



**PERFORMANCE CAPABILITY OF A
DAMAGED LIGHTER-THAN-AIR VEHICLE
OPERATING IN THE NEAR SPACE REGIME**

THESIS

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AFIT/GSS/ENY/06-M13

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Abstract

This study investigates the ability of a high-altitude airship to maintain lift following the compromise of its lifting gas envelope. Accepted engineering principles are applied to develop a model that provides comparative analyses for airship depressurization alternatives following hull compromise. Specifically, maintaining lifting gas envelope overpressure to provide controllability in wind currents while sacrificing some buoyancy is compared with allowing envelope depressurization to occur with the goal of maintaining greater buoyancy as long as possible. The model provides insights to alternatives for recovering a damaged vehicle and its payload. In particular, the analysis demonstrates that maintaining the ability to navigate while forfeiting buoyancy can provide additional down-range maneuver capability. In some cases preserving the airship's hull overpressure for some period of time following compromise, vice allowing a slow depressurization to atmospheric equilibrium, extends the distance a damaged airship can sustain controlled navigation as much as eighty percent. However, the airship will forfeit nearly twenty percent of the altitude it would otherwise preserve by not forcing a constant hull overpressure.

AFIT/GSS/ENY/06-M13

To my dad

Acknowledgments

I would like to thank my God for the opportunity to accomplish this academic program as well as for the many blessings He placed in my life. I'm particularly thankful to and for my awesome wife and terrific kids who each seeks to encourage me everyday. Their confidence gives me the courage to keep trying. Thanks also to my mom and dad who instilled in me the values of hard work and life-long learning.

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It has been said, "Everyman can be bigger than he is." I add to that: "...but not without support from others." So many people have challenged and encouraged me through this academic experience and have helped me grow and for that I say, "Thanks."

Charles W. Vogt, Jr.

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List of Symbols

B	constant
C	constant
C_D	drag coefficient
D	constant
F_B	buoyant force
F_D	drag force
g	gravity
H	atmospheric height
H	atmospheric pressure scale height
H^*	atmospheric density scale height
h	altitude
L_n	buoyant lift
m	mass
m_{gas}	lifting gas mass
m_{He}	helium mass
m_{pl}	payload mass
m_{st}	airship structural mass
m_{Total}	sum of payload and structural mass
p	pressure
p_{atm}	atmospheric pressure
p_{env}	airship envelope (or hull) pressure
p_o	atmospheric pressure at sea level
R	universal gas constant
T	temperature
T_{avg}	average atmospheric temperature
t	time
u	airship descent speed
v	speed of lifting gas leaking from hull
v_{max}	airship maximum cross range speed
w	elemental atomic weight
w_{air}	atomic weight air
w_{gas}	atomic weight lifting gas
w_{He}	atomic weight helium
z	atmospheric height
Δp	airship hull overpressure
ρ	density
ρ_{air}	atmospheric density
ρ_{airo}	atmospheric density sea level
ρ_{gas}	density lifting gas
ρ_{He}	density helium
ρ_{Heo}	density helium sea level
σp	density ratio

PERFORMANCE CAPABILITY OF A DAMAGED LIGHTER-THAN-AIR VEHICLE

OPERATING IN THE NEAR SPACE REGIME

1. Introduction

1.1 Motivation

Seamless war-fighting integration of United States military space systems is more critical today than any time prior. Theater commanders demand space asset support for critical remote sensing, communication, and precision navigation and timing to enhance their combat operations. But the commander's pull for support places severe technological and financial burdens on the US Air Force to provide that need. The Air Force Space Command Strategic Master Plan for FY 06 and beyond projects initial spending levels at nearly \$14 billion to support currently desired military programs. This spend level grows over the next 25 years to nearly \$23 billion. That level of spending is exhausting to the Air Force budget and demands that advancing technology keep pace in order to prevent cost growth. In the interim, the theater commander still waits for support.

Space Command is searching for a near term, low cost and low barrier solution to better providing support to the theater. Recently, the concept of lighter-than-air vehicles operating at suborbital altitudes in a region termed "near space" has sparked the imagination of space force providers. Near space represents a region of the earth's atmosphere mostly ignored by military planners. It is the region from approximately 65,000 feet to 300,000 feet. In this region the air density is too small to allow easy

exploitation by air-breathing winged aircraft. Simultaneously, the air density is too great to allow sustained orbital operations because of aerodynamic drag effects. Space Command has organized and taken the Air Force lead for developing lighter than air operational concepts in near space to support theater demands for communication and intelligence, surveillance and reconnaissance (ISR). The goal of this research paper is to contribute to the technical body of knowledge regarding vehicle operations in this atmospheric regime.

Advocates endorse the use of lighter-than-air vehicles to carry payloads with sensor suites more typically carried by either unmanned aerial vehicles (UAV) or orbital spacecraft. Numerous projects are currently underway to study concepts of using lighter-than-air vehicles in a theater to meet the ISR and communication needs of the commander. Because the system would be used in a military context, the question of survivability in a hostile environment has surfaced. One question frequently asked is, what impact will rupturing the vehicle's lifting gas envelope have on the system? The question is typically answered with references to a slow diffusion process that implies little concern in understanding the vehicle's ability to remain aloft. As well, anecdotal references are given regarding how difficult it is to destroy a weather balloon. The motivation of this research is to examine the survivability question and provide physical insights to the question about lighter-than-air vehicle survivability when its lifting gas envelope has been ruptured. In the end, this research provides a first-order methodology for understanding lighter-than-air vehicle survivability when an airship's gas envelope has been compromised. Insights will be gained about an airship's descent rates and range

capabilities through comparative analysis of possible post-damage survivability course of action options.

1.2 Background

Traditionally, the warfighter has come to expect a segment of their space support to be provided from an orbiting spacecraft located in some type of orbit about the earth. These satellites have provided electro-optical and infrared imaging from low earth orbits, timing and navigation from medium earth orbits, and communication from geostationary orbit. While these examples are hardly exhaustive of military missions and orbits, they represent the traditional way military planners have looked at space operations.

The Department of Defense (DoD) often finds itself in competition with other national agencies for support from space-based systems. A theater commander may desire imagery support from a national overhead electro-optical system to target a critical adversary asset. However, he doesn't own the imaging spacecraft and has to petition a national agency to provide service and then wait in line behind other national security priorities for photos.

Joint Warfighting Space (JWS) is a DoD program with the goal of providing the theater commander flexibility and agility in space support. JWS in its fullest sense is an operating concept. It's a rapid reaction networked space constellation, dedicated to the joint force commander and integrated with National Security Space systems. [5] The space system is projected to be a tactical system designed to operationalize space for the benefit of the warfighter. It will provide rapid access to space, placing systems on orbit in

days and weeks instead of months. The systems will be small spacecraft that are designed to operate for months and be interoperable with current and future theater assets.

The first funded step of JWS is two demonstrator satellites—TACSAT I and II (recently designated JWS SAT). TACSAT I, being built by the Naval Research Laboratory, is a cylindrical vehicle about 20 inches high and 40 inches in diameter. It will be outfitted with visible-light and infrared cameras and have its own Secret Internet Protocol Router Network (SIPRNET) address from which users can access data stored onboard the spacecraft. [14] The mission is designed to validate a concept of operations for a tactical imager spacecraft providing support to a theater commander. The demonstration vehicle is scheduled for launch no earlier than January 2006 on board a Falcon I booster.

The Falcon booster will make its debut flight as the first launch system developed to support JWS. In 2004, the Air Force and the Defense Advanced Research Programs Agency (DARPA) under the Operational Responsive Space (ORS) initiative, contracted with SpaceX Corporation to build a low-cost, rapidly-readied booster to support TACSAT. The system will cost less than \$6 million per launch and be processed for launch in only days.

TACSAT I had set a budget goal of placing the system on orbit for \$15 million; including launch costs. An additional \$15 million is set aside for TACSAT II. However, two follow-on demonstrations are waiting to be funded. Obvious is that the cost of on-orbit operations, even with significant reductions in launch costs, requires large capital investments. The funding required and technology development process makes it evident

that an on-orbit JWS segment is not feasible in the near years. However, the theater commander's need for support continues today.

To mitigate the lag in deploying JWS support, Space Command has looked for alternate operational concepts to bring space support to commanders. The Space Battlelab and command officials briefed the Air Force Chief of Staff in December 2004, on an alternative—high altitude, lighter-than-air vehicles. Following that meeting Space Command was directed to be the Air Force's lead on developing operational concepts for near space. The command's strategy is to develop both a traditional on-orbit and non-traditional near space approach to support JWS. The command is aggressively moving forward to develop lighter-than-air systems to support the non-orbital approach.

In early 2005, a research paper released by the battlelab detailed basic operational concepts for lighter-than-air technology. [16:13] It detailed the combat effects possible from near space as well as vehicle concepts that could support the capabilities. Its discussions included insights on survivability of lighter-than-air vehicles. The battlelab paper refers to a slow diffusion process that would cause a vehicle to fail if the lifting gas envelope is punctured. The paper adds anecdotal support by referencing a story of a renegade research balloon that required over 1,000 rounds from Canadian F-18s and six days time to bring down.

However, little attention has been given to a physical explanation of what occurs when a lighter-than-air vehicle's lifting gas envelope is punctured. In fact, the response has been to refer to the research balloon story to illustrate the robust nature of lighter-than-air systems. The generic, across-the-board application of this anecdotal evidence

can place into question the true survivability of an airship. Factors such as vehicle rigidity and control surface integrity can be compromised moving the system to failure more quickly depending on the system design. A vehicle that requires some overpressure to maintain its ability to be controlled may fail quickly when damaged. These insights may be extremely important to systems operators and planners who desire to recover the vehicle and its payload or maximize its remaining useful life over a specific location of interest.

1.3 Research Objectives

The aim of this research work is to begin examination of the diffusion process that will cause a lighter-than-air vehicle to fail when its gas envelope is damaged. The reason behind the work is to provide the community developing these systems with some critical thinking regarding this failure mode. While it is clear that the loss of lifting gas will affect buoyancy and result in decreased performance capability, the true impacts remain somewhat clouded by speculation and generalization. Possibly, a general understanding is all that is required for analysis and by examining this question it might be shown that anecdotal evidence does in fact sufficiently address the question of survivability.

Specifically, this project accomplishes three main objectives. First, it develops a mathematical expression to model lift capacity of a lighter-than-air vehicle with a damaged lifting gas envelope. Next, it attempts to characterize airship performance following hull damage—that is the ability to hold a course or maintain station. Finally, it examines possible time to failure criteria for a lighter-than-air vehicle operating under specified atmospheric conditions.

The vehicle concepts being considered for this mission are diverse. They range from a free-floating balloon to a rigid airship structure. For this reason the objectives will be examined with some respect given to vehicle type and capabilities. Because the free-floating system in the anecdote might behave differently than a propelled system, it is important to compare a navigable airship's performance with the free-floating system used as an illustration of survivability. It is hypothesized that since an airship relies on vehicle hull pressure to maintain its navigation capability, keeping the hull pressure higher following rupture will enable it to travel further down range. Conversely, allowing it to simply depressurize to atmospheric equilibrium will preserve altitude. The take away is initial insights into how survivability can or should be addressed by different lighter-than-air system operators and designers. The objectives should also provide a baseline to start future discussions regarding survivability.

1.4 Thesis Overview

This paper uses well-accepted engineering first principles to explain what occurs when a vehicle's lifting gas envelope is compromised. The intention is to provide a broad examination of performance expectations and will take advantage of well understood engineering assumptions to provide insights. The reader should be aware that in order to effectively model the process, simplifications must be made to provide the broad overview intended by this paper.

This analysis begins with understanding what makes a lighter-than-air system generate lift ability. The physical mechanisms that control the sudden loss of lifting gas by a lighter-than-air system are examined. An attempt is made to model how a

compromised vehicle would behave following damage. Governing equations are investigated to help illustrate performance capability and predict future performance. Well understood principles such as Newton's Laws of Motion, Archimedes' Principle, Bernoulli's Equation and the ideal gas law are leveraged to help explain performance.

Application is made across a small spectrum of vehicle types. Specifically, semi-rigid airships assumed to have a propulsion capability are examined for insights. An overview of lighter-than-air vehicle types is made in chapter two. The results from the application of the engineering modeling are captured to provide feedback on the impacts of losing lift.

This thesis is specifically designed to examine the question of what occurs after a system sustains damage. Aspects of a system's ability to evade attack, mitigate detection or avoid damage are not contained in this work. As well, this work will assume that the bounds of damage are not so severe that complete system integrity is lost. In other words, the system retains some ability to hold lifting gas and generate lift.

2. Literature Review

2.1 Chapter Overview

Lighter-than-air flight has been used for more than 230 years for numerous applications from sport to science. The phenomenon is hardly a new concept. Today, a warfighting application is emerging for high-altitude communication and surveillance platforms. Lighter-than-air platforms are being tested to support those applications. Lighter-than-air systems are based on well-understood engineering principles. The purpose of this chapter is to examine these principles and how they apply to lighter-than-air flight.

The chapter provides a physical understanding of principles used to develop a performance model of an airship. This sets the stage for examining performance of a combat damaged airship. The section begins with a discussion of the operating environment—Earth’s atmosphere—particularly the upper troposphere and lower stratosphere. Next, an examination of buoyant force and its associated lift capability will be made. Combining Newton’s laws of motion and Archimedes’ Principle regarding forces on a body immersed in a fluid, an expression is developed to describe lift capability of a lighter-than-air system.

2.2 Background

After a nearly 4,000 mile trip, a Canadian research balloon carrying an atmospheric research payload came to rest in a field in Finland. The 100 meter tall balloon had failed to terminate its three-day mission and drifted for 10 days over the Atlantic in August 1998. During that trip the rogue balloon threatened trans-Atlantic

flight routes and caused numerous flights to be redirected to prevent a collision with the erratic flight. The balloon, which can reach altitudes as high as 130,000 feet, caused enough concern to generate military responses from the United States, Canada, and Great Britain. Early in the episode the Canadian Air Force scrambled F-18 fighters to try to destroy the vehicle. Despite over 1,000 twenty millimeter cannon shots at the balloon, the fighters were unable to bring the vehicle down. [17:14] The exact altitude of this engagement was not verified. However, the damaged balloon continued to cross the Atlantic Ocean at altitudes between 27,000 and 37,000 feet. Many observers thought this errant flight might be the first lighter-than-air vehicle to make a round-the-world circuit. But not to be, on 3 September 1998, the balloon's flight ended.



Figure 2.1—Rogue Canadian research balloon shortly before landing in Finland after a 10-day flight. Children climb on the remains of the balloon after it returned to Earth's surface. [1]

This flight has become a lynch pin of anecdotal evidence of airship survivability. It is abundantly clear that simply puncturing the lifting envelope of the research balloon couldn't cause catastrophic failure. Although it's not clear how the vehicle was struck by the F-18's cannon, it is safe to assume that at least some projectiles fired at the balloon were able to puncture its skin. Yet the vehicle's flight continued for some time before

crashing to the earth. Using this anecdote as motivation, an exploration of physical principles involved in airship flight is warranted.

2.3 Airship and Lighter-than-Air Technology

Lighter-than-air flight is achieved by exploiting the propensity of a lighter fluid to rise to a point of equilibrium in a heavier fluid. Designing a vehicle to achieve this lift has a wide range of variation. Vehicles can be as simple as a helium-filled balloon or as complex as a framed and propelled lifting body containing a lifting gas. The most common lighter-than-air vehicles are weather balloons. Often weather balloons are in actuality not balloons as their skins are not “stretched” by the internal gas pressure. Instead, they are better described as envelopes that contain a lifting gas, which expands as the envelope rises. However, the envelope material will not stretch and will fail unless internal pressure is relieved as the gas expands. An airship, sometimes called a “dirigible,” can be considered a special case of balloon, which has been designed with a specific geometry that presents a lower aerodynamic resistance to motion. Usually, an airship has a propulsion system on board to allow it autonomy of motion rather than being subject to motion along the course of prevailing winds. Over time three main classes of airships (Figure 2-2) have been developed: non-rigid; semi-rigid; and rigid. [8:24]

The non-rigid airship is a pressurized gas envelope containing a lifting gas. Any type of payload can be contained in a carriage attached to the envelope. The envelope relies mainly on a small overpressure to maintain its shape and often vents lifting gas through some pressure relief system to prevent overexpansion as it rises. When gas expansion has completely filled the containing envelope, the vehicle has reached its

“pressure altitude”—the highest altitude it can achieve without increasing internal overpressure. Because these vehicles retain their geometry only by gas pressure, they are capable of only slow horizontal speeds—typically 20 to 40 knots. Higher speeds present the threat of deformation of the leading envelope surface due to high stagnation pressure. Also, non-rigid systems offer little resistance to bending and shear forces due to loading and environmental forces.

The second airship type is a semi-rigid vehicle. The semi-rigid airship is similar to the non-rigid, but adds a reinforcing keel along the base of the envelope and leading surface stiffener to the envelope. The keel adds strength to the envelope and allows payload capacities to be increased. The stiffener strengthens the forward edge and helps

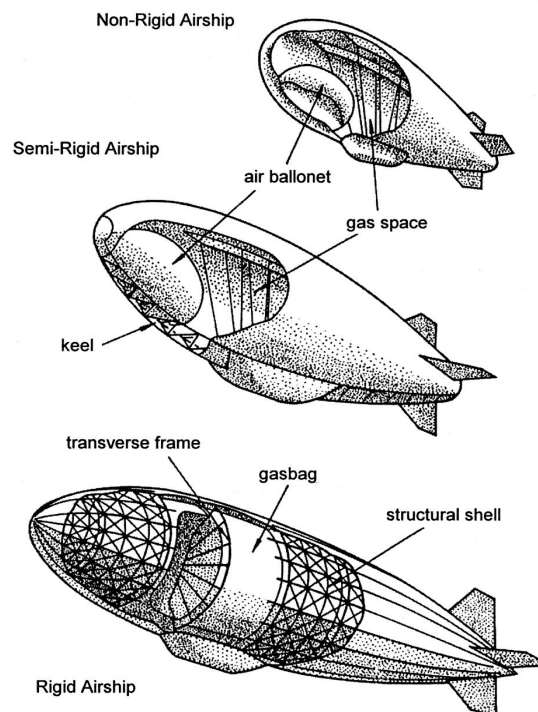


Figure 2.2—Types of Lighter-than-Air Airships

prevent deformation of the envelope due to pressure during forward motion.

The final airship type is the rigid vehicle. This type of vehicle contains a rigid structure or frame with a gas envelope or “bag” inside the frame. This frame provides several advantages. First, it resists shear and bending forces placed on the envelope by a payload and environmental forces. Next, it ensures the integrity of the envelope geometry under forces caused by increased forward velocity and does not require an “overpressure” condition to maintain the shape of the vehicle. Finally, it helps the vehicle maintain its geometry during descent.

Lighter-than-air vehicle geometry is often a function of system propulsion requirements. Some systems require no method of propulsion. These systems are known as free floating and will follow the prevailing wind currents as they soar.

Aerodynamically efficient geometry is not typically a concern for this type of vehicle and most often they are spherical. As the need for navigation and control of a vehicle increases, propulsion systems can be added. These systems are typically motorized propellers that move a vehicle. These systems are powerful enough to prevent the vehicle from being adversely affected by wind currents and allow steering to be accomplished.

Geometry is more important for this type of vehicle. Typically airships designs are tuned to an optimum fineness ratio to minimize drag forces on a propelled vehicle. The fineness ratio is simply a measure of the slenderness of the body and is a ratio of the vehicle’s length to its maximum diameter. [9:57] Research has demonstrated that larger fineness ratios have significant impacts on vehicle drag for operations in high head wind conditions.

