



Heated-Atmosphere Airship for the Titan Environment: Thermal Analysis

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Abstract

Future exploration of Saturn's moon Titan can be carried out by airships. Several lighter-than-atmosphere gas airships and passive drifting heated-atmosphere balloon designs have been studied, but a heated-atmosphere airship could combine the best characteristics of both. This work analyses the thermal design of such a heated-atmosphere vehicle, and compares the result with a lighter-than-atmosphere (hydrogen) airship design. A design tool was created to enable iteration through different design parameters of a heated-atmosphere airship (diameter, number of layers, and insulating gas pocket thicknesses) and evaluate the feasibility of the resulting airship. A baseline heated-atmosphere airship was designed to have a diameter of 6 m (outer diameter of 6.2 m), three-layers of material, and an insulating gas pocket thickness of 0.05 m between each layer. The heated-atmosphere airship has a mass of 161.9 kg. A similar mission making use of a hydrogen-filled airship would require a diameter of 4.3 m and a mass of about 200 kg. For a long-duration mission, the heated-atmosphere airship appears better suited. However, for a mission lifetime under 180 days, the less complex hydrogen airship would likely be a better option.

Introduction

Titan, the largest moon in the solar system, and the only moon with an atmosphere, is a high priority target for future science missions. The Cassini mission to Saturn landed a probe, Huygens, on the surface of Titan, but this probe only had a short lifetime on the surface, and had no mobility after landing. Future missions to Titan are desired with the capability to explore the nature of the moon and its environment in greater detail.

Several options have been considered as follow-on to the Huygens-Cassini mission. Of these, the main consideration for a Titan mission has been the type of vehicle used to collect data. A follow-on joint proposal between National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) has mentioned three desired vehicles. One was an orbiter similar to the Cassini orbiter. Another was a lake lander similar to Huygens, but with the emphasis of studying a lake instead of the atmosphere. The final vehicle was an atmospheric balloon. This proposed mission was called the Titan Saturn System Mission (TSSM) (TSSM 2009). The TSSM atmospheric balloon was planned to passively collect atmospheric data at an altitude of about 10 km. The power source of the electronics as well as the heat source for the balloon would come from a Radioisotope Thermoelectric Generator (RTG) (TSSM 2009). However, the TSSM would not be well suited to study the organic molecules that have accumulated around the moon. This has led to proposals to use controlled aerial vehicles that could move around the moon and land at various sites to collect samples. Several types of aerial vehicles could be used. These include: balloons, airships, vertical takeoff, and landing vehicles (such as helicopters), airplanes, gliders, and rockets.

Previous Work

Two earlier studies (Colozza et al. (Colozza 2003) and Lorenz (Lorenz 2000a)) compared different aerial vehicles for use on Titan. Wright et al. (Wright 2004) concluded that airships are the best for initial missions, with vertical takeoff and landing vehicles being considered for future missions due to the improved landing and takeoff ability. Lorenz et al. (Lorenz 2005) proposed an airship that would float and act as a balloon if propulsion were to fail either permanently or temporarily, providing an inherent redundancy to the flight capability for the mission. Designs for airplanes and vertical takeoff and landing vehicles would not have this capability, and hence failure of the propulsion system would likely be mission ending. Lorenz (Lorenz 2000a) considered a reference concept of a vertical takeoff and landing vehicle, selected for ease of landing at desired sites. Of these two design possibilities, the airship was the vehicle type analyzed in this report.

Airships are very similar to balloons, but instead of passively relying on winds to move (such as winds used for drift discussed in Lorenz et al. (Lorenz 2010)), they have an active propulsion system. Various airship designs are also commonly referred to as dirigibles, Zeppelins, and blimps. They could either use lighter-than-atmosphere gas or heated-atmosphere for lift. Studies have been conducted to understand the performance of Titan airships using lighter-than-atmosphere gas as the lifting gas. A paper by Duffner et al. (Duffner 2007) analyzes a hydrogen gas airship with a rover appendage for surface studies. Lorenz (Lorenz 2000b) discussed how an airship could maintain continuous flight with duty-cycled propellers for conserved power propulsion. The paper suggested that the surface could be studied by drop sondes, or by possibly landing the airship. Elfes et al. (Elfes 2005) and the ESA Titan Saturn System Mission report (TSSM 2009) proposed that excess heat from an RTG could be used for lift. Duffner et al. (Duffner 2007), Lorenz (Lorenz 2000b), and Wright et al. (Wright 2004) required an RTG for the electrical power needs. Additionally, the TSSM planned to use an RTG heated-atmosphere balloon; however, an RTG heated-atmosphere airship could make use of the waste heat of an RTG, saving launch weight by providing the initial lifting gas. It would also have the maneuverability of an airship for possibly greater science return.

