

DISSERTATION

SYSTEMS CONSIDERATIONS IN DESIGNING
A STRATOSPHERIC EARLY WARNING AIRSHIP

Submitted by
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In partial fulfillment of the requirements
For the Degree of Doctor of Philosophy
Colorado State University
Fort Collins, Colorado
Summer 2026

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ABSTRACT

SYSTEMS CONSIDERATIONS IN DESIGNING A STRATOSPHERIC EARLY WARNING AIRSHIP

Since 1957, the North American Aerospace Defense Command (NORAD) depends upon an array of ground-based radars to detect Russian bombers approaching the North American continent. Because radar signals are broadcasted line-of-sight, signals transmitted from ground-based radar towers are blocked by the curvature of the Earth. This signal blocking creates a "radar shadow" in which hostile aircraft can approach radar sites at very low altitudes and still not be detectable. One solution to this detection challenge would be to develop a remotely controlled airship capable of carrying a lightweight radar set aloft to very high altitudes in the stratosphere over the Arctic region for long durations. This concept would offer greatly extended air surveillance coverage and could act as a "tripwire" for the early detection of any advancing hostile forces. The proposed airship is a classic system example with various subsystems having numerous requirements, conflicting design considerations, and requiring effective component integration, and validation activities. Research also explores how new model-based system engineering tools could be used in conjunction with traditional system engineering processes to capture program requirements, assist component design activities, and conduct validation efforts to successfully realize this proposed early warning airship concept. Research to date has yet to uncover any examples of this proposed system and thus would be a unique contribution for both the systems engineering and NORAD air defense communities.

ACKNOWLEDGEMENTS

The reviewers of this dissertation have provided the author with many valuable corrections, improvements, and suggestions. The author wishes to express his sincere thanks to:

- Dr. Thomas Bradley, my advisor, who provided much-needed technical expertise whenever aerodynamic and power production issues arose. His excellent suggestion to use hydrogen to both float the airship and serve as its power source saved the day. And his merging various altitude and pressure calculations into a single integrated Excel spreadsheet was critical to my developing twelve computational blocks, linking them together using optimizing software, and producing optimized results for this research. Finally, his concern about crosswinds and their effect on mission duration resulted in superior results. Throughout, he gently pushed me to address various design concerns to make sure I was developing a high-quality systems engineering design. I absolutely could not have been successful without his ideas, guidance, and technical support.
- Dr. Aaron Brown, my co-advisor, who provided greatly appreciated assistance in various mechanical engineering issues. And he provided me with much-needed positive encouragement and great discussions as I worked through this research effort. I could not have been successful without his support, as well.
- Dr. Christopher Yoder (Balloon Technologist, NASA Wallops Flight Facility, Virginia) for his kind assistance during our numerous conversations about stratospheric balloon capabilities and technical aerodynamic calculations. He got me off to a great start.
- Dr. Amy Butler (Atmospheric Scientist, NOAA, Boulder, Colorado) who provided much appreciated early assistance and information regarding the Polar Vortex.

DEDICATION

This dissertation is dedicated in memory to the late Dr. Alexander Kossiakoff, former director of the Advanced Physics Lab at Johns Hopkins University. His pioneering systems engineering approach developed during the 1990s made a major impression on my thinking about systems engineering. As developed by Dr. Kossiakoff, his new approach provided a logical, systematic application of the formal scientific method for engineering a complex system. This formal method was a major step forward in providing a rigorous approach to accomplishing the systems engineering process and was employed continuously throughout my dissertation. This methodical approach made a lasting impression on me and my growing understanding of professional systems engineering endeavors.

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CHAPTER I. INTRODUCTION

1.1 Background

In 1955, the Soviet Union detonated its first thermonuclear weapon, shocking both American scientists and the intelligence community alike [1]. Most alarming, the Soviet Union was now capable of flying strategic bombers over the North Pole (the shortest attack route) and bombarding American cities at will with these new devastating weapons. This terrifying new airborne threat demanded an immediate air defense response.

Thus, in 1957, the North American Air Defense Command (NORAD) was formed. This new bi-national United States and Canadian military air defense alliance immediately went to work establishing an array of long-range radar sites along the arctic frontier to detect any Russian bombers approaching the North American continent. Today, NORAD's "North Warning System" consists of 13 Long-Range Radar (LRR) sites plus 34 gap-filling Short-Range Radars (SRR) positioned along the vast Canadian and Alaskan northern frontier (see Figure 1) [2].



Figure 1: NWS Radar Site at Baffin Island, Canada [3]

Each of the long-range AN/FPS-117 remote radars have an unclassified range of 250 nautical miles (see Figure 2), thus providing significant early warning detection of any Russian air threat approaching over the North Pole [4].



Figure 2: North Warning System [5]

1.2 Problem Description

But this radar detection system has limitations. Because radar signals are broadcasted line-of-sight, signals transmitted at low angles from radar towers are physically blocked by the curvature of the Earth. This physical signal blocking creates a "radar shadow" in which aircraft can approach radar sites at very low altitudes and still not be detectable (see Figure 3).

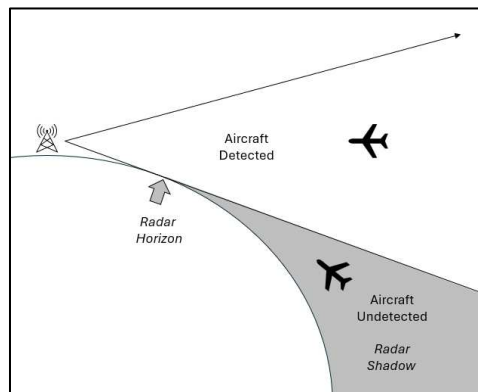


Figure 3: Radar Detection "Shadow"

To understand this “radar shadow” situation in more detail, the physical elements involved in computing the distance a radar beam travels can be visualized in Figure 4.

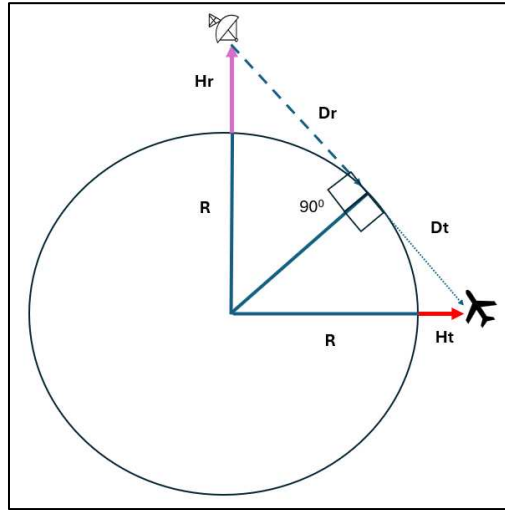


Figure 4: Radar Horizon and Target Visibility

Given the following variables (all in meters):

R	Radius of the Earth	6,300,000 m
H_r	Height of the radar above the Earth's surface	(As desired)
H_t	Height of the target above the Earth's surface	(As desired)
D_r	Radar's distance to the horizon grazing point	(To be computed)
D_t	Target's distance to the horizon grazing point	(To be computed)

By using Figure 4 and the Pythagorean theorem (Equation 1), the radar's detection of an airborne target can be calculated as follows [6]:

$$a^2 + b^2 = c^2 \quad (1)$$

For the radar distance triangle:

$$(D_r)^2 + (R)^2 = (R + H_r)^2$$

$$D_r = \sqrt{(H_r)^2 + 2RH_r} \quad (2)$$

And for the target distance triangle:

$$(D_t)^2 + (R)^2 = (R + H_t)^2$$

$$D_t = \sqrt{(H_t)^2 + 2RH_t} \quad (3)$$

Because $(H_r)^2$ and $(H_t)^2$ are very small compared to the Earth's radius, these two heights can be eliminated and the two distance equations approximated as:

$$D_r = \sqrt{2RH_r} \quad (4)$$

$$D_t = \sqrt{2RH_t} \quad (5)$$

Therefore, the direct visibility distance (D_v) from the radar to the target can be computed as the sum of these two distances:

$$D_v = \sqrt{2RH_r} + \sqrt{2RH_t} \quad (6)$$

Assuming targets approach at an extremely low altitude (H_t) (e.g., 300 m or 1000 ft), inserting various radar heights (H_r) produces horizon visibility distances (D_v) shown in Table 1.

Table 1: Radar Heights and Target Visibility Distances (Target Flying at 300 m)

Radar Height (H_r)		Horizon Visibility Distance (D_v)	
meters	feet	km	nautical miles
30	100*	81	44
3,050	10,000	124	67
8,842	29,000**	398	215
10,000	32,808	418	226
15,000	49,200	499	270
20,000	65,600	567	306
21,000	68,880	580	313
*Current NORAD ground radar towers			

****Typical AWACS surveillance aircraft altitude**

Simply as a matter of geometry, approaching hostile aircraft flying at very low altitudes would not be visible to NORAD until they were within 44 nautical miles of those ground sites. One solution to solving this radar shadow dilemma is to therefore raise the height of the radar in order to look farther “over the horizon” to more easily detect those approaching targets. There are several ways to accomplish this solution.

One method is to deploy unmanned "aerostat" radar surveillance balloons. Connected to the ground via a long tether, these fixed balloons can carry a radar up to 10,000 ft and remain aloft for days (see Figure 5). From Table 1, they can detect low flying targets out to 226 nautical miles.



Figure 5: Fixed Aerostat Radar Balloon [7]

Another method is using the E-3 AWACS surveillance aircraft which typically fly at 29,000 ft and thus can detect low-level targets out to 215 nautical miles (see Figure 6).



Figure 6: E-3 AWACS Radar Surveillance Aircraft [8]

Unfortunately, neither of these approaches are very satisfactory, long-term solutions. AWACS aircraft can remain airborne for only a limited time and then must land to refuel. Also, flying aircrew for long periods soon results in crew exhaustion. Thus, multiple AWACS aircraft must be employed to maintain dedicated 24/7 surveillance. Finally, the cost of maintaining such a fleet of surveillance aircraft for long periods of time is extremely expensive.

Likewise, tethered aerostats are no panacea; their biggest limitation is their vulnerability to bad weather. During thunderstorms, lightning strikes, or high winds they must be lowered for protection, thus resulting in mission cancellation [9]. The U.S. Army attempted to demonstrate the viability of using a radar aerostat to protect the national capital—and it proved to be a failure. In 2015, during high winds, the aerostat broke free, drifted for 100 miles across Maryland (dragging its 6,000-foot tether across communities and knocking down power lines) until it finally crashed on a farm in Pennsylvania. To no one’s surprise, DOD cancelled the program in 2017 [10].

However, one possible solution to solving NORAD’s “radar shadow” surveillance challenge would be to combine the advantages offered by both aerostat balloons and AWACS aircraft by combining both of their capabilities onto newly developing “High Altitude Airships” (HAA), often labeled as “High Altitude Platform Systems” (HAPS) (see Figure 7).



Figure 7: High Altitude Airship (Artist Concept) [11]

1.3 Proposed Solution

The proposed solution is to develop a remotely controlled unmanned airship capable of lofting a lightweight radar set to very high altitudes in the stratosphere for long durations over the Arctic, thus offering greatly extended air defense early warning coverage. During periods of required heightened readiness, this proposed concept combines the surveillance endurance offered by fixed aerostats with the high-altitude capability offered by AWACS aircraft, resulting in both extended air defense coverage as well as being free from disruptive winds and disruptive storms.

For example, stationing an airship above the Arctic frontier at 15 km (nearly 49,000 feet) would result in 270 nautical miles of low-level target detection.

Since NORAD's current detection range for very low-level targets is 40 nautical miles, this example provides an additional 230 nautical miles (425 km) of detection range. Given the cruising speed of Russian TU-95 strategic bombers (see Figure 8) is approximately 550 km/hour [12], this would provide nearly an hour of extra early warning time for NORAD to launch its air defense fighters to respond to any approaching Russian threat.



Figure 8: Russian Tu-95 BEAR Bomber [12]

1.4 Research Questions

The broad goal of this research is to determine if the proposed concept of a remotely controlled stratospheric early warning airship is theoretically possible. Designing such a vehicle can easily be viewed in systems engineering terms: the proposed concept is a classic system with various subsystems having numerous requirements, conflicting design considerations, and requiring successful component integration and validation activities.

1.4.1 Research Question 1

“Can the Geometry, Performance, Mass, Power Requirements, and Payload Systems Required of the Airship be Represented Parametrically Within An Integrated and Optimizable Mission System Model?”

- Task 1 – Determine Individual Components Parameters. This initial task will focus on developing specific parameters for the various subsystem components.
- Task 2 – Model Cascading Component Calculations to Derive System Totals. Using data from Task 1, this task now integrates those numerous parameters using Excel spreadsheets to develop an initial system viewpoint.
- Task 3 – Analyze the Probabilistic Performance and Risks. In this task, we are now in a position to isolate which parameters play critical roles in airship performance using Ansys Model Center® software. This Model-Based System Engineering (MBSE) graphic analysis tool allows highlighting problem areas and performance risks that need to be further refined.

- Task 4 – Optimize Factors Using Multidisciplinary Design Optimization. Finally, again using Model Center® software, subsystem factors will be repeatedly manipulated to determine the optimum combination of Size, Weight, and Power (SWaP) characteristics.

1.4.2 Research Question 2

“What Are the System Performance Characteristics that Make this Arctic Early Warning Airship System Feasible?”

- Task 5 – Define Ideal-Case (Inverse Design) Mission Performance Goals. Using the parameters and software tools developed in Research Question 1, this task will now determine what should be the ideal component and system performance goals.

- Task 6 – Identify Technology Gaps Affecting System Accomplishment. This task will compare the capabilities of current technologies to meet the ideal performance goals developed in Task 5 and suggest possible technology solutions.

1.4.3 Research Question 3

“What Combination of Achievable Technology and Operational Scenarios Produce Optimal Airship Surveillance and Make it Performance-Preferred?”

- Task 7 – Outline a Baseline Mission Scenario. This task describes a typical mission scenario. Areas of focus include estimated enroute travel times, on-station surveillance modes, and surveillance data and airship telemetry communication processes.

- Task 8 – Identify Operational Mission Options and Tradeoffs. Having outlined typical mission events, this task addresses any apparent mission constraints such number of airships required, nighttime operations, crosswind constraints, hydrogen production, etc.

- Task 9 – Define Why The System is Performance-Preferred. Finally, this task will explore the advantages of using this balloon-based surveillance system over other vehicle options.

CHAPTER II. LITERATURE REVIEW

Part I – Background Research

2.1 Introduction

To review, radar signals transmitted at low angles from radar towers are physically blocked by the curvature of the Earth, thus creating a "radar shadow" in which aircraft can approach at very low altitudes and still not be detectable. The proposed solution is to develop a remotely controlled airship capable of lofting a lightweight radar to very high altitudes for long durations over the Arctic Region, thus offering greatly extended air defense early warning coverage.

Designing such a unique vehicle can easily be viewed in systems engineering terms: the proposed concept is a classic system with various subsystems having numerous requirements and conflicting design considerations. Given the broad systems concept, it was necessary to investigate both the environment in which such an airship would operate as well as the various components that would comprise such a novel vehicle. This included researching the types of airship suitable for high altitude surveillance, the types of propulsion and power production commercially available, and the associated electronic payloads that would be reasonably required.

This literature review resulted in the identification of over 200 various governmental studies, scholarly journal articles, and technical books all related to airship design. Overall, analyzing, interpreting, and critically evaluating these technical documents in the context of this project was absolutely essential for answering the three guiding research questions for this project. The results of this research are outlined in the topical sections that follow.

2.2 Environmental Context

2.2.1 Investigation

An initial understanding of the many environmental factors affecting airship flight is essential before any systems engineering design activities can begin. The following is a brief review of the temperature, pressure, winds, ozone, and radiation elements found at stratospheric altitudes. All of these aspects play major roles in airship material selection and construction.

Stratosphere Overview. The troposphere begins at the Earth's surface, but its height varies. It is 18-20 km (11-12 miles) high at the equator, but just 8 km (5 miles) high at the poles [13]. Above that region lies the stratosphere, reaching up to 50 km (164,000 ft) (see Figure 9).

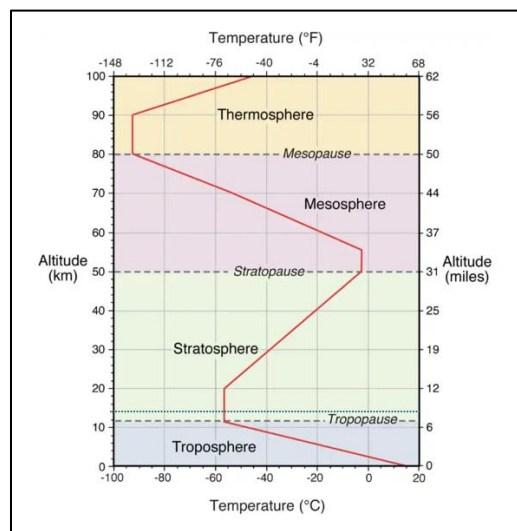


Figure 9: At Atmospheric Features [13]

Air Temperature. As one ascends, air temperature initially drops to nearly -60 C (-78 F) (see Figure 9). However, once one enters the broad ozone layer (generally from 15 km to 35 km), this temperature drop then reverses and begins to warm. This warming effect is due to the absorption of solar radiation by the ozone layer, which is concentrated around 25 km (15 miles). From 10 km to 20 km, the air temperature remains stable at a constant 216.65 K [13].

Atmospheric Pressure. Most of the air molecules in the atmosphere are held close to the Earth's surface due to the force of gravity. At sea level, atmospheric pressure measures 1013 millibar (mb) (or 101.3 kilopascals). Then, as one climbs altitude, atmospheric pressure decreases roughly 50% (500 mb) within the first 5 km. By the time one reaches 20 km (65,000 ft or 12 miles) the air pressure has decreased to about 7% of sea level (see Figure 10). Finally, at 21 km (70,000 feet) the air pressure measures only 44 mb (4.4 kPa) [14].

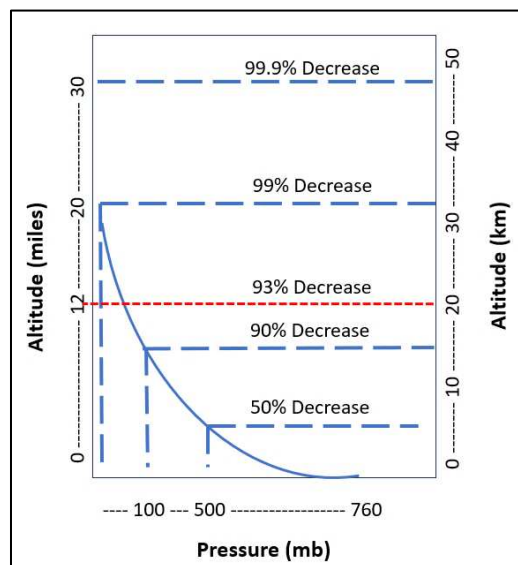


Figure 10: Pressure vs Altitude [15]

Winds Aloft. In addition to atmospheric pressure and temperature, winds aloft vary depending on altitude. Atmospheric circulation over the North Pole occurs in two separate layers (see Figure 11). From 8 km to 14 km (26,000 to 45,000 ft) above the Earth's surface exists a counter-clockwise rotational wind pattern called the "tropospheric polar vortex" (winds blowing west to east). Whenever this stream of air expands south it pushes cold arctic air downward, producing the famous freezing "jet streams" that occur during the winter across North America.

At very much higher altitudes, above 15 km (49,000 ft), exists a second rotational wind pattern, again traveling counter-clockwise called the “stratospheric polar vortex.” This second vortex forms when the North Pole is pointed away from the Sun and the Earth enters winter. However, since the stratosphere has very low air density, the actual airflow is much quieter [16].

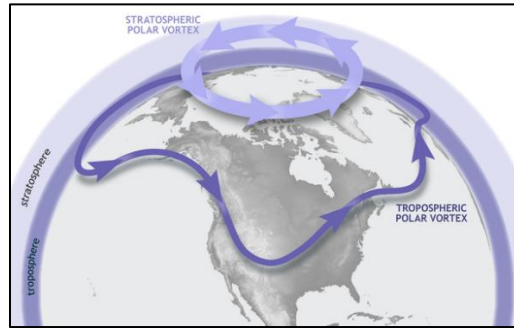


Figure 11: Polar Vortex Layers [17]

A study conducted by the U.S. Navy in 1972 determined lower tropospheric wind speeds typically peaked just after 10 km (32,800 ft) and averaged 20 meters/second (45 mph). These winds then decreased to nearly zero by 21 km (69,000 ft) (see Figure 12) [18]. Thus, it would appear the region between 10 km and 20 km should be reasonably calm for long duration airship operations.

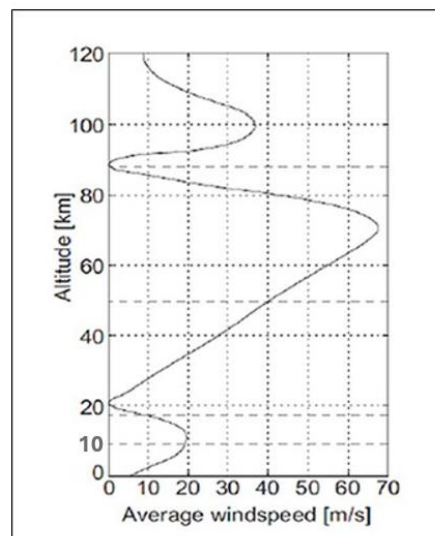


Figure 12: Typical Wind Velocity Profile [19]

Ozone Concentration. As solar radiation in the UV range (180-240 nm) strikes the Earth's upper atmosphere, it causes chemical reactions to occur, breaking apart normal oxygen (O_2) molecules. These individual oxygen atoms are then free to recombine into triplet molecules, forming ozone (O_3). As the radiation descends through the atmosphere, it encounters more and more oxygen molecules, thus creating more and more ozone until most of the solar radiation is consumed through these chemical reactions [20].

This effect creates a thick "ozone layer" throughout the lower portion of the stratosphere from approximately 15 km (49,000 ft) to 35 km (115,000 ft) above the Earth. This ozone layer absorbs up to 99% of the Sun's UV radiation which otherwise would be very damaging to life on the Earth's surface. While this ozone layer is very beneficial to life on Earth, ozone is also one of the most corrosive agents known. It can oxidize metals and is very toxic [21]. Thus, airships operating at high altitudes need to be especially protected against ozone corrosion hazards.

Solar Radiation. Further, this high-altitude solar radiation causes an additional concern for stratospheric airship operations. While direct estimates of solar energy may be expressed as watts per square meter (W/m^2), radiation data for solar electric (photovoltaic) systems are often represented as kilowatt-hours per square meter (kWh/m^2) [22].

At 20 km (65,000 ft), the solar radiation is about 25% stronger than at only 2 km (6,500 ft) under clear sky conditions. Unfortunately, due to the extremely thin atmosphere present at 20 km, successful heat transfer from a vehicle's hull outwards into the surrounding atmosphere is only one-third as efficient than at sea level. This can result in a larger vehicle heat gain and a smaller

vehicle heat loss; the net consequence is a phenomenon known as vehicle “superheating” which must be compensated for in some manner [38].

2.2.2 Analysis

This section began with a review of basic stratospheric atmospheric concepts that are vital to understand during later systems engineering activities. First, the presence of very low air temperatures and atmospheric pressures were discussed. Next, a short overview of tropospheric and stratospheric polar vortices was provided. It was noted the air at this high altitude is very dry, there is very little wind turbulence, and there are no clouds, rain, or thunderstorms occurring within this region. It was also observed moderate wind speeds occur between 15 to 23 km (49,200 to 75,500 ft), which would seem to make this high-altitude regime suitable for flight operations.

Overall, the information researched was very helpful in understanding the stratospheric environment in which the proposed airship is to operate. However, it also highlighted several key challenges facing the design of a very high-altitude airship with ozone corrosion and solar radiation superheating appearing to be the most troubling factors. These atmospheric challenges must be kept in mind throughout subsequent airship design activities.

2.3 Historical Context

2.3.1 Investigation

Over the past several decades, NASA has successfully conducted numerous high altitude research balloon launches in the Antarctic. Carrying various scientific payloads, these research balloons have achieved tremendous altitudes, often reaching almost 50 km (160,000 ft; essentially to the top of the stratosphere). Achieving these extreme altitudes allowed scientists to investigate solar energy particles, cosmic rays, and neutrino emissions. These balloons seemed to provide the altitudes desired for this new project.

NASA Research Balloons. During the 2000s, new “Super Pressure Balloons” (SPB) were developed that could hold millions of cubic feet of hydrogen, making possible “Ultra Long Duration Balloon” (ULDB) flights lasting weeks at a time (see Figure 13). Their helium envelopes use super-fine material measuring only 0.8 mils in density (equals 0.0056 kg/m^2) [23].



