# VERY LARGE LUXURY AIRSHIP (VLLA)

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**Since the advent of flight over 100 years ago, commercial aviation has evolved from an awe-inspiring experience to what some would argue as a humdrum, point to point, cattle car-like mode of transportation. This paper presents a large rigid airship (The Very Large Luxury Airship or VLLA) as an alternative to the current status quo in commercial flight that offer a luxurious eco-tourism adventure and puts the awe back into the experience of flight. An initial design is presented for a rigid airship that has the capacity for 150 passengers and 26 crew with a range of 4500 miles. The propulsion system will be constrained to meet environmental recommendations proposed by the European Union's ACARE for a 50% reduction in noise with a 80% and 50% reduction in NOx and $CO_2$ respectively. Initial sizing iterations predict an airship with dimensions of 712 ft x 203 ft x 107 ft for length, width, and height respectively. These predictions put the VLLA in the same class as the largest airships built in the 1930's by the Graph Zeppelin and Good Year company. However, using modern materials, propulsion, and lifting gas system, the VLLA is designed to offer a level of comfort and safety not possible in the 1930's all while reducing the environmental impact to the most strict requirements for aviation in development.**

## Nomenclature

| | | |
|---|---|---|
| $a$ | = | semi major axis length of the ceiling of the cabin |
| $C_d$ | = | drag coefficient |
| $C_f$ | = | friction coefficient |
| $D$ | = | drag force |
| $g$ | = | gravitational constant |
| $H$ | = | height of the cabin |
| $\lambda$ | = | (length/width) fineness ratio |
| $\mu$ | = | coefficient of viscosity |
| $Re$ | = | Reynolds number |
| $\rho$ | = | atmospheric density |
| $\theta$ | = | angle of slope for the walls of the cabin |
| $v$ | = | velocity |
| $V$ | = | volume |
| $x$ | = | horizontal distance from center of an ellipse to a point along its perimeter |

## I. Introduction

Ask the average person on the street if they have ever dreamt of flight and you will likely hear a resounding yes. This fascination has likely been fixed in the psychology of the human species since we first looked up and imagined ourselves as the birds we watched playing in the sky. The Ornithopter by Leonardo Da Vinci, shown in Fig. 1, is evidence of this fascination. As dreamers of flight we live in fortunate times. Much of the world's population has had an opportunity to experience flight; an experience so many of our ancestors had only dreamt about. But what is the reality of flight as we reflect on 106 years since Kitty Hawk?

**Figure 1. Leonado Da Vinci's ornithopter[1]**

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For most of us, flight has been a point A to point B endeavor; far from ideal. Passengers sit crammed in small seats arranged in stiff rows and columns, with a small window for a few passengers at a window seat to peak down from 32,000 feet on a flat topography of browns, yellows, greens and blues. Why have we accepted this as the reality of flight? Is it because the dream of playing amongst the clouds and viewing the mountains valleys and waterways from above has faded? The author proposes that this is not the case, and the dream is alive and well, however in the year 2010 it remains a idealistic dream for most.

Viewing the world from a distance far enough above to appreciate the connectedness of nature and the beauty of its complexity, but close enough so that one does not lose the topographical details, allows one to step out of his small day to day world and observe his own grand interconnectedness. This heighten sense awareness has incredible power to influence decisions and attitudes about how one treats the natural world and others.

There have been shining examples in air travel that have not only fulfilled the dreams flight for those aboard, but enthralled nations of people who looked up in amazement as giant airships slipped gracefully through the sky. The great era of the airship lasted from 1897 with the introduction of the Schwarz Metelclad, until the spring of 1940 when the Graf Zeppelin II (replacement to the infamous Hindenburg) was dismantled in Frankfurt Germany[2]. This era ended with the introduction of travel by airplane. After all, the airplane was faster and required a much smaller ground crew of one or two as opposed to small armies to manage landing and mooring. Today however, there has been a resurgence of interest in large airships. Partly brought about by interest from a defense program called Walrus, conducted by United States' Defense Advanced Research Projects Agency (DARPA). This program investigated the use of extremely large airships to move entire military units into battle zones. Interest has also grown from small start up businesses offering site-seeing flights aboard small 246 foot long airships. The site-seeing tours offered by today's entrepreneurs resembles the beginnings of the airship era of the early 1900's. This era saw the growth of the airship in both size, to 803 ft, and capability, with crew and passengers of 123 people carried aloft on transatlantic flights in the highest comfort and luxury.

