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PRELIMINARY ESTIMATES OF OPERATING COSTS FOR LIGHTER THAN AIR TRANSPORTS

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ABSTRACT: Presented is a preliminary set of operating cost relationships for airship transports. The starting point for the development of the relationships is the direct operating cost formulae and the indirect operating cost categories commonly used for estimating costs of heavier than air commercial transports. Modifications are made to the relationships to account for the unique features of airships. To illustrate the cost estimating method, the operating costs of selected airship cargo transports are computed. Conventional fully buoyant and hybrid semi-buoyant systems are investigated for a variety of speeds, payloads, ranges, and altitudes. Comparisons are made with aircraft transports for a range of cargo densities.

INTRODUCTION AND SUMMARY

Much of the present confusion over the viability of modern airships can be traced to the assumptions and methods used in the estimations of operating costs. For example, recent estimates of the direct operating costs (DOC) of airship cargo transports range from 0.5 to 15.0¢/available ton-statute mile. This paper will discuss a methodology of airship cost estimation and present a preliminary set of operating cost relationships for airship transports.

The starting point for development of the cost relationships are the DOC formulae of the Air Transport Association[1] and the indirect operating cost (IOC) categories developed jointly by Boeing, Lockheed, and Douglas[2]. These methods are commonly used for estimating operating costs of commercial aircraft and are founded on extensive operating experience and a vast data base. They are adopted in the present

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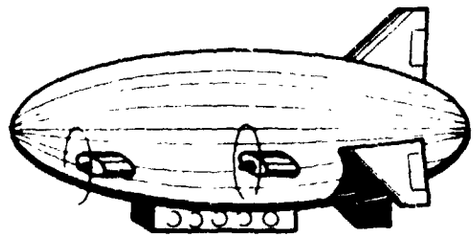
paper because of the many similarities between modern airships and aircraft. The formulae are examined element by element to assess the applicability to airships. Modifications are made where appropriate, and areas of uncertainty are pointed out. Additional elements required for airships, such as those associated with procurement and maintenance of the buoyant gas, are formulated.

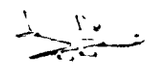
An airship performance model is necessary to define the airship configurations for input into the cost model. Such a performance model suitable for conceptual design has been developed expressly for the cost model used in this paper. The methods of performance analysis are discussed in the next section.

To illustrate the cost estimating relationships, the operating costs of selected airship transports are computed. A conventional fully buoyant, and a hybrid semi-buoyant airship are defined and discussed. The effects on operating costs of changes in cruise speed, gross takeoff weight, range, and cruise altitude are investigated. Comparisons are made with aircraft transports. The effect of cargo density on aircraft operating costs is assessed. The two airship configurations and the aircraft are illustrated in Figure 1.



FULLY BUOYANT

HYBRID



AIRCRAFT

Figure 1
Study Configurations

Any airship costing methodology must be regarded as highly speculative at the present time. It is hoped that the cost relationships developed in this paper will provide a temporary means for estimating airship costs as well as providing a starting point for developing more definitive relationships.

METHODS OF ANALYSIS

Performance

The airship performance analysis begins with the calculation of gas volume, V_{GAS}, and envelope volume, V_{ENV}, in terms of the specified buoyant lift, L_{BUOY}, as follows

$$\left.\begin{aligned} V_{GAS} &= \frac{L_{BUOY}}{K_G} \\ V_{ENV} &= \frac{\rho_{S.L.}}{\rho_{ALT}} V_{GAS} \end{aligned}\right\} \tag{1}$$

where $K_G = .06$ for Helium and $\rho_{S.L.}$ and ρ_{ALT} are the atmospheric densities at sea level and cruise altitude, respectively. Once V_{ENV} is known, the airship geometry can be determined.

