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# The Suitability of Hybrid vs. Conventional Airships for Persistent Surveillance Missions

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**A pair of numerical models were designed to compare the relative merits of lifting body hybrid airships and conventional ellipsoidal airships on a generic persistent surveillance mission drawn from the recent "Long Endurance Multi-Int Vehicle" Statement of Objectives. The models were based on standard-practice assumptions and publically available information, adapted for this mission where appropriate. Considerable effort was expended to accurately capture the unique aerodynamic and operational characteristics of the two ship types. While the lifting body hybrid airship model was capable of carrying more than twice the fuel load of the similarly-sized conventional ship, the much lower average fuel burn predicted for the conventional ship resulted in generally superior loitering performance.**

## Nomenclature

| | | |
|---|---|---|
| $\beta$ | = | buoyancy ratio |
| $C_D$ | = | drag coefficient |
| $C_{D0}$ | = | zero-lift drag coefficient |
| $C_L$ | = | lift coefficient |
| $D$ | = | drag |
| $k$ | = | drag-due-to-lift factor |
| $L$ | = | lift |
| $L/D_{max}$ | = | maximum lift to drag ratio |
| $\lambda$ | = | heaviness fraction |
| $S$ | = | reference area, generally $V^{2/3}$ for airships |
| $V$ | = | hull volume |

## I. Introduction

CURRENT interest in the use of air-buoyant vehicles as unmanned persistent surveillance platforms raises the question of the most appropriate vehicle configuration for very long endurance missions. In the Army's Long Endurance Multi-Payload Vehicle (LEMV) Statement of Objectives (SOO), the Army originally expressed explicit interest in a hybrid airship for a 20,000 ft, three-week endurance unmanned persistent surveillance mission.[1,2] This raises several key questions: What exactly constitutes a hybrid airship? Is the typical "lifting-body" hybrid airship like the SkyCat family and Lockheed's P-791 more suitable for this type of mission than a conventional ellipsoidal airship? Is there another superior airship configuration that is distinct from either multi-lobbed lifting-body hybrids or ellipsoidal conventional ships?

The purpose of this paper is to evaluate the relative merits of a lifting-body hybrid airship hull form as compared to the conventional ellipsoidal airship for long endurance missions, using the specifications of the recent RFI as a benchmark. The superiority of a conventionally ellipsoidal airship for the long-endurance mission will be demonstrated through a numerical mission analysis of both types of ships using conservative aerodynamic characterizations drawn from literature, and common-practice weight assumptions.

## II. Background

Historically, the literature has made plain the superiority of conventional airships over lifting-body hybrids for long endurance missions. In particular, the sprawling and analytically robust "Feasibility Study of Modern Airships"

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conducted by Goodyear for NASA in the 1970's analyzed almost every conceivable hybrid airship configuration for various civilian and military applications.[3] Strong conclusions were drawn from this study and similar contemporary studies as to the best airship configuration for generic endurance missions.[4-6] The conclusions were generally that airships operating at a low heaviness fraction and utilizing ellipsoidal hulls were more suitable for persistent surveillance missions, and that there was no particular benefit to using a lifting body hull form. More recently, even hybrid proponents such as Ken Nippress (Chief Scientist, Hybrid Air Vehicles) have drawn similar conclusions.[7]

The SkyCat 20, a typical example of the multi-lobed lifting-body hybrid, claimed only a 5-day manned endurance when configured for endurance flight.[8] At approximately 32,000 $m^3$ hull volume[†], it is not clear that this could be extended to 21 days, even if unmanned, without substantially increasing the size of the ship. This is particularly so since the LEMV mission definition significantly exceeds the design pressure height of the SkyCat 20[‡], and that would dramatically reduce the available fuel load due to the larger required ballonet and attendant reduction in gas lift.

More recently, however, assertions have been made regarding the capabilities of the lifting-body hybrids in this type of long endurance mission.[9] It is evident that momentum has recently shifted towards hybrid airships in a persistent surveillance role. Nowhere is this more apparent than in early versions of the LEMV Statement of Objectives which specified hybrid airships,[1] though this requirement is softened in the latest version.[2] However, this shift in attitudes toward hybrids for endurance missions is occurring without a rigorous reversal of the conclusions of the pre-existing body of literature. Current opinion among some lifting-body hybrid proponents appears to be that the relatively higher fuel burn of a lifting-body hybrid (LBH) is more than offset by the higher total available static heaviness and increased fuel load. This point is the primary issue to be addressed by the present study.

