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Airships for Planetary Exploration

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November 2004

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TABLE OF CONTENTS

<u>ABSTRACT</u>	1
<u>INTRODUCTION</u>	1
<u>PLANETARY ENVIRONMENTS</u>	2
ATMOSPHERIC ENVIRONMENT OF VENUS	3
ATMOSPHERIC ENVIRONMENT OF MARS	5
ATMOSPHERIC ENVIRONMENT OF TITAN	6
OUTER PLANETS (JUPITER, SATURN, URANUS, NEPTUNE)	6
<u>AIRSHIP EVALUATION</u>	7
AIRSHIP FOR VENUS	13
AIRSHIP FOR MARS	17
AIRSHIP FOR TITAN	18
OUTER PLANETS	19
<u>SUMMARY</u>	19
<u>REFERENCES</u>	20

Abstract

The feasibility of utilizing an airship for planetary atmospheric exploration was assessed. The environmental conditions of the planets and moons within our solar system were evaluated to determine their applicability for airship flight. A station-keeping mission of 50 days in length was used as the baseline mission. Airship sizing was performed utilizing both solar power and isotope power to meet the baseline mission goal at the selected planetary location. The results show that an isotope-powered airship is feasible within the lower atmosphere of Venus and Saturn's moon Titan.

Introduction

Most planets and some moons within our solar system have atmospheres. The presence of an atmosphere enables the possibility of utilizing vehicles that can fly within the atmosphere as a potential tool for planetary exploration. Atmospheric flight vehicles offer a unique science data gathering capability. Planetary air vehicles should be thought of as another tool in the exploration toolbox. They are not intended to take the place of other types of exploration vehicles but to complement them. They can be used in conjunction with land based (rovers and landers) and space based (orbiters) exploration to provide a complete set of capabilities for planetary exploration. Whereas rovers and landers can provide very high-resolution data on a local scale and orbiters can provide lower resolution data on a planetary scale, air vehicles can provide high-resolution data on a regional scale.

In addition to the unique imaging and remote sensing data collection capabilities of air vehicles, they also provide a means of direct sampling of a planet's atmosphere. This sampling can be performed over a region of the atmosphere and potentially over a range in altitudes. For example, an airship could be used to sample the atmosphere over a region looking for signs of life. This can be accomplished by searching for concentrations of biogenic gases (such as CH_4 , NH_3 , H_2S etc.) If a concentration of these are found, a future mission can be used to send a rover or lander to the site of interest to complete the investigation. An airship, if feasible, would provide a stable, slow-moving platform that could provide data of a large region.

One of the main obstacles to planetary air vehicles is the need for continuous power in order to remain in controlled flight. This issue is not as severe with airships as it is with aircraft since an airship's lift is not dependent on its velocity. Because of the inability to refuel, the mission duration, with a conventional combustion engine powered airship, will be limited to the amount of fuel & oxidizer that can be carried on board. This inherently limits the mission time to a duration of hours or at best days. Although useful and significant data can be collected within this time frame, the mission duration will be much less than that of landers, rovers (duration of months), or orbiters (duration of years). To make the mission duration of airships equivalent, a non-consuming power source (solar or nuclear) needs to be considered. The type of system that is applicable to a given mission will depend on the airship's characteristics and the environment in which it is to operate.

To achieve long duration flight, not only will innovative power and propulsion systems be needed but also innovative airship designs that take advantage of the environment in

which they are operating. A long duration airship for planetary exploration will need to be matched to and take advantage of the environment in which it is to fly.

Planetary Environments

The environment in which the airship will operate will dictate its capabilities and will be the determining factor in the airship's feasibility. Items such as atmospheric density, atmospheric composition, temperature, and solar radiation are the main characteristics that will influence the airship's design and mission capabilities.

The initial and most basic environmental requirement for an airship is the presence of an atmosphere. Of the planets within our solar system 7 of the 9 have atmospheres as well as 5 moons of the giant outer planets. This initial grouping of places with atmospheres is shown in figure 1.

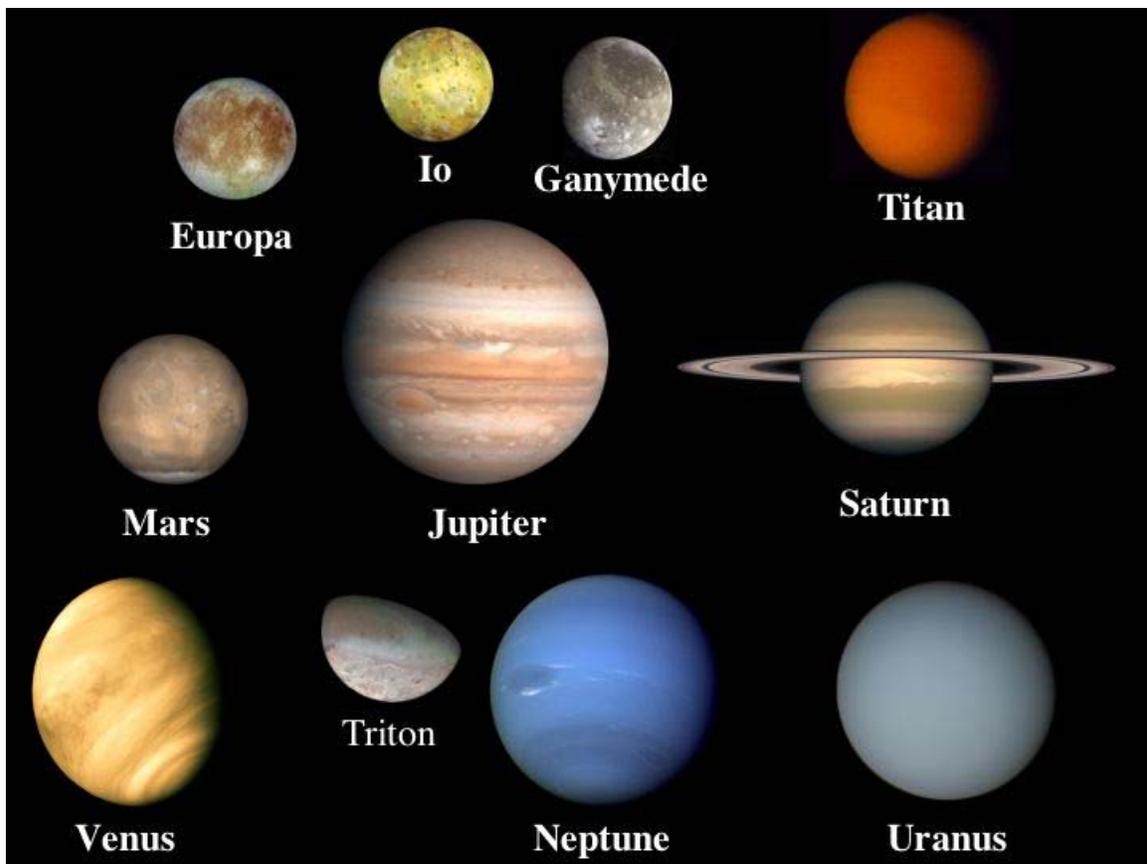


Figure 1 Planets and Moons within the Solar System with Atmospheres

Of the planets and moons shown in figure 1, not all have atmospheres capable of supporting the flight of an airship. Of the moons that have atmospheres (Europa, Io, Ganymede, Titan, and Triton) only Titan can be considered as a location potentially suited for flying an airship. Europa, Io, Ganymede, and Triton have very tenuous atmospheres that would not be capable of supporting an airship. The characteristics of the

planets and moons that have atmospheres potentially thick enough to support an airship are given in table 1.