The aerodynamic analysis follows Appendix A of reference 3. After the Reynolds number, R_N, has been computed, the skin friction coefficient, C_f, is determined from[4]

$$C_f = \frac{.03}{R_N^{1/7}} \tag{2}$$

The bag drag coefficient is[4]

$$C_{D_{BAG}} = C_f \left[4 \left(\frac{\ell}{d}\right)^{1/3} + 6 \left(\frac{d}{\ell}\right)^{1/2} + 24 \left(\frac{d}{\ell}\right)^{2.7}\right] \tag{3}$$

where (ℓ/d) is the fineness ratio. The drag coefficient is then

$$C_D = C_{D_{BAG}} + C_{D_F} \tag{4}$$

where C_{D_F} accounts for the fin and other miscellaneous components of drag and is taken as equal to .005 in the present study. The vehicle zero-lift drag is determined from

$$D_o = q\, C_D\, S_{REF} \tag{5}$$

where

$$S_{REF} = V_{ENV}^{2/3} \tag{6}$$

The lift coefficient is taken from reference 2 as

$$C_L = (0.5\pi R \sin\alpha + K_L \sin^2\alpha \cos\alpha) \frac{S_p}{S_{REF}} \tag{7}$$

where AR is the aspect ratio, α is the angle of attack, S_p is the platform area, and

$$K_L = 1.7\ AR\ e^{1-AR} \tag{8}$$

The drag due to lift coefficient, C_{D_i}, is obtained from reference 5 as

$$C_{D_i} = C_L \tan\alpha \tag{9}$$

For the hybrid airship, the angle of attack is selected by setting $C_{D_o} = C_{D_i}$. The vehicle dynamic lift and drag due to lift are

$$\left.\begin{aligned} L_{DYN} &= q\ C_L\ S_{REF} \\ D_i &= q\ C_{D_i}\ S_{REF} \end{aligned}\right\} \tag{10}$$

respectively. The fully buoyant airship is assumed to fly at zero angle of attack. Thus, the gross takeoff weight, W_{GTO}, and total drag, D, are given by

$$\begin{aligned} W_{GTO_{FULLY\ BUOYANT}} &= L_{BUOY} \\ D_{FULLY\ BUOYANT} &= D_o \end{aligned} \tag{11}$$

For the hybrid,

$$\left.\begin{aligned} W_{GTO_{HYBRID}} &= L_{BUOY} + L_{DYN} \\ D_{HYBRID} &= D_o + D_i \end{aligned}\right\} \tag{12}$$

The structural weight, W_{STRUC}, defined to be the empty weight minus the propulsion system weight, is obtained from

$$W_{STRUC} = K_{S1}\ V_{ENV} + K_{S2}\ L_{DYN} \tag{13}$$

where the second factor is zero for the fully buoyant airship. The first factor results from the "cube-cube" law governing scaling of airship empty weight and lift. The historical value of K_{S1} is .0325 but a value of .0250 is used in the present study, reflecting about a 25% improvement in structures and materials technology over the historical base. This is probably a conservative assumption when the great increases in structural and material efficiencies in the past 40 years are considered.

The horsepower required for cruise is determined from the fundamental relationship

$$HP_{CR} = \frac{S\ D}{550\eta_p} \tag{14}$$

where S is the cruise speed in feet per second and $\eta_p = .82$ is the propulsive efficiency. The rated horsepower is

$$HP_{RATE} = \frac{P_{S.L.}}{P_{ALT}} \sqrt{\frac{T_{S.L.}}{T_{ALT}}}\ \frac{HP_{CR}}{K_T} \tag{15}$$

where P and T are the atmospheric pressure and temperature, respectively, and K_T is the throttle setting, taken as .60 in the present study. Both diesel and turboprop engines were investigated, and it was found that the former gave superior performance in both the fully buoyant and hybrid airships. The weight of the diesel engines is

$$W_{ENG} = K_E \, HP_{RATE} \tag{16}$$

where K_E was taken as 1.0. The weight of the rotors and drivetrains, W_{DRV}, was estimated from empirical data and added to the engine weight to obtain the propulsion system weight, W_{PROP}.

The mission fuel requirements are determined from

$$W_{FUEL} = HP_{CR} \, SFC \, \frac{R}{S} \tag{17}$$

where SFC is the specific fuel consumption and R is the range. Finally, the payload may be determined from

$$W_{PAY} = W_{GTO} - W_{STUC} - W_{PROP} - W_{FUEL} \tag{18}$$

Cost

The development of a costing methodology for airships may follow one of two paths. First, there is the methodology based on past airship costs and past operating experience. This data base, however, is so old that it has limited use in the modern context. The economic situation and manufacturing techniques of today cannot be reflected accurately in a model based on historical airship data.