There are considerations other than pure aerodynamic suitability which are typically cited in order to promote hybrids over conventional ships. Chief among these is improved payload capacity and ground handling.[8] The assertion regarding payload capacity is substantially true, and is what makes lifting-body hybrids so well suited for heavy-lift missions. The assertion that hybrid air vehicles would be more manageable in ground handling than a conventional ship, however, rests on the higher static heaviness of the vehicle, more aerodynamic crosswind profile, and frequently the use of hovercraft-like skirt 'suction' to hold the ship on the ground. While the assertion with respect to the crosswind profile is tenable, it is not clear that the LBH would have a smaller operational 'footprint' once the runway requirements of a hybrid are accounted for, and it is not clear that the LBH would not need to be masted for intermediate-term parking in an austere environment. Goodyear reached this conclusion when designing a lifting body hybrid for the Navy, ultimately deciding to go with a conventional masting system similar to that used by the Navy for its own conventional ships.[5] It has also been demonstrated that significantly enhanced low-speed controllability can be achieved with a conventional ship through distributed vectorable propulsors, as with the Zeppelin NT and Guardian Flight System's Polar 400 which reduces ground crew and runway requirements,[§] significantly reducing any relative advantage that hybrids may have in this area. In any case, relative advantages or disadvantages in low-speed handling are not the focus of this study, but rather airborne mission suitability.

## III. Analytical Approach

This study develops a generic example of each type of airship, and compares the performance of each on the same mission. The chief interest is in the influence of hull shape and typical operation on the loiter endurance. As such, ancillary distinguishing features that a given vehicle might possess such as choice of power plant or other technologies will not be considered, and the same assumptions will be used for both types of ships.

Once each ship is characterized, including drag polars, typical heaviness fractions, payload fractions, buoyancy ratios etc., each model will be analyzed for loiter endurance. As these assumptions will strongly influence the outcome of the analysis, every effort will be made to double-check the reasonableness of assumptions, and give the 'benefit of the doubt' to the lesser-well-characterized LBH.

The normal procedure for calculating aircraft endurance involves deriving some type of closed form approximate solution for endurance or range based on the vehicle characteristics. For some vehicles and missions, this is quite suitable, but as Dr. Boyd points out, for hybrids great care must be taken to account for the mix of aerodynamic and buoyant lift.[8] The same is true for a conventional ship on an endurance mission; a long-endurance mission will

[†] Data from http://www.hybridairvehicles.net/products_skycat20.html as of 12 December 2009.

[‡] Same as prior footnote, and also available at: http://www.aerospace-technology.com/projects/skycat/ as of 12 December 2009.

[§] Unpublished report from Dr. Charles Perkins, Craig Brown, and Daniel Peterman, "Blackwater Airships Demonstration Report," Office of the Secretary of Defense/Advanced Systems & Concepts, 2008.

encompass such changes in heaviness and optimal operating speed that shifts in these key parameters must be accounted for throughout the entire mission. To that end, the ship endurance will be calculated by a numerical model which re-calculates these key parameters at regular intervals, and operational changes can be made throughout the 'mission' as appropriate. A thorough description of the model and the calculations are included in the "mission modeling" section.

### A. Defining "Hybrid"

It is appropriate to address here the definition of a 'hybrid' airship. There is no authoritative definition, but typical examples drawn from the literature indicate that a hybrid uses some combination of buoyancy, aerodynamic forces, and vectored thrust to improve handling and performance.[8,9] By this definition, any airship with vectored thrust meets the definition of a hybrid throughout most of the flight, as airships virtually always make use of some amount of aerodynamic lift to correct for off-equilibrium conditions. Recognizing, however, that such definitions are normally a matter of degree, some point to a buoyancy ratio of approximately 0.8 and below as the domain of the hybrid airship.[5,10] The author asserts that all airships, including hybrids, operate at various locations on a 'hybrid spectrum' and, particularly on a long endurance mission, are likely to cross this threshold at some point. The focus of this paper is not on the degree of "hybrid-ness" of the two approaches under consideration, but rather on the influence of the aerodynamic character of the hull forms on mission performance.

### B. Aerodynamic Characterization

A reasonable first-order aerodynamic characterization of these two ships requires only four pieces of information:

1) Hull volume V
2) Hull form[**]
3) Zero-lift drag coefficient $C_{D0}$
4) Drag-due-to-lift coefficient k

The SkyCat 20 is the lifting body hybrid for which there is the largest quantity of technical information available, is probably in a size class which presents the least technical risk for the LEMV proposal, and represents a reasonable step up from the largest lifting body hybrid ever flown, the P-791 prototype. This ship will be used to set the baseline volume at 32,000 $m^2$. Even if this proves to be an unsuitable baseline for this mission, the comparison of the two ship types at the same volume will still be informative.