Finally, when examining lighter-than-air vehicles it is important to understand the physics of an ideal gas. Both air and typically used lifting gasses are considered to behave like an ideal gas. An ideal gas is defined as a real gas that is not approaching liquefaction. [11:14] Such a gas can be modeled by the ideal gas equation.

$$\rho = \frac{pw}{RT} \quad (2.1)$$

This expression states that the density (ρ) of a gas is proportional to the pressure (p) and its atomic weight (w), and inversely proportional to its temperature (T), and a constant (R). Inside the airship's lifting gas envelope the pressure decreases uniformly with increasing altitude as the pressure surrounding the envelope decreases. Temperature changes inside the hull as it rises are assumed to be negligible in this analysis for reasons that will be discussed later. Since a fixed mass of gas exists inside the airship's hull, any changes in lifting gas density must result from pressure changes. The result is an increase in gas volume as the airship rises. Because very little elasticity is present in typical envelope materials the threat of rupture becomes an important consideration. To reduce the threat, many envelopes are equipped with overpressure valves or escape holes, which allow the optimum overpressure to be maintained as the vehicle rises. If volume can no longer be increased during ascent and gas is expelled to the atmosphere through a relief valve, a portion of the airship's lift capacity will be lost. The result might be the forced descent of the airship. This concept of lifting gas mass and its impact on lift will be examined further later in this chapter in a discussion of airship lift and volume calculations.

The lighter-than-air vehicle is optimized to operate in the confines of Earth's atmosphere. It capitalizes on the sea of air present over the planet's surface to develop buoyant lift. A good understanding of buoyancy and the Earth's atmosphere is appropriate to develop.

2.4 Fundamental Principles

2.4.1 Earth's Atmosphere

The Earth is blanketed with a layer of fluid held in place by gravity. We call this Earth's atmosphere. It is composed a number of elemental gasses commonly referred to as air. Also included in the atmosphere is water vapor. For the purpose of this work, Earth's atmosphere is assumed to be a dry mix of air's three major components: nitrogen (N_2), oxygen (O_2), and Argon (Ar). Each of these elements possesses mass and compose some portion of the air mixture. [2:72]

Table 2.1—Composition of Earth's Atmosphere

Basic composition of dry air in Earth's atmosphere

Component	Fraction	Molecular Wt
Nitrogen (N_2)	0.7809	28.01
Oxygen (O_2)	0.2095	32
Argon (A)	0.00934	39.95
Air	0.99974	28.95

Dalton's Law helps to explain the pressure exerted on Earth's surface and other portions of the atmosphere. Understanding that the individual constituents of air possess mass, then the total pressure exerted on a surface by air is simply the sum of the pressures from individual components contained in a given volume multiplied by their percentage composition of the total volume. If the Earth's atmosphere is taken as the control

volume, then a column of atmospheric height z exerts a pressure proportional to the sum of the weight of its components. Assume height z_2 is an atmospheric altitude above z_1 . The mass of air molecules at z_1 are additive with the mass of air molecules at z_2 exerting a total force at the base of the column. It is understood that the earth's atmospheric density decreases with altitude. Equation 2.2 shows that atmospheric pressure will decrease with increasing altitude. This idea can also be shown Figure 2.3. The figure shows how the pressure on a column of air decreases as the column height increases. The term dp is negative as pressure decreases as altitude increases because air density is decreasing.

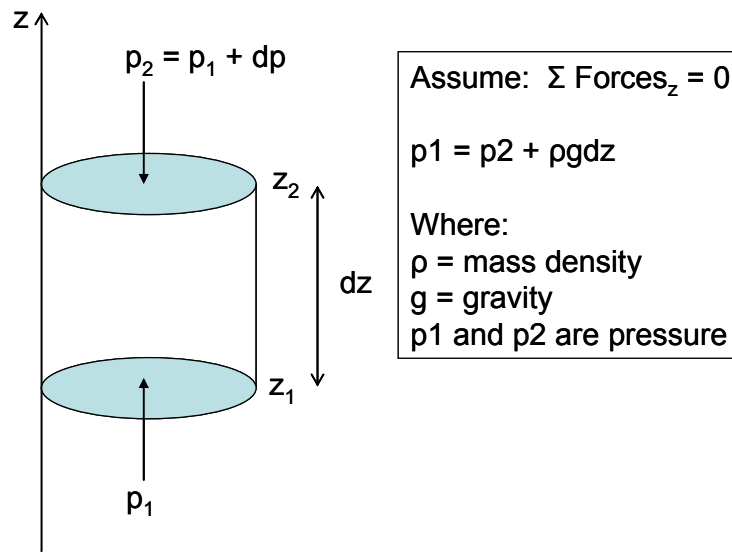


Figure 2.3—Atmospheric pressure change along a column of air

The previous description can be illustrated mathematically by looking at the density of a gas mixture. The force exerted by a column of air is the pressure exerted by the atmosphere multiplied over the area the pressure is exerted upon.

$$p = \int_{H1}^{H2} \rho g dz \quad (2.2)$$

Separating and solving the differential equation, pressure can be represented as a hydrostatic approximation.

$$\frac{dp}{dz} = -\rho g \quad (2.3)$$

This approximation assumes Earth's atmosphere is a well-behaved uniform fluid. This assumption is far from the truth. In fact Earth's atmosphere is far from uniform when examining a particular region. This fact quickly becomes evident to the pilot of an airplane flying on a hot summer afternoon. Ground heating of air causes mixing with cooler air masses above and results in rising air masses. The occupants of the plane experience this mixing in the form of a bumpy ride due to turbulence. In fact it is a mass of warm, less dense air moving through a mass of cooler air. Taken to another level, masses of rising and falling air, particularly of differing moisture contents contribute to create weather and produce the rain. Using the hydrostatic approach to predict the pressure exerted by a column of air assumes the Earth is a perfectly spherical mass with a gravitational acceleration vector pointing normal to the Earth's surface. At the intersection point Earth's surface is assumed to be flat.

The hydrostatic approximation provides sufficient understanding of the atmosphere's behavior to allow first-order modeling of the air mass surrounding Earth. The relationship provides a generalized characterization of the entire atmosphere as an aggregate and ignores regional inconsistencies. This can be better understood by looking at the composition of the atmosphere.

2.4.1.1 Composition of Earth's Atmosphere

Earth's atmosphere is a series of regions of gas that can be specifically characterized by their behavior—in specific their temperature. [21:24] The region nearest Earth's surface is the troposphere and extends 15 kilometers upward (approximately 50,000 feet). This is the region where humans as well as most life exist. It is characterized by a decreasing temperature gradient starting at an approximate 14° C (57° F) and declining linearly to -60° C (-76° F). About 85 percent of the atmosphere's mass is contained in the troposphere and it is a region of intense mixing.

The upper boundary of the troposphere—the tropopause—marks an altitude at which the temperature change profile reverses itself. The region above the troposphere is known as the stratosphere. It extends vertically to nearly 50 kilometers (approximately 164,000 feet). The temperature rises linearly with altitude in the stratosphere to an average of -2° C (28° F). There is little convective mixing in the stratosphere and it is relatively stable. Despite its stability it is important to understand that in the stratosphere atmospheric mixing via small scale turbulence continues to dominate diffusion, which occurs at greater altitudes when the mean free path between species becomes great enough to allow gas stratification. Therefore the mixing ratio of atmospheric gasses can be assumed constant. Nitrogen, stable oxygen, and ozone exist in sufficient density in the stratosphere to facilitate atmospheric mixing. In fact, this mixing process dominates the atmosphere to nearly 100 kilometers (328,000 feet) and the mean molecular weight of air remains essentially constant. [2:77]

Above the stratosphere are the mesosphere and thermosphere. These regions rise beyond 100 kilometers (over 300,000 feet) and experience both a decreasing and then again increasing temperature lapse rate through the thermosphere. These regions are beyond the scope of this project and for the purpose of the project need not be described further.

2.4.1.2 Properties of Earth's Atmosphere

It is well understood that both atmospheric pressure and density decrease with increasing altitude. As shown in Figure 2.4, both pressure and density decrease exponentially with height. The exponential pressure and density models have

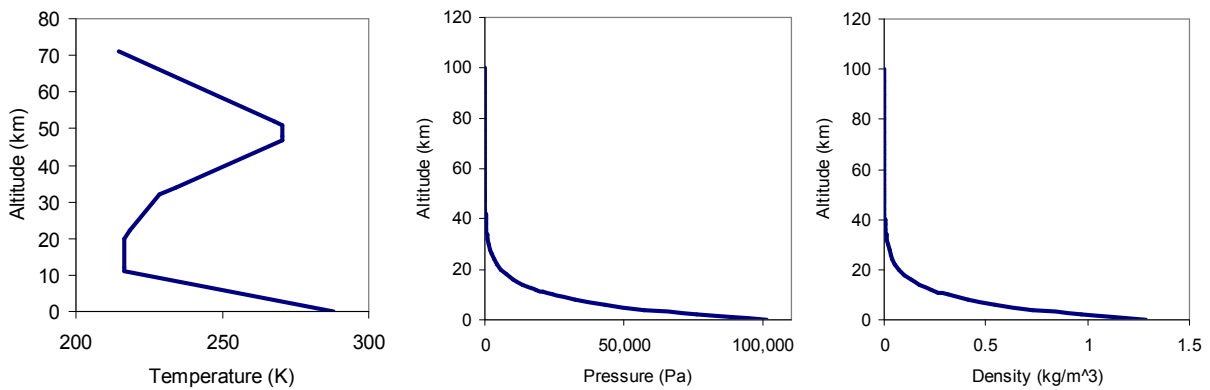


Figure 2.4—Atmospheric temperature, pressure and density gradients

demonstrated a high degree of accuracy in predicting values well in excess of 30 kilometers. [2:56] The basis for this atmospheric model is developing an exponential height constant to relate the rate of change of pressure or density with altitude and then solve for a value based on its proportion of the standard value. Values for atmospheric pressure and density can be predicted by the following equations:

$$p = p_0 \exp\left(-\frac{h}{H}\right) \quad (2.4)$$

$$\rho = \rho_0 \exp\left(-\frac{h}{H^*}\right) \quad (2.5)$$

H^* represents the scale height constant for modeling density and is related to H by adding the inverse of the temperature lapse rate to the inverse of H . However, since an isothermal atmosphere is being assumed the lapse rate is zero and H can be used as the scale height constant to model density.

Temperature lapse rates in Figure 2.4 reflect predictions modeled by a standard atmosphere model. These are included here to provide perspective on atmospheric temperature. To make use of the scale height model for pressure and density an average temperature based on lapse rates over operational altitudes should be developed

In the pressure equations a scale height constant H (kilometers) is used to parameterize the exponential ratio. This constant is defined mathematically as:

$$H = \frac{RT_{avg}}{g} \quad (2.6)$$

The scale height permits a first order pressure approximation based on an average atmospheric temperature and when combined with the ideal gas law can complete a mass balance of a continuous column of atmosphere acting on a cross-section of the earth's surface. The result is the hydrostatic pressure equation.

$$\frac{1}{p} \frac{dp}{dh} = -\frac{g}{RT} \quad (2.7)$$

This result yields the following differential equation, which when solved provides an estimate of atmospheric pressure.

$$\frac{p}{p_0} = \exp\left(-\int_0^h \frac{g}{RT} dh\right) \quad (2.8)$$

When predicting the atmospheric density scale height the isothermal atmosphere assumption allows the pressure scale height to be used to predict density. The scale heights are related by the expression

$$\frac{1}{H^*} = \frac{1}{H} + \frac{1}{T} \frac{dT}{dh} \quad (2.9)$$

Again, assuming the temperature lapse rate is zero due to the isothermal assumption the value of H^* is simply H .

Being able to relate the density of Earth's atmosphere at a given altitude is an important consideration for sizing an airship hull. As will be discussed later in this section, the density of the air displaced and the associated mass of lifting gas within the hull are critical for predicting the maximum altitude an airship can obtain.

The isothermal temperature assumption is important to the analysis of the airship. The ideal gas law can demonstrate that both pressure and volume relate proportionately to temperature. An increase in temperature will cause a proportional increase in either pressure or volume. This is evident when you take a simple helium party balloon outside on a cold winter day. The balloon can be assumed to be sealed with a constant mass of gas inside of it. When exposed to the cold temperature, the balloon's volume and pressure decrease visibly as it becomes smaller and less rigid. However, when dealing with the large volume of gas present in an airship, the impact of temperature changes in the atmosphere is of small consequence for a first order approximation. Typically the temperature gradient in the first 10 to 15 kilometers of the atmosphere (troposphere) is

approximated in a standard atmosphere as -6.5° Celsius/km. Between 10 and 15 kilometers the atmospheric temperature lapse rate goes to zero in a region known as the tropopause. This region can extend as high as 20 kilometers. Above the tropopause is the stratosphere, which is characterized by increasing atmospheric temperatures caused by absorption of solar ultraviolet radiation. The relatively slow changes in heating and cooling of the airship system at high altitudes and its surrounding environment allow it to be considered isothermal in this analysis despite known temperature changes.

2.4.2 Aerostatics

As alluded to earlier, an airship is able to generate lift by taking advantage of the phenomenon that a less dense fluid will rise to a point of equal density. This section seeks to explain the fundamental principles of airship lift and altitude requirements. Key to this section are the principles that lift capacity of an airship is a function of lifting gas mass and airship altitude is a function of the lifting gas volume. These design parameters for an airship are important to understand later when the performance of a damaged airship is being evaluated.

2.4.2.1 Airship Lift

High altitude airships are being pursued for their ability to lift important payloads to great altitudes. They accomplish this by displacing heavy air with a less dense gas that will rise to seek density equilibrium. A mass balance relationship can represent this principle.

$$mg < gV_{air}(\rho_{air} - \rho_{He}) \quad (2.10)$$

This expression says that as long as the weight of a structure is less than the difference between the weight of air displaced and the gas (in this case helium) displacing it, there will be an upward force generated. This force is known as the buoyant force. For the purpose of this paper, any reference to a lifting gas can be accepted to mean helium, unless specifically noted otherwise. As well, the helium will be considered to be unmixed with air or pure helium.

By understanding the mass balance relationship, it becomes apparent that the maximum weight or “lift capacity” [10:3] of an airship is a function of its lifting gas mass. An airship will rise until its buoyant force is equal to the weight it’s lifting (L_n).

$$L_n = gV_{air}(\rho_{air} - \rho_{He}) \quad (2.11)$$

A design factor in developing an airship is to ensure that the pressure relationship between the gasses inside and outside the airship hull is not impacted. That is, a constant pressure relationship must be maintained. In the case of an airship, that means a constant overpressure must exist inside the hull. If the pressure relationship is maintained then lifting gas pressure decreases uniformly with atmospheric pressure as the airship rises and the gas is able to expand its volume. As volume increases, gas density in the hull decreases and the buoyant force is maintained. The buoyant force will lift the airship until the hull volume is at a maximum and the pressure relationship between the hull and the environment can no longer be held constant. At this point the airship has reached its maximum or “pressure” altitude. [13:2]

An airship hull or envelope is designed to compensate for increasing lifting gas volume as it rises. Contained within the envelope are bladders containing air that’s used

as ballast. While on the ground these bladders, known as ballonets are inflated and can occupy as much as 40 percent of the airship's envelope. There are generally two on an airship—one forward to control pitch and one aft to control weight. As the airship begins ascent the ballonet volume decreases as air ballast contained in them is thrown overboard. This allows the lifting gas density to decrease and the airship to rise. The airship will continue to rise until the volume occupied by the lifting gas fills the void left by the air released from the ballonet. When this equilibrium is achieved a pressure height is established. When the ballonets are completely depleted the airship's total pressure height or maximum obtainable altitude is reached. To descend air is pumped into the ballonet thereby decreasing the system's sustainable altitude and the airship descends.

By accepting this design principle, a key assumption is made: the rate of change of the lifting gas density is equal to that of the air displaced. This gives a parameter called the “density ratio” (σ) and relates the density of helium to air at any altitude.

$$\frac{\rho_{air}}{\rho_{air0}} = \sigma = \frac{\rho_{He}}{\rho_{He0}} \quad (2.12)$$

Since the density rate of change is considered equal and the volume of displaced air in the envelope is the same as the volume of helium present, the net lift equation can be rewritten to demonstrate that lift is a function lifting gas mass present in the envelope.

$$L_n = m_{He} g \left(\frac{\rho_{air0}}{\rho_{He0}} - 1 \right) \quad (2.13)$$

Lifting gas mass should remain constant within the envelope as the airship rises. If ballonet deflation is controlled properly, the airship will rise to its maximum pressure height and maintain that altitude. If an airship rises above its pressure height the pressure

difference will be exceeded and lifting gas will be vented resulting in diminished lift capacity. To prevent this from happening, some ballonnet inflation is maintained preventing the airship from reaching its maximum altitude. However, for the purpose of this paper it will be assumed that the ballonets are completely deflated at pressure altitude and the airship maintains a constant altitude while operating prior to sustaining any hull damage.

2.4.2.2 Airship Volume

Pressure height of an airship is a function of the vehicle's hull size. Lifting gas must have sufficient volume to expand and achieve a similar density to the environment surrounding it. Therefore, correctly sizing the vehicle drives the altitude at which it will operate. As previously stated, maximum lifting gas volume is reached when the gas density is allowed to decrease without impacting the pressure differential in the hull. Since density is a ratio of the mass of a gas to its volume, the volume of a lifting gas expanded to the equivalent atmospheric density will provide rapid insight into how big an airship must be. The mass of helium used remains constant and the density of helium can be predicted as a function of altitude by taking advantage of the density ratio. The airship size can be predicted by the following equation.

$$V_{\max} = \frac{m_{He}}{\sigma_p \rho_{air0}} \quad (2.14)$$

In this equation σ_p represents the density ratio at the desired maximum altitude and ρ_{air0} is the density of air at sea level. Taking advantage of the density scale height model, the density ratio can be rewritten as a function of altitude:

$$\sigma_p = \frac{\rho_{air0} \times \exp(-\frac{h}{H})}{\rho_{air0}} \quad (2.15)$$

Taking advantage of the net lift and volume equations derived, it can be shown how large an airship is required to be in order to perform its mission. It is important to remember that for a first order approximation the lift generated by an airship is proportional to the mass of lifting gas on board, while its maximum altitude is proportional to the airship's hull volume.

By definition a high altitude airship is designed to operate above the normal operating regime of typical aircraft. This altitude is typically above 70,000 feet (21.32 kilometers). In theory this region, which is considered outside the definition of airspace controlled by the Federal Aviation Administration (FAA), extends to the ends of Earth's atmosphere above 300,000 feet. (> 91 kilometers). In reality a high altitude airship would operate between 70,000 and 100,000 feet. This operating altitude drives an airship's size requirement. The reason is that the lifting gas—a constant mass in a sealed hull—requires a large volume to sufficiently decrease density in proportion to its surrounding altitude.

