Evaluation of a Heated-Air Airship for the Environment of Titan

by

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Abstract

Future exploration of Saturn's moon Titan can be carried out by airships, which have the capability to study the atmosphere as well as the capability to land and study the surface at multiple locations. Several lighter-than-air gas airships and passive drifting heated-air balloon designs have been studied, but a heated-air airship could combine the best of both. A design tool was created to enable iteration through different design parameters of a heated-air airship (diameter, number of layers, and insulating gas pocket thicknesses) and evaluate the feasibility of the resulting airship. A baseline heated-air airship was designed to have a diameter of 6 m (outer diameter of 6.2 m), 3 layers, and an insulating gas pocket thickness of 0.05 m between each layer. This heated-air airship also had a mass of 161.87 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 desired long-term mission, the heated-air airship appears better suited. However for a desired mission under 180 days, the less complex hydrogen airship would likely be a better option.

Thesis Supervisor: John J. Leonard
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Nomenclature

A_c: Cross-sectional area, m^2
A_i: Inner surface area, m^2
A_o: Outer surface area, m^2
A_s: Surface area, m^2
D: Diameter, m
D_i: Inner diameter, m
D_o: Outer diameter, m
E: Energy per second, W
F_B: Buoyancy force, N
F_g: Force due to gravity, N
F_{sph}: Shape factor for a sphere
Gr: Grashof number
L: Thickness of material, m
L_c: Characteristic length, m
N: Number of layers
Nu: Nusselt number
$Nu_{combined}$: Combined Nusselt number
Nu_{forced}: Nusselt number due to forced convection
$Nu_{natural}$: Nusselt number due to natural convection
P: Pressure, Pa
P_{BC}: Boundary condition pressure, Pa
Pr: Prandtl number
Q: Thermal energy, W
Q_{in} Thermal energy in, W
Q_{out} Thermal energy out, W
R_s: Specific gas constant, J/kgK
R_{cond}: Thermal resistance due to conduction, K/W
R_{conv}: Thermal resistance due to convection, K/W
R_{th}: Thermal resistance, K/W
Ra: Rayleigh number
Re: Reynolds number
T: Temperature, K
T_{av}: Average temperature, K
T_{BC}: Boundary condition temperature, K
T_f: Final temperature, K
T_{grad} Average temperature of the temperature gradient, K
T_H: High temperature, K
T_L: Low temperature, K
T_i: Inner temperature, K
T_o: Outer temperature, K
T_t: Temperature of titan, K
T_w: Internal airship temperature, K
$T_{weighted}$: Weighted temperature, K

V:	Volume, m^3
V_{grad}:	Volume occupied by the temperature gradient, m^3
V_{mix}:	Volume occupied by the well-mixed gas, m^3

c:	Specific heat, kJ/kgK
g:	Gravity, m/s^2
h:	Convective heat transfer coefficient, W/m^2K
k:	Thermal conductivity, W/mK
k_{eff}:	Effective thermal conductivity, W/mK
m:	Mass, kg
m_{gas}:	Mass of lifting gas, kg
r_i:	Inner radius, m
r_o:	Outer radius, m
r_s:	Surface radius for convection, m
w:	Relative wind speed, m/s

ΔH:	Heat of vaporization, kJ/kg
ΔT:	Change in temperature, K

ε:	Emissivity
η_{carnot}:	Carnot efficiency
μ:	Dynamic viscosity, kg/ms
μ_{atm}:	Dynamic viscosity of the atmosphere, kg/ms
μ_s:	Dynamic viscosity at the surface, kg/ms
ρ_{atm}:	Atmospheric density, kg/m^3
ρ_{gas}:	Density of lifting gas, kg/m^3
σ:	Stefan-Boltzmann constant, W/m^2K^4

Chapter 1

1 Introduction

1.1 Titan Background

Titan is the largest moon of Saturn, and the second largest moon in the solar system. With a radius of about 2,500 km, it is even larger than the planet Mercury (radius of about 2,400 km). Other than just its size, there are a few attributes of Titan that make it an interesting place to study.

The first attribute is that Titan has a very thick atmosphere. The surface atmospheric pressure is about 1.6 atm (compared to Earth's 1 atm) [10]. Similarly to Earth, Titan's atmosphere is composed primarily of nitrogen, which makes up about 95% of the composition near the surface. The majority of the remaining 5% is methane [31]. Titan and Earth are the only two bodies in the Solar System to have an atmosphere composed primarily of nitrogen [26]. Because of Titan's thick atmosphere, the diurnal variation of temperature is quite small, about 1.2 K between day and night [21]. The temperature also varies slightly with latitude, ranging from about 90 K near the northern pole to about 94 K near the equator as measured by the Cassini orbiter between 2006 and 2008 [21].

The second attribute is that Titan has surface lakes. These lakes are believed to be composed of methane (or possibly ethane) instead of liquid water [36]. The temperature is cold enough on the surface of Titan (about 95 K) that methane condenses into the liquid phase. Figure 1-1 shows an image from the NASA Cassini orbiter that provided the definitive proof of suspected lakes. It captures a specular reflection of the sun a few months after equinox in 2009 as the northern hemisphere transitioned from winter to summer. Titan is currently the only body in the solar system, other than the Earth, that has known lakes. Additionally, it is believed that there is methane rain on Titan that resembles Earth's hydrologic cycle [36].

Figure 1-1: NASA Cassini Image of the Sun's Specular Reflection on a Presumed Northern Hemisphere Methane or Ethane Lake [Courtesy of NASA]

The third attribute is the abundance of organic molecules (or organics for short) that are present on Titan. These organics are thought to originate from the abundant methane in the atmosphere. Solar UV radiation in Titan's atmosphere converts methane into acetylenes and tholins, which are responsible for the orange haze of Titan's atmosphere [45]. Tholins are polymeric organic molecules that share several moieties (C-N and C=N) with the organic molecules making up life on Earth [45]. Tholins fall out of the atmosphere and eventually reach the surface of Titan. The ESA (European Space Agency) Titan Saturn System Mission report [43] mentions that the organics can come into contact with liquid water due to cryogenic volcanism as well as meteorite impact sites. This could create similar conditions believed to have been present when life began on Earth. Roe [36] and Sotin *et al.* [38] discuss possible signs of cryogenic volcanoes as another potential source of liquid water. Cryogenic volcanoes could also explain the supply of methane, since methane is broken down by solar UV radiation and would exhaust Titan's atmospheric supply in less than 30 million years [36]. All of these attributes make Titan a very interesting place to explore.

1.2 Previous Titan Missions

There have been very few missions to Titan mostly due to the long distance from Earth. Saturn's orbit is on average about 9.5 AU (1 AU or astronomical unit is the distance from

Earth to the Sun) [26]. This distance requires large velocity changes for orbital insertions to take place. A larger change in velocity necessitates a larger amount of rocket fuel. The increase in weight needed for more fuel also vastly increases the cost of any far-reaching missions. Even so, a few missions have already been sent near or to Titan.

Pioneer 11 was a probe sent into the outer solar system to study a number of environments. These included: a fly-by of the asteroid belt between Mars and Jupiter, Jupiter, Saturn, the solar wind, and the heliosphere. It was one of the first probes to venture into the outer solar system, along with Pioneer 10. Pioneer 11 had a flyby of Titan in 1979 [8].

Voyager 1 and 2 were similar to the Pioneer 10 and 11 probes. Their main mission was to study the outer planets, the solar wind, and the heliosphere. Voyager 1 passed by Titan in 1980. It was able to take images of Titan during the fly-by, but due to the thick haze in Titan's atmosphere, images of the surface could not be taken. Additionally, Titan's magnetic field and atmosphere were also studied [39]. The flyby of Titan by Voyager 2 was very similar to Voyager 1, only it passed by Titan in 1981 and then continued to Neptune and Uranus [40].

To date, there has only been one mission that has been sent to the surface of Titan. This mission was the Huygens probe, sent as part of the Cassini mission. The Cassini-Huygens mission was primarily an atmospheric probe with a Saturn system orbiter. The mission was launched in 1997, reached Saturn in 2004, and continues today with Cassini in orbit around Saturn [29]. Cassini-Huygens was a joint effort between NASA and ESA. NASA was responsible for the Cassini orbiter, which explores Saturn and its moons (not solely Titan). ESA was responsible for the Huygens probe, which was developed specifically to study Titan. The Huygens probe landed on Titan's surface with a landing system capable of landing on solid ground as well as floating on a lake. Most of our information about Titan has been obtained from this joint mission. Cassini continues to map the surface of Titan to find new features, while Huygens has already returned all of the data it will ever return. However, atmospheric composition, pressure, and wind speed as well as other properties have been measured and sent to Earth before the Huygens battery died [34].

1.3 Previous Studies for Future Missions

One of the first considerations for a Titan mission has been the type of vehicle used to collect data. A follow-on joint proposal between NASA and ESA has mentioned three desired vehicles. One was an orbiter like the Cassini orbiter. Another was a lake lander similar to Huygens, except 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 or TSSM [43]. Because this thesis will focus on mobile aerial vehicles, little consideration was given to landers or orbiters. The TSSM atmospheric balloon was planned to passively collect atmospheric data at an altitude of about 10km. The power source of the electronics as well as the heat source for the balloon would come from a Multi-Mission Radioisotope Thermal Generator (MMRTG)

[43]. However, the TSSM would not be able to study the organic molecules that have accumulated around the moon. This has led to the proposal of using controlled aerial vehicles that could move around the moon and land at various sites to take 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. Three studies (Colozza *et al.* [7], Lorenz [25], and Wright *et al.* [44]) compared different aerial vehicles for use on Titan. Wright *et al.* [44] concluded that airships are the best for initial missions with vertical takeoff and landing vehicles being considered for future missions due to the increased landing and takeoff ability. Lorenz *et al.* [24] mentioned that the default position of an airship would be to float and act as a balloon if propulsion were to fail either permanently or temporarily. However, airplanes and vertical takeoff and landing vehicles would fall out of the sky. Lorenz [25] considered a reference concept that was a vertical takeoff and landing vehicle due to the relative ease of landing at desired sites. Of these two considerations, the airship was the vehicle type analyzed in this thesis.

Airships can be considered as very similar to balloons, but instead of passively relying on winds to move, such as winds used for drift discussed in Lorenz *et al.* [27], they have an active propulsion system. These airships are also commonly referred to as dirigibles, Zeppelins, and blimps. They could either use lighter-than-air gas or heated-air for lift. Studies have been conducted to understand the performance of Titan airships using lighter-than-air gas as the lifting gas. Duffner *et al.* [10] completed a paper considering a hydrogen gas airship with a rover appendage for surface studies. Lorenz [26] discussed how an airship could maintain continuous flight with duty-cycled propellers for conserved power propulsion. The paper mentioned that drop sondes could be used to study the surface or by possibly landing the airship. Elfes *et al.* [12] and the ESA Titan Saturn System Mission report [43] mentioned the excess heat from an RTG could be used for lift. Duffner *et al.* [10], Lorenz [26], and Wright *et al.* [44] required an RTG for the electrical power needs. Additionally, the TSSM planned to use an RTG heated-air balloon; however, an RTG heated-air 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. Later chapters will provide more details about both the lighter-than-air gas and the heated-air airships.

Ong *et al.* [33] discussed entry into Titan's atmosphere and the necessity to provide thermal protection upon entry as well as parachute deployment once in the atmosphere. Fisher *et al.* [13] went one step further and discussed the feasibility of inflation while descending. After an airship is successfully deployed, it can move by utilizing two forms of propulsion. The first form utilizes an electrically driven set of propellers (airship, dirigible, Zeppelin, etc.). The second form involves passively moving with atmospheric winds (balloon or aerostat). The winds are predominately eastward or westward [42]. The first form of propulsion mentioned above would be needed for traversing northward and southward, as well as for hovering at a fixed location relative to the surface.

The material for the lifting gas envelope was also an important consideration. This was 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.* [19] proposed a combination of polyester and Mylar for an effective cryogenic balloon material. Their paper demonstrated that this material satisfactorily meets all the necessary constraints mentioned above.

1.4 Thesis Roadmap

The goal of this thesis has been to evaluate the design options for a robotic air vehicle that would be capable of exploring Titan. This thesis document is structured with the following chapters: Chapter 2 provides an introduction to possible power sources as well as the needed autonomy for an airship to operate on Titan. Chapter 3 describes the method that was utilized to compute an optimal design of the heated-air airship for Titan, which satisfies the design constraints. Chapter 4 focuses on the lighter-than-air gas airship design option and compares the estimated performance with that of a heated-air airship. Chapter 5 discusses the topic of in-situ resource utilization (ISRU) on Titan, which would be a great technological challenge, but should enable future space missions to become more affordable and sustainable. Chapter 6 describes future work and summarizes the results presented to conclude this thesis.

Chapter 2

2 Operations

2.1 Energy Sources

For any mission to Titan, a power source would be required to operate any moving part(s), operate the science instruments, and send the data collected by the science instruments back to Earth. Five different power sources are considered below.

2.1.1 Solar

Solar power has been a great renewable power source on Earth, and has even been utilized with several Mars explorers. Solar insolation on the surface of Earth is up to 1000 W/m^2. Consequently, since Titan is about 10 times farther from the sun than the Earth is, it has a solar insolation on the surface of only $1 W/m^2$, which is too low to be practical for missions requiring anything more than a few Watts [20]. This is in part due to Titan's high atmospheric opacity. Therefore, no photovoltaic cells, lenses, or mirror concentrators would be feasible.

2.1.2 Methane Combustion

The surface atmospheric conditions of Titan are such that methane combustion would be possible using stored oxygen to combust with atmospheric methane. This would be very similar to combustion on Earth, except oxygen would be used as the fuel and atmospheric methane would be used from the air, instead of the other way around. The atmospheric composition on Titan's surface is about 95% N_2 and 5% CH_4. Since this is the molar ratio, for every mole of CH_4 there are 19 moles of N_2 (5 divided by 95) [9]. This provides the ratio of nitrogen to methane that is used in the methane combustion equation (based per mole of oxygen):

$$O_2 + \frac{1}{2}CH_4 + \frac{19}{2}N_2 \rightarrow \frac{1}{2}CO_2 + H_2O + \frac{19}{2}N_2 + energy \qquad (2.1)$$

The thermal energy produced from this combustion can be determined by using the enthalpy of reaction. Table 2.1 below gives the enthalpy of the substances considered for methane combustion on Titan.

Table 2.1: Enthalpy of Reaction at 298 K [2]

Substance	**Enthalpy (kJ/mol)**
CH_4	-74.8
H_2O	-241.8
CO_2	-393.5
O_2	0
N_2	0

Equation 2.1 would generate approximately 401 kJ/mol of O_2. Then using conservation of energy

$$\Sigma E = Q_{in} - Q_{out} = 0 \tag{2.2}$$

along with the amount of heat absorbed by the reactant gases

$$Q = mc\Delta T \tag{2.3}$$

the final temperature after combustion can be determined (c is the specific heat, m is the mass, and ΔT is the change in temperature). Q_{in} is the leftover energy from the combustion reaction. $Q_{out} = Q_{N_2} + Q_{H_2O} + Q_{CO_2} + Q_{CH_4} + Q_{H_2O\_vaporization}$, is the combined heat that needs to be added to each component to first reach the reaction temperature of 298 K, and then for the products to reach the final end combustion temperature. Table 2.2 below gives the specific heat values as well as the mass of each component used to calculate the internal heat.