Figure 13: NASA Antarctic Balloon Launch [24]

Once sent aloft, these SPB flights passively float at very high altitude using stratospheric Antarctic counter-clockwise circular wind currents (see Figure 14) [25]. For example, in 2024, a NASA research mission flying a 39 million ft³ (1.1 million m³) balloon set a ULDB flight record lasting over 57 days aloft [26].

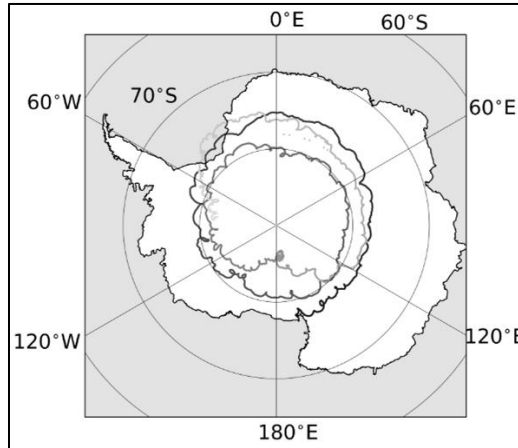


Figure 14: Antarctic Research Balloon Circumnavigation [26]

During this research, however, it became apparent using these large inflatable balloons would not be sufficient for this early warning project. While the balloons can be launched to extremely high altitudes, they have no means of propulsion to guide them once aloft. Nor do they employ any guidance or navigation systems, therefore can't be considered "remote controlled." Overall, these balloons did not provide enough subsystems to warrant a systems engineering approach. So, the author's research focus switched to steerable non-rigid airships (i.e., blimps).

U.S. Navy "High Platform II" Airship Program. While blimps have flown since before World War I, the modern era has been reluctant to develop large airships. After the explosive crash of the huge Hindenburg in 1937, development of airships came to a halt after World War II [27].

Thus, it was not until the late 1960s, with financial support from the U.S. Navy, that Raven Industries first began experimental work on the new "High Platform II" project, conceived to be a

small (24 m) (92 ft) demonstrator balloon capable of lifting a five-pound telemetry payload to 20 km. The vehicle was to fly during daylight, used solar cells for power, and so carried no batteries. It successfully flew in 1970 for two hours to an altitude of 20.4 km (66,900 ft), thus becoming the world's first stratospheric airship (see Figure 15). Fifty-five years later, this record still stands [28].



Figure 15: U.S. Navy High Platform II Airship [28]

A follow-on “High Platform III” design study was completed in 1971 with the new goal of lofting a 200 lbs payload to 80,000 feet and operating for four months. This study focused on improving specific airship characteristics but did not produce a prototype. The study determined the new goal was feasible, however further development was not funded by the U.S. Navy [28].

DARPA “Sentinel 1000” Airship Program. Ten years later, in 1985, the U.S. Navy issued a new request for proposals for a radar-carrying “Battle Surveillance Airship System (BSAS)”. The Westinghouse-Airship Industries team won the contract and began work on a subscale Operational Development Model which was labeled “Sentinel 1000.” However, the U.S. Navy funding for the project only lasted two years at which point the Defense Advanced Research Projects Agency (DARPA) stepped in with funding. The design was for a low-altitude surveillance airship manned by a pilot and up to 10 passengers [29].

Unfortunately, Airships Industries went bankrupt, forcing Westinghouse to manage the project itself. By 1991, the airship was finally completed and successfully flew. At that time, the Sentinel 1000 airship ranked as being the largest airship in the world [29] (see Figure 16).

Systems and flight testing continued for several years, but a catastrophic hangar fire destroyed the Sentinel 1000 airship in 1995. As a result, the project was then terminated.



Figure 16: DARPA Sentinel 1000 Airship [29]

While not a high-altitude airship, the Sentinel 1000 airship demonstrated that a very large airship could actually be constructed, and that its military surveillance mission had now regained some Department of Defense interest.

U.S. Army “HiSentinel” Airship Program. Ten years later, starting in 2005, Aerostar International (now a subsidiary of Raven Industries, who had built High Platform II in 1970) began working with the U.S. Army to launch its pioneering “HiSentinel” test program. The goal was to develop non-rigid solar-powered air vehicles capable of lifting payloads to near-space altitudes for 30-90 days. The test program’s final non-rigid vehicle, “HiSentinel80,” was 200 feet long and designed to carry an 80-pound communications relay payload [30] (see Figure 17).

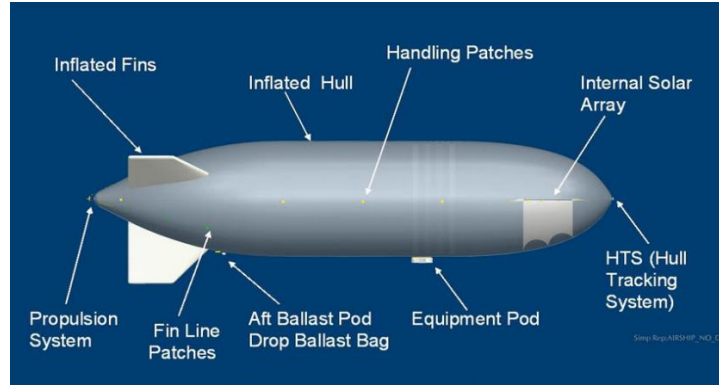


Figure 17: U.S. Army HiSentinel Airship Components [30]

Full inflation and integration testing of this massive 200 ft balloon was conducted inside the Alamodome in San Antonio, Texas (see Figures 18) [30].



Figure 18: U.S. Army HiSentinel80 Non-Rigid Airship [30]

Launched in 2010, HiSentinel80 achieved an altitude of 66,200 ft within 50 minutes (see Figure 19). During its ascent, the airship met with winds of 120 knots as it crossed 32,000 ft altitude. However, once it was traveled past these challenging conditions, ascent dynamics were effectively controlled and the platform remained stable for almost 8 hours [30].



Figure 19: U.S. Army HiSentinel80 at 66,200 ft [30]

Overall, the successful HiSentinel80 flight proved the non-rigid, high-altitude airship concept was definitely feasible. Key HiSentinel80 airship characteristics are listed in Table 2.

Table 2: U.S. Army HiSentinel80 Characteristics [30]

Airship Type	Helium; non-rigid
Length	60 m (200 ft)
Diameter	13 m (45 ft)
Altitude	20 km (66,200 ft)
Envelope Volume	6,800 m ³ (240,000 ft ³)
Envelope	200 denier Vectran and 30 denier Nylon with inflatable tail fins in “Y” configuration.
Propulsion System	1 x tail-mounted electric motor-driven propeller.
Lifting Mass	500 kg (1,100 lbs)
Payload	36 kg (80 lbs)
Power Source	Batteries supplemented by 5 x 1.2 kW photovoltaic panels (92 cells) delivering 50 watts power at 120V.
Endurance	1 day

Lockheed Martin “HALE-D” Airship Program. In 2008, the U.S. Army began funding the “High-Altitude Long-Endurance Demonstrator” (HALE-D), part of several Advanced Concept

Technology Demonstration (ACTD) programs conducted by the Department of Defense. Lockheed Martin won the contract for the program that focused on developing key technologies necessary for successful airship development [31]:

- High-strength, lightweight fabrics for envelope construction.
- Thin-film solar arrays and regenerative battery power supplies.
- Lightweight propulsion units for station-keeping at high altitudes.
- Flight controls and remote data link piloting.
- Thermal management over day to night environmental conditions.

The non-rigid, pressurized hull was made of metalized laminated fabric that reduced solar energy absorption. The propulsion system consisted of two flank-mounted electric motors attached directly to the non-rigid hull (see Figure 20) [31].

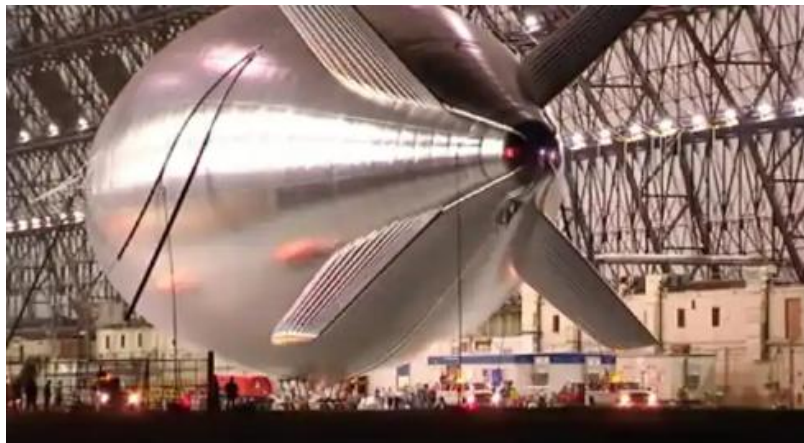


Figure 20: Lockheed Martin HALE-D [31]

In 2011, HALE-D conducted its first and only flight, launching from the Lockheed Martin development facility in Akron, Ohio (see Figure 21) [31].



Figure 21: HALE-D Launch [31]

While targeted to reach 60,000 feet, the test flight was terminated after reaching 32,600 feet due to an air valve freezing issue. As the airship was departing the testing area, it was decided to command an emergency recovery by releasing the helium gas. The airship descended for 2 hours and 40 minutes and crashed landed in a heavily wooded site in Ohio. As the equipment was being removed by the retrieval crew, a short circuit in the solar panels caused a fire to breakout, destroying the airship. After spending \$36 million on the test vehicle, no additional HALE vehicles were developed [31]. Key ISIS characteristics are listed in Table 3.

Table 3: Lockheed Martin HALE-D Characteristics [31]

Airship Type	Helium; non-rigid
Length	73 m (240 ft)
Diameter	21 m (70 ft)
Envelope Volume	14,158 m ³ (500,000 ft ³)
Propulsion System	2 x electric motor-driven propeller.
Lifting Mass	36 kg (80 lbs)

DARPA “ISIS” Airship Program. As the U.S. Army’s HiSentinel and HALE-D test programs were starting, the Defense Advanced Research Projects Agency (DARPA) also initiated its own airship design program entitled “Integrated Sensor is Structure (ISIS)” [32]. The goal of this cutting-edge program was to develop an integrated airship with a wide-area surveillance sensor inserted inside the airship’s airframe. This complex sensor was proposed to provide both Airborne Moving Target Indicator (AMTI) and Ground-based Moving Target Indicator (GMTI) capabilities using a single component (see Figure 22). The airship was to be constructed of a metalized, flexible, fabric laminate with extremely high strength-to-weight ratio. Powered by a solar photovoltaic array on top surface and regenerative hydrogen fuel cells, its proposed mission duration goal was 90 days [32].

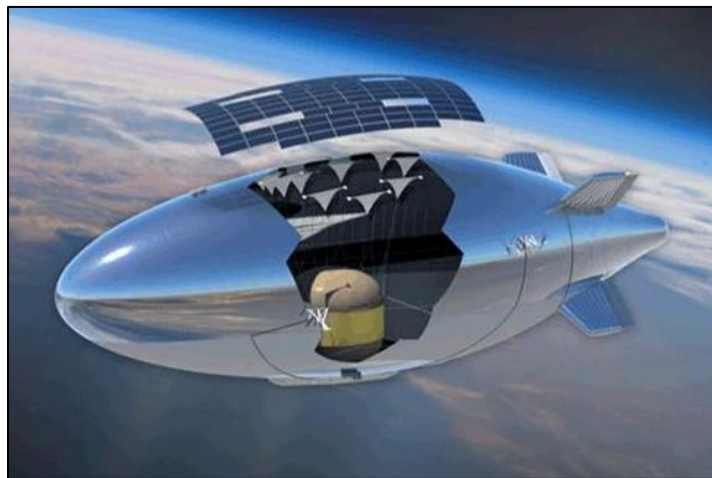


Figure 22: DARPA ISIS Airship with the Integrated Sensor [32]

Unfortunately, by 2012, the development of the sophisticated air-plus-ground surveillance sensor system had run into major development problems. The Government Accountability Office reported “ISIS has experienced technical challenges stemming from subsystem development and radar antenna panel manufacturing. Consequently, earlier this year DARPA temporarily delayed

airframe development activities, and instead will mainly focus on radar risk reduction activities” [32]. The USAF budget for FY 2016 later reported the ISIS program was “complete by FY 2015.”

Overall, \$486 million was spent on the project; no actual ISIS airship was ever constructed.

Key ISIS characteristics are listed in Table 4.

Table 4: DARPA ISIS Characteristics [32]

Airship Type	Helium; non-rigid
Length	150 m (490 ft)
Diameter	50 m (160 ft)
Altitude	20 km (65,600 ft)
Envelope Volume	48,100 m ³ (1,700,000 ft ³)
Propulsion System	4 x flank-mounted electric motor-driven propellers.
Radar Payload	3,000 kg (6,600 lbs)

Chinese “Yuanmeng” Airship Program. Also pursuing a similar HALE airship design were the Chinese, who successfully flew their “Yuanmeng” (“Dream”) airship in 2015 (see Figure 23). The Yuanmeng flew to 19 km (65,000 ft) carrying a 300 kg (660 lbs) payload for 22 hours to test controls and near-space flight performance. A report in the *People's Daily* suggests the airship might be used for communications purposes, as the ship is equipped with systems for wideband communication, data relay, high-definition observation, and spatial imaging [33]. Key Yuanmeng airship characteristics are listed in Table 5.



Figure 23: Yuanmeng Airship [33]

Table 5: Yuanmeng Characteristics [33]

Airship Type	Helium; non-rigid
Target Altitude	20 km (65,000 ft)
Length	75 m (246 ft)
Diameter	22 m (72 ft)
Envelope Volume	18,000 m ³ (635,664 ft ³)
Propulsion System	Nose and tail-mounted electric-driven propellers
Power System	Photovoltaic cells on the hull for power during the day and battery or fuel cells for power at night.
Payload	300 kg (660 lbs)
Endurance	6 months

United States “Sceye” Airship Program. Nine years later, in 2024, the New Mexico-based high altitude airship company Sceye Corporation successfully flew their own High Altitude Platform Station (HAPS) for more than 24 hours. This 82 m (270 ft) long airship uses a solar panel array mounted on top of the vehicle to generate power during the daytime and employs lithium sulfur batteries to store excess electricity for nighttime operation. These batteries also drive a tail-mounted, electrically driven propeller (see Figure 24) [34].



Figure 24: United States Sceye Airship [34]

The airship carried payloads including optical cameras intended to observe disasters such as floods and earthquakes, infrared cameras for helping to detect wildfires and methane leaks, and a synthetic aperture radar. The company has registered four airships with the FAA and states it has completed 20 test flights with these airships through 2024 [34].

The company advertises their hull fabric is five times stronger relative to weight, 1500 times more gas tight, and UV and ozone resistant. Their lithium-sulfur batteries have an energy density of more than 400 W-h/kg, nearly 2 times greater density than the best electric vehicle. And they use solar arrays that are said to be 85% lighter than typical solar cells [34].

Unmanned Aerial Vehicle Comparison. Finally, to compare key differences between non-rigid airships and UAVs, the following overview is provided for the MQ-9C “Triton”, a modern surveillance UAV being flown by the U.S. Navy [35] (see Figure 25).



Figure 25: MQ-4C Triton UAV [35]

A follow-on to the effective Air Force RQ-4 “Global Hawk” UAV, the Triton achieved initial operating capability in 2023 and was delivered to the Navy’s Pacific Fleet to operate in the U.S. Indo-Pacific Command’s area of responsibility to conduct maritime domain awareness. Triton’s autonomous airborne operations are supported by land-based command and control mission planners and sensor operators [35].

The UAV is propelled by a single turbofan engine with a service ceiling of 17,000 meters (55,000 ft), a maximum speed of 350 mph, and a range of 7,400 nautical miles. It carries the AN/ZPY-3 maritime surveillance radar which has a detection range of 200 NM and can remain airborne up to 30 hours [35].

While capable of being operated under remote control, having exceptional altitude capability, and of conducting a similar surveillance mission, the Triton’s major disadvantage is that it does not offer long-endurance capability; one of the important goals of this proposed NORAD early warning airship.

2.3.2 Analysis

This section provided a brief overview of airship development over the past fifty years. Although blimps flew during the first part of the 20th Century, their operational employment

eventually came to an end after World War II. But as improvements in gas envelope materials occurred, interest in testing airship prototypes was rekindled.

Starting in 1970, the Navy's small "High Platform II" airship successfully flew to 66,900 feet, setting the current world's altitude record for airships. The Navy's follow-on "High Platform III" design study then proposed building an airship capable of lofting 200 lbs to 70,000 feet, stating this goal was technically feasible at that time. Still, airship research stalled for the next several decades as the technology proved it was not yet capable of achieving airship design goals.

Twenty years later, in 1991, the DARPA Sentinel 1000 airship was completed and successfully flew and was, at the time, the largest airship in the world. But again, no further airship research efforts were forthcoming.

Another twenty years passed until 2010, when the "HiSentinel80" airship flew to over 66,000 feet carrying an 80-pound payload. This achievement was then followed in 2015, when the Chinese flew their "Yuanmeng" airship to 65,000 feet carrying an even larger 660 lbs payload. And starting in 2023, the United States Sockeye airship began conducting its effective flight trials. Thus, in just thirteen years' time, the pace of developing very large airships for stratospheric flight-testing purposes had increased significantly.

In summary, the concept of non-rigid airships being capable of transporting moderate sized payloads to stratospheric altitudes is supported by the available literature. Such a concept appears to be technically feasible and is supported by research studies, successfully flown prototypes, and ongoing commercial airship investments. This bodes well for this project.

Part II – Airship Research

2.4 Structural Research

2.4.1 Investigation

Gas Envelope Design. Airships fall into three basic classifications (see Figure 26) [36, 37]:

- Rigid. These airships consist of an airframe traditionally constructed of wire-braced girders supporting fabric skin. Internal compartments house separate gasbags. Lifting gas plays no part in maintaining the airship's outer shape. The massive Hindenburg zeppelin is an example.
- Semi-Rigid. These airships incorporate a long keel structure from nose to tail along the bottom surface that supports the airship's shape as well as the gas bag and propulsion. The modern Goodyear blimp is an example.
- Non-Rigid. Finally, these airships have no hard structure maintaining the airship's shape and is dependent solely upon its internal gas to maintain its shape. Internal suspension cables support propulsion and payload systems.

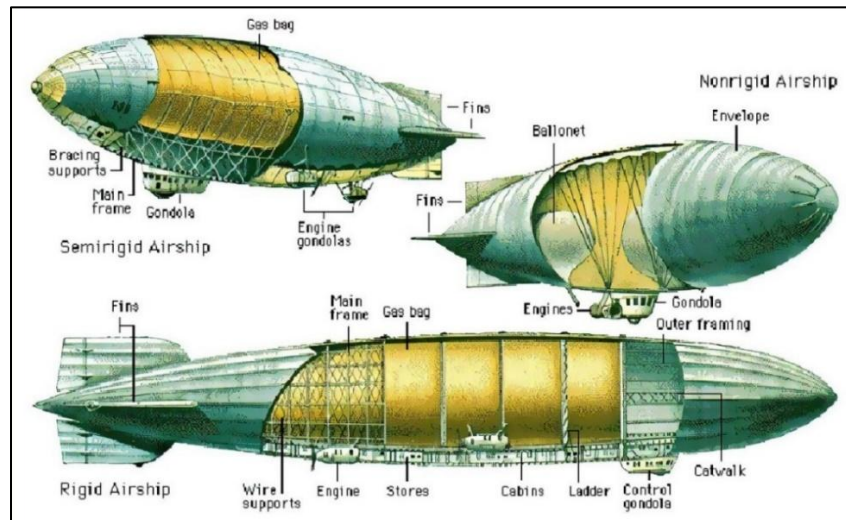


Figure 26: Types of Airships [38]

For non-rigid airships, the gas envelope forms the vehicle's overall shape and is the key element to a successful vehicle design. Most gas envelope airship designs have been low-drag, axisymmetric 2-dimensional bodies of revolution [39]. Various studies have produced standard profile factors useful for airship designers to consider (see Figure 27 and Table 6).

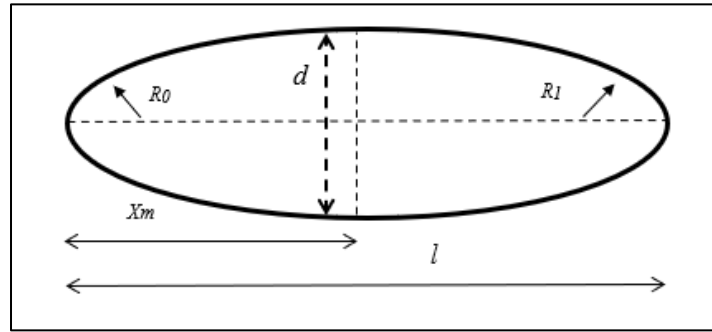


Figure 27: Key Airship Dimensions [39]

Table 6: Airship Envelope Design Factors

Parameter	Definition	Design Factors	Source
l	Length of airship	---	
d	Width of airship at widest point	$(.30) (l)$	[40]
l/d	Optimum Fineness Ratio	4.00	[39]
X_M	Distance of the maximum diameter to the nose	0.432	[39]
R_0	Radius of the curvature at the nose	0.589	[39]
R_1	Radius of the curvature at the tail	0.425	[39]
A_S	Surface area of envelope	$(0.6586) (l^2)$	[40]
V_E	Volume of envelope	$(0.0387) (l^3)$	[40]
D	Airship Drag	$\frac{1}{2} \rho C_D v^2 V_E^{\frac{2}{3}}$	[41]
F_L	Lifting Force	$\rho V_E 9.81$	[41]

The “Fineness Ratio” is the ratio of the length of the airship divided by its maximum diameter and is an expression of the airship’s aeronautical slimness. For large airships, a fineness ratio between 3 to 6 was recommended to maintain airship maneuverability [36].

Ballonets. For non-rigid airships to control their ascent and descent, flexible internal bladders called “ballonets” are installed inside the main gas envelope (see Figure 26). Separate from the lifting gas envelope, these bladders are connected to the outside atmosphere and control how much volume is available inside the lifting gas envelope. By inflating or deflating the ballonets, the space available for the lifting gas to expand within the envelope can be controlled.

As the airship climbs, the ballonets vent to allow more room for the lifting gas to expand; as the airship descends, outside air is pumped in to inflate the ballonets. This ensures the lifting gas maintains the airship envelope’s overall shape so it does not collapse. “Pressure altitude” is term denoting the altitude when all of the air has been vented from the ballonet and no further expansion of the lifting gas can occur [36].

Envelope Fabric. The ideal materials suitable for non-rigid gas envelope construction should have the following properties (see Figure 28) [42]:

- Materials that provide the lightest fabric weight available. For example: multi-layered, neoprene-coated polyester film measuring 103–113 g/m².
- High strength-to-weight ratio to minimize the weight of the envelope.
- Low permeability to minimize lifting gas loss.
- High tear resistance for damage tolerance.
- Resistance to low temperatures, humidity, and ultraviolet light.
- Flexibility to inflate and deflate over its service life cycle.

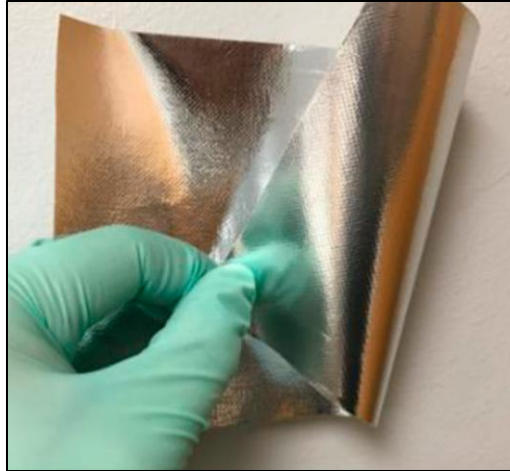


Figure 28: Multi-Layered Laminated Envelope Material [43]

Lifting Gas. When first flown by Count von Zeppelin in Germany in 1900 [44], “Zeppelin” airships used hydrogen as their primary lifting gas. It is the lightest chemical in existence and was easy to manufacture using the electrolysis process (i.e., splitting water into its separate hydrogen and water elements) [45]. Notably, a total of 84 Zeppelins were manufactured by Germany during World War I [46] and successfully flew for nearly four decades using hydrogen gas until the tragic *Hindenburg* airship fire that occurred in 1937 (see Figure 29) [47].



Figure 29: Hindenburg Airship Fire [48]

Beginning in the 1920s, the United States also became interested in establishing its own Zeppelin fleet and began purchasing German-manufactured Zeppelins for coastal surveillance. Initially, they too were filled using hydrogen gas tanks (see Figure 30).



