THE BASIC CHARACTERISTICS
OF HYBRID AIRCRAFT

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ABSTRACT: A number of missions or capabilities associated with LTA technology have not been accomplished by Heavier Than Air craft. Among these are the transportation of very heavy or very bulky loads and the ability to carry out extended duration flights at low speeds and low cost.

LTA technology appears capable of contributing to the solution of these problems; however, there are strong indications that the ideal solutions will not arise from the rebirth of LTA technology in the classical form of Zeppelins and blimps but in the form of hybrid aircraft which exploit the advantages of both aerostatic and aerodynamic techniques while avoiding the primary disadvantages of each. This paper establishes the basic characteristics of hybrid aircraft.

INTRODUCTION

The entire rationale of hybrid vehicles is based on the fact that LTA elements are less sensitive to the size and weight problems which are characteristic of aerodynamically supported vehicles. Figure 1 (From reference 1) illustrates this dominating characteristic of LTA elements. A typical hybrid aircraft is very insensitive to weight variations and thus exhibits different basic characteristics than the airplane and helicopter upon which our existing aerospace industry is established.

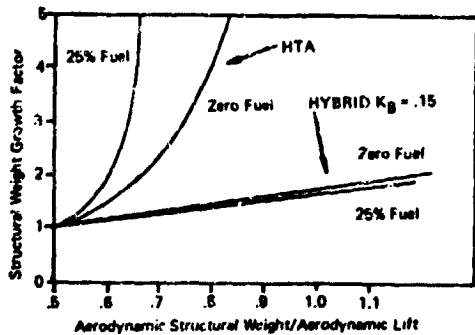* President, United Technical Industries, El Segundo, California

Figure 1
Structural Weight Growth
for a Constant Payload

The generalized structural weight equation for a hybrid machine is given by:

$$\frac{EW}{PL} = \frac{K_B(1-K_p+K_FK_p) + K_pK_S(1-K_F)}{1-K_F-K_B} \quad (1)$$

Where:

$K_B = \dfrac{\text{Structural weight of LTA element}}{\text{Lift of LTA element}}$

$K_p = $ Fraction of Payload carried by Aerodynamic Element

$K_F = $ Fuel Weight/Gross Weight

$K_S = \dfrac{\text{Structural Weight of HTA ele} \ldots \text{nt}}{\text{Lift of HTA element}}$

For a Pure HTA vehicle, $K_B = K_S$, $K_p = 1$, and the above reduces to:

$$\frac{EW}{PL} = \frac{K_S}{1-K_F-K_S} \quad (2)$$

A typical value of K_B is .15 or less and remains almost constant regardless of size while K_S is seldom less than .50 and grows as size increases. The advantage of adding an LTA element is illustrated by Figure 2 for the case of a hybrid with a $K_B = .15$ vs an HTA craft. For both aircraft the aerodynamic element weight/lift ratio, K_S, is allowed to grow. For the HTA craft the EW/GW ratio is identical to K_S, while for the Hybrid the EW/GW ratio is considerably less than K_S and remains in a practical range even when the Aerodynamic lifting structure far exceeds the lift produced by that structure. The overall vehicle weight (EW) required to carry a given payload (PL) is considerably less for the Hybrid than for the HTA craft and while the Hybrid machine should offer a significant cost saving over the HTA machine, the primary advantage of the Hybrid is that it makes very large sizes practical.
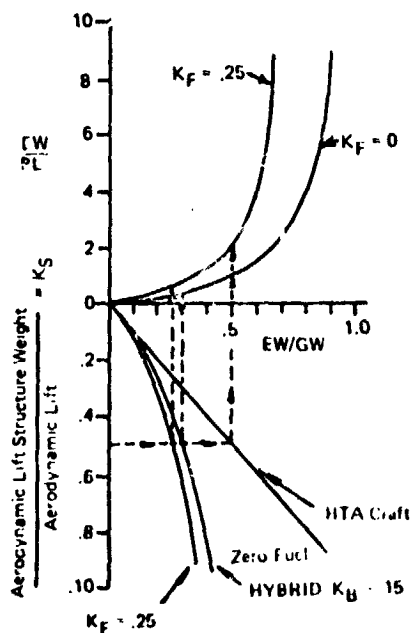

Figure 2.
Structural Weight Comparisons
HTAs vs HYBRIDS

The complexity of the problem can be appreciated from the following minimum list of factors which must be considered merely to categorize a hybrid vehicle:
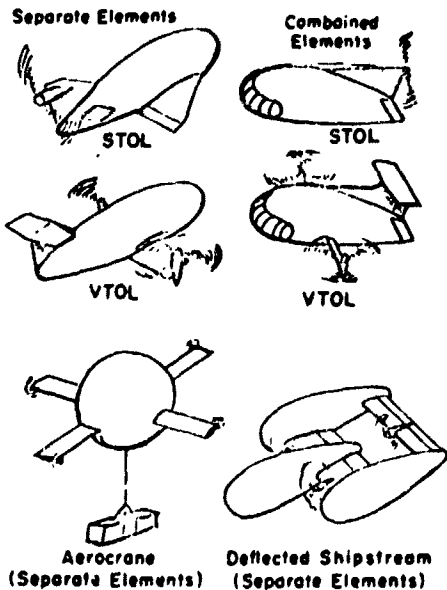
Separate Elements   Combained Elements

STOL   STOL

VTOL   VTOL

Aerocrone   Deflected Shipstream
(Separate Elements)   (Separate Elements)

Figure 3
Hybrid Configurations

D. Blimp

A. Airplane   Wing
                 Engine
                 Rotor
B. Autogiro
                 Engine
                 Rotor   E Hybrid
C. Helicopter   Engine

Figure 4
Generalized Aircraft

o   Airplane or "fixed wing" based hybrids vs helicopter or "rotary wing" based hybrids.

o   VTOL hybrids vs STOL hybrids.

o   Ballasted vs unballasted operation.

o   Separate static and dynamic lifting elements vs combining static and dynamic lift in one element. (Figure 3)