The aerodynamic characteristics of a typical modern conventional ellipsoidal airship are well established. The basic aerodynamic characteristics of the Navy's YEZ-2A taken from wind-tunnel data[11] will be used here as a proxy for the generic conventional persistent surveillance airship. The function describing the drag polar for this ship can be taken from a polynomial curve-fit of the appropriate set of data. For later comparison with the lifting body hybrid drag polar, the polynomial can be simplified to a pure parabolic form, in keeping with convention:

$$C_D = C_{D0} + k \cdot C_L^2$$
$$C_D = 0.325 + 0.85 \cdot C_L^2 \tag{1}$$

Aerodynamic characterization of the lifting body hybrid is somewhat more involved. To the author's knowledge, no publicly available body of wind tunnel data exists for the two- or three-lobed lifting body hybrid shape. Therefore the characterization will be done by analogy to the conventional ship, and verified against the limited data that is available. For a typical airship, the hull comprises the greatest part of the drag. Of the hull drag, the skin friction is the greatest part.[12] For this reason one would expect that a lifting body hybrid, with relatively more skin area for a given volume, will have a higher zero-lift drag coefficient. If we make the conservative assumption that the multi-lobed lifting body hybrid has form drag characteristics similar to a conventional hull, then any increase in the zero-lift drag coefficient for a given volume will be due to an increase in wetted area. For the double-hulled lifting body shape under consideration compared to the conventional hull, this ratio is estimated to be between 1.4 and 1.65, depending on the particular design, for a given enclosed volume. Therefore, to calculate the zero-lift drag coefficient for the lifting body, we start with the conventional hull as a baseline, and increase the drag due to skin friction by a factor of 1.5. This results in the zero-lift drag coefficient estimate shown in Table 1.

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[**] Multiple three-view drawings have been published for the SkyCat 20 over the years. For this study, the hull form was taken from: http://www.aerospace-technology.com/projects/skycat/skycat3.html as of 12/12/2009.

**Table 1. Break-down of hull zero-lift drag adjustment for the lifting body hybrid airship.**

| All Coefficients Basis $V^{2/3}$ | Conventional Airship | LBH |
|---|---|---|
| Drag of gondola and fins | 0.0044 | 0.0044 |
| Form Drag of hull | 0.0031 | 0.0031[††] |
| Skin friction drag of hull | 0.025[‡‡] | (0.025)x(1.5) = 0.0375 |
| Total Drag of Hull | 0.0281[§§] | 0.0405 |
| Zero-lift drag coefficient | 0.0325[***] | 0.045[†††] |

Next is the lift and induced drag characterization. Sufficient data is available to estimate the induced drag characteristics of the SkyCat 20. Using the data available in a fairly detailed treatment of the SkyCat family of airships,[8] it is possible to use the hull volume and planform area (estimated from three-view drawings for the SkyCat 20) to calculate what Dr. Boyd calls the "size scaling term." In this case, the size scaling term f = 16. From this the ratio of k and $C_{D0}$ can be derived as being in the range of 14-16. Note well that increasing the size scaling term, as with a larger ship, results in generally more favorable aerodynamic characteristics, and the SkyCat 20 produces characteristics at the lower end of the range for lifting body hybrids in general. Using the $C_{D0}$ determined above, it is a straightforward calculation to determine k, and generate a drag polar:

$$C_D = 0.045 + 0.67 \cdot C_L^2 \tag{2}$$

Plotting the lift-drag curves of each type of ship (see Fig. 1) allows an easy comparison. In keeping with the character of lifting bodies, this form allows for a wide range where the L/D is relatively insensitive to changes in $C_L$. Note well that this is only valid for airships that have a similar volume (within an order of magnitude) and that all coefficients are calculated using (hull volume)$^{2/3}$ as the reference area. This side-by-side comparison shows the relative advantages of each airship type. As one would expect, the conventional ship excels where little lift is needed. The hybrid excels when high lift demands showcase the superior induced drag characteristics of the LBH. Of course many other factors must be taken in to account in order to determine overall mission performance such as payload fraction, starting heaviness, water recovery and ending heaviness. It is also noteworthy that trim drag is not included in any of the above characterizations, and will not be considered for this analysis.

### C. Other Characterizations

An all-up-empty-weight (AUEW) including everything but the gases contained in the hull and ballonet can be estimated for the conventional ship using established guidelines as approximately 13,000 kg.[‡‡‡] For the SkyCat 20, the payload is 20,000 kg and the payload fraction is 0.48, producing a gross takeoff weight of 41,670 kg. The empty weight fraction is 0.35 producing an empty weight estimate of 14,600 kg.[8] The higher empty weight of the LBH can be attributed to the increased wetted (fabric) area, increased structural complexity, and additional stern thruster.

[††] It is probably optimistic to assume that form drag is not higher for the LBH.
[‡‡] 89% of total hull drag.[12]
[§§] Based on estimated in-flight Reynolds number of $1.7 \times 10^8$ using relations from Hoerner.[13]
[***] Based on YEZ-2A wind tunnel data.[11]
[†††] This estimate does not explicitly account for the frequently cited hover-craft style landing pads, which would likely increase this value.
[‡‡‡] Private correspondence with airship weights engineer John Bewley, 10 December 2009.