Planet	Gravitational Force	Temperature	Atmosphere Pressure / Density at the Surface	Atmospheric Composition
Venus	8.93 m/s ²	735 °K near surface to 175° K upper atmosphere	92.1 Bar ~65 kg/m ³	Carbon Dioxide ~97% Nitrogen ~3%
Mars	3.73 m/s ²	~220 °K	6.36 mBar ~0.02 kg/m ³	Carbon Dioxide ~95% Nitrogen ~3% Argon ~2 %
Jupiter	24.82 m/s ²	~165° K	>>1000 Bar	Hydrogen ~90% Helium ~10%
Saturn	10.49 m/s ²	~134° K	>>1000 Bar	Hydrogen ~96% Helium ~3%
Titan (moon of Saturn)	1.35 m/s ²	~100° K near surface to ~200° K upper atmosphere	1.5 Bars 5.8 kg/m ³	Nitrogen ~95% Methane ~3% Argon ~2%
Uranus	9.03 m/s ²	~76° K	>> 1000 Bar	Hydrogen ~83% Helium ~15% Methane ~2%
Neptune	11.57 m/s ²	~72° K	>> 1000 Bar	Hydrogen ~80% Helium ~19% Methane ~1%

Table 1 Atmospheric Characteristics of Candidate Locations for Airship Flight

Atmospheric Environment of Venus

The atmosphere of Venus is very thick, which is a benefit to airship flight. However the atmosphere is a place of environmental extremes. Near the surface, the atmospheric temperature is very hot (over 700°K) and there is very little useable sunlight due to the extensive cloud cover that covers the whole planet. This cloud cover resides within an altitude range of 45 km to 64 km above the surface. Near the surface, the atmosphere is very still with little wind. Towards the upper atmosphere the situation is completely reversed. It is relatively cold with temperatures under 200°K; there is abundant sunlight and the wind speeds are very high.

The main characteristics of Venus’ atmosphere that are needed to evaluate an airship’s feasibility include the temperature in °K (T), density in kg/m³ (ρ), viscosity in kg/m s (μ), solar attenuation (I/I₀), and wind velocity in m/s (V). These quantities are provided as functions of altitude (h) in kilometers by equations 1 through 8 [1].

$$T = 738.26 - 9.1909h + 0.17429h^2 - 0.007965h^3 + 0.0001518h^4 - 1.2336E - 6h^5 + 3.7325E - 9h^6 \quad [1]$$

$$\rho = 64.85 - 3.3257h + 0.067373h^2 - 0.00066981h^3 + 3.224E - 6h^4 - 5.6694E - 9h^5 - 1.8971E - 12h^6 \quad [2]$$

$$\mu = 3.5827e - 5 - 5.906E - 9h + 8.8642E - 7h^2 - 5.9485E - 8h^3 + 2.1929E - 9h^4 - 4.8611E - 11h^5 + 6.6513E - 13h^6 - 5.5001E - 15h^6 + 2.5199E - 17h^7 - 4.9099E - 20h^9 \quad [3]$$

Above the cloud layer there is an abundant amount of solar energy. The solar flux at the orbit of Venus is 2600 W/m², which is much greater than the 1360 W/m² available at Earth orbit. This nearly 100% increase in solar flux can significantly increase the performance of solar powered vehicles. Even within or below the cloud layer there may be sufficient solar energy to operate an airship. At the bottom of the cloud layer (45 km altitude), the solar intensity is between 520 W/m² and 1300 W/m² depending on the wavelength of the radiation being collected. The solar attenuation within the atmosphere is given by equations 4 and 5.

From 0 to 50 km altitude:

$$\frac{I}{I_o} = 0.10306 + 0.017383h - 7.99E - 4h^2 + 2.752E - 5h^3 - 5.2011E - 7h^4 + 3.874E - 9h^5 \quad [4]$$

From 50 km to 65 km altitude:

$$\frac{I}{I_o} = -1.3639 + 0.036023h \quad [5]$$

Above 65 km there is effectively no attenuation and therefore I/I_o has a value of 1.

The winds within the atmosphere blow fairly consistently in the same direction as the planetary rotation (East to West) over all latitudes and altitudes up to 100 km. Above 100 km, the winds shift to blow from the day side of the planet to the night side. The wind speeds decrease as a function of altitude from ~100 m/s at the cloud tops (60 km) to ~0.5 m/s at the surface. These high wind speeds and the slow rotation of the planet produce a super rotation of the atmosphere (nearly 60 times faster than the surface).

From the surface to 58 km altitude:

$$V = 0.89941 - 0.11201h - 0.017082h^2 + 0.0040604h^3 + 0.0010345h^4 - 9.96E - 5h^5 + 3.28e - 6h^6 - 4.7E - 8h^7 + 2.495E - 10h^8 \quad [6]$$

From 58 km to 66 km altitude:

$$V = 21498 - 1087.9h + 18.31h^2 - 0.10214h^3 \quad [7]$$

From 66 km to 100 km altitude:

$$V = -3860.1 + 637.42h - 32.206h^2 + 0.76199h^3 - 0.009357h^4 \\ + 5.783E - 5h^5 - 1.42E - 7h^6 \quad [8]$$

Atmospheric Environment of Mars

The atmosphere of Mars is very thin. Near the surface on Mars the atmospheric density is similar to the density of Earth's atmosphere at 30 km. The atmosphere is made up almost entirely of carbon dioxide. The temperature on Mars is on average much colder than on Earth. Although at certain times of the year and locations the temperature will rise above freezing, most of the time temperatures are well below the freezing point of water. The gravitational force on Mars is about 1/3 what it is on Earth. Therefore the lift that the airship must generate is only 1/3 what is needed on Earth. This reduced gravity (and hence lower lift requirement) is a large benefit for operating an airship. However the environmental conditions on Mars are not all beneficial. The low atmospheric density poses a significant problem for a lighter than the atmosphere vehicle. There are also a number of aerodynamics concerns with propeller operation and flight at the very low Reynolds numbers which will be encountered within this atmospheric environment. Most of these are based on flow separation that can affect the airship's stability, control, and propeller operation.

Similar characteristics of the Martian atmosphere, as those provided for Venus, are given in equations 9 through 16. These characteristics are needed to evaluate an airship's feasibility within the atmospheric environment of Mars.

The reference atmosphere used to estimate the characteristics of the Martian atmosphere was supplied by JPL.[2] This data was generated for a latitude of -20°. It provides data on temperature, viscosity, and density from just above the surface to nearly 10 km. From this data, curve fits were generated for temperature, density, and viscosity as a function of altitude.

$$T = 238.74 - 34.488h + 35.133h^2 - 15.96h^3 \\ + 3.7315h^4 - 0.47352h^5 + 0.030962h^6 - 0.000817h^7 \quad [9]$$

$$\rho = 0.014694 - 0.001145h + 4.6638E - 5h^2 - 9.7737E - 7h^3 \quad [10]$$

$$\mu = 1.2024E - 5 - 1.30002E - 6h + 1.0525E - 6h^2 - 3.6507E - 7h^3 \\ + 6.0536E - 8h^4 - 4.8317E - 9h^5 + 1.4911E - 10h^6 \quad [11]$$

Because of the thinness of the Martian atmosphere, the solar attenuation was assumed to be constant with a value of 0.85 over the complete altitude range. This attenuation was

due mainly to dust particles within the atmosphere and therefore is subject of significant variations throughout the Martian year. The incident solar energy available at Mars's orbital radius is 590 W/m^2 .