A very effective approach to isolating the important areas of hybrid vehicle interest is to define a totally generalized aircraft in which the fuselage, or working space, is identical for each aircraft, but the lifting means can be a wing (airplane), a rotor (helicopter or autogiro), a pure LTA system (Blimp), in Figure 4. The methodology can also be applied directly to a "rotary wing" as desired.
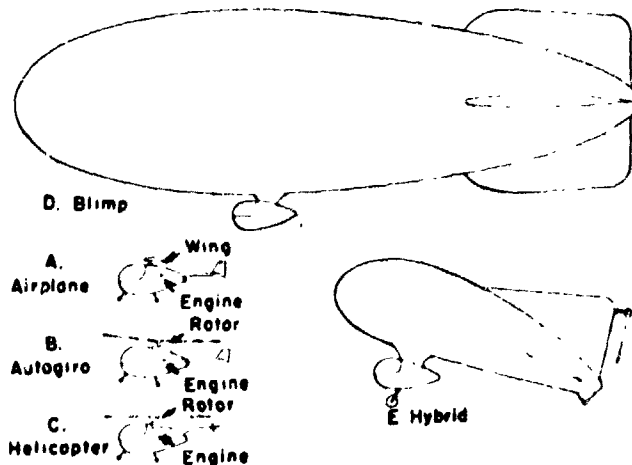
The hybrid machine thus can be treated as a generalized aircraft whose total lift capacity (i.e. gross weight) is provided by "p," the fraction of static lift, plus "1-p," the fraction of dynamic lift. For the case of combined elements, the volume of the "wing" is dictated by p; but with any given volume, the wing parameters (area, aspect, ratio, thickness, etc.) can be varied widely to produce a large family of surfaces with different dynamic lift characteristics.

There is a bit of irony involved in the hybrid aircraft of the type employing combined elements since the area available for the wing increases as the static lift percentage, p, increases. Maximum area is available for dynamic lift just when it is needed least, i.e., when the gas volume is enough to do the whole job. Nevertheless, this does not suggest a return to the pure LTA. Static lift elements still

appear to be best applied in combination with wings (or rotors) to allow them to fly slower, longer, or to carry larger loads. This is somewhat like adding a flap to a wing, but one which decreases rather than increases power requirements as speed is reduced. The enhancement of low-speed flight by the addition of LTA elements is paid for by large volumes, large frontal areas, and high drag which extracts a large power penalty at the higher-speed end of the spectrum. It also involves a handling and hangaring problem, when the vehicle is on the ground.

BUOYANT GAS LIFT CONSIDERATIONS

Light Gases

The buoyancy of a gas is simply the difference in density between air and the lifting gas. Several of the lighter gases are listed below with their densities and the ideal lift provided per 1000 ft^3 of the gas.

Gas	Density	Cp	Y	Lift per 1000 ft^3 (lbs)
Air	.0765	.24	1.4	0
Hydrogen	.0053	3.41	1.41	71
Helium	.0106	1.25	1.65	66
Neon	.0533	.246	1.64	23
Ammonia	.0451	.52	1.32	31
Methane	.0423	.59	1.3	34
Natural Gas	.0514	.56	1.27	25

A perusal of the above table makes it quite evident why the most common lifting gases are hydrogen and helium. Nothing else compares. The 7% lift loss of helium also seems a small price to pay for its non-flammability compared to hydrogen. The other non-flammable gas, neon, is poor in performance. The other flammable ones are all commercial gases and while they provide little useful lift capability for payload they can easily lift themselves and thus suggest aerial transportation by LTA vehicles.

Hot Air

One other gas, hot air, is commonly employed for lift, particularly in sport balloons. Its use is popular for the obvious reason that it is easily available. While not a factor in its choice, the low Cp of air also makes it cheaper to heat than, say, methane or helium. The lifting capability of air is directly proportional to the density difference between the hot lifting air and the outside free air.

As shown in Figure 5, a temperature increase of 152° (to a gas temperature of 212°F = boiling water) will produce a lift of 17.3 lbs for each 1,000 cubic feet of air. A 1000°F temperature rise will yield a lift of approximately 50 lbs. while a 2000°F rise is required to provide 61 lbs. A temperature of approximately 3400°F would be required to obtain 66 lbs., the lift of helium.
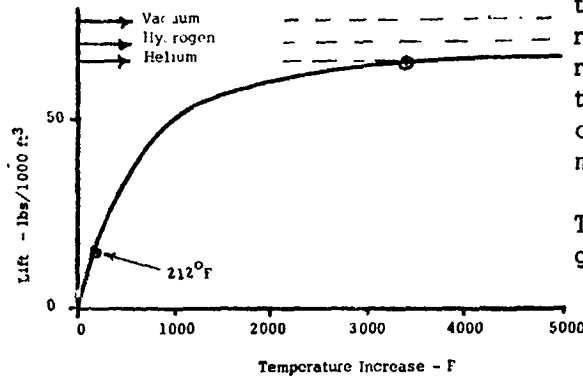
Figure 5
Lift Obtainable from Heating Air

Figure 5 shows considerable curvature in the lift characteristics indicating a severely reduced pay-off after 1000°F temperature rise. This is somewhat fortuitous because the lift obtainable by temperature rise is obviously limited by the capabilities of materials to contain the hot air.

The energy required to heat this air is given by:

$$\text{Btu/lb lift.} \quad = \quad T_o C_p \qquad (3)$$

This remarkably simple relationship states that each pound of lift costs the same in energy input regardless of the temperature level. For air at sea level standard temperature and $C_p = .24$, Eqn. 3 yields:

$$\text{Btu/lb lift} = 520 \, (.24) = 125$$

If we are to assume that this heating is obtained by burning a liquid hydrocarbon of 18550 Btu/lb costing 9¢ per lb (54¢/gallon) then the cost of lift by hot air is 9¢ x $\frac{125}{18550}$ = .06¢ per lb lift.

Helium therefore costs $\frac{1.06}{.0006}$ = 1770 times as much as a charge of hot air for the same lift.