Figure 30: Airship Hydrogen Refilling Tanks [49]

Later, however, as the Zeppelins were being delivered to the United States, they were converted to using helium gas, instead. The second lightest element, helium is a very rare and expensive gas to produce that is only available from certain western gas fields in the United States. (Because of this exclusivity, Germany never had the option to use helium for its Zeppelins.)

While the U.S Navy began World War II with only two blimp squadrons, by 1945 it had numerous airship units stationed in Florida, Texas, Louisiana, and across the Caribbean. Between 1942 and 1945, the Goodyear Corporation manufactured more than 150 airships for the U.S. Navy to serve in coastal defense surveillance missions and Atlantic convoy escort protection against German submarines.

However, due to the dramatic improvements in aircraft technology during World War II, the requirement for large, slow-moving blimps finally came to an end after the war. The last U.S. Navy blimps were decommissioned in 1948 [50].

USAF POBAL-S Airship Study. In 1975, the U.S. Air Force conducted a detailed analysis and design study for a proposed “Powered Balloon-Superpressure” (POBAL-S) airship concept (see Figures 31) [18]. The airship’s gondola houses the fuel cell and fuel tanks, the telemetry system, control units, the autopilot, and the mission payload (see Figure 32).

Overall, the POBAL-S study provided excellent metrics for consideration (see Table 7) during this project’s system engineering efforts (outlined in Chapter VI.)

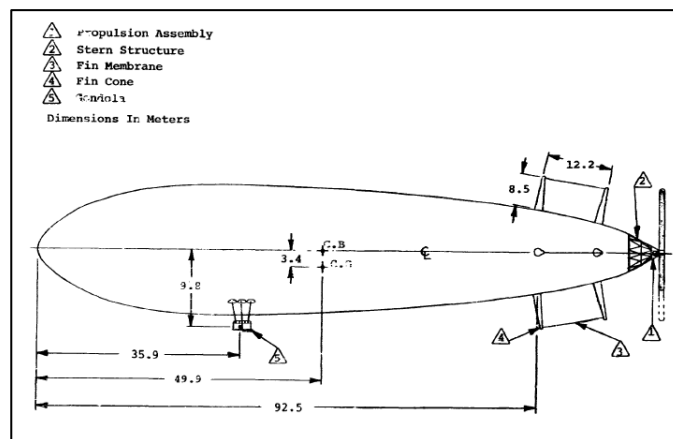


Figure 31: POBAL-S Airship Concept [18]

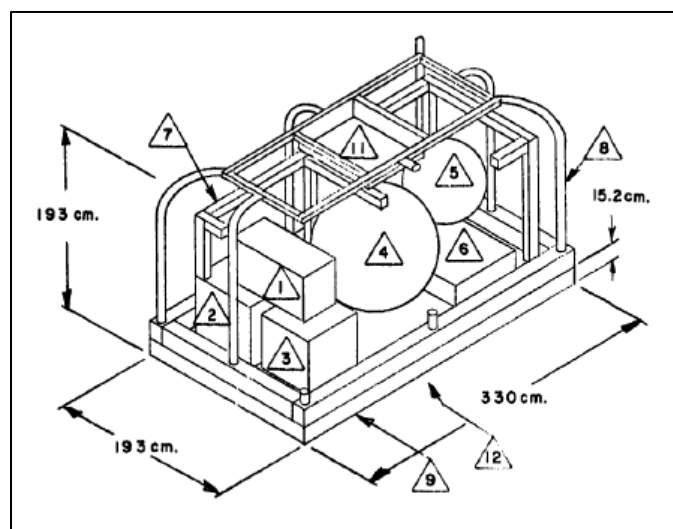


Figure 32: Equipment Gondola Layout [18]

Table 7: POBAL-S Airship Study Parameters [18]

<i>Parameters</i>	<i>Assumptions</i>
Airship Gas	Helium
Most Favorable Wind Altitude	21 km (70,000 ft)
Duration	7 Days
Daylight Power Source	Solar power
Nighttime/Backup Power Source	Batteries (24 hours)
Airspeed	16 knots
Payload Weight	90 kg (200 lbs)
<i>Balloon Assembly</i>	
Length	113 m (370 ft)
Average Diameter	23 m (75 ft)
Fineness Ratio (Length / Width)	5.0
Drag Coefficient	0.05
Envelope Volume	29,270 m ³ (1,034,00 ft ³)
Total Balloon Assembly Weight	1,244 kg (2,744 lbs)
Total System Weight	1,850 kg (4,080 lbs)
<i>Propulsion Assembly</i>	
Motor	1 x Lightweight, DC brushless
Input Power	1.8 kW @ 28VDC and 60A
Propeller	3 x Blades
Propellor Weight	20 kg (44 lbs)
Diameter	10 m (34 ft)
Speed	75 RPM
Total Propulsion Assembly Weight	72 kg (160 lbs)
<i>Flight Control Assembly</i>	
Radio Link	Narrowband VHF FM
Autopilot Power	220 Watts

NASA “AoA” Airship Study. Thirty years later, in 2007, NASA’s Langley Research Center conducted an “Analysis of Alternatives” study of various high-altitude long-endurance (HALE) unmanned aerial vehicles (UAV) configurations. This study resulted in numerous detailed criteria useful for subsequent airship design consideration (see Table 8). Like the POBAL-S study, this NASA study provided important design information used during the system engineering phase.

Table 8: NASA “AoA” Study Final Results [51]

	Parameters	Values
Operational	Endurance	180 days
	Loiter Altitude	18 km (59,055 ft)
	Support Required	12
	Risk Estimate	6
Geometry	Vehicle Length	139.6 m (458 ft)
	Vehicle Diameter	39.9 m (131ft)
	Lifting Gas Volume	116,393 m ³ (4,110,400 ft ³)
	Envelope Surface Area	14,201 m ² (152,858 ft ²)
	Maximum Skin Thickness	0.13 mm (0.0051 inch)
	Envelope Fabric	Spectra®
	Hull Mass	4,901 kg (10,804 lbs)
	Propulsion Mass	1,631 kg (3,596 lbs)
	Power Production Mass	6,347 kg (13,993 lbs)
	Mission Payload Mass	212 kg (467 lbs)
	Total Mass	13,212 kg (29,125 lbs)
Propulsion	Drag @ Max Power	11,948 N (2,686 lbs-force)
	Total Drag Coefficient	0.02555
	Total Power Required	638.7 kW
	Number of Fuel Cells	117

Helium Buoyancy Example. A vital decision at the beginning of airship design is determining the lifting gas (hydrogen or helium) to be employed. For this project, a comparison of the key characteristics of each was conducted. The following are the basic calculations that were used to determine approximate airship buoyancy using helium (see Table 9).

Table 9: Helium Buoyancy Parameters

Parameters	Values
Float Altitude	10 km
Air Pressure at 10 km [52]	26,436 Pa
Helium Gas Constant [53]	2077.1 J/kg-K
Temperature at 10 km [52]	223.15 K
Length (e.g., Goodyear Blimp)	75 m
Diameter	33 m
Gas Envelope Volume	24,544 m ³
Envelope Density [42]	0.1 kg/m ²
Air Density at 10 km (ρ_{air}) [52]	0.41271 kg/m ³
Gravitational Force	9.81 m/s ²

First, the helium density at 10 km is determined [54]:

$$\begin{aligned}
 \rho_{\text{helium}} &= \text{air pressure} / (\text{helium gas constant} \times \text{temperature}) \\
 &= 26,436.3 / (2077.1 \times 223.15) = 0.05703 \text{ kg/m}^3
 \end{aligned} \tag{7}$$

Then, the resulting Buoyancy Force (F_B) exhibited at 10 km is computed [55]:

$$\begin{aligned}
 F_B &= (\text{gas envelope volume}) (\rho_{\text{air}} - \rho_{\text{helium}}) (\text{gravity}) \\
 &= (24,544 \text{ m}^3) (0.41271 \text{ kg/m}^3 - 0.05703 \text{ kg/m}^3) (9.81 \text{ m/s}^2) \\
 &= 85,637 \text{ kg-m/s}^2 \text{ (e.g., Newtons)}
 \end{aligned} \tag{8}$$

As a result, the total mass capable of being lifted to 10 km by helium is [56]:

$$\begin{aligned}\text{Lifting Mass (M}_L\text{)} &= F_B / g \\ &= 85,637 / 9.81 = 8,729 \text{ kg}\end{aligned}\tag{9}$$

Next, the mass of the helium gas at 10 km is determined [57]:

$$\begin{aligned}\text{Helium Mass (M}_{HE}\text{)} &= (\rho_{\text{helium}}) (\text{volume}) \\ &= (0.05703) (24,544) = 1,400 \text{ kg}\end{aligned}\tag{10}$$

And the gas envelope's surface area is determined using the complicated equation [58]:

$$\begin{aligned}\text{Surface Area (A}_E\text{)} &= (4) * (3.14159) * (((((\text{Diameter}/2) * (\text{Length}/2))^1.6) \\ &+ ((2 * \text{Diameter}/2)^1.6) + ((\text{Length}/2) * (\text{Diameter}/2))^1.6) / 3)^{(1/1.6)} \\ &= 4,585 \text{ m}^2\end{aligned}\tag{11}$$

Followed by calculating the mass of the gas envelope itself [59]:

$$\begin{aligned}\text{Envelope Mass (M}_E\text{)} &= (\text{Envelope Density}) (\text{Surface Area}) (1.15) \\ &= (0.1) (4,585) (1.15) = 527 \text{ kg}\end{aligned}\tag{12}$$

Finally, to determine the equipment mass capable of being lofted to 10 km by helium, the envelope and helium masses are now subtracted from the total lifting mass:

$$\begin{aligned}\text{Equipment Mass (M}_E\text{)} &= (\text{Lift Mass}) - (\text{He Mass}) - (\text{Envelope Mass}) \\ &= (8,729) - (3,308) - (527) = 4,894 \text{ kg}\end{aligned}\tag{13}$$

This final mass is often labeled the “Useful Lift” of an airship.

(Note: as the envelope volume is increased to provide greater lift, the heavier both the envelope and its internal gas component become, thus increasing the airship's weight and thus possibly negating the lift originally intended to be improved. Balancing the combination of greater lift versus greater mass makes lofting heavy payloads to high altitudes very challenging.)

Hydrogen Buoyancy Example. For comparison, airship buoyancy calculations are now repeated using hydrogen values. First, the hydrogen density at 10 km is determined:

$$\begin{aligned}\rho_{\text{hydrogen}} &= \text{air pressure} / (\text{hydrogen gas constant} \times \text{temperature}) \\ &= 26,436.3 / (4124.2 [60] \times 223.15) = 0.02873 \text{ kg/m}^3\end{aligned}\quad (7)$$

Then, the resulting Buoyancy Force (F_B) exhibited at 10 km is computed:

$$\begin{aligned}F_B &= (\text{gas envelope volume}) (\rho_{\text{air}} - \rho_{\text{hydrogen}}) (\text{gravity}) \\ &= (24,544 \text{ m}^3) (0.41271 \text{ kg/m}^3 - 0.02873 \text{ kg/m}^3) (9.81 \text{ m/s}^2) \\ &= 92,453 \text{ kg-m/s}^2 \text{ (e.g., Newtons)}\end{aligned}\quad (8)$$

As a result, the total mass capable of being lifted to 10 km by hydrogen is:

$$\begin{aligned}\text{Lifting Mass (M}_L) &= F_B / g \\ &= 92,453 / 9.81 = 9,424 \text{ kg}\end{aligned}\quad (9)$$

Next, the mass of the hydrogen gas at 10 km is determined:

$$\begin{aligned}\text{Hydrogen Mass (M}_{HE}) &= (\rho_{\text{hydrogen}}) (\text{volume}) \\ &= (0.02873) (24,544) = 705 \text{ kg}\end{aligned}\quad (10)$$

And the mass of the gas envelope itself remains the same:

$$\text{Envelope Mass (M}_E) = 527 \text{ kg}$$

Finally, the equipment mass capable of being lofted to 10 km by hydrogen is:

$$\begin{aligned}\text{Equipment Mass (M}_E) &= (\text{Lift Mass}) - (\text{H}_2 \text{ Mass}) - (\text{Envelope Mass}) \\ &= (9,424) - (705) - (936) = 8,192 \text{ kg} \quad (13)\end{aligned}$$

As can be seen, using hydrogen allowed $8,192 - 4,894 = 3,298$ kg more equipment to be successfully launched. This illustrates the significant benefit of using hydrogen as the lifting gas.

Airship Volume. Volume is typically calculated as “length times width times height” and is shown as meter³. However, due to the unique “cigar” shape of airships, a special equation is used to account for their tapered nose and tail [41].

$$\text{Volume} = \left(\frac{1}{6}\right) (\pi) (\text{Length}) (\text{Diameter})^2 \quad (14)$$

Airship Drag. Finally, as an airship travels through the atmosphere it encounters air resistance to its motion which is labeled “drag” and is measured in kg/m² (or Newtons). This air drag resistance at takeoff is a combination of four key parameters (see Table 10) [61].

$$\text{Drag} = \left(\frac{\rho}{2}\right) (v^2) (C_D) (V^{2/3}) \quad (15)$$

Table 10: Airship Drage Parameters

Parameters	Values
Air density at sea level (i.e., takeoff) (ρ)	1.225 kg / m ³
Proposed velocity (v)	15.6 meters/second (35 mph)
Drag coefficient (C_D)	0.02 [62]
Airship dimensions	100 m x 33 m
Resulting gas envelope volume (V)	58,000 m ³

$$\begin{aligned} \text{Drag at Takeoff} &= \left(\frac{1.225}{2}\right) (15.6^2) (0.02) (58,000^{2/3}) \\ &= 4,466 \text{ kg-m}^2/\text{sec (e.g., Newtons)} \end{aligned}$$

For the airship to move forward, the propulsion system must overcome this constant inertia produced by the bulk of the gas envelope traveling through the sea level air density at takeoff. Once the airship begins to climb, the air density will begin to decrease, airship drag will begin to drop, and the airship’s travel will become much easier.

All of these special equations are critical and will be used extensively during airship design and simulation modeling efforts conducted in Chapter IV.

2.4.2 Analysis

This section opened by explaining the three different airship configurations (e.g., rigid, semi-rigid, and non-rigid.) It then addressed several key airship parameters such as length, diameter, fineness ratio, and surface area, and their recommended design factors.

Next, the function of the ballonets were explained. By inflating or deflating these ballonets, the overall shape of the non-rigid airship's massive gas envelop can be successfully maintained.

This was followed by an overview of key characteristics required of the gas envelope such as fabric type, minimum density and thickness, multilayer lamination, high strength-to-weight ratio, and low gas permeability. It was noted that Germany flew its Zeppelins for four decades using hydrogen as their primary lifting gas, while the United States chose to use helium.

With this structural background, the results from both the 1975 USAF "POBAL-S" and the later 2007 NASA "Analysis of Alternatives" studies were then introduced. Both studies provided important design parameters to be used during later airship design activities.

Next, the numerous factors involved in calculating an airship's buoyancy force were provided using both helium and hydrogen gas examples. Finally, examples for computing the airship's aerodynamic volume and drag resistance were provided.

As demonstrated in the buoyancy calculation examples, the decision to use either hydrogen or helium has an enormous affect on the lifting force of the airship. Thus, it was essential that a choice be made before subsequent literature research continued.

Because one of the key goals of this early warning airship is to attain stratospheric altitudes, it was decided that hydrogen should be used as the primary lifting gas as it provides the greatest lifting force. (This critical decision had a significant impact on the ensuing investigations into airship power production options, addressed later in Section 2.6.)

2.5 Propulsion Research

2.5.1 Investigation

Propulsion Motor Options. Having a better understanding of an airship's structure, the next step was to determine how it should be propelled. Unlike research balloons, one of the beneficial features of airships is their ability to maneuver in flight. This involves some specific power source providing energy to operate devices which rotate propellers that propel the airship. There are two basic airship propulsion options available (see Figure 33).

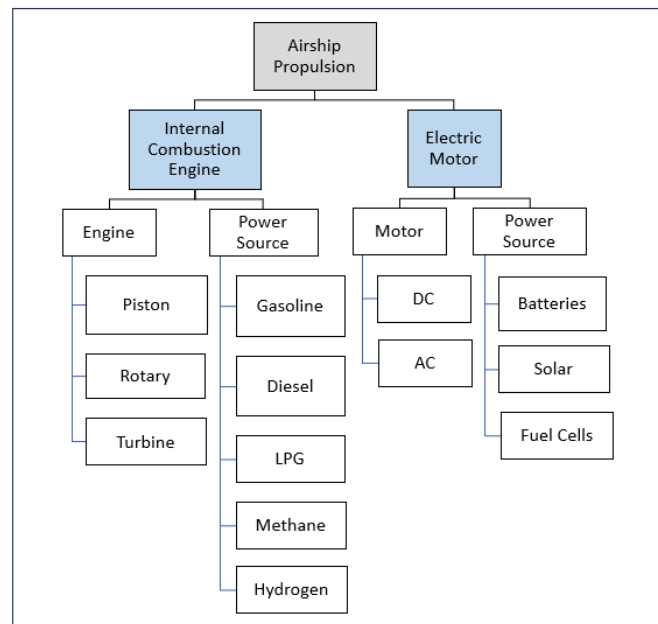


Figure 33: Airship Propulsion Options

- Internal Combustion Engine. These engines convert various fuels into mechanical energy through the use of rotating pistons, which then rotates a propeller that provides the required aerodynamic thrust for the vehicle. Known for both power and reliability, these types of engines have been the traditional means of airship propulsion [63].

- Electric Motors. Electric motors consume electrical power in watts as input and provide mechanical power (measured in either kilowatts or horsepower) at the motor shaft as output. Electric motors have fewer moving parts compared to internal combustion engines, require less maintenance and have lower weight, lower costs, and higher efficiencies [64].

Internal Combustion Engines. A good example of an internal combustion engine is the diesel motor. The energy content of diesel fuel is about 15 percent greater than gasoline [65]. Diesel fuel is primarily recommended for use in warmer climates due to its higher viscosity (the thick stickiness of a fluid), which is prone to becoming a gel when exposed to lower temperatures.

To compare the results of this airship design to more conventional designs, we can describe the baseline mass and energy required to power this vehicle with Diesel-fueled generator. The mass of the generator (reciprocating engine and generator) and fuel are dominated by the mass of the fuel. Diesel fuel has a lower heating value of 12 kWh/kg. For a 100 kW generator, operating at 15% efficiency (to include turbo-compression efficiency), this realizes a fuel consumption of 70 kg/hr. For a default mission duration of 30 days, this equates to 50,000 kg of diesel fuel. This mass far outweighs the airship, making it incapable of flight. In summary, using internal combustion engines for long duration missions was found to be not feasible.

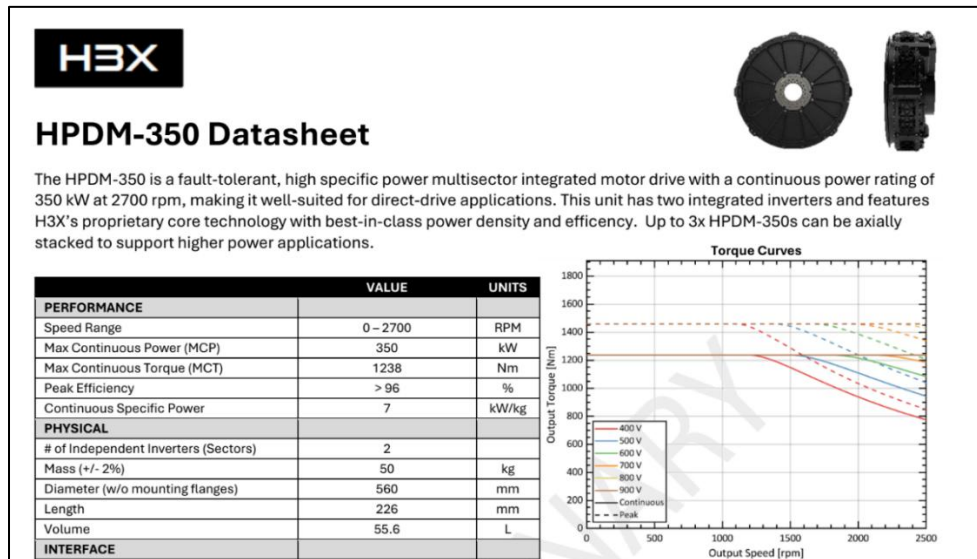
Electric Power Production. By comparison, electric motors powered by solar or fuel cell methods can offer similar power but without the need to carry heavy fuel storage tanks.

For example, the H3X Corporation's HPDM-350 is an integrated motor drive specifically designed for applications on electric aircraft [68]. A unique design feature is its ability to operate up to 14000 meters and down to -40 C. Weighing only 50 kg, it delivers high torque output eliminating the need for a gearbox and simplifying integration (see Figure 34 and Table 11). Overall, this electric motor seems to meet the electric propulsion needs of this project.



Figure 34: HPDM-350 Electric Motor [68]

Table 11: H3X HPDM-350 Datasheet [68]



Previously in 1978, the U.S. Navy awarded a contract to study propulsion systems for use in high-altitude airships under its “High Altitude Surveillance Platform for Over-the-Horizon Targeting” (“HI SPOT”) program [69]. In this study, a theoretical airship was to be propelled by an electric motor powering a stern-mounted propeller measuring 8 meters (26 feet) in diameter, rotating at 144 revolutions per minute (RPM), resulting in a speed of 25 knots (29 mph). This study came to the important conclusion that high-altitude propellers driving an air vehicle at low velocities must operate at only hundreds (and not thousands) of RPM.

Based upon this RPM insight, and assuming the HPDM-350 propulsor motor operates very slowly at only 90 RPM with 90% efficiency (producing an estimated 1,000 N-m of torque to drive the huge propellers), the required electrical power to the motor can then be calculated [70]:

- Convert RPM to Angular Speed:

$$\begin{aligned}\omega \text{ (rad/s)} &= (\text{Estimated RPM}) (2\pi/60) \\ &= (90) (0.1047) = 9.42 \text{ rad/s}\end{aligned}\tag{17}$$

- Calculate Power_{OUT}:

$$\begin{aligned}P_{\text{OUT}} \text{ (Nm)} &= (90\% \text{ Torque Efficiency}) (\omega) \\ &= (1,000 \text{ N-m}) (9.42) = 8,481 \text{ Nm}\end{aligned}\tag{18}$$

- Calculate Power_{IN}:

$$\begin{aligned}P_{\text{IN}} \text{ (kW)} &= P_{\text{OUT}} / (\eta \text{ Motor efficiency}) \\ &= 8,481 / 0.90 = 9,423 \text{ watts or } 9.5 \text{ kW per motor}\end{aligned}\tag{19}$$

This was another critical design milestone. Identifying a suitable motor for the project, and its resulting power demand, was critical in calculating the total amount of power that must be produced by the airship’s power subsystem, described later in Section 2.6.

Propulsor Placement. Multiple electric motors (called “propulsors” for airships) can be mounted either directly to the airship itself or onto a suspended gondola. For instance, electric motors employed on the Airlander 10 airship being developed in the United Kingdom are mounted on each side of the fuselage in order to vector thrust for flight control (see Figure 35) [71].



Figure 35: Airlander 10 Side-Mounted Propulsor [71]

For comparison, the Chinese Yuanmeng airship employs two main electric motors driving huge propellers mounted to both its nose and tail, plus four small maneuvering propulsors mounted along the flank of the airship (see Figure 36) [72].

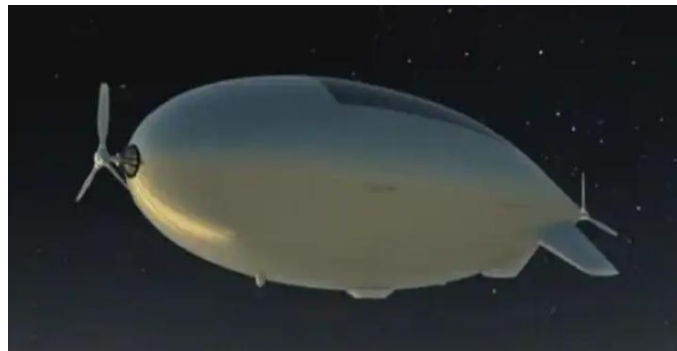


Figure 36: Yuanmeng Airship Twin Propulsors [72]

Propeller Design. For high propeller efficiency, air vehicles should ideally fly at low altitudes (i.e., greater air density), at high cruising speeds (high velocity) and have large propeller area achieved by either a large propeller diameter or a high number of engines [73]. Unfortunately, these ideal conditions do not apply well for high-altitude airship operations:

- Altitude. As previously shown, the air density at 21 km measures only 4.4 kPa. Accordingly, high-altitude propellers will have to be specially sized to ensure they can successfully “grab” the extremely low-density air sufficiently.
- Cruising Speed. Similarly, the proposed airship velocity is expected to reach up to 20 meters/second (45 mph), significantly slower than commercial aircraft speeds.
- Propeller Area. Finally, high-altitude flight requires very large propellers with measurements reaching up to 11 meters (36 feet) in diameter. They will also need to have a considerable blade “twist” design to effectively capture the extremely thin air. Figure 37 illustrates the large propellers and their significant blade twist used on the NASA Centurion very high-altitude test vehicle which was designed to operate at 30 km altitude [74].