Table 2.2: Specific Heats and Masses of Combustion Components

Component	Specific Heat (kJ/kgK)	Mass (kg/mol)
N_2	1	0.028
H_2O	4.2	0.018
CO_2	1	0.044
CH_4	2	0.016

For water vaporization, 40.63 kJ/mol was used. The combined equations of (2.2) and (2.3) give the following:

$$\begin{aligned} Q_{in} = {} & c_{N_2}\left(T_f - 95\right)m_{N_2} + c_{H_2O}\left(T_f - 298\right)m_{H_2O} + c_{CO_2}\left(T_f - 298\right)m_{CO_2} \\ & + c_{CH_4}\left(298 - 95\right)m_{CH_4} + Q_{H_2O\_vaporization} \end{aligned} \tag{2.4}$$

where m_x was the mass of component x, c_x was the specific heat of component x, and T_f was the final temperature. It should be noticed that the temperature differences were not identical. This was due to the differing roles of the gases. The reactant gases were formed at the reaction temperature of 298 and then were heated from that temperature. Methane would only be heated up to the reaction temperature before it would be consumed, and oxygen was assumed to already be at 298 K. Nitrogen would not react in methane combustion and therefore only absorbed heat from its starting temperature. Solving for the final temperature gives a value of about 2658 K. The maximum efficiency was determined by using the Carnot efficiency. The equation used was:

$$\eta_{carnot} = 1 - \frac{T_L}{T_H} \tag{2.5}$$

where T_L is the low temperature, and T_H is the high temperature. The high temperature is the final temperature calculated above, and the low temperature is the temperature of Titan's surface (95K). Therefore, the Carnot efficiency is 0.96. A real heat engine would achieve a lower efficiency, which could probably only reach about 50% of the Carnot efficiency or about 0.48.

To combust methane, there must be a concentration of methane that is high enough to overcome the lower flammability limit of 5% [3]. This is approximately the concentration of methane present on Titan's surface, but the lower flammability limit is in air at room temperature. Though, changes in inert gases such as atmospheric nitrogen have little effect on lower flammability limit [6]. Because the methane concentration on Titan would be very close to the lower flammability limit of methane, and the limit could change with decreases in temperature, extra methane would likely be needed. This could add more complexity to supply methane. Furthermore, there is less than 25% savings on weight by bringing oxygen instead of both oxygen and methane, since oxygen is heaver than methane [26]. To use this method, oxygen would either need to be continuously supplied or produced on Titan by melting and electrolyzing ice. This would require another power source to refuel a vehicle using methane combustion, which would only be feasible if a stationary power supply was setup on Titan and a renewable mobile power supply was refueled at the stationary one.

2.1.3 Geothermal

Roe [36] and Sotin *et al.* [38] suggest that cryogenic volcanoes could be present on Titan. One possibly identified volcano was determined to have a temperature of up to 200K at the volcano surface [38]. This indicates heat exchange between the hotter interior and the colder exterior of the surface, and could generate power just like geothermal power plants on Earth. However, while a geothermal plant would be great for a base or a stationary lander, it would not be feasible for a moving vehicle without another portable power supply such as batteries or methane combustion mentioned above. Even considering a stationary base or lander, there would still remain immense challenges associated with setting up the plant, which has yet to be proven possible by autonomous machines. Additionally, it is possible that there exists an inner liquid water and ammonia layer [26]. This would likely make a geothermal power plant infeasible compared to other power options.

2.1.4 Nuclear Reactor

A nuclear reactor would be ideal for a stationary power plant, or a very large vehicle such as the vehicles in the US Navy's nuclear fleet. In addition, a nuclear reactor on the surface could be used to process water into hydrogen and oxygen. Hydrogen could be used to fill balloons or airships, while the oxygen could be combined with methane (see Section 2.1.2 above) to provide fuel for a more mobile application. The benefits of using a nuclear reactor include: tremendous amounts of both electrical and thermal power, the fuel can last decades without refueling, and the nuclear fuel is lighter (and therefore cheaper to transport into space) than the equivalent chemical fuel. A significant difficulty of implementing nuclear reactors is their high mass. However, the biggest difficulty is not so much related to the technical challenges as it is to the political challenges. Critics of nuclear power suggest that a launch containing nuclear fuel might have a small chance of failing and irradiating the launch site or surrounding areas. In Russia, several nuclear reactors were used on 33 satellites from 1967 to 1988. In the US, only one spacecraft has been launched with a nuclear reactor. This was the SNAPSHOT mission in 1965 [17]. The most recent proposal for a nuclear reactor in space was NASA's Prometheus program, which was proposed (but not built) in 2004 [32].

2.1.5 Radioisotope Generator

A Radioisotope Thermoelectric Generator, or RTG, uses nuclear material 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 last for several decades. 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 in order to manage the dissipation of the excess heat that they generate. RTGs have already been used in many space vehicles and satellites such as the Voyager spacecraft discussed in Freedman *et al.* [14]. This demonstrates that RTGs are a viable option so long as large power requirements are not needed. Lorenz [26] even claims that an RTG is the only viable power source for a mission to Titan.

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) [37].

Based on the other options discussed in preceding sections, it appears that a radioisotope converter would be the best energy choice for many years to come. An MMRTG with about 100 W of electrical power and about 1700 W of thermal power, at the time of arrival at Titan, was used for the calculations in the following chapters [43]. The estimated mass of the MMRTG along with a battery system was assumed to be 100 kg.

2.2 Autonomy

Due to the distance between Titan and the Earth, the time required for a communication transmission to receive a signal in reply is greater than 2 hours [20]. This delay time would be infeasible for a human to manually operate an airship. In addition, it is very likely that changing winds would drastically move an airship during that delay. This indicates that at the very least, an airship would need obstacle avoidance for operating near the surface. Far less autonomy would be needed for higher altitude missions [20]. Human interaction could be limited to selecting desired sample sites. This would then require autonomous path planning and navigation. These autonomous algorithms could plot out a course, as well as compensate for winds that might otherwise prevent the airship from reaching certain targets. Because winds could quickly change the position of the airship, the onboard system would require a positioning determination algorithm to analyze the airship's current position. Once the airship reached a desired sample site, it would then autonomously collect data. Alternatively, it could acquire samples, return to a higher altitude, and then analyze the samples.

Potentially, one of the best types of navigation algorithms would be some form of visual Simultaneous Localization And Mapping (SLAM). Visual SLAM could use one or more video cameras to identify obstacles to avoid, determine its own location, and possibly identify interesting landing sites [28, 30]. Other forms of SLAM could be used, but by utilizing visual SLAM, fewer sensors would be required (assuming some form of camera would be desired). Furthermore, distances could also be estimated by using two cameras for stereovision [30]. This could eliminate the need for range finding sensors.

Providing more detailed solutions to the autonomy challenges described above are beyond the scope of this thesis. Gaines *et al.* [16] and Elfes *et al.* [11, 12] have more information on autonomous planning and execution for an airship on Titan. The Gaines *et al.* [16] paper discusses challenges and their proposed solutions, which they call "AerOASIS: Aerial Onboard Autonomous Science Investigation System."

2.3 Summary

This chapter provided an overview of possible power sources for a Titan airship. Of the power sources discussed, nuclear powered RTGs are the most practical for any near term small-scale exploratory mission such as an airship. This chapter also described how the 2-hour transmission time for communications between Earth and Titan would likely prevent humans from manually controlling an airship mission. Therefore, autonomous operation of an airship would be more appropriate. The next chapter provides a buoyancy and thermal analysis of an RTG-powered autonomous heated-air airship for Titan exploration.

Chapter 3

3 Heated-Air Airship

3.1 Buoyancy Calculations for Heated Gases

In order for an airship to float in an atmosphere, there must be enough buoyancy force to overcome the force of gravity. Buoyancy comes from the Archimedes principle that the weight of fluid displaced is the upward buoyancy force. In equilibrium (constant altitude) floating, this is exactly counteracted by the force of gravity. Equation 3.1 gives the buoyancy force:

$$F_B = V\rho_{atm}g = m_{gas}g \quad (3.1)$$

where F_B is the buoyancy force, V is the volume of the gas displaced, ρ_{atm} is the density of the atmosphere, g is the gravitational constant, and m_{gas} is the mass of the gas displaced. Equation 3.2 gives the force of gravity:

$$F_g = V\rho_{gas}g + mg \quad (3.2)$$

where F_g is the force of gravity, ρ_{gas} is the density of gas inside the airship, and m is the mass of the vehicle. Equation 3.3 sets Equations 3.1 and 3.2 equal to each other and solves for the volume:

$$V = \frac{m}{\rho_{atm} - \rho_{gas}} \quad (3.3)$$

Because the heated-air airship uses heated atmosphere, the density of the internal gas can be closely approximated from the ideal gas law:

$$\rho_{gas} = \frac{m_{gas}}{V} = \frac{P}{R_s T} \quad (3.4)$$

where P is the gas pressure, R_s is the specific gas constant (J/kgK), and T is the temperature of the gas. Assuming that the airship is a perfect sphere with internal diameter D, then the equation for a sphere's volume can be used to solve for the diameter. Equation 3.5 relates buoyancy to the diameter of a balloon, and Equation 3.6 relates buoyancy to the mass of the airship:

$$D = \sqrt[3]{\frac{6m}{\left(\rho_{atm} - \frac{P}{R_s T}\right)\pi}} \tag{3.5}$$

$$m = \frac{D^3\pi}{6}\left(\rho - \frac{P}{R_s T}\right) \tag{3.6}$$

3.2 Insulation Design

To achieve higher internal temperatures of the airship, the heat lost to the external atmosphere must be impeded with insulation. For a balloon or airship, the heat is lost through the envelope. One way this can be done is by using insulating material such as Aerogel in the envelope. Another would be to use air pockets with multiple layers of material. Since air has a relatively low thermal conductivity and is very abundant, it provides good insulation at a low cost. For example, double pane windows make use of air as insulation to reduce heat loss from or to a building (depending on the season). Terrestrial air is primarily composed of nitrogen much like the atmosphere on Titan, 78% vs. 95% by volume, respectively. This indicates that the same insulation strategies on Earth would also be effective on Titan. However, more layers for added insulation would also add more weight. This requires a trade-off between better insulation and total weight of the airship. The best insulation would not have any conductive pathways through the insulating gas. However, with a heated-air airship, this would require each layer to be unconnected and able to float free with respect to neighboring layers. Several spacers would be used to ensure that the insulating gas is the same thickness at all points. The conductive heat transfer through these spacers was not considered in the heat transfer calculations discussed in the following section.

3.3 Thermal Balance

The buoyancy equations (Equations 3.5 and 3.6), contain 3 unknown variables. These 3 variables are the airship diameter, the average temperature inside the airship, and the mass that can be lifted. There is however another relationship between the airship diameter and the average inside temperature. This relationship is due to heat transfer from the warm environment inside of the airship to the colder environment of Titan's atmosphere. Because the thermal source is an assumed constant power load (from the RTG), and the heat loss is proportional to the area, the larger the diameter the lower the inside temperature will be. Figure 3-1 shows an example case of an airship with two layers. The heat transfer mechanism, whether from the internal natural convection, the convection or conduction between layers, or the external convection, have all been considered to determine the inner temperatures.

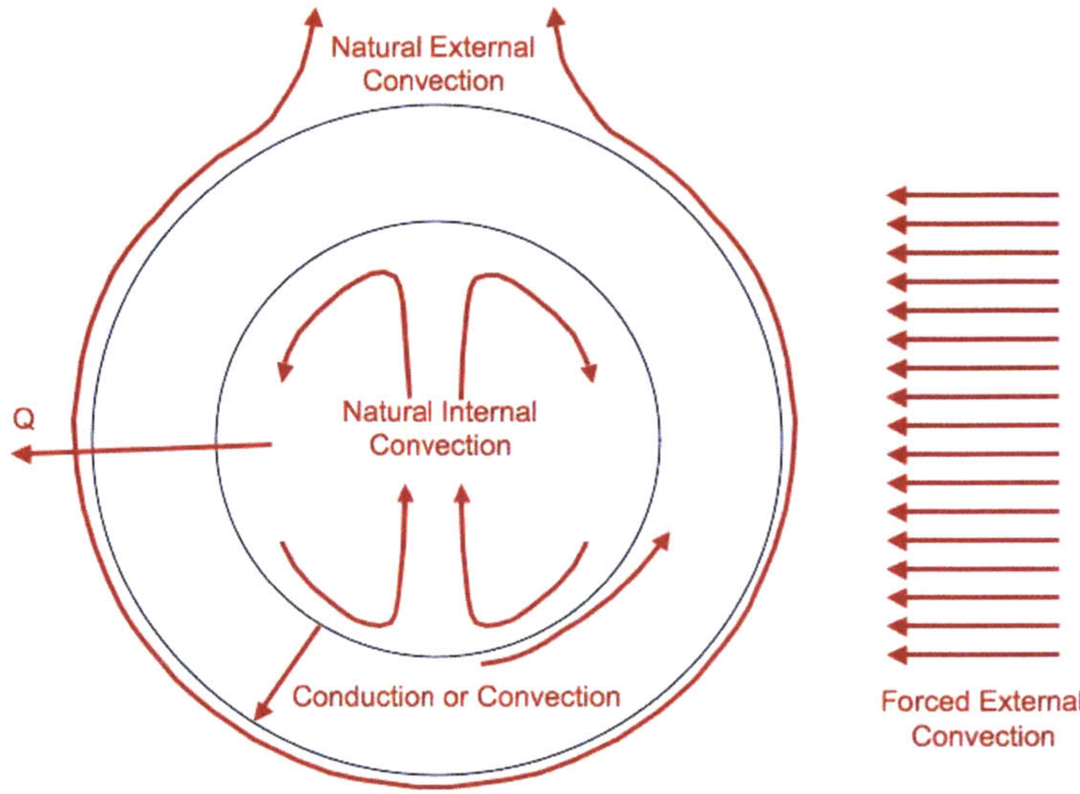

Figure 3-1: Diagram of Heat Effect of a Two-Layered Heated-Air Airship

The basic form of the heat transfer equation taken in the resistor analogy:

$$Q = \frac{\Delta T}{R_{th}} \tag{3.7}$$

where Q is the thermal load, ΔT is the change in temperature, and R_{th} is the equivalent thermal resistance. Figure 3-2 shows the thermal circuit diagram for a three-layer example:

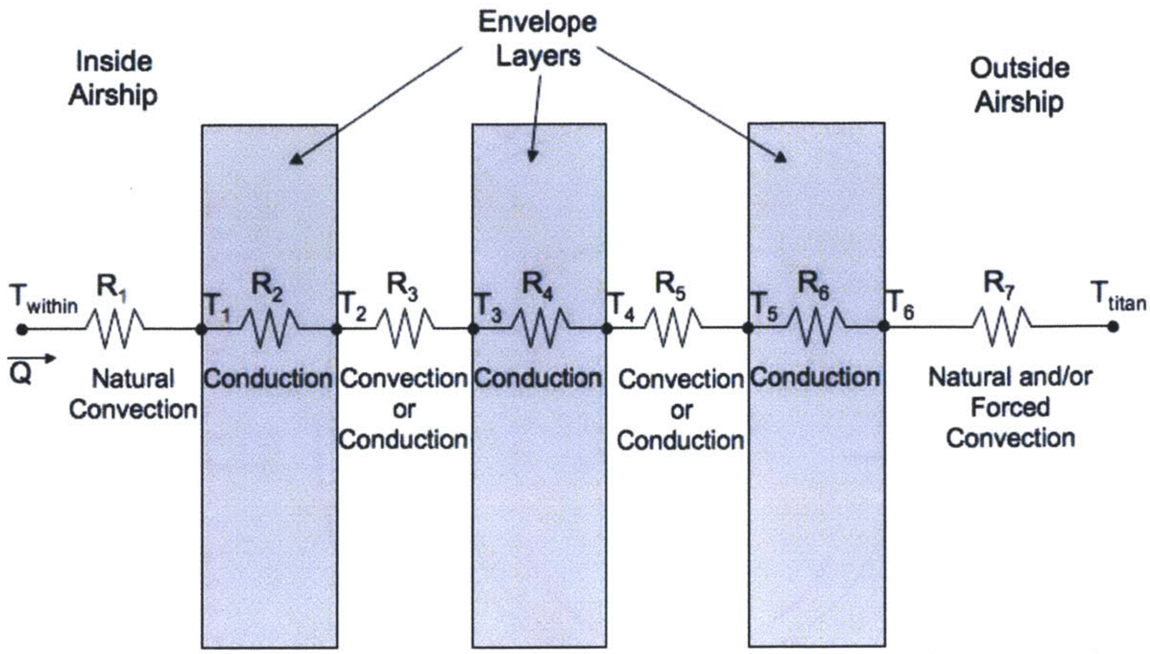

Figure 3-2: Three-Layer Thermal Circuit with Identified Methods of Heat Transfer

The equivalent thermal resistor for a three-layer airship would simply be the sum of all the resistors from Figure 3-2, and the ΔT would be the difference between the internal temperature and the temperature of Titan's atmosphere. The combined equation is then:

$$T_w = T_t + Q\left(R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7\right) \tag{3.8}$$

where T_w is the temperature within the airship, and T_t is the temperature of Titan's atmosphere. 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 RTG. The value of each of the thermal resistors must be determined. Equation 3.9 and 3.10 are the thermal resistor equations for conduction and convection respectively:

$$R_{cond} = \frac{L}{kA_c} \tag{3.9}$$

$$R_{conv} = \frac{1}{hA_s} \tag{3.10}$$

where L is the thickness of the material that the heat is conducting through, k is the thermal conductivity of the material, h is the convection heat transfer coefficient, A_c is the cross-sectional area, and A_s is the surface area. Equations 3.11 and 3.12 consider the thermal resistor equations for a sphere:

$$R_{cond} = \frac{r_o - r_i}{4\pi k r_i r_o} \tag{3.11}$$

$$R_{conv} = \frac{1}{4\pi h r_s^2} \tag{3.12}$$

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. Two quantities are needed to solve for the thermal resistance in the conduction case. These two quantities are 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. The following sections detail how the heat transfer coefficient is determined for each case.

3.3.1 Determining Inner Natural Convection

To determine the heat transfer coefficient for the innermost cavity (R_I in Figure 3-2), the Nusselt number for natural convection over a sphere was used (it was assumed that natural convection over a sphere is the same as inside a sphere). Equation 3.13 gives the Nusselt number (Nu) for natural convection over a sphere [5]:

$$Nu = 2 + \frac{0.589 Ra^{1/4}}{\left[1 + \left(\frac{0.469}{\mathrm{Pr}}\right)^{9/16}\right]^{4/9}} \tag{3.13}$$

where Pr is the Prandtl number, and Ra is the Rayleigh number. The Rayleigh number can be computed from equation 3.14:

$$Ra = Gr\,\mathrm{Pr} = \frac{L_c^3 \rho_{gas}^2 g \beta (T_w - T_1)}{\mu^2} \mathrm{Pr} \tag{3.14}$$

where Gr is the Grashof number, L_c is the characteristic length (the diameter for a sphere), T_I is the temperature of the inner layer from Figure 3-2, and μ is the dynamic viscosity of the gas inside the airship. β can be determined from Equation 3.15.

$$\beta = \frac{1}{0.5 T_{av}} \tag{3.15}$$

where T_{av} is the average temperature across the area being considered (T_w - T_I). The dynamic viscosity μ is determined from Equation 3.16 [43]:

$$\mu(T) = 10^{-6}(1.5125 + 0.0558 \cdot T) \tag{3.16}$$

After the Nusselt number from Equation 3.13 is determined, the heat transfer coefficient can then be determined from the following relationship:

$$h = \frac{Nuk}{L_c} \tag{3.17}$$

Internal natural convection was used as a first order approximation. In reality, there would be forced convection present due to a pressurizing fan discussed in Section 3.5. Future work could consider the effects of forced convection on the internal heat transfer.

3.3.2 Determining Heat Transfer Through Insulating Gas Pockets

An insulating gas pocket between two layers can transfer heat either through convection or conduction. The determining factor is whether or not the buoyancy force of the gas is enough to overcome the viscous forces of the gas. Convection takes place when Ra > 1708 [5]. The Rayleigh number for an enclosure between two concentric spheres is the following:

$$Ra = \frac{\rho_{gas}^2 g\beta(T_i - T_o)(r_o - r_i)^3}{\mu^2}\mathrm{Pr} \tag{3.18}$$

where T_i is the temperature of the inner surface and T_o is the temperature of the outer surface. If the Ra ≤ 1708 then the thermal resistance simply uses Equation 3.11 where the thermal conductivity k is determined from the relation [43]:

$$k(T) = 10^{-3}(1.078 + 0.08365 \cdot T) \tag{3.19}$$

However, if Ra > 1708 Equation 3.11 is still used, but the thermal conductivity used is k_{eff} found by using Equation 3.20 [5].

$$k_{eff} = 0.74k\left(\frac{\mathrm{Pr}}{0.861 + \mathrm{Pr}}\right)^{1/4}\left(F_{sph}Ra\right)^{1/4} \tag{3.20}$$

F_{sph} is the shape factor of a sphere, which can be determined by [5]:

$$F_{sph} = \frac{(r_o - r_i)}{(D_i D_o)^4\left(D_i^{-7/5} + D_o^{-7/5}\right)^5} \tag{3.21}$$

3.3.3 Determining the Forced and Natural Convection on the Outside Surface

To determine whether forced convection, natural convection, or both should be taken into account, there is a simple relationship. The relationship is Gr/Re^2. If this ratio is less than 0.1, then natural convection is negligible. If the ratio is greater than 10, then forced convection is negligible. Between 0.1 and 10, both natural and forced convection need to be taken into account. However, since the calculations have been done in a computer program, both natural and forced convection have been considered. To combine the forced and natural convection components into one Nusselt number, Equation 3.22 was used [5]:

$$Nu_{combined} = \left(Nu_{forced}^{n} + Nu_{natural}^{n}\right)^{1/n} \tag{3.22}$$

where n varies between 3 and 4 depending on the geometry. 3 would typically be used for vertical surfaces and 4 for horizontal surfaces. Yet, the difference in values had no noticeable effect when running the program discussed in Section 3.4, so arbitrarily 3 was used. The natural convection component was determined by using Equations 3.13-3.16. The forced convection required a few different calculations. The first step was to determine the Reynolds number:

$$\mathrm{Re} = \frac{wD\rho}{\mu} \tag{3.23}$$

where w is the relative wind speed. Once the Reynolds number was known, the final step was to determine the Nusselt number. Equation 3.24 for the Nusselt number is only considered valid for Re ≤ 80,000. However, Re is closer to $2.7*10^7$. To determine if Equation 3.24 could be reliably extrapolated for Re = $2.7*10^7$, the data was compared to experimental work done by Achenbach [1]. For a Reynolds number on the order of $2.7*10^7$, the Nusselt number for a cylinder (fairly close approximation for a sphere) was around 10,000. Equation 3.24 provided a Nusselt number of about 7000. Yet, the effect on the calculations for the airship resulted in less than 0.6% difference. Even accounting for an increased Nusselt number of 100,000 only resulted in a 1.5% difference in performance of the airship. Due to this small effect, Equation 3.24 was assumed to be a sufficient estimate.

$$Nu = 2 + \left(0.4\,\mathrm{Re}^{1/2} + 0.06\,\mathrm{Re}^{2/3}\right)\mathrm{Pr}^{0.4}\left(\frac{\mu_{atm}}{\mu_s}\right)^{1/4} \tag{3.24}$$

where μ_{atm} is the dynamic viscosity of the atmosphere and μ_s is the dynamic viscosity at the surface. Both dynamic viscosities can be determined from Equation 3.16. Once the combined Nusselt number was determined Equation 3.17 was used to find the heat transfer coefficient. Then Equation 3.12 was used to find the thermal resistance. To solve all these equations, a matlab program was written. The next section provides more detail about the program.

3.4 Iteration Program

A matlab program was written to evaluate 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. Table 3.1 below shows assumed constants that were used in the iteration program.

Table 3.1: Constant Properties with Assumed Values

Property	Value
Envelope Material Thickness	0.00003 m
Cryogenic Envelope Material Weight [19]	94 g/m^2
Estimated Thermal Conductivity of the Cryogenic Envelope Material	0.4 W/mK
Titan Pressure [15]	160 kPa
Titan Gravity	1.352 m/s^2
Titan Temperature	95 K
Wind Speed[1]	5 m/s
Specific Gas Constant for the Atmospheric Nitrogen	297 J/kgK
RTG Heat [43]	1700 W
Mass of RTG and Battery System [10]	100 kg
Mass of Instruments [10]	28.9 kg
Prandlt Number of Atmosphere [43]	0.796

A worst-case temperature of 95 K was assumed here. Operation at locations and times with lower temperature would result in the ability to carry a slightly higher payload mass. Figure 3-3 shows a diagram of a cross sectional view of an analyzed airship. The 3 parameters are indicated in blue (number of layers, diameter, and insulating gas pocket thickness). In red are the major heat transfer mechanisms. The heat transfer out is shown with the radial arrow and labeled as Q. In the inside sphere, there is natural convection, and on the outside there is natural and forced convection. The changes in the 3 parameters affect both the heat transfer and the buoyancy. There are 3 portions of the iteration program that consider the effects the parameters have on the heat transfer rate and buoyancy of an airship. This first portion is the main iteration program, the second portion is buoyancy evaluation, and the third portion is the thermal analysis.

[1] Wind speed is considered to be the relative speed difference between the airship and active wind with the variations in the wind with respect to time across the airship. This is because a completely unpowered airship would move with the wind and would have a relative wind speed of zero.

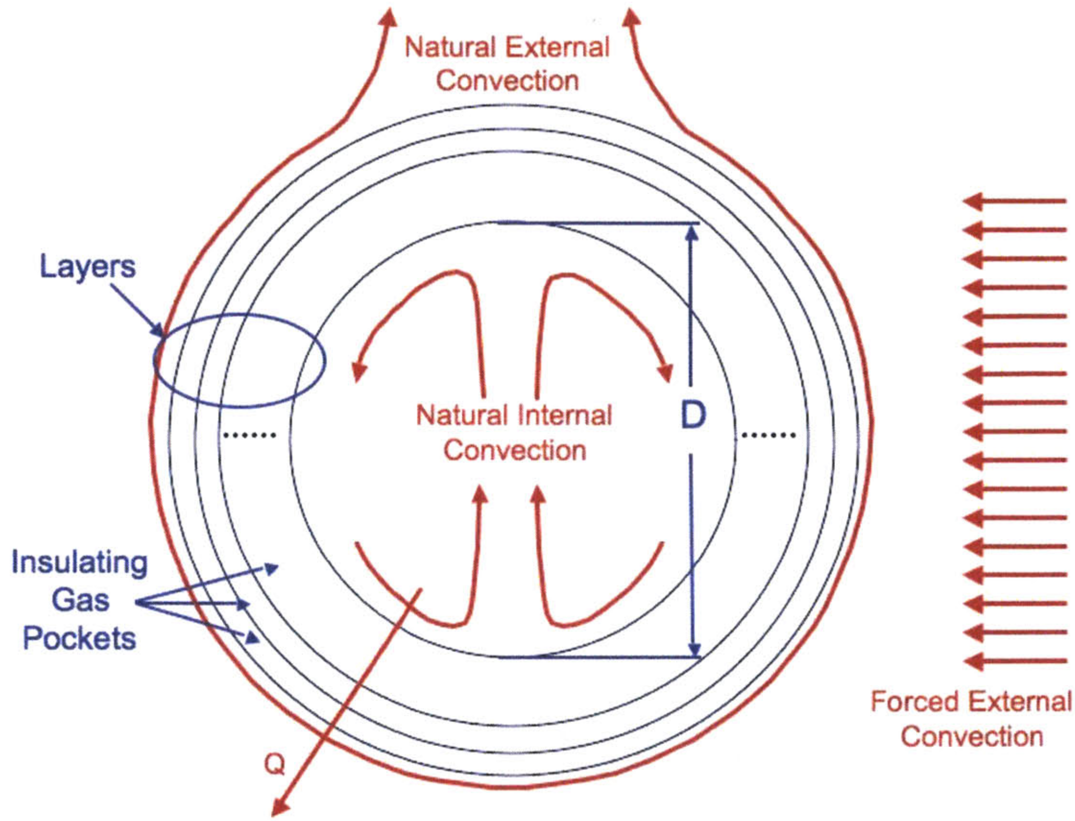

Figure 3-3: Diagram of Balloon Parameters and Thermal Effects

The main iteration program does exactly what the name implies. It iterates different values for the diameter, insulating gas pocket thickness, and number of layers. Then, it evaluates the deadweight and mass that can be lifted. The user can independently adjust the step size, the starting value, and ending value for each parameter. The program then starts by having a loop within a loop within a loop. Each loop iterates a different parameter, and because there are 3 parameters, there are 3 imbedded loops. These 3 loops ensure that every iterated value of each parameter will be matched together and evaluated. During each evaluation, the parameters (along with the constants for Titan shown in Table 3.1) are sent to the thermal analysis program. The thermal analysis program returns the average center temperature, the temperature at each wall, and the radius of each wall to be sent to the buoyancy program. The buoyancy program returns the mass that can be lifted (more information on the thermal analysis and buoyancy portions is given in the following paragraphs). The iteration program also calculates the total weight of the airship, which varies based on the weight of the enveloping material (a function of the weight of the material and how much is used, i.e. the total surface area of the airship). If the parameters can combine to produce an airship that creates enough lift to support the deadweight, then the parameters and evaluated variables are stored in a matrix to be later analyzed.

The thermal analysis portion is a separate function that is called by the main iteration program. Its purpose is to determine the temperature at each surface as well as the internal temperature T_w. Section 3.3 details the equations needed, as well as how they are used for a simple case of three layers. However, this thermal analysis function calculates the temperature for up to 100 layers (more layers could be used, but 100 was considered more than sufficient for a Titan airship design). Due to the temperature dependence for heat transfer as well as for the dynamic viscosity and thermal conductivity of Titan's air, the temperature was first estimated and then calculated. The calculated temperature was then compared to the estimated temperature. If the two temperatures were close enough to each other (across all temperature locations), then the program finished. Otherwise the calculated temperature was used as the estimated temperature for the next run. The output of this function was the internal temperature, an array of temperatures at each surface, the calculated outer diameter, the calculated total surface area of the balloon material, and an array of the radii for each surface.

The buoyancy evaluation portion is a separate function that is also called by the main iteration program. The output of this function is the liftable mass determined from Equation 3.6. Therefore, the following variables are needed as input: the diameter, the density of the atmosphere, the pressure of the atmosphere, the specific gas constant, and the temperature of the internal volume. Additionally, an array of temperatures at each surface, an array of the radius at each surface, and the number of layers were used. This enables the buoyancy force from each heated insulating gas pocket to be accounted for to determine the entire buoyancy force. The arrays of the temperature and the radius, as well as the internal temperature, come from the output of the thermal analysis.

