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Technical Feasibility of Loitering Lighter-than-air-Near-space Maneuvering Vehicles

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TECHNICAL FEASIBILITY OF LOITERING LIGHTER-THAN-AIR NEAR-SPACE MANEUVERING VEHICLES

THESIS

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Abstract

The near-space region of earth's atmosphere above 20 kilometers altitude is greatly underutilized. Lighter-than-air maneuvering vehicles, or airships, using the principle of buoyancy can take advantage of this region to become potential platforms for precision navigation, environmental monitoring, communication relays, missile warning, surveillance, and weapon delivery. These vehicles purportedly provide persistent coverage over large areas of the earth's surface at substantially lower costs than orbiting satellites. This study investigated the technical requirements to loiter an operational payload within this high altitude region using a lighter-than-air maneuvering platform. A parametric analysis was conducted to identify the critical technologies needed to achieve operational payload, power, altitude, and stationkeeping requirements. The research concluded feasibility of stationkeeping a 1000 kg payload in lower near-space (20-25 km) using current airship technologies. Solar powered electric propellers provided the best overall near-space loiter capability for missions beyond 30 days. Additional loiter capability can be attained for shorter missions using fuel cell technologies. Technology improvements in the airship's drag coefficient, envelope fabric density, and payload mass and power requirements are required to attain altitudes beyond 25 km.

Acknowledgments

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TECHNICAL FEASIBILITY OF LOITERING LIGHTER-THAN-AIR NEAR-SPACE MANEUVERING VEHICLES

1. Introduction

1.1 Motivation

Satellites have created huge advantages in the US military arsenal throughout the past several decades providing environmental monitoring, precision navigation, communication, missile warning, and intelligence surveillance & reconnaissance (ISR) platforms. While great for strategic peacetime uses where freedom of overflight is required, satellites have several drawbacks when supporting tactical military operations. Governed by the laws of orbital mechanics, a satellite with constant view of an area on the earth orbits above the earth at over 35,000 km altitude [1:121]. While the field of view at this distance is tremendous, the ground resolution that can be achieved is limited without very large aperture optics. In order to get better resolution a satellite would have to be placed in a much lower orbit, typically around 200 km [1:57]. Through the use of a polar orbit, these low earth orbit (LEO) satellites can track a single location on the ground for only a few minutes at a time with hours in between successive passes [1:110-113]. Many orbiting LEO satellites would be required to provide persistent sensor coverage and could very easily become cost prohibitive.

High altitude airborne platforms such as airplanes and unmanned aerial vehicles (UAVs) have been used to provide a lower cost persistent sensor coverage option for tactical operations. These systems have great ground resolution, while increasing altitude improves their sensor footprint coverage. Traditional aircraft have a practical upper altitude limit. Engine efficiency greatly diminishes from 20-25 kilometers due to decreasing oxygen levels where eventually internal combustion and turbine engines fail to operate [2:5]. Near these altitudes, decreasing air density requires higher fuel consumption which limits overall loiter time.

There exists a region of earth's atmosphere above 20 km that is between traditional aircraft and low earth orbiting satellites and remains underutilized for military applications. High altitude maneuvering lighter-than-air platforms using the principle of buoyancy can take advantage of this region to become potential platforms for ISR, precision navigation, environmental monitoring, communication relays, missile warning, and weapon delivery. These vehicles can provide persistent coverage over large areas of the earth's surface with a substantially lower cost than an earth orbiting satellite, while providing longer loiter times and larger ground footprints than traditional aircraft.

1.2 Background

The use of lighter-than-air vehicles for military applications is nothing new. Lighter-than-air vehicles or "aerostats" have played an important role on the battlefield for more than two centuries. Twelve years after its invention in 1782 by Joseph and Etinne Montgolfier, Frenchman Jean Coutelle was lifted 450 meters in a tethered balloon to observe enemy formations and movements of the French Revolution [3:98]. Surveillance balloons saw continued use throughout wars in the 19th century including the American Civil and Franco-Prussian Wars [3:101-109,122-127]. At the start of the 20th century, Brigadier Count Ferdinand von Zeppelin had become alarmed by the developments made by the French who had crafted a electric engine powered non-rigid airship that could fly at speeds up to 11 miles per hour to provide long-range surveillance and carry bombs. In response, the Count built a 420-ft long cigar shaped rigid hydrogen-filled airship, which became known as the Zeppelin. The Germans entered the first Zeppelin into military service in 1908 and were used mainly for supply and bombing missions during the World Wars. These low flying airships were found to be vulnerable to enemy fighter aircraft equipped with machine-guns and provided limited utility in hostile battlefields [4:48].

In the 21st century, military planners are exploring the use of high altitude airships to perform satellite type missions due to their lower costs and responsiveness to tactical battlefield users. One such concept is the Missile Defense Agency's Advanced Concept Technology Demonstration (ACTD) program.

The MDA High Altitude Airship (HAA) prototype being designed and built by Lockheed Martin will consist of a lighter-than-air multi-mission platform operating at 65,000 ft (19.8 km) for one month while providing 10 kilowatts of power to a 4,000-pound (1800 kg) payload [5:8]. MDA identified a number of potential military uses including: communication relay, missile warning, surveillance and control, position/navigation, weather monitoring, electronic countermeasures, and weapons platform [5:4].

The USAF Space Battlelab also has a current high altitude airship initiative known as the Near-Space Maneuvering Vehicle (NSMV). A prototype NSMV is being developed to operate in the underutilized region of airspace above 100,000 ft (30.5 km).

Utilizing a unique semi-rigid V-shaped design, the near-space maneuvering vehicle will use solar energy to provide power to the propeller-driven helium airship. The initial prototype will be designed to "demonstrate that a lighter-than-air vehicle, can reach an altitude of 120,000 ft (36.6 km) with a 100 lb (45 kg) payload, navigate 200 NM (370 km), loiter for 5 days, and safely return" [6].

Although aerostats and airships have been utilized for military uses for the past three centuries, short duration, low altitude missions have yielded only limited military value. More recently, however, new technologies are increasing the feasibility of enabling long duration very-high altitude platforms. These new technologies yield new potential and new questions for what is within the realm of possibility for the next generation airships.

1.3 Research Objectives/Questions

For the lighter-than-air platform to be operationally feasible, military planners are looking for a system that can: lift an operational payload to near-space altitudes, provide necessary power and propulsion to operate the payload, and loiter over the area of interest for months at a time [5:3]. The feasibility of such a concept depends on several key questions that still need to be answered within the airship community and are summarized in Table 1.

Table 1: Research Questions

1	Can a lighter-than-air near-space platform be made to loiter in near-space for extended durations?
2	What propulsion requirements are needed to provide 24 hr stationkeeping to a near-space airship?
3	What propulsion system technologies are available to achieve near-space stationkeeping?
4	What fineness (length/diameter) ratio is the most optimal configuration to provide the best overall lift and the lowest drag for a near-space platform?
5	What altitudes can be achieved with airships using current state-of-the-art technology?
6	What airship modifications can be made to improve loiter capabilities and achieve higher operational altitudes?

1.4 Thesis Overview

This study investigates the vehicle technology requirements to loiter an operational payload in near-space using a lighter-than-air maneuvering platform. A parametric analysis was conducted to identify the critical technologies necessary to meet vehicle power and stationkeeping requirements. A secondary result was a tool for easily assessing a design feasibility given a set of technical design parameters.

The literature review section familiarizes the reader with the near-space environment, the different types of lighter-than-air platforms, and some of the technologies needed to design a near-space loitering platform. The methodology section in chapter three describes the baseline design and explains the formulas and rationale used within the analysis and results. The results section plots the airship envelope volume and the maximum loiter capabilities as a function of altitude for the baseline design. Parameters of the baseline design are adjusted one at a time to understand their impact on the overall design. An improved design is also plotted as a function of airship volume to understand the benefits of improving all parameters together. Alternative power and propulsion options are also explored to identify a maximum loiter capability for the baseline design. The thesis ends by answering the research questions posed at the start of this effort and recommendations future areas of study.

2. Literature Review

2.1 Chapter Overview

There has been a great deal of high altitude platform research over the past five decades. Much of the research has been focused within the scientific community to support atmospheric research and environmental monitoring using high altitude balloons [7].

The literature review can be broken into three main focus areas: earth's atmosphere, Lighter-than-air platforms, and state-of-the-art technologies for use in high altitude platforms. The atmosphere as a function of altitude was examined for temperature, density, winds, ultraviolet radiation, atmospheric drag, geometric ground footprints, buoyancy, and property of lifting gases. Types of lighter-than-air platforms researched include zero-pressure balloons, super-pressure balloons, sky-anchor balloons, rigid airships, semi-rigid airships, and non-rigid (blimp) airships. State-of-the-art technologies for use in high altitude platforms include envelope materials, power technologies, and propulsion technologies.

2.2 Earth's Atmosphere

Central to any discussion of the use of lighter-than-air vehicles is an understanding of atmospheric dynamics. This section looks at the atmospheric make-up and how it changes as a function of altitude, location and season.

2.2.1 Temperature and Density

Meteorologists divide earth's atmosphere into five regions based on vertical temperature profiles: troposphere, stratosphere, mesosphere, thermosphere, and exosphere. The troposphere begins at the earth's surface, which acts as a source of heat resulting from absorption of visible sunlight. The temperature decreases with height in the troposphere at a rate of around 6 degrees per kilometer. Weather phenomena such as thunderstorms and clouds occur in this layer and the air is well mixed in this region. At the top of the troposphere is an isothermal region known as the tropopause. The tropopause connects the lower atmosphere to a lesser dense region known as the stratosphere at about 10 to 17 kilometers above the earth. The stratosphere is heated from the absorption of over 99% of the sun's ultraviolet (UV) radiation by oxygen and ozone. The stratosphere extends to about 50 kilometers where temperature begins to decrease again with altitude in the region know as the mesosphere. The mesosphere (50-90 km) is a region of very low-density air that extends to the coldest region of the atmosphere at about -90°C known as the mesopause. The two most outer regions of atmosphere (90-1000 km), the thermosphere and exosphere, experience very high temperature extremes between 500°C to 2000°C based on the amount of solar activity. Molecules in this region are spread further and further apart until finally the transition to space begins and hydrogen and helium molecules escape into space [8].

Density within the atmosphere falls exponentially with altitude. Air molecules near the surface of the earth are held together more tightly than the molecules in the higher atmosphere because of the gravitational pull of the earth on all the molecules above the surface molecules. The higher in the atmosphere you go, the fewer the molecules there are above you lowering the confining force. This compressibility effect causes the bottom 10% of the atmosphere to hold about 90% of the air as shown in Figure 1.

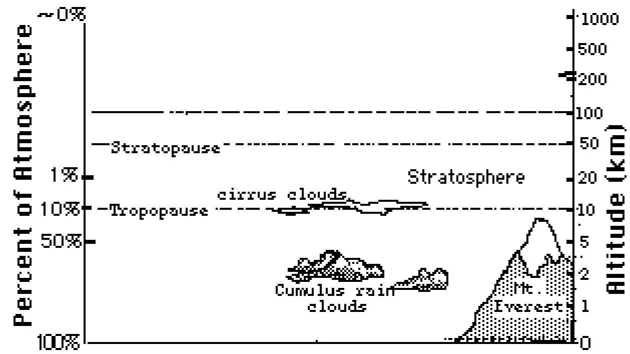

Figure 1: Percent of Atmosphere at Altitude

Atmospheric temperatures and densities in the regions of interest are plotted in Figure 2. Air Densities above 20 kilometers altitude are below one percent of the air density found at sea level [8].

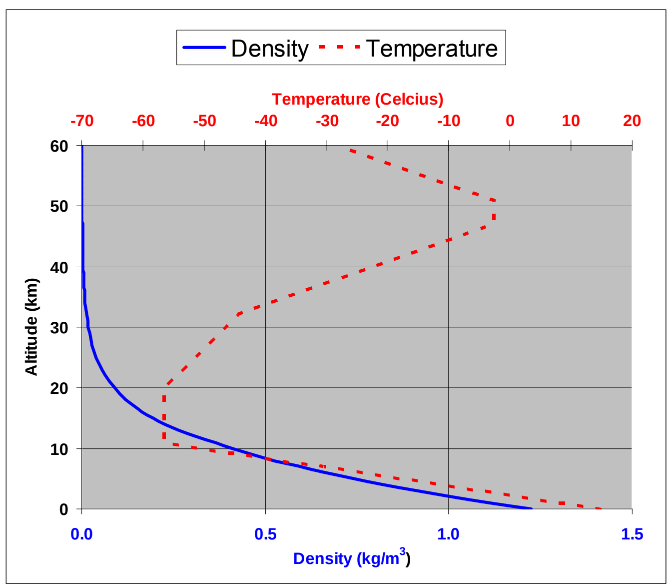

Figure 2: U.S. Standard Atmosphere Profile

2.2.2 Winds

Wind patterns vary greatly as a function of altitude and earth latitude (Figure 3). Mean zonal (East-West) winds tend to be largest near the two global jet streams at 40°

North and South latitudes causing large prevailing winds to exist at these latitudes. Meridional (North-South) winds are much lower by comparison but are highly variable throughout the day. The vertical wind component has its greatest impact in the equatorial regions where the highest atmospheric heating occurs. Overall, mean zonal winds present the largest concern when dealing with vehicle stationkeeping [9].

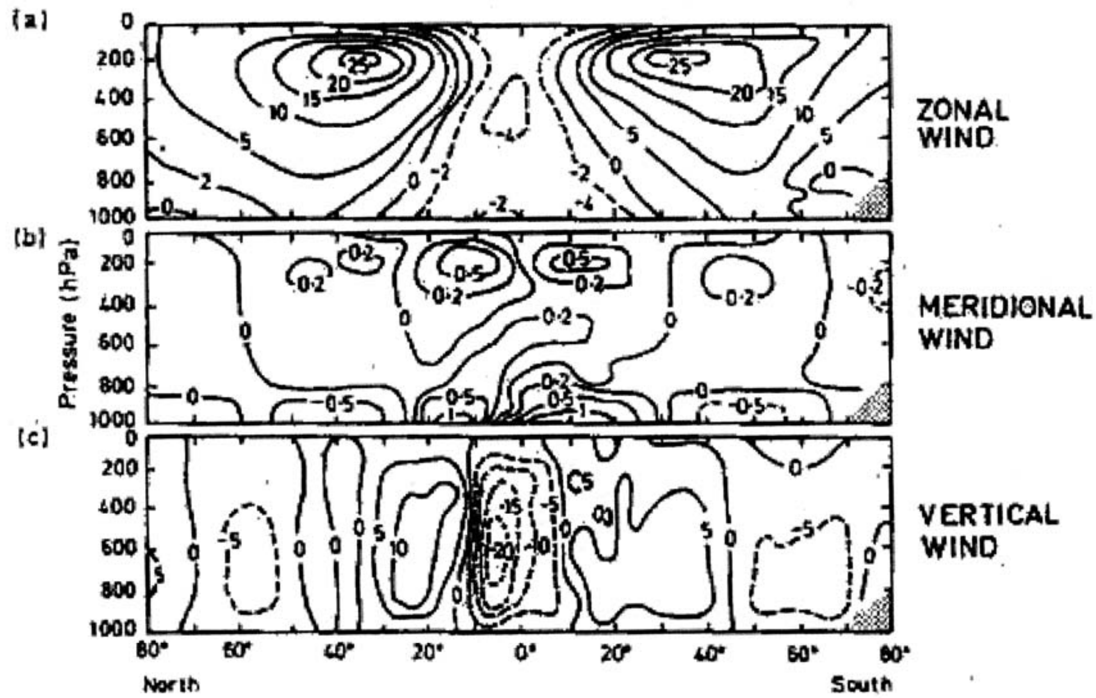

Figure 3: Annual Averages of Zonal, Meridional, and Vertical Winds by Latitude

Global wind patterns are also largely seasonally dependent with the strongest winds occurring in winter and summer months when contrasts between surface temperature and air temperatures are greatest [10:65]. Plotting seasonal wind conditions at forty degree North latitude represents the worst case expected average global wind conditions (Figure 4).

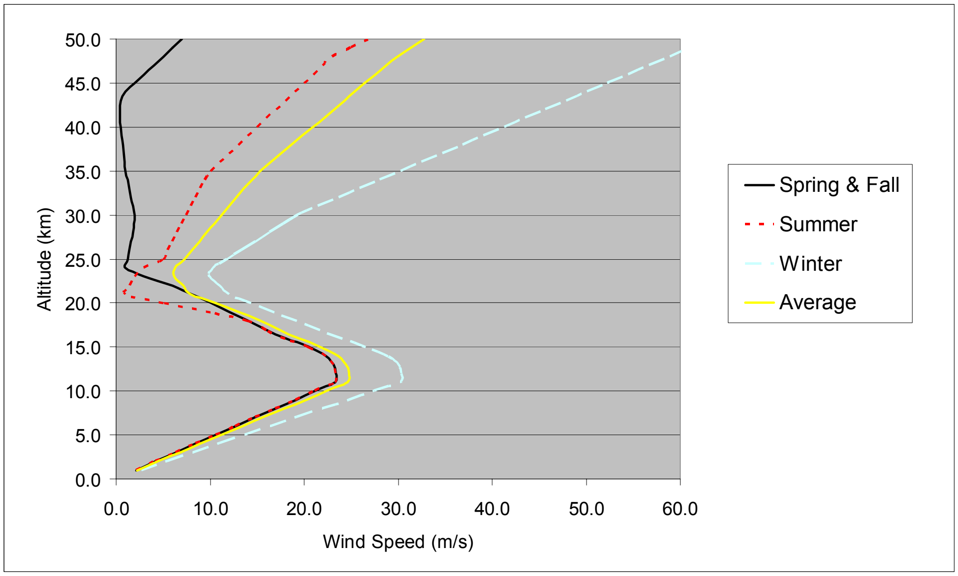

Figure 4: Mean Zonal Winds at 40 Degrees North Latitude [10]

2.2.3 Ozone Concentration & Ultraviolet Radiation

Another aspect that needs to be taken into account when designing a near-space airship is the overall exposures to ozone and ultraviolet radiation. Stratospheric ozone in the atmosphere (Figure 5) serves as the primary absorber of the sun's harmful ultraviolet (UV) radiation. The damaging effect of UV radiation at increasing near-space altitudes needs to be taken into account when designing the vehicles envelope material. Conversely, at lower near-space altitudes where UV radiation has been diminished, the corrosive effects of highly concentrated ozone gas need to also be considered [11:22.1-22.7].