The second possibility is to use techniques that have been developed for estimating costs in the air transport industry. This approach is natural since aircraft and airships have many characteristics in common. Both have a need for light weight and high performance to obtain optimum operational efficiency. In order to minimize the labor requirements, both will include sophisticated flight control and avionics systems. Minimum operating costs require a high degree of dependability and high utilization factors. Also, airships and aircraft will have to meet the same institutional and operational constraints since both will be performing their tasks under the jurisdiction of the same regulatory agencies. Therefore, the costing techniques based on air transport experience were used in this study since they were considered to be more applicable in predicting the economic characteristics of the airship.

The vehicle costs were derived using equations which compute cost as a function of weight. The equations compute separate costs for body structure, propulsion, avionics, crew station controls and panels, and final assembly. These are then summed to derive a first unit cost. Learning curve factors are applied next to arrive at the cost per unit for the production quantity. Airship unit costs were estimated from the same equations that were used for conventional aircraft. This assumption is probably conservative since there possibly are reasons why airship unit costs per pound of structure may be lower than those of aircraft.

The operating cost is divided into two parts — direct and indirect. The DOC's were computed using the Air Transportation Association (ATA) equations.[1] The indirect costs were derived using the equations developed jointly by Boeing, Lockheed, and Douglas[2] with a modification to include the gas replenishment needed for airships. Table 1 is a listing of the items in DOC's and IOC's.

A preliminary examination indicated that the land requirements for the aircraft and airships would be equal so those costs were not included in the study. Aircraft

Table 1
Operating Cost Elements

- **DIRECT OPERATING COST (ATA METHOD)**
  - CREW
  - FUEL
  - INSURANCE
  - MAINTENANCE
  - DEPRECIATION
- **INDIRECT OPERATING COST (LOCKHEED–BOEING–DOUGLAS METHOD)**
  - MAINTENANCE OF GROUND PROPERTIES AND EQUIPMENT
  - VEHICLE SERVICING
  - CARGO TRAFFIC SERVICING
  - RESERVATIONS, SALES, ADVERTISING
  - GENERAL AND ADMINISTRATIVE
  - GAS REPLENISHMENT

actually require more land for the runways, but the hourly utilization of the land is quite high wereas an airship when moored does not allow the land it occupies to be utilized for other airships. Due to their large sizes, fully buoyant airships may have an adverse effect on air traffic congestion. The hybrid airship would be superior to the fully buoyant airship in terms of land utilization and air traffic congestion.

The block time is very important to the productivity of the vehicle. The block times were computed by the following equations

$$\left.\begin{aligned} t_{AIRSHIP} &= \frac{R + .5\,S}{S\left(1-\frac{25^2}{S^2}\right)} \\ t_{AIRCRAFT} &= \frac{R + .5\,S}{S\left(1-\frac{75^2}{S^2}\right)} + \frac{1}{2} \end{aligned}\right\} \qquad (19)$$

where t = block time, hr; R = range, nautical miles; and S = cruise speed, knots.

The time to climb to and descend from cruising altitude is accounted for by the factor .5 S. In the denominator, the fractional quantity accounts for the effect of winds which are assumed to be 25 and 75 knots for the airship and aircraft, respectively. The correction is derived by assuming that the vehicle encounters a headwind over half the range and a tailwind of the same velocity over the other half. The aircraft block time also includes a half hour of ground maneuver time which is not necessary for the airship.

Table 2 lists the assumptions for the cost study. The utilization rates of airships will be considerably higher than those of aircraft due to the higher trip times. Further, it may be possible to do almost all maintenance in flight. Achievement of high utilization is important for airships due to their inherently poor productivity. It is assumed in the present study that ground time is only necessary for freight loading and unloading. The airship requires two crews for the long flights, but salaries were assumed to be paid only while the crew was actually working. The utilization and crew salary assumptions should be regarded as optimistic. The airships will require an annual total gas replenishment equal to about 25% of their volume. The price of Helium was taken as 10¢ per cubic foot.