3.5 Results

The results of the iteration program produce a list of potential parameters (diameter, insulating gas pocket thickness, and number of layers) as well as the lifting mass, deadweight, and extra payload. In order to narrow down the list of choices, consideration was given to the difficulty of achieving each. 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 determined for this airship. The parameters are presented in Table 3.2.

Table 3.2: 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

The code used for the iteration program can be found in Appendix A. Table 3.3 gives the temperatures at each node as indicated by Figure 3-2.

Table 3.3: Temperature Node Results

Temperature Node Label	**Temperature with 5 m/s Wind (K)**	**Temperature with no Wind (K)**	**Description of Node**
T_{within}	187.65	191.15	Average internal gas temperature
T_1	175.55	179.00	Temperature of the inside surface of the inner layer
T_2	175.54	179.00	Temperature of the outside surface of the inner layer
T_3	157.11	160.50	Temperature of the inside surface of the middle layer
T_4	157.11	160.50	Temperature of the outside surface of the middle layer
T_5	95.72	100.95	Temperature of the inside surface of the outer layer
T_6	95.72	100.94	Temperature of the outside surface of the outer layer
T_{Titan}	95	95	Temperature of Titan's atmosphere

The temperature drop through the envelope material (between T_1 and T_2, T_3 and T_4, and T_5 and T_6) shows that there is little thermal impendence through the material. The largest temperature drops were found to be across the insulating gas pockets. The insulating gas pocket heat transfer between the inner and middle layer was due to convection, where as the insulating gas pocket heat transfer between the middle and outer layer was due to conduction, and resulted in the highest temperature drop. Table 3.3 also shows that the temperatures were higher when there was no external forced convection (no relative wind). Figure 3-4 shows how the payload capacity was reduced due to the forced convection of the relative wind. There was about a 4% reduction in payload capacity for a diameter of 6 m. The x-axis represents the size of the inner diameter. The payload on the y-axis has been defined as the amount of mass that can be lifted after accounting for the RTG/battery system and the envelope material.

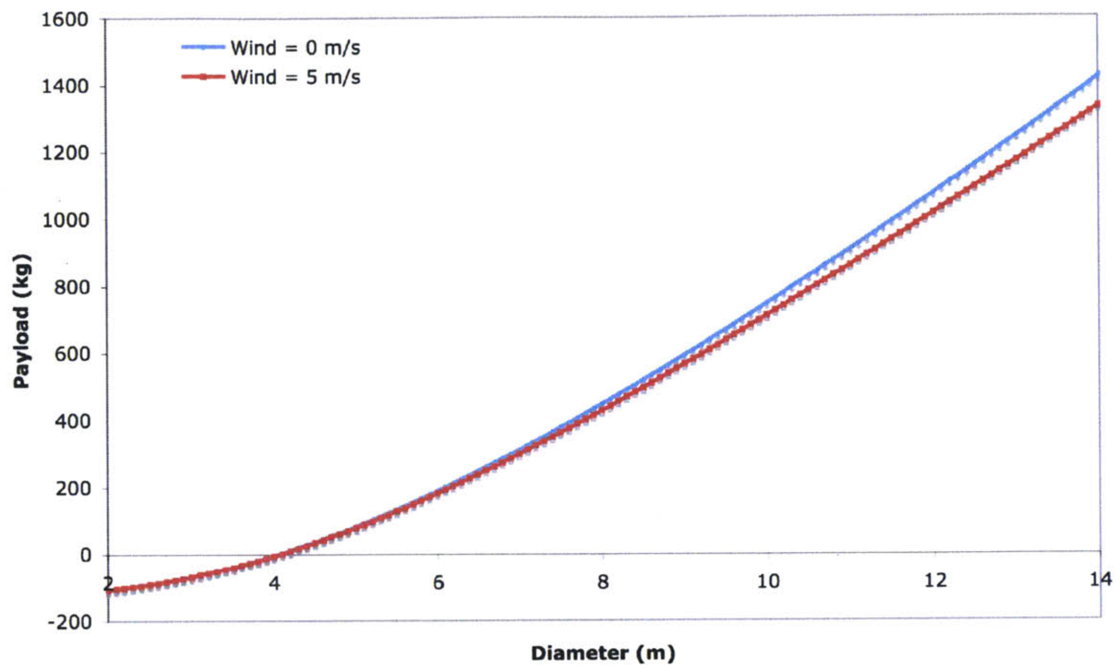

Figure 3-4: Effect of Relative Wind on the Payload for Different Internal Diameters with 3 Layers and an Insulating Gas Pocket Thickness of 0.05 m

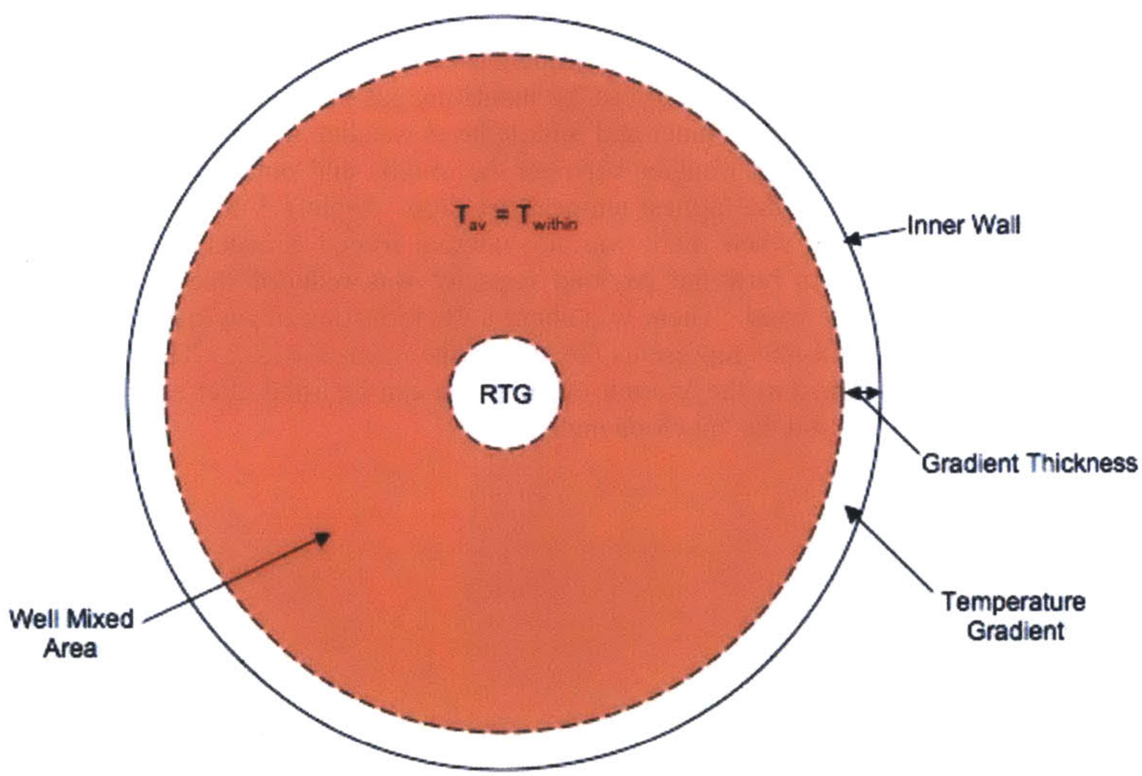

Figure 3-5: Diagram of Internal Temperature Approximation Due to Convective Mixing

In Figure 3-5 above, the red area represents the internal gas that would be well mixed. The average temperature of the red area (the well-mixed gas) was used as T_{within} for the heat transfer analysis. Around the RTG heat source and the inner wall, viscous forces prevent the localized gas from effectively mixing with the well-mixed gas. The viscous forces cause the temperature gradient that was used in the calculation for the internal convective heat transfer. For simplification, it was assumed that the gradient thickness would be negligible. This allowed the average temperature of the well-mixed gas to be used for the buoyancy calculation. Figure 3-6 shows the effect of using a weighted average temperature, of the well-mixed gas temperature with the internal wall temperature (T_{within} and T_1 respectively), for the buoyancy calculations.

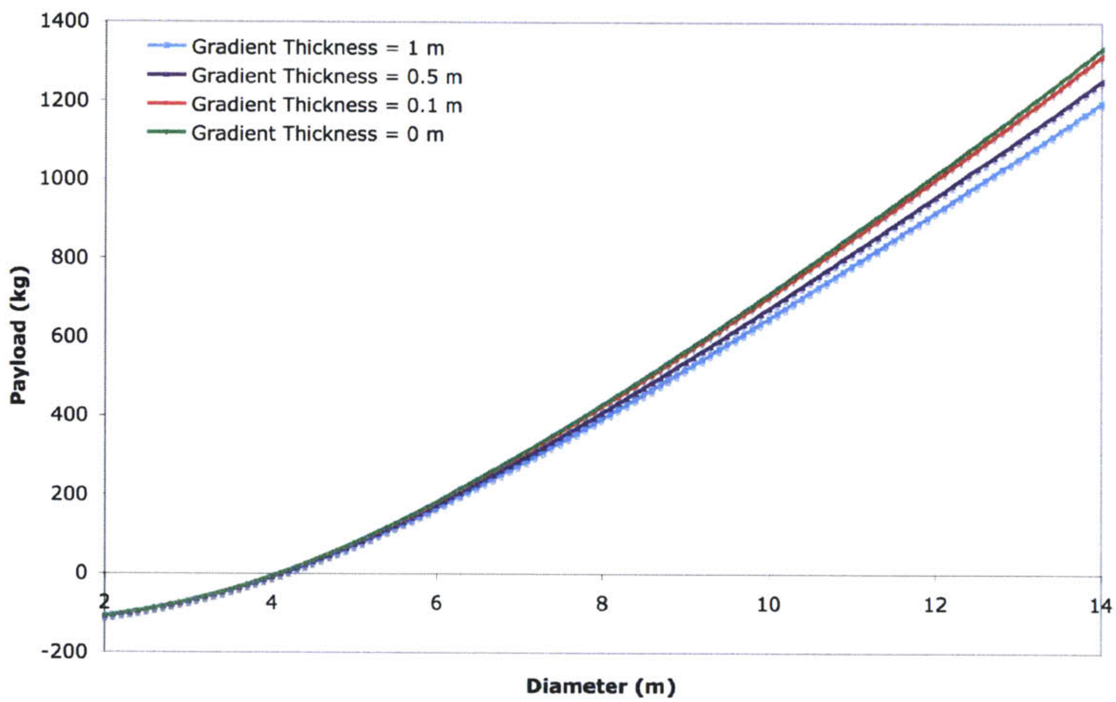

Figure 3-6: The Effect the Assumed Heat Transfer Gradient Thickness has on the Payload for Different Internal Diameters with 3 Layers and an Internal Gas Pocket Thickness of 0.05 m

The effect of assuming that the temperature gradient thickness would be 0.1 m results in about a 1% decrease in payload capacity for an airship with an internal diameter of 6 m. Similarly, a temperature gradient thickness of 1 m would result in a decrease of only about 9%. The weighed average for the buoyancy temperature was determined by the relative volumes of the well-mixed gas and the volume occupied by the temperature gradient. Equation 3.25 presents the calculation of the weighted average temperature with the temperature gradient considered.

$$T_{Weighted} = \left(\frac{V_{mix}}{V_{mix} + V_{grad}} T_w + \frac{V_{grad}}{V_{mix} + V_{grad}} T_{grad} \right) \tag{3.25}$$

where V_{mix} was the volume of the well-mixed gas, V_{grad} was the volume occupied by the temperature gradient, and T_{grad} was the average temperature of the temperature gradient. Because the temperature gradient was likely nonlinear, the temperature of the inside surface of the inner wall, or T_1, was used as T_{grad}.

Figures 3-7 and 3-8 show the effects of modifying the number of layers and the thickness of the insulating gas pocket, respectively. It should be noted that there is a significant increase in payload mass (over 250 kg) by adding 2 extra envelope layers compared to using a single layer. Though, with a few more additions, there is only a small increase in the payload mass. Figure 3-8 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.

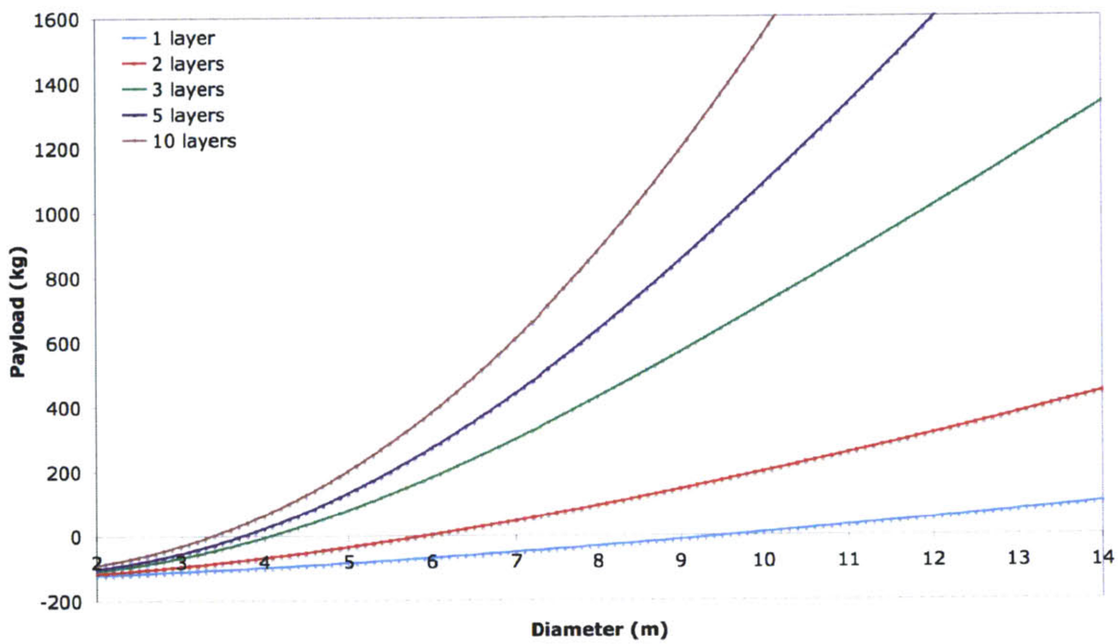

Figure 3-7: Airship Payload Sizing Due to Different Number of Layers and Internal Diameters with an Insulating Gas Pocket(s) of 0.05 m (When Applicable)

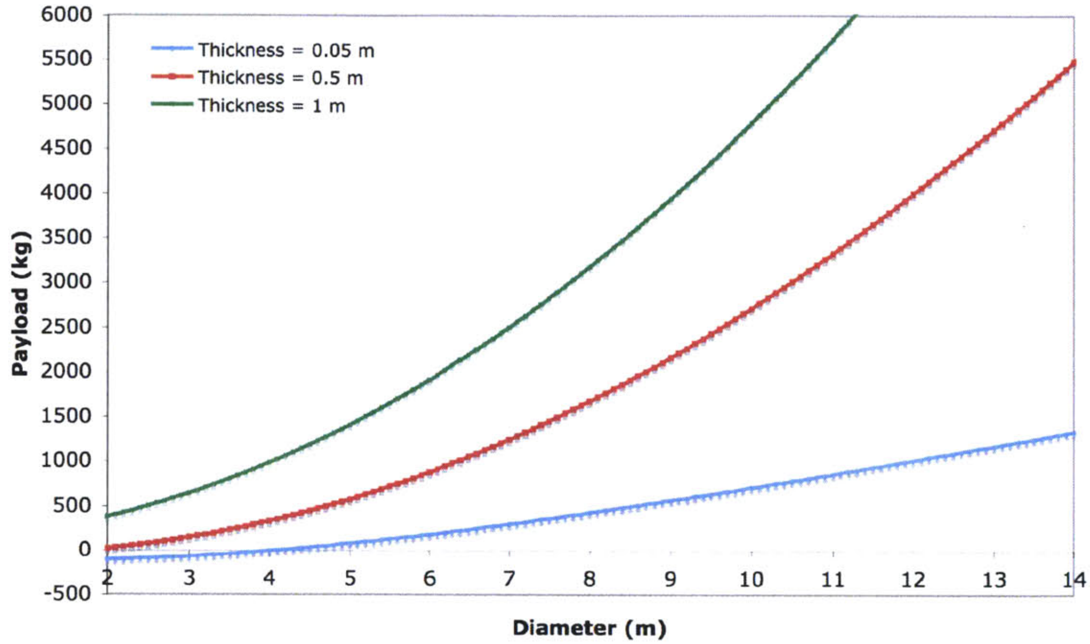

Figure 3-8: Airship Sizing Due to Different Insulating Gas Pocket Thicknesses and Internal Diameters with 3 Layers

The heated-air airship was designed primarily to interact with and explore the surface of Titan. As the airship's altitude increases, the payload mass 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/m^3 [21, 22]. Figure 3-9 shows the effect that the altitude has on the payload for different internal diameters. The baseline airship with a diameter of 6 m would be able to reach an 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 3 layers and an insulating gas pocket thickness of 0.05 m are those with an internal diameter between 5.2 m and 10.1 m.