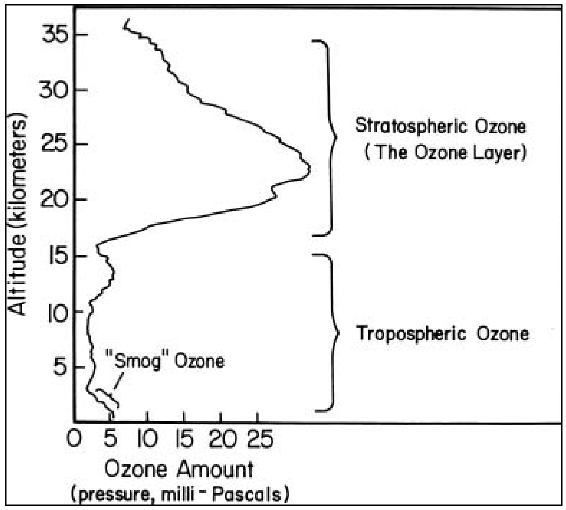

Figure 5: Ozone Concentration vs. Altitude

2.2.4 Atmospheric Drag

A key aspect that can greatly influence operational performance and mission duration is atmospheric drag. The amount of drag an airship will encounter is based the surrounding air density, the relative wind speed, the frontal area and a non-dimensional term called the drag coefficient. The drag coefficient is a number that aerodynamicists use to model all of the complex dependencies of drag on shape, inclination, and flow conditions [12:268-273]. The US Navy conducted wind tunnel experiments of model airships with different fineness (length/diameter) ratios in 1927 to determine drag coefficients of various shaped airships as shown in Table 2. A sphere with a fineness ratio of 1.0 yielded the highest experimental drag coefficients while a fineness ratio of 4.62 yielded the lowest overall drag coefficient. This point is where the total combination of pressure and friction drag forces is minimized [13:251-264].

Table 2: Drag Coefficients for Various Fineness Ratios

Fineness Ratio	10 m/s	25 m/s	Average Cd
1	0.108	0.113	0.111
1.5	0.0587	0.0467	0.053
2	0.0416	0.0328	0.037
3	0.0339	0.0291	0.032
4.62	0.03	0.0269	0.028
6	0.0324	0.0283	0.030
8	0.0332	0.0311	0.032
10	0.0366	0.0305	0.034

2.2.5 Ground Footprints

One benefit loitering near-space airships have over a traditional UAV like Global Hawk or Predator is its available ground footprint that can be seen from the vehicle at near-space altitudes. Figure 6 compares in-view horizon-to-horizon coverage from three relevant altitudes over Baghdad, Iraq. The inner circle shows maximum ground footprint available from a predator UAV at 8 km altitude and is capable of viewing only a portion of the city at any one time. The middle circle represents the ground footprint available at 20 km which represents the bottom of near-space and is also the altitude that the Global Hawk UAV operates. A platform at this altitude is capable of viewing a majority of the city. The outer circle represents the ground footprint available from a 30 km near-space platform. This higher near space altitude is capable of viewing a large metropolitan region.

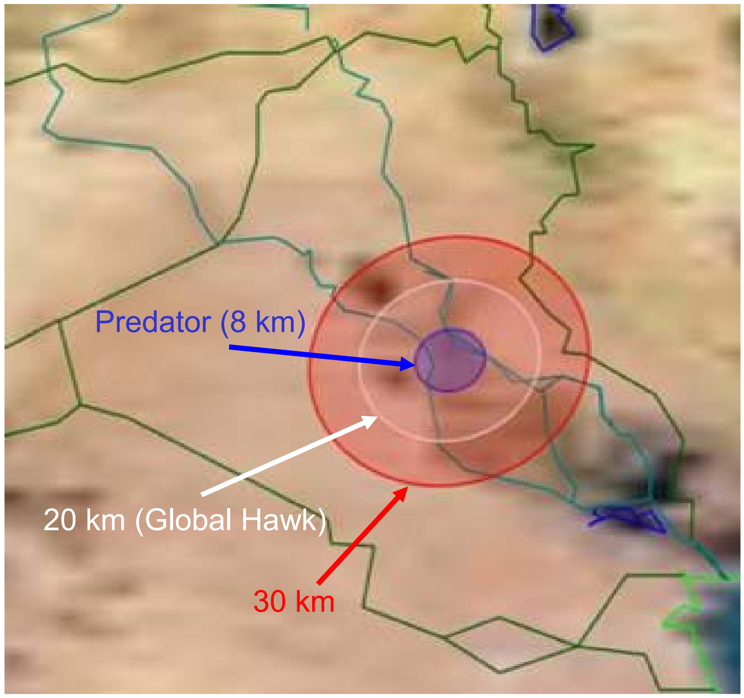

Figure 6: Ground Footprints from Near-Space Altitudes

2.2.6 Buoyancy Principle

The Greek mathematician and inventor Archimedes initiated the science of hydrostatics by discovering the principle of buoyancy while taking a bath. First published in 240 B.C. in a book titled *On floating bodies*, Archimedes stated that "the buoyant force on a submerged object is equal to the weight of the fluid that is displaced by the object". This so called "Archimedes" Principle describes the basis for buoyancy and static lift calculations in lighter-than-air vehicles as shown in equations 1-5 [14].

In determining the net forces acting on the airship, a free-body diagram of a static airship shows that the resultant force on the airship acting upward is the buoyancy force minus the weight of the airship is given by:

$$Force_{airship} = Force_{buoyancy} - Weight_{airship} \tag{1}$$

The weight of the displaced air equals the buoyant force, and weight is equal to the mass of air displaced times the acceleration due to gravity, expressed as:

$$Force_{buoyancy} = Mass_{air} \cdot Gravity \tag{2}$$

Equation 2 can also be written as the density of the displaced air multiplied by the volume of the air displaced as shown in equation 3:

$$Force_{buoyancy} = \rho_{air} \cdot Volume_{air} \cdot Gravity \tag{3}$$

The overall weight of the airship is the mass of the airship's internal gas multiplied by the force of gravity plus any additional structure weight and can be written as:

$$Weight_{airship} = \rho_{gas} \cdot Volume_{gas} \cdot Gravity + Weight_{structure} \tag{4}$$

Since the volume of air displaced is the same as the volume of gas in the airship, the resultant force of equation 1 can be written in the following form to become:

$$Force_{airship} = \left(\rho_{air} - \rho_{gas}\right) \cdot Volume_{gas} \cdot Gravity - Weight_{structure} \tag{5}$$

The weight of the structure represents the airship's weight minus the weight of the lifting gas to include the envelope material, the propulsion and power subsystems, structural support system, and payload weights.

When the resultant force on the airship is a positive number, the force is in the upward direction and the airship will begin to rise into the atmosphere. Conversely, if the force is a negative number the airship will fall back towards earth. When the resultant force on the airship is zero, the airship will float at altitude and the airship is displacing exactly its weight in air [14].

2.2.7 Lifting Gases

Using this principle of buoyancy, any potential lifting gas to be used for an airship application must have a molecular weight less than that of air. The properties of common lifting gases at mean sea level are shown in Table 3.

Table 3: Properties of Lifting Gases

Gas	Molecular Weight	Density (kg/m^3)	Lift Capability at MSL (kg/m^3)
Vacuum	0	0	1.20
Hydrogen	2.016	0.0832	1.12
Helium	4.003	0.166	1.03
Methane	16.03	0.665	0.54
Ammonia	17.03	0.707	0.49
Hot Air (100°C)	28.96	0.944	0.26
Air	28.96	1.20	0.00

2.2.7.1 Hydrogen

Early balloons and airships used hydrogen as a lifting gas due to its excellent lift capabilities and abundance. Hydrogen can be easily manufactured as a chemical reaction by-product when hydrochloric acid is exposed to mossy zinc metal or when sodium hydroxide is exposed to aluminum metal pellets. During the American Civil War special wagons with large wooden tanks full of acid were brought to the battlefields to generate needed hydrogen for reconnaissance balloons. The major issue with using hydrogen is the extreme fire and explosion hazards. Hydrogen gas is explosive in mixtures of more than four percent and is rarely used in airships today [15].

2.2.7.2 Helium

Helium gas is a natural by-product of the liquefaction of natural gas for pipeline shipment from particular natural gas fields located in the Oklahoma and Texas panhandles. Helium gas is a rare natural resource that accumulates in the same underground pockets as natural gas and is created over millions and millions of years from alpha particle decay in the surrounding radioactive rock. The US Bureau of Land Management controls nearly all of the world's helium supply and in the 1930's Germany was unable to get helium for their Zeppelin Airships because the US was concerned that helium had other military uses and horded it as a strategic material. For this reason, the Hindenburg was still lofted with hydrogen on its last disastrous flight [15].

2.2.7.3 Methane

Methane or Natural Gas is roughly half the weight of air and provides anemic, but useful lift. It can be used to fill airships, but it suffers from the same flammability and explosion hazard as hydrogen [15].

2.2.7.4 Hot Air

The density of air drops as it expands with temperature causing warmer air to rise. Positive lift is obtained by displacing a volume of colder air that is heavier than incoming hot air. When trapped in a balloon envelope, the hot air will generate lift because the air inside is actually lighter, or less dense than the cooler air outside. Hot air lifting capability depends on the relative temperatures of the air inside the balloon envelope and the outside surrounding air. Typical lift capabilities are between 0.2-0.3 kg per cubic meter for the recreational hot balloons [15].

2.2.7.5 Lifting Gas Summary

After the Hindenburg disaster of 1937, the use of hydrogen as a lifting gas has not found significant popularity. Helium, due to its excellent lift capability and safe handling characteristics, has become the standard lifting gas used in today's high altitude airships (Table 4).

Table 4: Comparison of Common Lifting Gases

Gas	Lift	Costs	Handling
Vacuum	Excellent	N/A	Difficult to contain
Hydrogen	Excellent	Low	Highly flammable
Helium	Excellent	Moderate	Safe
Methane	Good	Low	Toxic, highly flammable
Ammonia	Good	Low	Toxic, explosive
Hot Air (100°C)	Fair	Low	Safe

All lifting gases have decreased capabilities at high altitudes due to lower atmospheric densities. Figure 7 illustrates the lift coefficient of helium as function of altitude. It becomes apparent that there exists a practical upper limit to the altitude that any airship with appreciable mass can achieve when using only the internal gas to provide lift.

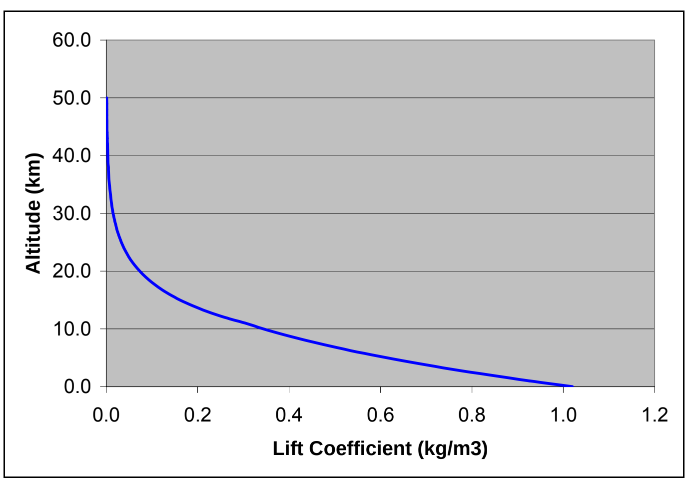

Figure 7: Helium Lift Coefficient vs. Altitude

2.3 Lighter-Than-Air Platforms

In the world of lighter-than-air platforms, there exist three non-powered types of balloon technologies: zero pressure, super pressure, and sky anchor and three types of powered airships: rigid, semi-rigid, and non-rigid (blimp).

2.3.1 Zero Pressure Balloons

Zero pressure balloons were first built and flown by Jacques and Joseph Montgolfier in November of 1782 [3:5]. The basic principle used in their balloon in 1792 has not changed for over 200 years and consist of a fabric envelope bag that is opened at the bottom and inflated with a gas that is lighter than the surrounding atmosphere. The term “zero pressure” is used because the internal gas pressure is equal to the external gas pressure at the base of the balloon with a slight overpressure inside the balloon to help maintain its shape.

Float altitude for a zero pressure balloon is achieved when the weight of the balloon and lifting gas equal the weight of the displaced air. This altitude fluctuates throughout the day as the gas contained within a high altitude balloon experiences solar heating. The perfect gas law tells us that when the temperature of the lifting gas rises, either the pressure will increase or the density will decrease as a result. In the case of a zero pressure balloon, gas is allowed to escape to maintain a zero pressure differential and the balloon begins to rise with the lower density lifting gas until a new equilibrium height is reached. At night the internal lifting gas cools and becomes denser causing the balloon envelope to decrease in volume and achieve a lower equilibrium altitude. The only way to maintain a constant altitude throughout this daily process is by venting gas when the gas temperature is rising or by dropping ballast when the gas temperature is falling. This cycle limits the mission duration of zero pressure balloons to about five to seven days. Near the north and south poles where the condition of 24 hours of daylight or darkness exist and gas temperatures remain fairly constant, which minimize ballast requirements, gas venting, and altitude changes allow zero pressure balloons to remain aloft for several weeks. Zero pressure balloons can carry several thousand kilograms to altitudes above 30 kilometers due to very low stress on the balloon envelope [7].

2.3.2 Superpressure Balloons

Superpressure balloons are similar to zero pressure balloons, except the envelope is sealed at the bottom to create a pressurized envelope. As the gas within the balloon heats, the internal pressure is allowed to rise but the overall density of the balloon remains constant. Keeping the envelope's volume and density constant allows the balloon to remain at a constant float altitude. The envelope materials need to withstand large stresses to contain the envelope pressure changes and are generally made of heavier materials than zero pressure balloons reducing the overall lift capability at high altitudes.

Significant research of superpressure balloons began after the invention of polyethylene during World War II. From 1968 to 1970, the National Center for Atmospheric Research (NCAR) conducted over 200 superpressure balloon flights at altitudes of 16-24 kilometers for durations of up to two years. Payloads were less than one kilogram and altitude deviations were less than 100 meters [15:52]. Today NASA's Ultra Long Duration Balloon (ULDB) program is working to demonstrate that a superpressure balloon that can lift a 6000 lb (2700 kg) scientific payload to 110,000 ft

(33.5 km) altitude for a minimum of 100 days with an ultimate goal of one year [7]. NASA's superpressure design consists of a pumpkin shaped balloon (Figure 8) to minimize envelope material stresses.

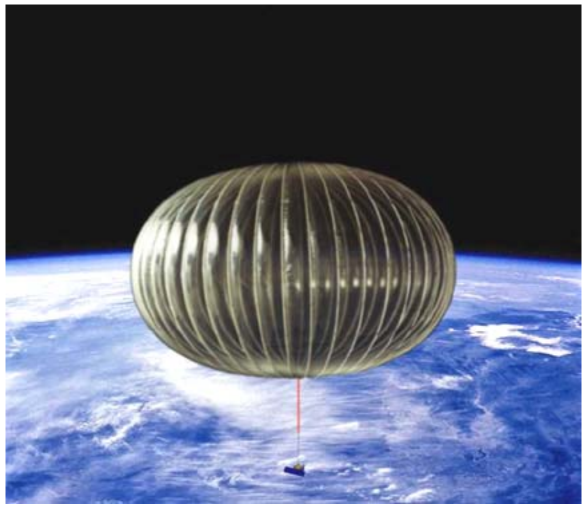

Figure 8: NASA ULDB Concept

2.3.3 Sky Anchor

The sky anchor is a hybrid system, combining zero and superpressure balloons in an attempt to stabilize zero pressure altitude excursions in order to achieve longer flights. The concept involves flying two balloons together to gain advantages of high lift capacity from the zero pressure balloon and altitude stability by using the superpressure balloon as ballast. When a superpressure balloon starts to rise due to internal gas warming, it becomes heavier than the surrounding air. The higher the system tries to ascend the heavier the superpressure balloon becomes resisting further upward motion. Limiting ascension decreases the amount of required venting of the zero pressure balloon [15:9].

Although good in theory, sky anchors have not been flown with much success. Handling and launching two balloons simultaneously has proven very difficult. One test program that did see limited success however was the National Scientific Balloon Facility (NSBF) in the later 1970s. After numerous launch problems, a sky anchor balloon carried a 227 kg payload to an altitude of 36 km for 4 days [15: 52].

2.3.4 Rigid Airships

As their name implies, rigid airships have an internal frame. The Zeppelins and the USS Akron and Macon were famous historical rigid airships. The rigid structure takes its shape from an internal aluminum frame. Rigid airships require a large internal volume to overcome the weight of the vehicle's support structure. Rigid airships are generally limited to lower altitudes where the internal gas has a good lifting capability as was indicated in Figure 7 [16].

2.3.5 Semi-rigid Airships

Semi-rigid airships comprise of a rigid lower keel and a pressurized envelope. The rigid keel is either attached directly to the envelope or hung underneath it. These airships were popular in the early 20th century and were used by the Brazilian aeronaut Alberto Santos-Dumont [16].

2.3.6 Non-rigid Airships

Non-rigid airships, also known as blimps, are the most common form seen today. They are basically large gas balloons and use slight internal overpressure to maintain their shape. Internal air compartments, called ballonets, are inflated or deflated with air to maintain a constant level of overpressure. All the airships currently flying for publicity use (Goodyear, Budweiser, MetLife, and Fuji) are non-rigid [16].

2.4 Airship Technologies

The following section identifies the critical airship technologies needed for an operational near-space airship design. Lightweight envelope material, power generation, and propulsion are needed to ensure an effective near-space design.

2.4.1 Envelope Materials

The envelope fabric of today's high altitude airships typically utilize a composite structure composed of several man-made materials such as Dacron, Polyester, Mylar and Tedlar, and is typically bonded with Hytrel. Such modern materials minimize helium leakage while standing up to damaging ozone and UV radiation environments. Airship material densities depend on the internal stresses in the material and are generally related to the volume of the lifting gas envelope. They can range from about 60 g/m^2 to 2000 g/m^2 with around 300 g/m^2 being typical [17]. The baseline for the parametric sensitivity study will use the typical value of 300 g/m^2.

2.4.2 Electrical Power

A power subsystem is needed for any electrical propulsion options as well as meeting the payload’s power requirement. Four functional categories must be considered in the design of any electrical power subsystem [1:407-427]. Power requirements for an operational airship can vary widely depending on propulsion and payload requirements and can become a critical driver in some of the electric propulsion options.

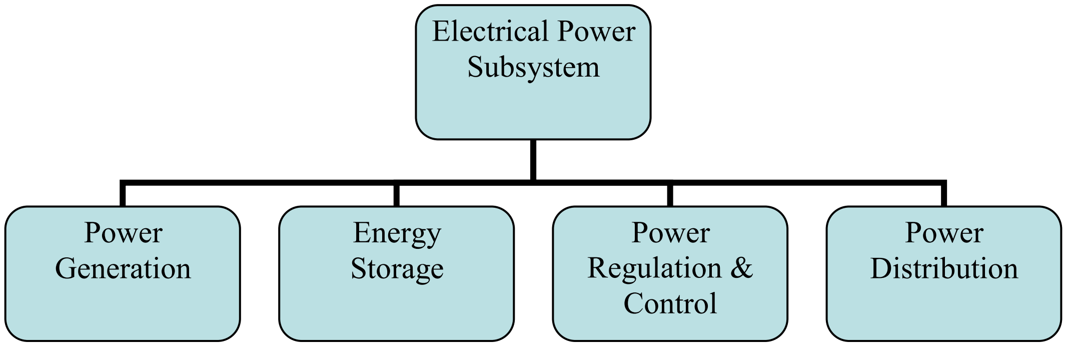

Figure 9: Electrical Power Subsystem Functional Breakdown

2.4.2.1 Power Generation

Batteries alone quickly become too massive to provide all the vehicle's electric power requirements when the mission extends beyond a few days. Typical power sources that are used to provide power from months to years aboard orbiting spacecraft include: solar photovoltaic, solar thermal dynamic, radioisotope, nuclear reactors, and fuel cells.