As with the Earth's environment, the wind speeds on Mars are highly variable with the time of year and location. At the Viking landing sites, the wind speeds were in the range of 2 to 7 m/s. These measurements were, however, taken within the boundary layer near the surface. Above the boundary layer it is estimated that the wind speeds can approach 50 m/s.

Atmospheric Environment of Titan

Titan's atmosphere is not as well documented as that of Venus or Mars. Little exploration of Titan has been performed to date. However, based on the images of Titan that have been taken by various sources (Voyager, Hubble, and Earth based telescopes), some properties of the Titan atmosphere can be inferred. The temperature, atmospheric density, and viscosity are given as functions of altitude in equations 12 to 14 [2].

$$T = 92.873 - 1.1415h + 0.016895h^2 - 5.3723E - 5h^3 \quad [12]$$

$$\rho = 5.4627 - 0.21851h + 0.00294h^2 - 1.2054E - 5h^3 \quad [13]$$

$$\mu = 6.439E - 6 - 1.5296E - 7h + 1.0343E - 8h^2 - 3.2876E - 10h^3 + 4.9672E - 12h^4 - 2.8791E - 14h^5 \quad [14]$$

There is little information on the winds within Titan's atmosphere. It is estimated that the wind velocities are on the order of tens of meters per second above the surface boundary layer. Winds within the boundary layer are estimated to increase linearly from 0 at the surface to 5 m/s at approximately 4 km in altitude [3].

The cloud cover and thick layer of smog within Titan's atmosphere significantly limits the amount of sunlight that reaches the surface. The smog is caused by ultraviolet light from the sun interacting with the abundant hydrocarbon molecules within Titan's atmosphere. The solar intensity at the orbit of Saturn is only 14.87 W/m^2 . This low solar intensity coupled with the clouds and smog within Titan's atmosphere keeps the surface of Titan fairly dark.

Outer Planets (Jupiter, Saturn, Uranus, Neptune)

The atmospheres for the outer, gas giant, planets are fairly similar. They are very cold in the upper layers and are expected to warm considerably at lower levels where the pressure increases. However, there are little details known about the atmospheres of these planets. On Jupiter, the Galileo probe measured the atmospheric temperature as it descended. This temperature changed from approximately 165 to 424 °K before the probe stopped transmitting data, at a pressure of approximately 22 bar. On these planets, the atmospheric pressure range extends from near vacuum at the upper atmosphere to 1000's (or millions) of bar at the lower atmosphere, and very high wind speeds probably extend deep into the atmosphere. The Galileo probe encountered wind speeds exceeding 400

mph well below the visible clouds on Jupiter. For airship applications however, the fact that they are mainly composed of hydrogen is the main issue. This basically eliminates the possibility of using a “lighter than the atmosphere” gas for the ship’s buoyancy.

Airship Evaluation

Based on the environmental conditions specified in the previous section, an evaluation of the feasibility of using an airship for exploration was performed for each of the potential locations. The requirements for the airship were that it would need to be capable of station-keeping at a given location as well as operating for an extended period of time of 50 earth days or more. Two types of propulsion / power systems were considered. These were a solar photovoltaic system and a nuclear radioisotope system. The isotope system can be considered for all of the potential planetary locations whereas the photovoltaic system would only be applicable to Venus and Mars. Beyond Mars the solar intensity is too low for photovoltaics to be a practical source of power for an airship.

The airship configuration chosen for the analysis was a standard cylindrical shaped with two motor systems located on pods. This configuration is shown in figure 2.

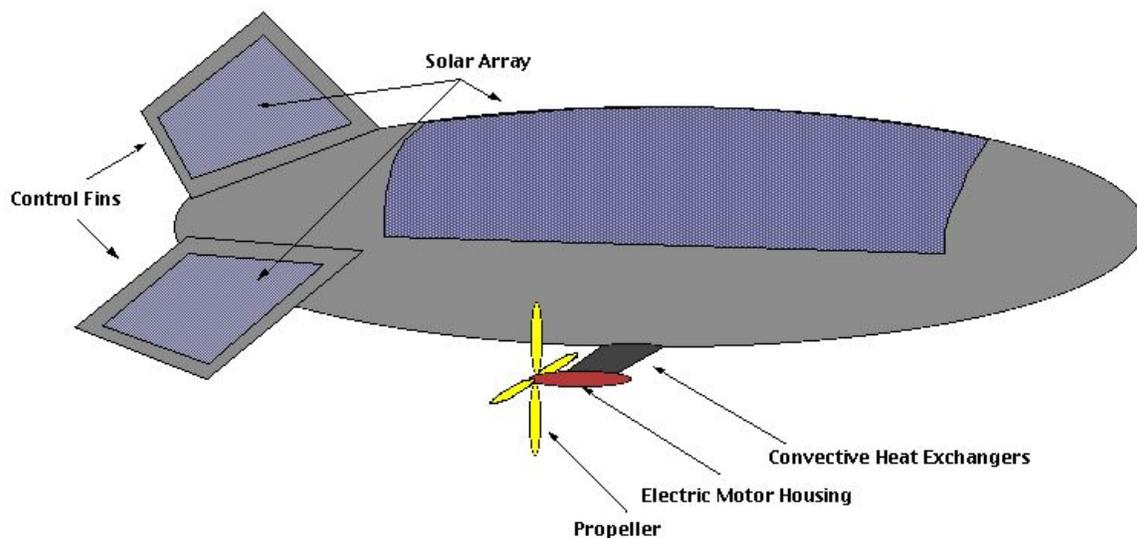


Figure 2 Base Airship Configuration

To determine the fin area, a number of existing airships were used to establish a ratio of fin area to airship volume. The ratio of fin area to airship volume (R_f) used for this analysis was $0.0121 \text{ m}^2/\text{m}^3$. For the solar powered airship, it is assumed that portions of the solar array would be located on the upper surface of the lower two fins and on both sides of the vertical fin.

The power required by the airship is given by the power needed to operate the onboard systems and payload and the power needed to overcome the drag on the airship and maintain station over a specified location. The airship drag (D), given in equation 15, is based on a volumetric drag coefficient (C_{dv}) and the airship volume (V_a) [4]. The volume can be determined from the length (l) and fineness ratio (f) of the airship. This

relationship is given in equation 16. For this analysis, it was assumed that the airship was to maintain position with the ability to maneuver. Therefore, the velocity (V) at which it is operating is the wind speed plus 1 meter per second. The drag equation is broken down into two terms: the first is the drag due to the airship; the second is the drag due to the heat exchanger. This heat exchanger drag is based on the cross-sectional area of the heat exchange (A_{he}) and the density of the atmospheric gas (ρ_o) as it exits the heat exchanger. This is given by equation 17 with a heat exchanger efficiency of 0.80. The drag due to the heat exchanger assumes a radiator thickness of 2.5 cm, free flow area to frontal area of 0.5, a friction factor of 0.03, and a heat transfer area to volume of 520 [5]. The heat exchanger drag is mostly a concern for the isotope powered airship since a considerable amount of heat must be removed to the atmosphere. For the solar powered airship it can be assumed that this term is zero.

$$D = \rho V^2 (0.5 C_{dv} V_a^{2/3} + A_{he} (3.28 \frac{\rho}{\rho_o} - 1.72)) \quad [15]$$

$$V_{as} = \pi L^3 (\frac{1}{4 f^2} + \frac{4}{24 f^3}) \quad [16]$$

$$\rho_o = \frac{\rho T}{0.8 T_e + 0.2 T} \quad [17]$$

The drag coefficient is based on the fineness ratio of the airship. The fineness ratio is the ratio of the length of the airship to its diameter (d) or width as given by equation 18. For this analysis a fineness ratio of 4 was assumed. The drag coefficient for this fineness ratio is 0.0266.

$$f = \frac{l}{d} \quad [18]$$

The assumed power requirements for the fixed systems are given in table 2. These power levels were assumed constant and the same for each airship location examined.