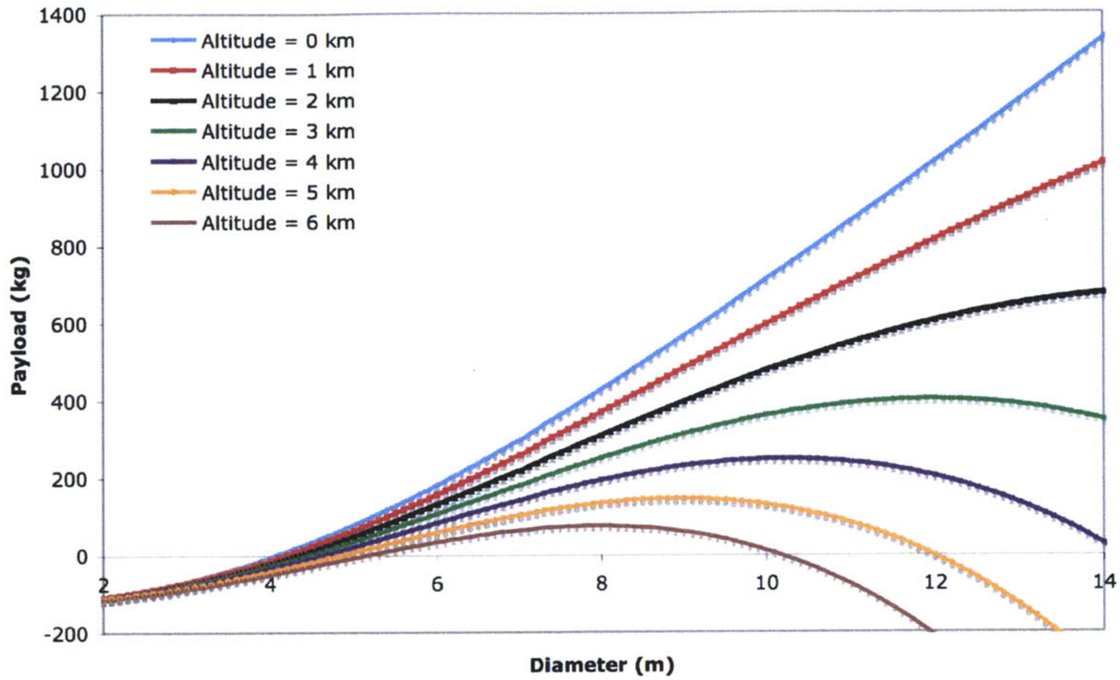

Figure 3-9: Payload Capability as a Function of Altitude for Different Internal Diameters with 3 Layers and an Insulating Gas Pocket Thickness of 0.05 m

3.5.1 Effects of the Heat Source on Sizing

As mentioned in Section 2.1.4, an ASRG unit could be substituted for the MMRTG unit that had been considered for the calculations in preceding sections. Additionally, 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 [37]. Figure 3-10 shows the effect that additional ASRG units would have on the resulting payload mass. 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.

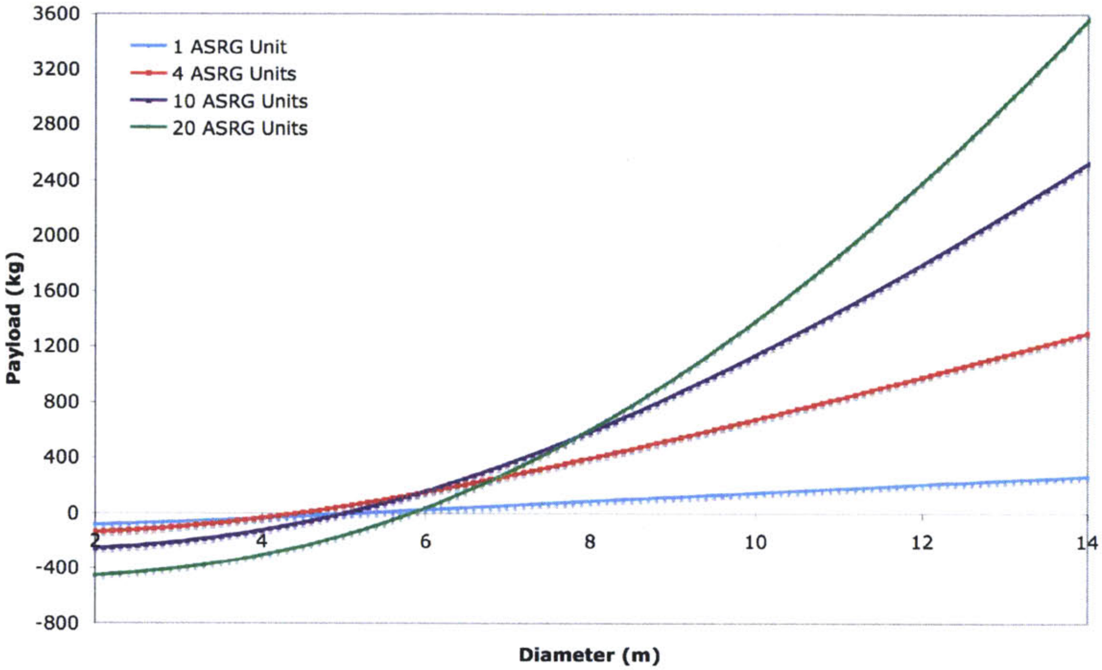

Figure 3-10: Effect of the Number of ASRG Units on the Payload Mass for Different Internal Diameters with 3 Layers and an Insulating Gas Pocket Thickness of 0.05 m

Figure 3-11 shows a comparison of using 1 MMRTG unit compared to 4 ASRG units (4ASRG units are required to match the thermal power output of 1 MMRTG unit). 1 MMRTG unit is lighter than 4 ASRG units, and because they have identical thermal power outputs, the MMRTG unit provides better performance. However, 1 ASRG unit has nearly an equivalent electrical power output as that of 1 MMRTG (beginning-of-life power of about 160 W compared to about 125 W respectively) [37, 43]. If more electrical power were desired, then 4 ASRG units would perform better as a power source compared to that of 1 MMRTG unit. 1 ASRG unit generates 500 W of thermal power compared to 1 MMRTG unit, which generates 2000 W of thermal power (both present beginning-of-life power outputs) [37, 43].

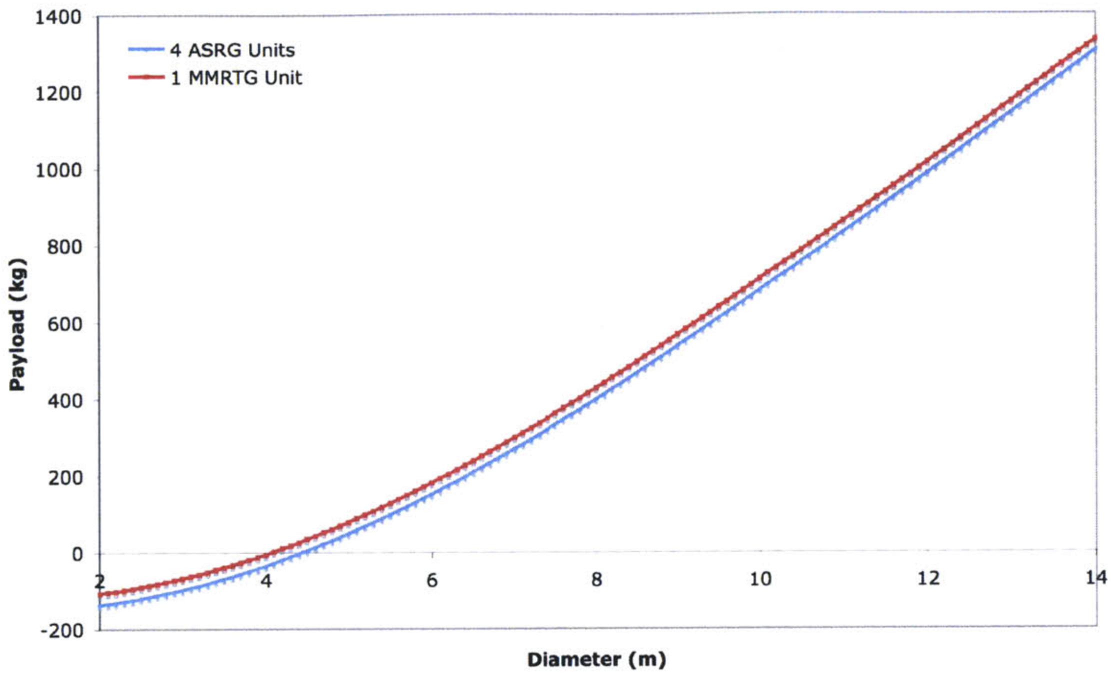

Figure 3-11: Comparison of 1 MMRTG Unit with 4 ASRG Units to Maintain Identical Thermal Power Outputs for an Airship with 3 Layers and an Insulating Gas Pocket Thickness of 0.05 m

3.6 Lifting System Design

Figure 3-12 below shows one possible design of a heated-air airship. The internal volume is slightly greater than a sphere with a 6 m diameter (113.1 m^3) at 117.8 m^3. Realistically, the airship shape will have an increased heat transfer rate proportional to the change in surface area. The airship shape had an increase in surface area of about 10%, but for simplicity it was approximated by a sphere of identical volume and surface area. This airship is 9.5 m long and 5 m wide. Figure 3-12 also shows the airship fully deployed. In this arrangement, the RTG is located in the center of the airship directly above the gondola. This is to ensure that the heat is used for lift and minimizes any thermal waste. The position chosen is the approximate center of the cross-sectional circle volume, though it is unclear where the optimum position would be located. The RTG was assumed to be supported by cables connected to the envelope material so that during inflation, the RTG could be lifted through the hole in the gondola (there for atmosphere to enter, as well as allow the RTG heat to be dissipated on the flight from Earth to Titan). The back fins are inflated fabric, and are therefore not rigid. This helps to ensure less complicated stowage and to minimize the required internal pressure. If solid fins where used, then either some form of rigid support or internal pressurization would be needed to keep the fins in place. The pressurization needed to support the inflated fabric fins was calculated using the top fin. The entire weight of the fin was balanced by the pressure of the internal gas multiplied by the area of the surface that faces in the direction opposite of gravity (the top edge of the fin). The gauge pressure was determined to be about 2.6 Pa to support the weight.

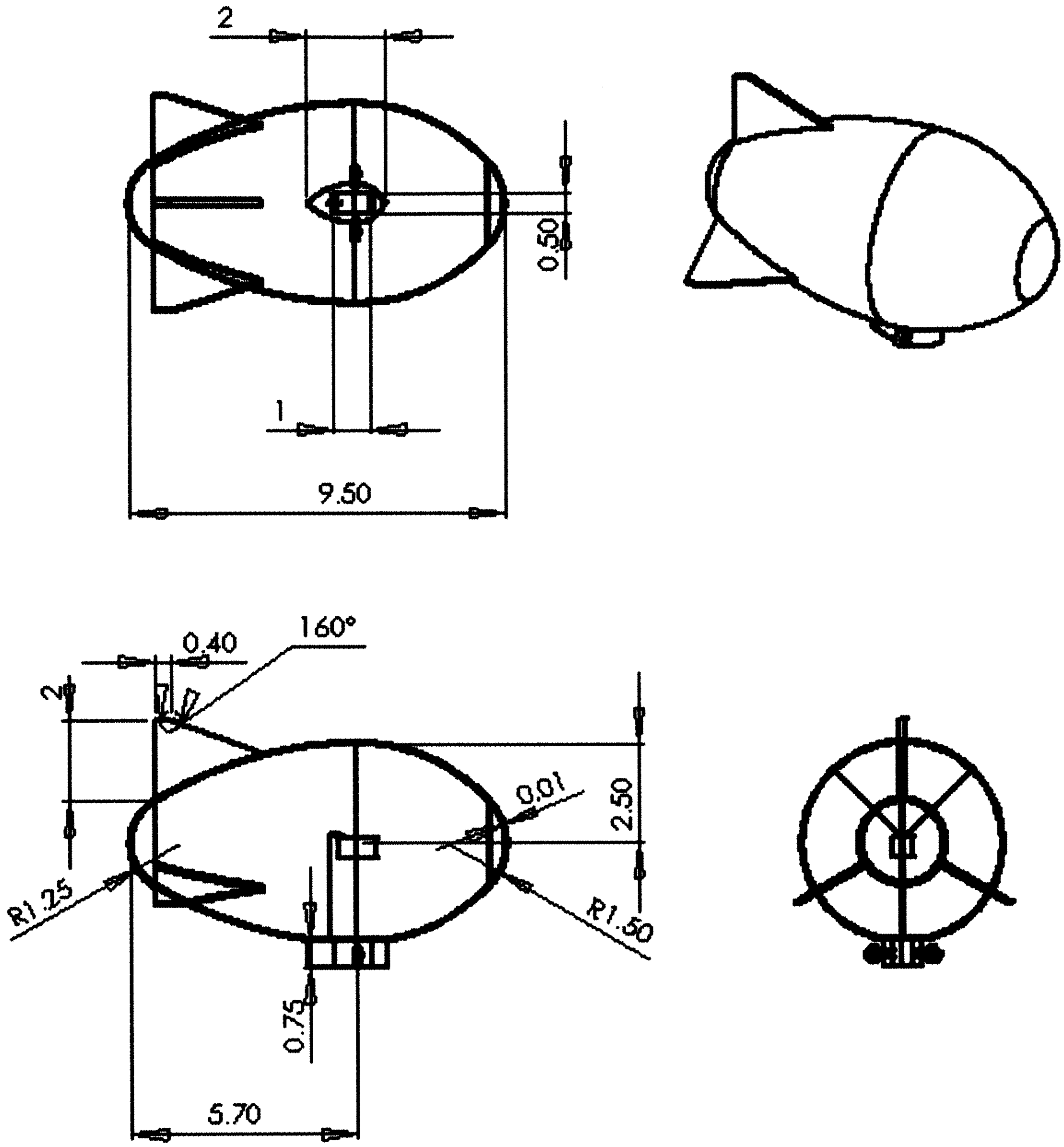

Figure 3-12: Drawing of a Conceived Heated-Air Airship

3.7 Other Heat Transfer Mechanisms

The heat transfer discussed in preceding chapters considered only convection and conduction. It should be noted that Dorrington [9] discussed the possibility of heat loss due to evaporating methane raindrops. After a methane rainstorm, an airship at a lower altitude could collect the raindrops on its surface. However, this heat loss was assumed to be small since methane rain may not be very frequent, and the outer temperature was determined to be less than 1 K above Titan's ambient temperature. Another heat transfer mechanism not considered was radiation.