Two key parameters for power generation are specific power and power output levels. For a near-space airship application, high specific power and output power levels on the order of several kilowatts will be needed. Table 5 highlights the characteristics of five potential power sources [1:410]. High specific power options of solar photovoltaic arrays and fuel cells appear to hold the most promise for possible airship use.

Table 5: Common Spacecraft Power Generation Sources

Design Parameter	**Solar Photovoltaic**	**Solar Thermal Dynamic**	**Radioisotope**	**Nuclear Reactor**	**Fuel Cell**
Power Range (kW)	0.2-300	5-300	0.2-10	5-300	0.2-50
Specific Power (W/kg)	25-200	9-15	5-20	2-40	275

2.4.2.1.1 Solar Photovoltaic

Photovoltaic solar cells, the most common power source for earth-orbiting satellites, convert incident solar radiation directly to electrical energy. Solar arrays in conjunction with secondary batteries have been used for many years to provide highly reliable spacecraft power.

Photovoltaic cells are made of special materials called semiconductors. When light shines on the cell, some of the energy is absorbed into the semiconductor material causing electrons to flow freely. Electric fields within the photovoltaic cells force the electrons to flow in one direction to generate a current. This current is drawn off the cell and defines the power that the solar cell can produce. Table 6 shows a list of available solar cell types and their efficiency to change sunlight into useable electricity [1:414].

Table 6: Solar Cell Efficiencies

Cell Type	**Wafer Silicon**	**Thin Film Silicon**	**Gallium Arsenide**	**Indium Phosphide**	**Multijunction GaInP/GaAs**	**Thin Film CuGa/InSe2 (CIGS)**
Theoretical efficiency	20.8%	12.0%	23.5%	22.6%	25.8%	20.0%
Laboratory efficiency	20.8%	10.0%	21.8%	19.9%	25.7%	18.8%
Production efficiency	14.8%	5.0%	18.5%	18.0%	22.0%	16.6%

Solar cells connected together in series and parallel configurations make up a solar array. The number of cells connected in series in one string determines the array's voltage. The number of parallel strings sets the current output of the array. Key design issues for solar arrays include required peak and average power levels, operating temperatures, shadowing, radiation environment, orientation to the sun, mission life, mass and area, cost, and risk [1:411].

2.4.2.1.2 Fuel cells

Fuel cells work by converting chemical energy of an oxidation reaction into electricity. Like primary batteries, fuel cells can operate continuously without sunlight. The main downside of fuel cells is they need to carry their own reactant supply, which for long missions can become quite large. The most popular version for air and space applications is the hydrogen-oxygen fuel cell because of its relatively high specific power (275 W/kg), the low reactant mass of hydrogen and oxygen, and water as a useful byproduct [1:411].

Research is on-going to reduce the large reactant mass by using a regenerative type system. Because the fuel-cell is a reversible process, electrolysis can be used to create more reactants from the water by-product. The addition of solar arrays can be used to provide the electrolysis energy during sunlight hours. A hybrid fuel cell/solar array may provide a more feasible option to explore for a high altitude airship.

2.4.2.2 Energy Storage

The main function of energy storage is to store the energy produced for later use. Some energy generation systems such as primary batteries and fuel cells also double as energy storage systems. Conversely, photovoltaic cells only produce energy in sunlight and need an energy storage system to provide the needed energy during eclipse cycles. Secondary batteries are the most common energy storage systems used today.

2.4.2.2.1 Secondary Batteries

Secondary batteries consist of electrochemical cells that can be recharged upon depletion by passing current in the opposite direction to the discharge current. Table 7 highlights the various secondary battery types available [1:420]. Of these, Lithium-Ion batteries offer the highest specific energy densities commercially available today. Sodium-sulfur batteries have superior energy density, but are not quite ready for operational use.

Table 7: Secondary Battery Characteristics

Battery Type	**Energy Density (W*hr/kg)**	**Pros**	**Cons**
Nickel-Cadmium	25-30	Space Qualified Widely used	Low depth of discharge Small temperature range Heavy & bulky
Nickel-Hydrogen	35-57	Space Qualified Good historical record	Medium depth of discharge Small temperature range
Lithium-Ion	70-129	Excellent energy density High depth of discharge Lightweight & compact	Still undergoing space qualification
Sodium-Sulfur	140-210	Superior energy density	Still under development

2.4.2.3 Power Regulation & Control

Vehicle primary power generation source, such as solar arrays and batteries, are often not well regulated. In addition, the solar array's electrical output often does not match the battery charging requirements. Controllers and regulators must cope with the voltage swings between charge and discharge, and be able to isolate faults and switch to redundant units while also serving as the center of the power distribution network. The amount of energy that is dissipated within the power regulation and control unit usually is around 20% of the total energy generated. Typical mass estimates for the power regulation and control unit is on the order of 0.025 kg/W of converted energy [1: 334].

2.4.2.4 Power Distribution

Primary power is distributed in low-voltage direct current for vehicles below 10kW. Above this level alternating current is typically used to reduce the vehicles mass associated with wiring. The power dissipated in wiring losses and switching equipment is around 2-5% of the vehicle's operating power and typically takes up around 1-4% of the overall vehicle's weight [1: 334].

2.4.3 Propulsion

High altitude airships operate above the altitudes of traditional air-breathing aircraft and below altitudes of orbiting spacecraft that utilize space propulsion options. This begs the question of which propulsion option might be most suitable for a high altitude airship. Thrust levels on the order of one kilonewton will be required to stationkeep an airship at near-space altitudes. The following section takes a look at possible air and space propulsion options.

2.4.3.1 Air Propulsion

For aircraft speeds that are very much less than the speed of sound, the aircraft is said to be subsonic. For subsonic aircraft, we can neglect compressibility effects and the air density remains nearly constant [18]. With the speed of sound at over 600 mph at near-space altitudes; a near-space airship will always remain well within this subsonic flow regime.

All aircraft propulsion systems produce thrust in a similar manner. Air enters the device through an inlet surface, and as a result of power that is applied to the device in some form, the kinetic energy of that air is increased. The associated increase in the momentum of the air that passes through the propulsion system results in a net reaction force or thrust.

There are a few types of aircraft propulsion systems being used today for various military and commercial applications. Among these are: propellers, turboprops, turbojets, turbofans, and ramjets. Since ramjet engines cannot operate in the subsonic regime, it will not be discussed as a viable option for airship propulsion (Figure 10).

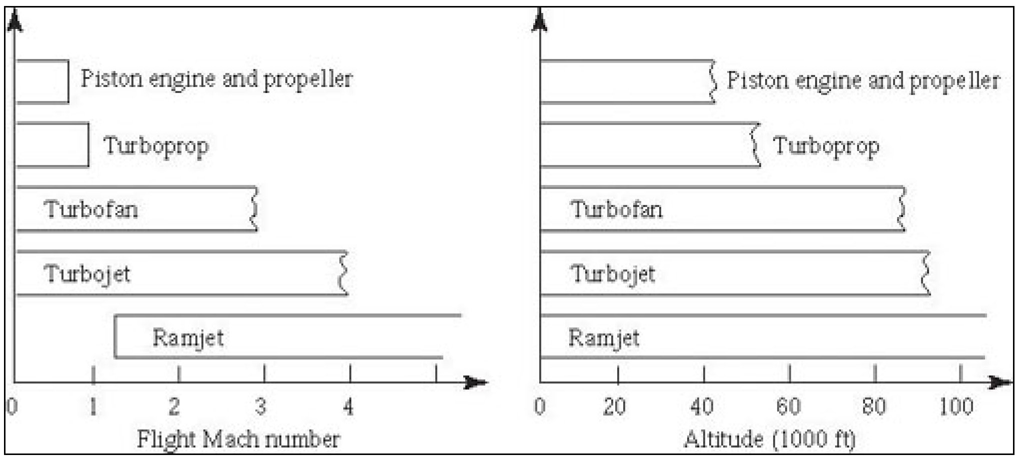

Figure 10: Aircraft Propulsion Operating Regimes

2.4.3.1.1 Propellers

Propeller-powered aircraft are very efficient for low speed flight. As the speed of the aircraft increases, however, regions of supersonic flow, with associated performance losses due to shock waves, occur on the propeller. This is the reason why propellers are not typically used on high-speed aircraft. Maximum thrust from propellers occur when the propellers tip speed falls between 0.88 and 0.92 Mach [18]. Engines that drive the propeller are engineered around this point for maximum efficiency.

Propellers work well for altitudes from sea level to 30 kilometers and higher moving large amounts of air at a slow speed. NASA's Environmental Research Aircraft

& Sensor Technology (ERAST) Program flew a solar powered high-altitude aircraft, named Helios, to a world-record altitude of 96,863 feet (29.5 km) in August 2001 [19]. The Helios powered fourteen electric motor driven propellers over two miles higher than any non-rocket powered aircraft had ever flown (Figure 11).

Figure 11: Helios High Altitude Aircraft

2.4.3.1.2 Jet Turbines

A basic turbojet engine (Figure 12) uses a gas turbine core that draws air in thru a compressor, enters a combustion chamber to heat up the compressed air and spins up a turbine. The turbine is connected to the compressor, which makes the compressor run faster forcing more air into the engine. The resultant hot gases are expelled at the rear of the engine to provide thrust. Turbo-Jets are more efficient at higher speeds providing only about 15% efficiency at 100 mph [17].

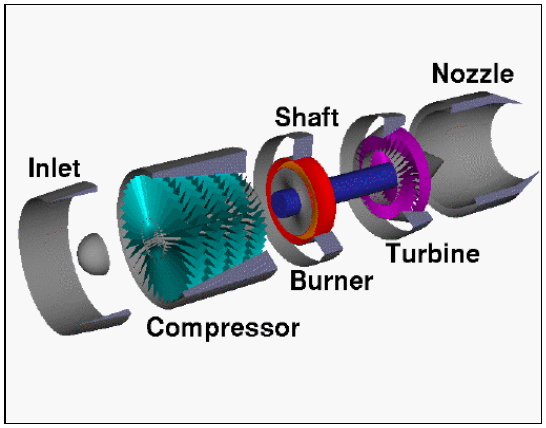

Figure 12: Turbojet Engine

In addition to the pure turbojet engine, the basic gas turbine core is also used to power turboprop and turbofan engines. The turboprop uses a gas turbine core to drive the propeller and a turbofan places a high by-pass fan in front of the gas turbine core. Both are used to accelerate a large amount of air at slower speeds than a traditional turbojet increasing overall fuel efficiency of the system.

The basic gas turbine core, however, can only be used at altitudes below 90,000 ft (27.4 km) altitudes. Altitudes above this altitude require an on-board supply of liquid oxygen to complete the combustion process [17]. One turbine engine concept that does not have this limitation is the positron turbojet.

2.4.3.1.3 Positron Turbojet

The positron turbojet (Figure 13) is unlike other turbojet engines, in that the combustion chamber is replaced by a heat exchanger. The engine's working fluid, air, is heated by passing through a heat exchanger. The heat source for the heat exchanger is produced by the annihilation of positrons with electrons in a matter-antimatter interaction. Two 511 keV gamma-rays are produced for every interaction which gives off energy in the form of heat to be absorbed by the heat exchanger. The engine's working fluid is heated by convection as it passes over the heat exchanger [20:20].

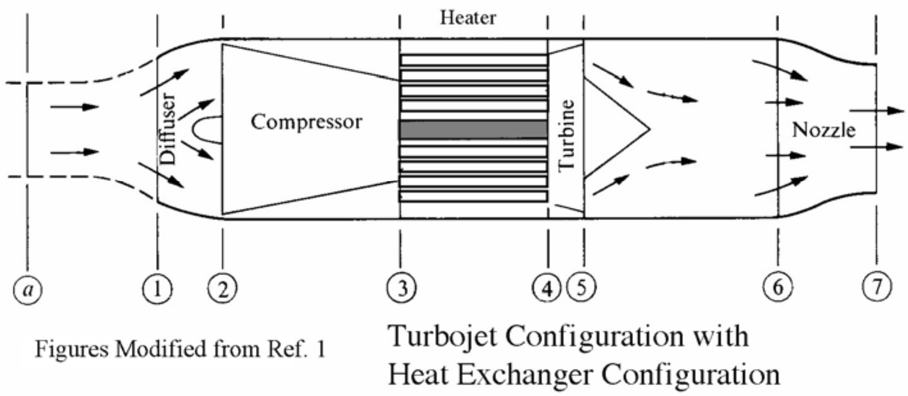

Figure 13: Positron Turbojet Concept

In a study conducted in 2003 by Positronics Research LLC [20], it was estimated that while about 10's of milligrams of uranium-235 fissioned material would be capable to fly a small aircraft (60 kg, lift-to-drag of 4 and a jet efficiency of 30%) the distance of 1000 miles, it would only require about 5 micrograms to fly the same aircraft 1000 miles using a positron-based annihilation system. It was also noted that the positron-powered engine does not have the same radiation limitations plagued by the fission-based system. The radiation hazard is minimal during operation with most of the energy absorbed into the heat exchanger through the effective attenuation of the gamma rays, and with the source turned off the annihilation gamma-rays are no longer created eliminating the radiation hazard altogether [20:21].

2.4.3.1.4 Air Propulsion Summary

Table 8 gives a quick summary of the aircraft propulsion types discussed. The electric driven propeller and the positron turbojet show the most promise being able to use aircraft propulsion to provide loiter capability to an airship operating above 20 kilometer attitudes.

Table 8: Aircraft Propulsion Options

Type	Operational Regime	System Weight	Fuel Weight	Advantages	Disadvantages
Electric Propeller	Subsonic	Low	None	Efficient at low speeds Proven at high altitudes	Limited to low speeds
Conventional Turbojet, Turboprop, & Turbofan	Transonic	Moderate	Moderate	Can be very efficient	No combustion at high altitudes without oxidizer
Positron Turbojet	Transonic	Moderate	Negligible	No combustion required	Complicated Unproven technology
Ramjet	Hypersonic	Moderate	Moderate	None	Does not work subsonic

2.4.3.2 Space Propulsion

There are many types of spacecraft propulsion options that can be considered to provide airship propulsion. All of which use propellants that are carried on-board to provide thrust. The propulsion concepts researched fall into three main areas: chemical, electric, and nuclear. Chemical based space propulsion include: cold gas, mono-propellant, bi-propellant, solid motor, water rocket, and hybrid thrusters. Electric based space propulsion options include: resistojets, arcjets, pulsed inductive, magnetoplasmadynamic (MPD), ion, and Hall effect thrusters. The only nuclear space propulsion option being considered for this study is the particle bed rocket.

A quick glance at the space propulsion summary in Table 9 yields several non-viable options [1:692]. Electric propulsion options such as resistojets, arcjets, ion, pulsed plasma, and hall-effect thrusters provide very little thrust and can be removed from further consideration. The specific impulse of a space propulsion system is a common term that describes the fuel efficiency and is inversely proportional to the fuel's mass flow rate. The higher the fuel's specific impulse the less on-board propellant needed for the same amount of required thrust making some of the chemical propulsion systems such as cold gas, monopropellants, and solid rockets less practical. In addition, solid propellant rockets are not throttleable and cannot be restarted. This leaves us with only a handful of potentially viable space propulsion options: liquid bipropellant thrusters, hybrid engines, water rockets, magnetoplasmadynamic and pulsed inductive thrusters, and particle bed rockets.

Table 9: Space Propulsion Options

Type	Propellants	Energy Source	ISP (Sec)	Max Thrust (N)
Water Electrolysis	$H_2O \rightarrow H_2 + O_2$	Electric/Chemical	400	500
Hybrid Engine	Nitrous Oxide and HTPB	Chemical	350	350,000
Particle Bed Rocket	Hydrogen	Nuclear (U-235)	1000	17,000
Cold Gas Thruster	Helium	High Pressure	75	200
Liquid Monopropellant	Hydrazine, H_2O_2	Exothermic decomposition	225	2,670
Liquid Bi-Propellant	O_2/H_2, O_2/RP1, N_2H_4/UDMH	Chemical	450	5,000,000
MPD Thruster	Argon	Magnetic	2000	200
Pulsed Inductive Thruster	Argon	Magnetic	7500	200
Solid Motor	Organic polymers	Chemical	300	5,000,000
Electothermal Resistojet	Hydrogen	Resistive Heating	700	0.5
Electrothermal Arcjet	Hydrazine gas	Electric Arc Heating	1500	5
Ion Thruster	Cesium, Xenon	Electrostatic	6000	0.5
Hall Effect Thruster	Cesium, Xenon	Electrostatic	2500	0.1
Pulsed Plasma Thruster	Teflon	Magnetic	1500	1.1

2.4.3.2.1 Liquid Bipropellant

Liquid bipropellant thrusters consist of a separate propellant and oxidizer that are allowed to mix and ignite in a thrust chamber. Although more complex than monopropellant designs the separate fuels can have a much higher specific impulse which results in a more energetic rocket. Liquid hydrogen and oxygen are among the highest specific impulses (450 seconds) available for a chemical based rocket. Liquid bipropellant thrusters are typically throttleable and can be shut-off and restarted as needed [1:694-696]. .

2.4.3.2.2 Hybrid Engine

Hybrid engines have elements common to both solid and liquid rocket engines and use both solid and gaseous/liquid propellants. The fuel is some type of inert rubber or plastic and the oxidizer is usually either liquid oxygen or hydrogen peroxide. A common design is to make the fuel is the shape of a cylinder with a hole down the center for the oxidizer to pass. The fuel is vaporized, burns with the oxidizer, and passes through a rocket nozzle to produce thrust. Hybrid rockets are usually very clean burning and unlike their solid rocket motor counterparts are not explosive by nature. Similar to liquid fueled rockets, hybrid engines can be throttled, shutdown and restarted, but are much more reliable due to a significant reduction in the number of moving parts.

A hybrid engine greatly outperforms solid and monopropellant liquid rockets and operate at efficiencies closer to the more complex bi-propellant rockets [21:5]. Due to its favorable safety and performance characteristics, a hybrid rocket engine was used in 2004 to usher in commercial space travel by propelling Burt Rutan's *Space Ship One* twice into space within a 14 day period to win the $10 million Ansari X-prize [22].

2.4.3.2.3 Water Rocket

A water rocket is a combination propulsion, power, and energy storage system. Water stored aboard the vehicle is electrolyzed into gaseous hydrogen and oxygen that is stored in on-board high-pressure tanks. These gases can either be burned in a bipropellant type rocket to generate thrust or be recombined to produce electric power. Solar arrays work during the day to electrolyze the gases for later use. This concept replaces the need for on-board batteries to provide energy during daily solar eclipse periods and generates water as a byproduct that can be reused.