With this baseline is established, the model must be 'modified' to allow a 20,000 ft pressure altitude, which involves incorporating a larger ballonet and accounting for the attendant large reduction in available gas lift. Most airships have a pressure altitude of less than 10,000 ft, and cited performance specs for the SkyCat 20 reference a 9,000 ft pressure altitude,[§§§] although it is not clear that the payload is a full 20 tons at that altitude. Maximum pressure height (altitude at which the ballonet is completely empty) is an important consideration as it influences required ballonet fill at takeoff, which drives gas lift. A higher pressure altitude requires a larger ballonet and reduces available gas lift which, leaving the empty weight unchanged or slightly increased (if the ballonet envelope must be physically enlarged), decreasing total lifting capacity. This reduces the gross takeoff weight, and therefore the payload or fuel capacity. It should be noted that accommodating a ballonet roughly half the size of the hull, as required for operation at 20,000 ft msl, is a challenge in a conventional ship. This challenge becomes significantly greater with a lifting body shape due to the more complex internal structure. Dr. Boyd points out that hybrids, "due to their sensitivity to atmospheric density, will not fly at high altitudes like fixed wing aircraft. The basic structure is simpler, and therefore lighter, with a relatively small ballonet. The ballonet size is directly related to maximum altitude."[8] It is likely, therefore, that the empty weight fraction provided by Boyd, and used herein to estimate the empty weight, is too small for a high-altitude mission. An additional 400 kg, attributed mostly to the increased ballonet fabric, will be added to the original weight estimated, to make the new empty weight 15,000 kg.

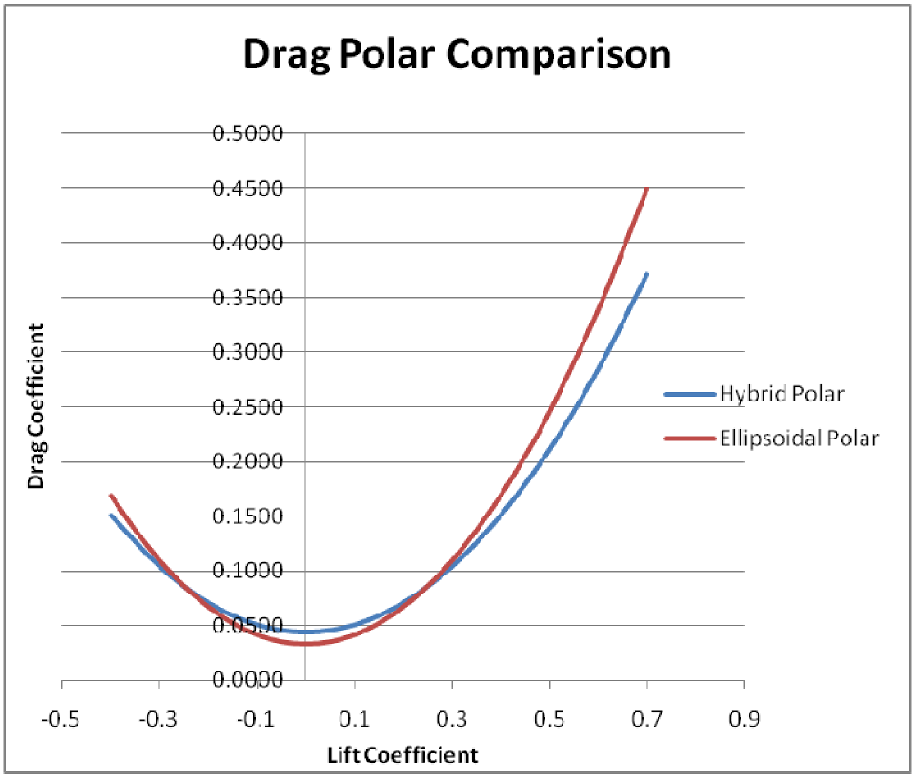


**Figure 1. Comparison of drag polars based on S = $V^{2/3}$.**

The high altitude nature of the mission highlights another important consideration for this analysis: the portion of vehicle mass supported by dynamic forces relative to buoyant forces. The buoyancy ratio β, defined as the gross weight (excluding gases in the hull and ballonet) divided by static (gas) lift will be used. Also, the heaviness fraction λ is useful for reference, defined as the gross takeoff weight divided by non-buoyant (dynamic) lift. Of course, β and λ must always total 1, even in the case of the "statically light" (gas lift exceeds gross weight) ship, when $\beta > 1$ and $\lambda < 0$, implying that negative dynamic lift is required to keep the ship in equilibrium. Note that dynamic lift can either be purely aerodynamic in origin, or the result of vectored thrust, but normally vectored thrust is not used in cruise and loiter portions of missions.

[§§§] Data from http://www.hybridairvehicles.net/products_skycat20.html as of 12/12/2009.