System	Continuous Power Level
Communications	50 W
Control and Operations	50 W
Payload	50 W

Table 2 Assumed System Power Levels

The operational efficiency of each of the components of the power system must also be taken into account when sizing the airship. The airship power train is shown in figure 3. The total efficiency of the drive train (η_p), given by equation 19, is composed of the motor controller efficiency (η_{mc}), electric motor efficiency (η_{em}), gearbox efficiency (η_g), and propeller efficiency (η_{prop}).

$$\eta_p = \eta_{mc} \eta_{em} \eta_g \eta_{prop} \quad [19]$$

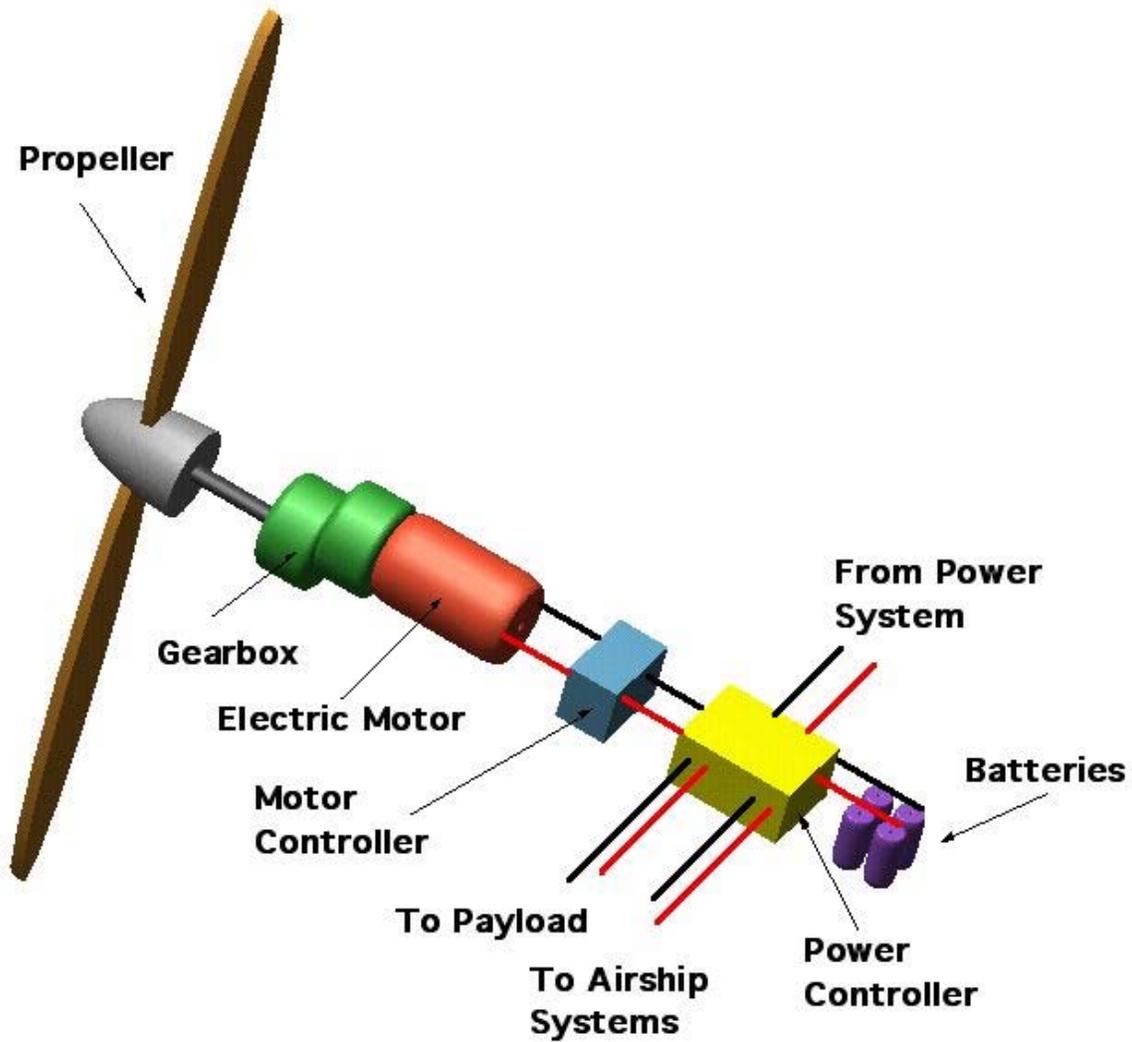


Figure 3 Propulsion System Drive Train

The operational efficiency associated with each of these components is given in table 3. They are combined to get the drive-line efficiency which consists of all components up to the propeller. The propeller efficiency has to be calculated based on a propeller sizing for the operational altitude and thrust requirement. These efficiencies are representative approximations for each of the components under optimized operating conditions.

Component	Efficiency
Control Electronics	η_{mc} 0.98
Motor	η_{em} 0.90
Gearbox	η_g 0.90
Drive Line Efficiency	η_p 0.794

Table 3 Drive Line Component Efficiencies

Sizing the propeller is an iterative process that is dependent on the airship flight speed and thrust requirement. To achieve the desired thrust at the needed airspeed, the propeller diameter, RPM, and pitch angle are iterated upon. The goal is to provide a combination of these that maximizes efficiency. For this analysis it was assumed that a variable pitch 2 bladed propeller was utilized [1,6]. Using this analysis, an approximation for the thrust (c_t) and power (c_p) coefficients were derived as a function of advance ratio (J). The thrust and power coefficient equations are valid for advance ratios within the range of 0.18 to 3.0.

$$c_t = -0.012122 + 0.14577J - 0.1408J^2 + 0.05374J^3 - 0.0068444J^4 \quad [20]$$

$$c_p = -0.012752 + 0.094954J - 0.053694J^2 + 0.017534J^3 - 0.0007872J^4 \quad [21]$$

The advance ratio, given in equation 22, can be expressed in terms of the flight velocity (V) the speed of sound within the atmosphere (a) and the desired tip Mach number (M).

$$J = \frac{V\pi}{\sqrt{(aM)^2 - V^2}} \quad [22]$$

By selecting a tip Mach number, the propeller efficiency (η_{prop}) can be calculated from the above equations.

$$\eta_{prop} = \frac{c_t J}{c_p} \quad [23]$$

Determining the total power required is an iterative process between sizing the airship to lift its mass and the power needed to overcome drag. As the airship mass gets larger, the amount of power needed will increase thereby increasing the necessary size of the airship. The total power (P) in watts required by the airship is given by equation 24.

$$P = \frac{DV}{\eta_p} + 150 \quad [24]$$

To determine the total power required, the airship volume must be known. The volume is dependent on the total weight that the airship must lift. The lifting force (L_a) of an airship is based on a centuries old principle discovered by Archimedes, “A body wholly or partly immersed in a fluid is buoyed up with a force equal to the weight of the fluid displaced by the body”. This principle is given by equation 25 where g is the gravitational force of the planet on which the airship is to operate. The ratio of the molecular weights of the lifting gas (MW_{lg}) and the atmosphere (MW_{atm}) is used to account for the weight of the lifting gas itself.

$$L_a = \rho V_a \left(1 - \frac{MW_{lg}}{MW_{atm}}\right) g \quad [25]$$

To estimate the total mass of the airship, it was broken down into a number of components plus the payload. Some of these components were assumed to be fixed masses and did not scale with the operating location or airship size. These fixed mass components are listed in table 4.