Dry steam exhibits similar characteristics to air and the use of steam as a lifting gas could prove interesting depending upon the propulsion system employed and the possibility of condensing and recycling the steam in an integrated lifting-propulsion cycle.

LIFTING VOLUME GEOMETRY

The choice of geometry for a lifting volume is a compromise between minimizing surface area and weight and maximizing the favorable external aerodynamic characteristics one wishes to exploit. Surface area, or weight, to contain any given volume of gas is minimized, obviously, by the use of a spherical container. Free balloons approximate spherical shapes.

Non-Lifting Shapes

In the case of true LTA vehicles (Zeppelins and blimps) the departure from a sphere is made in the direction of ellipsoids to reduce the frontal area and drag in the forward flight direction. The ellipsoid shapes of LTAs, which attain all or most of their lift statically, vary from the classically streamlined "Tear Drop" blimps to the Barrage Balloon "Sausages" and "Cigar Shaped" Zeppelins.

In the case of a hybrid aircraft, which obtains dynamic lift from its static lifting element, the lifting volume must be shaped to provide a more effective dynamic lifting surface since the static lifting force is less than the gross weight of the aircraft. Instead of "squashing" the meat ball into the sausage shape of a classical dirigible it is now more beneficial to flatten it into a hamburger or perhaps even into a true wing shape which has a longer span than chord. (Figure 6)
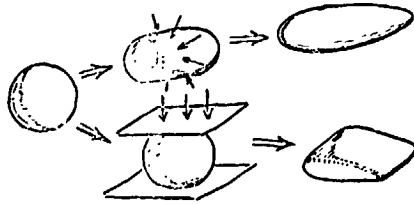

Departing from a sphere by increasing span (lateral stretching) while simultaneously reducing the thickness causes surface area and weight penalties more severe than longitudinal stretching but it does add dynamic lifting capability at a rapid rate.
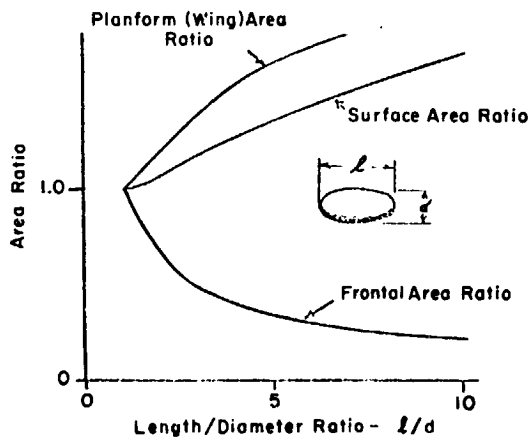
Figure 6
Various Shapes with the Same Volume

This is illustrated in Figure 7 which shows the area ratio relationships of an ellipsoid as compared with a sphere. Note that the frontal area can be reduced very much but one pays for this with considerable more surface area and structure to contain the gas volume. On the other hand, one also generates planform area which can act as a wing to provide dynamic lift.

Figure 7
Area Ratios of Ellipsoid Compared
to Sphere of the Same Volume

Lifting Shapes

The shapes defined in Figure 7 are representative of pure LTAs but do not provide as effective dynamic lift surfaces as those which have a greater span as is typical of airplane wings.

It is still desirable from a structure and weight viewpoint to depart as little from a sphere as possible while aerodynamically it is best to have a long span wing. Intuitively one might expect an optimum vehicle shape somewhat like a hemisphere. For the same volume as a sphere, the hemisphere would have 1.26 times the diameter or 1.59 times the wing area. Even the hemisphere is not a good airfoil shape and its frontal area/volume relationship is poor, being identical to that of the full sphere.

The area of a wing in terms of its volume is given by an equation of the form:

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$$A\ wing = K\ \_\ \frac{AR^{1/3}}{t^{2/3}} \times V^{2/3} \tag{4}$$

Where: AR = Aspect Ratio
t = Thickness ratio
V = Volume
K = Constant defined by the basic shape

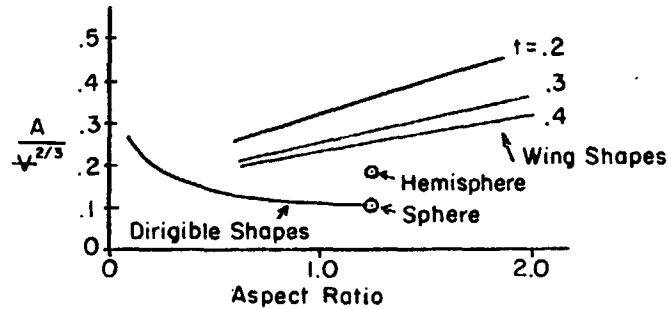Equation 4 is plotted for one value of K in Figure 8.

Figure 8
Effect on Aspect Ratio and
Thickness on Wing Platform Area

"AIRPLANE" HYBRIDS

For all practical purposes we can define a hybrid aircraft "wing" as being an air-
plane wing with a high-life device which allows it to maintain full lift at lower
speeds. In this case the high lift device is not a flap or slat which deflects the
airstream but it is simply a device which relieves the wing of part of its burden.
The amount of burden removed is defined by "p" which is the fraction of the gross
weight carried by static lift.

A given wing volume relative to total aircraft weight establishes the value of "p,"
but for this same value of "p" the volume can be arranged into an infinite variety
of wing geometries. For example, for any given fixed aspect ratio, a decrease in
thickness will increase wing area. Obviously this will affect performance more
than the thickness alone.