Table 2
Economic Assumptions

	AIRCRAFT	FULLY BUOYANT & HYBRID
CREW SIZE	3	3
UTILIZATION (HR/DAY)	11.67	23.40
FUEL COST ($/GALLON)	.25	.25
DEPRECIATION PERIOD (YRS)	15	15
RESIDUAL VALUE (%)	15	15
INSURANCE RATE (%)	2	2
GAS REPLENISHMENT (%/YEAR)	0	25

RESULTS

The study configurations are shown in Figure 1. The fully buoyant airship is of conventional ellipsoidal shape. The hybrid configuration has an elliptic cone forebody and an afterbody which fairs to a straight line trailing edge. The cross-sections are elliptical. The hybrid configurations represents an arbitrary choice of shape since the performance optimization model is not sufficiently detailed to account for all the interactions necessary for a configuration optimization. Thus, there may well be superior hybrid configurations to that considered here.

Table 3 shows the characteristics of the fully buoyant and the hybrid airship sized for 1,000,000 pounds of buoyant lift. Also shown for reference are the characteristics of a cargo aircraft of 500,000 pounds gross takeoff weight. The cruise speeds of the airships were selected to maximize the productivity-to-empty weight ratio and were found to be 100 knots in both cases. Due to the severe penalties associated with designing airships for high cruise altitudes, sea level altitude was assumed. Cruise altitude capability is then obtained by preheating the buoyant gas to fill the envelope at takeoff. The dimensions of the airships are large compared with those of the aircraft, with the hybrid being somewhat more compact than the fully buoyant. The horsepower of the hybrid airship is considerably higher than that of the fully buoyant due to the higher drag of the former. The hybrid airship has 724,000 pounds of dynamic lift at cruise in addition to its 1,000,000 pounds of buoyant lift. Both airships have 16.7×10^6 ft^3 of He.

The weight statements on Table 3 show that the fully buoyant airship and the cargo aircraft have about the same payload fractions and that that of the hybrid airship is somewhat lower. Consideration of the ratio W_{FUEL}/W_{PAY} indicates that the fully

Table 3
Vehicle Characteristics

	FULLY BUOYANT	HYBRID	AIRCRAFT
W_{GTO}, 1000 lbs.	1000	1724	500
W_{STRUC}	417	652	163
W_{PROP}	43	90	50
W_{FUEL}	195	497	116
W_{PAY}	345	484	171
CRUISE SPEED*, knots	100	100	462
CRUISE ALTITUDE, ft.	0**	0**	35,000
LIFTING GAS	H_e	H_e	—
GAS VOLUME, $ft.^3$	16.7×10^6	16.7×10^6	—
LENGTH, ft.	1032	658	160
RATED HORSEPOWER	27,700	70,640	—
RANGE, n.mi.	2700	2700	2700

*CHOSEN TO MAXIMIZE PRODUCTIVITY-TO-EMPTY WEIGHT RATIO
**ALTITUDE CAPABILITY OBTAINED BY PRE-HEATING GAS

buoyant is the most fuel conservative of the three, followed by the cargo aircraft. It appears that the extra lifting capability of the hybrid airship as compared with the fully buoyant airship is cancelled by its higher drag.

The operating cost breakdowns for the three vehicles are shown on Figure 2. Considering DOC first, the elements of depreciation, maintenance, and insurance are seen to be about the same for all three vehicles. The fuel cost is lowest for the fully

