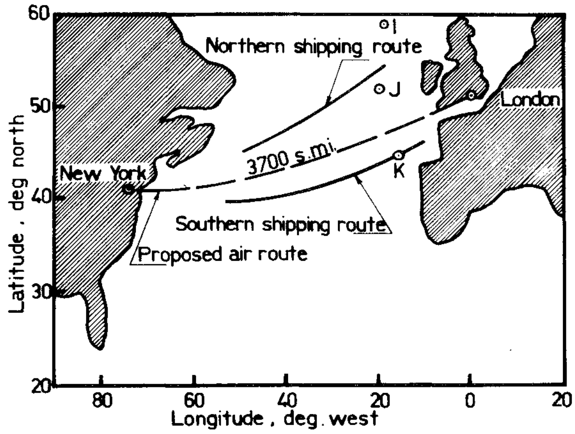


Fig. 2 Proposed route.

projected side area and decrease the gust loading problem. This also serves to increase the hull lift/drag ratio when blended into the wing. Marinized gas turbines, which are being developed for sea-level operation in hydrofoils and space effect ships, are used in conjunction with ducted shrouded propellers for increased propulsive efficiency.

The transportation of bulk freight in intermodal containers, which are compatible with truck and rail transport, has become the accepted means of operation. This is evidenced by the increased use of the highly efficient containership[3] and the recent introduction of the 747-F air containership[4] by Seaboard World Airlines. The Sea-Land SL-7 containership presently has a capacity of 1968 8×8×20-ft containers, whereas the aircraft will accomodate 13 to 14. Seaboard ultimately sees intermodal freight accounting for 90% of their business on the present Kennedy International Airport to London route. In this study, the same transatlantic route will be assumed.

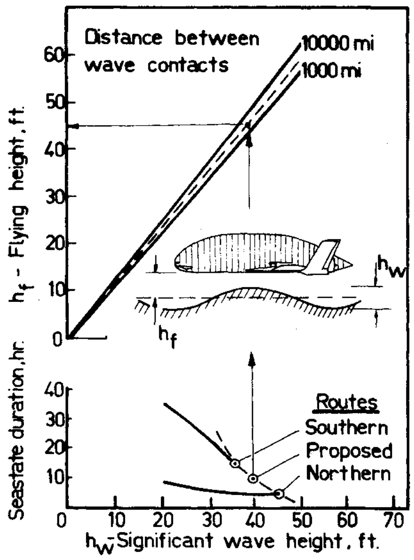


Fig. 3 Sea-state limitations.

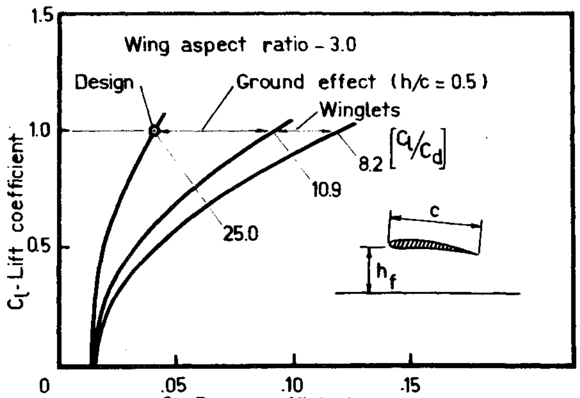


Fig. 4 Ground effect aerodynamics.

Table 1 Conventional airship description

Hull volume, ft^3	$V_{\text{hull}} = 2.43\, d^{3}$ [a]
Gas volume, ft^3	$V_{\text{gas}} = 0.95\, V_{\text{hull}}$
Hull aerostatic lift, lb	$\Delta_{a.s.} = 0.063\, V_{\text{gas}}$ [b]
Drag, lb	$D_h = 0.021\, q\, (V_{\text{hull}}^{2/3})$ [c]
Hull length/diameter	$L/d = 4.85$
Lift/drag ratio	$(\Delta/D_h)_{\text{airship}} = 3.832\, d/q$
Propulsive efficiency[9]	$\eta_p = 0.59$

[a] d = hull diameter, ft. [b] Helium, 0.063 lb/ft^3. [c] $q = \frac{1}{2}\rho U^2$, lb/ft^2.