Drag and power curves were calculated and computer-plotted for 60 combinations of
variables:

Static lift fraction of total: $p = 0.2, 0.4, 0.5, 0.6, 0.8$
Aspect ratios: $AR = 0.5, 1.0, 1.5, 2.0$
Thickness ratios: $t = 0.2, 0.3, 0.4$

Figure 9 is a plot of drag and power curves for the case of $AR = 1.0$, $t = 3$, $p = 0.5$.
It should be noted that they are quite similar to typical airplane curves, except that
the power required at low speeds is much lower than for airplanes since a signifi-
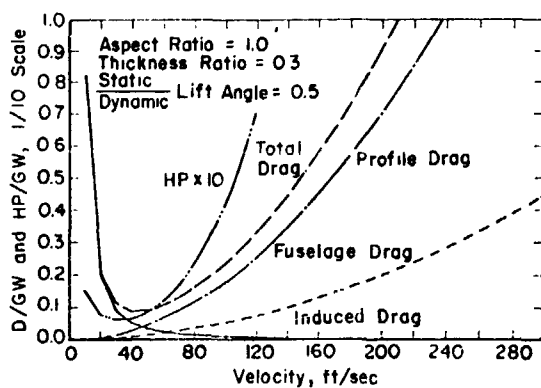cant fraction of the lift is supplied by the static lift element.

Figure 9
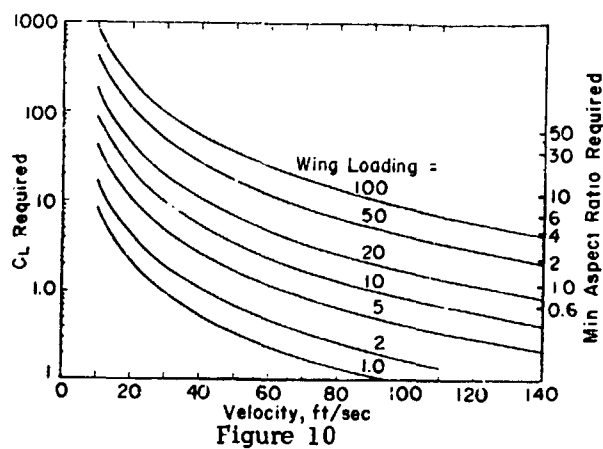Drag and Power Curves for
a Hybrid Vehicle

Figure 10
Wing Requirements
for Low Speed Flight

The minimum speed capability of an aerodynamically supported vehicle is a function of the wing loading and maximum lift coefficient, (Figure 10). The wing loading and lift coefficient are, in turn, functions of wing geometry (area, aspect ratio, etc). In the case of those airplane hybrids which employ their aerostatic lifting volumes also as aerodynamic surfaces, the aspect ratio and p factor both have a direct effect on the wing loading (Figures 8 and 11). The aspect ratio also has a direct effect on the maximum lift coefficient. Figures 11 and 12 illustrate the variation in wing loading and minimum velocity as affected by the p factor and aspect ratio.
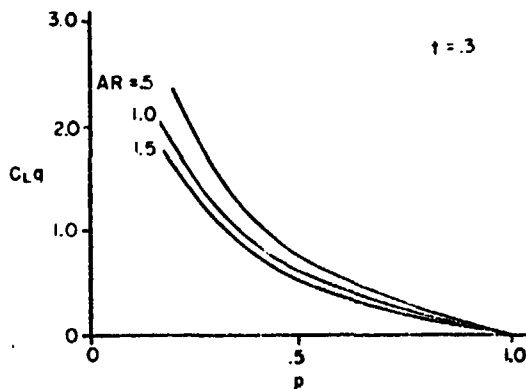

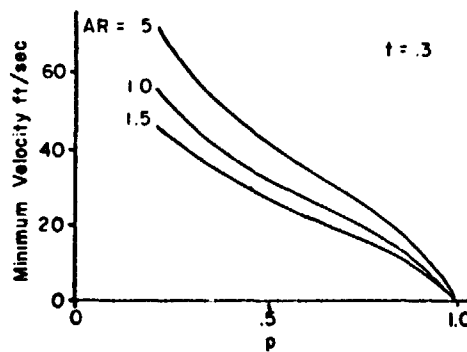Figure 11
Hybrid Aircraft Dynamic
Wing Loading

Figure 12
Hybrid Aircraft Minimum
Flying Speed

Several cases have been selected to illustrate the effect of the various parameters on vehicle power requirements. Rather than a display of the entire 480 computer plots, curves for 160 ft/sec (110 mph) and 50 ft/sec (35 mph) have been selected as basic indicators. Two additional curves were also chosen to illustrate the STOL characteristics: the power at 10 ft/sec (less than 7 mph), and the minimum power values. The speed at which minimum power occured generally fell below the 50 ft/sec checkpoint, thus illustrating the ability of a very simple hybrid aircraft to provide very low loiter speeds without flying on the back side of the power curve.
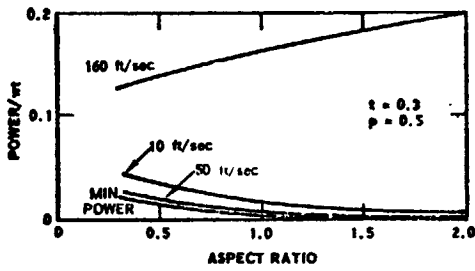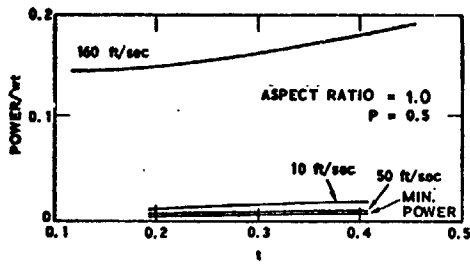
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Figure 13
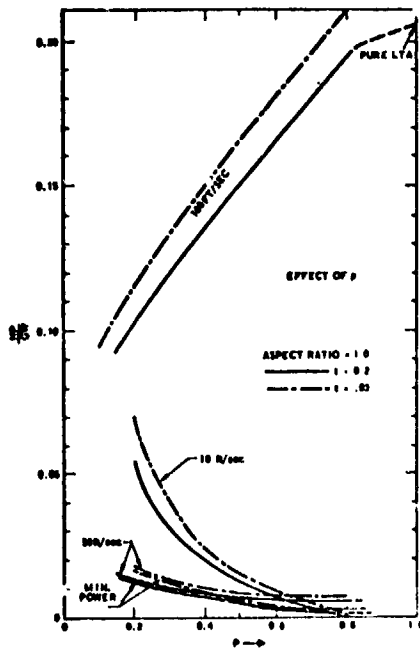Effect of Aspect Ratio

Figure 14
Effect of Thickness

Figure 15
Effect of p

Figure 13 illustrates the effect of aspect ratio when t and p are held constant at 0.3 and 0.5 respectively. Wing area increases with aspect ratio for a constant volume and thickness ratio. One would, therefore, expect this increased wing area at higher aspect ratios to manifest itself in improved low-speed performance but at the expense of drag during high speeds. Such is the case.