Using today's aerodynamic and structural analysis methods, along with modern materials and propulsion options, the modern airship can once again fulfill the dreams of flight; providing a unique experience and perspective of the world. Airships designed with these modern advantages may bring the ideal dream of flight not only to the very privileged few, but also to a much larger population of people, from several levels of income.

This paper will discuss the initial design of a large modern rigid airship with the scope limited to establishing mission requirements, configuration and initial sizing.

## II. Mission

### A. Market Analysis

The VLLA's target market is eco-tourism, primarily for people in the middle and above income levels. Travelers who are interested in sightseeing, exploration, and enjoying leisure vacations will love this style of travel. The current market is in it's infancy, with small scale operations in California and Germany[3,4]. The small scale market has shown great potential, using airships built by the Zeppelin company with short trips costing $500.00 they remained booked for the entire season[5]. Using these examples as a benchmark, the VLLA intends to expand the market to include longer trips which resemble those of the cruise ship or luxury train market. There are also examples of aircraft manufacturing companies with airships in the design phase intended to accommodate the type of travel the author are proposing. Lockheed Martin, World SkyCat ltd. and Aeros Corporation each have designs for large passenger airships. World SkyCat ltd. has designed the SkyCat. This airship is intended to be modular in design to accommodate cargo or passenger configurations. Aeros has introduced the Aeroscraft model ML866, designed as an improvement in travel for corporate sized aircraft.

Most journeys will be two to three days in length. The author envision voyages traveling along coast areas; for example flights along the coast of western US, from California up to Alaska. The airship will fly at altitudes of 1,500 above ground level (AGL) to afford the best view and experience for those on board. The VLLA will be designed with features to ensure the upmost comfort for long range travel, with both luxurious and economical style rooms.

The price for the two to three day cruse will range from $1000 to $3000 per person depending on what type of rooms the passenger desires. This price range is estimated using Airship Venture's ticket price of $500.00 for 2-3 hours sightseeing tours of coastal cities[6], and World SkyCat's estimates of $1000.00 per hour operating costs for their SkyCat[7], which is about half the size of the VLLA.

## B. Technical Feasibility

The Graf Zeppelin, using 1930s knowledge of aerodynamics, structures, materials, and propulsion was able to successfully obtain good performance for its time. Using airships of this type as a benchmark, one can extrapolate that improvements in size and performance using existing technologies is a reasonable task.

The VLLA will incorporate hybrid airship technology, meaning the total lift for flight will be a combination of both aerostatic and aerodynamic lift. The advantages of this design include greater efficiency, allowing the VLLA to meet its emissions requirements, and the ability to glide in the event of a complete loss of aerostatic lift which will increasing safety. Recent tests of the Lockheed Martin P-791 successfully proved the feasibility of the hybrid airship concept. Lighter and stronger materials will allow the VLLA to be of necessary size and shape to support our desired cabin volume and weight.

Continuing advances in aircraft propulsion efficiency will make possible the emissions requirements set for the VLLA. VTOL and STOL capabilities are one of the great advantages of airships and will be obtained by the employment thrust-vectoring along with buoyancy provided by the lifting gas. To increase the tolerance to inclement weather and winds which airships typically suffer, an adequate reserve of power will be available to handle such situations and increase safety.

## C. Economic Feasibility

To estimate the economic feasibility of the VLLA, the Aeroscraft ML866 and the Airbus A380 will serve as benchmark cases. The Aeroscraft ML866 has estimated production cost of $40 million[8] and the Airbus A380, which is a complex pressurized airplane, costs $327 million[9]. Using these examples, the author expect the cost of the VLLA to be bounded within this range.