The propulsion system would consist of a bipropellant rocket configuration where the gaseous hydrogen and oxygen would be burned in a combustion chamber and expelled through a nozzle to provide thrust. Any water needed for the propulsion system would be used to provide vehicle thrust and is unrecoverable ultimately limiting mission duration [23:1].

2.4.3.2.4 MPD Thruster

Magnetoplasmadynamic (MPD) thrusters have been studied since their inception in 1964 (Figure 14). They consist of an annular anode surrounding a central cathode. A high-current arc created between the anode and cathode ionizes and accelerates a gas propellant into a high velocity plasma stream. A benefit of a MPD thruster is the high exhaust velocity, which allows for significantly less propellant than chemical rockets to provide identical thrust. In addition, long mission lives of several thousand hours make MPD thrusters a potential propulsion option for high altitude airship use. Experimental versions exist, but have yet to be used in applications. The main issues to the MPD thruster concept is its excessive power needs to generate the high currents needed and corrosion of the electromagnets [24].

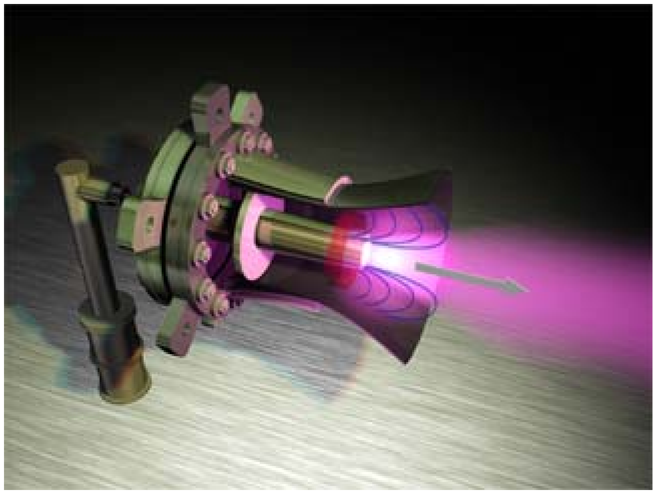

Figure 14: Self-field MPD Thruster

2.4.3.2.5 Pulsed Inductive Thruster

Pulsed inductive thrusters (PIT) are a form of spacecraft propulsion invented by TRW that uses perpendicular electric and magnetic fields to accelerate a propellant (Figure 15). A nozzle releases a puff of argon gas that spreads across a large flat induction coil of wire. A radial magnetic field induces a circular electrical field above the coil to ionize the gas propellant. The ionized gas generates a current flow in the resulting plasma opposite to the current in the coil flow, providing a mutual repulsion that rapidly blows the ionized propellant away to provide thrust. The thrust and specific impulse can be tailored by adjusting the discharge power, pulse repetition rate, and propellant mass flow [24].

A pulsed inductive thruster can have specific impulses of up to 7500 seconds and with no cathodes, they do not suffer from the corrosion problems that MPD thrusters encounter resulting in a longer mission life. Pulsed inductive thrusters are similar to MPD thrusters in that they have not been used in operations and have very high power requirements to produce any significant thrust [24].

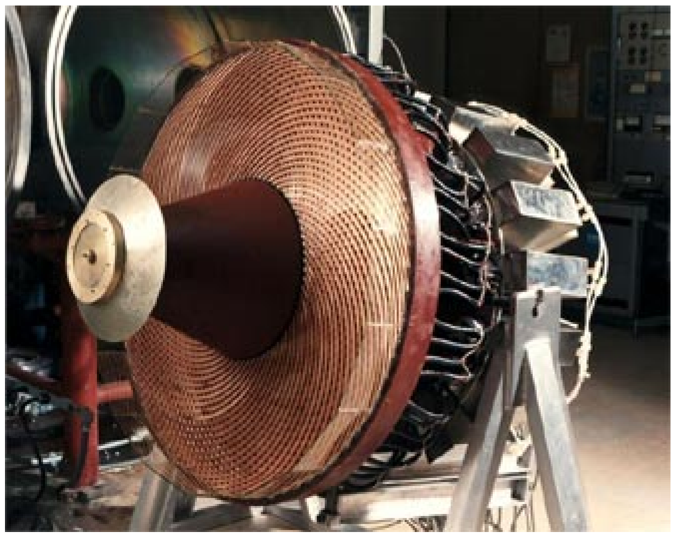

Figure 15: Pulsed Inductive Thruster

2.4.3.2.6 Nuclear Particle Bed Rocket

Nuclear rockets work by routing hydrogen through a nuclear reactor. The reactor is at a high temperature, which causes the hydrogen fuel to expand as it leaves the nozzle, producing a high amount of thrust. Nuclear rockets do not need an oxidizer, and they require much less fuel than similar sized liquid or solid fuel rockets. This allows a vehicle using a nuclear rocket to be more versatile than one employing chemical rockets. Disadvantages of nuclear rockets include radiation effects caused by the nuclear reactor, and the high weight of the engine assembly [25].

In the particle-bed (fluidized-bed, dust-bed, or rotating-bed) reactor, the nuclear fuel is in the form of a particulate bed through which the working fluid is pumped. This permits operation at a higher temperature than the solid-core reactor by reducing the fuel strength requirements. The core of the reactor is rotated (approximately 3000 rpm) about its longitudinal axis such that the fuel bed is centrifuged against the inner surface of a cylindrical wall through which hydrogen gas is injected. This rotating bed reactor has the advantage that the radioactive particle core can be dumped at the end of an operational cycle and recharged prior to a subsequent burn, thus eliminating the need for decay heat removal, minimizing shielding requirements, and simplifying maintenance and refurbishment operations [25].

2.4.3.2.7 Space Propulsion Summary

Table 10 highlights the important parameters of the space propulsion types discussed. Of the six types considered, the liquid bipropellant thrusters and particle bed rockets show the most promise to provide loiter capability for a near-space airship due to their favorable specific impulse, low electrical power requirements, and moderate propellant weights.

Table 10: Space Propulsion Weight Summary

Type	ISP	Electric Requirement	Propellant Weight
Liquid Bipropellant Thruster	450	Low	Medium
Hybrid Engine	350	Low	High
Water Rocket	400	Medium	High
MPD Thruster	2000	Massive	Low
Pulsed Inductive Thruster	7500	Massive	Low
Particle Bed Rocket	1000	Low	Medium

2.5 Chapter Summary

The information highlight within this chapter will be used to design a baseline airship system to identify maximum loiter and altitude capabilities. No major technical limitations were identified in the initial review and current technologies appear sufficient to make a near-space airship theoretically possible. Solar photovoltaic and fuel cell technologies will be analyzed to provide vehicle electrical power needs. Eight types of propulsion systems will be explored in greater detail to identify altitude and stationkeeping capability limitations. The next chapter examines the equations and assumptions used for the parametric analysis.

3. Methodology

3.1 Chapter Overview

Physical and practical limitations of an airship design were investigated to establish maximum achievable altitudes. Preliminary analysis was conducted with no propulsion system and a spherical shaped balloon where altitude versus platform size was determined for various payload power and mass requirements. Next, an electric propeller based propulsion subsystem was added to provide loiter capability to the spherical balloon. It quickly became apparent that a more slender vehicle would be required to maintain stationkeeping when the analysis yielded unfeasible solutions due to excessive drag associated with a spherical design. A baseline airship design concept was then generated around commercially available state-of-the-art technologies. Finally, a parametric sensitivity study was conducted around this baseline to identify critical technology drivers that limit the vehicles overall capabilities. The reminder of this section lays out the calculations and assumptions used in the analysis.

3.2 Assumptions

3.2.1 Sizing and balloon material limitations

A fairly good sense of practical limitations for the vehicle's lifting gas envelope was determined by examining the current lighter-than-air vehicle designs listed in Table 11. For the parametric study, overall vehicle size was plotted versus altitude to quickly identify feasible solutions that could be designed today. Considering Table 11, an upper limit of two million cubic meters was used in order to not constrain potentially larger designs that might become a reality in the future and to show exponential growth where applicable.

Table 11: Current High Altitude Lighter-than-air vehicle design volumes

Type	Design	Volume (m^3)
Airship	MDA High Altitude Airship (HAA)	147,000
Superpressure Balloon	NASA Ultra Long Duration Balloon (ULDB)	566,000
Zero Pressure Balloon	National Scientific Balloon Facility (NSBF) design	1,500,000

3.2.2 Baseline Airship Design

The following set of parameters was used as the baseline airship design for the parametric sensitivity study (Table 12):

Table 12: Baseline Airship Design Parameters

Baseline Airship Design Assumptions	
Payload Mass	1000 kg
Payload Power	5000 W
Power Generation	CIGS Flexible solar arrays
Power Storage	Li-ion Batteries
Daily Eclispe	12 hours
Propulsion	6 Electric Propellers
Propeller Diameter	3 meters
Lifting Gas	Helium
Fabric Density	300 g/m^2
Fineness Ratio	4.62
Structure Mass	20% of Total Mass

A payload mass and power of 1000 kilograms and 5000 Watts were chosen to allow for a fairly robust sensor package that would be able to accommodate several different types of communication and ISR platforms found in today's UAV and LEO satellite platforms [1:894-896].

Global Solar's thin film Copper-Indium-Gallium-diSelenide (CIGS) solar arrays with 100 watt/kilogram energy density are representative of current state-of-the-art power generation technology [26]. Sony Hard Carbon Lithium Ion Cells were chosen to handle energy storage due to their high energy/mass ratio of 129 W*hr/kg and manufacturing readiness. Sony's Li-Ion cells are currently being manufactured for use in next generation satellites and are undergoing life cycle testing [27].

A fixed baseline fabric density of 300 g/m^2 is based on typical state-of-the-art fabric commonly used in airship designs [17]. The reader should note that the fabric density on an actual airship design can vary widely and is determined by the vehicle's stress loads and material strength requirements as well as operational environment where ozone concentrations and ultraviolet radiation concerns can be addressed.

Six, low Reynolds number electric-driven propellers (3-meter diameter) were chosen as a baseline propulsion system due to their high efficiency, low weight, and proven use at high altitudes. Mass of the electric motors was extrapolated from those used on AeroVironment's Helios solar powered high-altitude aircraft design [19].

Daily eclipse durations of twelve hours were chosen to represent the average amount of solar eclipsing in mid-latitude regions of the globe.

The fineness ratio of 4.62 selected was based on a study conducted by the U.S. Navy in 1927 where through wind tunnel experiments were able to find an optimal airship length to diameter ratio where the combination of pressure and friction drag yielded the lowest drag coefficient [13].

A structure mass of 20% was used to represent all materials already not accounted for and include the vehicle's control & stability surfaces, internal ballonet subsystem, payload & propulsion support structures, and any additional thermal management requirements not already addressed in the envelope material selection.

3.3 Calculations

3.3.1 Drag force

To loiter a high altitude platform over one geographical area requires a propulsion force that is able to counter any drag forces caused by high altitude winds. The basic drag equation, as shown in equation 6, was used to quantify this force [12:263]:

$$\text{Drag} = \frac{1}{2} \cdot C_d \cdot \rho_{air} \cdot \text{Velocity}^2 \cdot \text{Area}_{frontal} \tag{6}$$

Where:

- Drag = drag force caused by high altitude winds (N)
- C_d = drag coefficient
- ρ_{air}= surrounding air density (kg/m^3)
- Velocity = wind speed seen at the vehicle (m/s)
- Frontal Area = Projected area perpendicular to air flow (m^2)

The frontal area for an airship is the projected area that you would see if the vehicle is heading straight for you. The frontal area can be estimated by knowing the airship's maximum diameter as seen from this frontal view (equation 7). This estimation assumes the vehicle is an ellipsoid or spherical shape and does not account for protruding payloads, fins, rudders, or any other parts sticking out from the hull and would need to be added on to the estimate. For this study, just the basic hull has been taken into account to calculate drag.

$$\text{Area}_{frontal} = \pi \cdot \frac{\text{Diameter}^2}{4} \tag{7}$$

If only the volume and fineness ratios are known, the following relationship in equation 8 can be used to calculate the airship's diameter [28]:

$$\text{Diameter} = \sqrt[3]{\frac{6 \cdot \text{Volume}}{\pi \cdot \text{FinenessRatio}}} \tag{8}$$

Where the fineness ratio is the airship's length divided by its diameter, which for a spherical shape would be a value of one.

3.3.2 Vehicle Mass

The total vehicle mass can be found by adding up all of the vehicle subsystems:

$$\begin{aligned}\text{Total\_vehicle\_mass} = {} & \text{PayloadMass} + \text{PowerMass} + \text{PropulsionMass} \ldots \\ & + \text{StructureMass} + \text{FabricWeight}\end{aligned} \tag{9}$$

Where the fabric mass is a function of the vehicle surface area and fabric density:

$$\text{FabricWeight} = \text{SurfaceArea} \cdot \rho_{\text{fabric}} \tag{10}$$

For an airship with known envelope volume and fineness ratio the surface area can be calculated as shown in equation 11 [28]:

$$\text{SurfaceArea} = \pi \cdot \frac{\text{Diameter}^2}{2} \cdot \left(1 + \frac{\text{Fineness} \cdot \text{asin}(\text{Eccentricity})}{\text{Eccentricity}}\right) \tag{11}$$

Where:

$$\text{Eccentricity} = \frac{\sqrt{\text{Fineness}^2 - 1}}{\text{Fineness}} \tag{12}$$

Combining Equations 10-11, the fabric weight then can be written in the form of equation 13 to become:

$$\text{FabricWeight} = \pi\cdot\frac{\text{Diameter}^2}{2}\cdot\left(1 + \frac{\text{Fineness}\cdot\text{asin}(\text{Eccentricity})}{\text{Eccentricity}}\right)\cdot\rho_{\text{fabric}} \tag{13}$$

In the special case of a sphere the eccentricity becomes zero, and a different set of calculations to find the surface area and fabric weight are need to avoid dividing by zero. For a sphere, equations 14-15 can be used to identify the surface area and fabric weight [28]:

$$\text{SurfaceArea}_{\text{Sphere}} = 4\cdot\pi\cdot\left(\frac{\text{Volume}_{\text{Envelope}}}{\frac{4}{3}\cdot\pi}\right)^{\frac{2}{3}} \tag{14}$$

$$\text{FabricWeight}_{\text{sphere}} = 4\pi\left(\frac{\text{Volume}_{\text{Envelope}}}{\frac{4}{3}\pi}\right)^{\frac{2}{3}}\cdot\rho_{\text{fabric}} \tag{15}$$

Several iterations are required to obtain the overall fabric weight for spheres and airships alike. This is because additional fabric weight requires a larger volume of lifting gas, which in turn generates a larger drag force. The larger drag force requires a larger propulsion system, which drives a larger volume of required lifting gas. This cycle continues until either the calculations converge to a solution or grows exponentially indicating either no solution exists or where the total volume constraints are exceeded.

3.3.3 Power Subsystem

The following section describes the assumptions and calculations used to estimate the power subsystem mass. Commercially available equipment based on state-of-the-art technologies was used to obtain state-of-the-art solar array and battery performances. The remaining information was obtained from the *Space Mission Analysis and Design* Textbook [1:407-427]. The overall power subsystem mass includes the addition of all onboard power systems as shown in equation 16.

$$\begin{aligned} Mass_{power\_subsystem} = {} & Mass_{Power\_Generation} + Mass_{Storage} \cdots \\ & + Mass_{Distribution} + Mass_{Regulation} \end{aligned} \tag{16}$$

3.3.3.1 Solar Arrays with Secondary Batteries

A near-space airship using solar arrays to provide electrical power requires a supporting energy storage system for operations during solar eclipse conditions. The solar array performance for the baseline design is based on the state-of-the-art 100 watt per kilogram thin film Copper-Indium-Gallium-diSelenide (CIGS) solar arrays designed by Global Solar for use in next-generation satellites and high altitude vehicles [26].

The most important sizing requirement for any solar array design is its demands for average and peak electrical power both at beginning and end of mission life. The average electrical power needed at end-of-life (EOL) determines the size of solar array and was obtained using the relationship in equation 17:

$$EOL\_performance = BOL\_performance \cdot (1 - annual\_degradation)^{mission\_years} \tag{17}$$

Typical values for the annual degradation for CIGS type solar cells of 2.75% [1: 417]

To estimate the solar array area required, the solar array must provide an entire days worth of power to the vehicle's energy storage system all within daylight hours. The power generated by the solar arrays includes the overall vehicle power needs in addition to all the losses within the power conversion units and distribution system, which is typically 20-25% [1:423-424]. Additional solar array area will also be needed to account for the cosine loss function, which occurs when the individual solar cells on the airship are not positioned normal to the sun [1:417].

To determine the mass of the secondary batteries that will be used in conjunction with the solar arrays as an energy storage device the number of discharge cycles that the batteries will experience must be determined. The number of discharge cycles for a battery determine the its overall depth of discharge. The depth of discharge assumption used for the Sony Hard Carbon Lithium Ion Cells is 80%, which is standard for Li-Ion cells with 1000 cycles or 3-year mission life [1:421]. Equation 18 assuming an eclipse duration of 12 hours and a battery capacity of 129 W*hr/kg was used to calculate the battery mass.

$$\text{Mass}_{\text{battery}} = \frac{(\text{Payload\_power} + \text{Vehicle\_power}) \cdot (\text{Eclipse\_duration})}{(\text{Depth\_of\_discharge}) \cdot (\text{Battery\_weight\_to\_capacity})} \tag{18}$$

Using the assumptions mentioned earlier in this section, a relationship between the overall power subsystem mass and eclipse duration was found (Figure 16).

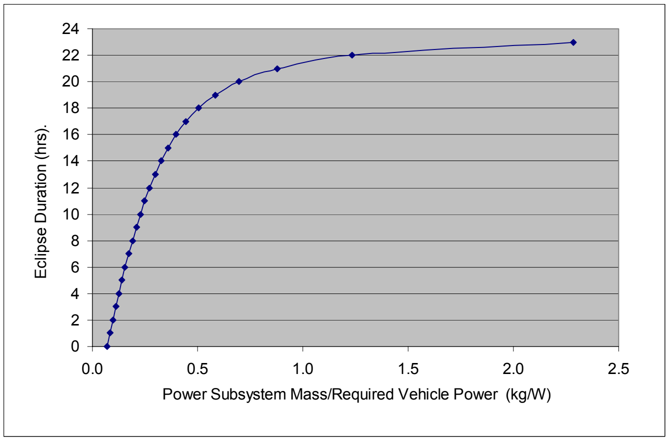

Figure 16: Power Subsystem Mass/Vehicle Power Vs Eclipse Duration

3.3.3.2 Fuel Cells

The fuel cell mass is based on the space shuttle fuel cell design with an energy/mass ratio of 275 W/kg plus weight of on board fuel required of 0.36 kg/kW*hr to generate the needed electricity [1:409].

3.3.4 Propulsion Subsystem

A propulsion system is needed to provide loiter capability over an area by generating an equal but opposite thrust to counteract the wind induced drag force on the vehicle.