Figure 14 illustrates the effect of thickness ratio. The effect of thickness ratio on power required is surprisingly small, at least for the particular conditions assumed (AR = 1.0, p = 0.5). The conclusion drawn from this trend is that factors other than power requirements would dictate the choice of thickness ratio. For example, structural weight and ground-handling conditions might both benefit from increased thickness. The former is obvious in that thick wing structures can be built lighter than thin ones for the same loads.

It is less obvious, however, that the increased thickness ratio increases the wing loading. This is due to the fact that for a given p the volume is fixed, and an increase in thickness ratio shows up as a decrease in wing area. This tends to reduce gust sensitivity and ground handling problems, which would be expected in aircraft with low wing loadings such as these. Even with modest values of p, the wing areas are much larger than for airplanes, and anything which can relieve the gust sensitivity would be beneficial.

Other things being equal, a thick airfoil would appear to be desirable. However, while the drags of these thick airfoils probably have been adequately accounted for in this study, there is some question as to the actual efficacy of these thick sections as lifting elements in a practical situation. Section thicknesses of much over twenty-five percent may leave much to be desired, particularly if they involve unknown side effects such as erratic

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pitching moments or other poor handling characteristics. For this reason, before any decisions are made regarding the use of airfoils of over a 30 percent thickness ratio, it is recommended that considerably more study be given to the matter than was possible in this effort.

As would be expected, the most critical parameter is p, the fraction of the lift carried by the static lifting element. This is the primary parameter that differentiates the hybrid from a conventional aircraft. The effect of p has been plotted in Figure 15, with the aspect ratio held constant at 1.0. Thickness ratios of 0.2 and 0.3 are shown.

The primary performance penalty for the hybrid aircraft, as with its cousin the pure LTA, lies in the high-speed drag and power requirements. The high-speed power problem is clearly illustrated by the upper curve. This curve has been extended by a dotted line to the estimated performance for a machine of $p = 1.0$. (There is a break in the curve because there would be no reason to maintain an $AR = 1.0$ wing shape for a 100 percent state lift machine, and the best configuration would revert to a blimp shape of AR of 0.3 or less.)

With modern structural techniques it appears that a hybrid aircraft employing a mixture of static and dynamic lift can meet a number of mission requirements and provide long endurance at low-loiter speeds more economically than helicopters, airplanes, or autogiros. The problem is the power requirement at higher speeds. Obviously if extensive periods of loiter are required, p should be larger; while if high speed is required, p should be small. Recognizing that the one asset LTA elements offer is economical low-speed flight, it would not be too logical to incorporate LTA elements in a design and then prevent their effective exploitation by making p too small.

At this point, without a further mission-oriented guide to detail design, it would appear that a hybrid vehicle will attain most of the advantages hoped for it with values of p between 0.4 and 0.6, ARs of approximately 1.0 and thickness ratios representing the best compromise between aerodynamic performance and structural weight. Regarding the structural weight, one would expect the weight of any gas filled structure to minimize as it approaches spherical shape. It is, therefore, fortunate that the aerodynamics of hybrids tend to favor ARs near 1.0, as this is about as close to a sphere as a wing can be made.

AIRFRAME WEIGHT

General

There is no parameter more significant to the performance of an aerial vehicle than airframe weight. For any given aircraft class and size, the empty weight/gross weight ratio is a direct measurement of design refinement and structural efficiency. The empty weight represents the actual flying hardware purchased. Where the useful load (UL) represents the job to be done, the empty weight represents the initial investment made to get it done. It should be minimized, of course, and the value of the practical minimum is a function not only of the aircraft type and size but of the state of the art in materials and structure. All aircraft types are trending toward an EW/GW ratio of 0.50, with several isolated examples already below this value.

Figure 16 shows the linear relationship between UL and EW. For a given gross weight, a pound added to one obviously requires a pound subtracted from the other.
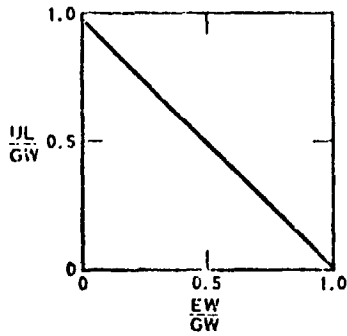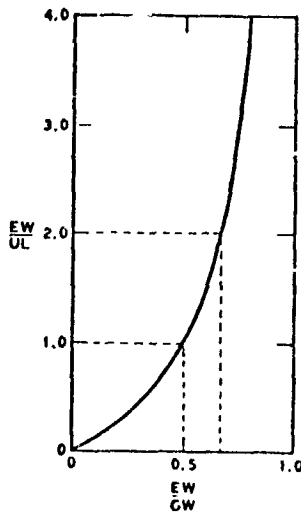
The significance of weight control for HTA craft is dramatically illustrated by plotting the EW/UL ratio. (Figure 17.) What appeared to be a rather innocuous increase in the EW/GW ratio now is seen to result in an extreme economic penalty when it is realized that a 30 percent increase in the EW/GW ratio from 0.50 to 0.67 results in doubling the size of the aircraft to carry the same useful load. This fact provides much of the incentive for employing LTA elements in the larger sizes rather than HTA elements (Ref. 1).

Figure 16
Useful Load - Empty
Weight Relationship

Heavier Than Air craft

The EW/UL ratio of several hundred aircraft of all Heavier Than Air types were plotted to determine the trends.