The material for the lifting gas envelope is also an important consideration. This is due to the atmospheric conditions as well as the necessary constraints for a working airship. The material must be nonporous, foldable for storage to Titan, resistant to tearing, and maintain these properties at cryogenic temperatures. Hall et al. (Hall 2008) proposed a combination of polyester and Mylar for an effective cryogenic balloon material. Their paper demonstrated that this material satisfactorily meets the necessary criteria discussed.

Radioisotope Generator

A Radioisotope Thermoelectric Generator (RTG), uses a nuclear isotope heat source and a thermoelectric (thermal-to-electrical) transducer to convert heat produced from radioactive decay to electricity. A commonly used fuel is Pu^{238} , which has a half-life of about 87 years, and therefore can support a mission for several decades. The plutonium is packaged into a standard general purpose heat source (GPHS) block for use in spacecraft applications. Each block produces 250 W of thermal power at its beginning of life and has a mass of 1.44 kg. The primary disadvantage of implementing RTGs is the low level of electrical power that they supply. Large power requirements would necessitate many RTG units, which would consequently increase the system's complexity, mass and cost. RTGs have been used in many space vehicles and satellites such as the Voyager spacecraft discussed in Freedman et al. (Freedman 1966). This demonstrates that RTGs are a viable option so long as large power requirements are not needed. Higher-efficiencies can be achieved through the use of a dynamic conversion technique instead of a thermoelectric element, for example, a Stirling converter. This has been demonstrated in the form of the Advanced Stirling Radioisotope Generator (ASRG) (Wong 2008), which can achieve conversion efficiencies near 30 percent.

For the following analysis the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) was assumed as the power and thermal source. This RTG is used on the Mars Science Laboratory. At the time of arrival at Titan, it will produce about 100 W of electrical power for about 1700 W of thermal power (TSSM 2009). The mass of the MMRTG along with a battery system is assumed to be 100 kg.

Buoyancy Calculations for Heated Gases

A balloon or airship for operation on Titan achieves its lift by use of a confined envelope of gas that is lighter than the surrounding atmosphere. This can be achieved either by using a lifting gas of lower molecular weight than the ambient (optimally hydrogen), or by filling the envelope from the surrounding atmosphere and heating the interior gas to a higher temperature, thus reducing its density (“heated atmosphere”). The heated-atmosphere approach has the advantage of not requiring fill gas to be brought from Earth. Hence, it is relatively insensitive to the gas leakage rate, and can achieve long duration flight as long as a heat source is available, without replenishing the fill gas. However, the approach required the gas to be at a higher temperature than the surrounding atmosphere, and hence the lift achieved depends on the thermal design. This work is intended to calculate the thermal analysis of such a design, in order to compare the heated-atmosphere and lifting-gas approaches for lift in the Titan environment.

In order for an airship to float in an atmosphere, the buoyancy force must overcome the force of gravity. Buoyancy comes from the Archimedes principle that the weight of fluid displaced equals upward buoyancy force. Because the airship uses heated atmosphere, the density of the internal gas can be closely approximated from the ideal gas law. For the buoyancy calculation, we can approximate the airship as a sphere with internal diameter D , calculated from the sphere’s volume. Thus, Equation (1) relates buoyancy to the mass of the airship, where P is the gas pressure, R_s is the specific gas constant (J/kgK), T is the temperature of the gas, ρ_{atm} is the density of the atmosphere, and m is the total mass that can be lifted. In order for the vehicle to achieve flight, its mass must be equal to or less than this mass.

$$m = \frac{D^3 \pi}{6} \left(\rho_{\text{atm}} - \frac{P}{R_s T} \right) \quad (1)$$

Thermal Balance

The buoyancy (Eq. (1)), contains three unknown variables: the airship diameter, the average temperature inside the airship, and the mass that can be lifted. The pressure within the envelope (P) is held near atmospheric pressure in order to minimize the stress on the envelope material. The relationship between the airship diameter and the average inside temperature is then calculated by analyzing the heat transfer from the warm environment inside of the airship to the colder environment of Titan’s atmosphere. The heat source (from the MMRTG) provides a constant flux of waste heat to the gas within the envelope. The heat loss to the environment is proportional to the surface area of the gas envelope: the larger the diameter, the lower the inside temperature will be. Figure 1 shows the thermal circuit diagram for a three-layer example.