Operation in Ground Effect

Operation in ground effect over the ocean to increase the aircraft performance by decreasing the induced drag is not new. It was first employed in the early 1930's[5] by pilots of commerical planes to help them extend their range while crossing the South Atlantic. Statistical studies of the ocean's topography has shown that operation in ground effect is practical, and increasing performance is realized as the vehicle size increases.

The Russians[5] have taken the lead in the development of wing-in-ground effect technology by designing a 500-ton research aircraft which was built by the Sormovo Shipyard at Gorki. The aircraft operates at heights of 25-50 ft above the water; has a speed of 300 knots, a wingspan of 125 ft, and a length of 400 ft, and is currently undergoing tests on the Capsian Sea. R. Lippisch, working in this country and in Germany,[5] has demonstrated the successful operation in ground effect of a 19.25-ft wingspan aircraft over waves up to 2.5-ft. high.

Operation in ground effect results in a large increase in the lift/drag ratio with a corresponding increase in aircraft range and endurance. Ground effect, however, is almost negligible at heights greater than one mean aerodynamic wing chord above the land or sea surface. For operation in high-sea states, the minimum flying height would be determined by the wave height.

The transatlantic operational route between New York and London used in this study is shown in Fig. 2. The approximately 3700-statute mile (3200-N.mi.) route passes between Weather Station J (20 W, 52 N) and Weather Station K (16 W, 45 N), where extensive measurements[6] of sea-state conditions have been made. The level of the significant wave height (h_w) and its persistence is shown in Fig. 3. The severest conditions, measured in the winter in these two areas, are seas having a significant wave height of 45 ft with a duration of 5 hr over the northern route, and a height of 35 ft with a duration of 15 hr over the southern route.

A probability analysis of flight in ground effect[7] over rough seas has shown that the distance between contacts with the wave crests increases dramatically for only small increases in flying height (h_f) (Fig. 3). If we superimpose the measured sea-state data on this curve, we find that a minimum flying height on the order of 45 ft will be required for the 3700-mile flight.

Ground Effect Aerodynamics

A ground clearance of no more than one half of a mean wing chord is necessary to realize a significant increase in the lift/drag ratio. This requirement, coupled with the minimum flying height of 45 ft for sea-state operation, dictates large wing chord with a low aspect ratio to keep the vehicle size within reason.

The aerodynamic performance in ground effect was based on an empirical analysis developed from model test results and available theory.[8] The analysis predicts the lift and drag characteristics of a wing, with or without end plates, in ground effect as a function of ground proximity and angle of attack. The drag polar for the wing alone is shown in Fig. 4.

The effect of the integrated vortex diffuser vertical stabilizer unit is seen to account for the first reduction in induced drag. The effect of flying in ground effect is seen further to reduce the induced drag. A flying height/mean aerodynamic chord (h_f/c) of 0.5 was selected as the minimum practical limit under severe weather conditions. For propeller powered aircraft, minimum power results in maximum endurance, hence minimum $C_L^{3/2}/C_D$ is selected as the operating point. This occurs at a C_L of 1.0. At this point the wing C_L/C_D is seen to increase from 8.2 to 10.9 by the addition of the vortex diffuser/vertical stabilizers and then to 25.0 by flying in ground effect. This is an increase of 349%, thus clearly demonstrating the value of flying in ground effect.

Table 2 Hybrid airship description

Hull	
Beam/depth	$B/d = 1.55$
Length/depth	$L/d = 4.67$
Hull volume, ft^3	$V_{hull} = 4.8\,d^3$
Gas volume, ft^3	$V_{gas} = 0.95\,V_{hull}$
Aerostatic lift, lb	$\Delta_{a.s.} = 0.063\,V_{gas}$
Propulsive efficiency	$\eta_p = 0.60$ @ 100 kt.
(based on analysis from Ref. 10)	$= 0.65$ @ 150 kt.
Hull + vertical stabilizer drag, lb	$D_h = 0.0376\,d^2 q$
Hull lift/drag ratio	$\Delta_{a.s.}/D_h = 8.0\,d/q + 1.0$
Wing	
Wing aspect ratio	$AR = 3.0$
Taper ratio	$\lambda = 0.33$
Lift coefficient	$C_l = 1.0$
Wing loading, lb/ft^2	$\Delta_{a.d.}/S_w = 34.0$ @ 100 kt.
	$= 76.4$ @ 150 kt
Mean aerodynamic chord, ft	$c = 1.333\,d$
Flying height, ft	$h = 0.67\,d$

Parametric Study

The technical and economic aspects of the vehicle concept were evaluated and compared with the 747-F and the conventional airship to determine its viability. Estimates of the available payload, productivity, and direct operating costs were made.