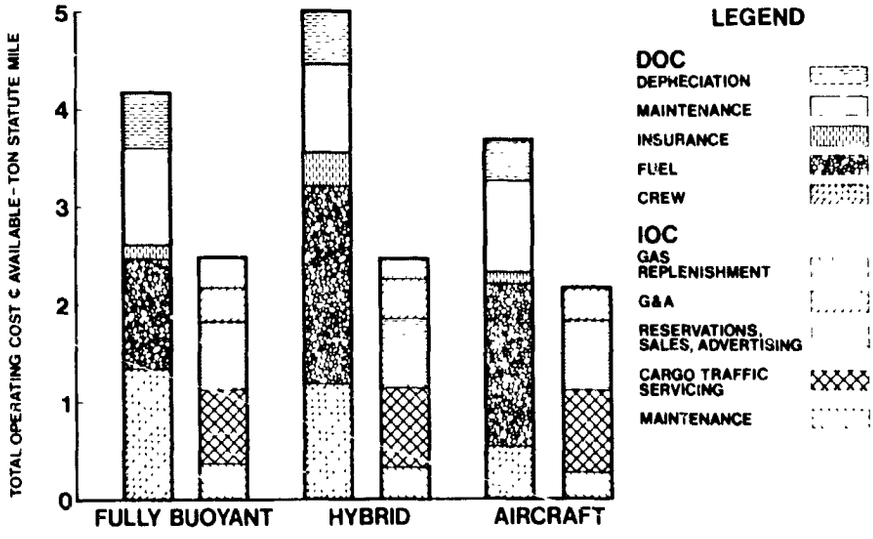


Figure 2
Operating Cost Comparison

buoyant airship and highest for the hybrid airship, reflecting the fuel economies of the three vehicles. The crew costs are high for the airships due to their relatively low speed and productivity. As mentioned earlier, the economic assumptions used to compute the airship DOC's must be regarded as optimistic. Most important of these assumptions are the high utilization rate and number of crew members (see Table 2). Use of the cargo aircraft utilization rate and the assumption of continuous pay for all crew members would give airship DOC values of twice those shown on Figure 2.

The IOC's of the airships are similar to those of the cargo aircraft except for the requirement for lifting gas replenishment. This results in slightly higher IOC's for the airships. Adding the DOC's and IOC's to get the total operating cost (TOC) gives values of 6.6, 7.4, and 5.8¢/available ton-statute mile for the fully buoyant airship, hybrid airship, and cargo aircraft, respectively. Although the depth of analysis is insufficient to draw conclusions based on small differences, it would seem that airships are at best marginally competitive with aircraft for the mission under consideration.

As is commonly believed, airships become more efficient as they become larger, as demonstrated in Figure 3. The tick marks denote the nominal vehicles of Table 3.

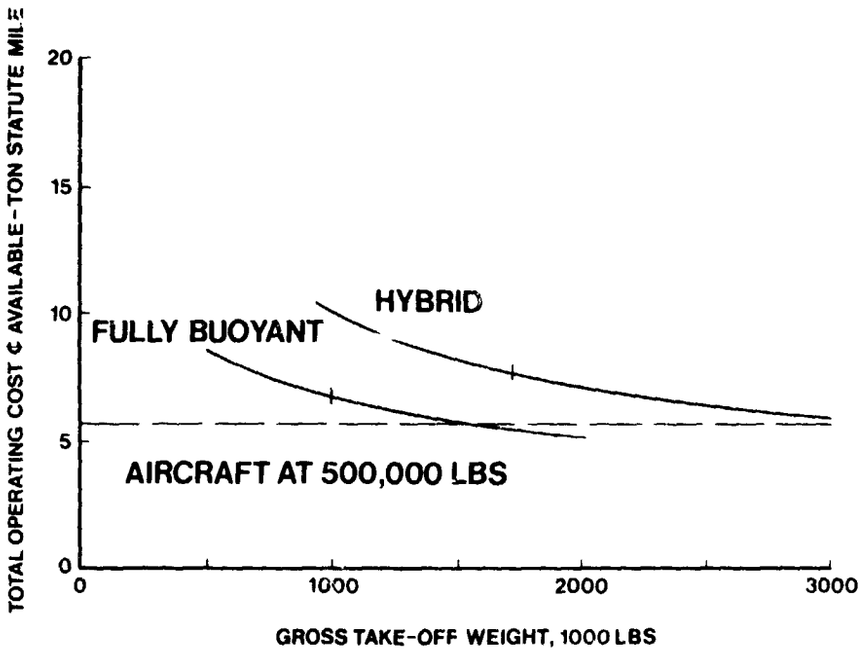


Figure 3
Effect of Take-Off Weight

The reason for this trend is not that the empty weight fraction decreases as is often stated (in fact, the "cube-cube" law implies a constant empty weight fraction), but rather that the skin friction decreases and the aerodynamic efficiency increases at the larger sizes. Figure 3 shows that the fully buoyant airship has the same TOC as the 500,000 pound cargo aircraft at a gross takeoff weight of about 1,400,000 pounds. The hybrid airship TOC only approaches that of the cargo aircraft at extremely large values of gross takeoff weight. At the large airship gross takeoff weights, a point of diminishing returns is reached beyond which further reductions in TOC are small.