A combination of statistical, design study, and analytical approaches has been employed to develop a weight and cost rationale which is accurate for each aircraft type and consistent between types, both HTA and LTA. By the use of computer correlated statistical data, certain insights were gained in both the weight and cost pictures which led to a novel approach towards determining weight and costs which appears to be more accurate and consistent than previously existing approaches, however space does not permit covering this material in this paper.

Figure 17
Empty wt/Useful
Load Ratio

For actual aircraft types the EW/UL ratios vary from 0.8 to almost 4.0. In other words, for the lighter designs the purchase of only 0.8 pound of airframe is required to lift 1 pound of useful load, while at the other extreme the purchase of 4 pounds of airframe is needed to lift 1 pound of useful load. The EW/UL ratio is obviously the more meaningful one in pricing an aerial vehicle to accomplish a particular mission.

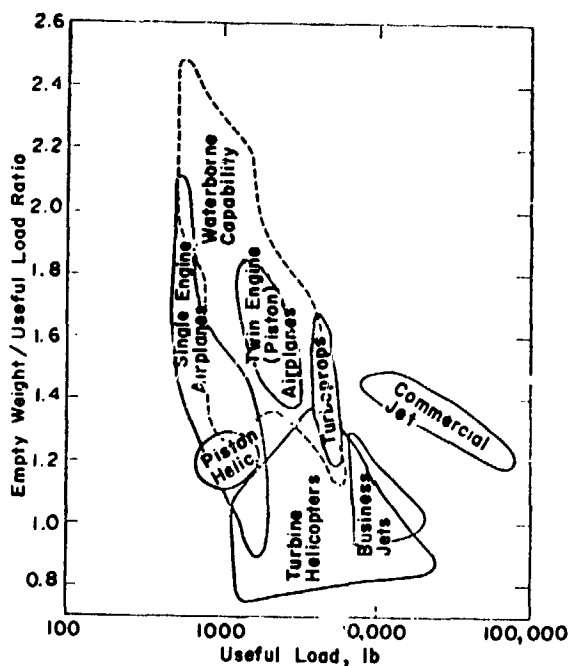The zones for a number of aircraft types are illustrated in Figure 18.

Figure 18

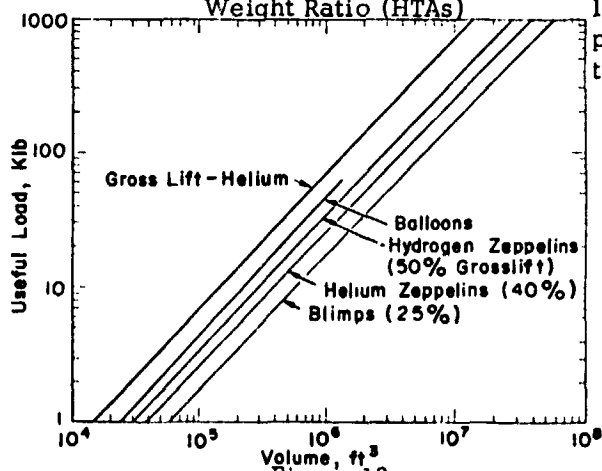Typical Values of Empty
Weight Ratio (HTAs)

Figure 19

Useful Load Capabilities
of LTA Craft

Lighter Than Air Craft

The Heavier Than Air types represent the overwhelming preponderance of aircraft. Their number and variety present a large base for statistical weight analyses but the Lighter Than Air (LTA) types are so few in number that a statistical analysis could be misleading particularly when most examples of the art represent obsolete practices. On the other hand, in some respects, the LTA types are simpler to analyze. For example, while the Heavier Than Air types are subject to the cube-square law, the static lift of an LTA type increases as the cube of its size right along with its empty weight, so that the efficiency of a giant machine should be no less than that of a small machine. Indeed, a plot of the limited data available (Figure 19) confirmed the linear (cube-cube) relationship to such a remarkable degree that it suggests more confidence in the ability to develop a weight rationale than was originally expected. The scatter of data points was so little for each discrete type of LTA as to provide certain insights regarding LTA potential on the basis of these observations:

o   The useful load ratio of rigid types of LTAs (Zeppelins) is considerably higher than for the nonrigid types (blimps). Useful-to-gross weight ratios of 40 to 50 percent are typical for Zeppelins, while blimps seldom exhibit ratios of better than 30 percent. (Blimps were not found inherently cheaper than rigid types either.)

o   The higher (50 percent) useful weight fraction for Zeppelins is associated with the hydrogen-filled types, while the 40 percent value is associated with the helium-filled types. The difference cannot all be accounted for by the 7 percent increased lifting ability of hydrogen. A small remainder is probably due to a somewhat more conservative design practice on the later American (helium-filled) models versus the earlier European (hydrogen-filled) models.

o   Nonvehicular-type LTAs (weather balloons, logging balloons, tethered Aerostats, etc.), manufactured with more modern materials and engineering than found in present blimps, attain useful load fractions of approximately 70 percent. To obtain a fair comparison with Zeppelins and blimps, of course, it would be necessary to add a propulsion system, fuel, and a "car" which would reduce the useful load values below those of Zeppelins but probably above existing blimps.

For the purposes of this study it was necessary to obtain representative weights of LTA elements. Furthermore, the LTA elements for hybrid types are not like conventional shapes for dirigibles or blimps but are of shapes closer to that of airplane wings. While struct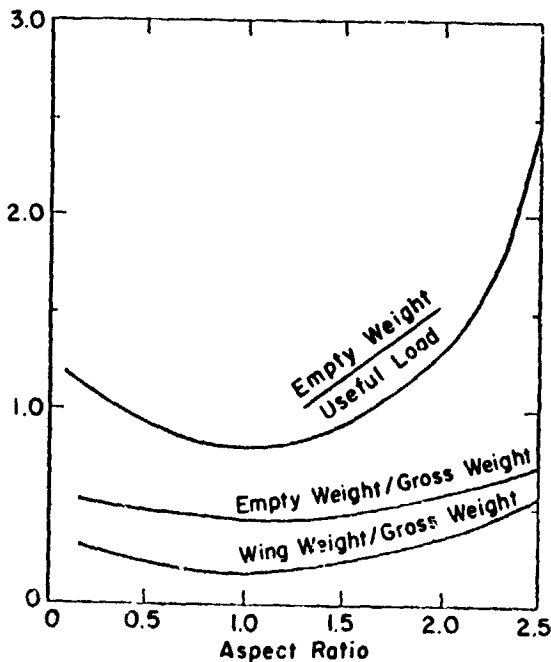ural shapes of almost any configuration can be attained with inflated structures, nothing was discovered that would indicate their superiority in weight, performance or cost except for the simpler (spherical) shapes. Since more data was available on metallic structure than on fabric, the weight was estimated as if the structure were rigid. Figure 20 illustrates the weight picture for "Fixed Wing" combined element hybrids.