Performance data for the conventional airship were based on a NASA test of a 1/20 scale model.[9] Using the data in this report, a description of the airship appears in Table 1. The hybrid airship is described in Table 2.

The parametric study covered a speed range from 75 to 150 knots and a vehicle gross weight range from 250 to 4000 tons (short). Hull volumes for the conventional airship and hybrid (G.E.) airship are compared in Fig. 5 and hull lengths are compared in Fig. 6. The hybrid (G.E.) sizes vary with speed as a consequence of varying wing loading.

The vehicle lift/drag ratios are compared in Fig. 7. The values for the hybrid (G.E.) airship remain relatively constant over the gross weight range, whereas those for the conventional airship increase dramatically with gross weight and decreasing speed.

Weight Estimation

The empty weight of the hybrid (G.E.) airship, based on data in Ref. 11, comprises three categories:

$$W_e = W_{wing} + W_{hull} + W_{propulsion,\ landing\ gear,\ control\ system} \tag{1a}$$

$$W_{wing} = k(\Delta_{a.d})^{1.4} \tag{1b}$$

$$W_{hull} = 0.572\,(\Delta_{a.s})^{0.88} \tag{1c}$$

$$W_{propulsion,\ landing\ gear,\ control\ system} = 0.2\,\Delta_g \tag{1d}$$

where W_{wing} and W_{hull} are in short tons

k = 0.0046 (100 kt.); = 0.0070 (150 kt.)
$\Delta_{a.s.}$ = aerostatic lift
$\Delta_{a.d.}$ = aerodynamic lift
$\Delta_g = \Delta_{a.s.} + \Delta_{a.d.}$

The empty weight of the conventional airship is considered to be the second term only. A comparison of the empty weight fractions is made in Fig. 8. A difference in wing weight accounts for the increase due to speed for the hybrid (G.E.) airship.

Payload Capacity

Both of the airship designs were assumed to use existing large gas turbines with a specific fuel consumption (s.f.c) of

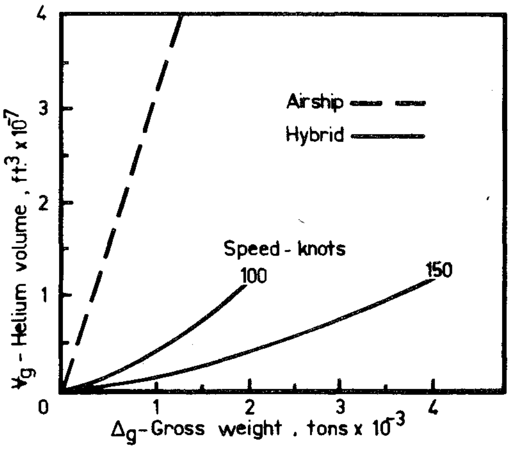


Fig. 5 Helium volume.

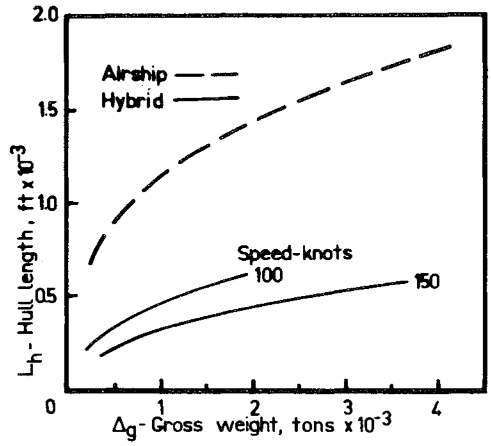


Fig. 6 Hull size.