Radiation heat transfer was not considered in the heat transfer analysis because its effects are small compared to convection and conduction. Using the parameters chosen and an assumed RTG external surface temperature of 300 K (due to insulation), the maximum radiation heat transfer was determined to be 54 W. This was the heat transfer from the middle layer to the outer layer. Between the inner layer and the middle layer, the radiation heat transfer was estimated to be less than 34 W. Furthermore, from the RTG surface to the inner layer, the radiation heat transfer was estimated to be less than 30 W. The equation used to estimate the radiation heat transfer was [5]:

$$Q_{rad} = \frac{A_i \sigma \left(T_i^4 - T_o^4\right)}{\frac{1}{\varepsilon} + \frac{1-\varepsilon}{\varepsilon}\left(\frac{A_i}{A_o}\right)} \tag{3.26}$$

where A_i was the surface area of the inner surface, A_o was the surface area of the outer surface, σ was the Stefan-Boltzmann constant ($5.67*10^{-8}$ W/m^2K^4), and ε was the emissivity taken as 0.03 for all surfaces. Figure 3-13 gives the values used to determine each radiation heat transfer between the RTG and the inner surface of the inner layer, between the inner layer and middle layer, and between the middle layer to the outer layer. The external radiation heat transfer was ignored due to the small temperature difference between the outer layer and Titan. The 54 W radiation heat transfer between layers is significantly smaller than the 1700 W heat transfer due to convection, and therefore was ignored. By ignoring radiation heat transfer, the combined heat transfer evaluation was simplified without losing much accuracy.

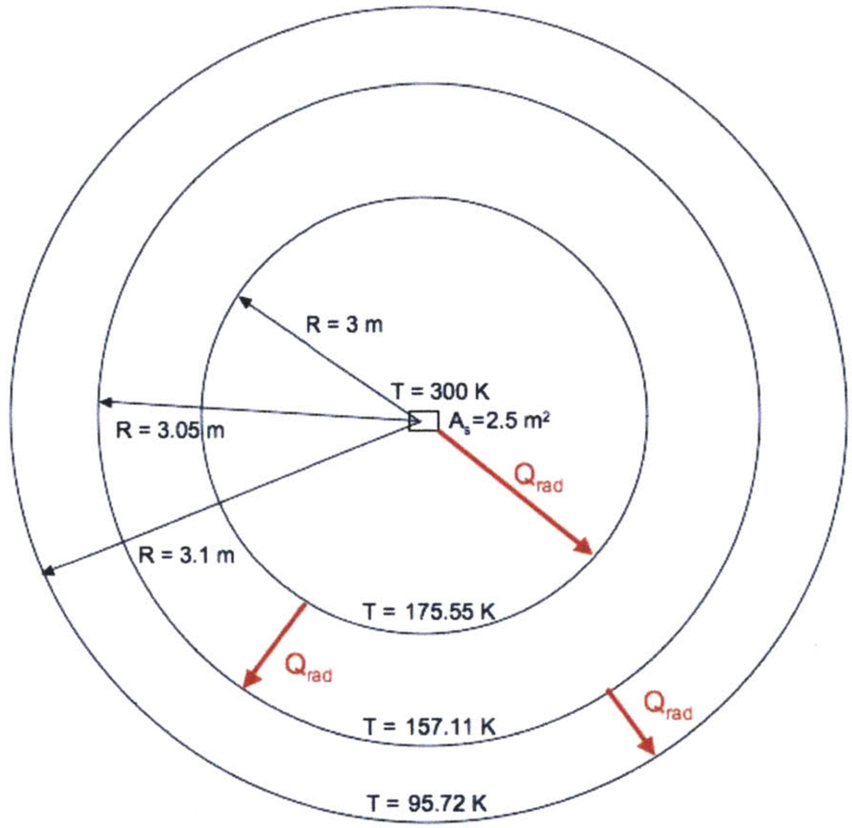

Figure 3-13: Radiation Heat Transfer Diagram with Included Parameters

3.8 Comparison

The NASA/ESA TSSM report contained a graph of their balloon-sizing curve for designing a 2-layer hot air balloon [23]. Their results were compared to the results of a 2-layer heated-air airship primarily to ensure that there were no major calculation errors in either the buoyancy or heat transfer analyses. Figure 3-14 presents the comparison of the sizing results, which were only considered for the change in the diameter [23].

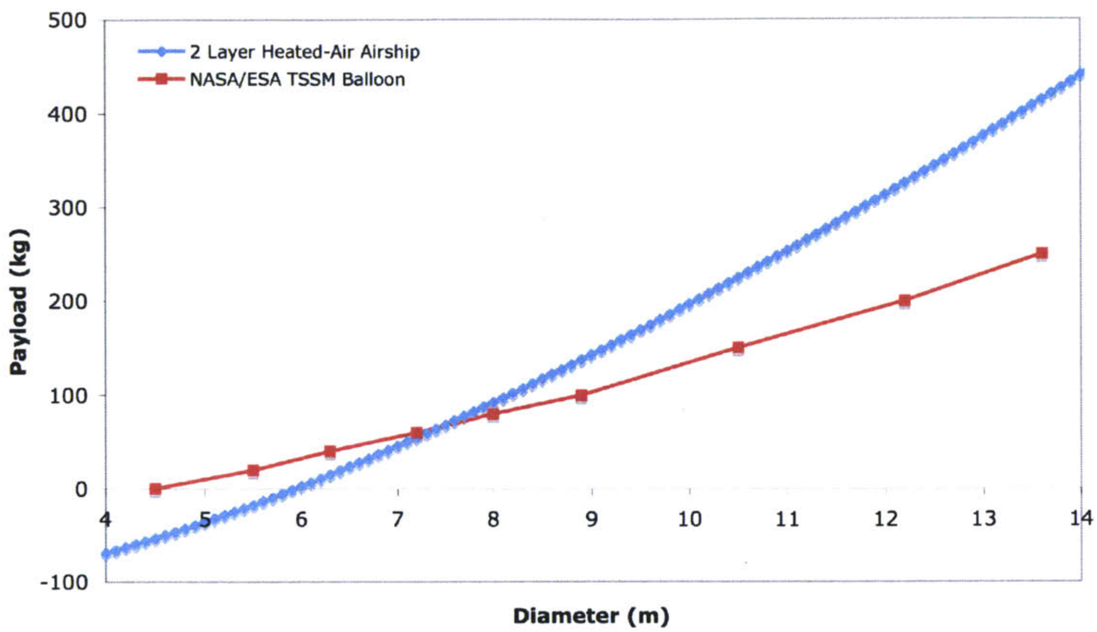

Figure 3-14: Sizing Comparison of a 2 Layer Heated-Air Airship with the NASA/ESA TSSM Report 2 Layer Balloon

The difference between results observed in Figure 3-14 is likely due to inconsistent design parameters, different operating altitudes, and possibly different internal gas temperatures. Table 3.4 shows a comparison between parameters.

Table 3.4: Parameter List

Parameter	**NASA/ESA TSSM Balloon** [43]	**Heated-Air Airship**
Total Mass	131.9 kg	161.9 kg
RTG Mass	45.2 kg	50 kg
Battery System Mass	N/A	50 kg
Payload Mass	~100 kg	~180 kg
Estimated Envelope Mass	39 kg	33 kg
Envelope Density	55 g/m^2	94 g/m^2
Outside Diameter	10.6 m	6.2 m
Number of Layers	2	3
Heat Output	1687 W	1700 W
Assumed Operating Altitude	10 km	Surface

It is remarkable that the results are so similar, and yet the operating altitudes are vastly different. It is possible that the NASA/ESA TSSM report balloon-sizing graph was calculated using Titan's surface conditions, and then assumed that these conditions would be largely unchanged with increasing altitude. Though with increasing altitude,. the temperature drops, which increases payload capacity. Also, the pressure drops, which causes a reduction in payload capacity. Figure 3-9 shows that the effect of the decrease in pressure outweighs that of the decrease in temperature.

3.9 Summary

This chapter discussed the thermal and buoyancy calculations that led to a feasible design for a heated-air airship on Titan. The resulting baseline airship had a diameter of 6 m (outer diameter of 6.2 m), 3 layers, and an insulating gas pocket thickness of 0.05 m between each layer. The overall mass of the airship was about 161.87 kg. The following chapter will introduce the design of a lighter-than-air gas airship that will be compared to the design and performance of the heated-air airship.

Chapter 4

4 Lighter-Than-Air Gas Airship

Many airships on Earth, such as blimps, use lighter-than-air gasses for lift. It is therefore a well-understood concept for earth-based transportation, and this understanding can be adapted to Titan, which has an atmosphere composed primarily of nitrogen much like our own planet.

4.1 Lifting Gas

The lifting gas in a lighter-than-air gas airship has only the requirement that the lifting gas must be less dense than the surrounding outside gas. This is part of the Archimedes principle mentioned in Section 3.1. Two commonly considered gases for airships are hydrogen and helium, because these two gases have very low densities. Helium has generally been preferred on Earth since the Hindenburg disaster in 1937. Due to the oxygen in our atmosphere, the hydrogen lifting gas can ignite, causing huge safety concerns. Helium on the other hand is stable, and will not react with gases in the ambient environment. However, Titan does not have oxygen in its atmosphere. This means that both hydrogen and helium are stable and therefore safe to use on Titan. Both gases could be used as a possible buoyancy gas, but hydrogen has been selected as the lighter-than-air gas to be compared with heated-air in this thesis. This was due to the increased performance of hydrogen over helium.

In addition to hydrogen and helium, methane is also lighter than the nitrogen atmosphere of Titan. This was determined by comparing the specific gas constant of the two gases. The density of a gas on Titan, calculated from Equation 3.4, decreases as the specific gas constant, R_s, increases. Table 4.1 provides the specific gas constants and densities for the gases used for lift, in addition to the atmospheric nitrogen. The densities were computed by using the surface temperature and atmospheric pressure (95 K and 1.6 atm) along with the specific gas constant from Table 4.1.

Table 4.1: Specific Gas Constant Values and Density for Constituents of Titan's Atmosphere and Lifting Gases at Titan Surface Conditions

Gas	**Specific Gas Constant (J/kgK)**	**Density (kg/m^3)**
N_2	297	5.75
CH_4	518.3	3.29
He	2077	0.82
H_2	4124	0.41

4.2 Buoyancy Calculations for Gases with Different Densities

The principle behind the implementation of lighter-than-air gas is the same as that of the heated-air. The only difference is in the manner in which the change in density (from Equation 3.3) is achieved. In the heated-air airship, the density of the lifting gas is lowered by providing heat, whereas the lifting gas for a lighter-than-air gas airship has a lower density due to the use of different gases. A modified version of the buoyancy code, mentioned for the heated-air airship, was used to size an airship considering different lifting gases. The code can be found in Appendix B. Considering hydrogen performs better than helium, a hydrogen filled airship was used to compare with the heated-air airship. An additional mass of about 20 kg was included to offset an estimated 0.112 kg/day leak rate determined from Duffner *et al.* [10]. The extra mass was assumed to be stored in the airship envelope by pressuring the hydrogen. This requires a pressure of about 3.5 atm. The volume is about 41.4 m^3 (radius of about 2.15 m).

4.3 Refillable Heated Methane Gas Airship

Methane gas is a lighter-than-air gas, but it must be heated to ensure that the methane gas inside the balloon does not condense into the liquid phase and lose buoyancy. The critical point of methane is at about 190.4 K and 4.6 MPa. The triple point is about 90.68 K and 11.7 kPa. Because it was assumed that the methane pressure was equal to the atmospheric pressure, the phase change temperature could be determined by using the Clausius-Clapeyron equation [4]:

$$\frac{d\ln(P)}{dT} = \frac{\Delta H}{RT^2} \tag{4.1}$$

where ΔH is the heat of vaporization, assumed to be 510 kJ/kg for methane. By integrating Equation 4.1, a relationship equating temperature and pressure for the boundary layer can be determined:

$$\int_{P_{BC}}^{P} d\ln(P) = \int_{T_{BC}}^{T} \frac{\Delta H}{RT^2} dT \tag{4.2}$$

$$\ln\left(\frac{P}{P_{BC}}\right) = \frac{\Delta H}{RT_{BC}} - \frac{\Delta H}{RT} \tag{4.3}$$

where T_{BC} is the boundary temperature and P_{BC} is the corresponding pressure. There are two pairs of boundary temperatures and pressures, which are the triple point and the critical point. If the critical point is used with the pressure of Titan, then the phase change temperature is at 115.58 K, and 119.67 K from using the triple point. To ensure that the methane lifting gas remains in the gas phase, the higher temperature was used. Then an extra 30% was taken from the difference between that temperature and the critical temperature. This 30% helps ensure that any condensation of methane is minimized. The 30% increased temperature was determined to be 141 K, which then became the desired minimum wall temperature of a methane gas lifting airship. A quick check with a one-walled airship showed that 141 K could not be maintained. This indicated that insulating layers would be needed, but since each layer would get colder they would need to be filled with atmospheric gas just like the heated-air airship. The heated-air airship iteration program was used by modifying the required inner wall temperature to be 141 K or greater, and by reworking the buoyancy program to take into consideration of heated methane as the lifting gas. The chosen parameters were determined as follows: a diameter of 5.2 m (5.48 m outer diameter), 3 layers, and an insulating gas pocket thickness of 0.07 m between each layer. The deadweight of the system was determined to be 262.18 kg with a lifting mass of 350.72 kg (about 88 kg of excess payload). The deadweight mass also included excess methane storage to supply methane to make up for loses due to leaks. The Duffner *et al.* [10] study assumed hydrogen leak rate of 0.112 kg/day was converted to methane leak rate by conserving the molar mass lost. Swain *et al.* [41] determined that hydrogen has a molar flow diffusion rate 3.15 times that of methane. This equated to a leak rate of 0.284 kg/day for methane. Because the methane leak rate has yet to be experimentally measured using a cryogenic envelope material at Titan conditions, the converted rate was used as an approximation. To ensure a successful mission even if no additional methane was collected, a 380-day supply was included or about 0.24 m^3 of liquid methane. Additionally, an extra refill tank of about 0.13 m^3 was included in case the collected methane proves to actually be ethane or any other unusable buoyancy gas (ethane is denser than the nitrogen atmosphere). The refill tank's contents could then be checked before combining with the methane tank. Alternatively, if the contents proved to be ethane, it could be dumped without wasting the reserve of methane.

4.4 Comparison of Airship Types

There are several criteria that have been used to compare an airship using hydrogen gas, heated methane, or heated-air for lifting. The criteria considered are the component complexity, deployment, and the estimated life of each system. Figure 4-1 shows the relative sizes of the airship types. The internal volumes are conserved even though the volumes of the heated-air and heated methane would be affected by changing of the shape from a sphere to an egg. It was assumed for simplicity that changes in shape had a negligible effect on heat transfer.