Figure 20
Typical Weight Characteristics of
Hybrid Aircraft (Fixed 'Wing' -
Combined Elements)

Figure 21
Size Effect on Hybrid Aircraft

EFFECT OF SIZE

While airplanes follow a cube-squared law and become less efficient as size increases, dirigibles follow a cube-cube law and tend to maintain a constant useful load/gross weight ratio, regardless of size variations. The hybrid exhibiting certain of the characteristics of each, would be expected to fall between the two.

The wing area ratio between two geometrically similar hybrid machines (i.e., those with identical values of p, AR, and t) varies as the 2/3 power of their volume ratio. In other words, as the size increases, the wing area grows only as the 2/3 power of the buoyant (static) lift and the dynamic wing loading of the larger machine is greater than for the smaller machine. Either its minimum flying speed or its lift coefficient must be increased. (See Figure 21.)

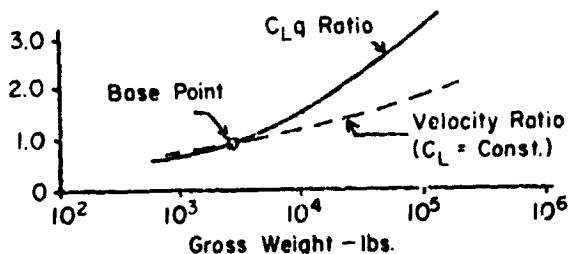Alternately, instead of maintaining similarity, the wing area could be increased (at the same volume) by decreasing the thickness ratio; or the aspect ratio could be increased to obtain a larger C_L margin. Both of these approaches would tend to increase "wing" weight. As size increases, there would appear to be less incentive to combine dynamic and static lift elements and favor separate elements. This is dramatically illustrated by Figure 22 and 23 which show, respectively, wing loadings

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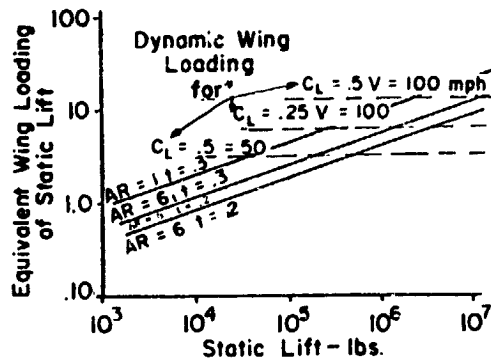for a fixed wing hybrid and disk loadings for a rotary wing hybrid.

Figure 22
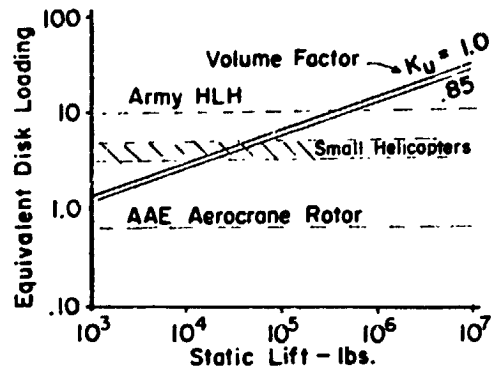Equivalent Wing Loadings of Static Lift

Figure 23
Equivalent Disk Loadings of a
Spherical LTA Lifting Body

In the first figure, the static lift equivalent wing loadings are shown in solid lines for several combinations of aspect ratio and thickness ratio. Superimposed (in dotted lines) are the dynamic wing loadings corresponding to the lift coefficients and forward velocities indicated. Note that as the static lift capability approaches a million pounds that the static "wing loadings" become equal to the dynamic wing loadings. In other words, the LTA elements become as "compact" (planform wise) as the HTA elements.

The same characteristic is illustrated in the second figure for a rotary wing hybrid. In the case of All American's "Aerocrane," the rotor system (the dynamic element) for a 50 ton payload model has a disk loading of only 0.6 lbs/ft^2 but the center balloon has an equivalent disk loading of approximately 5.5 which is higher than most existing helicopters (the Army's heavy lift helicopter had a specific design limit of 10 lbs/ft^2).

The planform densities of both fixed wing and rotary wing versions of the hybrid increase with the 1/3 power of the Static Lift, Ls:

$$\text{Fixed Wing Static Loading} \quad = f\left(\frac{t^{2/3}}{AR^{1/3}}, L^{1/3}\right) \quad (5)$$

$$\text{Rotary Wing Static Disk Loading} = f\left(L^{1/3}\right) \quad (6)$$

The thickness ratio and aspect ratio obviously drop out of the rotary wing case, at least for configurations where the static lifting element is an essentially spherical balloon as in the "Aerocrane."