**Table 2: Effect of pressure altitude on airship characteristics**

| | Lifting Body Hybrid (SkyCat 20) | | | Conventional Ship | | |
|---|---|---|---|---|---|---|
| | **9,000 ft** | **20,000 ft** | **% Change** | **9,000 ft** | **20,000 ft** | **% change** |
| **AUEW (kg)** | 15,000 | 15,000 | 0 | 13,000 | 13,000 | 0 |
| **GTOW (kg)** | 41,991 | 34,501 | -18 | 28,840 | 21,350 | -26 |
| **Ballonet size** | 25% | 48% | +92 | 25% | 48% | +92 |
| **Gas Lift (kg)** | 24,840 | 17,350 | -30 | 24,840 | 17,350 | -30 |
| **Dynamic Lift (kg)** | 17,151 | 17,151[****] | 0 | 4,000[††††] | 4,000 | 0 |
| **β** | 0.59 | 0.50 | | 0.86 | 0.81 | |
| **λ** | 0.41 | 0.50 | | 0.14 | 0.19 | |
| **Useful Load (kg)** | 26,991 | 19,501 | -28 | 15,840 | 8,350 | -47 |
| **Payload (kg)** | 1,134[‡‡‡‡] | 1,134 | 0 | 1,134 | 1,134 | 0 |
| **Avail. Fuel (kg)** | 25,857 | 18,367 | -29 | 14,706 | 7,216 | -51 |

For this analysis, it will be assumed that the absolute aerodynamic lift generated by each vehicle for takeoff remains constant regardless of the ultimate pressure altitude, although the inertia of the ship increases with increased ballonet fill. These adjustments are made for the LBH and the conventional ship in Table 2 (assumes sea-level takeoff and ISA standard conditions). It can be seen that since the conventional ship relies more heavily on buoyant lift than the hybrid, the reduction in gas lift affects fuel load more severely.

Other assumptions must be made in order to complete the analysis. In particular, specific fuel consumption, propeller efficiency, water recovery rate etc. The same assumptions will be used for both ships. Any benefit due to mounting the propulsors in the low-speed wake at the stern are difficult to precisely identify, and explicitly ignored in this treatment.[3] A summary of the assumptions is shown in Table 3.

**Table 3: Summary of Ancillary Assumptions**

| Category | Assumed Value |
|---|---|
| Specific fuel consumption (lb fuel/hp/hr) | 0.35 (diesel) |
| Propeller efficiency | 0.6 |
| Ship system power | 5,000 Watts |
| Maximum water recovery rate ($kg_{water}/kg_{fuel\ burned}$) | 0.65 |
| Payload mass (from SOO) | 1,134 kg |
| Payload power requirements (from SOO) | 16,000 Watts |

Finally, certain assumptions have to be made about how the ships would 'normally' be operated. In particular, airships don't typically operate at less than 5% static lightness, although with thrust vectoring this could conceivably be decreased to 10% or higher. Hybrids normally land slightly statically heavy. We will assume a landing at equilibrium to allow for maximum fuel burn and efficiency. Given these parameters, a water recovery rate can be calculated for each ship which results in the appropriate heaviness fraction at the end of the mission, as shown in Table 5.

**** While not strictly true, it is allowed that the larger ballonet will not change the basic aerodynamic characteristics and performance of the ship, so this value is left unchanged.

†††† This assumes a combination of vectored thrust and rolling takeoff. The Navy's larger ZPG-3W routinely operated at a heaviness fraction of 0.10 without vectored thrust.[14]

‡‡‡‡ The payload is fixed by the mission. The balance of the useful load is attributed to fuel.

**Table 4: Required Water Recovery Rate**

| Type | Max Fuel Burn (kg) | Desired Change in heaviness (kg) | Water Recovery Required (kg) | Landing heaviness (kg) | Effective Water Recovery Rate |
|---|---|---|---|---|---|
| Hybrid (landing at equilibrium) | 18,367 | 17,151 | 1,216 | 0 | 0.07[§§§§] |
| Conventional | 7,216 | 5,500 | 1,716 | -1,500 | 0.24 |

In the model, the "effective water recovery rate" is achieved by assuming a plausible nominal water recovery rate (0.65) and the water recovery is "switched on" at the appropriate point in the mission so that the correct amount of water is recovered. The author hopes to address the topic of optimized water recovery for long endurance missions in a future paper.

## D. Mission Modeling

As the ships burn off fuel and recover water, the heaviness and required lift changes. For maximum endurance, it is not minimum thrust (which occurs at the $L/D_{max}$) which is the ideal operating point, but the minimum *fuel burn* speed. Fuel burn is a function not of thrust but rather power, which is thrust times velocity. The minimum fuel burn speed is usually somewhat slower than the speed for $L/D_{max}$, and occurs at a particular coefficient of lift rather than a particular velocity. The speed for minimum fuel burn changes with the heaviness. A facility to adjust the speed is included in the model. For this analysis, the appropriate coefficient was determined iteratively in the model.