Figure 37: High-Twist Very High-Altitude Propellers [74]

Propeller Thrust. Finally, it is necessary to know the amount of thrust a particular motor and its propeller can generate to ensure it has productive forward movement. For example, the following values are given for a sea level takeoff (see Table 12).

Table 12: Thrust Parameters

Parameters	Values
Air Density at Sea Level	1.225 kg/m ³
Rotational Speed (RPM)	90 revolutions per minute
Propeller Diameter (D)	11 m (433 inches)
Propeller Pitch (P)	10 inches
Forward Speed (V)	0 m/s (static start at takeoff)

Thrust developed by a propulsor motor can then be computed using the following complicated equation [75]:

$$\begin{aligned}
 \text{Thrust (F)} &= (\text{Air Density}) * ((3.14159 * (0.0254 * \text{Diameter})^2) / 4) * \\
 &(((\text{RPM} * 0.0254 * \text{Pitch} * (1/60))^2) - (\text{RPM} * 0.0254 * \text{Pitch} * (1/60)) * 0) * \\
 &(\text{Diameter} / (3.29546 * \text{Pitch}))^{1.5} \quad (20) \\
 &= 805 \text{ Newtons (single motor)}
 \end{aligned}$$

For example, employing six motors (three mounted on each side of the airship) would produce $6 \times 805 \text{ N} = 4,828 \text{ N}$ of thrust. As this propeller thrusts exceed the 4,466 N of airship drag previously calculated (see Equation 15), the airship should successfully takeoff.

2.5.2 Analysis

This section began with the examination of airship engine options. Known for both power and reliability, internal combustion motors have been the traditional means of airship propulsion. However, because a key airship goal is long endurance, the amount of fuel necessary to operate an these motor for weeks at a time would require an abundant (and very heavy) on-board fuel supply. This made that propulsion option undesirable.

Electric motors were then reviewed. It was noted electric motors have fewer moving parts compared to internal combustion engines, require less maintenance and have lower weight, lower costs, and higher efficiencies. However, providing sufficient electrical power for weeks at a time would be a challenge. Data for a commercially available electric motor that offers high torque and was designed for high altitude flights was provided as a suitable example.

Next, it was noted a U.S. Navy study concluded high-altitude propellers driving air vehicles at low speeds must operate at hundreds, not thousands, of RPM. Calculations were performed using an example RPM value to generate a motor's electrical input requirement.

Then, it was shown that multiple electric motor propulsors can be mounted either to the nose, tail, or sides of the airship. Finally, this section closed with propeller design considerations and an example of calculating propeller thrust using a complicated equation.

Overall, using electric motors for airship propulsion is recommended. The effectiveness of specific propeller designs at very high altitudes remains a critical factor to verify during airship design and testing. However, the example of NASA's propeller used on the Centurion test vehicle flown at 30 km demonstrated large propellers are capable of operating at stratospheric altitudes.

2.6 Power Research

2.6.1 Investigation

Having determined the airship should be propelled using electric motors, the appropriate means for providing electrical power needed to be resolved. The advantages and disadvantages of each of these alternatives will be briefly outlined below. Similar to airship propulsion options, there are several airship power source options available that can again be classified by their engine differences (see Figure 38).

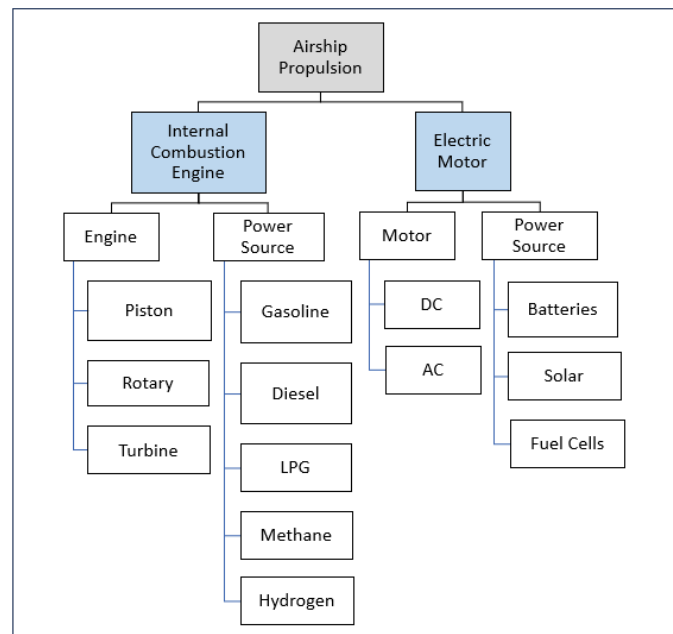


Figure 38: Airship Power Options

Battery Power Production. When proposing to use electrically driven motors to propel an airship, the first thought was to use batteries. A battery's energy capacity is the ability to deliver a certain amount of power over a time period and is measured in kilowatt-hours (kWh) [76].

Because battery power is limited, it is not a solution as a long-term airship power source. However, in an emergency situation, a battery assembly could provide short term (e.g., 1 hour) power to enable an airship to safely land. In an emergency, much less power would be required:

- 4 x motors for conduct descent.
- Guidance subsystem.
- Communications subsystem.
- Internal equipment power (e.g., equipment heaters, elevator servos, etc.).

A good source to provide this short-term power (e.g., provide 1-hour emergency power) would be lithium-ion 18605 C2-type lithium-ion battery cells (see Figure 39) [77]:

$$\text{Power (Watts)} = \text{Voltage (Volts)} \times \text{Current (Amps)}$$

$$\text{Power} = (3.7\text{V}) \times (3300\text{mAh}) = 12.2 \text{ Wh per cell.}$$

Thus, to achieve a 50 kW (50,000 W) emergency power would require 4,100 cells collected in a battery assembly. Given a single cell weighs about 49g, this assembly would weigh 200 kg.



Figure 39: Standard 18650 Battery [77]

Solar Power Production. A suitable means for providing continuous airship power can be accomplished using modern photovoltaic (PV) cells that convert sunlight into electrical energy. Thousands of PV cells could be mounted on the surface of the airship to generate significant power during daylight hours.

A good example is the commercially available Maxeon Air solar panel (see Figure 40). A very thin, bendable, glass-less, adhesive-backed panel, it generates 375 watts and could conceivably be attached to a curved airship envelope [78].

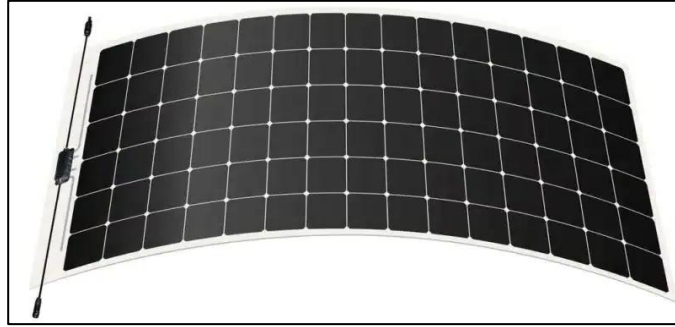


Figure 40: Maxeon Air Solar Panel [78]

Unfortunately, because of the Earth's 23-degree rotational axis tilt, solar energy does not strike the Earth uniformly at the poles. This makes collecting sufficient solar energy while operating in the Arctic very problematic. The available sunlight at the North Pole ranges from continuous sunlight during the summer to continual darkness during the winter months [79].

Using special software, it was determined for a vehicle to remain in constant line-of-sight of the sun while directly over the North Pole (i.e., “pole sitter”) on the winter solstice, the vehicle would need to be situated 349 miles in space! (see Figure 41) [80].

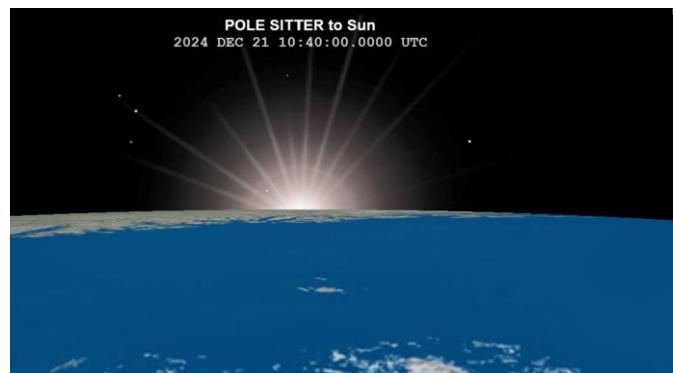


Figure 41: View of the Sun over North Pole on Winter Solstice [80]

Overall, while using solar panels to provide airship power is normally a reasonable option, using solar energy to power year-round Arctic airship operations was not practical.

Fuel Cell Power Production. An alternative power production option was to use fuel cells. A fuel cell converts the chemical energy of a fuel source (e.g., hydrogen) and an oxidizing agent (e.g., oxygen) into electricity, while producing water as a by-product of this chemical reaction. Several commercial “Proton-Exchange Membrane” (PEM) fuel cells are available that can generate hundreds of kilowatts of power (see Figure 42) [81]. The electricity generated is then fed into a power inverter to convert it from direct current to alternating current for airship use.

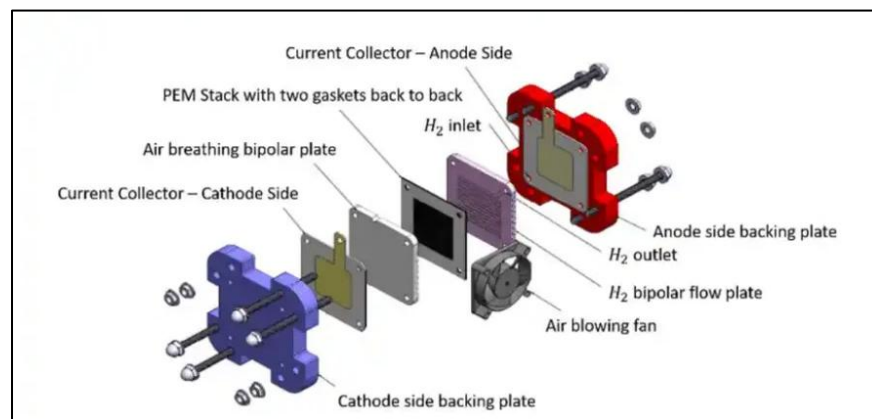


Figure 42: PEM Fuel Cell Elements [81]

For example, Toyota has developed a small hydrogen fuel cell that weighs 240 kg (529 lbs) and can produce up to 65 kW (see Figure 43 and Table 131) [82]. Appropriately insulated and heated to protect it against the cold of high-altitude operation, this component would be an excellent choice as it can produce sufficient electrical power and has low weight.

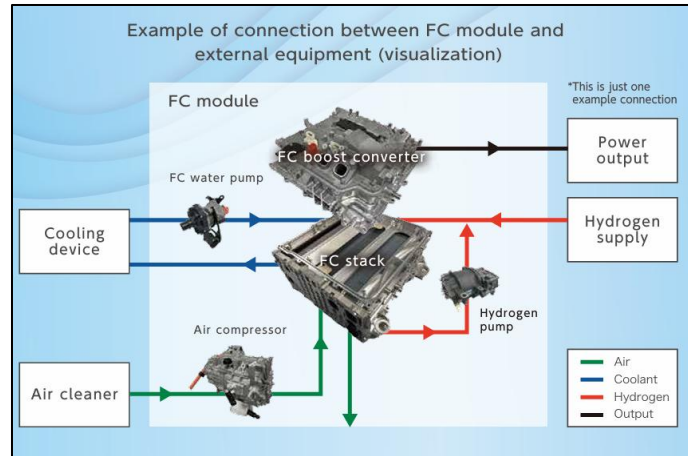


Figure 43: Toyota TFCM2s-F Hydrogen Fuel Cell [83]

Table 13: Toyota Fuel Cell Module Data Sheet [83]

TYPE		TFCM2s-B	TFCM2s-F
DIMENSIONS (LxWxH)		880 x 630 x 690	1270 x 630 x 410
WEIGHT (except FC coolant)		Approx. 235kg	Approx. 240kg
OUTPUT POWER (NET)	Rated Power (EOL)	65kW/85kW (65kW/68kW) ¹¹	
	MINIMUM	0kW (idle), 15kW	
	RESPONSE	40kW/sec	
OUTPUT VOLTAGE		400~750V DC (DC-DC converter included)	
EFFICIENCY PEAK (%)	STACK	66%	
	SYSTEM (incl. DC/DC converter)	56%	
TEMPERATURE RANGE	OPERATING	-30°~70°C (the maximum intake temperature is 45°C)	
	COLD START	-30°C	
	STORAGE	-40°~+85°C	
START-UP TIME	25°C	16sec	
	-30°C (COLD START)	<160sec ¹¹	
ALTITUDE		Max. 3,400m ¹²	
DURABILITY		Depends on load profile and coolant temperature	
COMMUNICATION		CAN 2.0 A (11bit ID)	
ELECTRICAL POWER SOURCE		12V DC	
FUEL	HYDROGEN QUALITY	Type I Grade D (ISO14687-2 2019) (SAE J2719)	
	PRESSURE	0.89~1.60 MPa abs ¹³	
AIR		Ambient air ¹⁴	
COOLING		Water cooled	
VIBRATION TOLERANCE		ISO19453-6 Category2	
INGRESS PROTECTION		IP66 & IP67 (excl. ACP breather)	
DESIGN STANDARDS ¹⁵		GTR13 / UN-R134 / UN-R100 / ISO 26262 ¹⁶ / ISO 6469-2,-3 / ISO 23273	

- Hydrogen Challenge. One kilogram of hydrogen contains 33.33 kW-h of usable energy [84]. Assuming the fuel cell operates at 90% efficiency, 1 kg should provide 30 kW of usable power for one hour. Therefore, it can be estimated how much hydrogen should be needed to generate up to 60 kW to last two months duration (see Table 14).

Table 14: Hydrogen Supply Durations (90% Fuel Cell Efficiency)

Desired Duration	Desired Power	Required H ₂ Supply
1 hr	30 kW	1 kg
1 hr	2 x 30 kw = 60 kw	2 x 1 kg = 2 kg
1 x Day = 24 hrs	60 kW	24 hrs x 2 kg/hr = 48 kg
7 x Days = 168 hrs	60 kW	168 hr x 2 kg/hr = 336 kg
30 x Days = 720 hrs	60 kW	720 hrs x 2 kg/hr = 1,440 kg
60 x Days = 1,440 hrs	60 kW	1,440 hrs x 2 kg/hr = 2,880 kg

Storage tanks capable of storing 5 kg of gaseous hydrogen at 700 bar pressure typically weigh 96 kg (211.6 lbs) (see Figure 44) [85]. As can be imagined, these huge storage tanks add significant weight to the airship. For example, storing just one day's requirement of hydrogen (48 kg) would take 10 tanks totaling 960 kg (2,116 lbs). For this reason, fuel cells supplied by numerous heavy hydrogen tanks made this option unsuitable.



Figure 44: Hydrogen Storage Tanks [86]

- Hydrogen Solution. For long duration missions, having sufficient battery power would require dozens of power modules, making the airship's weight too great to get airborne. Using solar power would seem to be the natural solution, but because the airship has a requirement to operate in the dark over the North Pole for weeks at a time, this power production option also proved unworkable. And the fuel cell option seemed impractical for similar reasons, again due to the need for dozens of heavy hydrogen tanks.

However, having decided to use hydrogen as the lifting gas of choice (see Section 2.4.2), the fuel cell option actually now seemed achievable *by using the gas envelope itself* as the fuel cell's hydrogen fuel supply. The need for lofting heavy storage tanks was now eliminated!

For example, an airship measuring 100 meters in length by 33 meters in diameter would have an envelope volume of approximately 58,000 m³ [59]. Filled completely with hydrogen, and starting at sea level (as altitude affects gas density), the initial hydrogen gas in the envelope would have a mass of almost 3,700 kg [87].

Therefore, when consuming 48 kg per day to produce 60 kW of power, there would theoretically be enough hydrogen to power the fuel cell assembly for a maximum of 77 days (understanding that in the end, all of the hydrogen would have been exhausted and the airship would no longer remain airborne) [88].

This was another major milestone in the airship design process, as it now confirmed given the appropriate size, an airship could have a sufficient supply of hydrogen (without employing heavy storage tanks) that could feed a fuel assembly to produce sufficient power for the airship.

Overall, the major subsystem design characteristics were now coming together.

2.6.2 Analysis

This section reviewed various battery, solar cell, and fuel cell options for consideration during upcoming system design activities.

First, battery technology and storage components were introduced. Because of the large number of batteries required to power the airship for long durations, and thus the significant weight these modules would add to the airship, this option was deemed unsuitable.

This was followed by a discussion of photovoltaic solar cell arrays, and the challenge of collecting solar energy continuously over the North Pole during the winter. While using solar panels to provide airship power during the summer months might be possible, for year-round Arctic air surveillance operations it was apparent that using solar power was also not practical.

Next was a discussion about fuel cell technology, hydrogen supply durations, and the need for numerous hydrogen storage tanks. Again, heavy storage tanks also made this option unusable.

However, having decided to use hydrogen as the lifting gas of choice, the need for heavy storage tanks was eliminated; the fuel cell supply would instead come from the gas envelope itself. An example was then provided showing that a moderately sized airship operating at high altitude could hold sufficient hydrogen to theoretically operate for over two months.

Overall, selecting hydrogen as the lifting gas was a major decision milestone in this project. It played a significant role in determining the amount of lifting gas required to reach high altitudes and the overall mission duration based upon projected hydrogen consumption rates.

It seems a workable power production solution had now been found.

Part III – Electronics Research

2.7 Guidance Research

2.7.1 Investigation

A general understanding of the main functions of vehicle guidance is essential before any systems engineering design activities can proceed. The following is a brief review of the navigation, guidance, and control (NGC) elements and their relationship to an airship's pitch, yaw, and thrust steering functions. All of these play a key major role in airship design and construction.

An airship guidance subsystem performs three connected tasks (see Figure 45) [89]:

- Navigation. This task determines a vehicle's current location (typically using Global Positioning Satellite [GPS] information) as well as the vehicle's own velocity.
- Guidance. This task determines the desired flight path for a vehicle, as well as determining any changes needed in velocity, to arrive at a desired location.
- Control. Finally, this task sends signals to a vehicle's engine and control surfaces (elevators and rudder) to implement all airship ascent, descent, and turning commands.

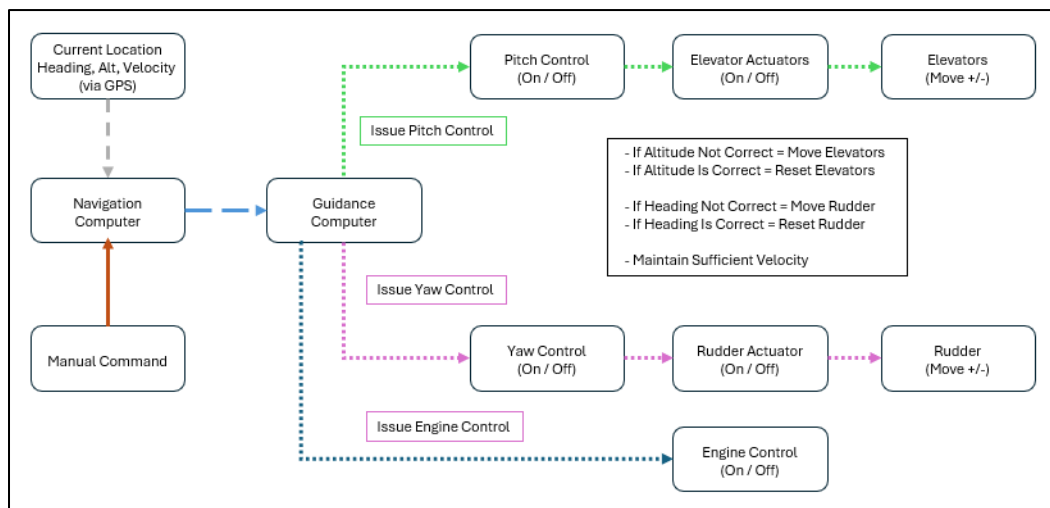


Figure 45: Navigation, Guidance, and Control Actions

Due to their enormous size, large airships have a sluggish response to steering commands. Commanding the tail elevators will slowly push the airship's nose up or down (pitch). Turning the fin rudder will guide the nose left or right (yaw). And commanding the propulsion unit will change the vehicles forward or reverse speed (thrust) (see Figure 46).

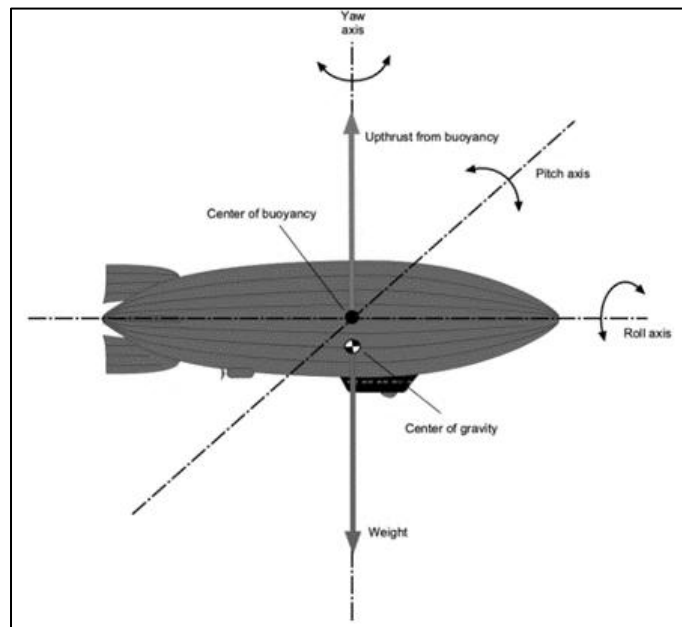


Figure 46: Three Axes of Movement [89]

Once the airship is manually flown into position, it will need to establish a prescribed station-keeping flight path circling a specific Arctic reference location. This will require the guidance subsystem to perform the necessary autonomous flight functions to guide the airship throughout the duration of patrol mission (unless the ground-based pilot chooses to assume manual airship control.) In general, the guidance subsystem performs the necessary pitch, yaw, and thrust steering functions in a continuous, self-correcting loop.

Compared to commercial aircraft, airships confront several guidance challenges [90]:

- They have fewer steering controls than degrees of freedom, reducing steering controls options and imposing restrictions on flight control solutions.
- They are low-dynamic vehicles due to their very large inertia and limited control authority, thus very sensitive to atmospheric turbulence and wind.
- The ultra-low temperatures at 20 km altitude impose considerable thermal stresses on the airframe, electric motors, and mechanical aileron and rudder flight actuators.

Facing these challenges, the flight control computer must be able to accurately establish the airship's current location, constantly plot that location against the desired destination, and control the airship to maintain it within close proximity of that final end point. The navigation, guidance, and control functions are typically combined into a single "Flight Control System".

For example, the IBM AP-101B flight control computer was a vital component of the Space Shuttle's avionics system providing flight control, navigation, and communication support [91]. Each Space Shuttle flight control computer weighed 64 lbs, required 550 Watts of power, and had a Mean Time Between Failures (MTBF) rating of 10,000 hours (see Figure 47) [92].



Figure 47: AP-101B Flight Control Computer [93]

2.7.2 Analysis

This section introduced the three basic functions performed by airship guidance. These tasks are typically performed by a flight control system that maintains the known location of the airship, plots its projected destination, and then issues continuous engine and flight control signals to steer the vehicle accordingly to maintain its desired route of flight.

The ability of the guidance element to perform these interrelated tasks is technically feasible given this is routinely done on large commercial aircraft and smaller UAVs. Large airship inertia, wind sensitivity, and ultra-low temperature effects on exterior flight control actuators will be key concerns as the project advances from design to testing.

2.8 Detection Research

2.8.1 Investigation

The primary mission of this proposed airship is to provide NORAD with an early air defense warning capability that extends the detection distance of their current FPS-117 ground-based radars located across Alaska and Canada (see Figure 48).

As such, it is important to have a general understanding of the main components of a radar device and how these various elements function.