## D. Mission Specification

1) Passengers: 150
2) Crew: 26, example crew makeup as follows:
    a. Pilot crew of 6 to facilitate multiple shifts
    b. 1 attendant per 10 passengers
    c. 1 chef and 3 cooks
    d. 6, ground docking, engineer and maintenance personnel
3) Cargo: Luggage, food and drink for trips durations of up to 51 hours
4) Spacious cabin area to accommodate 150 passengers with private rooms and public dining and recreation areas
5) Range: 4,000 nm
6) Cruise altitude: 1,500 ft AGL
7) Maximum altitude of 10,000 ft AMSL
8) VTOL/STOL
9) Environmental impact: meet goals set by the EU's ACARE, Advisory Council for Aeronautics Research in Europe
    a. Reduction in noise of 50%
        i. With a 737-800 as a benchmark 177 passenger aircraft, this would be 44 db at MGWTO (737-800 at TO = 88 dB)
    b. 80% reduction of $NO_x$ and 50% reduction of $CO_2$ emissions

## E. Critical Mission Requirements

There are two requirements that have been categorized as critical. These requirements will be both challenging to meet and drive the overall design of the airship. These requirements are:

- Environmental impact requirements:
    - The goals set by the European Union's ACARE are challenging measures which are hoped to be met by aircraft by the year 2020. Meeting these challenges with existing technology will be a primary driver of the design.
- Cabin space:

- Size and layout of cabin will drive overall shape and size of the airship. There has not been an airships built with the cabin size the author are proposing.

### F. Mission Profile

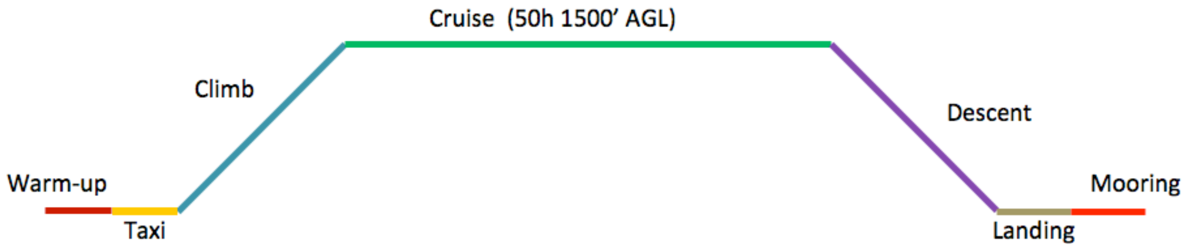


**Figure 2. Mission profile of the VLLA**

## III. Initial Configuration and Sizing

A sketch of the initial configuration of the VLLA along with a cabin layout is shown in Fig. 3. The cabin is designed to have two levels, with the perimeter of the top level reserved for passenger and crew personal rooms. There is a large open area extending from the bottom floor to the ceiling of the second floor throughout the cabin with exception of the rooms around the perimeter of the second floor. This is intended to promote a feeling of scale and openness.

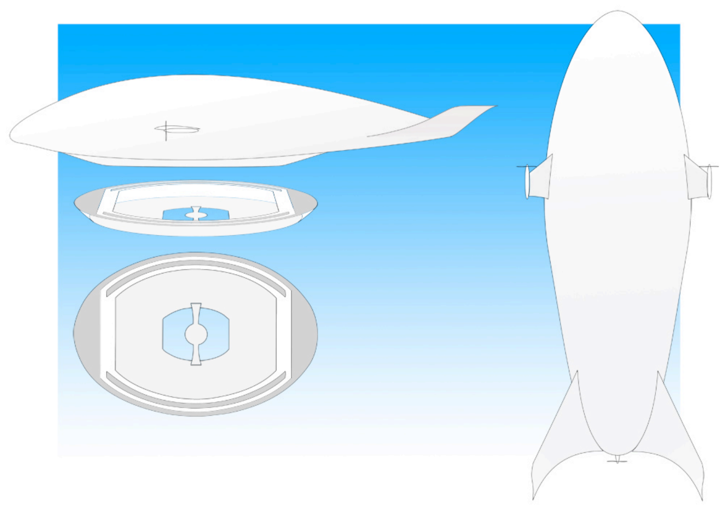

**Figure 3. Sketch of VLLA exterior and cabin.** *The dark shaded regions of the cabin represent the locations of room for passengers and crew, with large rooms fore and aft.*

### G. Shape

The exterior shape is a primary design consideration. Factors dependent on exterior shape include:

- Vehicle Aerodynamics
- Aesthetics
- Construction Feasibility

*1. Aerodynamics*

Based on the merits of safety and controllability, the VLLA is designed to be a hybrid airship, so that a fraction of total lift is generated aerodynamically. A wider fuselage/gas envelope is desired to maximize the aerodynamic lift. Unfortunately, form drag greatly increases if this approach is overstated. For an optimum reduction in form drag, the VLLA should be long and slender. However, a long slender body will not produce lift very efficiently and doesn't make sense for a hybrid airship. An estimate for drag on an airship is determined by modeling the airship as an ellipsoid, the total drag on the body of the airship is estimated using Eq. (1).

$$D = \frac{1}{2}\rho v^2 V^{\left(2/3\right)} C_d \tag{1}$$

Where the coefficient of drag is given by the equation (2), with $C_f$ evaluated as turbulent boundary layer over a flat plate using Eq. (3). This relation is derived from wind tunnel test of large bodies of revolution and described in Ref. 10.

$$C_d = C_f\left(4\lambda^{(1/3)} + 6\lambda^{(-7/6)} + 24\lambda^{(-8/3)}\right) \tag{2}$$

$$C_f = \frac{0.045}{\mathrm{Re}^{(1.6)}} \tag{3}$$

Plotting $C_d$ as a function of fineness ratio, shown in Fig. 4, indicates that the fineness ratio should be as close to 4.65 as possible. If the fineness ratio is increased above this value, $C_d$ will increase (along with a loss of aerodynamic lift due to the narrowing of the envelope). It is important to note that a lower fineness ratio is desirable on the merits of increased aerodynamic lift. However, as apparent in Fig. 4 the $C_d$ increases sharply at a fineness ratio of 3.5 and below. From this analysis a fineness ratio of 3.5 is selected for the VLLA as a compromise between lift and drag.

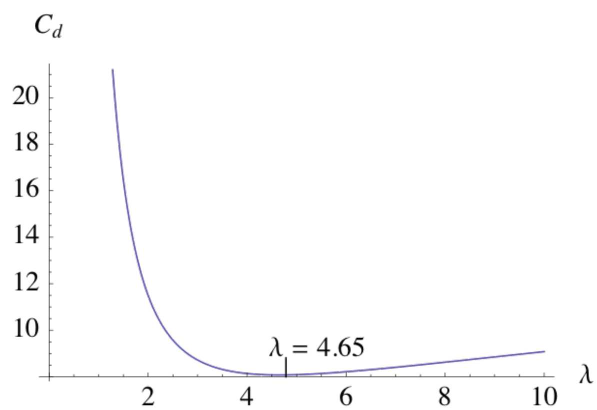


**Figure 4. $C_d$ trends as a function of the fineness ratio.**

*2. Aesthetics*

An aircraft may meet or exceed all technical requirements, but it may not be commercially viable if it appears awkward and unnatural. A great deal of merit is placed on the VLLA's appearance because it is destined for the commercial and leisure markets.

One of the goals of the VLLA is to impart a sense of awe in those who witness the craft in flight. Being over 700 feet in length, the shear size of the VLLA will be an impressive sight itself. However, sheer size alone is not always beautiful. To define the overall shape of the VLLA the author looked to nature for inspiration, and found the shape of the whale to be not only aesthetic, but also an example of nature's solution to efficiently move a large body through a fluid medium.

*3. Note on Manufacturing Feasibility*

Modern composites allow the use of smooth curves and compound surfaces. This allows the designers freedom to optimize shape for aerodynamics and aesthetics. However, complexity does not come free and penalties in manufacturing costs will occur if the shape becomes too complex. The VLLA will be designed with modern materials to maximize aerodynamics and, to a smaller degree aesthetics, while attempting to balance complexity to minimize manufacturing cost.