PROPULSION SYSTEMS

The combination of LTA elements and large size has a devastating effect on the propulsion problem. The problem can be appreciated by an examination of the equation for the torque requirement for a rotor (or propeller) per lb of thrust.

$$Q_T = \sqrt{T}\left(\frac{K_1}{V_T} + \frac{K_2}{\sqrt{DL}}\right) \quad (7)$$

Note that this equation is not non-dimensional but includes the thrust (i.e., size) to the 1/2 power. Typical cases have been plotted on Figure 24.
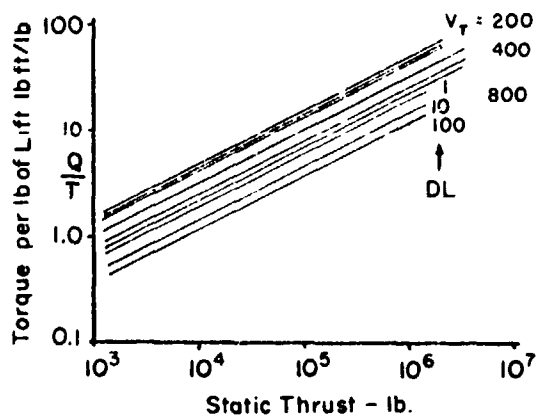
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Figure 24
Rotor Torque Requirements

Y-axis: Torque per lb of Lift lb ft/lb, $\frac{Q}{T}$, values 0.1, 1.0, 10, 100

X-axis: Static Thrust – lb., 10^3, 10^4, 10^5, 10^6, 10^7

$V_T = 200$, 400, 800
DL = 10, 100

Note that as the thrust requirements increases from, say, 3,000 lbs to 300,000 lbs, the torque increases from approximately 1 lb-ft/lb thrust to 10! Torque requirements can be reduced slightly by increasing the tip speed (Vt) or the disk loading (DL) but these are second order effects. The basic size problem predominates! This torque problem has such severe effect on gear box weight that there is a real incentive to consider non mechanical drive systems particularly in the larger sizes. Reaction drive systems (pressure jets, tip engines, etc.) have been studied for years for heavy lift helicopters, but the large sizes of LTAs and hybrids indicates a need to examine such drives for forward propulsion as well. In light of the characteristic speed spectrum, the forward thrust element most pertinent to LTAs and hybrids is the basic, open propeller (or rotor, in the case of the helicopter types).

For certain configurations, particularly fixed wing VTOL hybrids, ducted propellers or fans appear to offer many attractive features and must, of course, be considered. Ducting does lead to some size reduction, which improves compactness, particularly if the ducting represents an integral part of the airframe structure. As with disk loading or tip speed, however, ducting has only a second order effect on torque requirements and ducted propulsion or lifting systems cannot be expected to provide any significant weight saving over unducted systems. Their primary advantage is involved in the degree to which ducting contributes to the attainment of a practical integration of elements into a desirable overall configuration.

The severe torque problem of driving very large rotors, propellers and fans places the propulsion system right at the forefront of required technological improvements. In the case of the "Aerocrane" Heavy Lift System, tip mounted turboprops presently appear to solve the problem very effectively. For "Fixed Wing" Hybrids, no such obvious solution is available. Most LTA hybrid configurations merely suggest multiples of a conventional power pod driving conventional propellers, or, perhaps in the case of VTOL hybrids, multiple ducted fans.

Configurations which more fully integrate the propulsion and lift functions must be explored to determine if the problems of very large size are alleviated by such integration as opposed to maintaining separate functions.

The simplest integration objective would be to employ the propulsion system on a basic dirigible to reduce the aerodynamic drag by its effect on the boundary layer. Figure 25a illustrates the simplest case of a single conventional (though large) propeller or rotor in the pusher mode so that it tends to prevent boundary layer separation over the aft portions of the vehicle.

Figure 25b illustrates a configuration inversion in which the propeller is ducted and employs drastic diffusion to attain good propulsion efficiency from a small, lightweight propeller. A judicious choice of inlet location allows effective boundary layer management and the lack of external diffusion on the afterbody is also favorable toward maintaining a stable boundary layer. This configuration should also

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provide inherent directional and pitch stability without tail surfaces. Also, the larger internal gas volume aft result in a rearward shift of the center of life compared to conventional shapes. This is good.
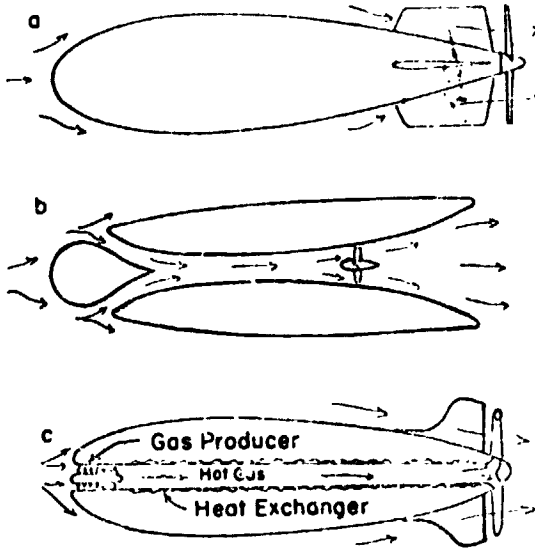
Finally, of course, one can consider exotic cycles. Figure 25c illustrates a system in which lightweight turbine gas generators produce the hot air which heats the lifting air or gas by a heat exchanger and then, after partial cooling, provides the propulsion at a high propulsive efficiency with a warm cycle pressure-jet driven propeller.

Alternately, steam cycles can be envisioned in which the steam first provides propulsion via a turbine and then passes to the lifting "bag" (cell or shell) where it produces lift and then condenses to return to the "boiler."

Of course, one can even speculate on the possibility of envelope materials attaining a $1,000°+F$ temperature capability thus making hot air as economically attractive for commercial operations as it has been for sport ballooning.

Figure 25
Aero/Propulsion Integration
Systems for Dirigibles

CONCLUSIONS

The very nature of a hybrid aircraft defines them as "light" aircraft and regardless of their size or configuration they may be synthesized from rather simple state-of-the-art elements which are well enough defined as to allow accurate overall parametric and detailed performance estimates.

The two primary problems involved in exploiting hybrid aircraft are: to define otherwise impractical missions and operations which become economically viable on the basis of applying LTA technology and then to tailor optimum hybrid aircraft around such missions. It is most important to fully appreciate the operational handicap associated with any vehicle which requires the use of ballast and how the elimination of ballast narrows the choice of configuration to those very few which can attain a suitable loading and efficiency balance between aerodynamic, aerostatic and propulsive elements.

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