Consider the equation for V_{max} (equation 2.14). The mass of lifting gas is constant based on the total weight of the system's structure and payload. However, the density of the gas in the denominator will decrease with increasing altitude. The result is an increasing volume requirement to allow the density to decrease. Figure 2.5 demonstrates how large an airship's hull volume can become. For example, a vehicle weighing 100,000 kilograms requires a volume in excess of two million cubic meters to

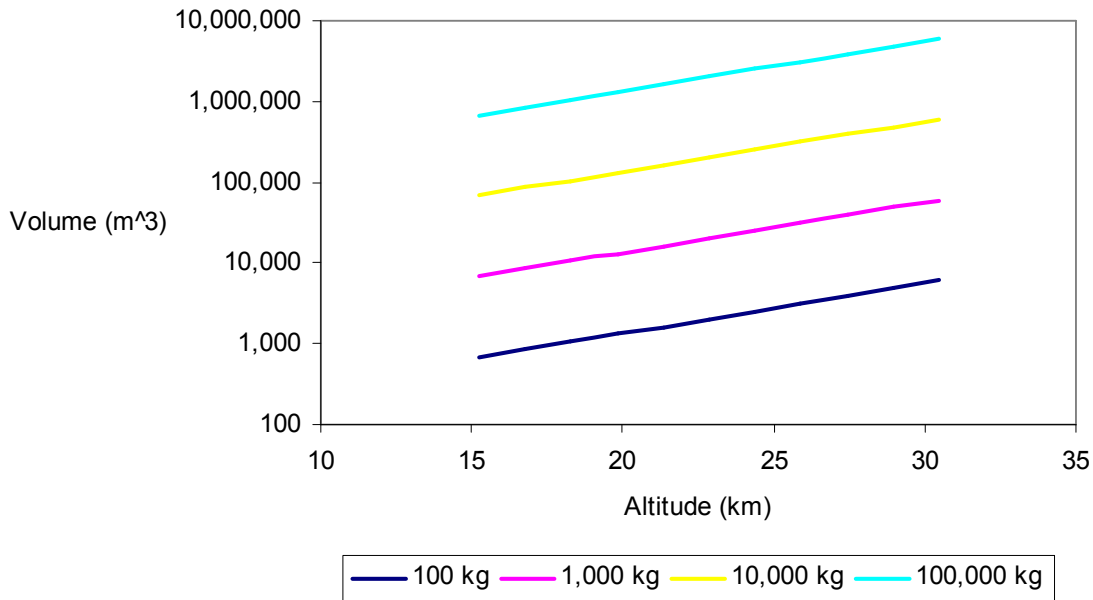


Figure 2.5—Comparison of lifting gas volume required to reach a pressure altitude given a required mass of lifting gas.

reach an altitude of 80,000 feet. That’s nearly the size of the Houston Astrodome, which has a diameter of 710 feet and height of 208 feet. It is obvious that sheer size of an airship operating at altitudes nearing 100,000 feet can create difficulties for logistics as well as operation and begin to limit their practicality. However, for lower near space altitudes there remains application.

2.5 Conclusion

The purpose of this section has been to introduce the concepts of airship design and physical principles that enable lift to be generated by controlling rising gases. This basic understanding will enable a look into what occurs when an airship hull is compromised. The vignette introducing this section provided an illustration of a compromised lifting gas hull that seemed to defy the concept that simply puncturing the hull will bring a quick end to the vehicle’s flight. The following section will begin to

examine what occurs when the hull is compromised and provide initial insights to the question of how much survival time does a vehicle have after being compromised.

3. Methodology

3.1 Chapter Overview

It's important to understand how an airship will perform after having its hull damaged. Upon some analysis, the introductory illustration of a rogue research balloon may or may not be entirely sufficient to describe the performance of a damaged airship. Despite sharing the common thread of using buoyancy to provide lift, the balloon and airship are distinct from each other. Dissimilarities such as propulsion systems and aerodynamic shaping added to an airship begin to show the difference between the two systems. Structural rigidity is also added to the airship design to support the system's performance. This further helps to distinguish the airship from its distant cousin the rogue research balloon.

The objective of this chapter is to develop a methodology for a "first-look" at expected performance of an airship after its lifting gas envelope has been punctured. The illustration has been presented of how Canadian Air Force fighters fired on the rogue balloon as it soared across the Atlantic and unsuccessfully brought its flight to a quick stop. Does the story hold possible similarities for an airship? A model will be developed to look at the question of what impact hull damage has on the survivability of a high-altitude airship. The model can provide planners and operators an estimate of how quickly lift will be lost and what the descent of an airship might look like.

3.2 Courses of Action

As discussed in the previous chapter, for a first-order examination the lift of a lighter-than-air vehicle is dependent primarily on the mass of lifting gas contained in the

vehicle's envelope. If lifting gas is lost then the overall ability of the system to generate lift is degraded. At this point buoyant force generated becomes less than overall system weight and the vehicle begins to descend. The descent rate will be related to the lifting gas mass flow rate, which may be quite small due to the small overpressures required by an airship to maintain its shape and the size of the puncture in its hull. The airship typically has an ellipsoidal geometry to minimize drag forces when moving horizontal or down range and allow better performance of attached propulsion systems. The airship's flight is unlike that of a weather balloon. A balloon is generally spherical and having no onboard propulsion system, it drifts with prevailing wind currents.

An airship is generally a controlled system that works to optimize the vehicle's flight. Often control fins are attached to the hull to help direct the vehicle's heading. As well, the previously discussed ballonets are built into the hull to help control ascent and descent as well as trim the vehicle's attitude during flight. The weather balloon lacks this sophistication.

The design differences enable different courses of action for an airship when its hull is compromised. In the first case, control is maintained by sacrificing buoyancy, while in the second case buoyancy is preserved longer, but may result in loss of control or ability to steer against the wind. In both cases the end result is a zero-pressure balloon—a hull in which the pressure inside is essentially the same as the atmosphere that surrounds it. Unique methodologies can be developed to study these two cases and provide insights on what might be possible when trying to recover a damaged airship or move it to an

advantageous location for flight termination. The remainder of this chapter examines the physical principles that enable analyses.

3.2.1 Case 1: Maintaining Hull Overpressure

The airship uses an internal overpressure in its lifting gas envelope to help maintain the vehicle's shape. Although not large, this overpressure is important to prevent bending moments applied to the hull from "kinking" it. [6:13] As well, the pressure helps prevent nose deformation of the vehicle caused by stagnation pressure on its leading edge. Khoury and Gillett give a design estimate of the overpressure required for a non-rigid airship.

$$\Delta p = 125 + .033v_{\max}^2 \text{ (units: km/hr)} \quad (3.1)$$

In the equation, Δp represents the pressure difference between the lifting gas within the hull and the atmospheric pressure at a given altitude. The desire is to maintain a constant Δp as altitude changes in order to maintain airship hull rigidity. It is obvious that airship speed will impact the overpressure so the parameter v appears and should be the additive result of both vehicle's inertial velocity and the speed of any head wind. The overpressure must be designed not only for the speed of the vehicle, but also for the environment in which it will operate.

The essence of this first course of action is to maintain vehicle rigidity following a breach of the hull so that controlled horizontal motion can be attempted. As long as the vehicle maintains its shape the aerodynamic rationale designed into the airship can be exploited at least until overpressure can no longer be maintained. As the vehicle

descends it can be steered in a direction that is advantageous to operator's attempt to successfully recover the vehicle or terminate its flight.

The ideal gas law as discussed in chapter two allows us to analyze the descent of the damaged airship. Recall that the law stated that for an ideal gas the product of its volume and pressure is proportional to its mass given an isothermal environment. Since a constant overpressure is maintained in the hull the relationship is simplified to being a relationship of changing volume driving change in lifting gas mass.

To understand the mass change Bernoulli's equation for a compressible fluid is used to begin analysis. Bernoulli's principle states that along a streamline of fluid motion, the mechanical energy per unit mass is conserved. This principle assumes motion of an inviscid and incompressible fluid. Because lifting gasses are compressible, Bernoulli's equation can be modified to accommodate this fact and can be represented as follows.

$$RT \int \frac{dp}{p} + \frac{v^2}{2} + gz = C \quad (3.2)$$

For this relationship C represents a constant. Since the pressure inside the airship hull is assumed uniform or equal at all points, the potential term is neglected and z is assumed to be zero. The benefit of this relationship is the estimate it provides for lifting gas escape velocity. Using a model of horizontal flow of a fluid from a tank in a free jet, the dynamic pressure can provide an estimate of the escaping fluid's average velocity across a pressure change. [11:122] By integrating the equation and then solving for the velocity an estimate is gained of the average velocity of a lifting gas molecule as it is accelerated from rest inside the hull to some speed as it exits the hull into the atmosphere.

$$v = \sqrt{2RT \ln\left(\frac{p_{env}}{p_{atm}}\right)} = \sqrt{2RT \ln\left(1 + \frac{\Delta p}{p_{env}}\right)} \quad (3.3)$$

In this case p_{env} represents the lifting gas pressure within the hull, while p_{atm} represents the surrounding atmospheric pressure. Because the pressure difference is relatively small between the pressures inside and outside the hull, compressible effects are minimal and satisfactory results could be obtained using the standard Bernoulli equation. By understanding how fast lifting gas escapes from the compromised hull, the mass loss rate can be determined from known quantities.

$$\frac{dm}{dt} = \dot{m} = v \rho_{gas} A \quad (3.4)$$

A is defined as the area of the puncture in the vehicle's hull. Using the ideal gas equation to represent ρ_{gas} and substituting equation 3.3 in for velocity, the mass loss can be rewritten.

$$\dot{m} = \frac{w_{He} A}{RT} (p_{env}) \sqrt{2RT \ln\left(1 + \frac{\Delta p}{p_{env}}\right)} \quad (3.5)$$

Once the mass loss rate is determined, solving for gas loss over small time intervals enables the calculation of the volume of displaced air by the hull. Also recall that the volume of lifting gas is equivalent to the volume of displaced air. In the previous chapter it was stated that airship design included ballonnet internal to the hull which inflate and maintain internal overpressure as well as change the volume of the lifting gas. Khoury and Gillett suggest that ballonnet size can extend to 40 percent the overall hull volume when fully expanded. [6:178] This design principle will be applied to this analysis. Understanding the how lifting gas volume changes, both lifting gas density and air

density can be defined for a given time interval and all the information required to complete a mass balance of the system at a given instant is available. A mass balance will provide the descent acceleration the vehicle will experience as lifting gas flows from the hull.

Figure 3.1 illustrates the forces acting on an airship as it begins to descend. Using what we know about lift gas mass, an equation describing acceleration is developed. The ideal gas equation is used to help describe the buoyant force (F_B) and appears in the equation as the ratio of pressures between the atmosphere and the lifting gas. The structural mass (m_s) when multiplied by gravitational acceleration describes the weight contribution of the vehicle to vertical acceleration. Finally, the drag force (F_D) is described in the equation by the atmosphere's density (ρ_{air}) and the vehicle's descent

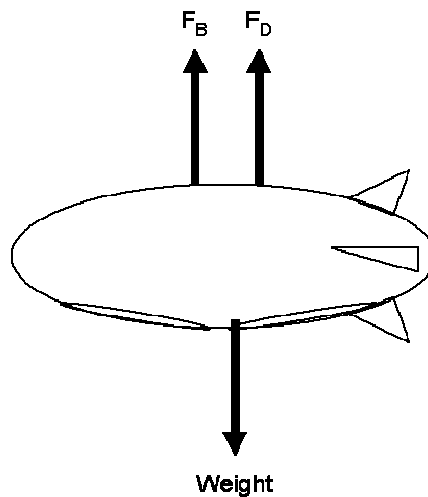


Figure 3.1—Description of forces acting on an airship during descent.

velocity (u) as well as its cross-sectional area (A) and drag coefficient (C_D) normal to the direction of motion.

$$a = \frac{g}{m_{total}} (m_{gas} (\frac{p_{atm} w_{air}}{p_{env} w_{gas}} - 1) - m_s) + \frac{u^2 \rho_{air} A C_D}{2m_{total}} \quad (3.6)$$

The ellipsoidal shape of an airship's hull produces a drag force on the descending vehicle. For simplicity the airship's C_D will be characterized by that of a cylinder ($C_D=0.3$). [23:418] Once acceleration is understood, all relevant position information about the vehicle can be determined at each time interval. Since the design limit for lifting gas volume expansion is 60 percent of its maximum hull volume based on ballonnet size, once this limit is reached the vehicle can no longer maintain constant overpressure. Pressure inside the hull will begin to fall until it reaches atmospheric pressure. At this point the rationale for the current descent analysis becomes invalid and predicting lifting gas loss using the ideal gas law requires that changes in both hull pressure and volume be considered. This methodology is developed in the following case.

3.2.2 Case 2: Hull Pressure Equalization

The analytical advantage of attempting to maintain a constant overpressure within the vehicle's hull is its presentation of only one unknown quantity—volume. Once volume can be defined the analysis proceeds quickly. However, it may be advantageous to allow a damaged airship to descend while the lifting gas pressure decreases with mass loss until it reaches the pressure of the surrounding atmosphere. The rationale for pursuing this case over the constant overpressure case is the decreased loss rate of lifting gas and hence preservation of buoyancy. The implication is that a vehicle may remain at a higher altitude where more favorable wind conditions exist to allow down-range navigation to a suitable recovery/termination location. This case is more similar to the

research balloon anecdote than was the previous case. However, significant difference still exists. The main difference is that a hull overpressure still exists with uniform pressure distributed across the envelope. Hence the airship is still capable of sustained navigation according to the overpressure design relationship of Khoury and Gillett.

The analysis for the slow depressurization case depends on the relationship of pressure and volume to help describe mass loss. Previously the ideal gas law was used to demonstrate pressure and volume effects on the airship as it rises. Additionally, it showed how volume and pressure impacted mass loss via an overpressure valve when gas expansion became too great for the hull's size. Mass flow from the hull can be represented by the ideal gas equation by summing the contribution of the volume change at constant pressure and the pressure change at constant volume. This idea is represented in the following equation:

$$\frac{dm}{dt} = \dot{m} = \frac{dp}{dt} \frac{V w_{gas}}{RT} + \frac{dV}{dt} \rho_{gas} \quad (3.7)$$

The benefit of this relationship is that it helps to understand how pressure and volume change as the airship depressurizes and descends. Mass flow can be defined as previously discussed using the velocity component of the dynamic pressure term in the Bernoulli equation. The mass flow rate can be used in equation (3.7) to determine rates of change for hull pressure and volume as the airship descends.

A difficulty may come in defining the contribution of the differential terms to the total mass loss rate. If a contribution relationship can be established, both the differential changes in pressure and volume can be defined and depressurization can be analyzed. For a first-order approximation it could be assumed that both pressure and volume

changes account equally for changes in mass flow. Although it's unlikely these proportions are completely accurate, they can provide sufficient insights into the question of accounting for mass flow. For sake of comparison, the weighting of the pressure and volume effects can be modified. Either portion can be given a greater or lesser weight to study how it might impact the mass flow. The important restriction in applying weighting factors is to ensure that the sum of the factors is exactly one. As a sensitivity test a weighting factor of .33 was given to the pressure change rate and (1-.33) was given to the volume change rate. That is to say that pressure change with time accounted for one-third of the mass flow while the volume change accounted for two-thirds. These values were tested in the descent acceleration equation to determine what impacts exist.

Figure 3.2 compares descent acceleration for the two mass flows cases. Although slightly different in magnitudes the two cases produced very similar acceleration rates. Both show a rapid acceleration downward followed by a deceleration period and then a

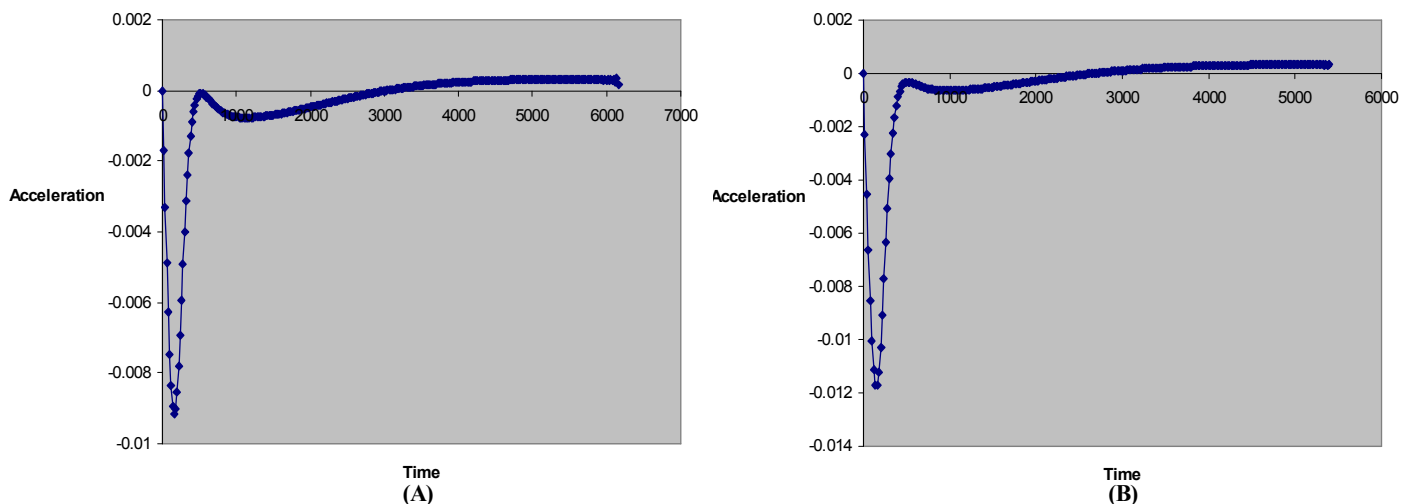


Figure 3.2—Comparison of descent acceleration (m/sec²) over time (sec) for an airship that has a hull puncture diameter of one foot. In Figure A pressure accounts for approximately one-third lifting gas mass flow escaping from the airship hull and in Figure B pressure accounts for one-half the mass flow.

decrease toward zero as terminal velocity is reached. Although there is some slight difference in peak acceleration between the two sets of proportions, the time impact is small. This comparison of acceleration over time helps to illustrate that varying the weighting factor may not have significant influence on the first-order analysis. Since that is the case, for this analysis we will assume the pressure change rate contributes equally with volume change rate to define mass flow.

Understanding how pressure affects the change in gas mass in the hull enables the calculation of descent acceleration for a damaged airship. Because the mass flow equation provides insight into how the overpressure changes during descent, the same calculation previously used in case one can be reapplied here

Again, acceleration of descent can be calculated and over a given time interval the descent rate and actual descent can be calculated using simple kinematics equations. Unlike the previously discussed case, which required a constant overpressure inside the airship hull to conduct analysis, this case simply requires that an overpressure exist between the hull and the atmosphere. Cross-range velocity and distance can be determined for the depressurizing airship by using Khoury and Gillett's relationship between hull overpressure and cross-range speed. Eventually the hull will depressurize and forward motion will no longer be sustainable. At this point hull pressure will be equal to that of the surrounding atmosphere and any overpressure is exhausted. It's at this point the analysis methodology must change to reflect the new relationship between the hull and atmospheric pressures.

3.2.3 Hull Pressure Reaches Atmospheric Pressure

In both cases previously considered the eventuality for a damaged airship hull is the total loss of any overpressure. This zero-pressure condition is well described by Lewitt in his treatise as a “flabby” airship. [8:86] This condition is most similar to the rogue balloon illustration introduced in the preceding chapter. The airship still contains a certain mass of lifting gas creating a buoyant force. However, the airship has no structural rigidity to neither properly support its payload nor maintain any aerodynamic shaping to assist in horizontal or down-range flight.

Because the pressure ratio between the lifting gas and atmospheric air will be essentially unity, the density of the lifting gas depends solely on atmospheric pressure (continuing on with the isothermal assumption). As the airship descends lifting gas density will increase. If we assume a fairly slow descent (airship not falling like a rock) we can define this process as diffusive and therefore assume the lifting gas and atmospheric gasses are unmixed in the hull. The lighter lifting gas will stratify itself above the heavier atmospheric gases as in Figure 3.3. Since lifting gas is no longer flowing out of the hull, the mass does not change but its volume will decrease and its density will increase.

The bubble of lifting gas that occupies the top portion of the unpressurized hull is subject to “sloshing” similar to a bubble of air trapped underwater. The performance of the airship is limited because its structure is “flabby” and any controlled horizontal motion is difficult develop. It’s at this point in the analysis that only descent can be

modeled with any confidence and horizontal motion is assumed to be controlled largely by prevailing atmospheric currents.

Descent analysis is straight forward. The ideal gas relationship is used to predict lifting gas density changes as the hull pressure changes. Because the hull pressure is essentially equal to the atmospheric pressure, an atmospheric scale height prediction of pressure provides the necessary insight to complete the analysis. The mass flow is not required for this portion of the descent as we have shown that lifting gas is no longer expelled from the airship as it descends. Since no additional gas is lost the vehicle will maintain a constant buoyant force for the remainder of its descent. However, it will always be less than the vehicle weight and the airship will eventually fall to the ground.