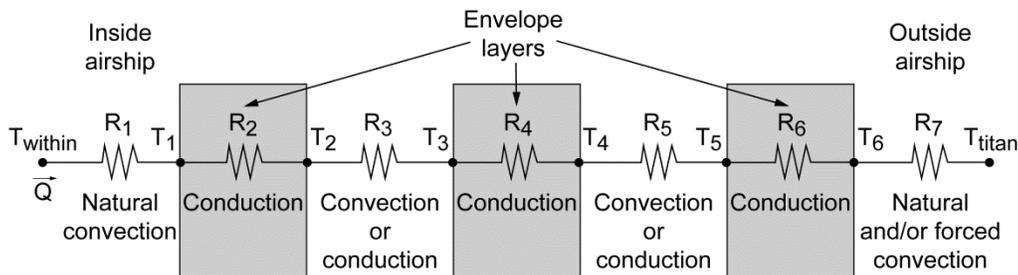


Figure 1.—Three-layer thermal circuit with identified methods of heat transfer.

The equivalent thermal resistor for a three-layer airship is simply the sum of the resistors from Figure 1. The equation for the internal temperature is given by Equation (2), where T_w is the temperature within the airship, and T_i is the temperature of Titan’s atmosphere.

$$T_w = T_i + Q(R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7) \quad (2)$$

The temperature of Titan’s atmosphere is assumed to be 95 K and the thermal load Q is an input variable set by the amount of isotope used in the MMRTG. The value of each of the thermal resistors must be determined. The thermal resistance for conduction through the material layers is given by Equation (3) and the thermal resistance for convection from the inner and outer surfaces is given by Equation (4), where r_o is the outer radius, r_i is the inner radius, and r_s is the radius of the surface where convection is taking place.

$$R_{\text{cond}} = \frac{r_o - r_i}{4\pi k r_i r_o} \quad (3)$$

$$R_{\text{conv}} = \frac{1}{4\pi h r_s^2} \quad (4)$$

Two quantities are needed to solve for the thermal resistance in the conduction case: the thickness of the material and thermal conductivity of the material. For the convection cases, only the heat transfer coefficient (h) needs to be solved for.

Iteration Program

The effects of the three main design parameters (the diameter, number of layers, and the thickness of the insulating gas pockets) on the mass of the vehicle as well as the mass that can be lifted were evaluated. An iteration program was utilized since thermal resistance depends on the temperature, and the temperature affects the thermal resistance. Table 1 shows the assumed values and constants that were used in the iteration program.

The wind speed here is the relative speed difference between the airship and the actual wind velocity. For example, a completely unpowered airship would move with the wind and would have a relative wind speed of zero. A temperature of 95 K was assumed for the atmosphere, representative of the highest (i.e., worst case) atmospheric temperature. Since the lower the atmospheric temperature, the greater its density and therefore buoyancy force, operation at a lower temperature would result in the ability to carry a slightly higher payload mass.

TABLE 1.—CONSTANT PROPERTIES WITH ASSUMED VALUES

Property	Value
Envelope material thickness	0.00003 m
Cryogenic envelope material weight (Hall 2008)	94 g/m ²
Estimated thermal conductivity of the cryogenic envelope material	0.4 W/mK
Titan pressure (Friedlander 1986)	160 kPa
Titan gravity	1.352 m/s ²
Titan temperature	95 K
Wind speed	5 m/s
Specific gas constant for the atmospheric nitrogen	297 J/kgK
RTG heat (TSSM 2009)	1700 W
Mass of RTG and Battery System (Duffner 2007)	100 kg
Mass of instruments (Duffner 2007)	28.9 kg
Prandlt number of atmosphere (TSSM 2009)	0.796

Results

A number of parameters, including diameter, insulating gas pocket thickness, and number of layers as well as the lifting mass, deadweight, and extra payload, can be adjusted to affect the design output. In order to narrow down the list of choices, consideration was given to difficulty. For an example, larger numbers of layers are more difficult to build, and a heavier deadweight means more fuel would be expended for launch. With these considerations in mind, a satisfactory set of feasible parameters was chosen for the baseline airship. The parameters are presented in Table 2.