As the ships approach static equilibrium, the minimum fuel burn speed will approach zero. Since the long endurance surveillance mission will require station-keeping, there is a minimum practical speed. The annual average winds at 20,000 feet over Bagdad are approximately 30 knots, and this will be used as the initial minimum value,[15] as in the RFI.

The mission analyzed herein consists of a cruise out to station, loiter, and a return. The takeoff, climb and landing portions are vanishingly small portions of the total flight duration, and will be neglected in this analysis. No fuel reserve will be assumed. A numerical model of that mission and based on the characteristics derived above was used to generate the performance estimates. A simplified description of the model operation follows in Figure 2. The time step was 0.01 hours, which from testing has been shown sufficiently small that there is no appreciable accuracy to be gained by making the step smaller. Numerical error is on the order of 1%, and far less than the error thought to exist in the other characterizations.

Check that fuel remains
Calculate required aerodynamic lift (difference of gross weight and static lift)
Calculate lift coefficient based on current density and velocity
Compute drag coefficient from aerodynamic characterization
Compute drag for current density and velocity
Compute power required at the propeller (thrust * velocity) / (prop efficiency)
Compute fuel burn rate
Compute incremental fuel burn (rate * time step length)
Add incremental fuel burn to running total and calculate remaining fuel
Compute incremental water recovery (incremental fuel burn * operative water recovery rate)
Add incremental water recovery to running total
Compute new ship heaviness to account for fuel burn and water recovery
Adjust ship velocity for minimum fuel burn
Advance one time step, and repeat

**Figure 2. Basic numerical modeling procedure.**

[§§§§] In practice, the hybrid is likely to be heavy enough to mitigate the need for a water recovery system.

## IV. Results and Discussion

Loiter time on station available for each ship is presented in Table 5. A one hour "cruise out" leg at 80 knots and 20,000 feet prior to loiter, and a similar return leg, is included in the analysis, but the endurance listed is the time on station only. The objective for this mission is three weeks, or 508 hours.

**Table 5. Endurance (Loiter Time On Station) Results**

| Type | Endurance (days) | Total Fuel Burn (kg) | Average Fuel Burn (kg/hr) |
|---|---|---|---|
| Lifting Body Hybrid | 7.6 | 18,365 | 101 |
| Ellipsoidal Conventional | 10.0 | 7,215 | 30 |

These results make it plain that, for ships of roughly similar displacement volume, the conventional ship is superior. In this day of concern regarding aircraft emissions, it is notable that the conventional ship burns nearly 61% less fuel in addition to providing longer endurance. Both ships fall well short of the three week mark, though the conventional ship comes closer. The key driver of average fuel burn for both ships is the minimum station-keeping speed. The influence of station-keeping speed on endurance is shown in Fig. 3. Both ships would benefit from less demanding station-keeping requirements, but the hybrids relative performance improves as station-keeping requirements become more demanding. Above fifty knots, the hybrid is superior, and the gap grows with increased speed.

The general operating profile of the two ships can be seen in Figs. 4 and 5. These figures are based on a lower resolution run than the actual results, to simplify data processing, but clearly demonstrate the phases of operation. The conventional ship, starting at 80 knots from the cruise leg, immediately slows down to the airspeed which produces the most efficient loiter at an angle of attack of around 15 degrees, about 34 knots. As the airship lightens, the speed gradually decreases until the minimum station keeping speed is reached. This speed is held for the duration of the mission, and as the ship continues to lighten, the angle of attack reaches zero, the fuel burn reaches a minimum, and then the angle of attack becomes negative to accommodate the statically light operation, and the fuel burn gradually increases again. At around 135 hours the water recovery turns "on" and reduces the rate at which the ship lightens.

The hybrid profile is similar except that the efficient operating speed starts out much higher at the beginning of loiter, at around 60 knots. A much greater percentage of the mission is spent slowing down to the minimum station