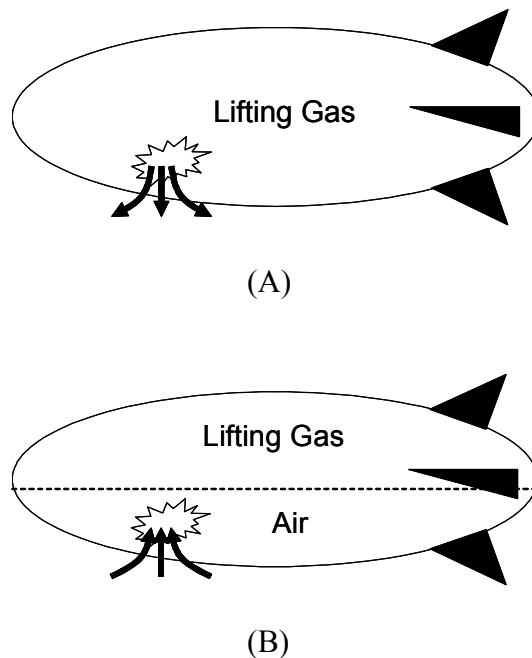


Figure 3.3—Stratification of lifting gas and atmospheric constituents occurs following airship hull pressure equalization. (A) Atmospheric gasses cannot enter hull because of lifting gas overpressure and lifting gas flow out of the hull. (B) Atmospheric gasses begin to enter the airship hull after pressure has equalized resulting in stratified layers of lifting and atmospheric gasses.

Some difficulty will be realized in determining acceleration because of the airship's "flabbiness" during this portion of descent. The coefficient of drag is important to control the velocity of the descent in this case. However, the lack of rigidity in the hull at this point complicates the vehicle's geometry. Previously, a drag coefficient for a flow across a cylinder was used to help estimate drag on the hull during descent. This assumed sufficient overpressure existed within the hull to maintain a geometry roughly similar to a cylinder. The sloshing of the lifting gas bubble inside the hull makes it hard to predict a constant drag coefficient. For the sake of simplicity in this case, a drag coefficient similar to that used previously can be used again in this analysis. By doing this we are neglecting impacts of the sloshing gas bubble has on vehicle's center of gravity and vehicle pitch angle during descent. This approximation assumes stability in the gas bubble and a continued descent with a relatively low pitch angle, symmetric mass distribution about the center of gravity, and no induced horizontal forces causing down range motion other than prevailing atmospheric winds.

An important consideration in this zero-pressure condition is that the gas volume is characterized by a hydrostatic pressure gradient, which previously was absent. Additionally, the location of the hull compromise is an important consideration as it will determine with volume of lifting gas remaining in the damaged hull. Since the capability of navigation is lost at this point, analysis of this condition produces little insight. An airship will drift with the wind, if it is even able to maintain stability following depressurization. Analysis of airship performance after pressure equalization will not be modeled.

3.2.4 Down Range Motion

It's of interest to operators and planners to understand more than how much time is available before an airship reaches a recovery/termination altitude. The first case considered the tactic of maintaining constant hull overpressure for as long as possible. The purpose was to maintain sufficient control of the vehicle to attempt some horizontal motion. Although the vehicle will be descending, in the constant overpressure case some estimate of horizontal distance or range needs to be made.

The simplest analysis is to solve for range covered by finding the product of the vehicle's horizontal velocity component and the time required for hull overpressure to begin to fall. During this time the vehicle will retain sufficient rigidity to maneuver to and assume a down-range course. For further simplicity the vehicle's horizontal velocity component will be assumed constant for the entire period the hull will be able to maintain a constant overpressure.

Khoury and Gillett provide a typical cruise speed range for an airship of 25 to 35 knots. [6:491] This range accounts for airship size, geometry, and also that it is not operating with a damaged hull. Higher speeds are attainable but are highly condition dependent. Considering the high altitude where the vehicle is operating, its large size, and the current challenge of developing propulsion systems to maneuver the airships, an estimate within the previously stated range seems acceptable. Complexities such as changes in hull pressure gradients due to the horizontal acceleration will be neglected and assumed not to exist or contribute to the lifting gas flow rate from the airship. Finally, a

down-range estimate will be provided to give initial insights to horizontal distance covered.

3.3 Summary

The case of the rogue research balloon traveling over 4,000 miles has stimulated interest in developing a methodology for studying the descent of a damaged airship. The aim is to develop a method for rapid estimation of how much time is available to move a damaged airship to a recovery/termination location. But the question remains on what is the best course of action to take to move that airship. A constant hull pressure could be maintained to allow some period of controlled flight or the hull pressure could be allowed to fall to zero over some period of time and conserve altitude.

Methodologies were developed to assess both cases—constant overpressure and slow depressurization. Both analyses capture insights that can be taken from the ideal gas equation and Bernoulli's principle and translated into mass balance equations. The constant overpressure case was fairly straight forward to develop because the airship hull pressure was constant in order to maintain vehicle structure. Lifting gas mass flow was easy to calculate because it required only knowing the lifting gas volume change. The case of slow depressurization added complexity. This case required an understanding of both pressure change and volume change to characterize mass flow. Providing a relative contribution factor of pressure change and volume change to the mass flow allows the change in hull pressure during descent to be predicted over small time intervals. By developing these two methodologies an analysis of the optimum course of action for recovery/termination can be performed.

A final portion of the analysis examines what occurs when the hull's overpressure has been depleted and the lifting gas pressure is equal to the atmospheric pressure. Again this case took advantage of a simplifying fact that since lifting gas flow from the hull had ceased when the overpressure equaled zero, volume of gas was the only factor affecting lifting gas density. Thus, as the vehicle descends, the gas density increases and its volume decreases. Since the process is slow it is assumed the lifting gas and atmospheric gases remain stratified with the lighter gas trapped in a "bubble" above the atmospheric gasses. This allows the assumption that lifting gas mass remains constant for this portion of the analysis.

These methods of analysis can provide insights into performance under certain conditions. The intention is to use them to understand relative outcomes and compare their utility. Further exploration of when a constant overpressure or slow pressure equalization course of action is most advantageous is the subject of the following chapter.

4. Results and Analysis

4.1 Chapter Overview

The methods developed in chapter three for analyzing the performance of a high-altitude airship that has sustained damage to its gas envelope were integrated into a model. In this chapter, the model is used to examine airship survivability. It's good to remember the modeling axiom that "every model is wrong; some are useful," as analyses of events are conducted. The goal is not to provide an exact answer predicting exactly how long a vehicle can survive. There are numerous considerations that make it very challenging to provide those types of insights given the broad view of analysis this paper has developed. However, comparative analyses provided by examining two distinct courses of action to follow when an airship hull sustains damage will provide useful insights to help the planner or operator decide what actions to take.

This chapter begins with a review of possible courses of action that might be taken to extend the survivability of an airship. Specific attention will be paid to examining what will occur if the rigidity of an airship is maintained after the hull is compromised. Two questions to be addressed are: how long can the vehicle maintain its required overpressure after being damaged and how far can the vehicle travel while maintaining the structural rigidity required to maintain control surface integrity? A comparative analysis will provide insights regarding how an airship will perform if the hull overpressure is not maintained and the vehicle is allowed to depressurize. Finally, an examination of the isothermal atmosphere assumption will be made to validate the model

results. Impacts of atmospheric pressure, density, and temperature lapse rates in the stratosphere and troposphere will be examined and compared.

Ultimately, the comparative analyses should provide recommendations that will be documented in the final section of this paper. Table 4.1 provides an overview of the insights to be developed using data developed by the airship model.

Table 4.1—Analysis questions

Question 1: How long can an airship maintain required pressure to provide the needed rigidity to sustain navigation capability following compromise of its hull?
Questions 2: How far can an airship maneuver following compromise of its hull?
Question 3: How long will it take for an airship to reach pressure equilibrium with the atmosphere following compromise of its hull?
Questions 4: How do atmospheric pressure, density, and temperature lapse rates impact the results of the isothermal model?

4.2 Analyses

4.2.1 Case 1: Maintaining Hull Overpressure

If an airship's hull is damaged allowing lifting gas to escape and depressurization to begin, it might be desirable to attempt to keep the hull pressure at its design pressure for as long as possible. The capability to maintain a constant hull overpressure would enable the airship to retain its design structure and provide integrity to its aerodynamic control surfaces. However, maintaining a constant overpressure would likely increase the loss flow rate of lifting gas resulting in a sacrifice of buoyancy. Eventually the ability to maintain constant overpressure will be lost but the opportunity to control and maneuver the vehicle for a short period might prove advantageous in recovering it or its payload. Methods for maintaining overpressure were discussed in the preceding chapter. The

method discussed in this paper was to begin expanding the ballonnet contained within the airship's hull until its design limit for inflation is reached. Depending on the size of the hole and the designed overpressure, a mass flow rate for lifting gas loss can be calculated by utilizing Bernoulli's equation and the ideal gas law. The gas loss results in diminished buoyancy. Using Newton's law for motion, characterization of the airship's vertical acceleration can be made.

Currently, the United States Army Space and Missile Defense Command (SMDC) has started an advanced concept technology demonstration to launch an unmanned high altitude airship for a one-month flight. The vehicle will "station-keep" at altitudes above 65,000 feet with the goal of operating a multi-mission sensor/communications suite. SMDC requirements call for the airship to deliver a 500 pound payload to altitude with a cruise speed capability of 20 knots. An artist's rendering of such an airship is shown in Figure 4.1 and additional information is available in Appendix D.



Figure 4.1—Lockheed Martin illustration of its high altitude airship concept vehicle [18]

The requirements for the Army's airship demonstration provide a baseline for developing modeling inputs. Notional operating requirements are required to supply inputs for modeling an airship's survivability. Table 4.2 outlines model inputs used to conduct this analysis of airship survivability. Consistency between inputs is important to

Table 4.2—Airship model inputs

Initial Altitude	21.315 km (70,000 feet)
Structural Mass (vehicle and payload)	1,000 kg
Vehicle Cruise Speed	50 km/hr (30 km/hr speed into a 20 km/hr wind)
Fineness Ratio	4 : 1
Length / Diameter	81 m / 20 m

ensure the integrity of modeling. The modeling will provide data on speed, range, and altitude for an airship while varying the hole size in the lifting gas envelope. Model inputs are notional but are related to requirements for the Army's high-altitude airship program.

The story commonly used to illustrate airship survivability describes a free-floating research balloon that was allegedly shot by Canadian fighter jets. The story alleges as many as 1,000 twenty-millimeter projectiles were fired at the balloon. It is unknown how many actually hit the balloon, but it has to be assumed that some projectiles punctured the balloon's skin. Since this story forms the basis for analysis, the equivalent puncture size of a single projectile forms the initial collection of data from the

model. Following on, modeling is made for equivalent hole sizes up to a puncture diameter of three feet. Analysis comprised making comparative measures to determine possible advantages of attempting to maintain a constant overpressure. It has been generally speculated in survivability discussions that a small puncture to an airship's skin would drive a slow escape of lifting gas. The result would be a fairly substantial reaction time to maneuver the airship for navigation down range. The model data for a single puncture of the size of a 20-millimeter projectile validates the idea of a slow process. The time estimate for hull depressurization provides ample time for maneuvering the airship and navigating it down range. The results illustrated in Figure 4.2 provide the model's estimations of the airship's ability to be successfully navigated following a 20-millimeter diameter hull puncture and attempts by operators to maintain a constant overpressure in the hull for as long as possible. Appendix C presents model results for a variety of hole sizes up to a three-foot diameter hole (.91 meter).

Down range velocity for the airship remains constant following a puncture as long as the design overpressure can be maintained. However, speed begins to fall off exponentially when a constant overpressure can no longer be maintained due to complete expansion of ballonnet inside the airship hull. The velocity decrease is due to the design relationship between over pressure and the square of the maximum down-range velocity. It was stated empirically that an airship with a small hole in its hull would have some time to maneuver before it is lost and the model bears this out. Model results for a 20 millimeter diameter hole indicate the airship will have approximately 40 hours to maneuver before exhausting its design overpressure. This will provide the airship an

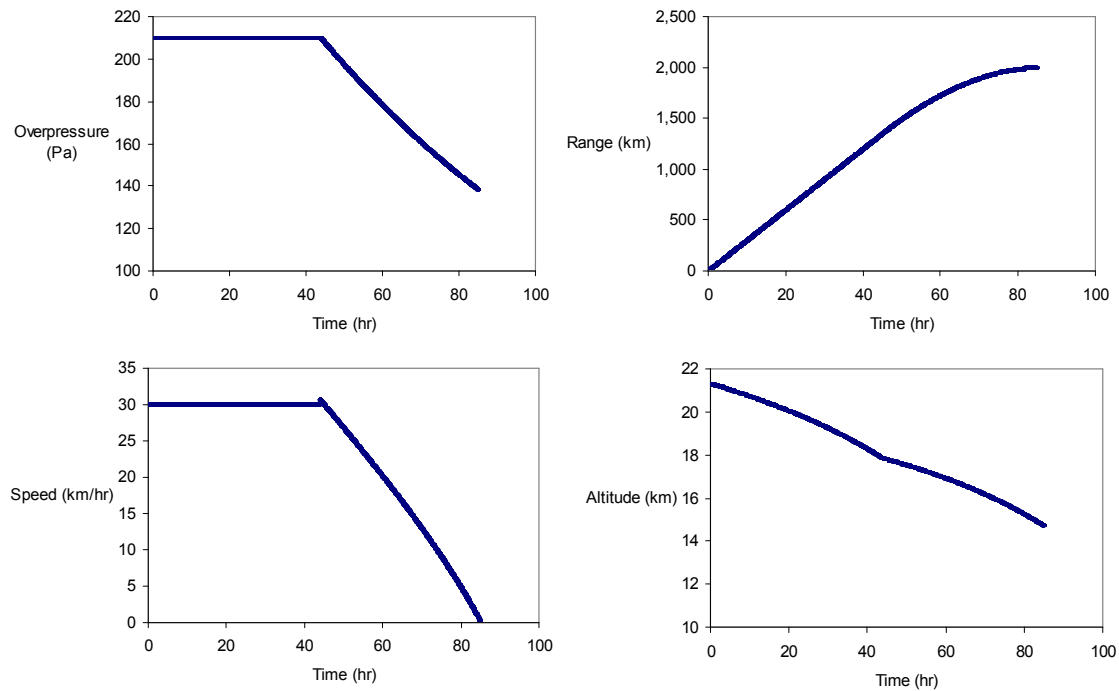


Figure 4.2—Predictions of hull depressurization, down range speed, range, and altitude for an airship with a 20 millimeter diameter hole in its lifting gas envelope.

opportunity to travel toward a recovery location at a constant speed. After losing its design overpressure, the model indicates the airship would have another period nearly as long in which its hull overpressure would decrease until it reaches atmospheric pressure. During that period the airship would be capable of maintaining a continuously decreasing velocity related to its instantaneous overpressure, further extending its possible range. Indications are the airship would have in excess of 80 hours of controllable flight, at least 40 of which would be with the hull at designed overpressure. This would provide operators with nearly 2,000 kilometers of down-range travel to maneuver the airship.

Beyond the point that the airship hull pressure equalizes with the atmospheric pressure, the airship's down-range travel may not terminate. However, it will become

difficult to characterize. The hull will lack any aerodynamic integrity to withstand stagnation pressure on its forward edge and lose all capability to maintain its fineness ratio. Model analyses beyond this point are difficult to conduct and it is assumed that at this point the vehicle is no longer capable of controlled flight. Although it remains aloft, it will drift with prevailing winds, which could be considered detrimental to the vehicle recovery operation.

Model results are best used when they are able to provide insights relative to other cases, which would allow comparisons of performance. The same modeling analysis was conducted on an airship that had experienced hull compromises of up to three feet in diameter. Significant decreases in the airship's range capability were noted as the size of the hole in the hull was increased. It seems intuitive to expect that as the hole size is increased depressurization occurs at a faster rate. This is borne out in the model's data as represented by Figure 4.3. The depressurization rate initially appears to increase slowly as the initial hole size increases by a factor of 10. Closely inspecting the resulting data shows that for small holes on the order of less than six inches the range capability falls by an order of magnitude for every three inches of diameter increase. For hole diameters between six inches and one foot the corresponding range decrease is another order of magnitude. Finally, results for hole sizes ranging from one foot to three feet in diameter the range decreases another order of magnitude. This fairly rapid decrease in range capability relative to hole size indicates a need for operators to be able to quickly select a course of action and begin its execution. The airship's range capability as shown in Figure 4.3 reflects the change in depressurization rates. Hole sizes with a diameter

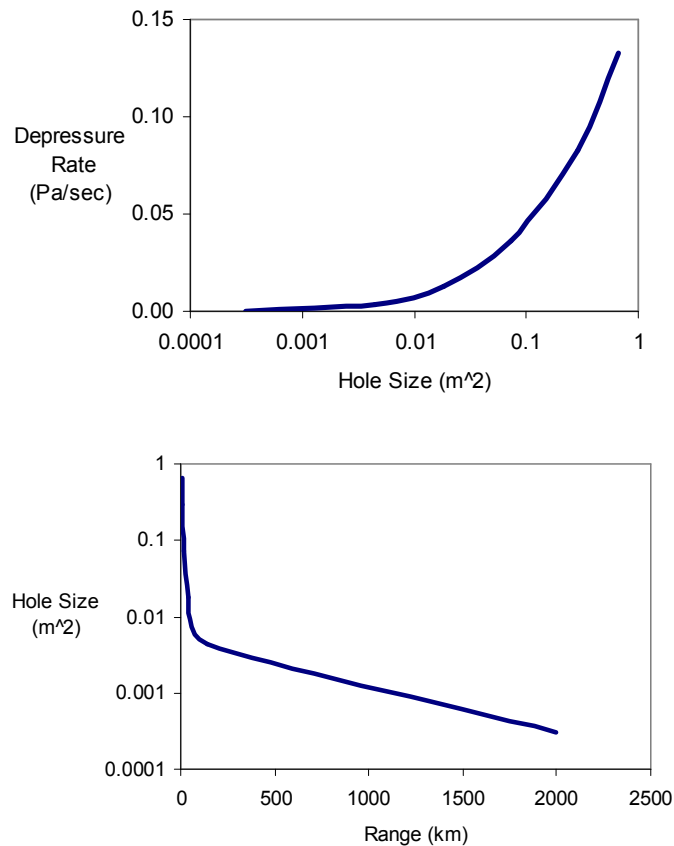


Figure 4.3—Average depressurization rate for the modeled airship and corresponding down-range travel capability for the vehicle given a range of hull puncture sizes.

greater than six inches significantly decrease the possible down-range distance the airship can attain. The airship modeled rapidly loses range when the hole size in its hull exceeds six inches in diameter. As expected the down range distance is shorter for larger holes.

However, Figure 4.4 shows an interesting result. An airship that sustains greater damage will maintain a greater altitude at pressure equalization. This altitude difference can be as much as 25 percent for the largest hole size modeled. The reason for this altitude advantage is a shorter time of forced overpressure and the corresponding lower loss of lifting gas mass. Despite significantly shorter down-range travel capabilities, the airship with a greater puncture size can maintain an altitude advantage that may be able to be

exploited. The capability to keep an airship at a greater altitude may provide an extended useful life for a system that is not a priority to recover. A disposable communications relay or altitude-tuned sensor may be kept over a location at a more advantageous altitude; something not possible if the vehicle descends too quickly. This altitude advantage could be exploited to minimize or eliminate loss of coverage times experienced while a replacement vehicle is deployed.