3.3.4.1 Air Propulsion

For most aircraft type propulsion the surrounding air is used as the working fluid to provide the needed thrust. Thrust is a function of the density of the air for air propulsion systems and drops off as altitude increases.

3.3.4.1.1 Propellers

In a propeller driven system, propeller momentum theory relationships (equations 19-20) are needed to calculate the systems induced velocity and power requirements [29:164-178].

$$\text{Velocity\_induced} = \sqrt{\frac{\text{Velocity}_{\text{free}}^{2}}{4} + \frac{\text{Thrust}}{2\cdot \text{Area}_{\text{prop}}\cdot \rho_{\text{air}}}} - \frac{\text{Velocity}_{\text{free}}}{2} \qquad (19)$$

$$\text{Power}_{\text{required}} = \text{Thrust}\cdot\left(\frac{\text{Velocity}_{\text{free}}}{2} + \sqrt{\frac{\text{Velocity}_{\text{free}}^{2}}{4} + \frac{\text{Thrust}}{2\cdot \text{Area}_{\text{prop}}\cdot \rho_{\text{air}}}}\right) \qquad (20)$$

Where:

- Thrust = thrust needed to counteract drag forces (N)
- Prop Area = the circular area swept out by propeller (m^2)
- Velocity Free = the ambient wind speed (m/s)

3.3.4.1.2 Turbojets

The static thrust of a turbojet is directly proportional to the air density and uses the relationship of equation 21 [29: 230-232]:

$$\text{Static\_Thrust}_{\text{altitude}} = \frac{\rho_{\text{altitude}}}{\rho_{\text{msl}}}\cdot \text{Static\_Thrust}_{\text{msl}} \qquad (21)$$

Positron Turbojets have a similar performance and size characteristics to conventional turbojet engines. The static thrust of the positron turbojet used in the analysis is based on 90% the performance of the LOCAAS small combustion-based turbojet engine [20:49]. The LOCAAS turbojet has a thrust to weight ratio of 0.5 kg/N at sea level. This gives the positron turbojet a thrust to weight ratio of 0.45 kg/N at sea level. At altitude the thrust to weight ratio is related to the fraction of air density compared to sea level as shown in equation 22 which allows the mass of the positron turbojet to be found as shown in equation 23.

$$\text{Thrust\_to\_weight}_{\text{altitude}} = \text{Thrust\_to\_weight}_{\text{msl}} \cdot \frac{\rho_{\text{altitude}}}{\rho_{\text{msl}}} \tag{22}$$

$$\text{Mass}_{\text{positron\_turbojet}} = \frac{\text{Thrust}_{\text{required}}}{\text{Thrust\_to\_weight}_{\text{altitude}}} \tag{23}$$

3.3.4.2 Space Propulsion

With no air available, space propulsion systems typically carry a working fluid onboard to provide the needed thrust. This working fluid is characterized by a term known as specific impulse or ISP. The relationship between specific impulse, thrust and mass flow rate is shown in equation 24 [1:689]:

$$\text{Specific\_Impulse} = \frac{\text{Thrust}}{\text{gravity} \cdot \text{mass\_flow\_rate}} \tag{24}$$

With specific impulse inversely proportional to the mass flow rate, the higher the fuel's specific impulse the less on-board propellant needed for the same amount of required thrust. Therefore higher specific impulse systems are usually preferred for long duration missions.

The required mass flow rate of a space propulsion system depends on the amount of thrust needed over the life of the mission. With changing wind conditions throughout the year, and average thrust requirement is generated by calculating drag forces using monthly mean zonal winds and averaging the results. This average thrust requirement allows for an annual propellant budget to be obtained. An operational airship can expect varying propellant usage throughout the year with the more usage in the winter months and lowest in the spring and fall.

Electrical Propulsion thrusters typically have very large electrical requirements. For the MPD & PIT thrusters examined, five kilowatt of electrical power required per Newton of thrust was used in the airship sensitivity analysis [30].

3.4 Chapter Summary

This chapter discussed the rationale of the baseline airship design and reviewed the calculations and assumptions used in the parametric analysis. Chapter 4 presents the analysis in a logical fashion allowing the reader to understand my thought process used to obtain the overall results and conclusions of this research.

4. Analysis and Results

4.1 Chapter Overview

A systematic analysis approach was used to provide the reader with an understanding of each design parameter and significance on the overall airship design. The analysis began by determining the altitude limitations for a simple floating spherical balloon using various fabric weights. The next step identified the amount of drag forces encountered if the balloon was held stationary at altitude. With the drag forces known, the vehicle's shape was lengthened to a more traditional airship design to identify any reduction in drag forces. From this basic analysis a baseline airship was found using current state-of-the-art relevant technologies. A parametric sensitivity analysis around this baseline established critical technology design drivers needed to improve the airship's overall design.

4.2 Spherical Balloon

High Altitude balloons such as the NASA ULDB superpressure design utilize very lightweight composite fabric at 62 g/m^2, while airships use a more robust composite fabric typically around 300 g/m^2 but can vary widely from around 50-2000 g/m^2. Fixing certain system parameters (Table 13), maximum achievable altitudes can be determined at various fabric densities using the buoyancy principle stated in equation 5.

Table 13: Free Floating Balloon Assumptions

Payload Mass	1000 kg
Payload Power	5000 W
Power Generation	CIGS Flexible solar arrays
Power Storage	Li-ion Batteries
Propulsion	None
Lifting Gas	Helium
Fineness Ratio	1

Figure 17 represents the absolute best that can be achieved using these assumptions. Changing the vehicle's shape for instance would require additional fabric to hold the same volume of lifting gas. Adding a propulsion system for stationkeeping will instead require a larger volume of lifting gas, which in turn would require more fabric.

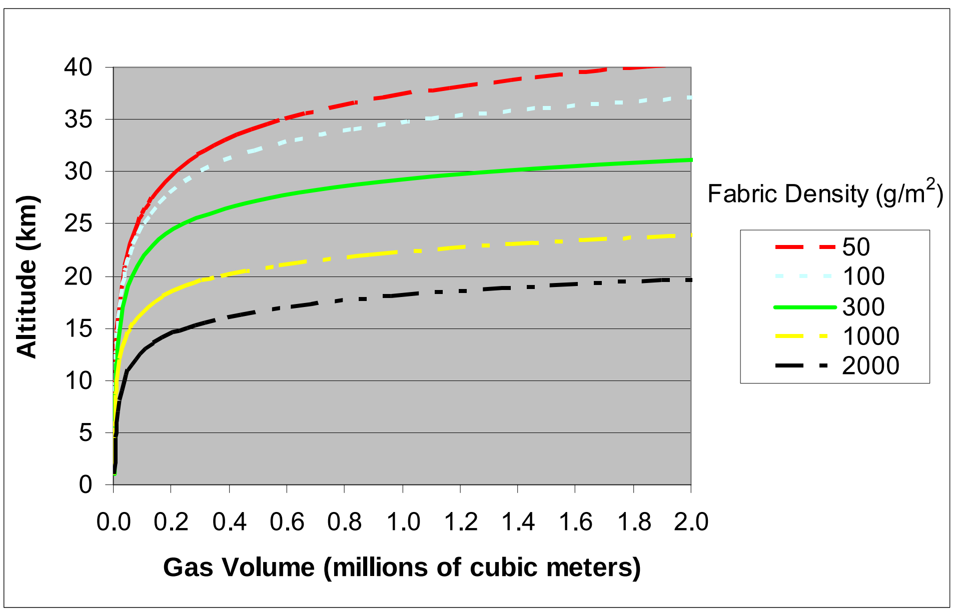

Figure 17: Balloon Volume vs. Altitude at Different Fabric Densities

Even with no propulsion system for stationkeeping, the heaviest airship fabrics are insufficient to lift the baseline payload into near-space. It turns out that fabric density is one of the primary critical drivers to achieve near-space altitudes with an operational airship.

Spherical shapes may by optimal for lifting payloads, but they are not suitable for stationkeeping in high winds due to their large frontal projected areas. A more slender shaped vehicle would be needed to properly loiter in the presence of any appreciable winds; hence the typical elongated airship designs seen today.

4.3 Baseline Airship Design

Using the baseline airship design assumptions, enumerated earlier in Table 12, expected drag forces for average and maximum expected wind conditions were obtained using equations 6-8 (Figure 18).

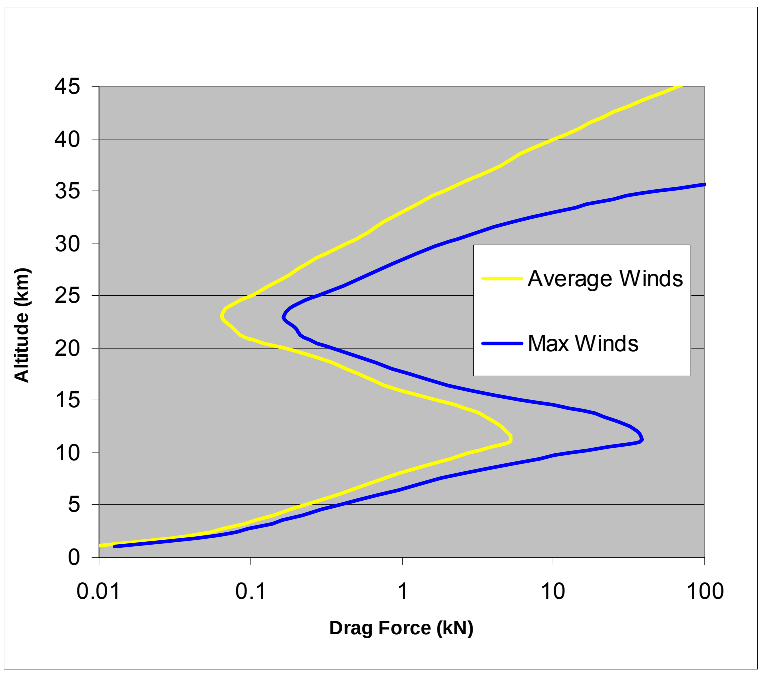

Figure 18: Expected Drag Forces While Loitering at Altitude with Baseline System

Examining the above chart, the reader might notice the relatively low drag forces present within the 20-25 kilometer attitude range. This is the first indication that an operational "sweet spot" may exist for near-space airships.

4.4 Airship Parametric Sensitivity Study

A sensitivity study of the baseline airship design assumptions was conducted to identify critical technology drivers for an improved loitering airship design. For each case the baseline airship was used with a single varied control parameter to understand the effect of airship envelope volume vs. altitude for that single parameter. Each chart will allow the reader to see the effect of adjusting a single parameter from the baseline assumptions. Identifying these critical drivers will focus scientists and engineers to apply limited resources properly to obtain the best possible design.

The first control parameter studied shows how the airship volume envelope needed to loiter at altitude changes in increasing wind conditions (Figure 19). As wind speeds increase, a larger propulsion system is needed to counteract the additional drag forces. This larger propulsion system requires a larger envelope volume to obtain an identical altitude.

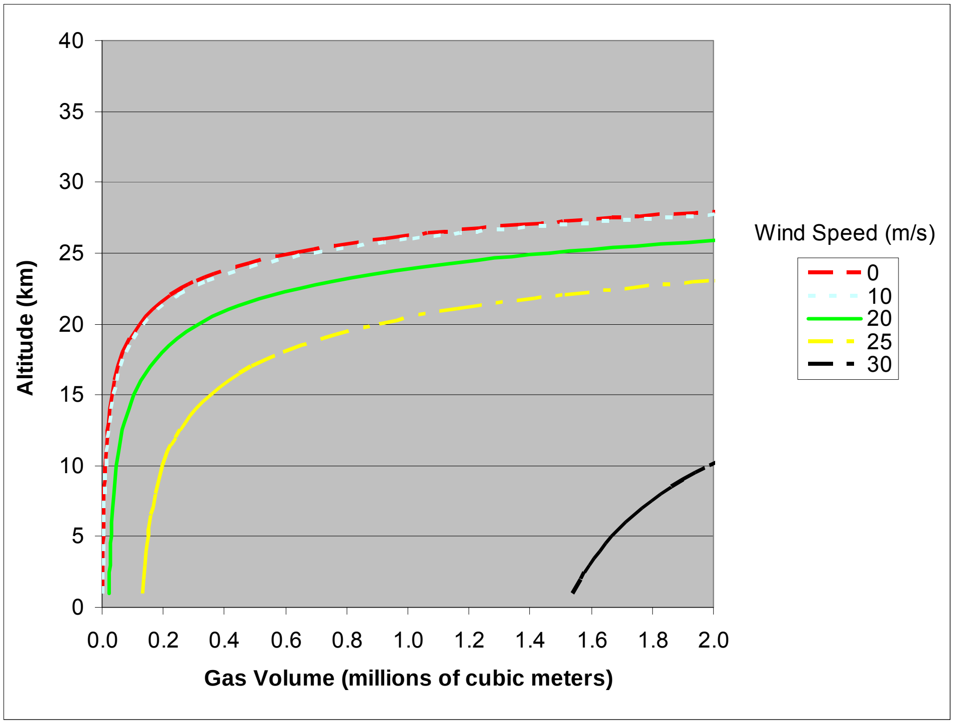

Figure 19: Airship Volume vs. Altitude at Different Winds for Baseline Airship Design

Three constant wind speeds of 0 m/s, 10 m/s, 25 m/s were used to represent the baseline wind conditions of no winds, low winds, and high winds respectively. Even though the wind speed greatly varies with altitude, these reference values were chosen so the impact of the remaining control parameters could be studied without the complexity of wind speed variability.

4.4.1 Fineness Ratio

The fineness ratio represents the vehicle's length to diameter ratio. Fineness ratio from 2 to 8 were plotted against the 4.62 baseline value holding all other parameters constant in 0 m/s, 10 m/s, and 25 m/s wind conditions.

Adjusting the fineness ratio in low wind conditions (Figure 20) has very little impact on the overall airship performance and is primarily attributed to larger fabric requirements to achieve a similar envelope volume for the higher fineness ratio vehicles.

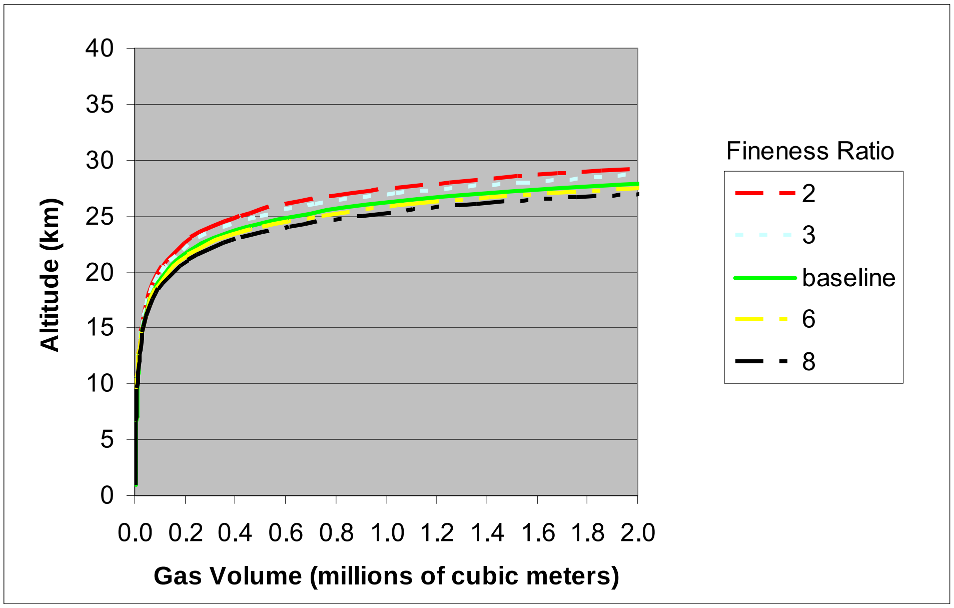

Figure 20: Airship Volume vs. Altitude at Different Fineness Ratios in Low Winds

Adjusting the fineness ratio in High wind conditions (Figure 21) can have a huge impact on the vehicles loiter capabilities. Lower fineness ratios have much higher drag coefficients as well as projected frontal areas that very quickly yield impractical design solutions. The reader should note that the baseline airship with a fineness ratio of 2.0 was unable to converge to a solution in high wind conditions and hence is not shown in the figure. High fineness ratios have only very slight improvements on the vehicles loiter capabilities, but do become more important as wind speeds increase. High fineness ratio vehicles may be also be more challenging to manufacture with higher fabric stress and the potential for buckling issues that would need to be considered in a final design.

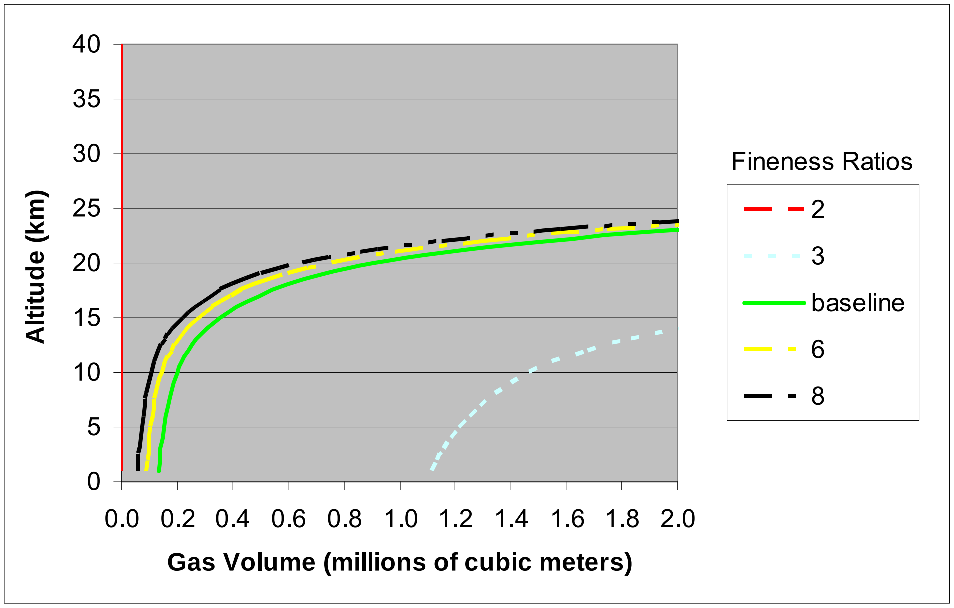

Figure 21: Airship Volume vs. Altitude at Different Fineness Ratios in High Winds

4.4.2 Fabric Density

Fabric density from 50 to 2000 g/m^2 were plotted against the 300 g/m^2 baseline value holding all other parameters constant in 0 m/s, 10 m/s, and 25 m/s wind conditions. Adjusting the fabric density in all wind conditions (Figures 22-23) has a large impact on the overall airship performance and is a critical technology driver for an operational near-space airship.