### H. Engine Configuration

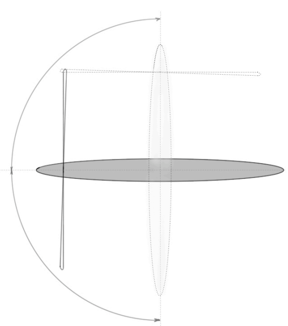

**Figure 5. Main engine range of thrust vectoring.**

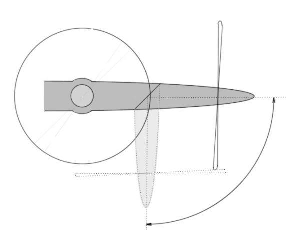

**Figure 6. Rear engine assembly.**

The VLLA will employ two main engines that will able to vector up and down through an arc of 180 degrees providing thrust for takeoff (VTOL mode) and forward airspeed (cruise mode) as shown in Fig. 5. A smaller engine, located at the stern of the airship, will drive two propellers to provide yaw and pitch control at slow forward airspeed. The rear engine configuration will have one propeller fixed so that the plane of the blades will be vertical and parallel to the longitudinal axis of the airship to provide yaw control. A separately controlled propeller will be mounted on the rear engine assembly so that the propeller plane axis can pivot 90 degrees as shown in Fig. 6. This engine will provide pitch control at low airspeed with the plane axis pointed downward, and thrust in forward flight with the plane axis pointed aft. This engine configuration is modeled after the modern Zeppelin NT.

## I. Cabin Size and Placement

To obtain the overall dimension of the cabin a Mathematica script is written that calculates the size of an ellipse needed to accommodate the 142 passenger (remaining 8 passengers will have large suites at the fore and aft locations of the second floor of the cabin) in 169 square foot rooms with 1.5 passengers per room. The logic of the script is described below:

- Inputs:
  $l$ = Distance from the tip of the ellipse to the start of the main rooms along the major axis (area reserved for large suites)
  $d$ = Depth of each room
  $\lambda_{cabin}$ = Fineness ratio of the cabin
- Total room floor area required ($S_f$) = (number of passengers / passengers per room) (Floor area per room)
- Calculate floor space obtained with an estimated initial second story floor semi-major axis ($a_f$), the given cabin fineness ratio ($\lambda_{cabin}$), and compare to total room floor area required. The calculations are re-iterate until values converge. The floor area along the perimeter arcs, between the large rooms at the fore and aft of the cabin, is integrated as shown in Eq. (4).

$$S_F = 2\left( \int_{-a_f+l}^{a_f-l} \sqrt{\left( a_f / \lambda_{cabin} \right)^2 \times \left( 1 - x / a_f \right)^2} \, dx - \int_{-a_f+l}^{a_f-l} \sqrt{\left( a_f / \lambda_{cabin} - d \right)^2 \times \left( 1 - x / (a_f - d) \right)^2} \, dx \right) \quad (4)$$

It is apparent that for a given overall length, an ellipse with a fineness ratio of one would yield the most floor space. However, lower fineness ratios require a wider ship which will have a drag penalty.

Total cabin volume ($V_{Cabin}$), as sketched in Fig. 7, is calculated using Eq. (5). Table 1 shows the results of the cabin sizing, allowing for an isle of 6 ft between the arcs of rooms.

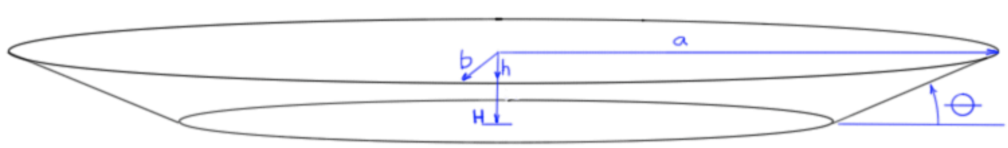


**Figure 7. Sketch of the cabin model used to obtain the total cabin volume.**

$$V_{Cabin} = \pi \int_0^H \left( a + h\tan(-\theta) \right) \left( \frac{a}{\lambda_{Cabin}} + h\tan(-\theta) \right) dh \quad (5)$$

$$a = \frac{(H-2)}{2\tan(\theta)} + a_f$$

The results for the cabin size estimates show the VLLA will require a large cabin to meet requirements for passenger space and room configuration. Therefore, the VLLA's cabin will be half inside the envelope with the bottom floor extending into the airstream. This configuration is chosen as a compromise between aerodynamic efficiency, fineness ratio chosen for the airship envelope, and space requirement for lifting gas and fuel.