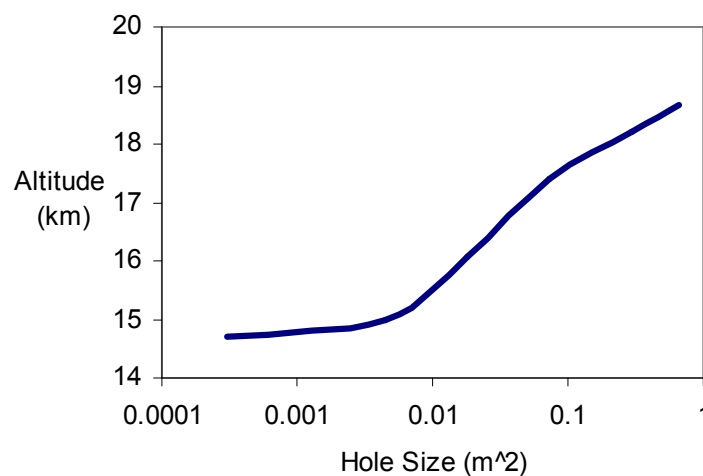


Figure 4.4—Predicted altitude at atmospheric pressure equalization for an airship maintaining constant overpressure for some period following a hull compromise.

As seen in the initial set of performance curves hull depressurization is characterized by two distinct phases: a period of constant overpressure followed by another period of pressure falling to equalize with the surrounding atmosphere. The change in processes is evident by a “knee” in the depressurization curve. In this region beyond the knee in the curve the airship’s hull depressurization process becomes solely based on the instantaneous difference between the envelope and atmospheric pressures. Since the hull pressure is decreasing from its initial design pressure, the velocity the

lifting gas is escaping is slower. This can be illustrated using Bernoulli's equation. A larger overpressure will result in a higher average velocity of lifting gas escaping from the hull. It's likely that not attempting to maintain a designed overpressure will result in a slower loss of lifting gas and possibly provide greater attitude capability. It warrants examining the case of allowing the hull to depressurize without attempting to maintain design overpressure.

4.2.2 Case 2: Allowing Hull Depressurization

The natural tendency is for a gas to flow from a region of higher pressure to a region of lower pressure. Simply put, that is the basis for examining case two. If a lifting gas envelope is compromised, the flow of gas will be out of the hull into the atmosphere. This process will continue as long as a pressure difference exists. Case two examines whether the airship's performance would be enhanced by a slower loss of lifting gas by not maintaining hull pressure as in case one. Since buoyancy is a function of lifting gas mass as stated earlier, then there may be some benefit to preserving the amount of lifting gas on board the airship. Case two proposes slowing the loss rate of lifting gas over case one in order to preserve lift.

The same model used to characterize the airship's performance following loss of constant overpressure was applied to this question. The same starting atmospheric parameters and vehicle performance requirements used in case one were used in this portion of the analysis. The analysis included looking at a baseline hull compromise equivalent to a hole made by a 20 millimeter projectile and then ranging it up to three feet in diameter. Figure 4.5 shows the performance characteristics of an airship allowed to

undergo depressurization without attempting to maintain its design overpressure. The data is compared with the airship's performance while maintaining a constant overpressure for the same size hole.

As with case one and empirical predictions, allowing the hull to depressurize through a small hole provides a significant period of controllable flight. Interestingly essentially the same time to reach atmospheric pressure equalization within the hull is

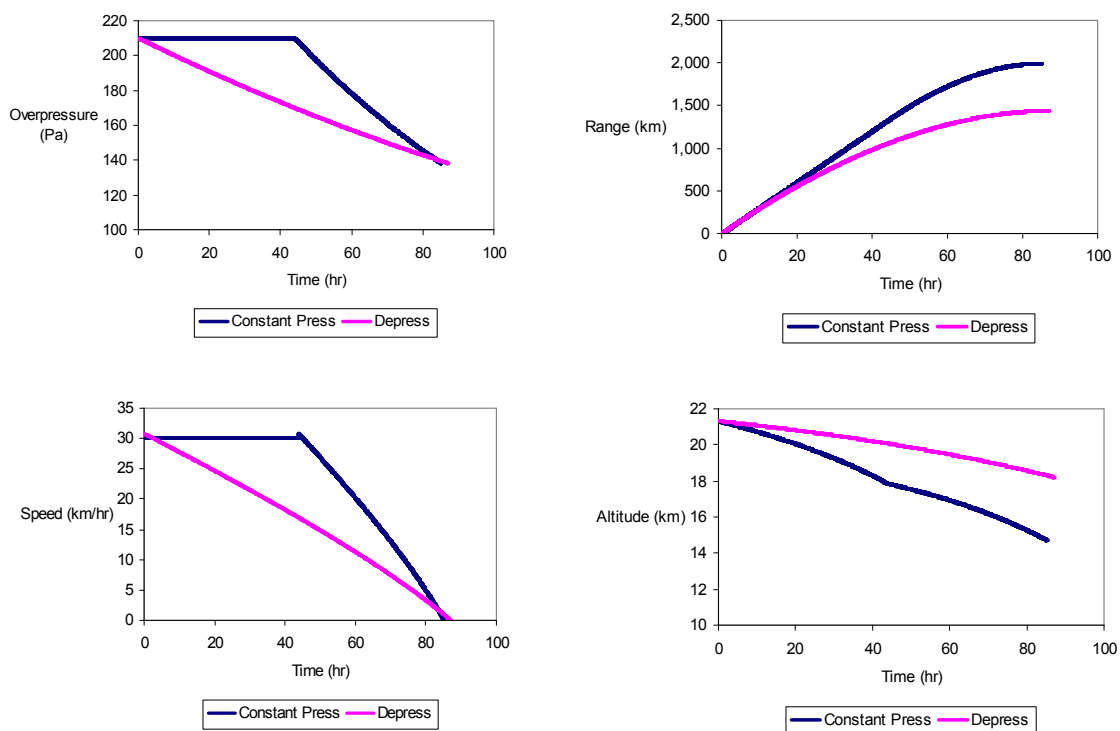


Figure 4.5—Predictions of hull depressurization, down range speed, range, and altitude for an airship with a 20 millimeter diameter hole in its lifting gas envelope. Comparison is made with performance of the airship when a constant overpressure is maintained for some period of time.

noted in both scenarios. However, because velocity is exponentially related to the airship's design overpressure, a significantly lower down-range speed is predicted. The end result is a less favorable prediction of down-range distance when the airship is

allowed to slowly depressurize. Distance traveled during slow depressurization is about 27 percent less than distance covered while maintaining a constant overpressure for a 20 millimeter diameter hole. However, as the hole size reaches the upper end of the range modeled, the slowly depressurizing airship covers 85 percent less distance than the airship maintaining constant overpressure. Figure 4.6 shows that for larger hole sizes range capability is improved by attempting to maintain the airship's design overpressure. The advantage of keeping the airship's design overpressure at design level as long as possible is realized in down-range distance capability—especially for larger hole sizes.

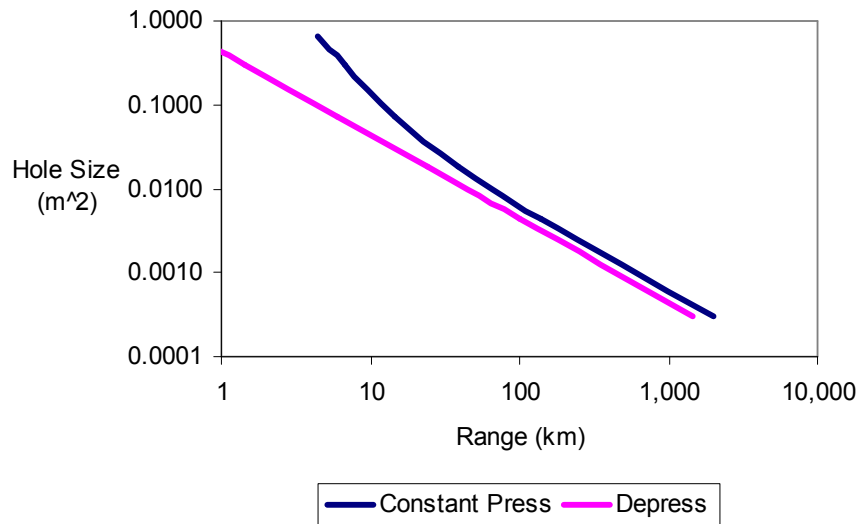


Figure 4.6—Down-range distance capability decreases more rapidly for an airship undergoing slow depressurization than when design overpressure is maintained. This becomes increasingly severe as hole sizes increase.

The advantage of allowing a slow depressurization is in preservation of altitude. Modeling indicates that the airship allowed to undergo slow depressurization retained nearly 20 percent more of its initial altitude than an airship maintaining a constant overpressure. The average descent rate for an airship with a 20 millimeter diameter hole

undergoing slow depressurization is .019 meters/second; more than 50 percent slower than the airship that is maintaining a constant overpressure. The slower depressurization drives a smaller lifting gas loss rate than when a constant overpressure is maintained. Attempts to maintain a constant overpressure actually drive an increasing mass flow rate from the hull as shown in Figure 4.7. The increasing rate is due to the greater difference in hull and atmospheric pressure as the airship descends. Conversely, slow depressurization creates a decreasing difference between hull and atmospheric pressure and lifting gas mass is preserved.

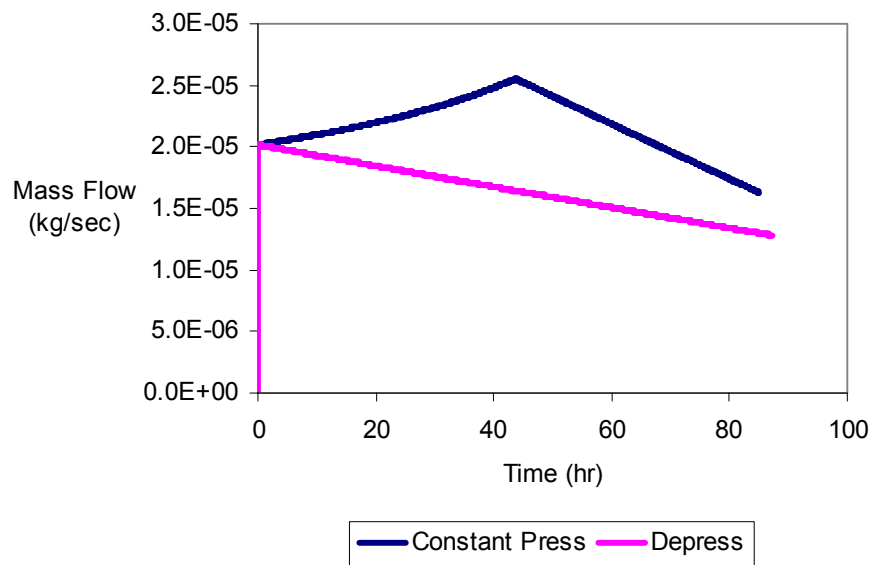


Figure 4.7—Mass flow rate comparisons for the constant pressure and slow depressurization cases. The increasing loss rate for the constant overpressure case is due to increasing pressure differences between hull and atmospheric pressures and results a decreased altitude at atmospheric equalization

The slower descent rate advantage of allowing depressurization might be beneficial for extending the useful life of a damaged vehicle providing communication or sensor coverage over a specific location. If recovery of the system is not critical and wind

conditions are favorable, slow depressurization could allow a system to remain high over a location longer. The advantage is seen as a decrease in the loss of coverage time over a location while a replacement is deployed. This advantage can be exploited for communication relays, which increase line of sight transmissions for radio broadcasts, or for an altitude-tuned sensor that's useful life can be extended by preserving altitude. Additionally, preserving altitude may provide improved range by allowing the vehicle to travel above stronger jet stream winds that exist below 70,000 feet. Despite control surface integrity compromises, less intense head winds may allow an airship to increase its range at a higher altitude.

4.2.3 The Isothermal Assumption

An important assumption made in developing the airship model is the isothermal atmosphere assumption. The airship performance data developed by the model is based on an earth's atmosphere in which its constituents are well mixed and maintain a constant concentration. This type of atmosphere allows the determination of a scale height, which is based on an average temperature within the atmosphere and was discussed in chapter two. As stated earlier, by the ideal gas law pressure is proportional to temperature, so atmospheric pressure can be affected by temperature. Because airship performance is closely related to atmospheric pressure, it is worthwhile to examine the assumption that an atmospheric temperature lapse rate can be neglected in this model.

Atmospheric pressure, temperature, and density lapse rates can be modeled accurately by the US Standard Atmosphere, 1976. This atmospheric model divides the earth's atmosphere into several layers based on altitude extending from sea level to

beyond 100 kilometers. [19:21] In each of these atmospheric layers a series of equations characterize the lapse rates for pressure, temperature, and density specific to that layer. The airship modeling was conducted primarily in two of the atmospheric regions—layers two and three. Both layers are defined as the stratosphere by the model. Layer two reaches from 11 kilometers altitude (above sea level) to less than 20 kilometers. This region is characterized by an isothermal layer generally understood meteorologically to have a temperature lapse rate equal to zero. Layer three lies above 20 kilometers to less than 32 kilometers and exhibits an increasing temperature with altitude. Figure 4.8 shows atmospheric temperature, pressure, and density profiles as defined by the Standard Atmosphere model. In the graphs the values are compared with profiles generated using the isothermal assumption.

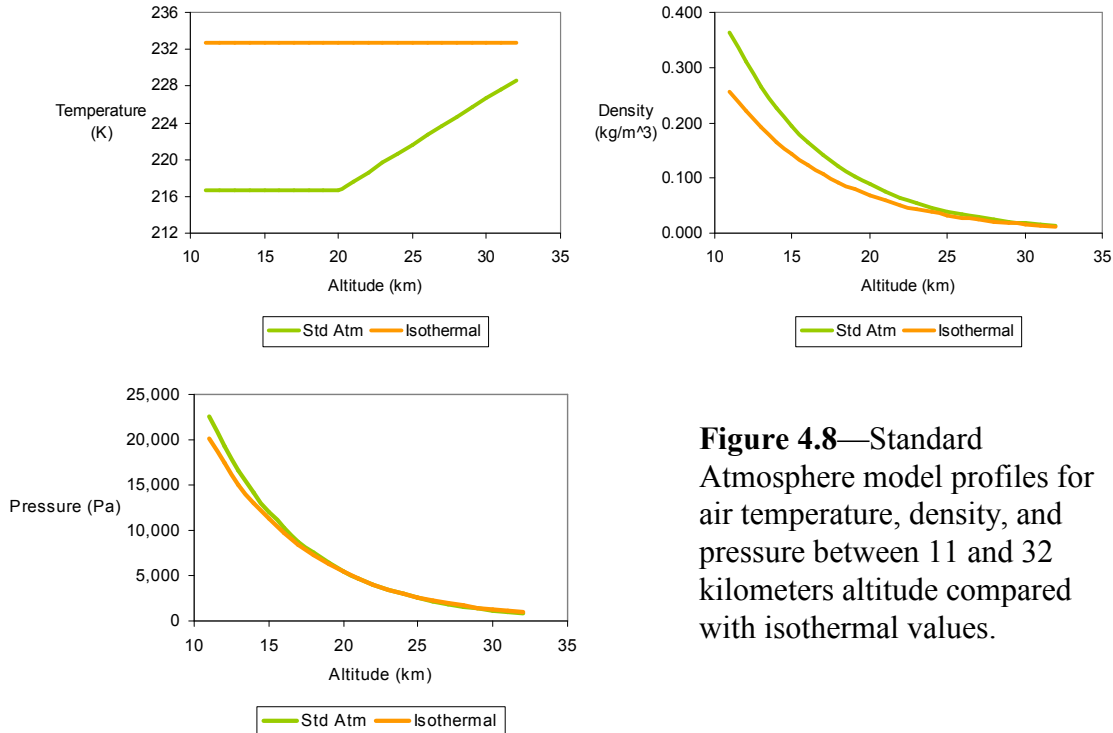


Figure 4.8—Standard Atmosphere model profiles for air temperature, density, and pressure between 11 and 32 kilometers altitude compared with isothermal values.

Mathematical expressions for atmospheric temperature, pressure, and density of a standard atmosphere were inserted into the model in place of their corresponding isothermal atmosphere model value. [15:13] These equations are listed in Appendix A. The model was asked to produce output for an airship under the same conditions as the case one analysis with a corresponding gas envelope hole size equal to a 20 millimeter diameter projectile. The output results are shown in Figure 4.9 as compared to the same scenario assuming isothermal conditions.

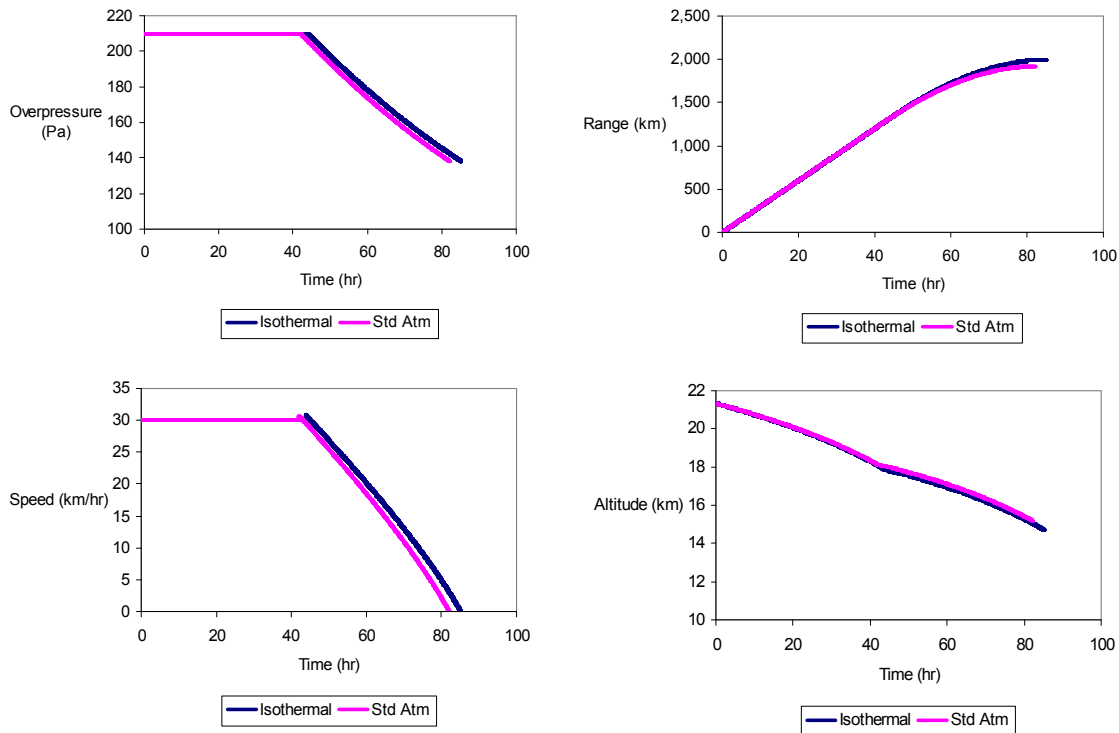


Figure 4.9—Comparison of performance characteristics for an airship modeled in a US Standard Atmosphere 1976 model and an isothermal atmosphere model.

The output using the standard atmosphere provided closely corresponding results, deviating less than 3.5 percent over the controllable flight portion of the airship’s depressurization. Differences are likely due to slightly smaller mass flow rates predicted

by the standard atmosphere. This is evident from the range and altitude results in Figure 4.9. Lower mass flow rates are evident by the decreased range and increased altitude predictions the model provides for the standard atmosphere.

4.3 Summary

Building on the understanding of airship design, Bernoulli's Principle, the ideal gas law, and atmospheric characteristics, a model was developed to provide data on performance parameters of a damaged airship. Airship design and performance requirements provided predictions on how an airship's survivability is impacted by the damage it sustains. Important maneuver capabilities such as down-range speed, distance, and altitude were characterized as a function of hull overpressure for tailored scenarios. The data developed by the model provided insights on options to pursue to extend the life of a damaged airship.