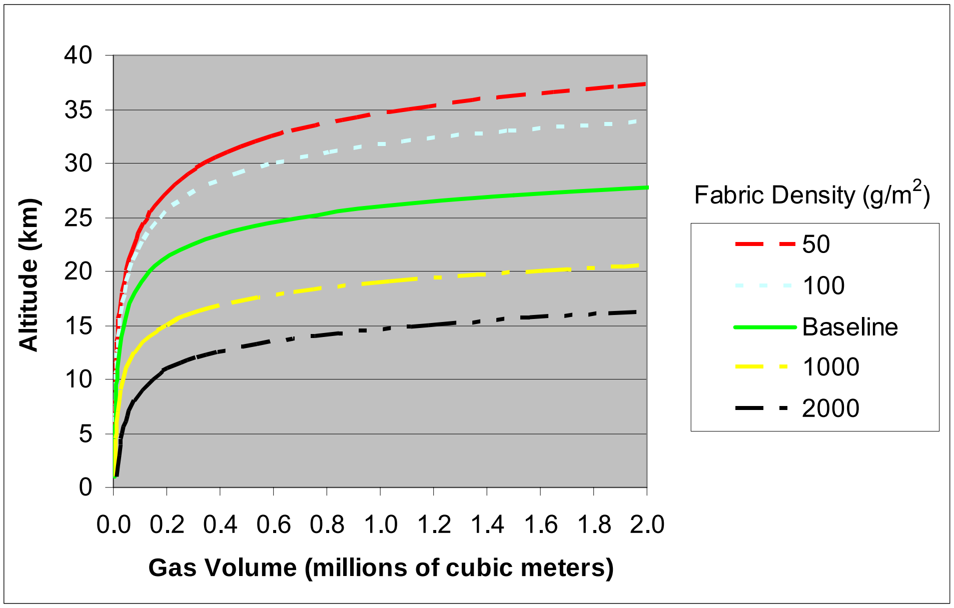

Figure 22: Airship Volume vs. Altitude at Different Fabric Densities in Low Winds

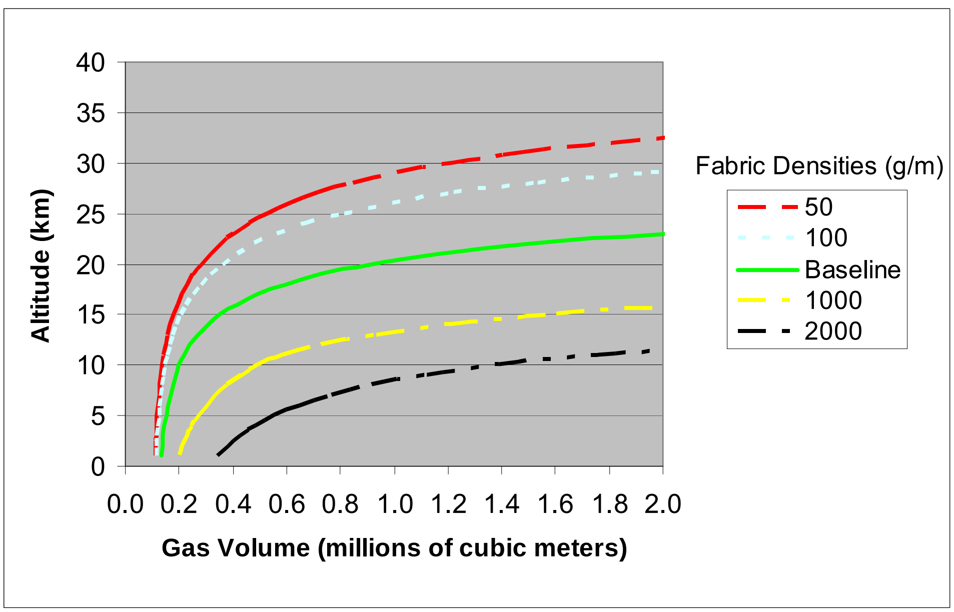

Figure 23: Airship Volume vs. Altitude at Different Fabric Densities in High Winds

4.4.3 Payload Mass & Power

Payload mass & power requirements from 100 kilogram & 500 Watts to 10,000 kilogram & 50,000 Watts were plotted against the baseline value of 1000 kilograms & 5000 Watts holding all other parameters constant in 0 m/s, 10 m/s, and 25 m/s wind conditions. Adjusting the payload mass & power requirements in all wind conditions (Figures 24-25) can have a moderate impact on the overall airship performance and reducing payload requirements may become important to reach near-space altitudes especially in higher wind environments.

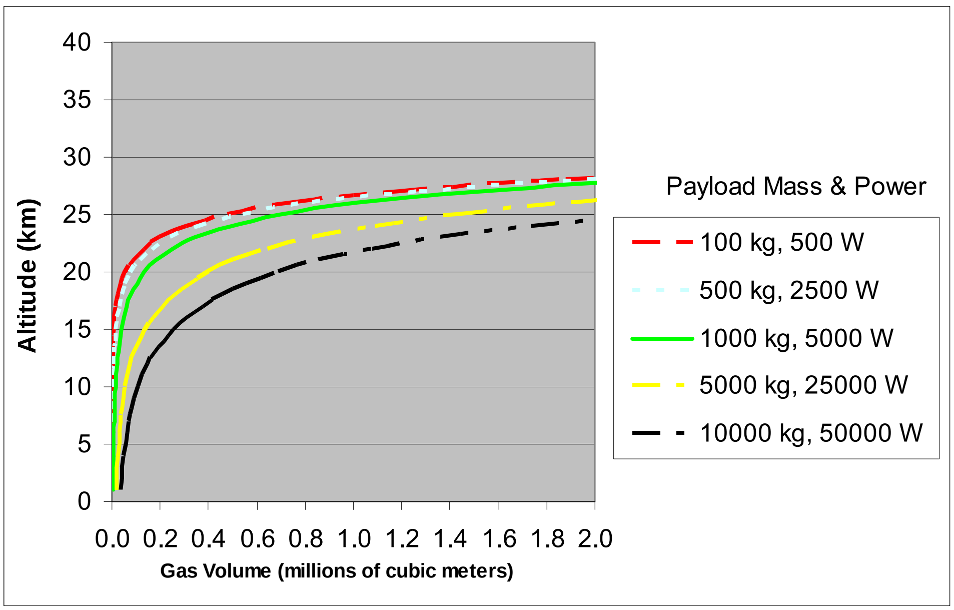

Figure 24: Airship Volume vs. Altitude at Different Payload Requirements in Low Winds

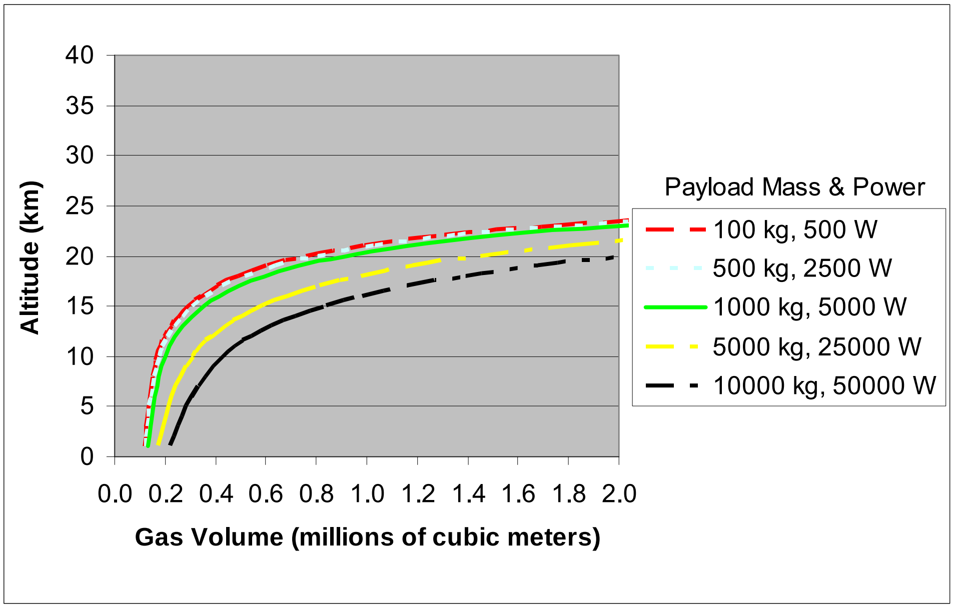

Figure 25: Airship Volume vs. Altitude at Different Payload Requirements in High Winds

4.4.4 Structure Mass Ratios

Structure mass ratios from 0 to 40 percent were plotted against the 20 percent baseline value holding all other parameters constant in 0 m/s, 10 m/s, and 25 m/s wind conditions. Adjusting the structure mass ratios in low wind conditions (Figure 26) has only a small impact on the overall airship performance. High wind conditions (Figure 27) do begin to have a more significant impact and needs to be reduced wherever possible if the airship is expected to operate in high wind conditions.

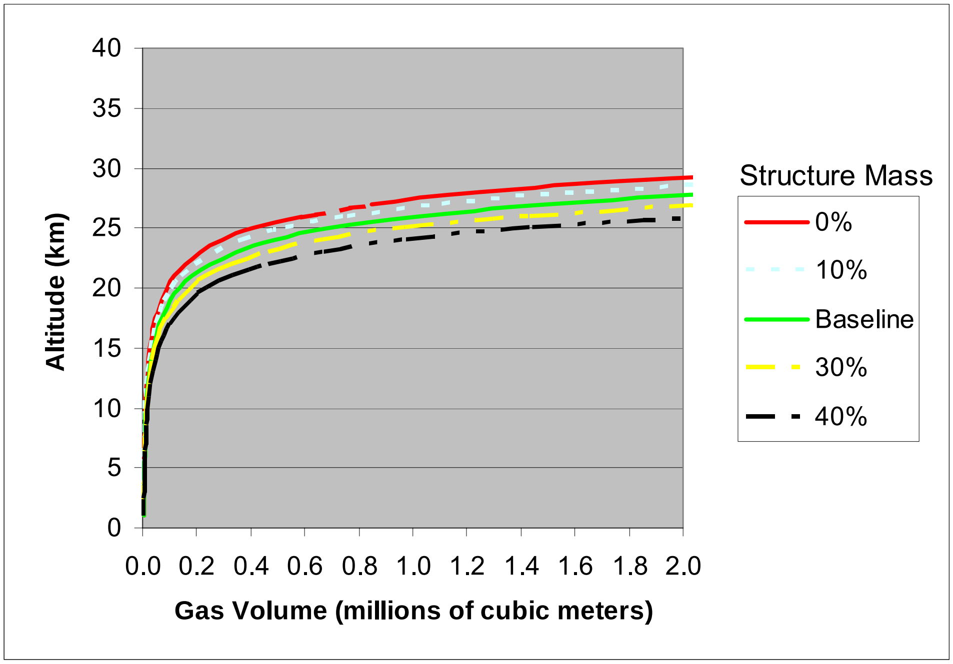

Figure 26: Airship Volume vs. Altitude at Different Structure Mass Ratios in Low Winds

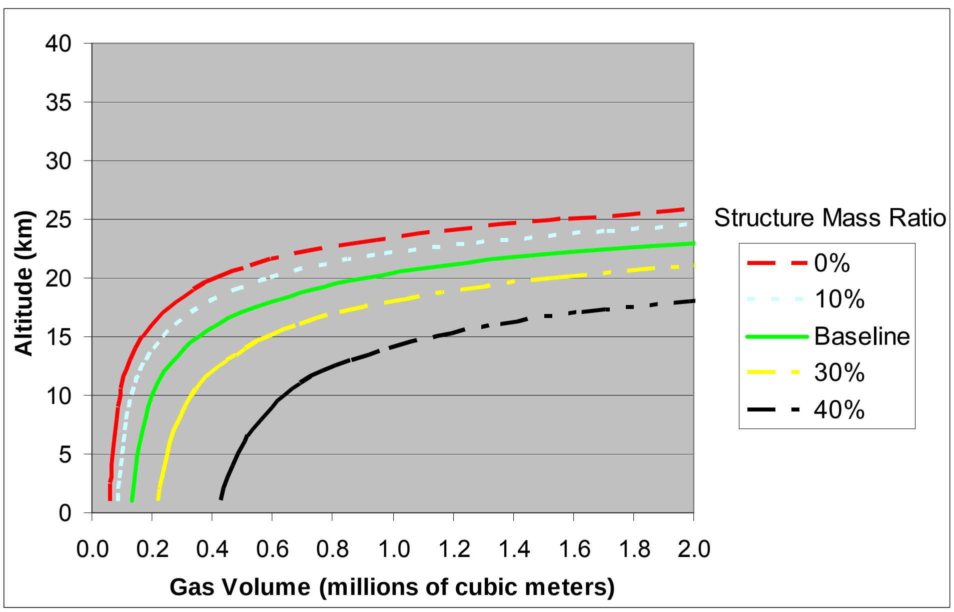

Figure 27: Airship Volume vs. Altitude at Different Structure Mass Ratios in High Winds

4.4.5 Electric Propellers

Propeller diameters from 1.5 to 5 meters were plotted against the 3 meter baseline value holding all other parameters constant in 0 m/s, 10 m/s, and 25 m/s wind conditions. Adjusting the propeller diameter in low wind conditions (Figure 28) has almost no impact on the overall airship performance. High wind conditions (Figure 29) have a significant impact on propeller size of a loitering airship. This is due to lower efficiencies at higher speeds. It is much more efficient to accelerate a large amount of air slowly as opposed to moving a small amount of air quickly. As the thrust requirement increases a larger propeller diameter becomes critical. If a larger propeller diameter is not feasible, another option is to add additional propellers to increase the thrust levels.

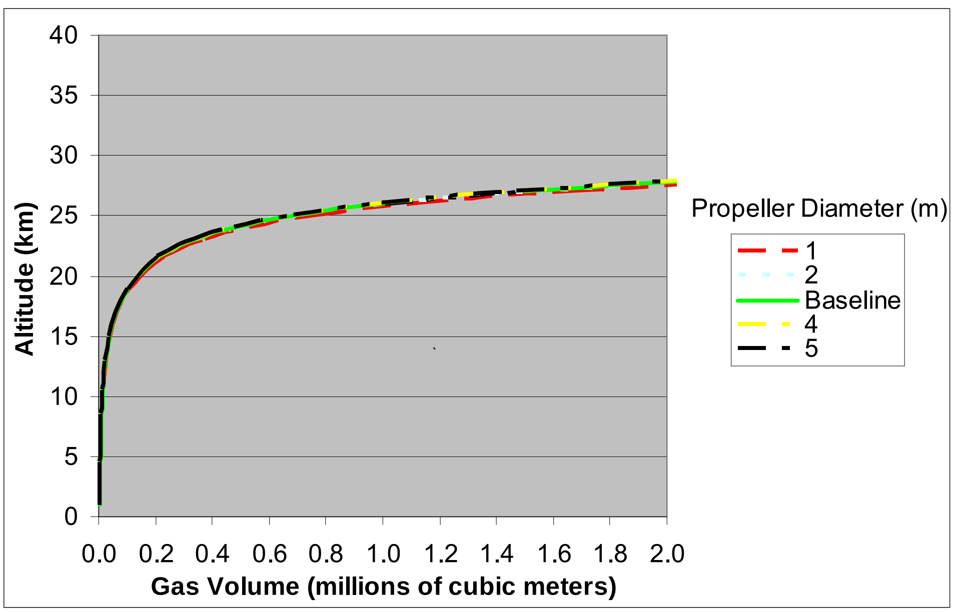

Figure 28: Airship Volume vs. Altitude at Different Propeller Diameters in Low Winds

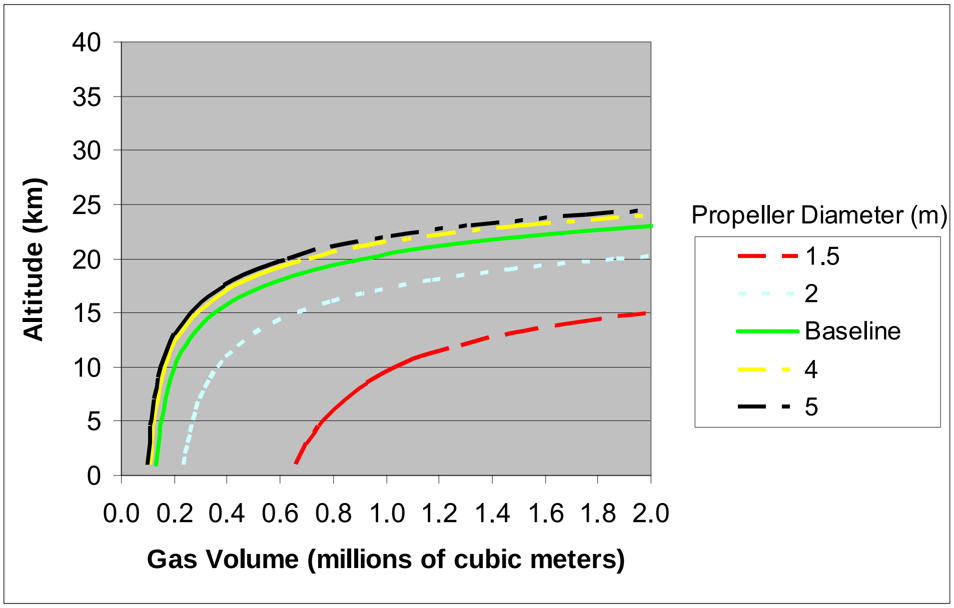

Figure 29: Airship Volume vs. Altitude at Different Propeller Diameters in High Winds

If increasing the propeller diameter becomes impractical, the number of electric propellers can be increased. The number of electric propellers from 2 to 10 was plotted against the 6 propeller baseline value holding all other parameters constant in 0 m/s, 10 m/s, and 25 m/s wind conditions. Adjusting the number of electric propellers in low wind conditions (Figure 30) has almost no impact on the overall airship performance. High wind conditions (Figure 31) have a significant impact on the number of propellers needed for a loitering airship. A combination of larger or increased number of propellers will allow the airship to operate more efficiently in high wind conditions.