**Table 1. Results from cabin sizing analysis.**

| Volume ($ft^3$) ($V_{Cabin}$) | Length (ft) ($2*a$) | Width (ft) ($2*b$) | Height (ft) ($H$) | Wall Slope (degrees) ($\theta$) | Depth of large suites (ft) ($l$) | Depth of main rooms (ft) ($d$) | Cabin fineness ratio ($\lambda_{cabin}$) |
|---|---|---|---|---|---|---|---|
| 1.15E6 | 398 | 199 | 22 | 45 | 20 | 12 | 2 |

## J. Lifting Gas management

The VLLA will use a system of large, ambient pressure lifting bags and high pressure storage tanks to accommodate for changes in pressure with altitude and temperature. This design is chosen over a ballasting method historically used on the merits of increased control and safety.

The lifting gas system will consist of numerous inflatable bags of helium that occupy the envelope's volume when inflated as shown if Fig. 8. During descent, or increases atmospheric density, helium will be removed from the low pressure lifting bags and stored at high pressure as pictured in Fig. 9. The opposite process is done for ascent.

The ability to rapidly inflate or deflate the individual helium bags will increase the VLLA's CG range. Another advantage to this system is that the aerostatic lifting force can be easily reduced so that the airship is no longer neutrally buoyant for ground handling. This represents a large advantage over other airships that require mooring and are highly vulnerable to ground winds.

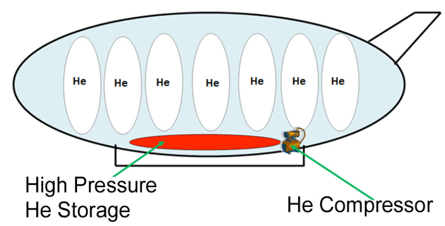


**Figure 8. Lifting bags in cruise or ascent**

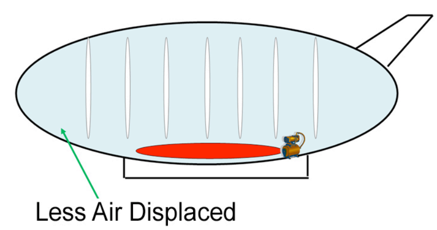


**Figure 9. Lifting bags in descent mode.**

## K. Tail Configuration

To reduce drag, weight, increase aft ground clearance, and accommodate the center-located rear engine, a butterfly tail configuration is selected. A butterfly tail also has an aesthetic advantage over conventional designs.

## L. Envelope Sizing

*4. Total Weight*

In general, the total weight of an aircraft, as described by Roskam[11], can be subdivided into three primary components. These components are *Payload Weight*, *Fuel Weight*, and *Empty Weight*. In order to determine the payload weight, it is estimated:

- Average weight of each passengers is 175 lbs
- Handy luggage for each passenger is 30 lbs
- 14,000 lb of cargo.

Summing these estimates yields a payload weight estimate of 50,080 lb.

Empty weight as a function of total weight is determined from the weight

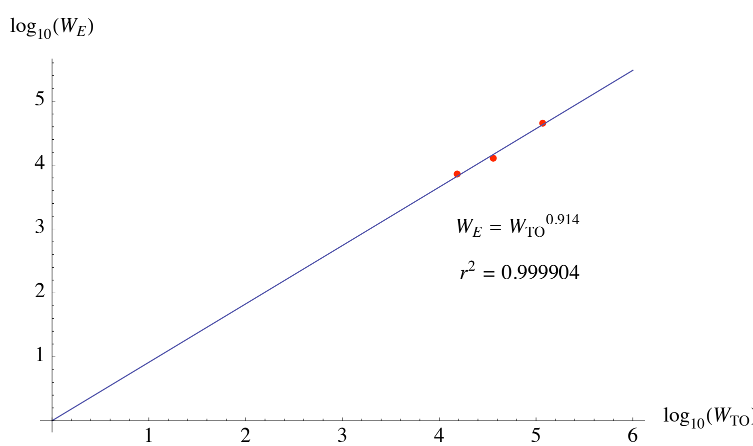


**Figure 10. Weight trend for modern airships.**

trends of published measured, and estimated data for modern airships (shown in Table 2). From this weight data, it is determined that $W_E = W_{TO}^{0.914}$. Weight trend fit shown in Fig. 10.