The fully buoyant airship is superior to the hybrid airship at all values of gross takeoff weight and both are noncompetitive with the cargo aircraft at values below 1,000,000 pounds.

The sensitivites of TOC to cruise speed for the two airships are shown in Figure 4.

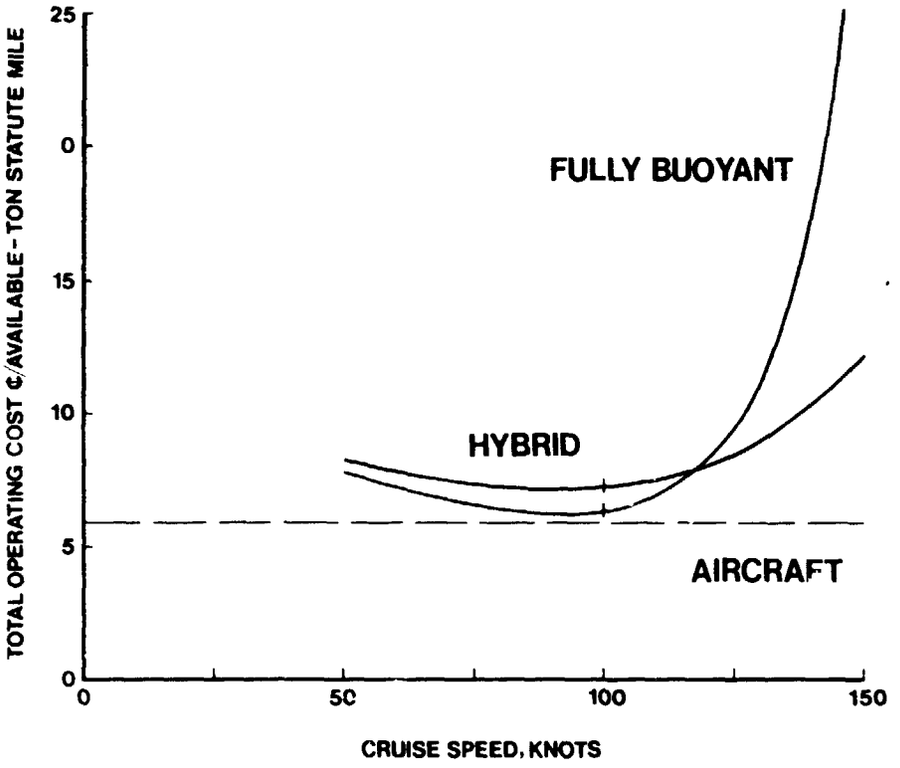


Figure 4
Effect of Cruise Speed

Also shown for reference is the TOC of the cargo aircraft which cruises at 462 knots. At lower airship speeds, around 50 knots, the fuel consumption is low and the payload fraction is high. The productivity, however, is very low. At higher speeds, around 150 knots, the drag becomes prohibitively high and the payload fraction becomes low. The result of these trends is that minimum TOC is achieved at around 100 knots for both airships, thus justifying the original choice of this cruise speed. The figure shows that the hybrid airship is much less sensitive to cruise speed than is the fully buoyant airship.

There is a severe penalty for flying at cruise altitudes appropriate for transcontinental flights as shown in Figure 5. If the requirement is for a 10,000 foot altitude, the TOC is approximately double that of the sea level case. At 20,000 foot, both airships have negative payloads. (Reducing the cruise speed or the range would give positive payloads at 20,000 feet.) To avoid venting gas, it is desirable to preheat the buoyant gas to expand it to the envelope volume prior to takeoff.