The robustness of the model was challenged by examining a key atmospheric assumption—that atmospheric temperature effects have minimal impact on a first-order analysis. Using the 1976 US Standard Atmosphere model to develop atmospheric temperature, pressure, and density lapse rates, the model produced data that deviated less than 3.5 percent from the output developed from an isothermal model. The reproduction of such data lends credibility to the assumption that for this analysis the atmospheric effects on airship performance can be modeled assuming an average temperature.

5. Conclusion

5.1 Conclusion

Survivability concerns for a damaged airship have on occasion been anecdotally answered with the 1998 flight of a rogue Canadian research balloon. Is this a fair comparison for survivability of a self-propelled, navigable airship? Critical for the design of an airship is the hull overpressure. It is strongly correlated to an airship's maximum down range velocity. The idea of survivability needs to be well understood as conclusions are made. If airship survivability is tied to the ability to maintain control over the vehicle and its performance, then its survivability must be related to the overpressure of its lifting gas hull. Once the overpressure is depleted the airship is a free-floating vehicle. If survivability is based on the operator's ability to recover the airship or its payload, then only the controllable portion of flight can be considered during analysis.

This chapter synthesizes ideas developed regarding impacts to airship survivability. Understanding airship performance when damage occurs can drive a course of action to take to best utilize a resource. Knowing possible courses of action to take after an airship is damaged can help shed light on what steps to take with a crippled airship.

It seems Thome correctly postulated that a punctured balloon would descend slowly as lifting gas diffuses into the atmosphere. The data produced by the model for both courses of action support his contention. However, in his paper Thome's reference was to a free-floating vehicle and not a navigable airship. Despite modeling support that a damaged balloon may stay aloft several days, its motion would be directed solely by the

prevailing wind currents and have no autonomy in setting a course heading or maintaining a position. Viewing survivability without the ability to take positive steps to navigate an airship into a position to recover it and/or its payload is the communication equivalent of sending a message in a bottle at sea. The chance of the message reaching the correct audience is small. Similarly, leaving a damaged airship to float freely as the Canadian research balloon did leaves little guarantee that any hope exists of recovering it or exploiting its remaining capabilities. This is particularly valid in a conflict situation where hostile intentions and sensitive operations can impact the recovery process. Yes, it is possible for an airship to remain aloft for days and travel for thousands of miles as was demonstrated in the research balloon scenario. But, its course and speed can only be passively postulated by meteorological predictions, rather than be positively controlled by an on-board control system. In terms of survivability, the balloon example only provides evidence an airship might be able to stay aloft for significant duration. The application of Thome's example by lighter-than-air proponents to the case of airship survivability has shortcomings that need to be understood quantitatively.

This paper focused on developing a physical model to help understand survivability of an airship. It has added insights on how maneuverable an airship is following a compromise to its lifting gas hull. Through the modeling three valuable insights have been gained. First, it is likely that an airship with a compromised hull will not quickly fall out of the sky, but may stay aloft for a considerable amount of time. However, during only a portion of that time will the airship actually be able to navigate on a heading. Eventually the airship will become free floating, unable to withstand

aerodynamic loads caused by moving against atmospheric currents. An interesting model result for the airship is that whether hull overpressure is maintained constant or it is allowed to deflate slowly, the time to reach atmosphere pressure equalization is essentially the same.

Second, an airship can maximize its cross-range distance following damage by attempting to maintain its designed hull overpressure. Using mechanisms such as ballonnet inflation, an airship can maintain its design overpressure and sustain for a portion of time its aerodynamic design. Preserving its hull shape and overpressure allows the airship to reach maximum cross-range speeds as suggested by Khoury and Gillett's design relationship between hull pressure and speed. Since a greater average speed is maintained by keeping the pressure constant for some period, down-range distance is improved 28 percent over slow depressurization. In addition, the likelihood of being able to follow the most favorable heading for recovery is increased because the aerodynamic properties of the airship can be preserved. But increased range comes with a price and that is altitude loss. Modeling demonstrates that the longer an airship attempts to maintain a constant overpressure, the greater the loss of altitude. This gives rise to the third insight.

A slowly depressurized airship will retain greater altitude at atmospheric pressure equalization than one that attempts to maintain hull overpressure. Model comparisons suggest that by slowly depressurizing an airship, nearly 20 percent more altitude may be preserved. This may be an important consideration if the desire is to maintain coverage over an area and altitude is an important consideration. Additionally, stronger jet stream

winds are typically found at altitudes below 70,000 feet. Preserving altitude and navigating against a lower speed wind in some cases could be advantageous. Despite having a slower speed capability, less head wind could result in a better average cross-range speed and greater distance.

5.2 The Way Ahead

Space Command is working vigorously to set a course for developing methods to utilize near space for the benefit of warfighters. Technical feasibility studies and demonstrations have already shown the benefits of placing a communication relay above a battlefield to extend radio broadcasts over the horizon. Combat Skysat was a successful demonstration by the space battlelab of how communication lines can be extended by placing a radio relay on a balloon and releasing it over the battlefield. Its initial success has set the stage for exploring more options on how to operate in near space. The Missile Defense Agency's attempt to fly a true airship at near space altitudes continues the effort to exploit near space operations. Since these vehicles are carrying important payloads and themselves can be special pieces of equipment, insights need to be developed regarding how to increase their survivability.

Operators and planners value having recovery options that present scenario specific advantages. It is important for high-altitude airship designers to comprehend what occurs when the lifting gas hull is compromised. Likewise, users must expect designers to think through scenarios to ensure the ability to recover or maximize the utility of a damaged airship is explored. This study focuses on a small portion of the survivability question, which is understanding basic options available to the operator or

planner once an airship has been damaged. Additional systems work on this topic can include: examining alternative methods for preserving hull overpressure; developing rapid damage assessment processes to assist in survivability course of action selection; or designing an aerial processes for recovering an airship at a designated recovery location. A possible technical topic is computational fluid dynamic modeling of lifting gas escaping from the airship hull in order to validate the use of Bernoulli's equation. Each of these topics will need to be addressed as part of the overall survivability question.

5.3 Summary

This paper provides insights about high-altitude airship survivability. Much is being said about airship survivability, most of it anecdotal. There is no doubt that a damaged lighter-than-air vehicle can travel a great distance despite sustaining damage. A 1998 trans-Atlantic balloon flight example is the most noted. If merely staying aloft is the most important aspect of survivability then the rogue balloon flight is a sufficient example of capability. However, if survivability includes the ability to positively control a vehicle following damage, then a physical assessment is needed.

An airship depends on its lifting gas to maintain altitude. When its gas envelope is compromised and gas flows out the vehicle it will descend. How quickly it descends and where it will no longer be able to be controlled are key questions regarding survivability. Two scenarios were explored in this work: maintaining a constant overpressure to preserve airship aerodynamics; or allowing slow depressurization to maintain altitude. Analysis demonstrates that when an airship maintains a constant overpressure for some period of time following damage, its ability to navigate down

range is increased. Alternatively, when the airship is allowed to depressurize slowly it will preserve altitude otherwise lost when a constant pressure is maintained. Eventually, regardless of the course of action taken the airship's hull will equalize with atmospheric pressure. At this point the ability to navigate is lost and the vehicle will be forced to simply drift with atmospheric currents.

Understanding options exist can be important when a war-fighting asset is damaged. Recovering it or maximizing its remaining life can be important strategic decisions. Careful attention needs to be given to the survivability question of high-altitude airships. Continued technical study needs to be conducted on the performance of damaged airships and quantifiable results must accompany anecdotal evidence regarding the question of survivability.

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Appendix A – 1976 United States Standard Atmosphere Model Equations [15:13] [20]

h = altitude above sea level

T_o = absolute temperature at sea level = 288.15 K

ρ_o = density of air at sea level = 1.225 kg/m³

P_o = standard air pressure at sea level = 101325 Pa

Lapse Rates for Region: 11 km < h < 20 km

$$\text{Temperature (K)} = T_o(.751865)$$

$$\text{Pressure (Pa)} = P_o(.223361)\exp((10999-h)/6341.4)$$

$$\text{Density (kg/m}^3\text{)} = \rho_o(.297076)\exp((10999-h)/6341.4)$$

Lapse Rates for Region: 20 km < h < 32 km

$$\text{Temperature (K)} = T_o(.682457+h/288136)$$

$$\text{Pressure (Pa)} = P_o(.988626+h/198903)^{-34.16319}$$

$$\text{Density (kg/m}^3\text{)} = \rho_o(.978261+h/201010)^{-35.16319}$$

Appendix B – Model Output Data Case 1 – Constant Overpressure

time inc = 10 sec	mw H ₂ = 0.000 g/mole	g = 6.31E-3 m ³ Pa / mole K	ss area = 1048.30 m ²	rho0 = 1.20 kg/m ³
H = 5.82 km	mw air = 0.000 g/mole	T = 232.15 K	beta coeff = 81.2 m	speed = 1.20 m/s
p0 = 101325 Pa	gravity = 9.81 m/sec ²	init alt = 70.000 m	A = 20.0 m	
mass st = 1000 kg	delta p = 210 Pa	area hole = 0.0728 m ²		

time sec	P Pa	mass H ₂ kg	mass air kg	mass tot kg	accn m/sec ²	v km	h km	h ft	v H ₂ m/sec	m dot kg	delta m kg	vol H ₂ m ³	50% vol m ³	Distance km
10	4.450	169	1.000	1.169	0.000	0.000	21.42	70.000	6.75	0.005	0.05	17.592	10.812	0.00
10	4.450	169	1.000	1.169	-0.002	-0.024	21.315	69.999	6.75	0.005	0.05	17.514	CONTINUE	0.08
20	4.450	169	1.000	1.169	-0.005	-0.070	21.314	69.997	6.75	0.005	0.05	17.508	CONTINUE	0.17
30	4.451	169	1.000	1.169	-0.007	-0.140	21.313	69.992	6.75	0.005	0.05	17.499	CONTINUE	0.26
40	4.452	169	1.000	1.169	-0.008	-0.230	21.310	69.985	6.75	0.005	0.05	17.489	CONTINUE	0.33
50	4.453	169	1.000	1.169	-0.011	-0.339	21.307	69.974	6.75	0.005	0.05	17.478	CONTINUE	0.42
60	4.456	169	1.000	1.169	-0.012	-0.461	21.302	69.958	6.75	0.005	0.05	17.460	CONTINUE	0.50
70	4.459	168	1.000	1.169	-0.013	-0.592	21.296	69.939	6.75	0.005	0.05	17.440	CONTINUE	0.58
80	4.462	168	1.000	1.168	-0.013	-0.727	21.289	69.915	6.74	0.005	0.05	17.417	CONTINUE	0.67
90	4.467	168	1.000	1.168	-0.013	-0.859	21.281	69.887	6.74	0.005	0.05	17.392	CONTINUE	0.75
100	4.473	168	1.000	1.168	-0.012	-0.984	21.271	69.856	6.74	0.005	0.05	17.363	CONTINUE	0.83
110	4.479	168	1.000	1.168	-0.011	-1.098	21.260	69.819	6.73	0.005	0.05	17.331	CONTINUE	0.92
120	4.486	168	1.000	1.168	-0.010	-1.200	21.248	69.779	6.73	0.005	0.05	17.297	CONTINUE	1.00
130	4.494	168	1.000	1.168	-0.008	-1.289	21.235	69.737	6.72	0.005	0.05	17.261	CONTINUE	1.08
140	4.503	168	1.000	1.168	-0.008	-1.367	21.221	69.692	6.71	0.005	0.05	17.223	CONTINUE	1.17
150	4.512	168	1.000	1.168	-0.007	-1.434	21.207	69.645	6.71	0.005	0.05	17.184	CONTINUE	1.25
160	4.521	168	1.000	1.168	-0.006	-1.492	21.192	69.598	6.70	0.005	0.05	17.143	CONTINUE	1.33
170	4.531	168	1.000	1.168	-0.005	-1.543	21.177	69.545	6.69	0.005	0.05	17.101	CONTINUE	1.42
180	4.542	168	1.000	1.168	-0.005	-1.589	21.161	69.493	6.69	0.005	0.05	17.058	CONTINUE	1.50
190	4.553	168	1.000	1.168	-0.004	-1.630	21.144	69.439	6.68	0.005	0.05	17.014	CONTINUE	1.58
200	4.563	168	1.000	1.168	-0.004	-1.668	21.128	69.385	6.67	0.005	0.05	16.970	CONTINUE	1.67
210	4.574	168	1.000	1.168	-0.004	-1.703	21.111	69.329	6.66	0.005	0.05	16.926	CONTINUE	1.75
220	4.586	168	1.000	1.168	-0.003	-1.736	21.093	69.272	6.65	0.005	0.05	16.882	CONTINUE	1.83
230	4.597	168	1.000	1.168	-0.003	-1.767	21.076	69.214	6.64	0.005	0.05	16.838	CONTINUE	1.92
240	4.609	168	1.000	1.168	-0.003	-1.797	21.058	69.155	6.64	0.005	0.05	16.793	CONTINUE	2.00
250	4.621	168	1.000	1.168	-0.003	-1.825	21.039	69.095	6.63	0.005	0.05	16.747	CONTINUE	2.08
260	4.634	168	1.000	1.168	-0.003	-1.852	21.021	69.034	6.62	0.005	0.05	16.699	CONTINUE	2.17
270	4.646	168	1.000	1.168	-0.003	-1.878	21.002	68.972	6.61	0.005	0.05	16.650	CONTINUE	2.25
280	4.659	168	1.000	1.167	-0.003	-1.904	20.983	68.910	6.60	0.005	0.05	16.601	CONTINUE	2.33
290	4.672	167	1.000	1.167	-0.002	-1.928	20.964	68.846	6.59	0.005	0.05	16.551	CONTINUE	2.42
300	4.685	167	1.000	1.167	-0.002	-1.952	20.944	68.782	6.58	0.005	0.05	16.501	CONTINUE	2.50
310	4.698	167	1.000	1.167	-0.002	-1.975	20.924	68.718	6.57	0.005	0.05	16.451	CONTINUE	2.58
320	4.713	167	1.000	1.167	-0.002	-1.997	20.905	68.652	6.56	0.005	0.05	16.399	CONTINUE	2.67
330	4.728	167	1.000	1.167	-0.002	-2.019	20.884	68.586	6.55	0.005	0.05	16.349	CONTINUE	2.75
340	4.743	167	1.000	1.167	-0.002	-2.040	20.864	68.519	6.54	0.005	0.05	16.297	CONTINUE	2.83
350	4.758	167	1.000	1.167	-0.002	-2.061	20.843	68.451	6.53	0.005	0.05	16.246	CONTINUE	2.92
360	4.769	167	1.000	1.167	-0.002	-2.081	20.823	68.383	6.52	0.005	0.05	16.193	CONTINUE	3.00
370	4.784	167	1.000	1.167	-0.002	-2.101	20.801	68.314	6.51	0.005	0.05	16.141	CONTINUE	3.08
380	4.798	167	1.000	1.167	-0.002	-2.120	20.780	68.244	6.50	0.005	0.05	16.087	CONTINUE	3.17
390	4.813	167	1.000	1.167	-0.002	-2.139	20.759	68.174	6.49	0.005	0.05	16.033	CONTINUE	3.25
400	4.828	167	1.000	1.167	-0.002	-2.157	20.737	68.104	6.48	0.005	0.05	15.979	CONTINUE	3.33
410	4.844	167	1.000	1.167	-0.002	-2.175	20.716	68.031	6.47	0.005	0.05	15.924	CONTINUE	3.42
420	4.859	167	1.000	1.167	-0.002	-2.193	20.695	67.959	6.46	0.005	0.05	15.869	CONTINUE	3.50
430	4.875	167	1.000	1.167	-0.002	-2.210	20.672	67.887	6.45	0.005	0.05	15.813	CONTINUE	3.58
440	4.891	167	1.000	1.167	-0.002	-2.227	20.649	67.814	6.44	0.005	0.05	15.757	CONTINUE	3.67
450	4.907	167	1.000	1.167	-0.002	-2.244	20.627	67.740	6.43	0.005	0.05	15.703	CONTINUE	3.75
460	4.923	167	1.000	1.167	-0.002	-2.260	20.604	67.666	6.42	0.005	0.05	15.648	CONTINUE	3.83
470	4.939	167	1.000	1.167	-0.002	-2.276	20.581	67.591	6.41	0.005	0.05	15.593	CONTINUE	3.92
480	4.956	167	1.000	1.167	-0.002	-2.292	20.558	67.516	6.40	0.005	0.05	15.538	CONTINUE	4.00
490	4.972	166	1.000	1.166	-0.002	-2.307	20.535	67.440	6.39	0.005	0.05	15.484	CONTINUE	4.08
500	4.989	166	1.000	1.166	-0.002	-2.323	20.512	67.364	6.38	0.005	0.05	15.428	CONTINUE	4.17
510	5.006	166	1.000	1.166	-0.002	-2.338	20.489	67.287	6.37	0.005	0.05	15.373	CONTINUE	4.25
520	5.023	166	1.000	1.166	-0.001	-2.352	20.465	67.210	6.36	0.005	0.05	15.318	CONTINUE	4.33
530	5.041	166	1.000	1.166	-0.001	-2.367	20.442	67.132	6.35	0.005	0.05	15.262	CONTINUE	4.42
540	5.058	166	1.000	1.166	-0.001	-2.381	20.418	67.055	6.33	0.005	0.05	15.206	CONTINUE	4.50
550	5.075	166	1.000	1.166	-0.001	-2.395	20.394	66.975	6.32	0.005	0.05	15.151	CONTINUE	4.58
560	5.094	166	1.000	1.166	-0.001	-2.409	20.370	66.896	6.31	0.005	0.05	15.095	CONTINUE	4.67
570	5.112	166	1.000	1.166	-0.001	-2.423	20.346	66.816	6.30	0.005	0.05	15.039	CONTINUE	4.75
580	5.130	166	1.000	1.166	-0.001	-2.436	20.321	66.736	6.29	0.005	0.05	14.983	CONTINUE	4.83
590	5.148	166	1.000	1.166	-0.001	-2.450	20.297	66.656	6.28	0.005	0.05	14.926	CONTINUE	4.92
600	5.167	166	1.000	1.166	-0.001	-2.463	20.272	66.575	6.27	0.005	0.05	14.870	CONTINUE	5.00
610	5.185	166	1.000	1.166	-0.001	-2.476	20.247	66.494	6.26	0.005	0.05	14.814	CONTINUE	5.08
620	5.204	166	1.000	1.166	-0.001	-2.488	20.222	66.412	6.25	0.005	0.05	14.757	CONTINUE	5.17
630	5.223	166	1.000	1.166	-0.001	-2.501	20.197	66.330	6.24	0.005	0.05	14.701	CONTINUE	5.25
640	5.243	166	1.000	1.166	-0.001	-2.513	20.172	66.247	6.22	0.005	0.05	14.644	CONTINUE	5.33
650	5.262	166	1.000	1.166	-0.001	-2.526	20.147	66.165	6.21	0.005	0.05	14.588	CONTINUE	5.42
660	5.282	166	1.000	1.166	-0.001	-2.538	20.122	66.081	6.20	0.005	0.05	14.531	CONTINUE	5.50
670	5.301	166	1.000	1.166	-0.001	-2.550	20.096	65.997	6.19	0.005	0.05	14.475	CONTINUE	5.58
680	5.321	165	1.000	1.165	-0.001	-2.562	20.071	65.913	6.18	0.005	0.05	14.418	CONTINUE	5.67
690	5.341	165	1.000	1.165	-0.001	-2.573	20.045	65.829	6.16	0.005	0.05	14.361	CONTINUE	5.75
700	5.361	165	1.000	1.165	-0.001	-2.585	20.019	65.744	6.15	0.005	0.05	14.304	CONTINUE	5.83
710	5.382	165	1.000	1.165	-0.001	-2.596	19.993	65.659	6.14	0.005	0.05	14.248	CONTINUE	5.92
720	5.402	165	1.000	1.165	-0.001	-2.608	19.967	65.573	6.13	0.005	0.05	14.191	CONTINUE	6.00
730	5.423	165	1.000	1.165	-0.001	-2.619	19.941	65.487	6.12	0.005	0.05	14.134	CONTINUE	6.08
740	5.444	165	1.000	1.165	-0.001	-2.630	19.914	65.401	6.11	0.005	0.05	14.077	CONTINUE	6.17
750	5.465	165	1.000	1.165	-0.001	-2.641	19.888	65.314	6.09	0.005	0.05	14.020	CONTINUE	6.25
760	5.486	165	1.000	1.165	-0.001	-2.652	19.862	65.227	6.08	0.005	0.05	13.964	CONTINUE	6.33
770	5.507	165	1.000	1.165	-0.001	-2.663	19.836	65.139	6.07	0.005	0.05	13.907	CONTINUE	6.42
780	5.529	165	1.000	1.165	-0.001	-2.673	19.809	65.052	6.06	0.005	0.05	13.850	CONTINUE	6.50
790	5.551	165	1.000	1.165	-0.001	-2.684	19.781	64.963	6.05	0.005	0.05			