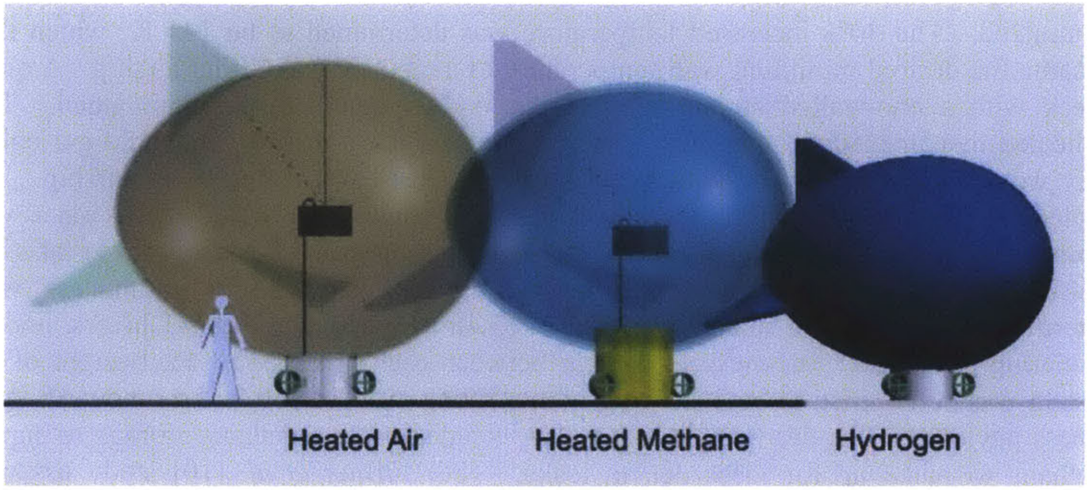

Figure 4-1: Scaled Representation of Airship Types Conserving the Internal Volume

4.4.1 Design/Component Complexity

Each airship type operates differently, and therefore requires slightly different components and/or different designs. One issue is the RTG. For a lighter-than-air gas airship (or hydrogen airship), the RTG can be packaged within the gondola, while the heated gas alternative would benefit by having the RTG elevated. Though, it is unclear where the optimum location would be. Another issue is the added layers for insulation. Building one airship is greatly simplified over building several airships one inside the other. Another issue is how the airship will be pressurized. The hydrogen airship can use a pressured tank of hydrogen to inflate the airship once, and then separate from the tank. However, for the heated-air and methane airships, a pressurizing fan will be needed to ensure the fins are properly supported. The final issue considered applies only to the methane airship. This issue is the need to find, store, and refill leaked methane gas. This adds both weight and additional systems such as pumps.

4.4.2 Deployment

In order to offset hydrogen leakage, the hydrogen airship was pressured with hydrogen gas. It could inflate while descending in the atmosphere to prevent the need for carrying a hydrogen storage tank. The hydrogen tank could be detached after inflating the airship. Fisher *et al.* [13] discusses how this can be done during descent. The heated-air and methane airships could be inflated the same way except with their respective gas instead of hydrogen. Additional time would be required to heat the gas for buoyancy to occur. It is conceivable that the heated-air airship could be filled like a parachute by funneling in the atmosphere. However, an analysis study would need to be conducted to prove that this method would not overstress the airship's envelope material.

4.4.3 Life of system

An important consideration when comparing the different types of airships is how long each could potentially last on Titan. One possible failure mode would be due to the decay of the RTG. The Pu^{238} core has a half-life of about 87.7 years. The relation between the number of years and the decrease in the RTG power is the following:

$$Q_{decrease} = Q_{RTG}\left(1 - 0.5^{\frac{x}{87.7}}\right) \tag{4.4}$$

where $Q_{decrease}$ is the amount of thermal power decrease, Q_{RTG} is the starting thermal power, and x is the number of years of decay. The minimum thermal power to stay buoyant was determined by modifying the thermal analysis code. First the minimum internal temperature can be determined by rearranging Equation 3.6 to solve for temperature (T). This temperature could then be used in a slightly modified thermal analysis code to use the internal temperature and determine the heat transfer Q. The heat transfer Q would need to be supplied by the RTG, so ($Q_{RTG} - Q$) becomes the $Q_{decrease}$ in Equation 4.4. Solving for x gives the number of years that an airship can remain buoyant. The heated-air airship could then last for about 154 years before it would lose all buoyancy, and the methane airship could last up to 131 years. It should be noted that after 131 years of decay for the methane airship, the predicted inner wall temperature would be at the vaporization temperature for methane. This means that the airship would fail due to condensation of the internal gas. The relatively long operational life of the RTG indicates that another failure mode would be more likely to occur before the end of the RTG life.

Another failure mode possibility is envelope leakage. If the methane airship proved unable to collect an adequate amount of methane and had the assumed leak rate of 0.284 kg/day, the designed supply would only last for 380 days. Similarly, with the assumed leakage rate of 0.112 kg/day and no refueling mechanism, the hydrogen airship would fail in 180 days. However, hydrogen could be supplied from the atmospheric methane as discussed in Hall *et al.* [18]. Hydrogen could potentially be replaced with as little as 20 W. Using Equation 4.4 and a starting power of 100 W would mean that after 203 years, all power would be dedicated to replacing hydrogen. Though, considering the extra loss due to the deterioration of the thermocouples to transfer thermal power to electrical power, the life of the system would be a little under 100 years. This is due to a combined deterioration of about 1.6% a year [43]. Yet, the leakage rate increases with each pinhole gap in the envelope material. It is expected that several pinhole gaps will be created during the deployment of the airship (as the envelope material whips around in the air before being fully inflated). This is bad news for the hydrogen and methane airships, but is minimized for the heated-air airship (so long as any holes do not have a large effect on the heat transfer) [18].

4.4.4 Summary Based on Current Data

There is a great amount of complexity associated with the methane airship, and no guaranty of finding an adequate amount of methane to keep it going without some downtime (assuming methane is extracted from the air).

The hydrogen airship is the simplest option considered in this thesis, but it has a short life of around 180 days in flight (or potentially 100 years with hydrogen renewal and added complexity). However, even after lift is no longer achievable, additional data could still be collected since power would likely remain for many years, and the sensors would likely continue to work. Though, this would only allow data to be collected from a single location, which could potentially limit the overall value of the mission, unless prolonged localized weather study was of practical interest.

The heated-air airship appears to provide the best characteristics of both the methane and the hydrogen airships. The implementation would be simpler and less dependant than methane, and possibly have a longer lifetime than both. Additionally, pinhole gaps would not affect a heated-air airship nearly as severely as they would on lighter-than-air gas or methane airships. Additionally, with extra layers, if one layer were to fail, it would likely not be a catastrophic failure. Furthermore, Friedlander [15] claims that below 50 km altitude, heated-air vehicles would have better performance over hydrogen vehicles.

4.5 Summary

This chapter introduced a lighter-than-air gas airship to be compared with the heated-air airship discussed in Chapter 3. The designed concept of the most feasible lighter-than-air gas airship was determined to be a hydrogen-filled, 4.3 m diameter, 200 kg airship. The heated-air airship was determined to be larger but lighter than the lighter-than-air gas airship, and the heated-air airship had a longer estimated flight time, even considering adding additional complexity to the lighter-than-air airship. The next chapter will discuss in-situ resource utilization possibilities that could potentially reduce costs for future exploratory missions on Titan.

Chapter 5

5 In-Situ Resource Utilization Possibilities

In-situ resource utilization involves making use of local resources that are present on other astronomical bodies such as Titan. This allows for huge savings in the cost of sending these same resources from Earth. One such resource that has already been mentioned in the preceding sections is Titan's atmosphere in the case of the heated-air airship. Though, there are other possible useful resources that Titan has to offer. At the time of this thesis, it would be impractical to make use of these local resources. However, there is potential that in the future ISRU may be a motive for novel missions or may enable further exploration.

5.1 Methane Collection

Methane is abundant on Titan. Methane is present in the atmosphere, and there is a resupply of methane (possibly from surface lakes or underground reservoirs) [25]. This leads to several possible methods of obtaining methane. The first is by extracting methane out of the atmosphere. Cooling and condensing methane from the air is one way this can be done. The analogy to this would be water condensation on Earth such as on a cold beverage sitting on a table. On Titan, this could be done by creating some form of a cold surface that drains into a storage tank. However, the process could be simplified by letting Titan's own weather condense methane and rain, and merely catch the methane rain. The problem with catching rain is the reliance on rain as well as the catch basin being located at the rain site. Because this makes collecting rain uncertain, it would be better to extract methane from previous rains that have collected in natural basins (or methane lakes), which is the second possible collection method. Survey missions could determine the locations of possible methane lakes. Though, the lakes on Titan could also contain ethane. It would then be important to find several lakes in the hope that at least one of them would contain methane. Another method would be to extract methane from ice. It is possible that liquid methane has seeped into the icy surface or has mixed with liquids after an event such as a meteorite collision, and refroze with the liquid water. This method is probably the riskiest, as well as the most challenging. However, the desired uses for the methane would likely determine the best method of collection. For instance, the methane airship mentioned in preceding sections would benefit by collecting methane from the air. That way the airship's path of exploration could be directed by interesting sites instead of by possible methane sources.

5.2 Water Ice

A large portion of Titan is believed to be composed of frozen water with a possible subterranean ocean composed of water and ammonia [43]. With heat and electricity, water can be melted and electrolyzed into hydrogen and oxygen. Both of these gases could be useful, as follows. They could be combusted together to have a portable energy system (assuming the exhaust water doesn't freeze and block the exhaust). Alternatively, the oxygen could be used with methane as discussed in Section 2.1.2. The left over hydrogen could then be used to fill buoyant vehicles. Another use could be for rocket fuel. This could either be implemented with both the oxygen and hydrogen like rockets currently used on Earth, or oxygen and methane for a methane rocket. The primary difficulty would be to transport a rocket to Titan and assemble it once there just so that it could be fueled on Titan.

5.3 Prospecting

To find other valuable resources, prospecting will be needed. The first step would be to map the surface of Titan to understand the various geological features and the availability of surface accessible minerals and metals. After that, ground penetrating radar and other similar types of instruments could be used to determine what is beneath the surface as well as the accessibility of those resources. Currently, nothing is known about any reachable and valuable resources. Though, autonomous or semi-autonomous machines would be the best instruments to extract any valuable resources. This is due to the surface conditions present on Titan. It would be very difficult for humans to function at Titan's 95 K surface temperature. However, Pollack *et al.* [35] mentions that it could be possible to terraform Titan in the future in order to make the surface conditions less severe for humans. This proposal however, is not likely to occur any time in the next few centuries, and is well beyond the scope of this study.

5.4 Summary

This chapter discussed potential cost-saving in-situ resource utilization possibilities, not including the Titan atmosphere that could be utilized in the heated-air airship concept. Both methane and water could be harvested, but so far a need has not been expressed that would necessitate the corresponding research expense. The next chapter presents the thesis conclusion along with future work.

Chapter 6

6 Conclusion

A heated-air airship and a heated methane airship have been designed and compared to a lighter-than-air gas (hydrogen) airship. Overall, the heated methane airship has been determined to be an inferior choice due to its added complexity, heavier weight, and higher risk, compared to the other types of airships presented in this thesis. While the hydrogen airship is an inherently simpler design for several missions, the thermal airship is superior for others. Table 6.1 presents the results of the major design parameters for both the heated-air airship and the hydrogen airship.

Table 6.1: Major Baseline Design Parameter Results

Parameter	Heated-Air 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

The hydrogen airship has a heavier mass (~200 kg) compared to the heated-air airship (~162 kg) in the deployed state. Additionally, the heated-air airship has a longer possible flight life of up to 154 years compared to 180 days for the hydrogen airship. At the expense of complexity, the hydrogen airship could renew the hydrogen supply and potentially last up to 100 years assuming no increase in the hydrogen leak rate. For a desired long-term mission, the heated-air airship appears better suited. However, for a desired mission under 180 days, the less complex hydrogen airship would likely be a better option.

6.1 Future Work

Future Titan missions will likely consist of lake landers, airships or balloons, and orbiters. The Cassini-Huygens mission provided a massive amount of information about Titan, but even more information should be collected to develop an effective follow-up mission. The thermal analysis discussed in this thesis was developed over the years for Earth use. It is unclear whether or not the Earth derived equations will hold true for Titan conditions. It will be necessary to carry out tests at Titan temperature and pressure with a gas mixture similar to Titan's atmosphere. A set of simpler tests could be carried out in 100% nitrogen, which is a close approximation of Titan's atmosphere. These simpler tests could include Titan temperature and then Titan pressure. These tests could be simpler to perform compared to testing at full Titan conditions, and would provide an indication of the validity of the Earth derived heat transfer equations for use in Titan conditions.

Another area of future work consists of the automation challenges. Algorithms that manage path planning, navigation, and positioning will require development. In particular, the algorithms must demonstrate that they will satisfactorily perform after the long journey to Titan. This can likely be evaluated on Earth using a full-scale test airship. Parallel to this, it will also be imperative to thoroughly test that the hardware will be resilient in Titan's challenging environment.

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Appendix A: Heated-Air Airship Matlab Code

Main Iteration Code:

```
%iterates D number of layers and thickness of air pockets

clear all

dD =.1; %resolution of temperature iteration
dtstart = .01; %resolution of thickness
dN = 1; %resolution of layers

Dmax = 20;
Nmax = 3;
tmax = .05;


Dstart = 1;
Thick = 3*10^-5; %m thickness of cryogenic material
Thick2 = .05; %m thickness of air gap between layers
greater = Thick2; %allows dt to change it's order of magnitude
N = 3; %number of layers
w=5; %m/s wind speed relative to balloon


Q=1700; %W
m=28.9+100; %kg  RTG/battery, instrument
P=162.12*10^3; %Pa
g=1.352; %m/s^2
R=.297*10^3; %J/kgK
Tt=95; %K
p = P/(R*Tt); %kg/m^3 calculated from the ideal gas law
k=.4; %W/mK from max of polyester
kmat = k;
Pr=0.796; %Prandlt number
Mat = 94; %g/m^2


tic

tot=0;
numb=1;
while(N<=Nmax)
   Z(numb)=N;
   t=Thick2;
   dt=dtstart;
```

```
counter=1;
while(t<=tmax)
   Y(counter)=t;
   D=Dstart;
   i=1;
   while(D<=Dmax)
      X(i)=D;

      %iterates the temperatures at each layer
      %consider both convection and conduction on the outside
      [Twarray(i), AllTemps, Do(i), As(i), Radii, xvalue] = heat_CtD_outside(D, Q, p,
g, Tt, k, Thick, t, Pr, w, N, P, R);



      deadweight(i) = Mat*As(i)/1000 + m; %total mass of the balloon


      %Uses the calculated Tw for the average internal temp
      Teff = Twarray(i);

      %use gradient weighted average
      %C1 = 111.97;
      %C2 = 1.127;
      %Teff = (C1/(C1+C2)*Twarray(i) + C2/(C1+C2)*AllTemps(1));

      [masslift(i)] = buoyancy(D, p, P, R, Teff, AllTemps, Radii, N);

      extra = masslift(i)-deadweight(i);
      masspayload(i) = masslift(i)-deadweight(i);


      %if(extra>=0) %makes sure the balloon can lift itself
         tot=tot+1;

         M(tot, 1) = X(i); %diameter
         M(tot, 2) = Y(counter); %thickness
         M(tot, 3) = Z(numb); %number of layers
         M(tot, 4) = Teff;  %center temperature
         M(tot, 5) = masslift(i);
         M(tot, 6) = deadweight(i); %envelope, instruments, and RTG weight
         M(tot, 7) = masslift(i)-deadweight(i);%-28.9; %payload weight

      %end
```

```
      D=D+dD;
      i=i+1;
    end
    if(t>=greater) %adjusts the step size for the thickness for quicker calculations
      dt=t*10;
      greater=greater*10;
    end
    t=t+dt;
    counter=counter+1;
  end
  N=N+dN
  numb=numb+1;
end

toc

M1 = M(:,1);
M2 = M(:,2);
M3 = M(:,3);
M4 = M(:,4);
M5 = M(:,5);
M6 = M(:,6);
M7 = M(:,7);
```