The effect of range on the total operating cost of the two airships and the aircraft is shown in Figure 6. The TOC of the fully buoyant airship and the cargo aircraft increases slightly with increasing range. The TOC of the hybrid airship increases

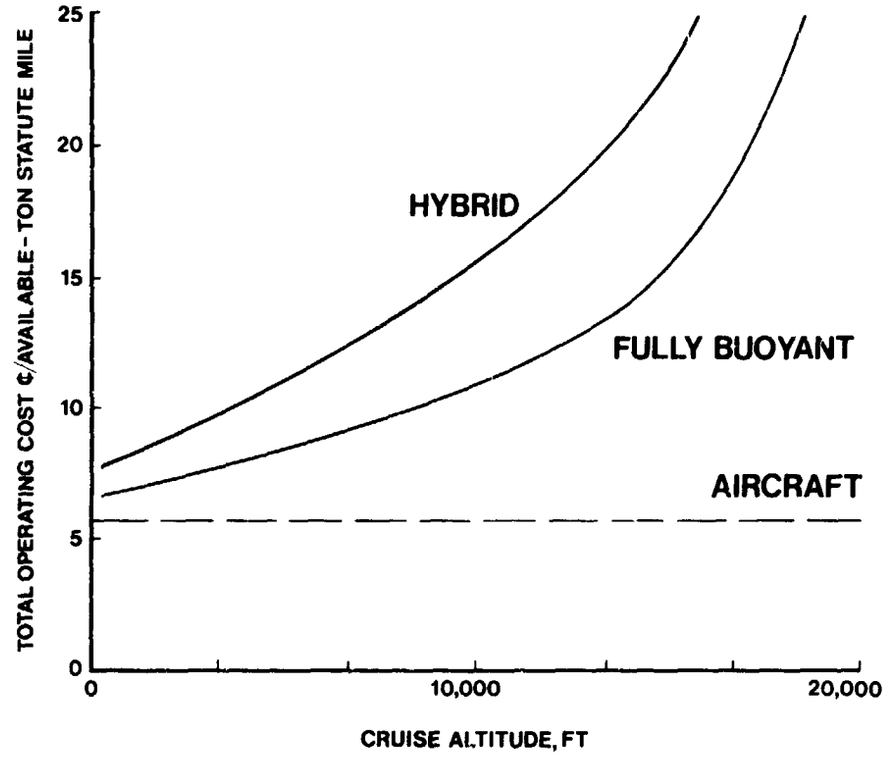


Figure 5
Effect of Cruise Altitude, No Preheat

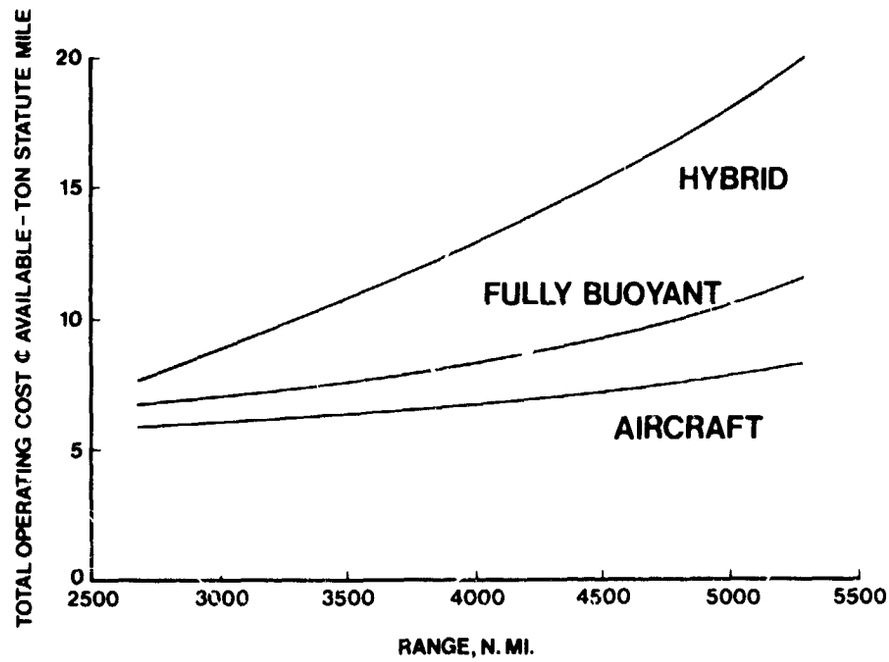


Figure 6
Effect of Range

more rapidly due to the relatively high fuel fraction and low payload fraction of this vehicle. At the longer intercontinental ranges of 5000 n. mi., the hybrid airship is not competitive with the fully buoyant airship or the cargo aircraft.