Case 1 Data (continued)

time inc. =	10	sec	mw He =	0.009	kg/mole	B =	8.314	J/m ³ Pa / mole K	rho0 =	1.29	g/m ³	as area =	1648.5	m ²	speed x-range =	39	km/hr
time =	6.82	min	mw air =	0.029	kg/mole	T =	232.68	K	rho He =	0.179	g/m ³	drag coeff =	0.43				
mass =	101325	Pa	gravity =	9.81	m/sec ²	init alt =	59240	m	dp/dt factor	0.5		A =	81.2	m			
mass st. =	1000	kg	p cov	210	Pa	area hole =	0.0726	m ²	dV/dt factor	0.5		B =	20.3	m			

[illegible]

line inc = 10	sec	mw He = 0.004	mole	R = 8.314	m ³ Pa / mole K	rho0 = 1.20	g/cm ³	vs area = 1648.36	m ²	speed x-range = 30
line air = 6.82	sec	mw air = 0.029	g/mole	T = 232.68	K	rho0 He = 0.179	g/cm ³	drag coeff = 0.2		
p0 = 101325	Pa	gravity = 9.81	m/sec ²	mit alt = 70000	21315	km	dpr/dt factor = 0.5	A = 81.2	m	
mass st = 1000	kg	p.op = 210	Pa	area hole = 0.0728	m ²		dV/dt factor = 0.5	B = 2023	m	

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Isothermal Assumption Test Data

time inc = 10 sec	time He = 0.004 kg/mole	R = 8.314 m ³ Pa / mole K	sa area = 1640.30 m ²	tho = 1.720 kg/m ³
l = 5.63 km	ma ar = 0.020 kg/mole	T0 = 288.15 K	area conv = 0.3	tho = 0.3
mu = 19.122 Pa	gravity = 9.81 m/sec ²	21.315 km	A = 6.14 m	tho = 0.3
mass st = 1000 kg	delta p = 0.110 Pa	area hco = 0.072 m ²	R = 8.314 m ³ Pa / mole K	

time sec	P atm	mass He kg	mass st kg	mass tot kg	accnt m/sec ²	v fall m/s	ut m	vt m	v He m/sec	m out kg/sec	delta m m ³	vol He m ³	50% vol m ³	Dist x-m km	ut m	ho air m	temp K
0	4.452	169	1.000	1.169	0.00000	0.000	21.32	70.000	6.54	0.00490	0.04896	16.407	9.844	0.00	21315	0.071148	217.966
10	4.452	169	1.000	1.169	-0.00243	-0.024	21.315	69.999	6.54	0.004896	0.04896	16.402	CONTINUE	0.08	21314.76	0.071148	217.966
20	4.452	169	1.000	1.169	-0.00492	-0.0726	21.314	69.997	6.54	0.004896	0.04896	16.397	CONTINUE	0.17	21314.03	0.071151	217.968
30	4.452	169	1.000	1.169	-0.007158	-0.144	21.313	69.992	6.53	0.004896	0.04896	16.390	CONTINUE	0.25	21312.89	0.071189	217.965
40	4.453	169	1.000	1.169	-0.009257	-0.237	21.310	69.984	6.53	0.004897	0.04897	16.382	CONTINUE	0.33	21310.22	0.071176	217.963
50	4.455	169	1.000	1.169	-0.010997	-0.347	21.307	69.973	6.53	0.004897	0.04897	16.371	CONTINUE	0.42	21306.72	0.071203	217.961
60	4.457	169	1.000	1.169	-0.012226	-0.469	21.302	69.957	6.53	0.004898	0.04898	16.359	CONTINUE	0.50	21302.36	0.071243	217.957
70	4.461	169	1.000	1.168	-0.012634	-0.597	21.296	69.938	6.53	0.004900	0.04900	16.341	CONTINUE	0.58	21296.08	0.071297	217.953
80	4.465	168	1.000	1.168	-0.012792	-0.725	21.289	69.914	6.53	0.004902	0.04902	16.321	CONTINUE	0.67	21289.83	0.071368	217.947
90	4.470	168	1.000	1.168	-0.012771	-0.847	21.280	69.886	6.52	0.004905	0.04905	16.298	CONTINUE	0.75	21282.30	0.071449	217.938
100	4.478	168	1.000	1.168	-0.011125	-0.958	21.271	69.855	6.52	0.004908	0.04908	16.272	CONTINUE	0.83	21270.78	0.071547	217.934
110	4.483	168	1.000	1.168	-0.009653	-1.057	21.260	69.820	6.51	0.004912	0.04912	16.243	CONTINUE	0.92	21260.21	0.071657	217.928
120	4.489	168	1.000	1.168	-0.008540	-1.142	21.248	69.783	6.51	0.004915	0.04915	16.212	CONTINUE	1.00	21248.76	0.07178	217.912
130	4.498	168	1.000	1.168	-0.007321	-1.215	21.237	69.743	6.50	0.004920	0.04920	16.179	CONTINUE	1.08	21236.94	0.071912	217.898
140	4.507	168	1.000	1.168	-0.006276	-1.278	21.224	69.701	6.49	0.004924	0.04924	16.144	CONTINUE	1.17	21223.85	0.072053	217.887
150	4.516	168	1.000	1.168	-0.005425	-1.332	21.211	69.657	6.48	0.004928	0.04928	16.107	CONTINUE	1.25	21210.52	0.072202	217.874
160	4.526	168	1.000	1.168	-0.004756	-1.380	21.197	69.612	6.48	0.004933	0.04933	16.069	CONTINUE	1.33	21196.72	0.072368	217.861
170	4.535	168	1.000	1.168	-0.004241	-1.422	21.182	69.565	6.47	0.004938	0.04938	16.031	CONTINUE	1.42	21182.5	0.072519	217.847
180	4.545	168	1.000	1.168	-0.003847	-1.461	21.168	69.517	6.47	0.004944	0.04944	15.991	CONTINUE	1.50	21167.80	0.072686	217.833
190	4.556	168	1.000	1.168	-0.003543	-1.496	21.153	69.468	6.46	0.004949	0.04949	15.950	CONTINUE	1.58	21152.92	0.072857	217.818
200	4.566	168	1.000	1.168	-0.003306	-1.529	21.138	69.418	6.45	0.004954	0.04954	15.908	CONTINUE	1.67	21137.63	0.073034	217.803
210	4.577	168	1.000	1.168	-0.003115	-1.561	21.122	69.368	6.44	0.004959	0.04959	15.866	CONTINUE	1.75	21122.02	0.073214	217.788
220	4.588	168	1.000	1.168	-0.002957	-1.590	21.106	69.314	6.43	0.004966	0.04966	15.823	CONTINUE	1.83	21106.12	0.073399	217.773
230	4.600	168	1.000	1.168	-0.002824	-1.618	21.090	69.261	6.43	0.004972	0.04972	15.780	CONTINUE	1.92	21089.94	0.073588	217.757
240	4.612	168	1.000	1.168	-0.002708	-1.645	21.073	69.207	6.42	0.004978	0.04978	15.739	CONTINUE	2.00	21073.49	0.07378	217.740
250	4.623	168	1.000	1.168	-0.002609	-1.672	21.057	69.152	6.41	0.004984	0.04984	15.691	CONTINUE	2.08	21056.77	0.073970	217.724
260	4.636	168	1.000	1.168	-0.002513	-1.697	21.040	69.096	6.40	0.004990	0.04990	15.646	CONTINUE	2.17	21039.81	0.074176	217.707
270	4.648	167	1.000	1.167	-0.002428	-1.721	21.023	69.040	6.39	0.004996	0.04996	15.600	CONTINUE	2.25	21022.59	0.07438	217.690
280	4.661	167	1.000	1.167	-0.002342	-1.744	21.005	68.982	6.38	0.005002	0.05002	15.554	CONTINUE	2.33	21005.15	0.074587	217.673
290	4.674	167	1.000	1.167	-0.002269	-1.767	20.987	68.924	6.37	0.005009	0.05009	15.507	CONTINUE	2.42	20987.48	0.074788	217.656
300	4.686	167	1.000	1.167	-0.002203	-1.788	20.970	68.865	6.36	0.005015	0.05015	15.460	CONTINUE	2.50	20969.51	0.074991	217.639
310	4.700	167	1.000	1.167	-0.002145	-1.811	20.951	68.808	6.36	0.005022	0.05022	15.413	CONTINUE	2.58	20951.47	0.075202	217.622
320	4.713	167	1.000	1.167	-0.002092	-1.832	20.933	68.746	6.35	0.005029	0.05029	15.365	CONTINUE	2.67	20933.16	0.075448	217.605
330	4.726	167	1.000	1.167	-0.002043	-1.853	20.915	68.685	6.34	0.005036	0.05036	15.317	CONTINUE	2.75	20914.63	0.075703	217.588
340	4.740	167	1.000	1.167	-0.002005	-1.872	20.896	68.624	6.33	0.005043	0.05043	15.269	CONTINUE	2.83	20895.91	0.075969	217.571
350	4.754	167	1.000	1.167	-0.001938	-1.891	20.877	68.562	6.32	0.005050	0.05050	15.220	CONTINUE	2.92	20877.1	0.076238	217.554
360	4.768	167	1.000	1.167	-0.001888	-1.910	20.858	68.499	6.31	0.005057	0.05057	15.171	CONTINUE	3.00	20857.8	0.076513	217.537
370	4.783	167	1.000	1.167	-0.001845	-1.929	20.839	68.436	6.30	0.005064	0.05064	15.121	CONTINUE	3.08	20838.61	0.076799	217.520
380	4.797	167	1.000	1.167	-0.001804	-1.947	20.819	68.372	6.29	0.005071	0.05071	15.071	CONTINUE	3.17	20819.14	0.077088	217.503
390	4.812	167	1.000	1.167	-0.001764	-1.964	20.799	68.307	6.28	0.005078	0.05078	15.021	CONTINUE	3.25	20799.36	0.07738	217.478
400	4.827	167	1.000	1.167	-0.001726	-1.982	20.780	68.242	6.27	0.005086	0.05086	14.971	CONTINUE	3.33	20779.68	0.077736	217.460
410	4.842	167	1.000	1.167	-0.001690	-1.999	20.760	68.176	6.26	0.005093	0.05093	14.921	CONTINUE	3.42	20759.7	0.078074	217.435
420	4.857	167	1.000	1.167	-0.001655	-2.016	20.740	68.110	6.25	0.005101	0.05101	14.871	CONTINUE	3.50	20739.56	0.078427	217.417
430	4.872	167	1.000	1.167	-0.001622	-2.031	20.719	68.043	6.24	0.005109	0.05109	14.821	CONTINUE	3.58	20719.23	0.07879	217.390
440	4.888	167	1.000	1.167	-0.001591	-2.047	20.699	67.976	6.23	0.005116	0.05116	14.771	CONTINUE	3.67	20698.76	0.079136	217.372
450	4.904	167	1.000	1.167	-0.001562	-2.063	20.678	67.908	6.22	0.005124	0.05124	14.721	CONTINUE	3.75	20678.13	0.07949	217.345
460	4.920	167	1.000	1.167	-0.001532	-2.078	20.657	67.840	6.21	0.005132	0.05132	14.671	CONTINUE	3.83	20657.35	0.079859	217.329
470	4.936	166	1.000	1.166	-0.001504	-2.093	20.636	67.771	6.20	0.005140	0.05140	14.621	CONTINUE	3.92	20636.42	0.080214	217.303
480	4.952	166	1.000	1.166	-0.001477	-2.108	20.615	67.702	6.19	0.005148	0.05148	14.571	CONTINUE	4.00	20615.34	0.080583	217.284
490	4.969	166	1.000	1.166	-0.001452	-2.122	20.594	67.633	6.18	0.005156	0.05156	14.521	CONTINUE	4.08	20594.11	0.080964	217.266
500	4.985	166	1.000	1.166	-0.001427	-2.137	20.573	67.562	6.17	0.005164	0.05164	14.471	CONTINUE	4.17	20572.74	0.081338	217.248
510	5.002	166	1.000	1.166	-0.001403	-2.150	20.551	67.492	6.16	0.005172	0.05172	14.421	CONTINUE	4.25	20551.24	0.081715	217.231
520	5.019	166	1.000	1.166	-0.001380	-2.165	20.530	67.421	6.14	0.005181	0.05181	14.371	CONTINUE	4.33	20529.59	0.082095	217.202
530	5.036	166	1.000	1.166	-0.001358	-2.178	20.508	67.349	6.13	0.005189	0.05189	14.321	CONTINUE	4.42	20507.81	0.082478	217.180
540	5.053	166	1.000	1.166	-0.001337	-2.191	20.486	67.277	6.12	0.005197	0.05197	14.271	CONTINUE	4.50	20485.89	0.08286	217.158
550	5.071	166	1.000	1.166	-0.001316	-2.205	20.464	67.205	6.11	0.005206	0.05206	14.193	CONTINUE	4.58	20463.85	0.083151	217.136
560	5.088	166	1.000	1.166	-0.001297	-2.218	20.442	67.132	6.10	0.005215	0.05215	14.140	CONTINUE	4.67	20441.67	0.083442	217.114
570	5.106	166	1.000	1.166	-0.001278	-2.231	20.420	67.059	6.09	0.005224	0.05224	14.087	CONTINUE	4.75	20419.36	0.083736	217.092
580	5.124	166	1.000	1.166	-0.001259	-2.243	20.397	66.985	6.08	0.005232	0.05232	14.033	CONTINUE	4.83	20396.93	0.084033	217.070
590	5.142	166	1.000	1.166	-0.001241	-2.256	20.374	66.911	6.07	0.005241	0.05241	13.980	CONTINUE	4.92	20374.38	0.084332	217.047
600	5.160	166	1.000	1.166	-0.001224	-2.269	20.352	66.838	6.06	0.005250	0.05250	13.927	CONTINUE	5.00	20351.63	0.084634	217.025

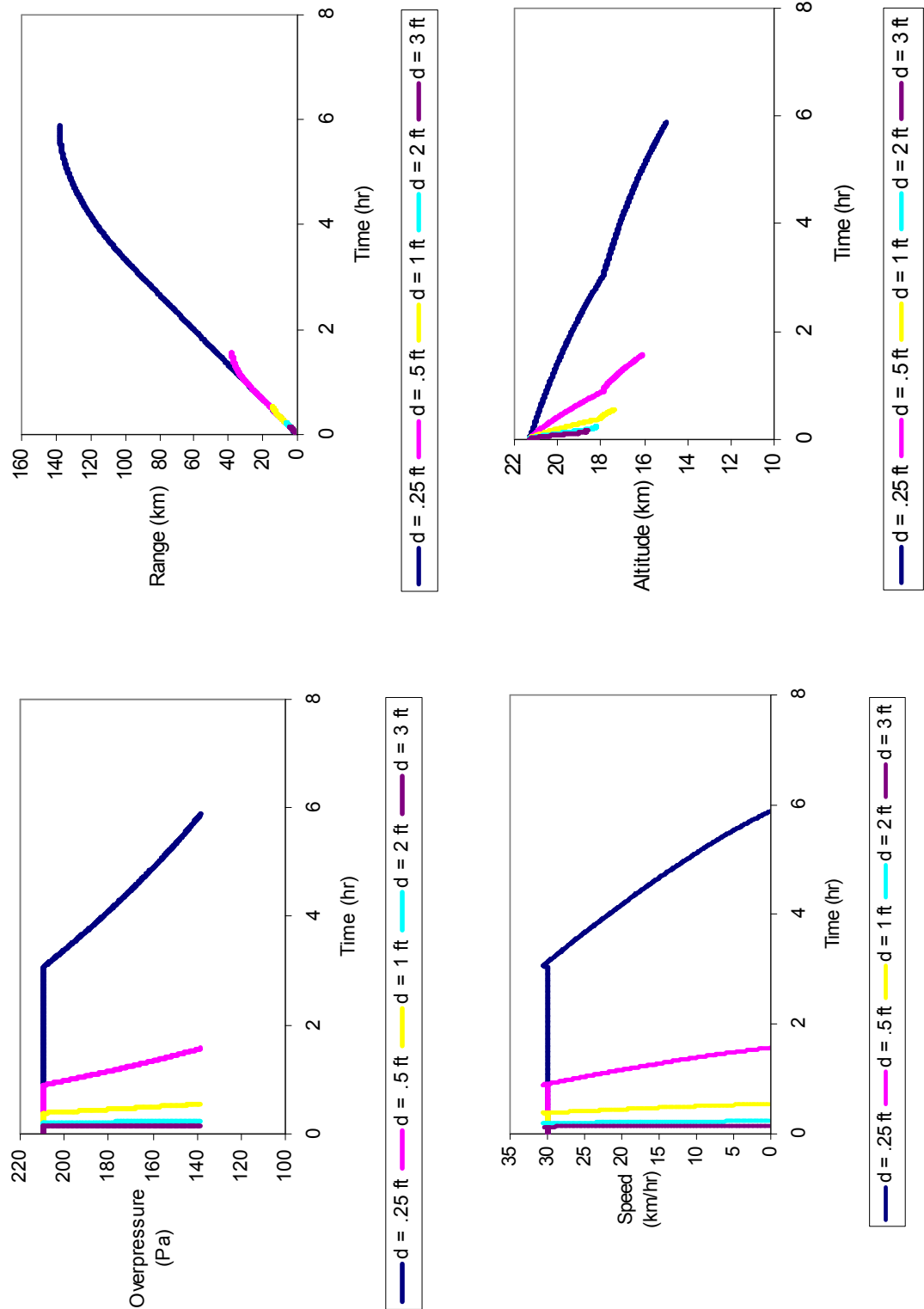
Isothermal Data (continued)

time inc. = 10 sec	mw He = 0.004 kg/mole	R = 8.314 m ³ Pa / mole K	rho 0 = 1.225 kg/m ³	ss area = 1648 m ²
H = 6.52 cm	mw air = 0.029 kg/mole	T 0 = 288.15 K	rho0 He = 0.173 kg/m ³	drag coeff = 0.3
rho = 101325 Pa	gravity = 9.81 m/sec ²	init alt = 18.26202 km	diff factor = 0.5	A = 81.2 m
mass = 1000 kg	rho = 210 Pa	rho hole = 0.0728 m ²	diff factor = 0.5	B = 20.4 m