Component	Mass (kg)
Flight Control Computer	3.8
Communications Equipment	4.6
Flight Control Sensors	3.5
Payload	20.0

Table 4 Aircraft Fixed Component Masses

Because the masses of some of the components will depend on the airship's total mass (M_{ac}) and or power requirement, determining the total mass is an iterative process. The mass for the structure (M_s) is based on the density of the envelope material (ρ_e , assumed to be 0.25 kg/m^2) and assumes that the internal structure scales as 1/4 of the total mass of the airship [7].

$$M_s = R_f V_{as} \rho_e 1.2 + 0.25 M_{as} + \pi d L \rho_e \quad [26]$$

The electric motor mass (M_{em}) [8], motor controller mass (M_{mc}) [8], gearbox mass (M_g) [8], and mass of the power conditioning system (M_{pc}) [7] are based on a linear scaling with power output. The lower limit at which the equations are valid are listed after each equation. If the required power was sufficiently small so that the calculated mass of any component was below this minimum then the minimum value was used.

$$M_{em} = \frac{P \eta_{mc}}{1291} \quad (\text{minimum of 0.5 kg}) \quad [27]$$

$$M_{mc} = \frac{P}{6233} \quad (\text{minimum of 0.1 kg}) \quad [28]$$

$$M_g = \frac{P \eta_{em} \eta_{mc}}{3278} \quad (\text{minimum of 0.3 kg}) \quad [29]$$

$$M_{pc} = \frac{P}{1000} \quad (\text{minimum of 0.2 kg}) \quad [30]$$

The solar array mass (M_{sa}) is given by the specific mass of the array in kilograms per meter squared (estimated to be 1 kg/m^2) multiplied by 80% of the total area available for the solar array (S_a).

$$M_{sa} = S_a 0.8 \quad [31]$$

The total output of the solar array is calculated based on the incident solar radiation on the array [7]. The incident radiation is dependent on the shape of the array and the attenuation due to the atmosphere. The array output or power available (P_a) is given in

equation 32. It is based on the mean solar intensity at the planet's orbit (I_{om}) in watts per square meter and the attenuation due to the atmosphere (I/I_o).

$$P_a = 0.8S_a I_{om} \left(\frac{I}{I_o} \right) \eta_{sc} \sum_{\beta=-\frac{\pi}{2}}^{\beta=\frac{\pi}{2}} A_l \sin(\theta_l) \quad [32]$$

It is assumed that the array is placed on the upper half of the airship envelope (as shown in figure 2) and on the tail fin surfaces. The local solar elevation angle (θ_l) is the elevation to the sun as seen from a specific segment of the solar array. This angle will depend on the inclination of the solar array segment (β), the angle of the solar array segment cells to the horizontal. The calculation of the local solar elevation angle is given in reference 7. The solar cell efficiency (η_{sc}) is based on the efficiencies of thin film solar cells and was assumed to be 8% above the clouds on Venus and on Mars and 5% below the clouds on Venus due to the increased operational temperature.

The isotope power system includes the engine, isotope heat source, and radiator. The required radiator area (A_{he}) is given by equation 33 and the total engine system's mass (M_{ie}) is given by equation 34.

$$A_{he} = \frac{P}{\eta_e \varepsilon (T_e - T_a) \rho V c_p} \quad [33]$$

$$M_{ie} = \frac{P}{P_s} + A_{fr} M_{sr} \quad [34]$$

For the isotope system, a Stirling engine is used as the thermal to electrical conversion device. The specific power of the engine (P_s) including the heat source was estimated at 6 W/kg. The radiator size for the engine will depend on the temperature difference between the incoming ambient temperature (T_a) and the engine heat source temperature (T_e), estimated to be 950 °K, and the total power required by the airship (P). The operational efficiency of the Stirling engine (η_e) was estimated at 27%. The radiator specific mass (M_r) is estimated to be 11.18 kg/m² based on present day lightweight radiator designs [9] and its efficiency (ε) was assumed to be 0.8 [5].

The battery shown in figure 3 is used only with a solar powered system. For the isotope system this component would be eliminated. The battery mass (M_b) is based on a silver-zinc rechargeable battery that has the capacity to provide 5 minutes of full operational power to the airship with a depth of discharge of 80%. The silver-zinc battery was chosen because of its very high discharge rate capability and its operating temperature range of -20 to +30°C. This type of battery has an estimated energy density of 150 W-Hr/kg. Using this energy density and the 5-minute full power capacity, the mass of the battery is given by equation 35.

$$M_b = P_r 6.94 E - 4 \quad [35]$$

The propeller mass (M_{prop}) is based on the propeller diameter, given in equation 36, and the number of blades (n_b). With the diameter and number of blades known, the mass of the propeller will depend on the volume of each blade, its material density (ρ_{prop}), and the void percentage within the blade (F_b). Using the airfoil cross-sectional area and the chord length distribution given in reference 8, the volume of the propeller blade (V_{prop}) can be calculated. This volume is given by equation 37 and the total propeller mass is given by equation 38. For this analysis it was assumed that a carbon composite, with a density of 1380 kg/m^3 , is used to construct the propeller and the void percentage within the blade is 50% of the volume.

$$d_p = \sqrt{\frac{D\pi^2}{c_t((aM)^2 - V^2)}} \quad [36]$$

$$V_{prop} = 9.25739E - 5d_p^3 \quad [37]$$

$$M_{prop} = \rho_{prop}n_b(1 - F_b)V_{prop} \quad [38]$$

The last mass item is the margin mass. This is used to account for various miscellaneous items and is assumed to be 10% of the calculated airship mass. Using this mass margin, total airship mass (M_{as}) for the solar powered airship and for the isotope powered airship is given by equations 39 and 40, respectively.

$$M_{as} = (31.9 + M_s + M_{em} + M_{mc} + M_g + M_{pc} + M_{sa} + M_b + M_{prop})1.1 \quad [39]$$

$$M_{as} = (31.9 + M_s + M_{em} + M_{mc} + M_g + M_{pc} + M_{ie} + M_{prop})1.1 \quad [40]$$

Airship for Venus

Both a solar and isotope powered airship can be considered for flight on Venus. For a solar powered airship, since there is a thick atmosphere and cloud cover, it was assumed that all solar radiation below the clouds was diffuse. Therefore below the cloud layer, there was no variation in array output based on array or airship position relative to the location of the sun.

With the solar powered airship, below the cloud layer, the availability of power is the driving factor for the airship design. Its size is based on the ability to collect enough power from the solar array to operate the propulsion system and other ship systems. The airship is therefore sized for this requirement. Using the mass-scaling relationships given above and assuming helium as the lifting gas, mass estimates of the airship were made. Due to the high-density environment of the Venus atmosphere, the lift produced by the envelope volume was more than sufficient to lift the airship and its associated systems. In fact much of the envelope would need to be filled with atmospheric gas with only a small volume utilized by the lighter lifting gas. Because of this, the mass scaling of the airship

is not a critical factor in the analysis. The lifting capacity of an airship as a function of altitude is shown in figure 4 with helium as the lifting gas. This figure shows the total mass that can be lifted on Venus as a function of altitude and airship size.