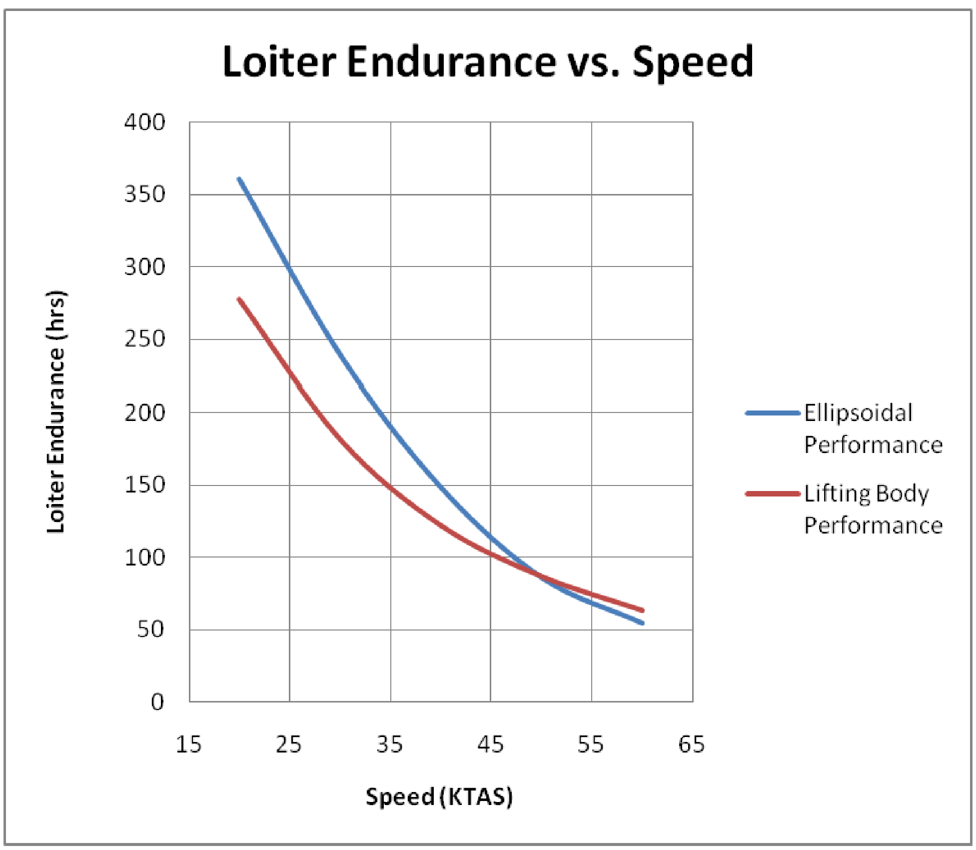


**Figure 3. Loiter endurance as a function of minimum station-keeping speed.**

keeping speed as fuel is burnt off. Recall that the model seeks minimum fuel burn speed – if the ship slowed to 30 knots immediately, the average fuel burn would increase, not decrease. Also, as the hybrid never reaches statically light operation, the fuel flow gradually diminishes, as heaviness is reduced, throughout the entire loiter phase.