Thermal Analysis:

```
function [Tw, T, Do, As, r, uratio]=heat_CtD_outside(D, Q, p, g, Tt, kmat, Thick,
Thick2, Pr, w, N, P, R)
%function to go through N layers of balloon and return the inside temp
%the outer diameter, the surface area of the balloon material (As), and the
%array of radii. same as heatNlayers but convection and conduction on the
%outside always

tol = 10^-6;

%guesses of temperatures
Tw = 200; %temp inside the balloon

j=2*N;
%temperature at each node (twice the number of layers
while (j>0)
  T(j)=200-j;
  j=j-1;
end
```

```
%first run through

Tm(1) = (Tw+T(1))/2;
B(1) = 1/Tm(1);
j=2;
iter = 2;
while(iter<=N)
   Tm(iter) = (T(j)+T(j+1))/2;
   B(iter) = 1/Tm(iter);
   j=j+2;
   iter=iter+1;
end

j=1;
while(j<=2*N)
   k(j) = 10^-3*(1.078+.08365*T(j));
   j=j+1;
end

j=1;
while(j<=2*N)
   u(j) = 10^-6*(1.5125+.0558*T(j));
   j=j+1;
end
uatm = 10^-6*(1.5125+.0558*Tt);

r(1)=D/2;
r(2)=D/2+Thick;
j=3;
while(j<=2*N)
   r(j)=r(j-2)+Thick+Thick2;
   if((j+1)<=2*N)
      r(j+1)=r(j-1)+Thick+Thick2;
   end
   j=j+2;
end

Ra=zeros(1,N);
Ra(1) = (2*r(1))^3*g*p^2*B(1)*(Tw-T(1))*Pr/(u(1)^2);
j=2;
iter = 2;
while(iter<=N)
   Ra(iter) = ((r(iter+1)-r(iter))^3*g*p^2*B(iter)*(T(j)-T(j+1))*Pr/(((u(j)+u(j+1))/2)^2));
   j=j+2;
   iter=iter+1;
```

```
end

Re = w*2*r(2*N)/(u(2*N)/p);


j=1;
counter = 1;
change = 1;
while(j<2*N)
  h(j) = k(j)/(2*r(j))*(2+.589*Ra(counter)^(1/4)/(1+(.469/Pr)^(9/16))^(4/9));
  if(change)
    counter=counter+1;
    change = 0;
  else
    change = 1;
  end
  j=j+1;
end
h(j) = k(j)/(2*r(j))*(2+(.4*Re^(1/2)+.06*Re^(2/3))*Pr^.4*(uatm/u(j))^(1/4));

Nuout = h(2*N)*2*r(2*N)/k(2*N);


%Determines whether to consider natural convection, forced convection, or
%both
Gr = (2*r(2*N))^3*g*p^2*B(N)*(T(2*N)-Tt)/uatm^2;
Raconv = Gr*Pr;
Nuconv = 2+.589*Raconv^(1/4)/(1+(.469/Pr)^(9/16))^(4/9);
hconv = Nuconv*k(2*N)/r(2*N);
if((Gr/Re^2)<.1)  %Natural convection is ignored
  Rthout = 1/(h(2*N)*4*pi*r(2*N)^2);
elseif((Gr/Re^2)<10); %Both Natural and Forced are considered
  %to sum up Nu's need to use equation from p532 from my book
  %n is either 3 or 4
  Nucom=(Nuconv^3+Nuout^3)^(1/3);
  htemp = Nucom*k(2*N)/r(2*N);
  Rthout = 1/(htemp*4*pi*r(2*N)^2);
else %Forced convection is ignored
  Rthout = 1/(hconv*4*pi*r(2*N)^2);
end



%internal natural convection and external forced convection
Rth = 1/(h(1)*4*pi*r(1)^2) + Rthout;
j=1;
```

```
iter=2;
while(j<=N)
   %sums up all the wall conduction resistance
   Rth = Rth + (r(iter)-r(iter-1))/(4*pi*kmat*r(iter-1)*r(iter));
   j=j+1;
   iter=iter+2;
end

j=1;
iter = 2;
array = 1;
while(j<N)
   %sums up all the air pockets
   Tav = (T(iter)+T(iter+1))/2;
   kair = 10^-3*(1.078+.08365*Tav);
   if(Ra(j+1) <= 1708)
      %acts as conduction
      Rth=Rth + (r(iter+1)-r(iter))/(4*pi*kair*r(iter)*r(iter+1));
      conduction(array) = 1;
      array = array+1;
   else
      %acts as convection
      Fsphere = (r(iter+1)-r(iter))/((2*r(iter)*2*r(iter+1))^4*((2*r(iter))^(-
7/5)+(2*r(iter+1))^(-7/5))^5);
      keff = kair*.74*(Pr/(.861+Pr))^(1/4)*(Fsphere*Ra(j+1))^(1/4);
      Rth = Rth + (r(iter+1)-r(iter))/(keff*pi*4*r(iter)*r(iter+1));
      conduction(array) = 0;
      array = array + 1;
   end
   iter=iter+2;
   j=j+1;
end
Twnew = Tt+Q*(Rth);


count = 1;
while(count<=2*N)
   Rth = Rthout;
   j=2*N-1;
   while(j>=count)
      %conduction loop
      Rth = Rth + (r(j+1)-r(j))/(4*pi*kmat*r(j)*r(j+1));
      j=j-2;
   end
   j=1;
   iter = (2*N)-2;
```

```
  while(j<=((2*N-count)/2))
    %sums up all the air pockets
    Tav = (T(iter)+T(iter+1))/2;
    kair = 10^-3*(1.078+.08365*Tav);
    if(Ra((iter/2)+1) <= 1708)
      %acts as conduction
      Rth = Rth + (r(iter+1)-r(iter))/(4*pi*kair*r(iter)*r(iter+1));
    else
      %acts as convection
      Fsphere = (r(iter+1)-r(iter))/((2*r(iter)*2*r(iter+1))^4*((2*r(iter))^(-
7/5)+(2*r(iter+1))^(-7/5))^5);
      keff = kair*.74*(Pr/(.861+Pr))^(1/4)*(Fsphere*Ra((iter/2)+1))^(1/4);
      Rth = Rth + (r(iter+1)-r(iter))/(keff*pi*4*r(iter)*r(iter+1));
    end
    iter=iter-2;
    j=j+1;
  end
  Tnew(count) = Tt+Q*Rth;
  count=count+1;
end


repeat = 0;
j=1;
while(j<=2*N)
  if(abs(T(j)-Tnew(j))>tol)
    repeat = 1;
  end
  j=j+1;
end


i=1;
while(abs(Tw-Twnew)>tol || repeat)


  %Iterates until all temps match previous or runs too long
  Tw = Twnew;
  T = Tnew;

  p(1) = P/(R*(Tw+T(1))/2);
  j=2;
  iter = 2;
  while(iter<=N)
    p(iter)=P/(R*(T(j)+T(j+1))/2);
    j=j+2;
```

```
    iter = iter+1;
  end
  p(N+1) = P/(R*(T(2*N)+Tt)/2);

  Tm(1) = (Tw+T(1))/2;
  B(1) = 1/Tm(1);
  j=2;
  iter = 2;
  while(iter<=N)
    Tm(iter) = (T(j)+T(j+1))/2;
    B(iter) = 1/Tm(iter);
    j=j+2;
    iter=iter+1;
  end

  j=1;
  while(j<=2*N)
    k(j) = 10^-3*(1.078+.08365*T(j));
    j=j+1;
  end

  j=1;
  while(j<=2*N)
    u(j) = 10^-6*(1.5125+.0558*T(j));
    j=j+1;
  end
  uatm = 10^-6*(1.5125+.0558*Tt);

  r(1)=D/2;
  r(2)=D/2+Thick;
  j=3;
  while(j<=2*N)
    r(j)=r(j-2)+Thick+Thick2;
    if((j+1)<=2*N)
      r(j+1)=r(j-1)+Thick+Thick2;
    end
    j=j+2;
  end

  Ra(1) = (2*r(1))^3*g*p(1)^2*B(1)*(Tw-T(1))*Pr/(u(1)^2);
  j=2;
  iter = 2;
  while(iter<=N)
    Ra(iter) = ((r(iter+1)-r(iter))^3*g*p(iter)^2*B(iter)*(T(j)-
T(j+1))*Pr/(((u(j)+u(j+1))/2)^2));
    j=j+2;
```

```
  iter=iter+1;
end

Re = w*2*r(2*N)/(u(2*N)/p(N+1));


j=1;
counter = 1;
change = 1;
while(j<2*N)
  h(j) = k(j)/(2*r(j))*(2+.589*Ra(counter)^(1/4)/(1+(.469/Pr)^(9/16))^(4/9));
  if(change)
    counter=counter+1;
    change = 0;
  else
    change = 1;
  end
  j=j+1;
end
h(j) = k(j)/(2*r(j))*(2+(.4*Re^(1/2)+.06*Re^(2/3))*Pr^.4*(uatm/u(j))^(1/4));

uratio = uatm/u(j);

Nuout = h(2*N)*2*r(2*N)/k(2*N);


%uses both natural and forced convection.  found on page 531
Gr = (2*r(2*N))^3*g*p(N+1)^2*B(N)*(T(2*N)-Tt)/uatm^2;
Raconv = Gr*Pr;
Nuconv = 2+.589*Raconv^(1/4)/(1+(.469/Pr)^(9/16))^(4/9);
hconv = Nuconv*k(2*N)/r(2*N);

  %to sum up Nu's need to use equation from p532 from my book
  %n is either 3 or 4
  Nucom=(Nuconv^3+Nuout^3)^(1/3);
  htemp = Nucom*k(2*N)/r(2*N);
  Rthout = 1/(htemp*4*pi*r(2*N)^2);
  both = 1;


%internal natural convection and external convection
Rth = 1/(h(1)*4*pi*r(1)^2) + Rthout;
j=1;
iter=2;
while(j<=N)
%sums up all the wall conduction resistance
```

```
  Rth = Rth + (r(iter)-r(iter-1))/(4*pi*kmat*r(iter-1)*r(iter));
  j=j+1;
  iter=iter+2;
  end

  j=1;
  iter = 2;
  array = 1;
  while(j<N)
     %sums up all the air pockets
     Tav = (T(iter)+T(iter+1))/2;
     kair = 10^-3*(1.078+.08365*Tav);
     if(Ra(j+1) <= 1708)
        %acts as conduction
        Rth=Rth + (r(iter+1)-r(iter))/(4*pi*kair*r(iter)*r(iter+1));
        conduction(array) = 1;
        array = array+1;
     else
        %acts as convection
        Fsphere = (r(iter+1)-r(iter))/((2*r(iter)*2*r(iter+1))^4*((2*r(iter))^(-
7/5)+(2*r(iter+1))^(-7/5))^5);
        keff = kair*.74*(Pr/(.861+Pr))^(1/4)*(Fsphere*Ra(j+1))^(1/4);
        Rth = Rth + (r(iter+1)-r(iter))/(keff*pi*4*r(iter)*r(iter+1));
        conduction(array) = 0;
        array = array + 1;
     end
     iter=iter+2;
     j=j+1;
  end
  Twnew = Tt+Q*(Rth);


  count = 1;
  while(count<=2*N)
     Rth = Rthout;
     j=2*N-1;
     while(j>=count)
        %conduction loop
        Rth = Rth + (r(j+1)-r(j))/(4*pi*kmat*r(j)*r(j+1));
        j=j-2;
     end
     j=1;
     iter = (2*N)-2;
     while(j<=((2*N-count)/2))
        %sums up all the air pockets
        Tav = (T(iter)+T(iter+1))/2;
```

```
        kair = 10^-3*(1.078+.08365*Tav);
        if(Ra((iter/2)+1) <= 1708)
          %acts as conduction
          Rth = Rth + (r(iter+1)-r(iter))/(4*pi*kair*r(iter)*r(iter+1));
        else
          %acts as convection
          Fsphere = (r(iter+1)-r(iter))/((2*r(iter)*2*r(iter+1))^4*((2*r(iter))^(-
7/5)+(2*r(iter+1))^(-7/5))^5);
          keff = kair*.74*(Pr/(.861+Pr))^(1/4)*(Fsphere*Ra((iter/2)+1))^(1/4);
          Rth = Rth + (r(iter+1)-r(iter))/(keff*pi*4*r(iter)*r(iter+1));
        end
        iter=iter-2;
        j=j+1;
      end
      Tnew(count) = Tt+Q*Rth;
      count=count+1;
    end

    i=i+1;
    repeat = 0;
    j=1;
    while(j<=2*N)
      if(abs(T(j)-Tnew(j))>tol)
        repeat = 1;
      end
      j=j+1;
    end
end

Tw = Twnew;

As=0;
j=2*N;
while(j>0) %determines the total surface area to use for the weight of the material
    As = As + 4*pi*r(j)^2;
    j=j-2;
end


%calculates the outer diameter
Do = 2*r(2*N);
```

Buoyancy Evaluation:

```
function[mass] = buoyancy(D, p, P, R, Tw, T, r, N)
%returns the calculated liftable mass from the buoyancy equation
%inputs: the Diameter, the density of titan, Pressure of titan, ideal gas
%constant, an array of the temperature at each surface, an array of the
%radii at each surface, and the number of layers


%first calculates the mass lifted from the inner layer
m(1) = D^3*pi/6*(p-P/(R*Tw));

mass = m(1);
 i=2;
 j=2;
 %a loop to calculate the mass lift for each insulating gas pocket
 while(i<=N)
    Tav = (T(j+1)+T(j))/2;
    m(i)=(4/3*pi*(r(j+1)^3-r(j)^3))*(p-P/(R*Tav));
    j=j+2;
    i=i+1;
 end

 mass = 0;
 i=1;
 %sums up all the different layers of gas to get the overall mass lift
 while(i<=N)
    mass = mass+m(i);
    i=i+1;
 end
```

Appendix B: Lighter-Than-Air Gas Airship Matlab Code

```
clear all
%calculates the size of a balloon to lift is weight as well as equipment,
%using a lifting gas only (done by changing the ideal gas constant R)


tol=10^-5;

m=28.9+100+20; %kg RTG/battery, instrument, extra gas
Patm=162.12*10^3; %Pa
Tt=95; %K
Ratm=.297*10^3; %J/kgK
patm = Patm/(Ratm*Tt); %kg/m^3 calculated from the ideal gas law
Mat = 94; %g/m^2

R = 4124; %J/kgK hydrogen value

pgas = Patm/(R*Tt);
mv = m;
r = ((3*mv)/(4*pi*(patm-pgas)))^(1/3);
V = 4/3*pi*r^3;
A = 4*pi*r^2;

mvnew = (m + A/1000*Mat)*1.3;

while(abs(mv-mvnew)>tol)
  mv = mvnew;
  P = Patm + 20*R*Tt/V;
  pgas = P/(R*Tt);
  r = ((3*mv)/(4*pi*(patm-pgas)))^(1/3);
  V = 4/3*pi*r^3;
  A = 4*pi*r^2;

  mvnew = (m + A/1000*Mat)*1.3;
end


r %the radius of the airship

mvnew %the total mass of the airship

P=P*9.86923267 * 10^-6 %the pressure of the airship in atm
```