0.4 lb/shp-hr. The fuel weight was determined for the 3700-mile flight assuming a 20% margin. The payload weight was determined from

$$W_p = W_u - W_f = \text{payload (short tons)} \tag{2a}$$

$$W_u = \Delta_g - W_e = \text{useful load (short tons)} \tag{2b}$$

$$W_f = \frac{0.00321\ (\text{s.f.c})\ RD}{\eta_p} = \text{fuel weight (short tons)} \tag{2c}$$

where

R = range = 3700 statute miles
D = drag (short tons)

The endurance (E_h) in hours, for the 3700-mile trip at the investigated block speeds, is shown in Table 3. The payload capacitites are compared in Fig. 9. It is seen that the hybrid (G.E.) airship, at speeds of 100 to 150 knots, has payload capacities comparable to the 75-knot airship up to a gross weight of about 1000 short tons. The effect of speed on the airships payload capacity is also evident.

The 8×8×20-ft containers were assumed to be equivalent to those in use on the 747-F.[4] The 2000-lb tare weight container has a useable interior volume of 1138 ft^3, a maximum floor loading of 400 psf, and a maximum net weight capacity of 11.5 short tons. An average container weight of 7.1 short tons (cargo density = 10.7 lb/ft^3) was assumed for the study. This corresponds to a payload weight of 6.1 short tons. The number of containers which could be carried was

$$N\text{(integer)} = W_p/7.1 = \text{no. of containers} \tag{3a}$$

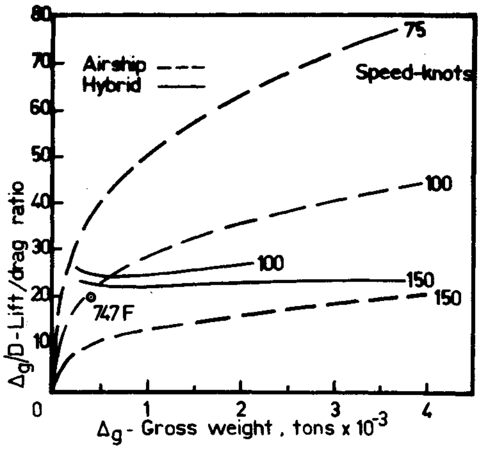


Fig. 7 Vehicle lift/drag ratio.

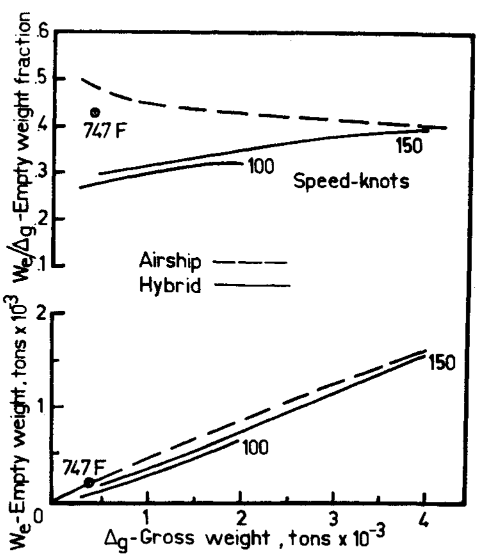


Fig. 8 Vehicle empty weight.

$$W_{\text{container payload}} = 0.86 \ W_p \tag{3b}$$

Productivity

It is possible to load and unload the 747-F, with a 14 container capacity, in 0.5 hr. Thus, the block time per trip, at 0.05 hr/container, including loading, flight, and unloading, is

$$T = E_h + 0.1 \ N \tag{4}$$

The utilization rate (U) is based on the premise that it increases with a decrease in block speed. The utilization rates are shown in Table 4. Productivity is thus

$$P(\text{short tons-mi/yr}) = 0.86 \ W_p UR/T \tag{5}$$

The productivity of the hybrid (G.E.) is seen (Fig. 10) to increase with speed, whereas the opposite is true for the conventional airship. In addition, the hybrid's productivity is somewhat higher than the airship's up to a gross weight of about 2200 to 2500 tons.

Operating Cost

Estimation of the operating cost becomes extremely tenuous because of assumptions which must be made concerning the first cost of the aircraft. However, for this analysis the same assumptions were made for both the hybrid and conventional airship and, therefore, while not accurate in an absolute sense, should be accurate on a comparative basis.