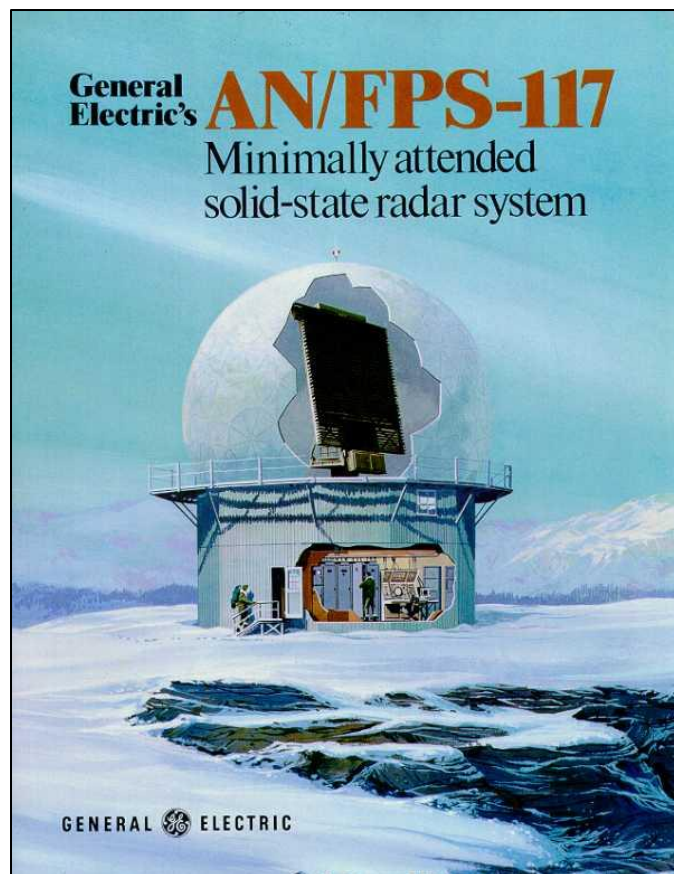


Figure 48: Illustration of FPS-117 Radar Site [94]

Major Radar Components. The radar subsystem is an excellent example of a “system of systems.” Radar systems typically consist of five major components: 1) the transmitter, 2) the antenna, 3) the receiver, 4) the signal processor, and the operator display (see Figure 49) [95].

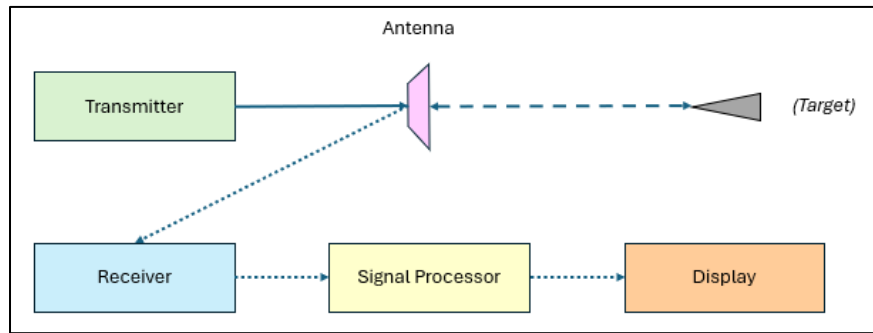


Figure 49: Illustration of Basic Radar Components

- Transmitter Characteristics. The role of the transmitter is to generate sufficient, specific RF energy to illuminate a target at a great distance from the radar.

First, a high-voltage power supply generates the necessary energy to enable radar pulses to travel hundreds of miles and range from kilowatts (kW) up to multiple megawatts (MW) [95].

Next, this power is provided to the waveform generator, which first produces the radar’s baseline transmitted radio frequency (RF) (often called the “carrier signal” or “carrier wave.”) Depending on the radar set, this RF signal typically falls within either in the L-Band (1-2 GHz), S-Band (2-4 GHz), or X-Band (8-12 GHz) [95].

The waveform generator then rapidly “pulses” this constant RF carrier signal on-and-off thousands of times per second. This “on-and-off” is labeled “pulse repetition frequency” (PRF). PRF can range from 100 to 100,000 cycles per second. Each transmitted pulse is extremely short, typically lasting from 0.1 to 10 microseconds in duration [95].

(Note: The “frequency” in which the RF pulses are being transmitted is not the same as the radio frequency of the carrier wave. These are two different uses of the term “frequency.”)

- Antenna Characteristics. The antenna serves two purposes. First, during the “transmit time,” it radiates the radar’s RF energy into the environment as a narrowly focused beam. And second, during the “receive time,” the antenna listens for any returning reflected “echoes.” As these “echo” waves return, they either merge or cancel each other as they arrive, resulting in certain regions having stronger or weaker echo returns. This is called the “antenna pattern” and is measured in decibels (“dB”). The strongest echo reception occurs directly in front of the antenna (called the “main lobe”), while lesser echo reception occurs on either side of the antenna (called the “sidelobes”) due to this RF wave cancellation effect (see Figure 50) [96].

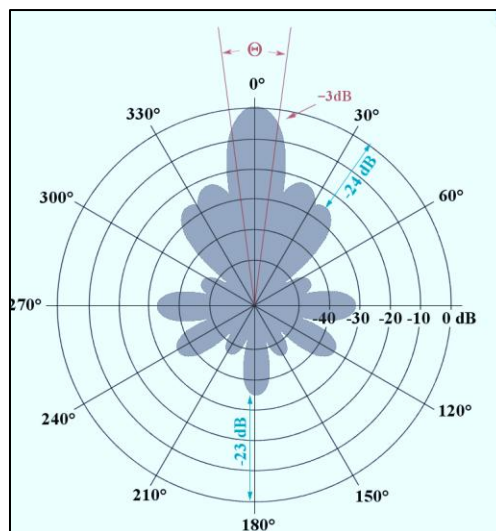


Figure 50: Radar Antenna Pattern [96]

- Receiver Characteristics. While the radar’s transmitted RF signal is measured in powerful kilowatts or megawatts, the received signals (having traveled out hundreds of miles, then back again to the antenna) are measured in extremely weak milliwatts, down to even nanowatts. The receiver amplifies these tremendously faint returning signals, occurring often millions of times, so they may be successfully processed [97].

- Signal Processor Characteristics. As radar echo signals are received, they are arranged by their time of arrival, thus corresponding to different ranges. They are also sorted by their frequency shift, thus corresponding to their velocity. The signal processor then sorts the received signal strength within each of these numerous bins to isolate the genuine targets [99]. Operating at stratospheric altitudes, the transmitted energy would be aimed at just the edge of the distant horizon upwards. The goal would be to avoid illuminating large areas of the Earth's surface, as the reflected radar energy could swamp the receiver with clutter, requiring extra signal processing to resolve any targets flying at very low altitudes trying not to be discovered.

- Display Characteristics. Finally, the processed radar signals are displayed for operator assessment, typically using digital screens that can display various aircraft information. Originally, the display consisted of a phosphorescent screen with a sweeping arm that rotated every 6 seconds (as seen in movies and television.) These old displays have since been replaced with digital displays that provide much more data (e.g., altitude, identification codes, call signs, etc.) which greatly help the operator in better interpreting the radar presentation.

Radar Range Equation. A radar's overall performance is directly affected by the strength of the radar's transmitted signal, the strength of the target's reflected signal coming into the receiver, and the strength of other conflicting signals interfering with that target's received signal. The ratio of the target's signal strength to all the other noise also being received is called the "Signal-to-Noise Ratio" or SNR. Typically, a target's signal needs to exceed all noise received by 13 decibels to be considered a genuinely detected target [95] .

The numerous factors that drive this SNR value can be described using the multi-parameter equation called the “Radar Range Equation (RRE)” [98]:

$$\text{SNR}_{\text{LINEAR}} = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B_n L_s} \quad (21)$$

For example, an airport surveillance radar has the following characteristics (see Table 15).

Table 15: Detection Subsystem Characteristics [96]

Numerator	Values
P_t = peak transmit power (in watts).	1.4 MW
G_t = gain of the transmit antenna (linear value, not decibels).	33 bd (2000 linear)
G_r = gain of the receive antenna (linear value, not decibels).	33 bd (2000 linear)
λ = carrier wavelength (in meters).	0.1 m
σ = mean radar cross section (RCS) of target (in meters ³).	Small Aircraft (1 m ³)
Denominator	Values
$(4\pi)^3$ = area of a transmission sphere (1984).	1984
R^4 = radar-to-target range (in meters).	60 NM (111,000 meters)
k = Boltzmann’s constant (1.38×10^{-23} watt-sec/K).	1.38×10^{-23} watt-sec/K
T_s = system noise temperature (in K).	950 K
B_n = receiver bandwidth (in Hz).	1.67 MHz
L_s = total system loss (linear value, not dB).	8 bd (6.3 linear)

Inserting these values into the RRE results in:

$$\text{SNR}_{\text{LINEAR}} = \frac{(1.40 \times 10^6) (1995) (1995) (0.1) (0.1) (1)}{(1984) (111,000)^4 (1.38 \times 10^{-23}) (950) (1.67 \times 10^6) (6.3)} = 1.3 \text{ Db}$$

Integrating this signal power across 21 pulses equals:

$$\text{SNR}_{\text{TOTAL(LIN)}} = (21) (1.3) = 27.3 \quad (22)$$

Converting total linear SNR back into decibels:

$$\text{SNR}_{\text{TOTAL(dB)}} = 10\log_{10}(27.3) = 14.4 \text{ dB} \quad (23)$$

Overall, because this example exceeds 13 dB, this airport radar example has a reasonable SNR for detecting small aircraft at 60 nautical miles range.

Regarding real-world components, several lightweight commercial radars could be considered for this project. One excellent option is the Leonardo “Seaspray 7500E V2” Active Electronically Scanned Array (AESA) radar (see Figure 51 and Table 16) [99]. This same airborne surveillance radar is currently employed on General Atomics MQ-9 UAVs [100].



Figure 51: Seaspray 7500E V2 Radar [99]

Table 16: Detection Subsystem Characteristics [99]

Frequency	X-Band
Type	Active Electronically Scanned Array (AESA)
Max Range	320 nautical miles (368 miles)
Weight	104 kg (230 lbs)
Power Consumption	3.6 kW
MTBF	2,000 hrs (83+ days)

2.8.2 Analysis

This section proposed airships could be positioned far off the Arctic coastline to increase radar early warning timing. It then reviewed the fundamental components making up a typical radar set, as well as the technical parameters used in the Radar Range Equation. These parameters will need to be considered during later design efforts. It closed with an example of a lightweight surveillance radar currently being used by a military surveillance UAV.

2.9 Communications Research

2.9.1 Investigation

Operating the guidance and radar components would not be possible without being able to directly communicate with the airship during its surveillance patrol. The following discussion provides a review of data link systems and the challenges of communicating with air vehicles over the North Pole. It concludes with a proposed solution to meet that communications challenge.

Tactical Data Links. A Tactical Data Link (TDL) (previously termed a “Tactical Digital Information Link” or TADIL) is an electronic data transmission means allowing participating military units to transmit tactical data to each other using UHF radio. This enables command and control centers to create a “Common Operating Picture” allowing friendly forces to observe the battlespace, identify threats, and acquire targets (see Figure 52) [101].

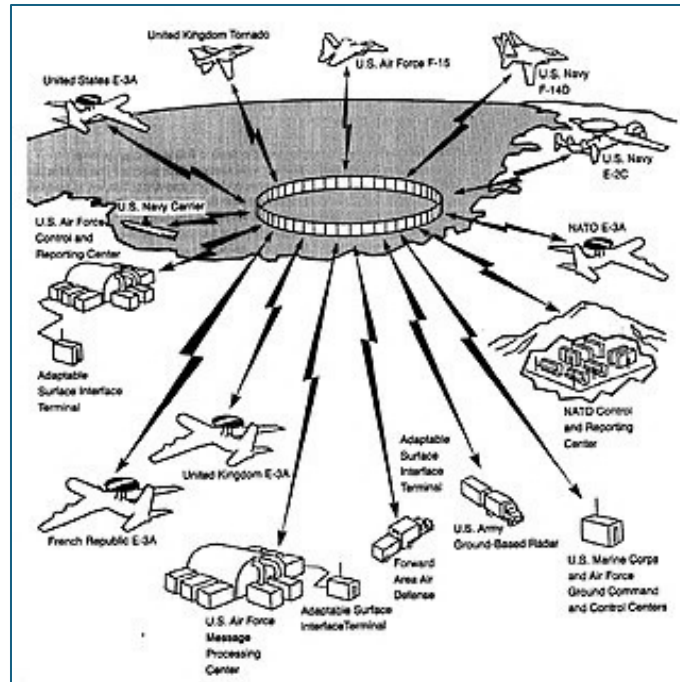


Figure 52: TDL Network with Multiple Participants [102]

Various TDLs have been developed over the years that use differing message encoding methods and have been labelled “Link-1”, “Link-4”, “Link-11”, etc. Today, the TDL currently being used between military aircraft, ships, and ground units is “Link-16” (also labeled as “TADIL-J” with the “J” standing for “Joint” [e.g., multi-service] users) [103].

Link-16 data links operate in the UHF frequency band from 960 to 1215 MHz (L-band) and uses a synchronized Time Division Multiple Access (TDMA) approach. During a 12-second “frame” there are 1,536 slots (128 time slots per second) allocated to each user (see Figure 53). All users listen to all data transmissions while awaiting their specific turn to transmit during this 12-second frame. Users can enter or depart the network at any time as the network continues to operate. This TDMA approach ensures the overall network is not controlled by a single network control station that, if it became inoperable, would then collapse the entire network [104].

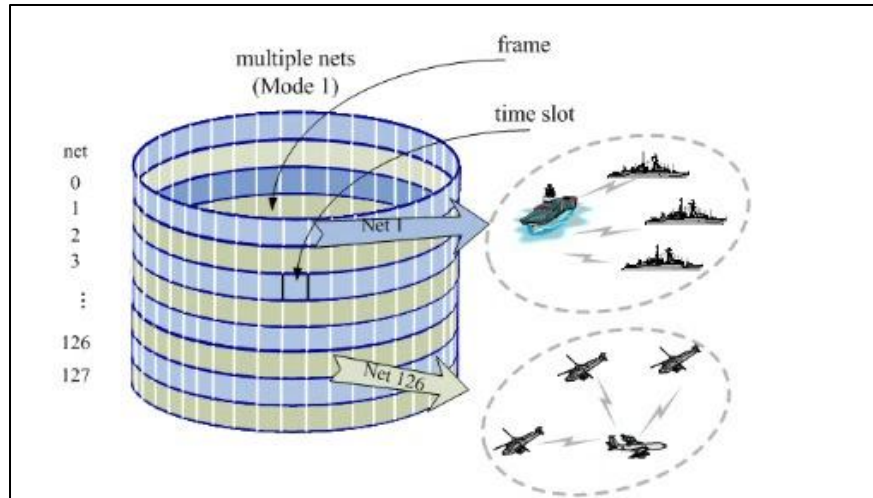


Figure 53: Multi-Network Link-16 Architecture [103]

Arctic Communications Challenge. It is being proposed that early warning airships will be operating off the northern coast of North America to assume patrols across the Arctic region. Maintaining communications over this vast region will be very challenging. For example, from Barrow, Alaska to Svalbard, Norway is over 3,300 km (2,100 miles) (see Figure 54) [105].



Figure 54: Long Distance Communications Challenge [106]

Unfortunately, these extreme distances are much too great for using normal UHF radio transmissions for ground-to-airship communications, as UHF communications works best at a maximum line-of-sight transmission limit of approximately 300 miles [104].

Understanding this communications challenge, since the 1980s, NORAD has relayed all Arctic radar site data to both Alaskan and Canadian NORAD air defense headquarters using commercially available satellite communications services. Currently, the Anik F4 satellite (operated by Telesat Canada) supports NORAD's northern tier data communications needs [107].

The Anik F4 satellite was built by Lockheed Martin and launched in 2000. It consists of 24 transponders operating in the C-band (3.7 to 4.2 GHz) for data transmissions. It is stationed in a geostationary orbit over 22,000 miles above the Earth and provides excellent coverage over North America, to include the northern Arctic region (see Figures 55) [108].

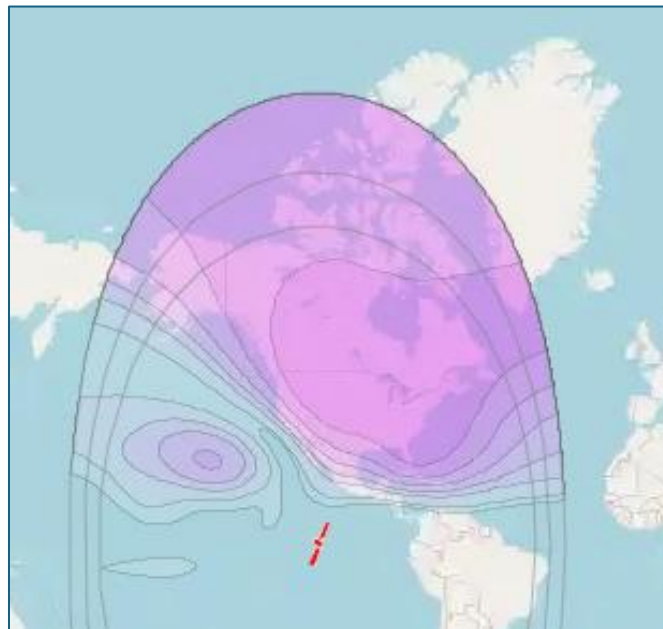


Figure 55: Anik F4 Satellite Coverage (Example) [108]

Proposed Communication Solution. Starting in 1995, the U.S. Navy began work on designing a special “Satellite TADIL-J” to improve data communications between dispersed ships located far beyond normal UHF transmission range [113].

Later, in 2023, the U.S. Space Force successfully conducted the first-ever Link-16 broadcast from space to ground stations. Their tests sent Link-16 signals up to multiple Low Earth Orbit satellites (orbiting between 100 and 1,000 miles above the Earth), then down to various ground-based receivers operating in the L-Band frequency range (1 to 2 GHz) [110].

Because the early warning airships will be operating throughout the high Arctic region, they will unfortunately not be able to transmit their radar data to geostationary satellites orbiting above the Equator, as the Earth physically blocks the transmission path to geostationary satellites from any air vehicle operating above the 82 parallel [111].

However, an alternative solution would be to use satellites orbiting in a “Molniya” orbit (Russian for “lightning”) which has a very high inclination rising over the North Pole. Accelerated by the Earth’s gravity, these satellites move quickly around the South Pole at their perigee. Then, as they begin their climb upwards, their rapid orbital speed begins to slow down until they eventually reach their apogee. Consequently, they spend nearly two-thirds of their 12-hour interval near the top of their orbit, thus allowing extended contact time with users located in the Arctic [112] (see Figure 56).

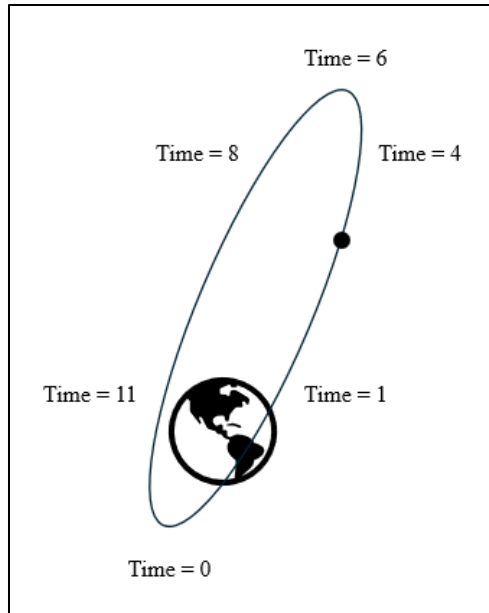


Figure 56: Molniya Satellite Orbit (Example)

One excellent example of a commercially available data links communication set that could support these types of airship communication needs is the Multifunctional Information Distribution System (MIDS) Joint Tactical Radio System (JTRS) terminal manufactured by L3 Harris. It is used extensively on both aircraft and maritime vessels throughout the Department of Defense (see Figure 57 and Table 16) [113].



Figure 57: L3 Harris MIDS JTRS Terminal [113]

Table 17: Communications Subsystem Characteristics [113]

Frequencies	1030 to 1060 MHz (L-Band)
Power Consumption	350 watts
Link 16 Messaging	TADIL J
Protected Data Rate	1 Mbps
Crypto Modes	Yes
Component Size	0.34 m ² (13.5 inches ²)
Component Weight	23 kg (50.6 lbs)

2.9.2 Analysis

This section reviewed several key communication concepts. First, sharing data between users via military data links was introduced. Next, the communication range challenge facing this airship design was illustrated. The NORAD satellite communications process was then described, showing how radar data is currently relayed via satellite to ground Air Defense headquarters. It was proposed a similar approach could be used to transmit airship sensor data using Link-16 via satellite operating in a Molniya orbit. Overall, the concept of relaying sensor data via satellite is supported by current military data link communication examples.

2.10 Control Research

2.10.1 Investigation

Airship Autonomous Control. As the airship is being proposed to patrolling over the Arctic region for several weeks at a time, it needs to employ an internal control mechanism to monitor its own altitude, location, heading, and speed and be capable of implementing self-corrections. This type of internal control falls under the general area of “control theory.”

A common closed-loop control architecture is termed the “Proportional–Integral–Derivative” (PID) controller. This control loop continuously calculates the error value between a desired set point (SP) and a measured process variable (PV), and applies corrections based on proportion, integral, and derivative terms (denoted P, I, and D) [114] (see Figure 58).

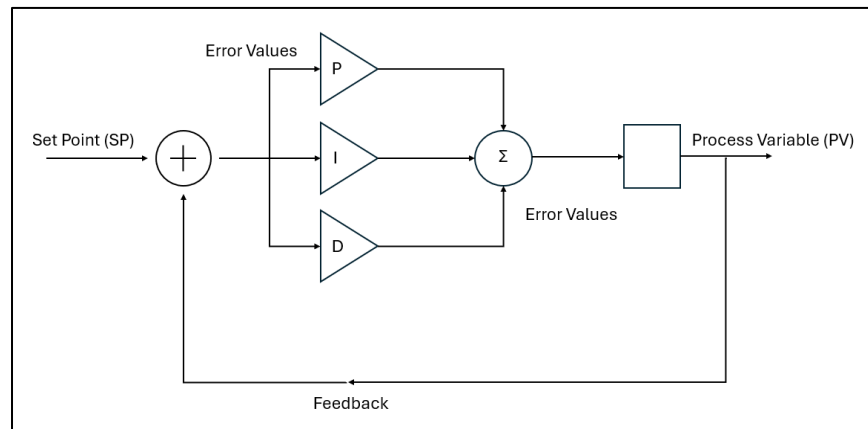


Figure 58: PID Control Schematic (Example) [114]

- Proportional Control (P). This feature measures the difference between the SP and the PV and is considered the “error value.” The purpose of this function is produce an immediate reaction on the output and bring the process value back to the set point. However, efforts to rapidly correct a system may result in wide swings as the system oscillates attempting to stabilize.
- Integral (I). Every time the controller performs its calculations, the new calculated integral value is added to the integral total. As the integral is continuously accumulated over time, the longer it takes for the process value to reach the set point, the more affect the integral will have on the output. Adding the I value makes the P adjustments go more smoothly.
- Derivative (D). If the process value is approaching the set point too fast, the derivative will limit the output to prevent the process value from overshooting the set point. While the P-term considers the current error value and the I-term considers previous errors, the D- term compensates for sharp fluctuations, preventing overshoots and oscillations.

Airship Manual Control. This systems control approach would be implemented automatically by the airship's guidance element during flight operations. However, to control the airship during takeoffs and landings, the airship pilot would be able to override these automatic PID control signals and assume manual control of the airship using a proposed ground-based Airship Control Station (ACS).

While not strictly an airship subsystem itself, for the proposed airship concept to be successful, a ground-control component is essential. Similar to current UAV ground control stations in use today (see Figure 59) [115], a similar remote-control approach could be used for this project. Airship telemetry could be data linked from the airship via commercial satellites to the ACS for pilot awareness and airship control. This proposed ACS suite would allow the pilot to monitor all airship subsystem telemetry in real-time and send manual flight control signals to the airship during critical phases of flight. Given the long duration flight goal of the airship, shifts of pilots would rotate through the ACS to off-set pilot fatigue. In addition, a back-up ACS suite could be maintained if the primary ACS were to suddenly fail.



Figure 59: Airship Control Station Example [115]

2.10.2 Analysis

This section reviewed the fundamental PID control concept necessary for use during autonomous airship operations. It also introduced an example of an ACS suite, modeled after current UAV control stations, to demonstrate how a pilot could monitor and control the airship during flight operations. Overall, the control concept seems technically feasible.

Part IV – Summary

Given the broad systems concept involved, it was necessary to investigate both the environment in which such an airship would operate as well as the possible components that would comprise such a novel vehicle. This research included examining the atmospheric environment in which the airship would operate, studying the various types of airships suitable for high altitude surveillance, investigating the types of propulsion and power production means commercially available, and the associated electronic payloads that reasonably would be required.