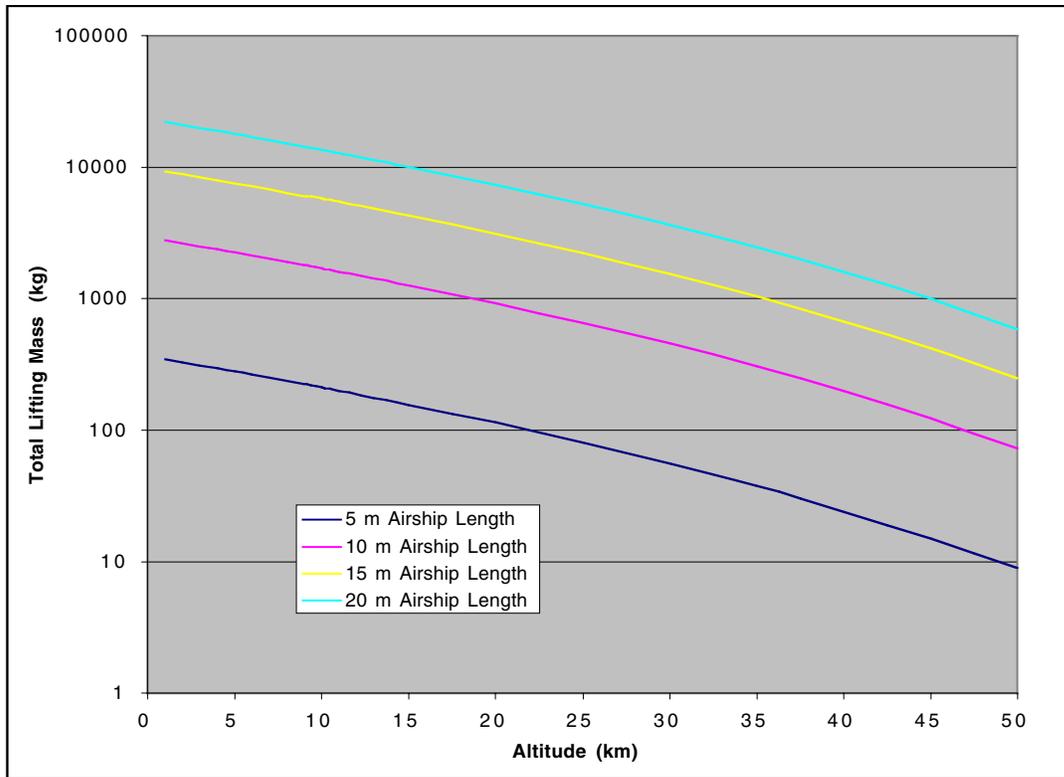


Figure 4 The Lifting Capacity of Various Size Solar Airships vs. Altitude on Venus Using the analysis outlined above, the power required for maintaining station above a specific location and the power available from the solar array was determined for airship sizes up to 20 m in length. Airships larger than 20 m in length were deemed not reasonable for autonomous deployment and operation within the Venus atmosphere. The power required and available was calculated from near the surface to an altitude of 50 km. These results are shown in figure 5.

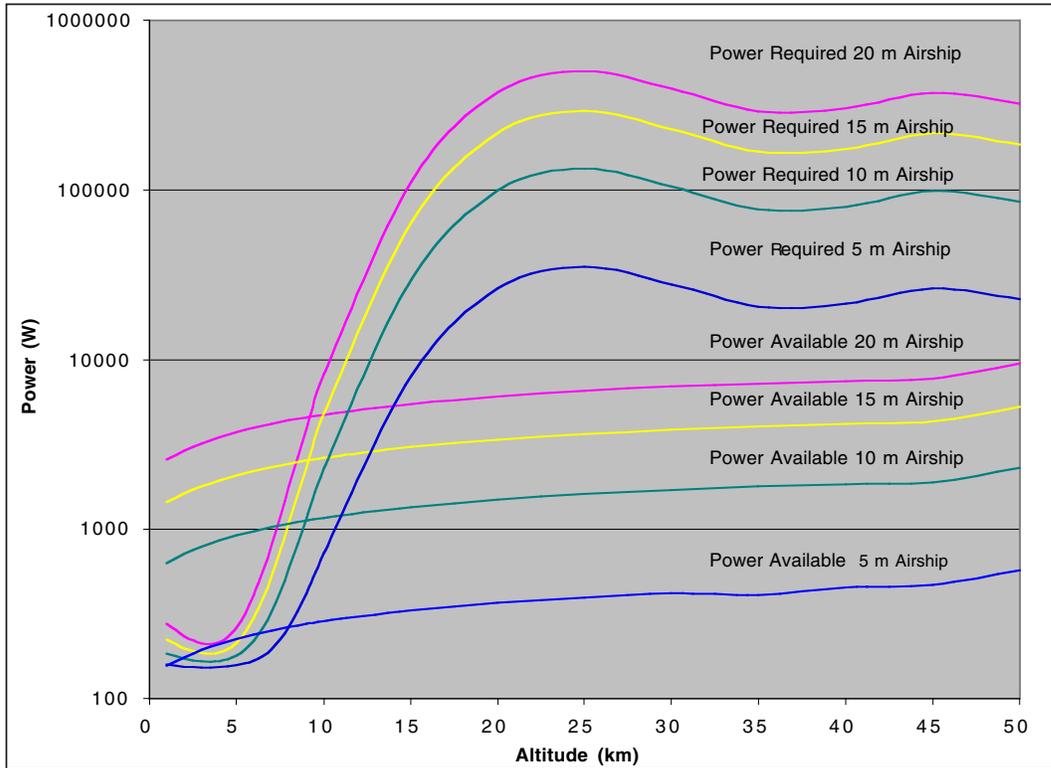


Figure 5 Power Available & Power Required for Various Size Solar Airships on Venus

From this figure it can be seen that there is a sharp rise in required power that occurs near 10 km in altitude. This rise is due to the increasing wind speeds that occur with increasing altitude. Because of this significant rise in the power required to maintain station, it is not feasible to operate a solar powered airship, of the sizes examined, above approximately 10 km in altitude due to the high wind speeds that occur at and above this altitude. Below this altitude, the required airship size necessary to operate within the Venus environment was determined and is given in figure 6. This figure shows required airship size for altitudes up to 9 km.

Although low altitude operation was feasible based on the assumptions used, there are significant issues that would need to be addressed with getting a solar powered airship to operate near the surface of Venus. The main issue is the high atmospheric temperature. Significant materials development would be needed for the vehicle to operate for prolonged periods of time within this high temperature environment.