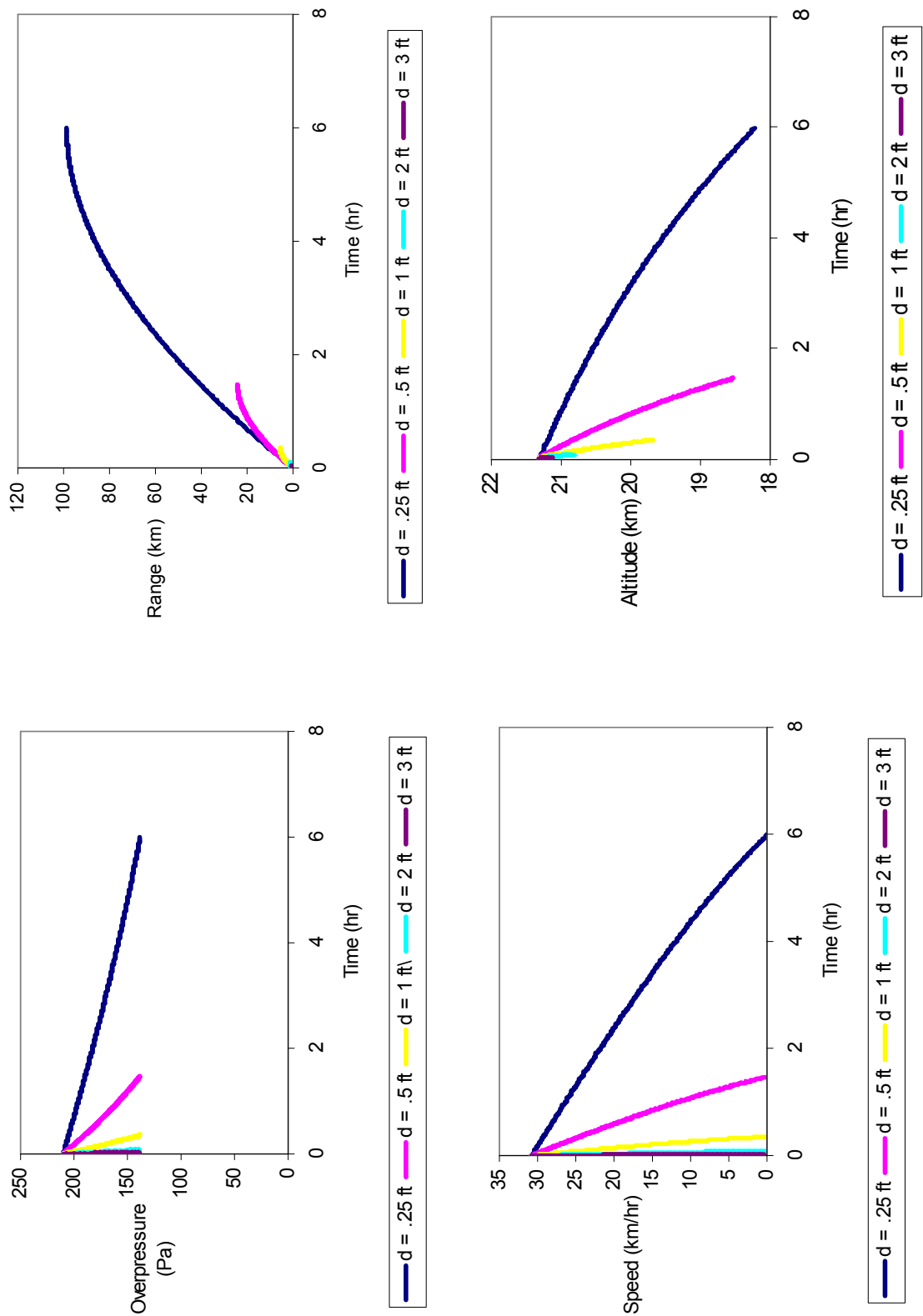
sec	time	P atm	P env	delta P	P top	mass He kg	mass tot kg	rho He m/sec	mass flow kg/sec	delta m kg	rho H ₂ m ³	delta vol m ³	P v m/sec ²	V m/sec	dt m	dt ft	dt m	temp K	rho air kg/m ³	vel average km/hr	dist x-range km
1390	7.198.994	7.408.894	0.00	210.0000	165.4396	1.165.440	5.12	0	0	0.016453	10.055.29	0	0	18.263	59.976	18262.82	216.6499	0.115757	30.752	11.580	
1400	7.198.994	7.407.520	1.37420	208.6258	165.3792	1.165.378	5.11	0.006137132	0.0613713	0.016450	1.865051	-0.00130337	-0.0130337	18.263	59.976	18262.92	216.6499	0.115759	30.340	11.664	
1410	7.199.042	7.406.296	1.36969	207.5801	165.3170	1.165.317	5.09	0.008115884	0.0811588	0.016447	1.858938	-0.00259229	-0.0259229	18.262	59.974	18262.71	216.6499	0.115760	29.926	11.747	
1420	7.199.494	7.405.375	1.25899	205.8900	165.2561	1.165.256	5.07	0.009304585	0.0930459	0.016444	1.852907	-0.0038383	-0.038383	18.261	59.972	18262.71	216.6499	0.115763	29.510	11.829	
1430	7.200.362	7.404.893	1.36063	204.8303	165.1953	1.165.195	5.06	0.006073173	0.0607317	0.016441	1.846638	-0.0049870	-0.049870	18.260	59.968	18262.70	216.6499	0.115803	29.092	11.910	
1440	7.201.807	7.404.981	1.35605	203.1743	165.1348	1.165.135	5.04	0.005051591	0.0505159	0.016438	1.840414	-0.006402	-0.06402	18.258	59.961	18262.69	216.6499	0.115838	28.672	11.990	
1450	7.203.930	7.405.153	1.35141	201.6229	165.0745	1.165.075	5.02	0.003026291	0.0302629	0.016435	1.834110	-0.007714	-0.07714	18.256	59.953	18262.72	216.6499	0.115884	28.240	12.068	
1460	7.206.817	7.407.293	1.34671	200.4761	165.0145	1.165.014	5.00	0.000077717	0.0007777	0.016432	1.827730	-0.0094236	-0.094236	18.252	59.942	18262.48	216.6499	0.115943	27.824	12.146	
1470	7.210.518	7.409.652	1.34194	199.1342	164.9546	1.164.955	4.99	0.005853551	0.0585355	0.016429	1.821260	-0.0072775	-0.072775	18.248	59.929	18248.48	216.6499	0.116016	27.397	12.222	
1480	7.215.050	7.412.847	1.33710	197.7971	164.8950	1.164.895	4.97	0.005962672	0.0596267	0.016426	1.814695	-0.003873	-0.03873	18.244	59.914	18243.75	216.6499	0.116102	26.968	12.297	
1490	7.220.391	7.418.896	1.33218	196.4649	164.8356	1.164.836	4.95	0.005939679	0.0593968	0.016423	1.808024	-0.0036458	-0.036458	18.238	59.896	18238.43	216.6499	0.1162	26.538	12.370	
1500	7.226.493	7.421.631	1.32720	195.1377	164.7764	1.164.776	4.93	0.005916387	0.0591639	0.016420	1.801268	-0.003512	-0.03512	18.232	59.877	18232.46	216.6499	0.11631	26.102	12.443	
1510	7.233.290	7.427.108	1.32215	193.8156	164.7175	1.164.717	4.91	0.005892822	0.0589282	0.016417	1.794406	-0.003332	-0.03333	18.226	59.855	18225.97	216.6499	0.116429	25.665	12.514	
1520	7.240.735	7.433.205	1.31704	192.4985	164.6588	1.164.659	4.89	0.005869015	0.0586901	0.016414	1.787476	-0.003153	-0.03153	18.219	59.833	18219.16	216.6499	0.116557	25.236	12.584	
1530	7.248.668	7.439.854	1.31189	191.1867	164.6003	1.164.600	4.87	0.005845002	0.0584500	0.016411	1.780480	-0.002975	-0.02975	18.212	59.808	18211.63	216.6499	0.116693	24.795	12.653	
1540	7.257.108	7.446.988	1.30669	189.8800	164.5421	1.164.542	4.85	0.005820818	0.0582082	0.016408	1.773428	-0.002798	-0.02798	18.204	59.783	18203.88	216.6499	0.116838	24.340	12.721	
1550	7.265.970	7.454.549	1.30146	188.5785	164.4842	1.164.484	4.83	0.005796453	0.0579646	0.016405	1.766320	-0.002621	-0.02621	18.196	59.756	18195.82	216.6499	0.116984	23.893	12.787	
1560	7.275.207	7.462.490	1.29620	187.2822	164.4265	1.164.426	4.81	0.005772053	0.0577205	0.016403	1.759192	-0.002446	-0.02446	18.187	59.729	18187.48	216.6499	0.117133	23.444	12.852	
1570	7.284.794	7.470.775	1.29092	185.9914	164.3690	1.164.369	4.79	0.00574752	0.0574752	0.016400	1.752022	-0.002270	-0.02270	18.179	59.701	18178.88	216.6499	0.117297	22.991	12.916	
1580	7.294.671	7.479.376	1.28561	184.7058	164.3117	1.164.312	4.77	0.00572291	0.0572291	0.016397	1.744822	-0.002096	-0.02096	18.170	59.672	18170.04	216.6499	0.11746	22.535	12.979	
1590	7.304.946	7.488.271	1.28029	183.4255	164.2548	1.164.255	4.75	0.005698239	0.0569824	0.016394	1.737696	-0.001923	-0.01923	18.161	59.642	18160.96	216.6499	0.117629	22.077	13.040	
1600	7.315.292	7.497.483	1.27496	182.1495	164.1980	1.164.198	4.73	0.005673615	0.0567362	0.016391	1.730567	-0.001749	-0.01749	18.152	59.612	18151.71	216.6499	0.11779	21.615	13.100	
1610	7.325.994	7.506.877	1.26961	180.8809	164.1415	1.164.142	4.71	0.005648749	0.0564879	0.016388	1.723311	-0.001577	-0.01577	18.142	59.580	18142.23	216.6499	0.117976	21.150	13.159	
1620	7.336.947	7.516.563	1.26426	179.6167	164.0853	1.164.085	4.69	0.005623946	0.0562395	0.016386	1.716044	-0.001405	-0.01405	18.133	59.549	18132.57	216.6499	0.118156	20.682	13.216	
1630	7.348.136	7.526.492	1.25889	178.3578	164.0293	1.164.029	4.67	0.005599112	0.0559911	0.016383	1.708857	-0.001234	-0.01234	18.124	59.518	18122.77	216.6499	0.11834	20.211	13.272	
1640	7.359.553	7.536.657	1.25352	177.1042	163.9736	1.163.974	4.65	0.005574296	0.0557429	0.016380	1.701763	-0.001064	-0.01064	18.113	59.483	18112.7	216.6499	0.118527	19.736	13.327	
1650	7.371.193	7.547.050	1.24813	175.8561	163.9181	1.163.918	4.63	0.005549362	0.0554938	0.016377	1.694658	-0.000895	-0.00895	18.103	59.450	18102.51	216.6499	0.118718	19.257	13.381	
1660	7.383.052	7.557.665	1.24275	174.6134	163.8628	1.163.863	4.61	0.005524489	0.0552449	0.016374	1.687545	-0.000726	-0.00726	18.092	59.418	18092.15	216.6499	0.118912	18.774	13.433	
1670	7.395.122	7.568.498	1.23735	173.3760	163.8078	1.163.808	4.59	0.005499585	0.0549996	0.016372	1.680432	-0.000556	-0.00556	18.082	59.381	18081.63	216.6499	0.119109	18.298	13.484	
1680	7.407.399	7.579.543	1.23195	172.1441	163.7531	1.163.753	4.57	0.005474671	0.0547467	0.016369	1.673321	-0.000389	-0.00389	18.071	59.346	18070.96	216.6499	0.11931	17.797	13.533	
1690	7.419.879	7.590.796	1.22655	170.9175	163.6986	1.163.699	4.55	0.005449752	0.0544975	0.016366	1.666246	-0.000225	-0.00225	18.060	59.311	18060.13	216.6499	0.119514	17.302	13.581	
1700	7.432.557	7.602.254	1.22114	169.6964	163.6443	1.163.644	4.53	0.005424831	0.0542483	0.016363	1.659129	-0.000059	-0.000476	18.049	59.273	18049.18	216.6499	0.119721	16.803	13.628	
1710	7.445.431	7.613.912	1.21574	168.4806	163.5903	1.163.590	4.51	0.005399909	0.0539999	0.016361	1.652009	-0.000139	-0.00139	18.038	59.238	18038.04	216.6499	0.119931	16.299	13.673	
1720	7.458.496	7.625.767	1.21033	167.2703	163.5366	1.163.537	4.49	0.005374991	0.0537499	0.016358	1.644894	-0.000070	-0.00070	18.027	59.201	18026.78	216.6499	0.120144	15.790	13.717	
1730	7.471.750	7.637.815	1.20491	166.0654	163.4831	1.163.483	4.47	0.005350078	0.0535008	0.016355	1.637801	-0.000005	-0.000174	18.015	59.164	18015.38	216.6499	0.12036	15.276	13.759	
1740	7.485.189	7.650.055	1.19950	164.8650	163.4298	1.163.430	4.45	0.005325172	0.0532517	0.016353	1.630726	-0.000001	-0.000140	18.004	59.126	18003.89	216.6499	0.120577	14.757	13.802	
1750	7.498.811	7.662.483	1.19409	163.6718	163.3768	1.163.377	4.43	0.005300270	0.0530028	0.016350	1.623606	-0.000001	-0.000130	17.992	59.088	17992.19	216.6499	0.120791	14.233	13.840	
1760	7.512.613	7.675.096	1.18867	162.4831	163.3241	1.163.324	4.41	0.005275393	0.0527539	0.016347	1.616521	-0.000001	-0.000120	17.980	59.049	17980.4	216.6499	0.121026	13.702	13.878	
1770	7.526.592	7.687.892	1.18326	161.2996	163.2718	1.163.272	4.39	0.005250523	0.0525052	0.016345	1.609478	-0.000001	-0.000110	17.968	59.010	17968.49	216.6499	0.121263	13.168	13.914	
1780	7.540.747	7.700.869	1.17785	160.1220	163.2193	1.163.219	4.37	0.005225660	0.0522567	0.016342	1.602399	-0.000001	-0.000103	17.956	58.970	17956.45	216.6499	0.121484	12.634	13.950	
1790	7.555.075	7.714.024	1.17244	158.9496	163.1673	1.163.167	4.35	0.005200833	0.0520083	0.016340	1.595127	-0.000001	-0.000104	17.944	58.930	17944.29	216.6499	0.121717	12.075	13.983	
1800	7.569.573	7.727.356	1.16703	157.7825	163.1156	1.163.116	4.33	0.005176017	0.0517602	0.016337	1.588187	-0.000001	-0.000110	17.932	58.890	17932.02	216.6499	0.121953	11.516	14.015	
1810	7.584.241	7.740.862	1.16163	156.6208	163.0640	1.163.064	4.31	0.005151222	0.0515122	0.016334	1.581050	-0.000001	-0.000118	17.920	58.849	17919.63	216.6499	0.122191	10.955	14.046	
1820	7.599.076	7.754.541	1.15622	155.4647	163.0128	1.163.013	4.29	0.005126455													

Appendix C – Modeling Performance Data

Case 1 – Maintain Constant Overpressure



Case 2 – Slow Depressurization



Appendix D – Army High-Altitude Airship Publication



UNITED STATES ARMY
SPACE AND MISSILE
DEFENSE COMMAND

Future Warfare Center

High Altitude Airship



Summary

- Station-keeping Endurance—1 month
- Station-keeping Altitude—65,000 ft mean-sea-level (MSL)
- Payload Weight—500 lb
- Payload Power—3 kW
- Cruise Speed—25 kts
- Station-keeping Accuracy— < 2 km 50 percent of time, <150 km 95 percent of time
- Command and Control—Remotely Piloted

HAA is an Advanced Concept Technology Demonstration (ACTD), with Office of the Secretary of Defense oversight, North American Aerospace Defense Command user sponsor, U.S. Army lead service, Missile Defense Agency executing agent/technical manager, Space and Missile Defense Technical Center transitional manager, and Space and Missile Defense Future Warfare Center operational manager.

The objective of this ACTD is to demonstrate the engineering feasibility and potential military utility of an unmanned, untethered, gas-filled, solar powered airship that can fly at 65,000 feet. The prototype airship developed under this effort will be capable of continuous flight for up to a month while carrying a multi-mission payload. This ACTD is intended as a developmental step toward an objective HAA that can self-deploy from the continental United States (CONUS) to worldwide locations and remain on station in a geo-stationary position for a year or more before returning to a fixed launch and recovery area in CONUS for service on the ground.

Secure the High Ground

High Altitude Airship

Future Warfare Center

Program Objectives

- Design and produce a lighter-than-air, High Altitude Airship — Advanced Concept Technology Demonstration (ACTD) Prototype
- Demonstrate the feasibility and potential military utility of an unmanned, untethered, airship that can fly at nominal 65,000 feet mean-sea-level altitude for up to one month while carrying a multi-mission payload

Benefits

- Persistent 24/7 capability
- Low cost, rapid reconstitution of capabilities
- Multi-mission, exchangeable/repairable/upgradable payloads
- Long duration aloft greater than an unmanned aerial vehicle
- Low inherent detectability, observability
- Repositionable
- Improves performance of nearly all sensors

Altitude

The desired altitude to operate an HAA is approximately 65,000 feet. This is due to many factors, including it is above the weather and Federal Aviation Administration air traffic control. The winds are relatively benign and the thin atmosphere allows for extended range of Electro-Optical/Infra-Red (EO/IR) equipment. Importantly, at 65,000 feet, the HAA will have more than a 600-mile footprint on the ground

Experimentation Architecture

The HAA fits into a layered architecture. It operates at the same altitude as the U2 and Global Hawk. While not providing the same ability for quick reaction operations, once on station, it provides long endurance continuous/persistent support that is not practical using combinations of manned and unmanned aircraft. Because it maintains geo-stationary position at 12 miles above the Earth, it does not have the latency issues associated with geo-synchronous satellites. The airship serves a transformational purpose by filling the capability gap between aerial vehicles and satellites.



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Vita

Major Charles W. Vogt, Jr., graduated from the University of Arizona in Tucson, Arizona with a Bachelor of Science degree in Mechanical Engineering in Dec 1990. He was commissioned through the Detachment 20 AFROTC at the University of Arizona.

His first assignment was at Norton AFB, California as a developmental engineer in September 1991. He cross-flowed into space and missile operations in February 1994, and held crew commander, instructor, and flight commander positions at the 341st Space Wing, Malmstrom AFB, Montana and the 45th Space Wing, Cape Canaveral AFS, Florida. During this time he completed a Master's of Science Degree in Engineering Management from the Florida Institute of Technology in Melbourne, Florida. Prior to arriving at the Air Force Institute of Technology (AFIT), Major Vogt served as Deputy Division Chief, Contingencies Analyses Division, Air Force Studies and Analyses Agency in the Pentagon. In September 2004, he entered the AFIT Graduate School of Engineering and Management as an intermediate developmental education (IDE) student. Upon graduation, he will be assigned to Headquarters Air Force Space Command A-3RS, Peterson Air Force Base, Colorado.

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14. ABSTRACT This study investigates the ability of a high-altitude airship to maintain lift following the compromise of its lifting gas envelope. Accepted engineering principles are applied to develop a model that provides comparative analyses for airship depressurization alternatives following hull compromise. Specifically, maintaining lifting gas envelope overpressure to provide controllability in wind currents while sacrificing some buoyancy is compared with allowing envelope depressurization to occur with the goal of maintaining greater buoyancy as long as possible. The model provides insights to alternatives for recovering a damaged vehicle and its payload. In particular, the analysis demonstrates that maintaining the ability to navigate while forfeiting buoyancy can provide additional down-range maneuver capability. In some cases preserving the airship's hull overpressure for some period of time following compromise, vice allowing a slow depressurization to atmospheric equilibrium, extends the distance a damaged airship can sustain controlled navigation as much as eighty percent. However, the airship will forfeit nearly twenty percent of the altitude it would otherwise preserve by not forcing a constant hull overpressure.					
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