Figures 2 and 3 show the effects of modifying the number of layers and the thickness of the insulating gas pocket between the layers, respectively. It is seen that there is a significant increase in payload mass (over 250 kg) by adding two extra envelope layers compared to using a single layer, but with more additions, there is only a small increase in the payload mass. Figure 3 shows that, as the insulating gas pocket thickness increases, the payload mass increases. However, it should be noted that as the insulating gas pocket thickness increases, the outer diameter also increases.

The heated-atmosphere airship was designed primarily to interact with and explore the surface of Titan. As the airship's altitude increases, the payload mass capability diminishes until the airship reaches an altitude where neutral buoyancy takes place. From the surface to an altitude of 20 km, both the temperature and the density of the atmosphere decrease approximately linearly. At the 20 km altitude, the temperature was estimated to be 78 K and the density of the atmosphere was estimated to be 2 kg/m³ (Jennings 2011, Justus 2004). Figure 4 shows the effect that the operating altitude has on the payload for different internal diameters. The baseline airship with a diameter of 6 m would be able to reach a maximum altitude of 6 km. Different designs would be required to reach higher altitudes, such as an airship with a larger diameter. An airship with an internal diameter of about 8 m is shown to have the highest payload mass at an altitude of 6 km (about 75 kg). At 6 km, the range of feasible airships with three-layers and an insulating gas pocket thickness of 0.05 m are those with an internal diameter between 5.2 and 10.1 m.

TABLE 2.—BASELINE CASE DESIGN

Parameter	Value
Inner diameter	6 m
Outer diameter	6.2 m
Number of layers	3
Insulating gas pocket thickness	0.05 m
Average internal temperature	187.7 K
Deadweight	161.87 kg
Lift mass	343.5 kg
Extra payload mass	181.63 kg

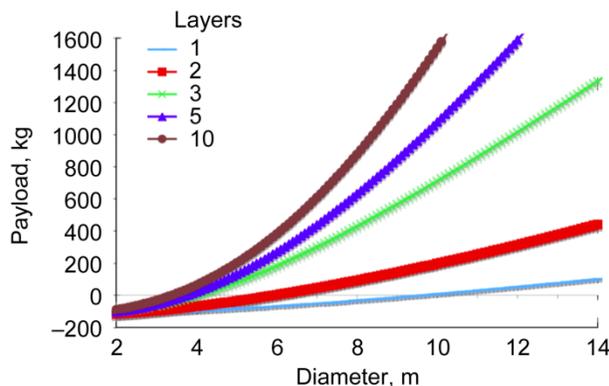


Figure 2.—Effect on airship payload sizing of number of layers and internal diameters, for an insulating gas pocket(s) of 0.05 m (when applicable).

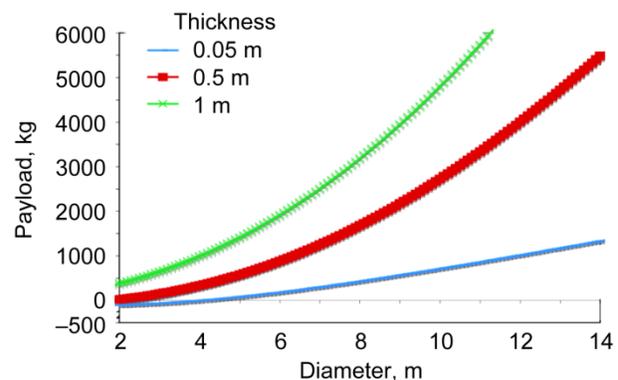


Figure 3.—Effect on airship sizing of insulating gas pocket thicknesses and internal diameters, for case of airship with three layers.