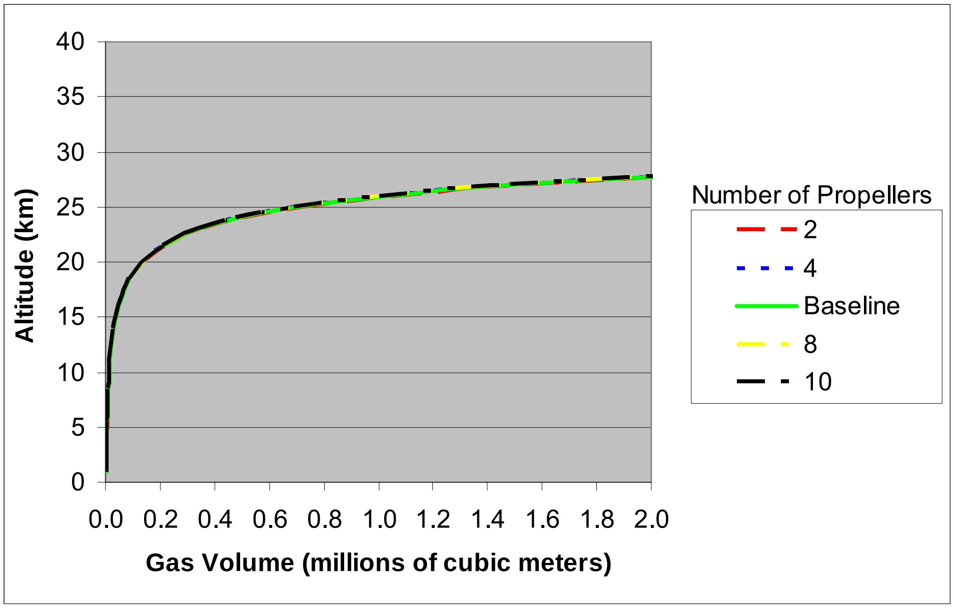

Figure 30: Airship Volume vs. Altitude with Different Number of Engines in Low Winds

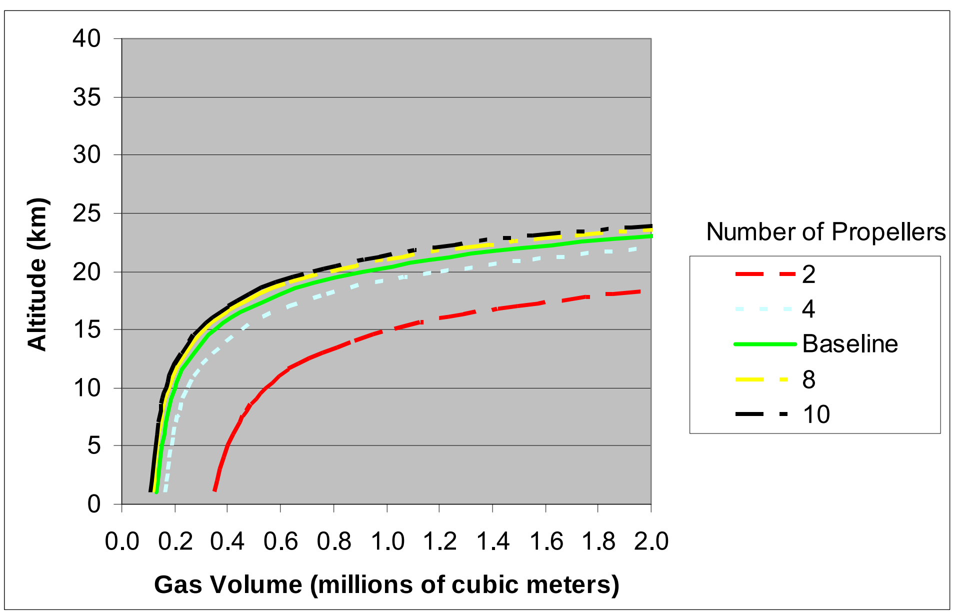

Figure 31: Airship Volume vs. Altitude with Different Number of Engines in High Winds

4.4.6 Eclipse Duration

Eclipse duration from 8 to 16 hours were plotted against the 12 hour baseline value holding all other parameters constant in 0 m/s, 10 m/s, and 25 m/s wind conditions. Adjusting the eclipse duration in low wind conditions (Figure 32) is negligible, but high wind conditions (Figure 33) do begin to have a more significant impact. Even though the length of daily eclipse cannot be controlled, it is important to understand the limitations that might occur in different operational scenarios.

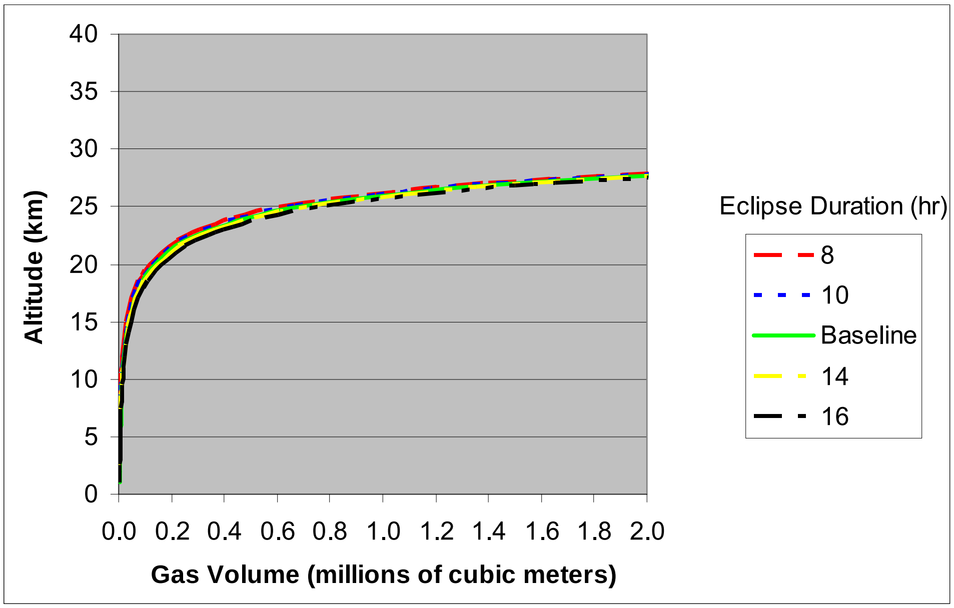

Figure 32: Airship Volume vs. Altitude at Different Eclipse Durations in Low Winds

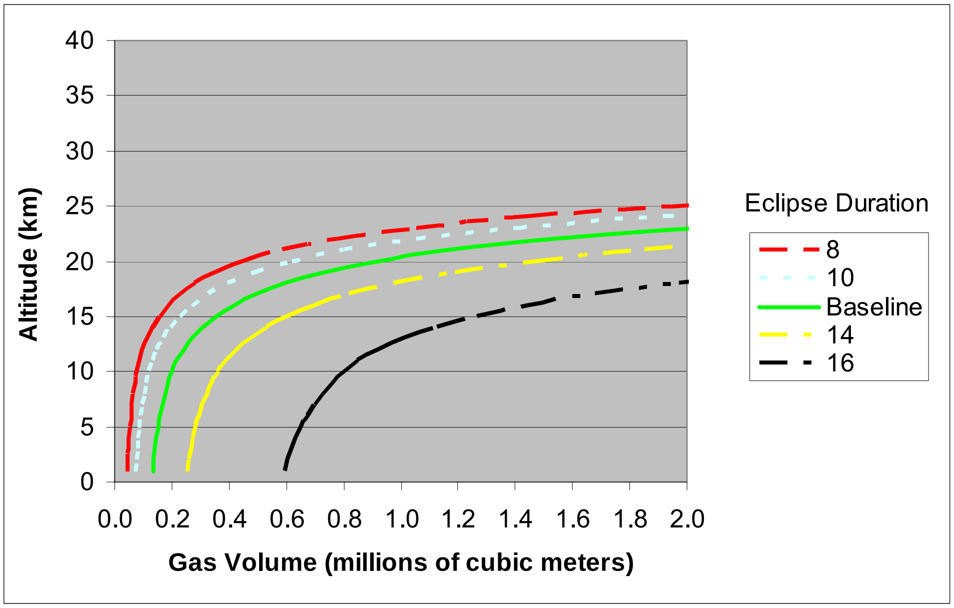

Figure 33: Airship Volume vs. Altitude at Different Eclipse Durations in High Winds

4.4.7 Parametric Study Summary

Summary of the parametric sensitivity study is shown in Table 14.

Table 14: Parameter Sensitivity Study Summary

Varying Parameter	No Winds	10 m/s winds	25 m/s winds	Summary
Fineness Ratio	Small	Small	Very Large	Impact directly tied to Drag Coefficient, and frontal area
Fabric Density	Large	Large	Large	Moderate Impact across the wind spectrum
Payload Mass & Power	Moderate	Moderate	Moderate	Moderate Impact across the wind spectrum
Structure Mass	Small	Small	Moderate	Impact increases with wind conditions
Propeller Diameter	No effect	Negligible	Moderate	Impact increases with wind conditions, tied to Number of Engines
Number of Propellers	No effect	Negligible	Moderate	Impact increases with wind conditions tied to propeller diameter
Eclipse Duration	Negligible	Negligible	Moderate	Impact increases with wind conditions

The reader may ask what the airship capabilities are possible if all the baseline parameters could be improved. A hypothetical improved parameter design has been constructed in Table 15. By plotting the capabilities of an airship based on these improved parameters (Figure 34), the reader can get a sense of how much additional performance might be possible once better technologies become available. The greatest benefit of an airship using the improved design parameters occur in high wind conditions where the airship gas volume is greatly reduced.

Table 15: Improved Design Parameters

Improved Airship Design Assumptions	
Payload Mass	100 kg
Payload Power	500 W
Power Generation	CIGS Flexible solar arrays
Power Storage	Li-ion Batteries
Daily Eclispe	12 hours
Propulsion	10 Electric Propellers
Propeller Diameter	4 meters
Lifting Gas	Helium
Fabric Density	100 g/m^2
Fineness Ratio	4.62
Structure Mass	10% of Total Mass

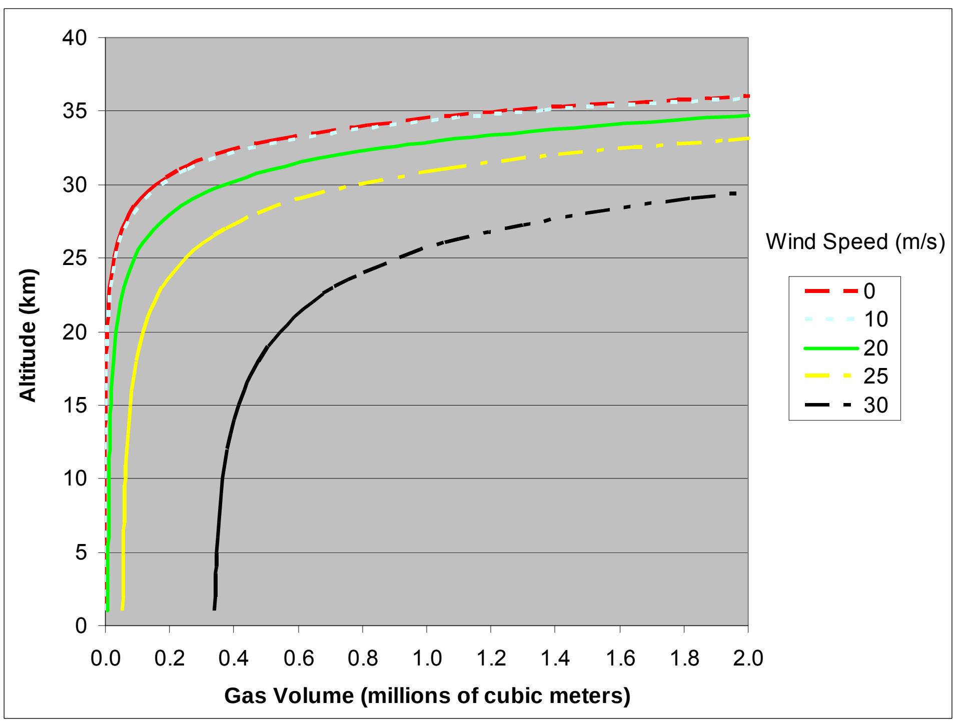

Figure 34: Airship Volume vs. Altitude with Improved Design at Different Wind Conditions

4.5 Propulsion & Power Subsystem Alternatives

The following charts (Figure 35-42) show the maximum wind conditions that the baseline design airship can loiter in if its envelope volume is limited to 1 million cubic meters. Even though 1 million cubic meters might seem excessively large for today's technologies it identifies an upper limit without constraining future more ambitious endeavors.

4.5.1 Air Propulsion

Air propulsion options have been the basis for some of the high altitude platforms to date utilizing electric propellers with either a solar array/battery or fuel cells for power. This section compares some of these configurations against the baseline airship design to identify the strengths and weaknesses of each design.

4.5.1.1 Electric Propeller

Figure 35 highlights the differences between loitering a spherical shaped balloon, which is best for overall lift, and the more slender baseline airship design, which loiters better in high winds. The performance of an electric-powered propulsion system is not greatly impacted by mission length, as no on-board propellants are required. The baseline solar powered electric propeller system discussed herein is based on a 3-year mission life.

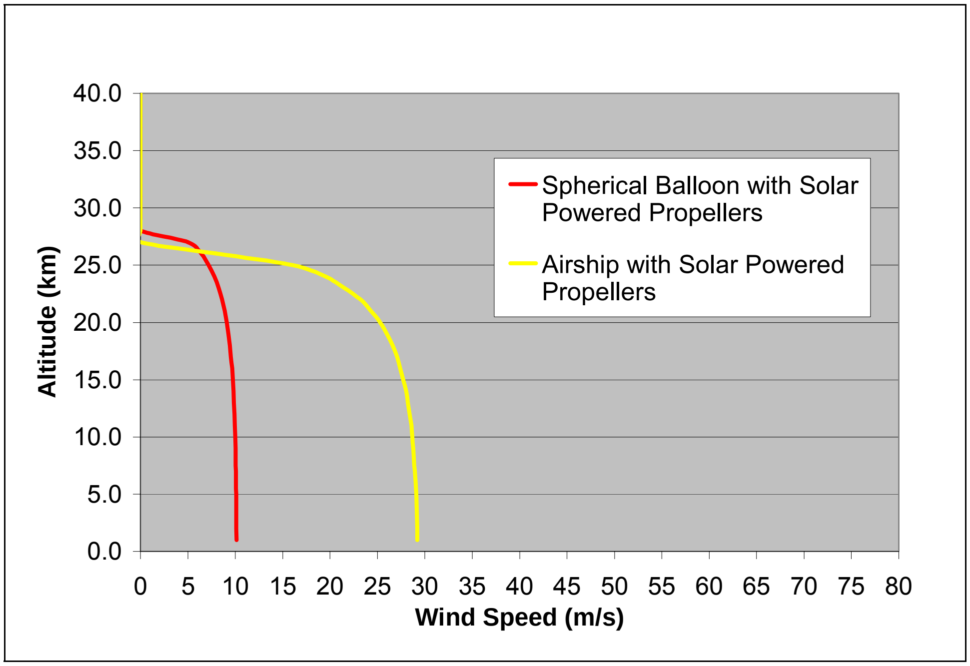

Figure 35: Loiter Capability with Solar Array Powered Electric Propellers

When the solar array and battery power subsystem is replaced with high energy density fuel cells (Figure 36), the vehicles loiter capability is greatly dependant on mission length and the amount of on-board propellant needed to run the electric propellers. For short missions of 30 days or less, fuel cell powered airships can loiter in higher winds than their solar array/battery counterpart.

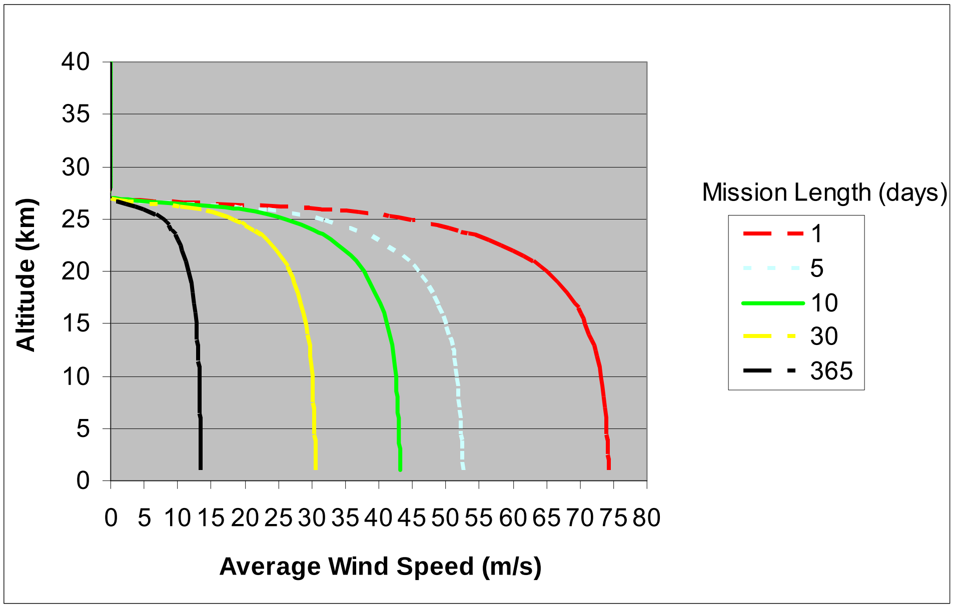

Figure 36: Airship Loiter Capability with Fuel Cell Powered Electric Propellers

4.5.1.2 Positron Turbojet

The loiter capability of the baseline airship using a positron turbojet based propulsion system and assuming a 1 year mission life was calculated using equations 21-23 (Figure 37). The performance of a positron based turbojet is not greatly impacted by mission length with negligible on-board propellant requirements. The turbojet's thrust capability falls off proportional with altitude as a result of lower air densities with increasing altitudes.

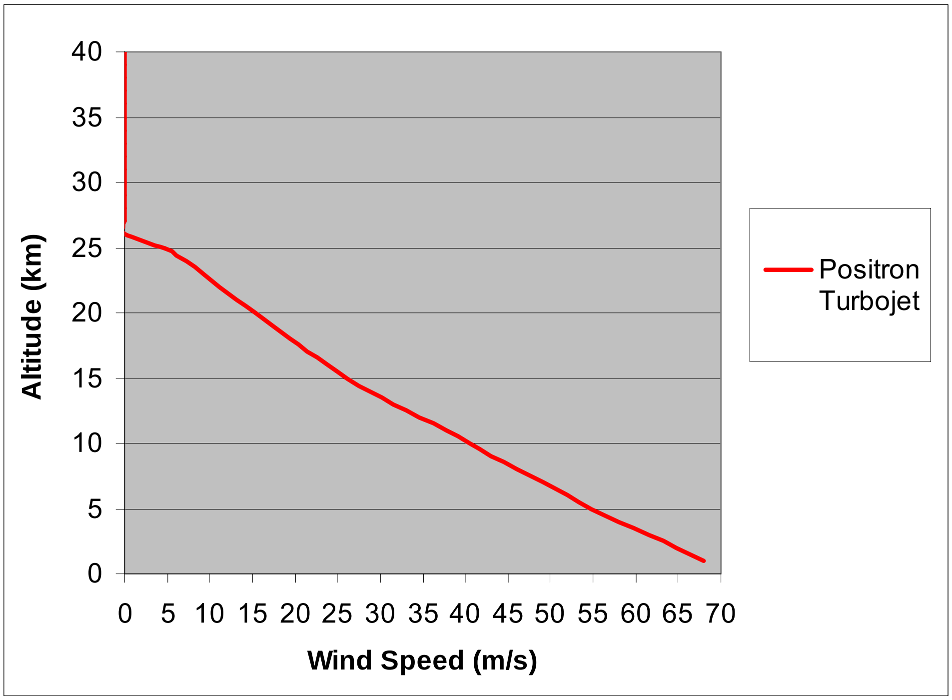

Figure 37: Airship Loiter Capability with Positron Turbojet Propulsion

4.5.2 Space Propulsion

Common to all space propulsion types, the amount of propellant carried to support a mission greatly impacts the overall capability of the system, which directly related to the propellants specific impulse characteristics. This section highlights the capabilities of chemical, nuclear, and electrical based propulsion systems to provide stationkeeping of the baseline airship design.