Table 3 Endurance at various block speeds

Block speed, kt.	Endurance, hr
75	42.9
100	32.2
150	21.4

Table 4 Utilization rate at various block speeds

Block speed, kt.	U, hr/yr
75	6250
100	6000
150	5500

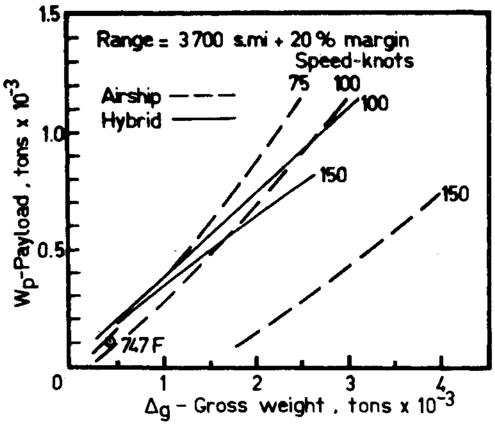


Fig. 9 Payload comparison.

The first cost was derived from data in Ref. 11 which gave the cost in 1969 dollars, based on the empty weight, for a production run of 200 aircraft. The data were corrected to 1975 dollars and extrapolated to higher empty weights. The total first cost is

$$\text{first cost (\$)} = \text{aircraft cost} + \text{helium cost (\$0.035/ft.}^3)$$

$$= 13.0 \times 10^6 + 7.77 \times 10^7 (\log W_e - 2.0) \tag{6}$$

The total operating costs are defined as the sum of the direct and indirect operating costs

$$\text{T.O.C. (\$/yr)} = \text{D.O.C.} + \text{I.O.C.}$$

$$= \text{D.O.C.} + 0.5 \text{ D.O.C.} \tag{7}$$

where

$$\text{D.O.C.} = \text{depreciation (1st cost/12 yr)}$$

$$+ \text{maintenance (0.025 1st cost)}$$

$$+ \text{insurance (0.03 1st cost)}$$

$$+ \text{fuel} \left(\frac{\$0.50}{\text{gal}}\right) \left(\frac{1}{6.5 \text{ lb/gal}}\right) \left(\frac{W_f}{1.2 \ E_h}\right) (2000 \ U)$$

$$+ \text{helium replenishment} \left(\frac{\$0.035}{\text{ft}^3}\right) (0.25 \ V_{\text{gas}})$$

$$+ \text{crew salary}$$

Crew salary for the hybrid is calculated on the basis of 3 flight crew @ \$31,200/yr and 5 ground crew @ \$14,560/yr, for a total of \$166,400/yr. For the conventional aircraft, the salary is based on 5 flight crew @ \$31,200/yr, 10 onboard technicians @ \$20,800/yr, and 5 ground crew @ \$14,560/yr, for a total of \$436,800/yr. The T.O.C. is divided by the productivity to obtain \$/available ton-mile (Fig. 11) and, as expected, it decreases with increasing size and decreasing speed for the hybrid airship, which has lower operating costs up to a gross weight of about 1000 tons.

Potential Profit

The only metric which can be used effectively to judge relative merit in a comparison between the two airship designs is the profit which may be realized on an annual basis. Assuming a freight rate structure equivalent to that currently charged for the 747-F containers (\$ 762/short ton) and a 100% load factor, the annual potential revenue R is

$$R = (\$\ 762/\text{short ton})\ (0.85\ W_p U/T) \tag{8}$$

The potential profit P is then

$$P = R - \text{T.O.C.} \tag{9}$$

and the break-even load factor (B.E.L.F.) is

$$\text{B.E.L.F.} = \text{T.O.C.}/R \tag{10}$$

The final and most meaningful comparison between the hybrid and conventional airship is shown in Fig. 12. The hybrid (G.E.) airship offers a higher potential profit up to a gross weight of about 1500 tons, after which size effects make the 75- to 100-knot airship more profitable. Based on these results, a 150-knot 1000-ton gross weight hybrid (G.E.) airship, offering a 43% higher profit over the 75-knot airship, was selected as the feasible design point.

A graphic comparison of the range of hybrid (G.E.) and conventional airships that were studied is shown in Fig. 13.

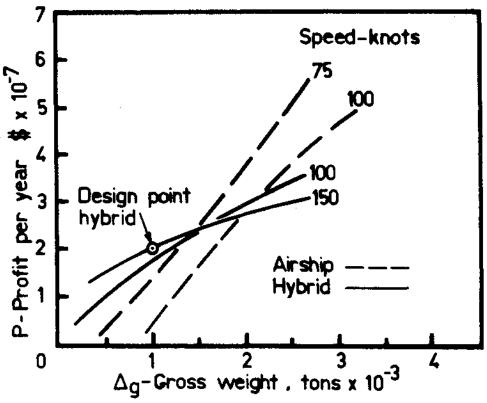


Fig. 12 Potential profit.