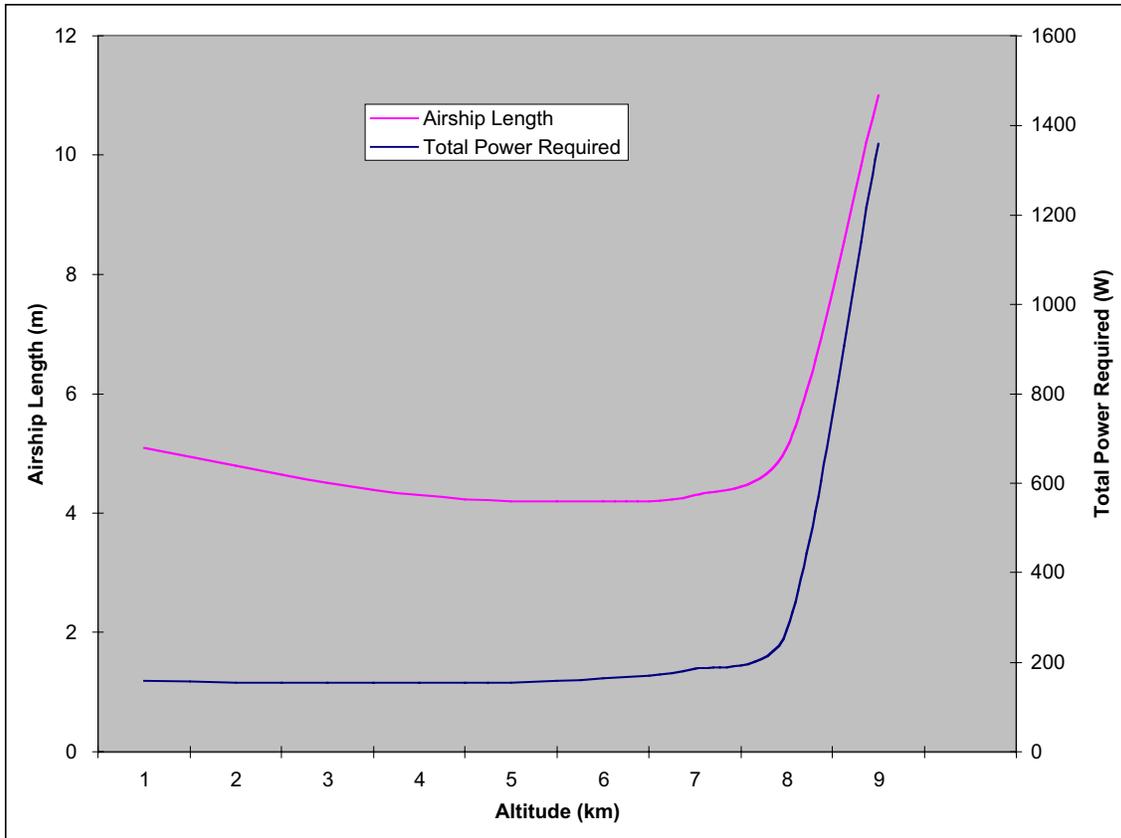


Figure 6 Solar Airship Total Power and Size as a Function of Altitude on Venus

The second and equally critical issue is the operation of solar cells within the environment near the surface on Venus. Solar cell performance generally increases with lower operational temperatures. Therefore it may be very difficult to produce any reasonable efficiency out of a solar array operating at such high temperatures. In addition to the temperature, the spectrum of light reaching the surface is mostly on the red side of the spectrum due to the very thick atmosphere. Very little blue light reaches the surface. However it is this blue portion of the spectrum that most present-day solar cells utilize in producing power. To take advantage of the light that does reach the surface, a new type of solar cell would need to be developed.

The method described above was also used to evaluate an isotope-powered airship for flight on Venus. The results of this analysis are shown in figure 7. Above about 11 kilometers in altitude there were no airship solutions that converged for either mass or power. Therefore, based on this analysis above 11 km, the isotope-powered airship is not feasible on Venus for a station-keeping mission.

Below 11 km it was possible to maintain station with a reasonable size airship. Even though the temperatures are very high near the surface the very thick atmosphere enables sufficient heat transfer from the isotope engine. At around 10 km in altitude the airship size and power requirements increase significantly. As with the solar powered airship, this is due to the increase in wind speed that occurs at these altitudes. For a low altitude

exploration vehicle, the isotope-powered airship holds promise for use on Venus. It is better suited to high temperature operation than the solar powered airship and, as an additional benefit, its required size is smaller.

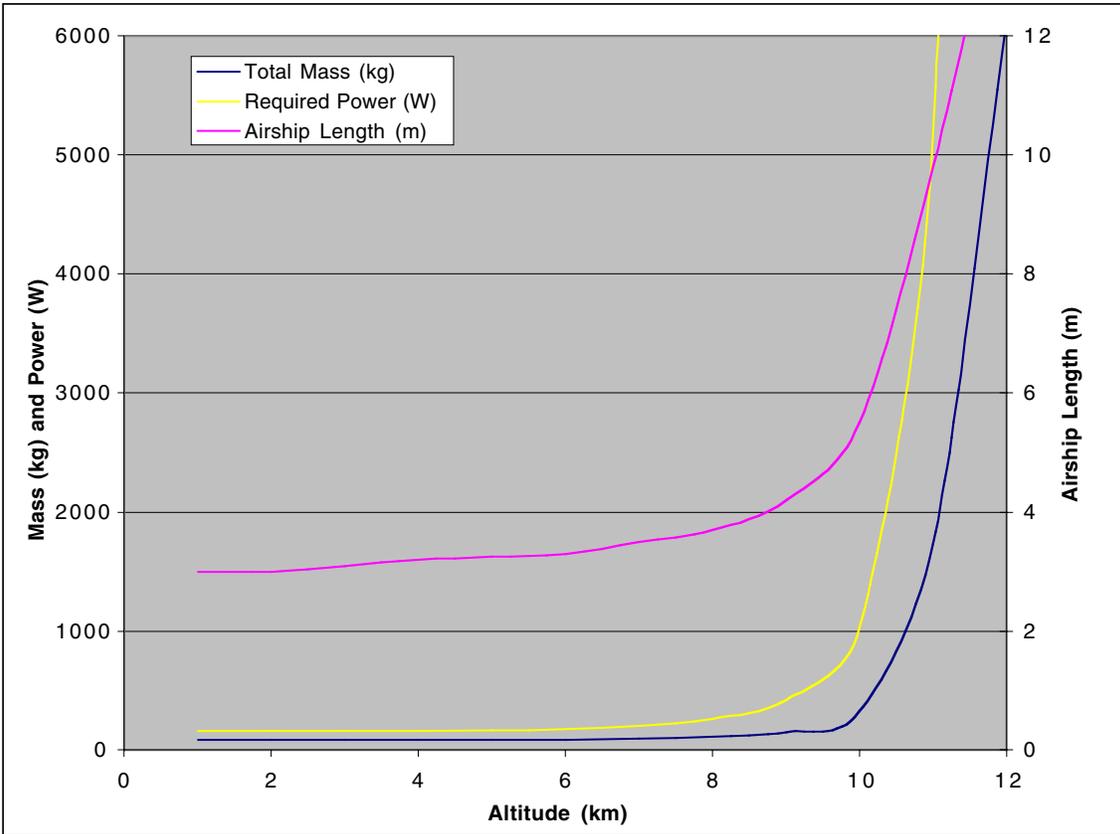


Figure 7 Mass, Power & Length of an Isotope-Powered Airship on Venus

Airship for Mars

Due to the low atmospheric density on Mars, designing and flying an airship that relies on buoyancy for lift is a difficult task. This is especially true for a solar powered airship because of the low solar intensity at Mars. To meet the station-keeping mission, the airship would need to collect enough energy during the day to provide power throughout the nighttime period. This also requires an energy storage system such as a regenerative fuel cell system. The atmospheric density near the surface of Mars is similar to the density at 30 km altitude on Earth. It was assumed that the airship, if feasible on Mars, would operate near the surface. Therefore, the wind velocity used was 2 m/s. This is a representative wind speed near the Martian surface based on data returned from the various landers and rovers that have operated on the surface.