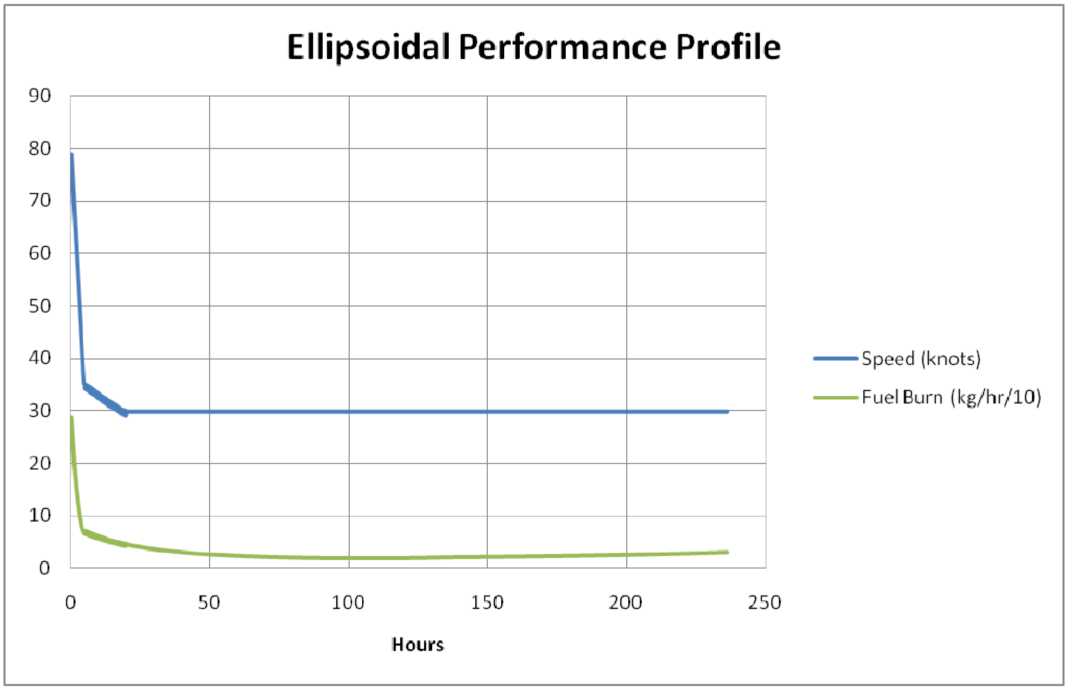


**Figure 4. Operating profiles of the ellipsoidal airship. Units in legend.**

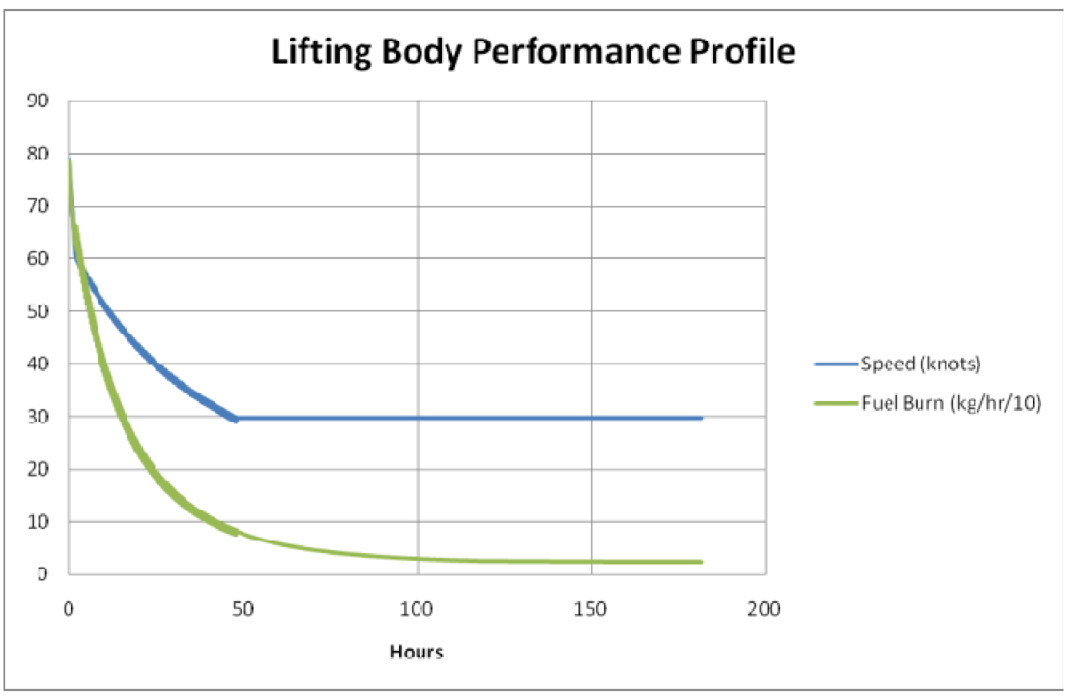


**Figure 5. Operating profiles of the lifting body hybrid airship. Units in legend.**

The author is aware of operating practices and technologies in development which can reduce the induced drag of the conventional ship when operating heavy, and allow takeoff with an increased heaviness fraction, permitting more fuel for the conventional ship and helping to close the fuel-load gap with the hybrid. It is hoped that these enhancements will be the subject of a future paper. The author confesses that the nuances of the hybrid and its operation are less well-understood. However, every effort was made to grant the hybrid the "benefit of the doubt." The estimates of the AUEW are thought to be reasonable good-faith estimates, probably within 10% of the true value, and probably optimistic.

## V. Conclusion

The conclusion reached by virtually every publically available study conducted up to this time is supported by the results of this study: the conventional ship is inherently better suited to the long-endurance mission than the lifting body hybrid. This superiority derives from the lower zero-lift drag of the ellipsoidal hull form which lends itself well to a mission profile which is driven more by efficiency than speed. If the induced-drag-reducing character of the lifting-body airships could be captured without the penalty of increased wetted area necessitated by the lifting-body approach, airships operating at higher heaviness fractions would be more suitable for endurance missions, and may find their already robust suitability for heavy-lift missions enhanced as well. Critical responses to the author's assumptions, methods and conclusions are welcome.

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[1]US Army Space and Missile Defense Command, "Draft Statement of Objectives (SOO) for Long Endurance Multi-Int Vehicle (LEMV)". Solicitation Number: W91260-LEMV, Notice Type: Sources Sought, Original Posted Date: April 22, 2009, Changed and Reposted May 29, 2009, Archived on August 9, 2009, URL: https://www.fbo.gov/index?&s=opportunity&mode=form&id=8a9576adda671991e001a322c98a6a44&tab=core&tabmode=list [cited 13 December 2009].

[2]US Army Space and Missile Defense Command, "Revised Draft Statement of Objectives (SOO) for Long Endurance Multi-Int Vehicle (LEMV). Solicitation Number: W91260-LEMV, Notice Type: Special Notice, Original Posted Date: August 10, 2009, Posted Date: September 15, 2009, Archive Date: December 1, 2009, URL: https://www.fbo.gov/index?s=opportunity&mode=form&id=5104ef5311642702aa0c49ab43cc50a6&tab=core&_cview=1 [cited 13 December 2009].

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