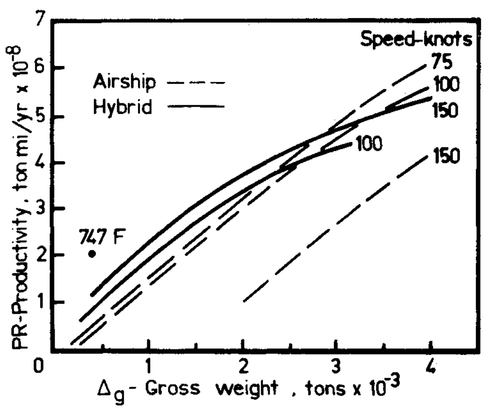


Fig. 10 Productivity.

Item	747F	Hybrid			Airship		
Speed-knots	450	150			75		
Δ_g-Tons	388	500	1000	2000	500	1000	2000
W_p-Tons	100	193	347	658	161	392	895
$\forall_g$-Ft.^{3} x 10^{-6}	—	0.5	1.5	4.2	16.	32.	64.

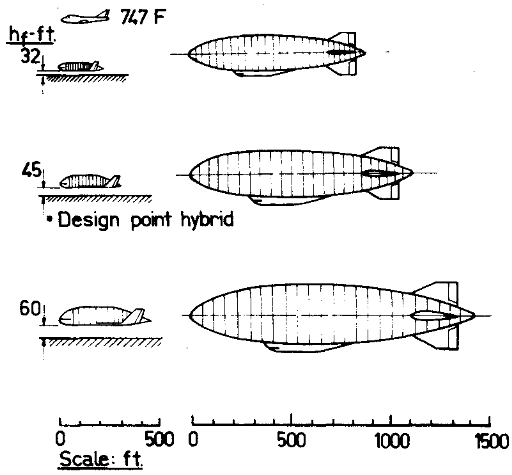


Fig. 13 Airship comparison.

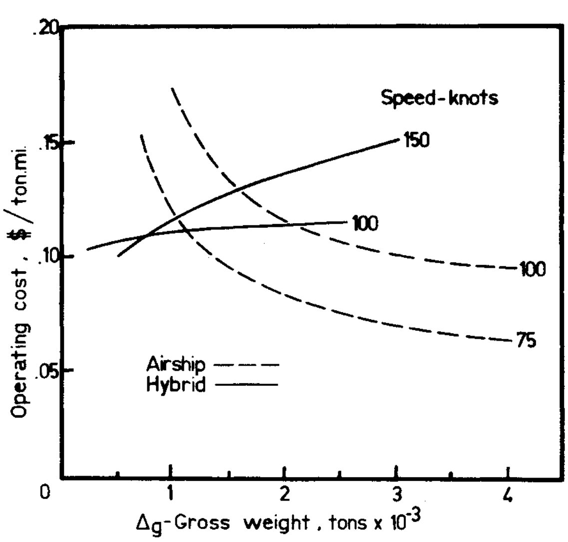


Fig. 11 Total operating cost.

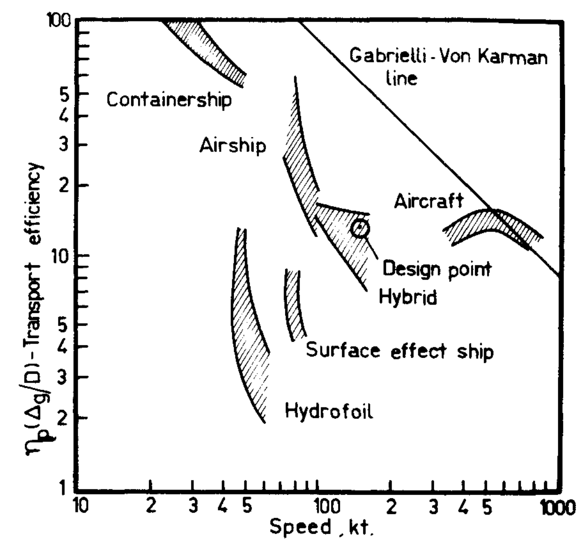


Fig. 14 Transport efficiency.