The result of this literature review was the examination of over 200 scholarly documents. Conducting this review was vital for better understanding of the factors involved in airship design, with structural dimensions, propulsion motors and propellers, and power production topics being of central interest. All three of these research topics, as well as the electronics research conducted, resulted in identifying either comprehensive academic or government research findings or commercially available solutions. All of these elements will inform the system engineering activities conducted in Chapter 4.

Overall, this literature review indicates the concept of developing a high altitude, long endurance early warning airship is technically sound. In order to effectively accomplish that task requires the use of a structured systems engineering methodology. That systematic approach is outlined next in Chapter 3.

CHAPTER III. METHODOLOGY

3.1 Systems Engineering Vee Model

During the 1990s, Forsberg and Mooz argued legacy systems engineering practices were flawed. They believed that these heritage approaches often presented an incomplete portrait of the actual engineering processes involved, restricted the practice of concurrent engineering, and obscured the important role systems engineering actually offers. They identified the shortcomings of the regimented linear sequence of activities moving along a horizontal line, the diagonal stair-stepping “waterfall” model frequently employed, the bifurcated “hardware upward/software downward” path that gave the false impression these two parts of a project can be managed separately, and the “spiral development” model that shows more flexibility but still obscured the role of system engineering in successful project development [116].

To resolve these shortcomings, in their pivotal paper they proposed what is now known as the systems engineering “Vee” model [117] (see Figure 60). Unlike the waterfall model, in their approach there is no prohibition against doing detailed work early in the development cycle. In fact, both hardware and software feasibility models may be necessary during user requirements clarification to ensure stakeholder agreement.

Flowing down the left side of the Vee, key phases are completed to identify greater functional and component details, feasibility, and risks. Similarly, working up the right side there are numerous testing phases to verify accomplishments or return to the left side to rework steps. In addition, incremental “spiral” development activities can be supported as internal build cycles nested inside each of these major “Vee” phases.

In their new model, Forsberg and Mooz pointed out that descending down the left side of the “Vee” included both downward iterations to establish feasibilities and identify risks but also permitted upward (reverse) iterations to refine user requirements or resolve design problems. Thus, unlike the waterfall model that flowed only downstream, their model allows traveling in both forward and reverse cycles as the overall design itself moves down the “Vee” model [117].

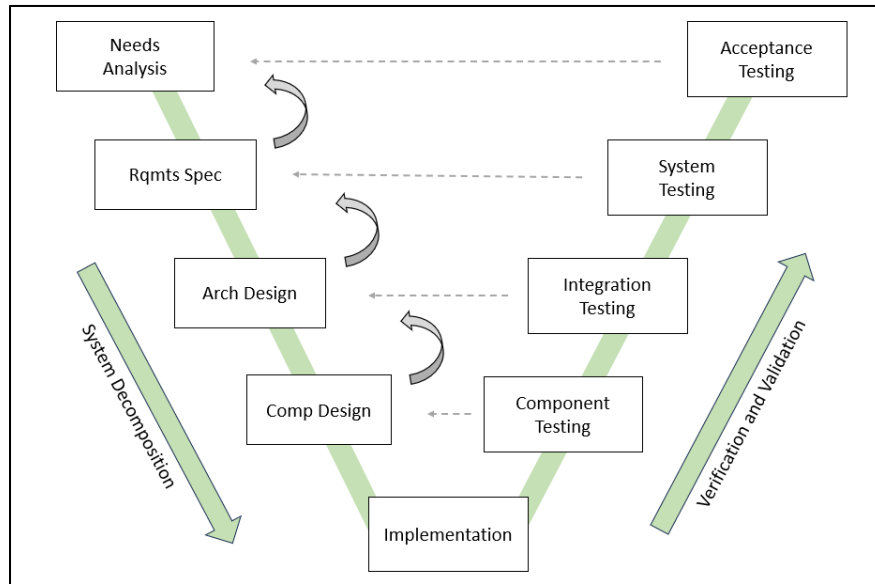


Figure 60: Systems Engineering “Vee” Model [Author’s Interpretation]

3.2 Systems Engineering Formal Method

During this same time, driven by Johns Hopkins University’s need for a new textbook describing systems engineering fundamentals, in 1992 Kossiakoff and Sweet drafted their important textbook, *Systems Engineering: Principles and Practice*, in which they stated:

“Learning how to be a successful systems engineer is entirely different from learning how to excel at a traditional engineering discipline. It requires developing the ability to think in a special way, to acquire the ‘systems engineering viewpoint,’ and to make the central objective the system as a whole and the success of the mission” [118].

As developed by Kossiakoff and Sweet, using this approach provides a logical, systematic application of the formal scientific method when engineering a complex system. Their formal method was a major step forward in providing a rigorous approach to accomplishing the systems engineering process (see Figure 61) [118].

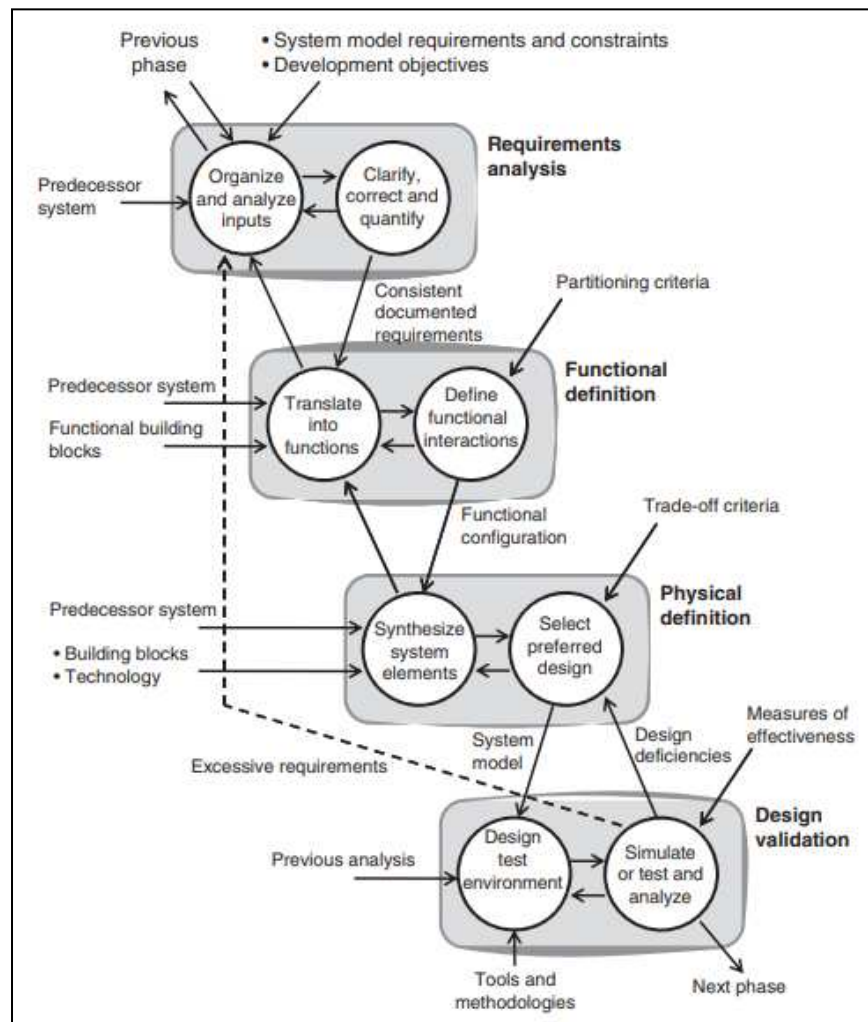


Figure 61: Systems Engineering Formal Method [118]

This formal method consists of four core design activities applied recursively throughout each systems engineering phase:

- "Requirements Analysis" is understanding the operational environment, defining the problem, and clarifying the resulting system requirements during each stage of engineering.
- "Functional Definition" is translating those system requirements into discrete functions the system must perform and the potential interfaces between those functions.
- "Physical Definition" involves developing alternative designs for those functions and interfaces and selecting the preferred approach through trade-offs.
- "Design Validation" then evaluates all significant aspects of the applicable design level to ensure it meets all system requirements and constraints.

These four core design activities are then applied repeatedly throughout the life cycle of a system which can be described as falling into three comprehensive Stages [118].

During “Stage I – Concept Development”, valid needs for a new system are established that are both technically and economically feasible. Potential system concepts are then explored, system performance requirements are validated, and the most attractive system concept is eventually defined. These tasks are accomplished through three Phases (see Figure 62).

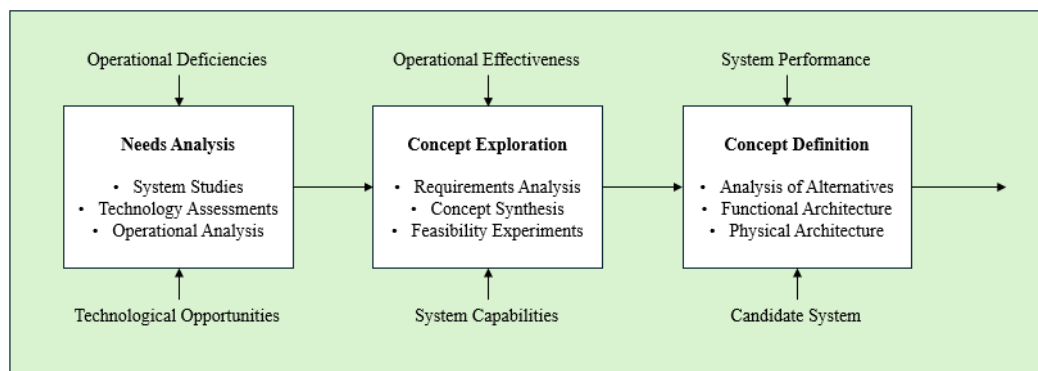


Figure 62: Stage I Concept Development Phases [123]

Next, during "Stage II – Engineering Development", subsystems are defined, component specifications are identified and tested. A realistic system is then constructed, tested, integrated, and evaluated. These tasks are accomplished through three Phases (see Figure 63).

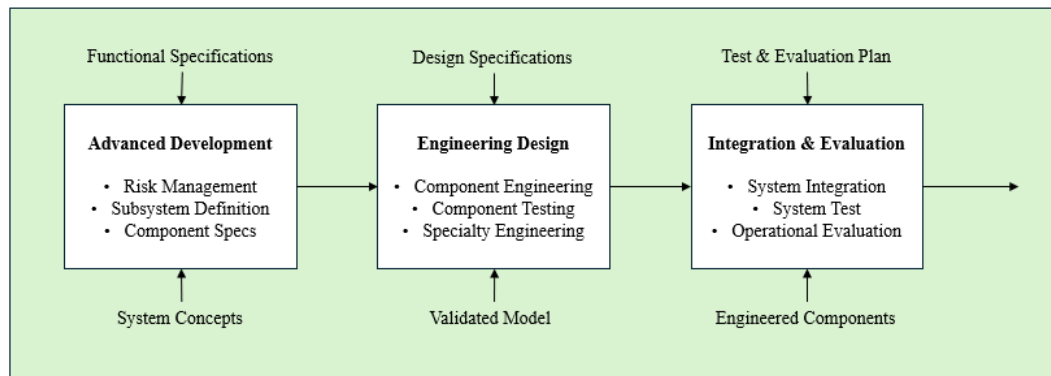


Figure 63: Stage II Engineering Development Phases [118]

Finally, during “Stage III – Post-Development”, a physical device is manufactured, shipped to users for employment, supported over its useful life, and then disposed. These activities are accomplished through three Phases (see Figure 64).

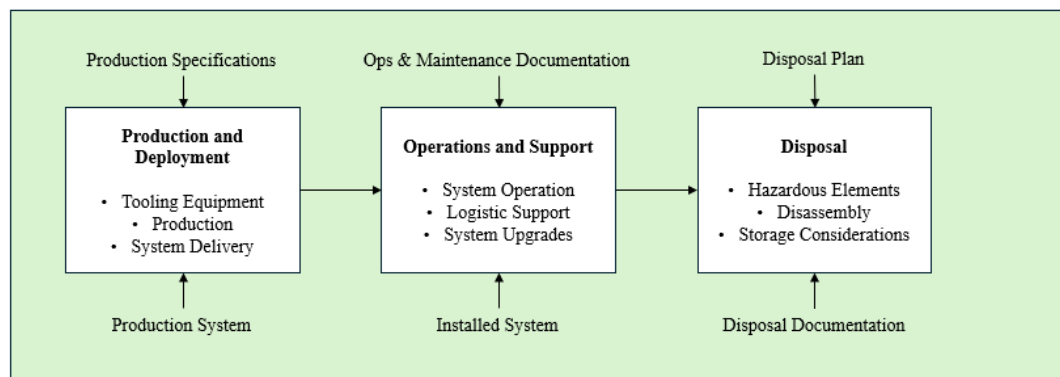


Figure 64: Stage III Post-Development Phases [118]

As a result, Kossiakoff and Sweet’s four formal, iterative design activities of “requirements analysis,” “functional definition,” “physical definition,” and design validation” can now be added into each of the individual “Vee” model systems engineering phases (see Figure 65).

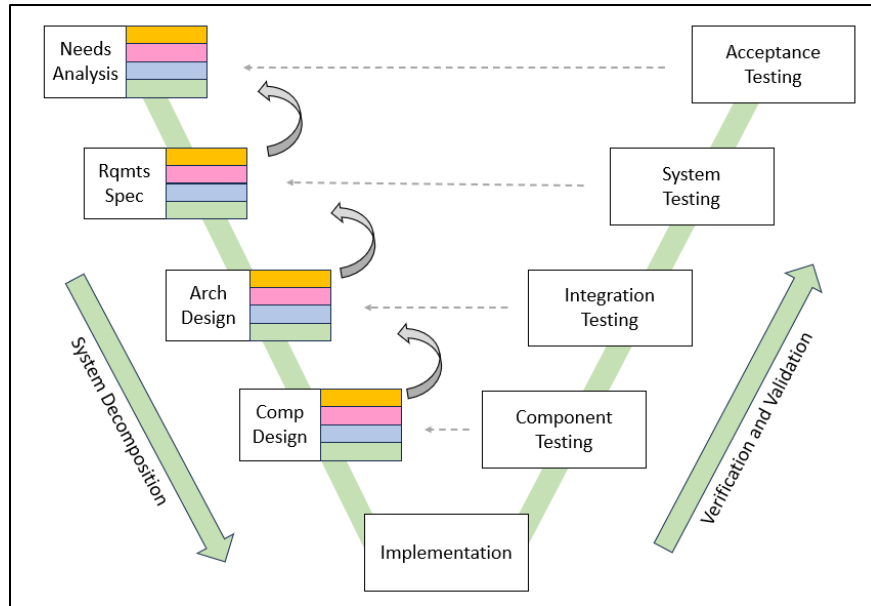


Figure 65: Vee Model with Added Formal Design Activities

3.3 Systems Engineering Architecture Process

Finally, in 2019, Borky and Bradley introduced their Model-Based Systems Architecture Process (MBSAP) [119]. With digital Model-Based Systems Engineering (MBSE) software becoming more prevalent, they proposed systems engineers needed to incorporate a stronger “architectural” approach using three fundamental viewpoints (see Figure 66).

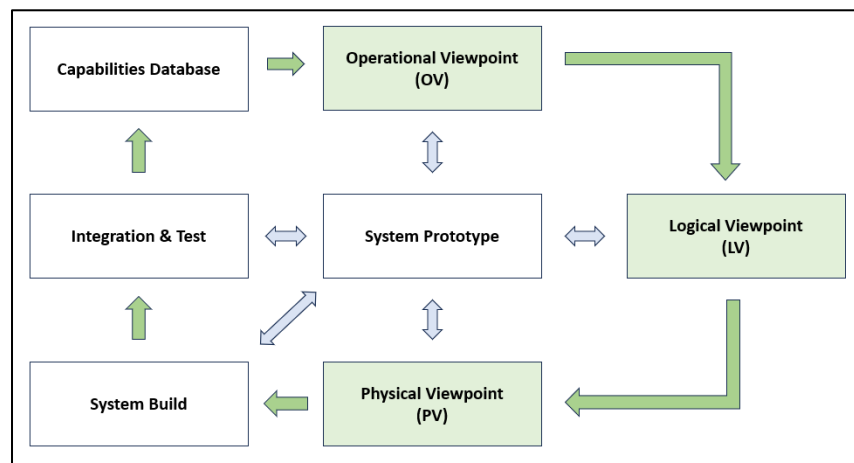


Figure 66: MBSAP Process [119]

Their architectural approach is drawn as a closed loop, implying that MBSAP is an iterative process which follows seven phases [119]:

1. Efforts begin with working with stakeholders to develop desired system capabilities which are maintained in a central database for easy retrieval and updating.

2. The next phase translates these required capabilities into a high-level architectural context termed the “Operational Viewpoint” (OV). This viewpoint helps stakeholders perceive the overall system in order to help identify and resolve major issues or ambiguities.

3. The next phase transforms the OV into a “Logical Viewpoint” (LV). Here, MBSE tools are used to define the specific details of system elements, services, functions, information exchanges, and behaviors derived from the OV. This level defines *what* is to be built.

4. Architectural modeling is completed by mapping the LV to the “Physical Viewpoint” (PV), which serves as the basis for the eventual implementation of both hardware and software. This level now defines *how* it will be realized.

5. The System Build phase then actually implements system construction.

6. Which is then followed by system Integration and Testing activities.

7. And it is culminated in the development of a System Prototype, which can be used to refine the previous architectural phases as lessons learned become available in an iterative architectural process.

Examining a system through Operational, Logical, and Physical viewpoints helps guide the designer through the “Vee” model with a better understand of each phase’s intent and deliverables.

These three different approaches were then integrated into a single systems engineering methodology to provide a solid foundation for project research, building system concepts and requirements, and motivating the development of airship design simulations.

Overall, using these three recognized system engineering approaches in an integrated methodology helped to ensure this airship project was successfully developed (see Figure 67.)

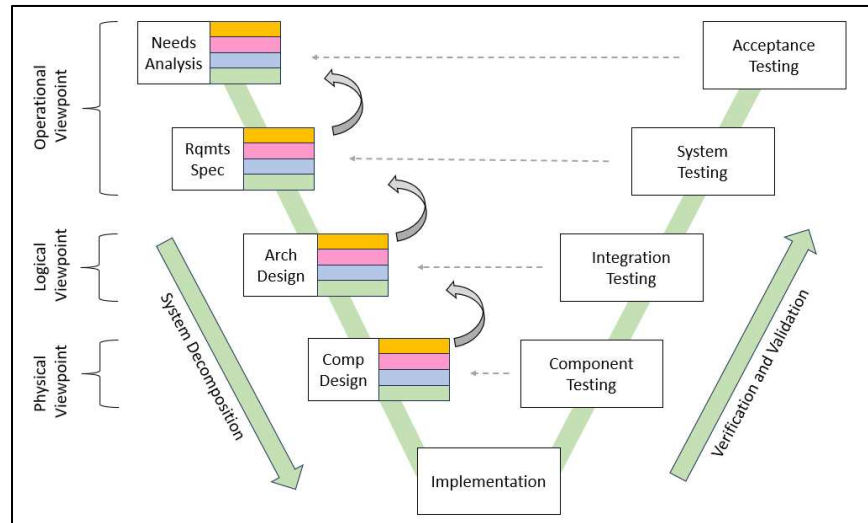


Figure 67: Author's Integrated Systems Engineering Methodology

3.4 Design Structure Matrix

During system engineering and architectural design phases, key airship design and performance parameters became apparent. After many iterations, 75 design parameters were eventually identified for analysis and grouped into 12 functional categories (see Figure 68).

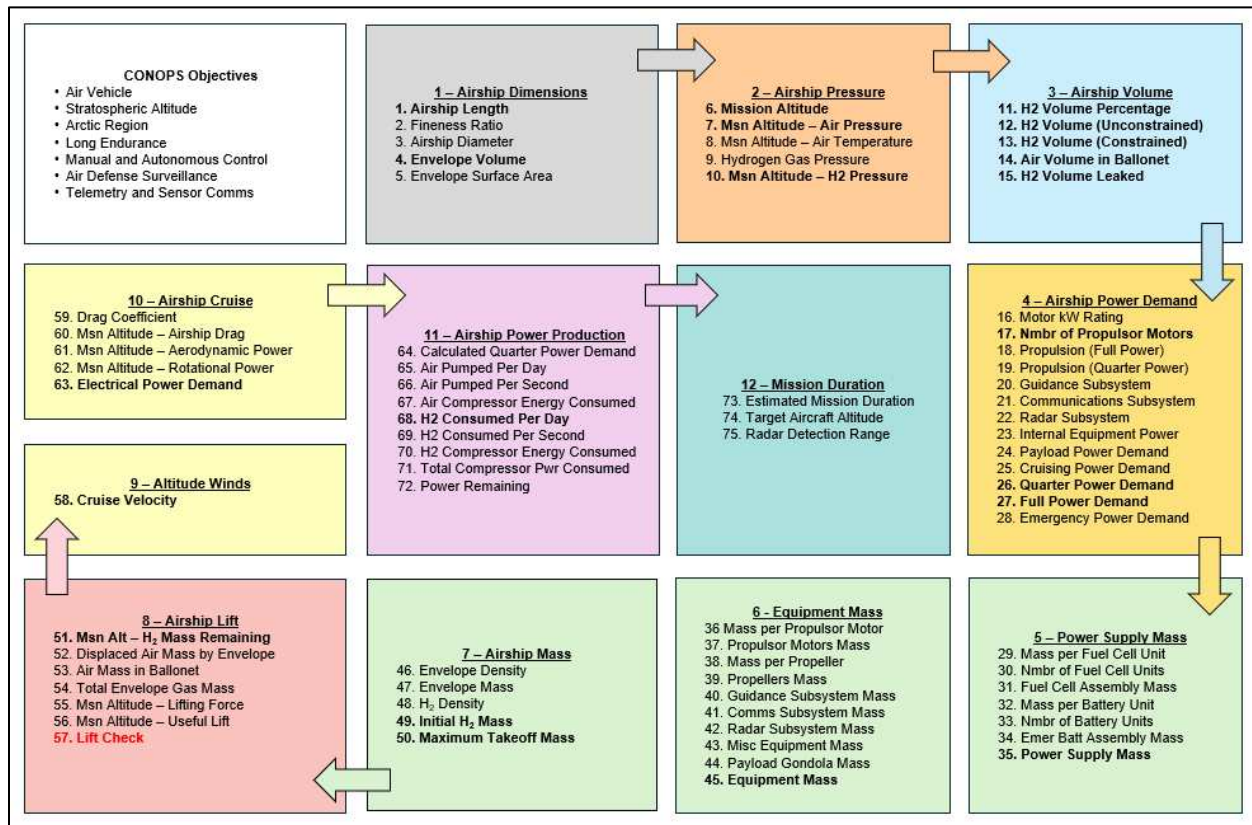


Figure 68: Airship Design Parameters

These functional categories were then arranged using a Design Structure Matrix (DSM) consisting of twelve interconnecting “Computational Analysis” (CA) blocks (see Figure 69). The DSM provides a compact visual representation of a complex system in order to develop solutions supporting design decomposition and recursive analysis. Lines indicate how calculated outputs from each CA block flow as inputs into one or more subsequent blocks beneath them. The DSM clearly illustrates various forward and feedback flows and can demonstrate modeling iteration loops [120].