**Table 2. Weight data for three modern airships.**

| Name | LZ N 07[12] | LZ N 17[12] | Skycat 20[13] |
|---|---|---|---|
| Total Volume ($ft^3$) | 289,580 | 600,349 | 1,099,416 |
| Total Weight (lb) | 15,322 | 36,156 | 117,185 |
| Empty Weight (lb) | 7,255 | 12,831 | 45,292 |
| Payload (lb) | 4,079 | 11,685 | 29,000 |
| Fuel (lb) | 3,988 | 11,640 | 42,893 |

Fuel weight can be subdivided into two components of *Useful Fuel* and *Reserve Fuel* with 15% of useful fuel selected as reserve. Useful fuel is determined from products of thrust required, specific fuel consumption (estimated to be 0.35[14]) and number of flight hours. To determine thrust required, predictions for drag are performed at level, un-accelerated flight at cruise altitude, where the thrust required is equal to total drag. The total drag is estimated by modeling the airship as a large ellipsoidal body, choosing initial dimensions as inputs, and calculated using Eq. (1). However, the dimensions of the airship are dependent on the total weight. This is because the airship must be large enough to contain a sufficient volume of helium to provide neutral buoyancy at maximum altitude. As a consequence, the airship's dimensions are both inputs and outputs to the estimation of total weight. An iterative process is written as a Mathematica script to quickly converge on estimations for total weight as a function of flight speed, flight duration, payload weight, specific fuel consumption, atmospheric density at cruise and max altitude, and fineness ratio. A benefit of estimating max gross weight in this way is that the envelope size and thrust required at cruise fall out in the solution.

## IV. Results

The results of the initial design analysis for the VLLA are shown below in Table 3 as compared to 6 other airships that range from 1930's era large airships, to modern airships that are still in the design phase.

Other notable results are the estimations for total drag and therefore power required at cruise which is calculated to be 2,503 hp and the total fuel weight of 105.5 tons.

**Table 3. Results of initial sizing of VLLA as compared to other airships.**

| Name | *VLLA* | Graf Zeppelin[15] | Hindenburg[16,17] | GZ-20A[18] | Voyager[19] | SkyCat 20[13] | Aeroscraft ML866[20] |
|---|---|---|---|---|---|---|---|
| Type | Transport | Transport | Transport | Transport | Transport | Transport | Transport |
| Manufacturer | NA | Zeppelin | Zeppelin | Goodyear | 21st Century Airships Team Inc. | World SkyCat ltd. | Worldwide Aeros Corporation |
| Length (ft) | *712* | 776 | 804 | 192 | 223 | 266 | 210 |
| Diameter (ft) | *203* | 100 | 135 | 50 | 19 | 134.5 | 118 |
| Height (ft) | *107* | 100 | 135 | 59.5 | 125.6 | 72 | 56 |
| Volume ($ft^3$) $10^6$ | *7.513* | 3.707 | 7.062 | 0.2027 | 0.532 | 1.1 | 1.388 |
| Weight (tons) | *212* | 95 | 255.75 | 6.42 | not found | 58.6 | not found |
| Speed (mph) | *90* | 72 | 76 | 50 | not found | 85 | 138 |
| Range (miles) | *4500* | 4900 | 4560 | not found | not found | 2700 | 3100 |
| Altitude (ft) | *Cruise 1500 (max 10,000)* | 650 (max 6000) | 650 | 1000-3000 (max 10,000) | not found | 9000 | 5000 |
| PAX | *150 +26 crew* | 20 +36 crew | 72 +40crew | 6 +1pilot | 19 +2 pilots | 70 | not found |

## V. Discussion

The results obtained from the initial design analysis appear to reasonable approximation when compared to airships in Table 3. The closest match in terms of size is the Zeppelin Hindenburg, with the VLLA having a larger gas volume and smaller total weight. This seems reasonable since the Hindenburg used hydrogen, a more efficient lifting gas (albeit volatile), and a heavier structure, using 1930's materials and engineering methods.

The method employed for sizing the VLLA relies on drag estimations that have been intended to be over-estimations. In estimating drag, the VLLA was modeled as a axisymmetric ellipsoid. In reality, the VLLA is designed to be wider than it is tall to obtain a factor of lift generated aerodynamically. Work is underway to model a simplified geometry that better represents the VLLA for CFD analysis in order to obtain a better estimation of drag, and to obtain the pressure distribution for aerodynamic lift estimations. Engine sizing and selection will then be performed to ensure critical environmental mission requirements are met.

## Acknowledgments

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