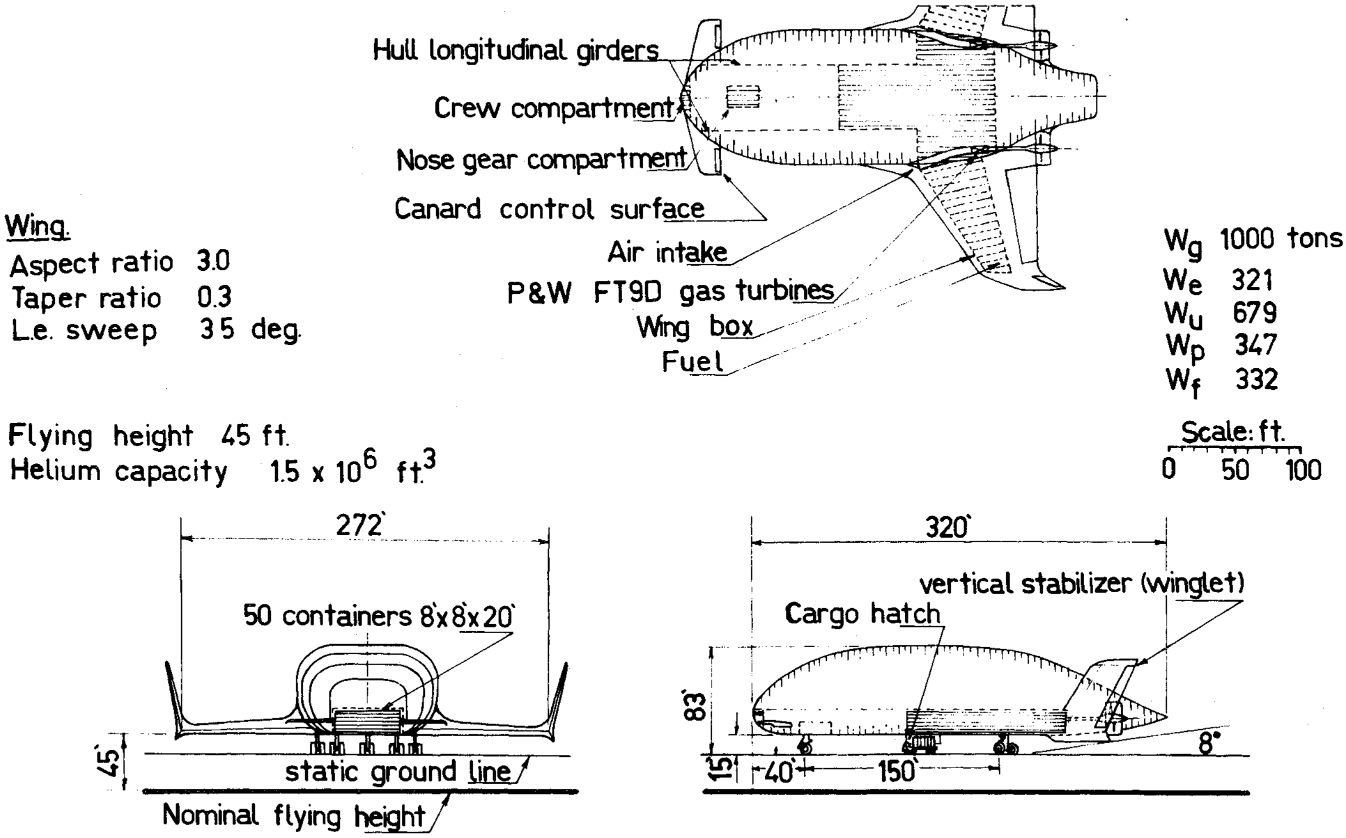
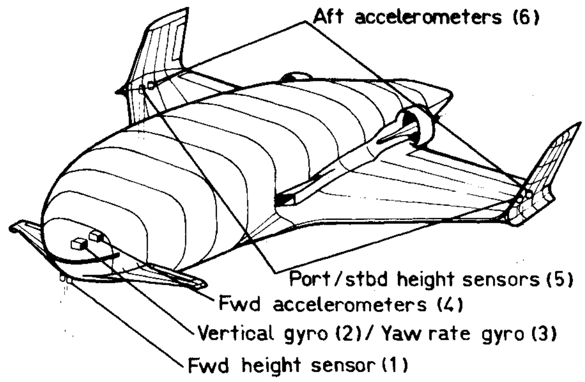


Fig. 15 Hybrid (G.E.) airship – inboard profile.



sensor	pitch	roll	yaw	heave
1	x			x
2	x	x		
3			x	
4	x			x
5		x		
6	x	x		x

Fig. 16 Active control system.