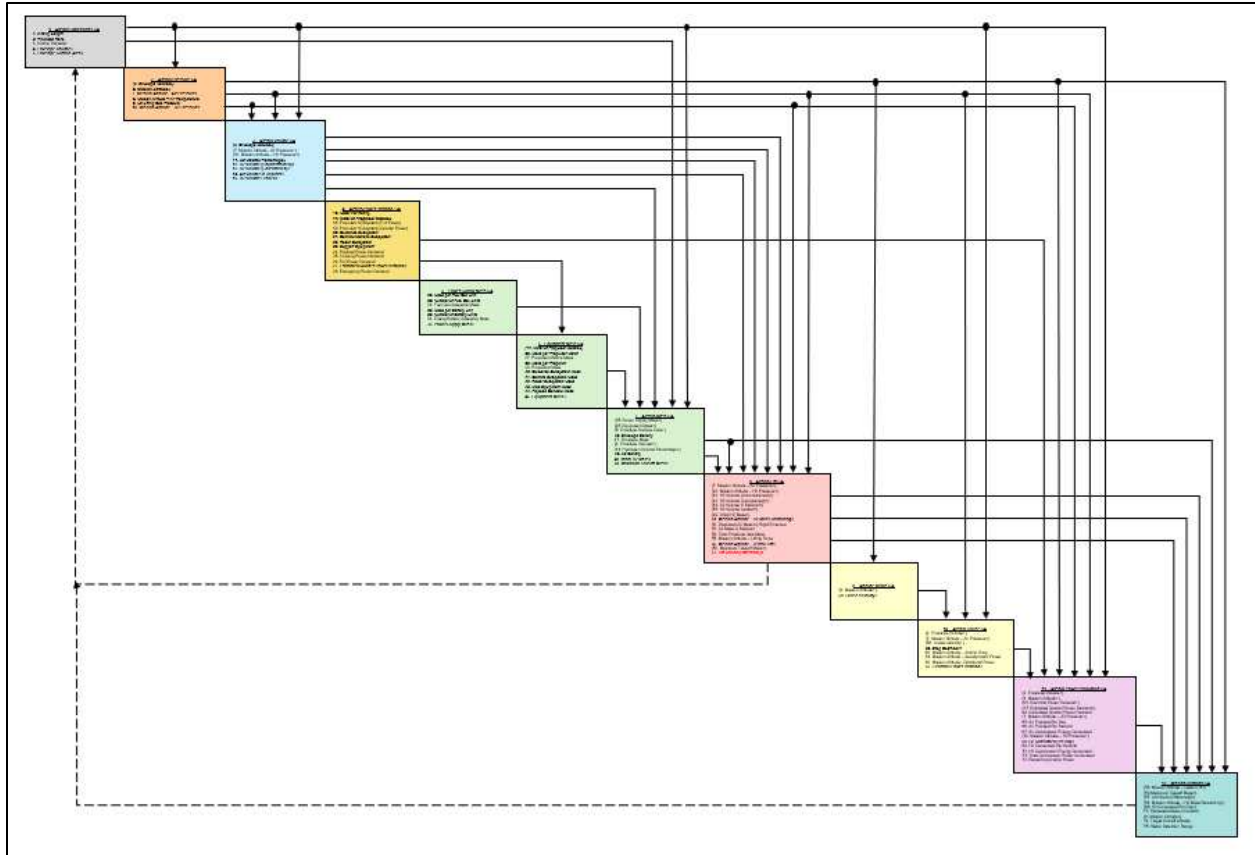


Figure 69: Airship Design Structure Matrix

3.5 Multidisciplinary Design Optimization

Finally, Multidisciplinary Design Optimization (MDO) is a field of engineering that focuses on the use of numerical optimization for the design of systems that involve a number of disciplines or subsystems [121]. Using MDO allows a designer to mathematically implement the DSM, analyze the relationships between parameter inputs and outputs, and optimize their values.

One means of conducting MDO analysis is through the use of modeling software such as the Ansys “ModelCenter®” tool [122]. Using this modeling tool, Excel spreadsheets containing parameter data were uploaded into each CA block, then logically connected to form the project’s DSM (see Figure 70). Then, a specialized Optimizing Tool generates thousands of test inputs (see Figure 71) into those CA blocks during each simulation run.

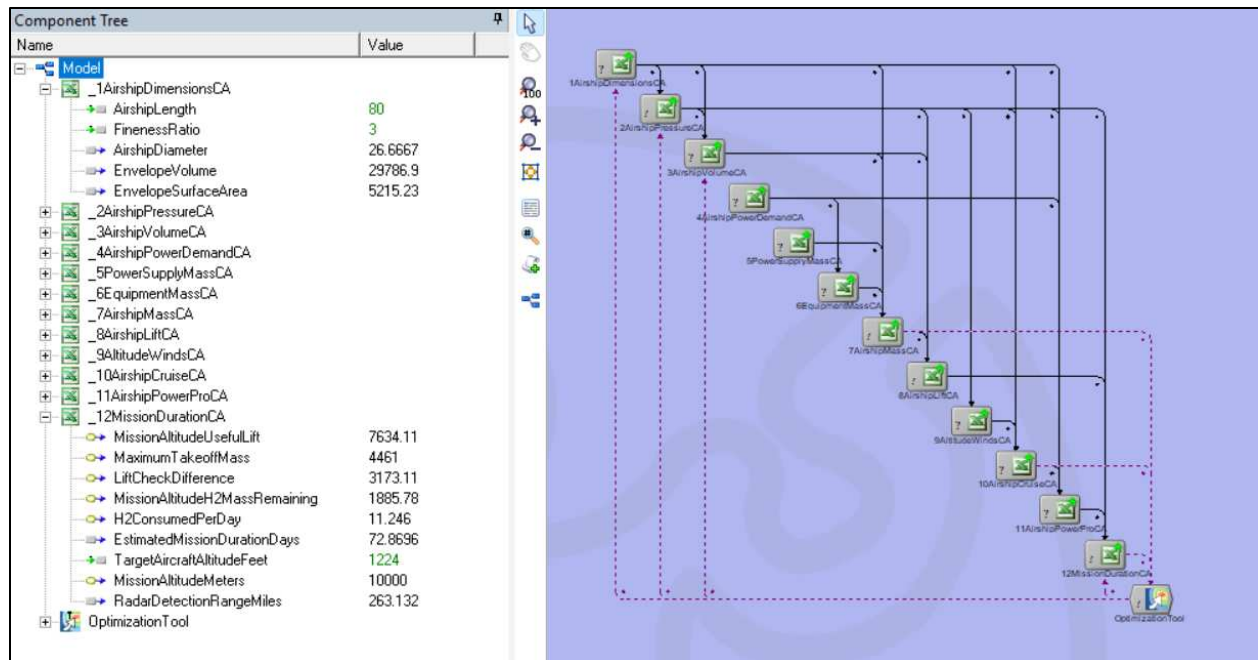


Figure 70: Ansys ModelCenter® DSM Example [122]

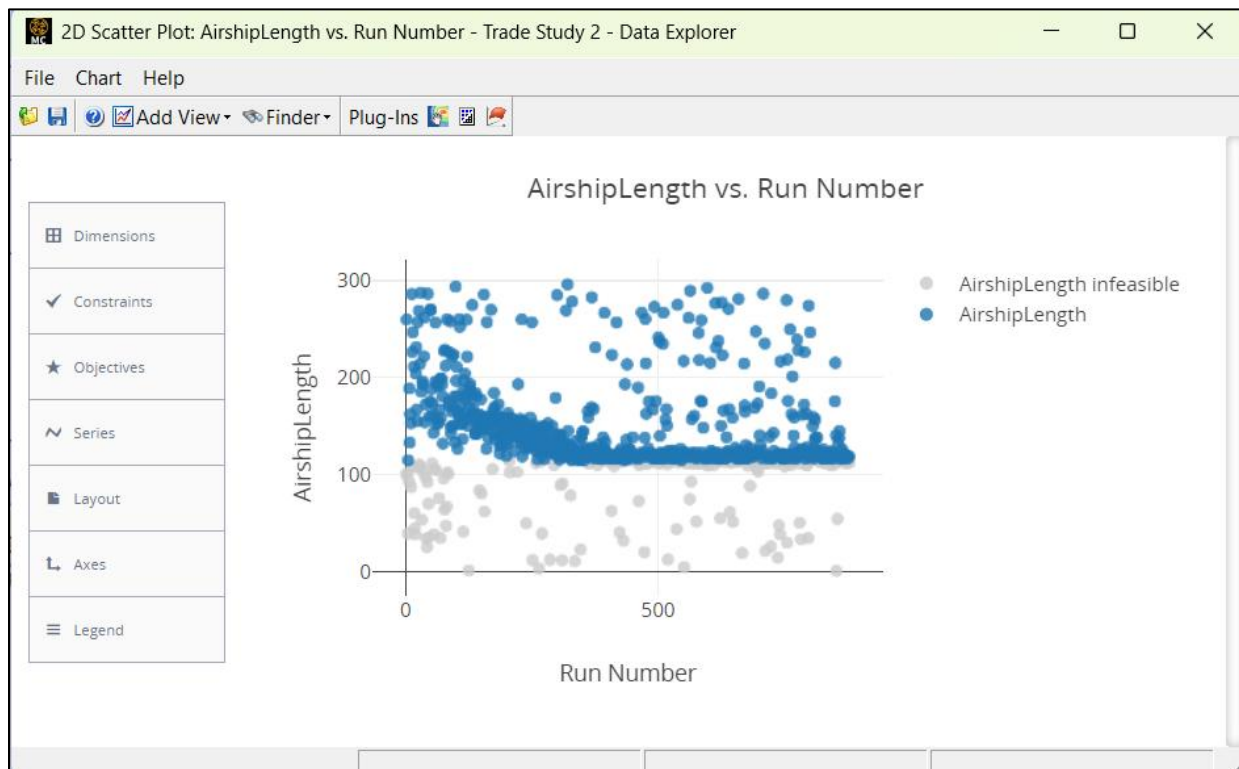


Figure 71: Ansys ModelCenter® Optimization Tool Example [122]

3.6 Summary

The literature review indicated the concept of developing a high altitude, long endurance early warning airship was technically sound. In order to effectively accomplish that task required the use of structured systems engineering methodology. This Chapter outlined that approach.

Overall, this research project used an integrated system engineering methodology in order to successfully develop the early warning airship system by:

- Incorporating Forsberg and Moos's basic systems engineering Vee model.
- Applying Kossiakoff and Sweet's four iterative design activities in each phase.
- Following Borky and Bradley's model-based systems architecture methodology.
- Implementing a Design System Matrix to document key input and output values.
- And using Multidisciplinary Design Optimization to obtain optimum values.

Details regarding the specific DSM parameters, their associated CA block calculations, and the use of MDO simulation analysis tools are explored in greater detail next in Chapter IV.

CHAPTER IV. SYSTEMS ENGINEERING

4.1 Needs Analysis

This phase of systems engineering confirms a valid operational need exists for a system and that a feasible approach can be developed at an affordable cost and within an acceptable level of risk. Overall, this phase addresses "*what*" the system needs to provide [118] and is the beginning of defining the "Operational Viewpoint" [119].

Operations Analysis. During this first step, the needs of stakeholders must be identified. Typical stakeholders include users, operators, organization decision makers, parties to any agreements, regulatory agencies, developing agencies, support organizations, and society at large. It is important to differentiate between stakeholder *needs* (which are the capabilities or features a user desires from the new system) and system *requirements* (which become the formal design criteria the system must comply with) [118].

Identifying stakeholder needs is done through "needs elicitation." This can be accomplished using interviews, questionnaires, and/or workshops [123]. One effective method of eliciting these system needs is through the application of "Use Case" diagrams. These are SysML diagrams that describe the system's behavior as it responds to user requests to achieve their goals. Use Cases can help convey top-level requirements in understandable, nontechnical terms to stakeholders in order to elicit their feedback and corrections [124].

For example, using Cameo Systems Modeler™ software [125], a Use Case diagram could be developed outlining the main flight functions a pilot would need to perform (see Figure 72.) This diagram could then be modified, working with users, as they identify missing or alternative functions the system needs to provide or accomplish.

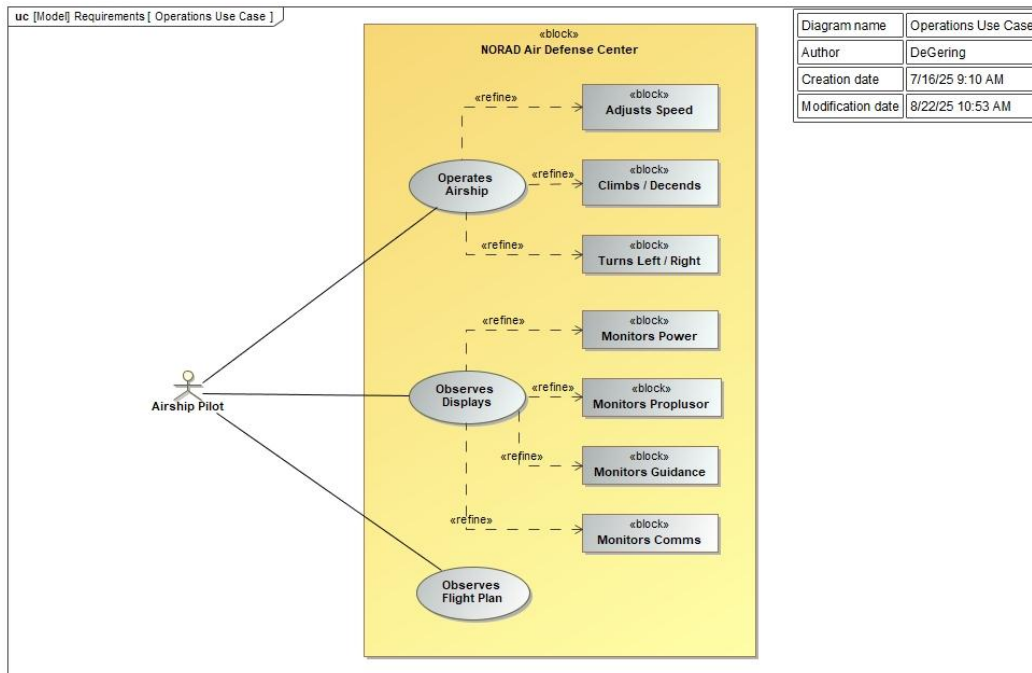


Figure 72: Airship Pilot Use Case Diagram [124]

Other requirements sources include formal requirement documents (such as an “Initial Capabilities Document” [ICD] or “Systems Requirements Document” [SRD]), determining deficiencies having developed in the current system, and developing an overall system “Concept of Operations” (CONOPS) [118].

Recognizing the North Warning System’s limitations regarding the detection of low altitude aircraft, there appears to exist a legitimate need for an augmenting air defense surveillance system. Based upon published unclassified guidance it was determined NORAD’s key air defense surveillance objectives generally consist of the following [126]:

- Providing continuous aerospace surveillance of northern North America.
- Supporting long range radar operations.
- Providing a usable radar a minimum of 96% of the time on a monthly basis.
- Restoring interrupted radar data within 3 hours.

Using these key NORAD air defense surveillance objectives as elicited system needs, a notional stratospheric early warning airship CONOPS was developed (see Table 18). Now the user has a vision of what the solution to their problem should look like.

Table 18: Proposed CONOPS.

Stratospheric Early Warning Airship Concept of Operation
"Employ an unmanned air vehicle operating at stratospheric altitudes over the Arctic Region for long durations, maneuvering under both manual and autonomous flight control, performing air defense surveillance against large aircraft, and communicating both vehicle telemetry and sensor data to NORAD for vehicle flight operations and air defense assessment."

Functional Analysis. During this next step, the key operational objectives taken from the CONOPS were then translated into the basic functions that must be performed by the proposed system (see Table 19). Both the ability to meet stakeholder needs and the associated technological feasibility must be demonstrated by the functions identified [118].

Table 19: Functional Analysis Results

Key Operational Objectives	Basic Functions
Air Vehicle	1-Structural
Operations at Stratospheric Altitude	1-Structural
Operations over the Arctic	1-Structural
Maneuvering Capability	2-Propulsion
Manual Flight Guidance	3-Guidance
Autonomous Flight Guidance	3-Guidance
Strategic Air Defense Surveillance	4-Detection
Vehicle Telemetry Transmission	5-Communications
Sensor Data Transmission	5-Communications
Long Duration	6-Power
Vehicle Flight Control	7-Control
NORAD Air Defense Assessment	7-Control

Feasibility Definition. Next, it is necessary to visualize the physical makeup of the system. At this point, no attempt is made to determine the optimum design or any of the components required, which will be done later. Developmental areas that were considered included [118]:

- Identifying the principal media required in each basic function (e.g., material, energy, signal, or data) to be employed by the proposed system (see Table 19).
- Viewing the proposed system in relation to various current systems and the ability to incorporate any portion of such legacy systems or infrastructures.
- Considering the impact of using advanced technology by using prototyping to demonstrate the feasibility of certain proposed subsystems.
- An estimation of the general costs involved in developing the new system.

Table 20: Principal Media Requirements.

Key Operational Objectives	Basic Functions	Media Required
Air Vehicle	1-Structural	Material
Operations at Stratospheric Altitude	1-Structural	Material, Energy
Operations over the Arctic	1-Structural	Material, Energy
Maneuvering Capability	2-Propulsion	Material, Energy
Manual Flight Guidance	3-Guidance	Material, Energy, Signal, Data
Autonomous Flight Guidance	3-Guidance	Material, Energy, Signal, Data
Strategic Air Defense Surveillance	4-Detection	Material, Energy, Signal, Data
Vehicle Telemetry Transmission	5-Communications	Material, Energy, Signal, Data
Sensor Data Transmission	5-Communications	Material, Energy, Signal, Data
Long Duration	6-Power	Material, Energy
Vehicle Flight Control	7-Control	Material, Energy, Signal, Data
NORAD Air Defense Assessment	7-Control	Material, Energy, Signal, Data

Needs Validation. Finally, during requirements elicitation activities, scores of requirements would have been generated by numerous users. A systematic examination of the validity of these numerous needs would then be conducted. This step includes reviewing the basic soundness of the stakeholder's needs, analyzing the feasibility of meeting those needs with the functions identified, and validating the physical media identified at this point. The overall goal of this step is determining the basic soundness of the proposed system solution [118]. Typical validation activities include:

- Defining validation criteria.
- Designing or adapting a model with operational scenarios.
- Demonstrating the cost-effectiveness of various proposed systems.
- Formulating the case for investing in development of each proposed system.

Derived performance requirements are the essential foundation to a successful project. Once established, care must be taken not to needlessly modify these requirements or continue to add new ones as the project progresses. There are numerous examples of projects that eventually failed due to the never-ending addition or modification to “final” requirements that everyone had previously agreed to [127, 128, 129].

Having completed the above steps, the “Needs Analysis” phase in Forsberg and Mooz's systems engineering Vee model has now been accomplished, Kossiakoff's four formal methodology steps have been completed, and Borky and Bradley's “Operational Viewpoint” is beginning to take shape (see Figure 73).

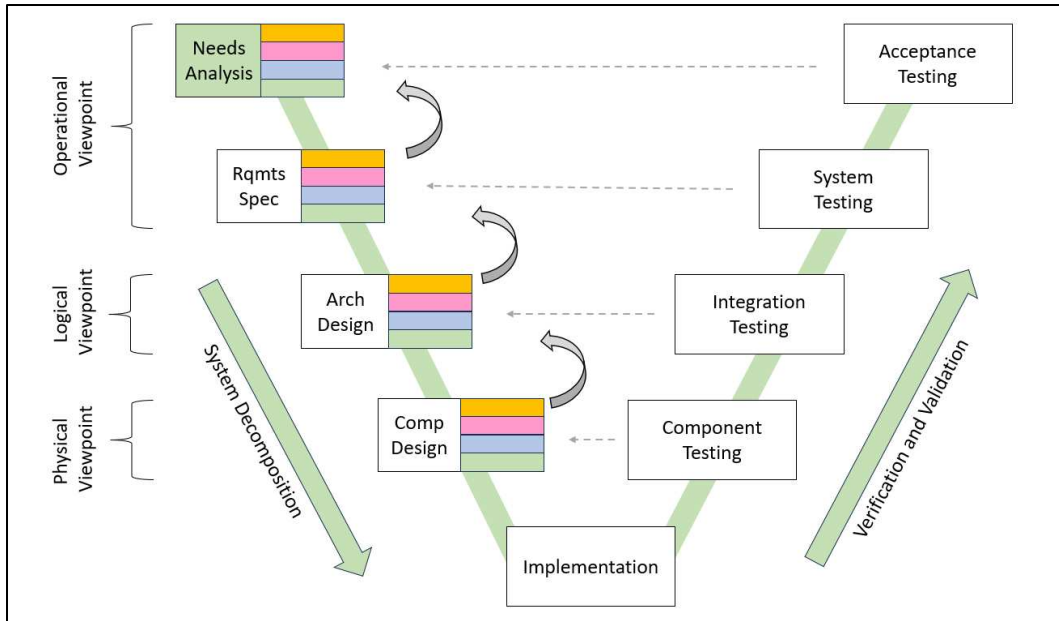


Figure 73: Project Systems Engineering Vee Model (Phase Completed)

4.2 Requirements Specification

During this next phase, the *operationally*-oriented viewpoint of the proposed new system was converted into an *engineering*-oriented viewpoint, with the primary objective of deriving a set of performance requirements that serve as the basic structure of the desired system. These various activities address "*how well*" the proposed system needs to perform [118].

Requirements Analysis. A system engineering requirement is "a statement that identifies a system, product or process characteristic or constraint which is unambiguous, clear, unique, consistent, stand-alone, and verifiable, and is deemed necessary for stakeholder acceptability" [130]. Per the INCOSE "Guide to Writing Requirements," clear and concise requirements are less taxing to interpret during system design, as well as simpler to verify, validate, and to identify defects during manufacturing and integration [131]. Characteristics of a well-stated requirement are that it should be:

- Necessary – Serves a defined purpose in the proposed system.
- Appropriate – Intent and detail is proper to the system level involved.
- Unambiguous – Intent is clear and can be interpreted in only one way.
- Complete – Sufficiently describes the qualities to be met.
- Singular – States only one system factor.
- Feasible – Can be accomplished within constraints and acceptable risk.
- Verifiable – Worded such that it can be satisfactorily confirmed.
- Correct – Is an accurate, error-free representation.
- Conforming – Meets approved standard writing guidance.

A common shorthand version of the above list is that system requirements need to be "Specific, Measurable, Appropriate, Realistic, and Traceable" (SMART) [131].

Requirements Formulation. During the next step, performance parameters required to meet the operational requirements need were formulated. Each derived requirement was classified as being either a “Measure of Effectiveness”, “Measure of Performance”, or “Technical Performance Measurement” [132] (see Figure 74).

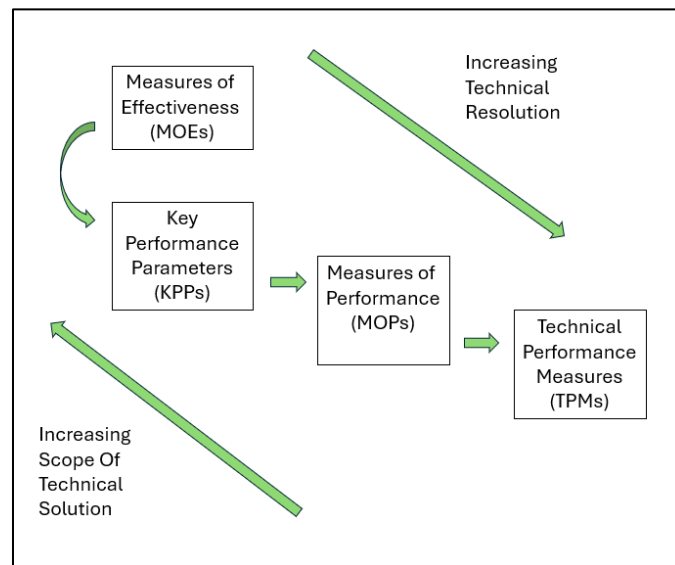


Figure 74: Relationship of the Technical Measures [132]

- Measures of Effectiveness (MOE). MOEs are “operational” measures of success that are closely related to achieving mission or operation objectives. The MOE refers to the system as a whole, while “Key Performance Parameters” (KPPs) assesses effectiveness. MOEs measure the mission accomplishment and answers the question “Are we doing the *right thing*?” [133].
- Measures of Performance (MOP). Identifying the KPPs of the system helps to define the MOPs. These metrics measure the physical or functional attributes relating to the system operation. They are *system-specific parameters* such as speed, range, or other performance features. Understanding MOPs helps inform whether a particular MOE has been achieved. MOPs measure task completion and answer the question “Are we doing *things right*?” [133].

- Technical Performance Measures (TPM). Finally, while MOPs measure physical functional attributes relating to *the system as a whole*, TPMs measure attributes *within the components* to determine how well the system is meeting specific requirements. TPMs track unit reliability, availability, maintainability, technical accuracy, etc. Any “out-of-bounds” TPMs can be a signal to replan fiscal, schedule, or human resources [134].

Derived Requirements. Sources for these requirements included the NORAD Agreement, numerous NASA airship studies, and the characteristics of airship prototypes currently under development. Based upon that background, Table 21 summarizes the author’s notionally derived system requirements developed as the results of that exploration process.