4.5.2.1 Chemical Rockets

The critical driver to determining the capability of a chemical based rocket is the specific impulse of the propellant (equation 24). The mass of the propellants that need to be carried to support the propulsion system can quickly become impractical for extended missions. Among the chemical based propulsion systems studied (liquid bi-propellants, hybrid engines, and water electrolysis), the technology with the highest specific impulse, a liquid bi-propellant rocket with a specific impulse of up to 450 seconds, was plotted (Figure 38) to determine maximum loiter capability for chemical based propulsion systems. Safety concerns might drive the designer to a hybrid engine or water electrolysis technologies, but this trade-off will yield a lower stationkeeping performance when compared to a bi-propellant system. All of the chemical rocket options provide inferior performance to the baseline propeller design.

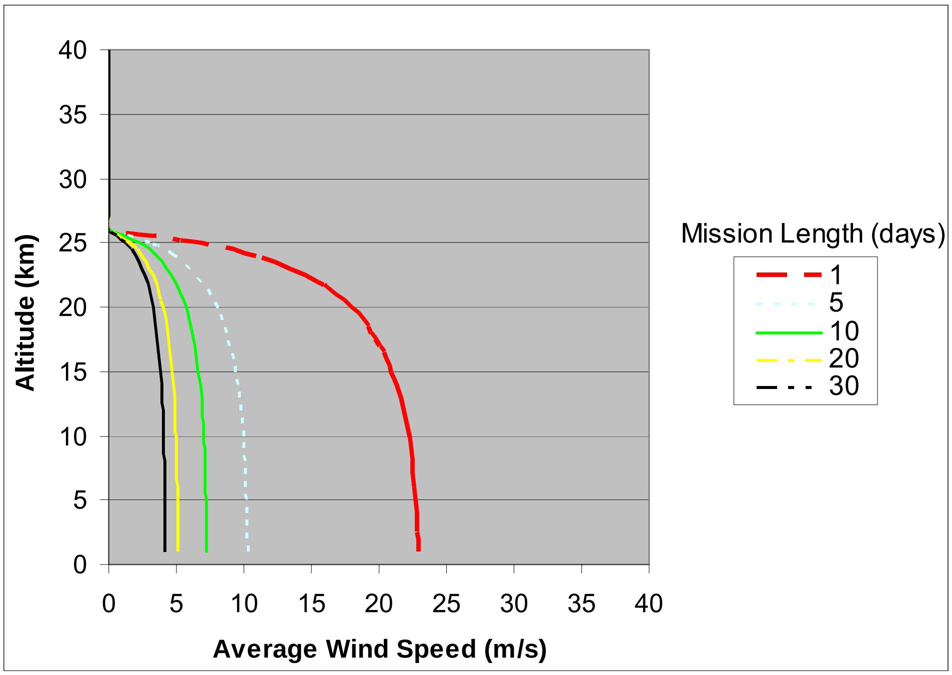

Figure 38: Airship Loiter Capability with Bi-propellant Rocket Propulsion

4.5.2.2 Nuclear Propulsion

A nuclear particle bed rocket benefits from a high specific impulse of 1000 seconds limiting the on-board propellants needed. Figure 39 plots the loiter capability using a particle bed rocket propulsion system for the baseline airship.

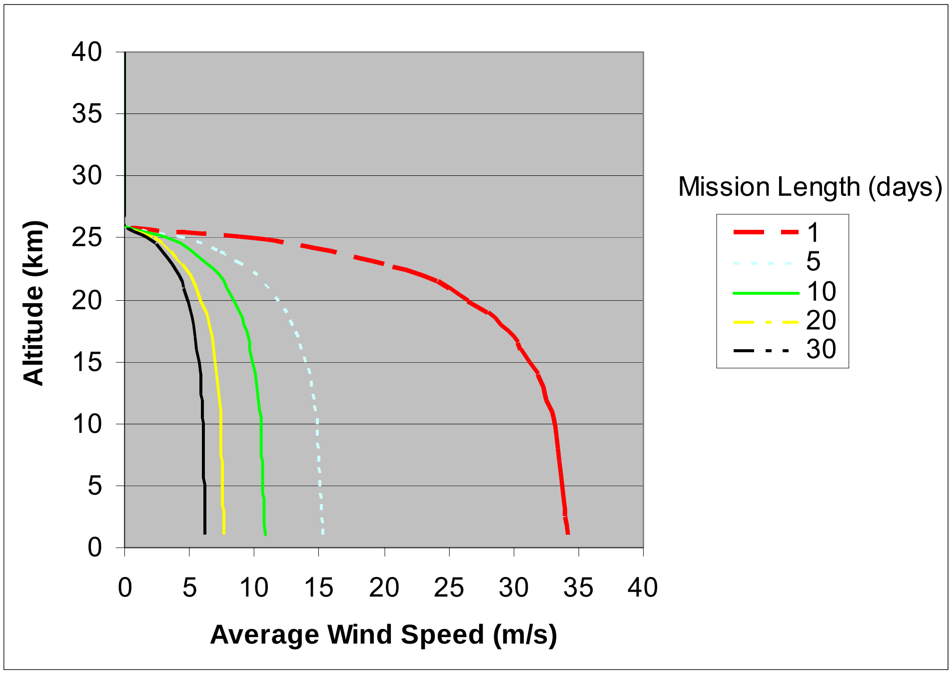

Figure 39: Airship Loiter Capability with Particle Bed Rocket Propulsion

4.5.3 Electric Propulsion

Electric based propulsion such as Magnetoplasmadynamic (MPD) and pulsed inductive thrusters benefit from very high specific impulses that as high 7500 seconds. The critical driver in these types of propulsion systems is the very large electrical power requirement that can quickly become massive for any length mission. Figures 40-41 plot the loiter capability of the baseline system using MPD thruster propulsion powered by solar array and fuel cell technologies respectively. For any useful airship design a more practical electric power source would need to be identified.

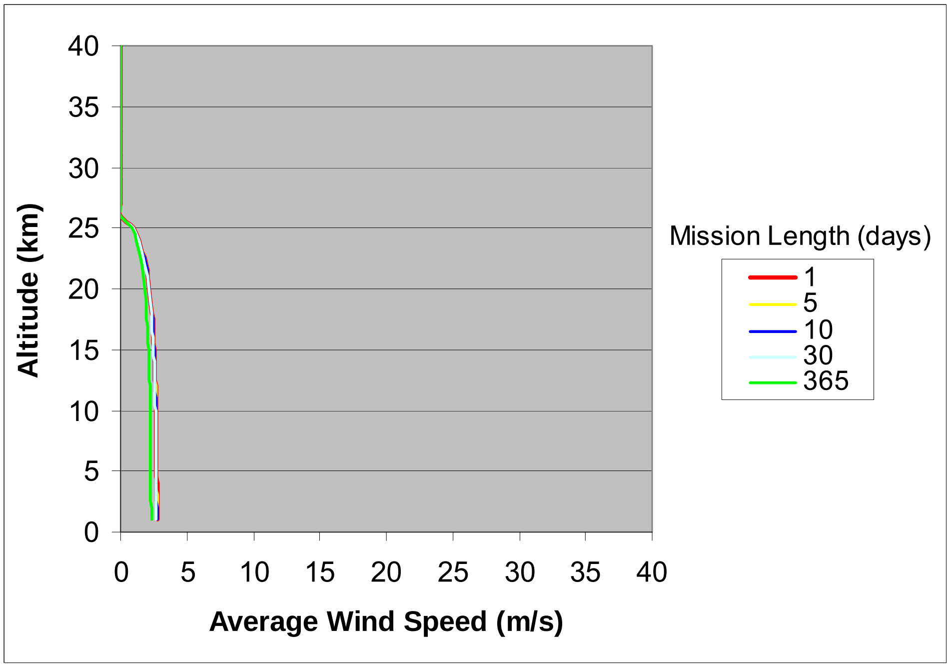

Figure 40: Airship Loiter Capability with Solar Array Powered MPD Thrusters

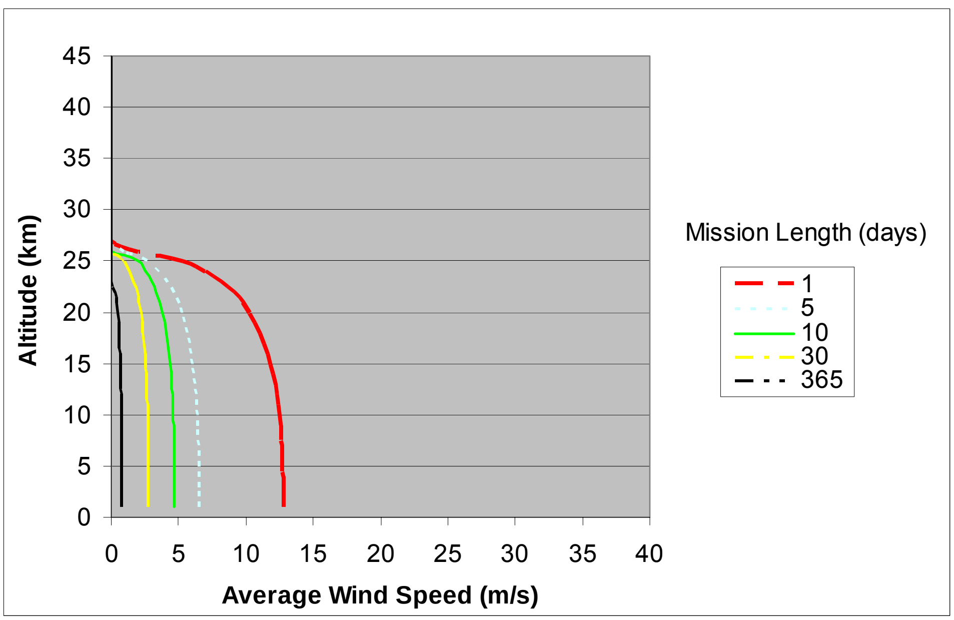

Figure 41: Airship Loiter Capability with Fuel Cell Powered MPD Thrusters

4.5.4 Propulsion & Power Study Summary

For any mission beyond 30 days in duration the solar array powered electric propeller option is the best overall propulsion option to maintain stationkeeping. If the baseline design parameters are improved as listed in Table 15, maximum loiter capabilities increase significantly in the near-space regime as shown in Figure 42.

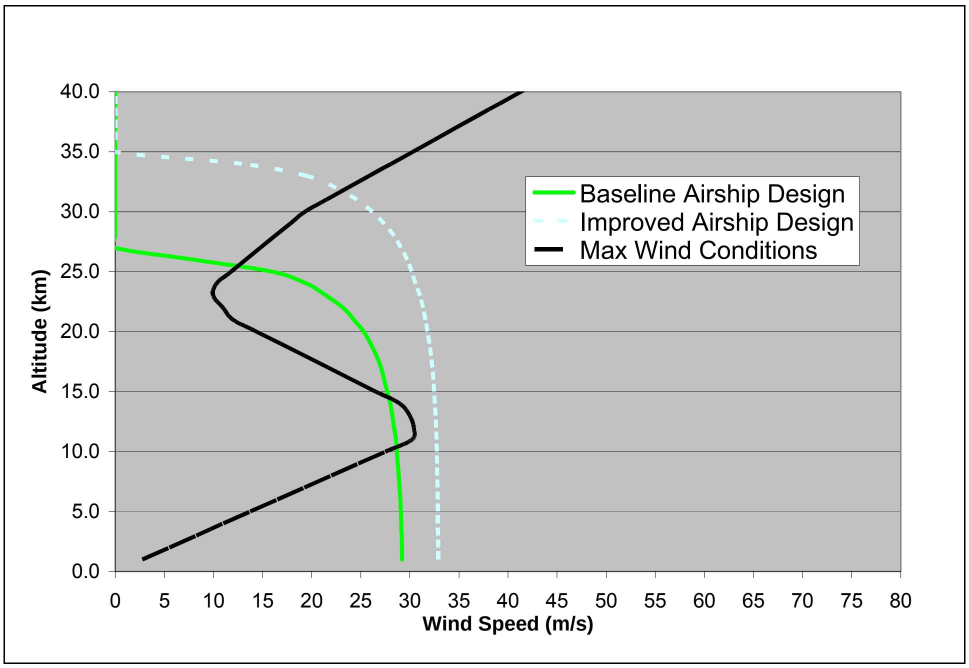

Figure 42: Maximum Loiter Capability for Baseline and Improved Airship Designs

4.6 Chapter Summary

This chapter illustrates the technical feasibility of a loitering airship using available technologies in the lower altitudes of near-space. Critical drivers to achieving a more capable airship design include: drag coefficient (fineness ratio), fabric density, payload power & mass requirements, and structure mass. Solar photovoltaic and fuel cells are good candidates to provide adequate power needs, while electric driven propellers appear to be the best overall propulsion option available today for missions of one month or longer.

Chapter 5 summarizes the technical feasibility of a near-space airship design by answering the initial questions posed in Table 1 and makes recommendations for future research efforts.

5. Conclusions and Recommendations

5.1 Chapter Overview

The objective of this study was to examine technical requirements for a lighter-than-air platform to loiter for an extended duration in near-space. The strategy adopted to answer this problem was to identify current state-of-the-art technologies that could be used to support a near-space airship. From this baseline a parametric sensitivity study was conducted to identify the designs critical drivers.

5.2 Conclusions of Research

Six questions were posed at the start of this research effort and have been answered in Table 16 below.

Table 16: Answers to Research Questions

1	**Can a lighter-than-air near-space platform be made to loiter in near-space for extended durations?**
Answer	Slender shaped maneuverable airships can be designed using current technologies to loiter in lower near-space altitudes (20-25 km) in wind speeds 25 m/s or less for durations of 30 days or longer.
2	**What propulsion requirements are needed to provide 24-hour stationkeeping to a near-space airship?**
Answer	Due to high altitude prevailing winds, a "sweet spot" in the 20-25 kilometer altitudes exists where below 300 newton drag forces are encountered in maximum wind conditions. These drag forces increase steadily to around 2 kilonewtons at 30 kilometer altitudes. Loitering at altitudes above 35 kilometer become increasingly difficult where drag forces of over 100 kilonewtons would frequently be encountered.
3	**What propulsion system technologies are available to achieve near-space stationkeeping?**
Answer	Solar array powered electric propellers appear to be the best option available today for long duration missions of one month or greater. Positron turbojet technologies loose capability at increasing altitudes, but may prove to be a worthwhile option to explore for future long term missions. All space propulsion options are severely limited in the amount

	of propellants that can be carried on-board resulting in very short mission durations of only a few days.
4	**What fineness (length/diameter) ratio is the most optimal configuration to provide the best overall lift and the lowest drag for a near-space platform?**
Answer	When designing a near-space platform capable of loitering over a single area above the earth, a slender airship design is required. Spherical balloons, although great for lift, present a large frontal area, which creates a very large drag component. A more slender airship will greatly reduce this frontal drag. A fineness ratio of 4.62 gives the best overall airship volume while minimizing the frontal drag component.
5	**What altitudes can be achieved with airships using current state-of-the-art technology?**
Answer	The baseline airship design used in this research (Table 12) is capable of loitering in the lower altitudes (20-25 km) of near-space for durations of 30 days or longer. With additional improvements in airship technologies using an improved design (Table 15) altitudes of 30 km become achievable.
6	**What airship modifications can be made to improve loiter capabilities and achieve higher operational altitudes?**
Answer	To improve loiter capabilities; the vehicle's overall drag coefficient needs to be reduced to lower the drag forces encountered in high wind conditions. Consider altering the shape of airship and placing payload and other support equipment inside the lifting envelope. Lower envelope fabric weights would be necessary to obtain operational altitudes above 25 kilometers.

5.3 Significance of Research

Loitering near-space airships would reduce the reliance on strategic satellite platforms and provide a cost effective alternative providing 24-hour coverage over a conflict region to support the battlefield commander's mission objectives. This research identified the feasibility of a near-space airship design and the critical technologies needed to achieve a more capable system.

5.4 Recommendations for Future Research

This research identified the technical limitations of a near-space loitering airship. Throughout the course of the research several issues were identified that would need to be addressed in order to field an actual system including: launch and recovery, logistical support, survivability, cost analysis, alternative stationkeeping methods, payload specific requirements.

One of the more significant limitations in fielding an operational lighter-than-air near-space airship is the wind constraint needed at launch. Turbulent winds of any appreciable magnitude can be devastating when attempting to launch a large near-space airship. Experienced launch teams typically wait until the perfect conditions exist making launch on demand practically impossible. Alternative methods for deployment should be explored in-depth to identify potential solutions for a more responsive operational capability.

Another research area that may provide improved altitude capabilities would be to consider alternative stationkeeping methods. If operating at altitudes above 30 kilometers is desired, instead of increasing the overall propulsion requirements to loiter at extreme altitudes, the airship could essentially drift over the area later to be lowered to around 25 kilometers for a return trip using a smaller propulsion system. A larger constellation of airships would be required to ensure constant coverage at altitude but might prove to be a feasible alternative if higher altitudes are required.

Lastly a detailed cost analysis should be conducted of the different technically feasible options. Some options, while technically feasible, might prove to be cost prohibitive. Once this analysis is complete, a cost comparison can be made against current UAV and satellite alternatives.

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Vita

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His first assignment was at Los Angeles AFB as a cost estimator for the Defense Meteorological Satellite Program (DMSP) in June 1996. In January 1998, he was assigned to the systems engineering division of DMSP and was responsible for spacecraft integration & test and launch related issues. Upon launch of the S15 spacecraft in December 1999, he was transferred to the Directed Energy Directorate of the Air Force Research Laboratory at Kirtland AFB. While stationed in New Mexico, he served as the Laser Effects Test Facility Manager and became the Director of the Missile Assessment Center. In August 2003, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to the National Reconnaissance Office's Signal Intelligence Directorate.

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14. ABSTRACT

The near-space region of earth's atmosphere above 20 kilometers altitude is greatly underutilized. Lighter-than-air maneuvering vehicles, or airships, using the principle of buoyancy can take advantage of this region to become potential platforms for precision navigation, environmental monitoring, communication relays, missile warning, surveillance, and weapon delivery. These vehicles purportedly provide persistent coverage over large areas of the earth's surface at substantially lower costs than orbiting satellites. This study investigated the technical requirements to loiter an operational payload within this high altitude region using a lighter-than-air maneuvering platform. A parametric analysis was conducted to identify the critical technologies needed to achieve operational payload, power, altitude, and stationkeeping requirements. The research concluded feasibility of stationkeeping a 1000 kg payload in lower near-space (20-25 km) using current airship technologies. Solar powered electric propellers provided the best overall near-space loiter capability for missions beyond 30 days. Additional loiter capability can be attained for shorter missions using fuel cell technologies. Technology improvements in the airship's drag coefficient, envelope fabric density, and payload mass and power requirements are required to attain altitudes beyond 25 km.

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