The size advantages of the hybrid (G.E.) airship clearly are demonstrated.

The transport efficiency (equivalent lift/drag ratio) of several transocean vehicles is shown in Fig. 14 and compared to the Gabrielli-Von Karman line. Conventional airships and the hybrid (G.E.) airship are seen to fill the transport gap between the containership and the jet transport. It is interesting to note the comparison with the hydrofoil and surface effect ship.

Design Point Aircraft

General Characteristics

The general arrangement of the 1000-ton design point aircraft is shown in Fig. 15. The weight breakdown is shown in Table 5.

Table 5 Weight breakdown for design point aircraft

	Weight, short tons	
Empty weight	321	
Useful weight	679	
Payload		347
Fuel		332
Gross weight	1000	

With a hull helium volume of 1.5×10^6 ft^3, approximately 5.5% of the gross weight is supported aerostatically. Thus, the aerodynamic/aerostatic breakdown for a gross weight of 1000 short tons is: aerostatic lift – 54 short tons; aerodynamic lift – 946 short tons.

Loading of 50 8×8×20-ft containers is accomplished through a hatch in the bottom of the hull (Fig. 16) by either an onboard crane system or ground handling equipment of the type used on the 747-F. Payload cubeage is 64,000 ft.[3]

The design point aircraft is also the minimum size hybrid which meets the minimum flying height criterion of 45 ft. It should be pointed out that this minimum flying height exists only under extreme weather conditions. If weather conditions permit, the flying height may be reduced to an h/c of about 0.25, which would result in a further increase in lift/drag ratio.

This size hybrid will require two Pratt and Whitney FT-9 D gas turbines (Ref. 12), which are marinized versions of the JT-9D turbo-fan engine. Marinization of these engines, which are rated at 35,000 shp each, is accomplished by the removal of the aft section and the addition of a power turbine and gearbox. The power plants are mounted internally in the hull on the wing box and drive two ducted pusher propellers which are mounted aft in the hull boundary layer to maximize propulsive efficiency

Active Control System

Operation of the hybrid airship in ground effect will require an active control system, similar to that now in use on the Navy's hydrofoil craft, for stability augmentation in the heave, pitch, and roll degrees of freedom. Incorporation of an active control system also will permit the hybrid (G.E.) airship to be designed for reduced structural loading. This will result in reduced structural weight through maneuver-load and gust-load control, and reduced static stability requirements. Decreased static stability will permit decreased vertical and horizontal stabilizer size, weight, and drag, with an attendant decrease in fuel consumption.

The required sensors are shown in Fig. 16. These include a vertical gyro for pitch and roll angles yaw rate gyro hull-mounted vertical accelerometers, and bow- and wing-mounted sonic wave-height sensors. A summary of functional objectives for the hybrid airship control system is also shown in Fig. 16.

In addition to the control system, a bow-mounted forward-looking radar system will be required for ship collision avoidance. At an approximate height above the water of 65 ft, a range of 10 to 18 nautical miles will result. The installation of an over-the-horizon radar could be used to measure ocean surface motions and wind characteristics at a distance of 220 to 600 nautical miles. This would allow modification of the flightpath to avoid weather conditions.

Structural Concept

The proposed structural concept, shown in Fig. 15. comprises a wing box coupled to the hull longitudinal girders, forming the primary structure. The hull itself is of semimonocoque construction (skin and stringer shell). The wing box also serves as the fuel cell with a capacity of 102,000 ft^3.

Conclusions

The hybrid (G.E.) airship concept developed in this paper is shown to offer both size and economic advantages over the conventional airship up to vehicle gross weights of 1500 tons. A 1000-ton hybrid (G.E.) airship, selected as a feasible design point, would offer a 43% higher potential annual profit.

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