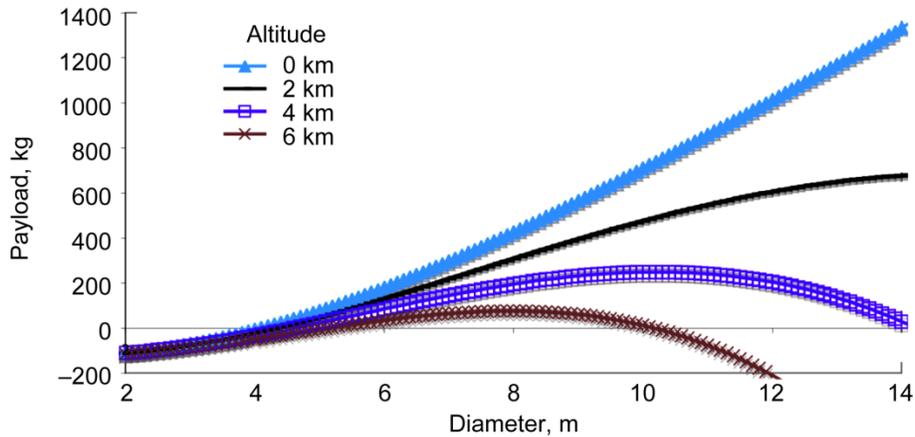


Figure 4.—Payload capability as a function of altitude for different internal diameters for baseline airship with three layers and an insulating gas pocket thickness of 0.05 m.

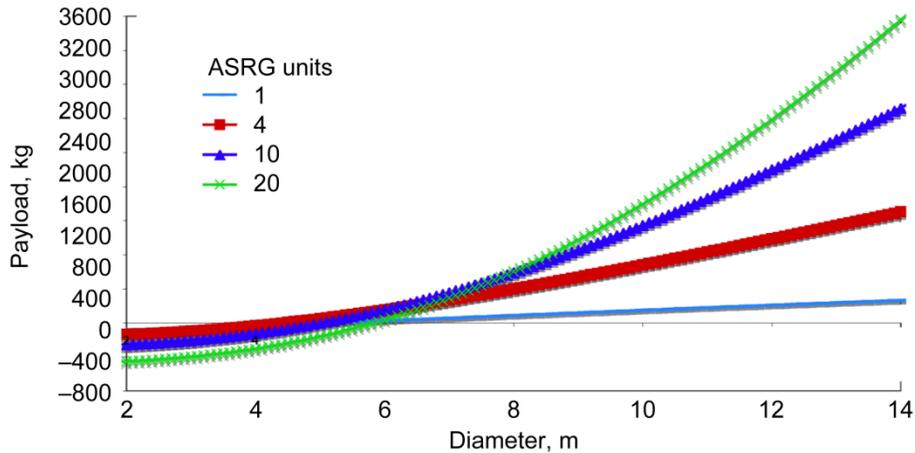


Figure 5.—Effect of the number of ASRG units on the payload mass for different internal diameters with three layers and an insulating gas pocket thickness of 0.05 m.

Effects of the Heat Source on Sizing

As mentioned previously, an ASRG unit could be substituted for the MMRTG unit used for the calculations in preceding sections, increasing the amount of electrical power produced from a given amount of isotope. Multiple ASRG units could be combined to add additional thermal or electrical power. Each ASRG unit has a mass of about 20 kg and a thermal output of about 500 W (Wong 2008). Figure 5 shows the effect that additional ASRG units would have on the resulting payload mass. Increased payload can be achieved by increasing the number of ASRG units used. For example, with an internal diameter of 10 m, 20 ASRG units could support about 1200 kg of payload more than a single ASRG unit could. However, the additional 19 ASRG units weigh 380 kg. The additional weight would make it much more expensive to launch from Earth.

Conclusion

While a hydrogen airship is an inherently simpler design for several missions, the thermal airship is superior for others. Table 3 presents the results of the major design parameters for both the heated-atmosphere airship and a comparable hydrogen airship.

The hydrogen airship has a heavier mass (~200 kg) compared to the heated-atmosphere airship (~162 kg) in the deployed state. Additionally, the heated-atmosphere airship has a longer possible flight life of up to 154 years compared to 180 days for the hydrogen airship. This was determined by the time it takes the MMRTG unit to decay to the point of neutral buoyancy at the surface, compared to the leak rate for the hydrogen airship. For a desired long-term mission, the heated-atmosphere airship appears better suited. However, for a desired mission under 180 days, the less complex hydrogen airship would likely be a better option.

TABLE 3.—MAJOR BASELINE DESIGN PARAMETER RESULTS

Parameter	Heated-atmosphere airship	Hydrogen airship
Mass (kg)	162	200
Diameter (m)	6	4.3
Number of layers	3	1
Insulating gas pocket thickness (m)	0.05	N/A

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