Current cargo transport aircraft are frequently limited not by cargo weight but by cargo density. Cargo aircraft are designed for a cargo density of about 10 lb/ft^3. For cargos of lesser density, the full payload weight cannot be carried. The effect on TOC is shown in Figure 7, where it is assumed that the airships are not limited by cargo density constraints. The effect on the cargo aircraft TOC is severe, and at a cargo density of 5 lb/ft^3 the cargo aircraft TOC is double that of the airships. Therefore, it may be concluded that airships are more attractive than aircraft for transport of low density cargo.

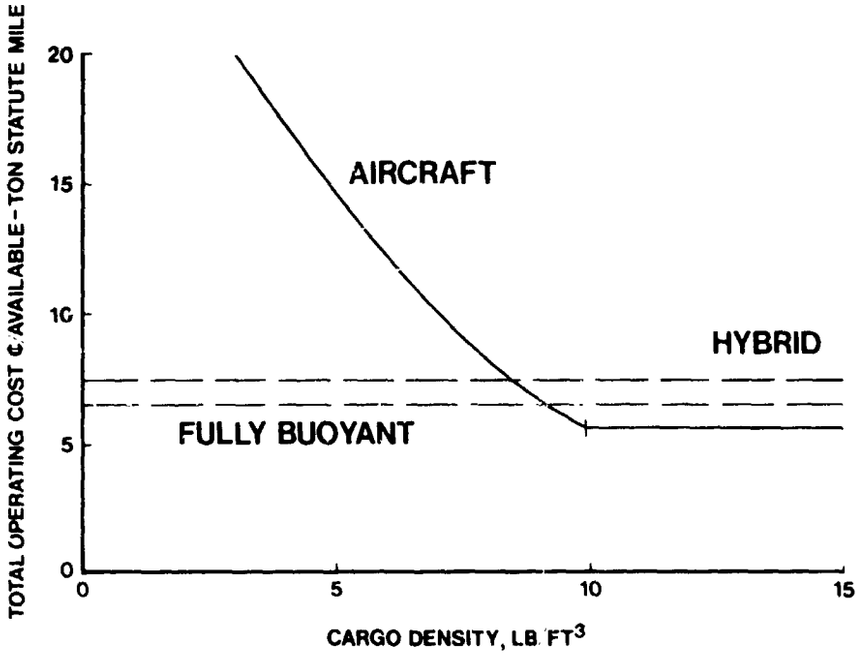


Figure 7
Effect of Cargo Density

CONCLUDING REMARKS

The results have shown that airships are marginally competitive with aircraft on established freight routes. Using somewhat optimistic assumptions for airship economic analysis gives airship total operating costs which are slightly higher than those for aircraft. There are, however, several categories of missions which are potentially attractive for airships, many of which were not considered in this study. Among these are: (1) transport of low density or indivisable bulky cargo (examples of the latter would be modular housing or nuclear reactor components); (2) transport to or from undeveloped sites (examples are transport of agricultural crops from sites which have no road or runway access and supply of developing nations); (3) missions in which the unique features of airships are of use (these features are high endurance and hover and V/STOL capability; the missions include surveillance and intra-urban transportation); (4) use as special purpose vehicles (examples are an oil/gas transporter in which the gas serves as the buoyant gas, and a hospital ship for disaster relief); and (5) military missions.

The parametric results show that airships are highly sensitive to cruise speed and altitude selection. It is important to select the optimum cruise speed correctly. It is highly desirable to preheat the buoyant gas in order to minimize the effects of altitude requirements.

The fully buoyant and hybrid aircraft designs were found to have about the same economic performance. The extra lifting capability of the hybrid is counteracted by its greater drag. The operating costs being equal, there are some operational factors favoring the hybrid. The hybrid would have less sensitivity to cruise speed, superior low speed control characteristics, and greater ease of ground handling as compared with a fully buoyant design.

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