Since this airship required an energy storage system, the modeling tool described in reference 7 was utilized. The modeling tool was designed to evaluate the feasibility of a high altitude long endurance airship for Earth based applications. However, by modifying the environmental conditions to those of the Mars environment, it was capable of being utilized to model a solar powered airship on Mars. Using this modeling tool, no solutions

were found for a solar powered airship that could station-keep on Mars, carry the desired payload, and meet the size restriction of a maximum of 20 m in length.

Similar results were found for the isotope-powered airship. Based on the analysis and component scaling given above, no solutions were found for airship sizes up to 20 m in length within the Mars environment.

Airship for Titan

Due to its distance from the sun and the thick haze and cloud cover surrounding the moon, a solar powered airship would not be feasible within the Titan atmosphere. An isotope-powered airship, however, should operate well within this environment. Titan's environmental conditions are ideal for a lighter than the atmosphere vehicle. It has a thick atmosphere that is one and a half times as dense as Earth's and can provide significant lift. Also the atmosphere is composed mainly of nitrogen that is compatible with almost all materials. The cold atmospheric temperatures also provide an excellent heat sink for the Stirling engine thereby increasing its efficiency and minimizing radiator size. The sizing results for an isotope powered airship on Titan are given in figure 8.

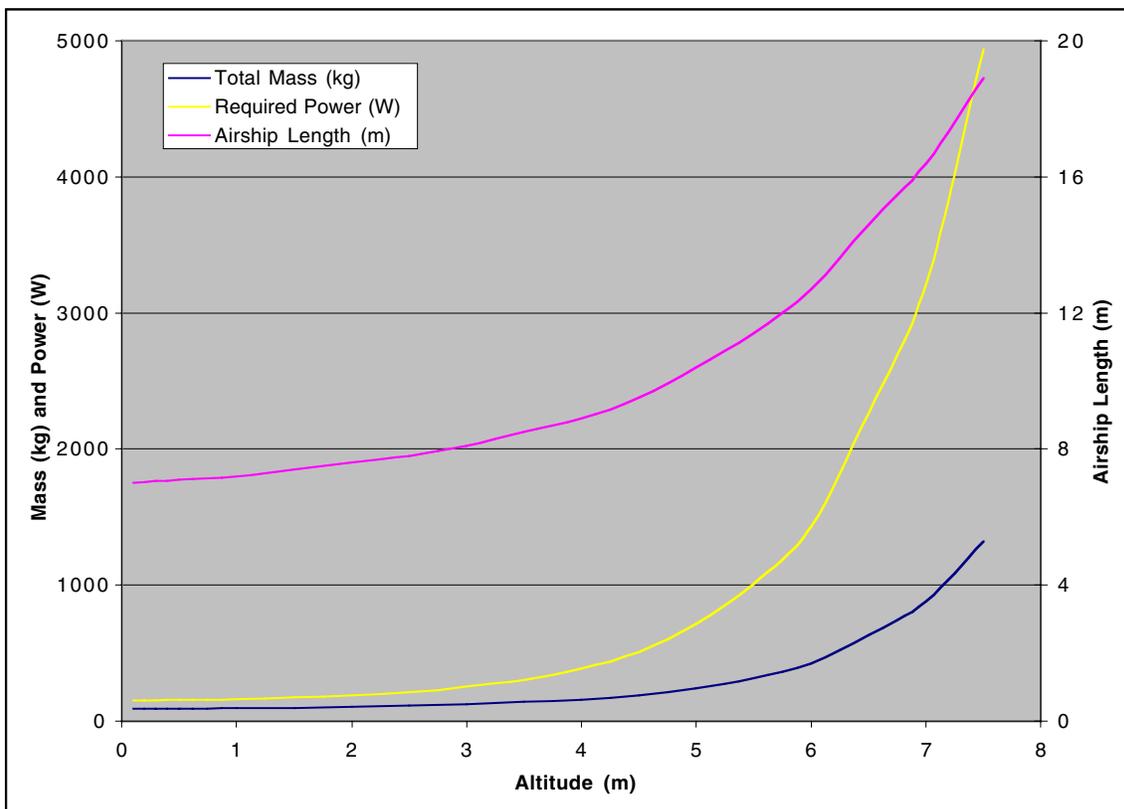


Figure 8 Mass, Power & Length of an Isotope-Powered Airship on Titan

Results were obtained for altitudes up to 7.5 km. Beyond this there were no solutions for a station-keeping airship, due mainly to the increasing wind velocity. The results for the

isotope-powered airship on Titan show that there is a wide range of operation with reasonable sized airships.

Outer Planets

The outer planets present an interesting problem for an airship design. Their atmospheres are very thick and dense, however they are mostly made of hydrogen. Therefore the conventional approach of using a less dense gas to provide the buoyancy force is not possible. The wind speeds within the atmosphere of the outer planets are estimated to be very high. It would not be practicable to try and produce an airship that can fly faster than the estimated wind speeds. However since there is no planetary surface in the sense of the inner planets in which to station-keep above, the ability to station-keep is not as important. There are two potential approaches that can provide a lighter than the atmosphere vehicle for flight within these hydrogen atmospheres.

The first is to heat the atmospheric gas within the airship envelope to provide buoyancy. This is similar to a hot air balloon in which the density of the gas decreases as the temperature increases providing a buoyancy force. The main obstacle to this approach is the heat needed to maintain an elevated gas temperature within the airship envelope. The cold thick atmosphere provides a significant heat sink to the warmer gas within the airship. Maintaining a high enough gas temperature will require a significant amount of heat as well as a substantially insulated gas envelope.

The second option is to produce a neutrally buoyant vehicle by utilizing a pressure vessel and evacuating it. This type of vehicle is more akin to a submarine than to an airship but should be applicable to operation within the atmospheres of the outer planets. The flight altitude of this type of craft can be changed by pumping gas into and out of a storage or ballast tank, similar to how a submarine works. This type of vehicle doesn't require the energy expenditure of heating up the lifting gas as in the previous option and therefore may be more practical.

Both of these concepts are sufficiently different in design and operation from the standard airship model previously described that they are beyond the scope of this analysis. For a future analysis, both of these concepts should be considered and evaluated as potential means of flight within the atmospheres of the outer planets.

Summary

The use of an airship for planetary exploration shows potential for certain locations. Airships can bring a unique approach to planetary exploration. Their ability to operate within the atmosphere and maintain station or move slowly over a specific location provides an unmatched capability for science data gathering and communications. With this capability comes some significant limitations. The airship's capabilities and feasibility are highly dependent on the environmental conditions. Atmospheric density and wind speed play critical rolls in this feasibility. After examining the potential planets of operation, both Venus and Titan are likely candidates for airship operation. On both these locations, the airship's operational range was limited to the lower region of the atmosphere (below approximately 10 km in altitude). Airships of reasonable size were capable of performing the station-keeping mission and carrying the desired payload

within these environments and altitude range. For use in these environments, the airship would need to be isotope-powered using a Stirling heat engine for thermal to electrical energy conversion.

The outer, gas giant, planets also pose an interesting application for a neutrally buoyant vehicle. The most applicable type of vehicle for the exploration of the outer planets would be more like a submarine than an airship, in that it would be a pressure vessel evacuated to hold out the atmosphere (like a submarine) instead of generating lift at atmospheric pressure with a less dense gas, like an airship. The analysis of this type of neutrally buoyant vehicle was beyond the scope of this work but it is recommended that it be further investigated in any subsequent analysis.

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