Table 21: Derived System Requirements

ID	Type	Derived Requirement	Source	Measure
R1.0	Universal Requirements (applies to all airship components.)			
R1.0.1	Construction	Shall be an air vehicle.	CONOPS	MOE
R1.0.2	Altitude	Shall be capable of operating in the stratosphere above 10 km (32,800 ft).	CONOPS	MOE
R1.0.3	Environment	Shall be capable of operating over the Arctic Region.	CONOPS	MOE
R1.0.4	Duration	Shall be capable of operating aloft for at least 60 continuous days.	CONOPS	MOE
R1.0.5	Certification	Shall pass all required FAA flight certifications.	FAA Policy	MOP
R1.0.6	Life Cycle	Shall have a life cycle of 10 years.	Derived	MOP
R1.0.7	Temperature	Shall be capable of operating to -60 C.	Derived	TPM
R1.0.8	Reliability	Shall meet MTBF rate of 1,500 hrs.	Derived	TPM
R1.1	Structural Requirements			
R1.1.1	Lift Gas	Shall be inflated using hydrogen gas.	Derived	MOP
R1.1.2	Envelope Fabric	Shall be constructed using material that shall not exceed a maximum density of 0.20 kg/m ² .	Derived	TPM

R1.1.3	Length	Shall not exceed 300 m in length.	Derived	TPM
R1.1.4	Diameter	Shall not exceed 100 m in diameter.	Derived	TPM
R1.1.5	Volume	Shall not exceed 500,000 m ³ in volume.	Derived	TPM
R1.2	Propulsion Requirements			
R1.2.1	Maneuvering	Shall be capable of maneuvering in flight.	CONOPS	MOE
R1.2.2	Motor Power	Shall employ electrically driven engine(s).	Derived	TPM
R1.2.3	Propeller Altitude	Shall employ propeller(s) rated for operations in the stratosphere above 10 km (32,800 ft).	Derived	TPM
R1.2.4	Propulsor Speed	Shall be capable of propelling the airship a minimum of 8.9 m/s (20 mph).	Derived	TPM
R1.3	Guidance Requirements			
R1.3.1	Manual Guidance	Shall be capable of receiving manual guidance commands from ground stations.	CONOPS	MOE
R1.3.2	Autonomous Guidance	Shall be capable of autonomously computing flight path and velocity commands to maintain programmed surveillance patrol.	CONOPS	MOE
R1.3.3	Safety Return Mode	Shall be capable of autonomously computing flight path and velocity corrections to return airship to base if communications are lost.	Derived	MOP
R1.4	Detection Requirements			
R1.4.1	Range	Shall be capable of detecting an aircraft mission at a distance of 400 km (250 miles).	CONOPS	MOE
R1.4.2	Radar Cross Section	Shall be capable of detecting a 125 m ² -sized aircraft target.	Derived	TPM
R1.5	Communications Requirements			
R1.5.1	Vehicle Telemetry	Shall be capable of communicating vehicle telemetry with ground stations.	CONOPS	MOE
R1.5.2	Sensor Data	Shall be capable of communicating sensor data with ground stations.	CONOPS	MOE
R1.5.3	Data Link	Shall be capable of employing Data Link 16 via satellite relay.	Derived	TPM

R1.6	Power Requirements			
R1.6.1	Power Production	Shall be capable of producing a minimum of 50 kW to power all airship subsystems.	Derived	TPM
R1.7	Control Requirements			
R1.7.1	Manual Control	Shall be capable of initiating manual vehicle control, when selected.	CONOPS	MOE
R1.7.2	Autonomous Control	Shall be capable of engaging autonomous vehicle control, when selected.	CONOPS	MOE
R1.7.3	Vehicle Flight Plan	Shall be capable of uploading flight plan information into vehicle.	Derived	MOP
R1.7.4	Vehicle Telemetry Display	Shall be capable of displaying vehicle telemetry for airship pilot flight operations.	Derived	MOP
R1.7.5	Sensor Data Display	Shall be capable of displaying surveillance sensor data for NORAD operator assessment.	CONOPS	MOE

These derived requirements can then be digitally illustrate using Cameo Systems Modeler™ to create a formal MBSE Requirements Diagram (REQ) (see Figure 75.)

As industry moves towards implementing full MBSE, having all requirements identified and inserted into a single, formal digital database will act as an Authoritative Source of Truth (ASOT) for all subsequent digital engineering efforts.

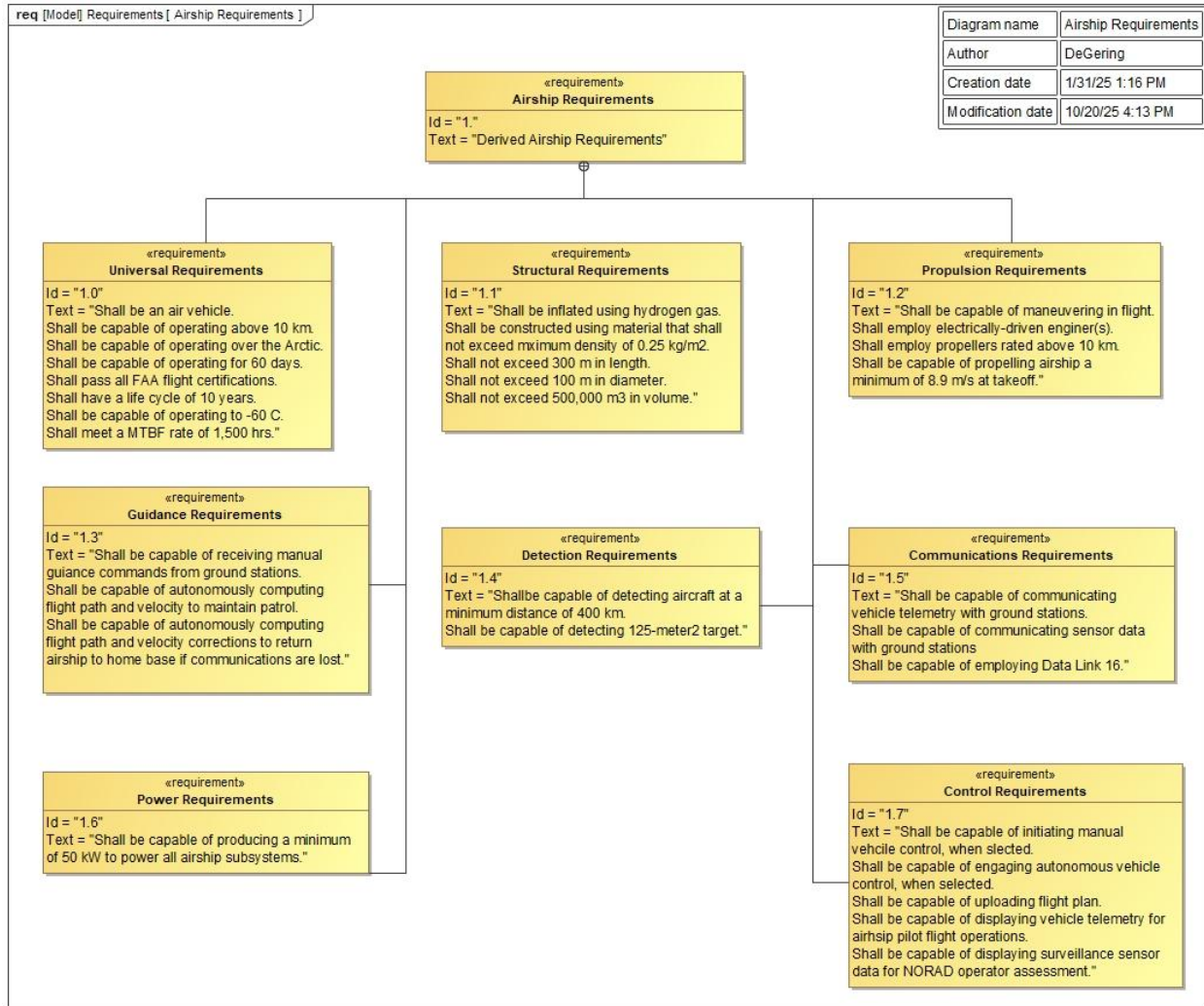


Figure 75: System Requirements SysML Diagram

Having completed the above steps, the “Requirements Specification” phase in Forsberg and Mooz’s systems engineering Vee model has now been accomplished, Kossiakoff’s formal “Concept Exploration” actions have been completed, and over 30 derived requirements have been defined reflecting Borky and Bradley’s “Operational Viewpoint” (see Figure 76).

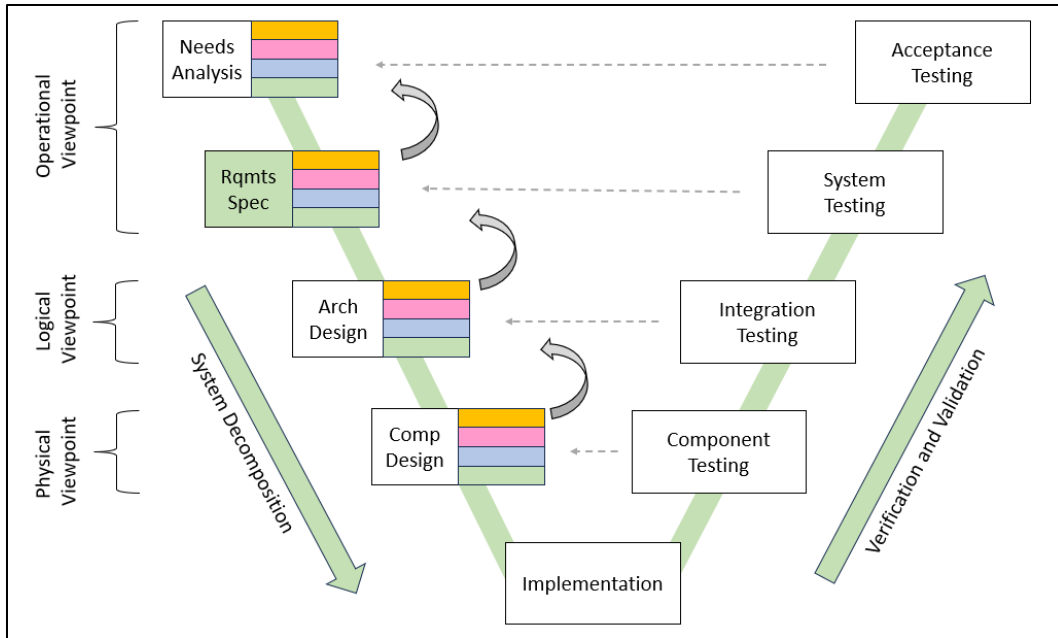


Figure 76: Project Systems Engineering Vee Model (Phase Completed)

4.3 Architecture Design

During this next phase, the focus was on the detailed process of moving from abstract functions to concrete parts, then components, assemblies, and finally subsystems. To accomplish this process, it was essential that elements be designed, developed, produced, and tested as separate, self-contained building blocks. This “modularity” concept allows the development of an orderly hierarchy of interacting components with well-defined interfaces [118].

System Architecting. Designing complex components can best be accomplished using “system architecting,” an approach championed by Eberhardt Rechtin in the 1990s [135]. In an oral history, Rechtin stated:

“My conclusion was that with good architecting you had a chance of astounding success. With no architecting or poor architecting, you stand a great chance of a disastrous failure. It was that clear. In between you can say, “Well, if there was or wasn't an architect it may or may not have made some difference one way or the other.” But a larger and larger number of people are beginning to recognize that unless you do that front end in a much different way than our standard regulations say, unless you get that process started properly, you are in trouble.” [136].

As outlined by Rechtin, the essence of architecting is *structure* – bringing form to function, bringing order out of apparent chaos, or converting partially formed ideas into a workable concept. The structure can be described in behavioral science terms, in functional terms, and in relational terms. Thus, the architect plays various roles during the system development effort (see Figure 77; the thicker lines indicate strongest architect involvement.).

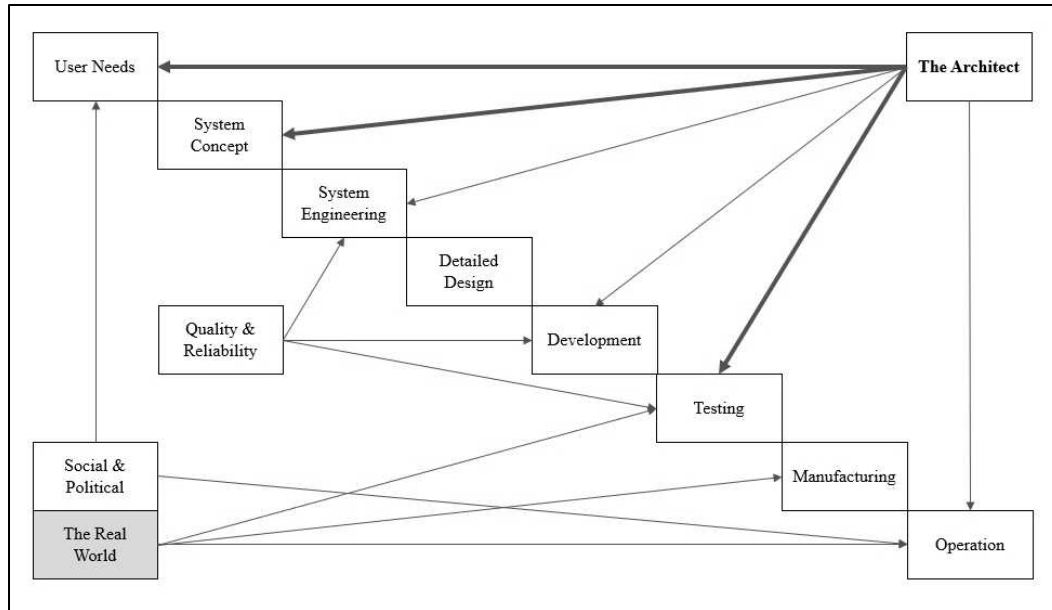


Figure 77: System Architect's Role [135]

During the architectural design phase, the goal is to develop system functional specifications, a specifically defined system concept, and a detailed plan to ensure engineering program success. In keeping with system engineering methods, a recursive architecting approach is typically used to develop the top-level design and its associated functional features.

As the new system design gains acceptance and maturity, the role of the system architect diminishes. The systems architect now becomes an advisor, focusing on user interests and objects, and assisting the engineers during system acceptance. The essence of architecting is structuring, simplification, compromise, and balance [135].

Functional Architecture. Translating the previously derived system requirements into specific system functions involved several major architecture steps [118]:

- Determining the four media classes (e.g., signal, data, material, energy) involved.
- Identification of the functions to be performed.
- Defining relationships between functions and performance requirements.

- Integrating all functional interfaces.

Considering these sequential design steps, it was now envisioned the proposed airship should be able to accomplish the following general flight and subsystem activities:

- Power is supplied to power all vehicle elements.
- The pilot initiates manual vehicle control through the communications relay to the central communications element to control the airship's propulsion and steering.
- Airship equipment telemetry is relayed for display to the pilot for awareness.
- Under pilot control, the airship launches, travels to its designated surveillance location, and initiates its autonomous on-station patrol lasting for multiple weeks.
- The radar is then activated and begins relaying its sensor data down to ground units to be displayed to air defense personnel for operational assessment.
- When the surveillance mission is finished, the pilot re-initiates manual vehicle control to depart off-station, return to base, and land the airship. The mission is complete.

A common means for representing these general functions is using a basic Functional Flow Block Diagram (FFBD) [137]. FFBDs help illustrate both the system's functionality as well as the flow of various media across a system. The derived functional architecture is shown in Figure 78.

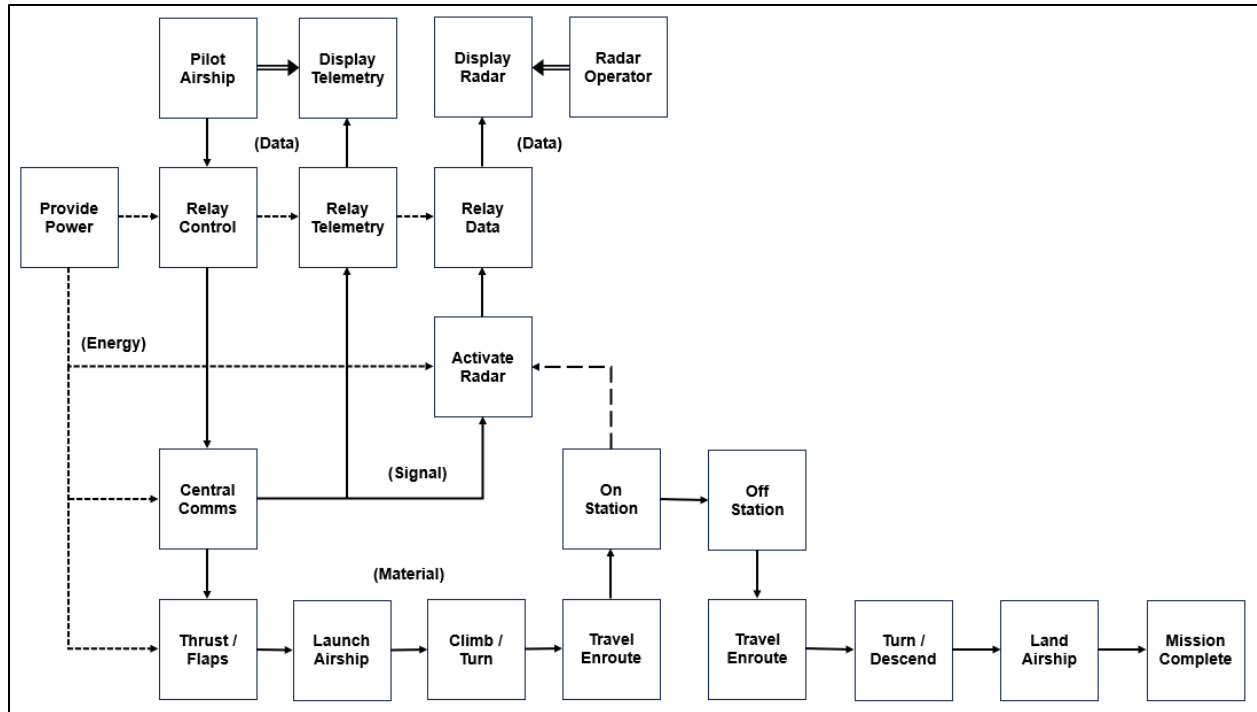


Figure 78: Airship FFBD Diagram

Based upon the derived requirements previously developed, it is proposed the airship system should consist of the following seven subsystems:

- Structural Subsystem, which provides the physical airframe.
- Propulsion Subsystem, consisting of one or more electric motors and their controls.
- Guidance Subsystem, providing navigation, guidance, and control functions.
- Detection Subsystem, which conducts the air defense surveillance operation.
- Communications Subsystem, providing two-way communications capability.
- Power Subsystem, which provides continuous power to the airship.
- Control Subsystem, providing airship control and surveillance displays.

In the beginning, these seven subsystems can be illustrated using a simple “Block Definition Diagram” [124] as show in Figure 79.

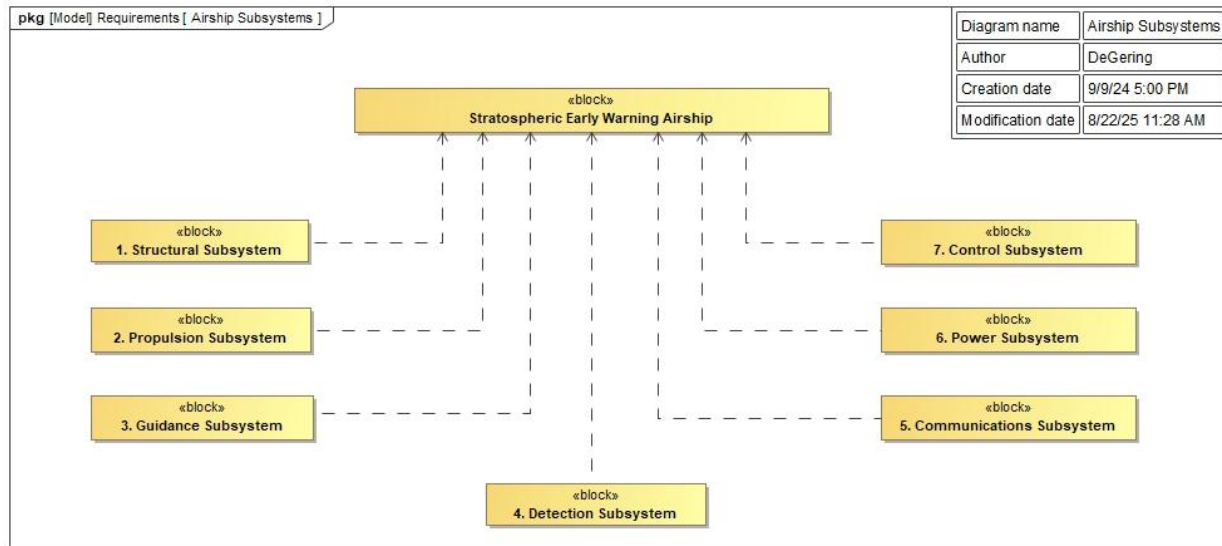


Figure 79: Airship Subsystems Block Definition Diagram

As more work progresses and more specifics are uncovered, the architecture becomes much more extensive. These subsystems can then be explored in greater detail in order to examine the major inputs and outputs expected to occur between each subsystem. This is illustrated by using a more comprehensive “Internal Block Diagram” [124] shown in Figure 80.

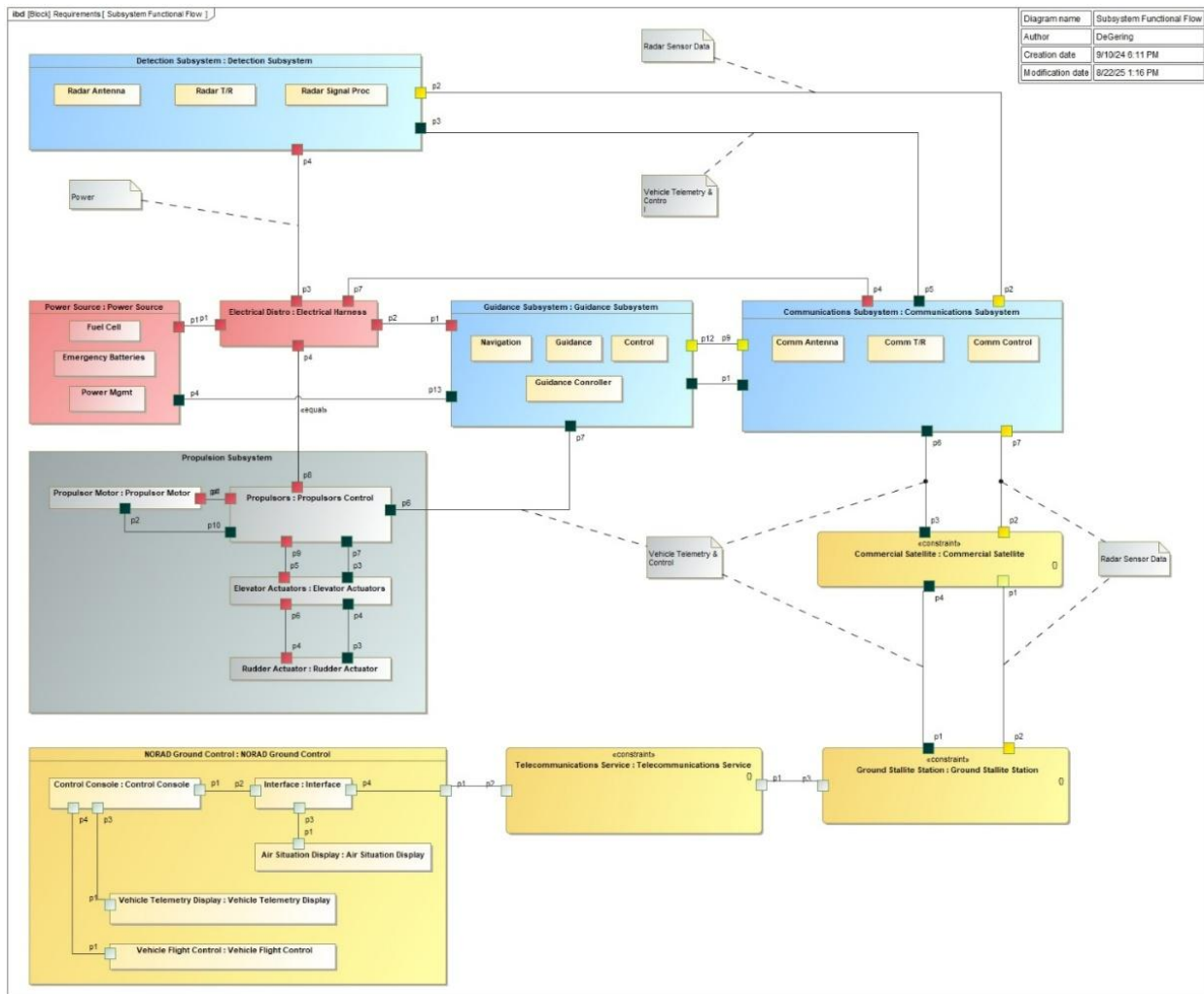


Figure 80: Airship Subsystems Internal Block Diagram

In this more detailed diagram, airship commands are shown originating at the NORAD control center, traveling through the telecommunications network up to the satellite, then down to the airship where they are received by its communications subsystem. Control signals then flow to the various propulsion, guidance, power, and radar subsystems. Both subsystem health telemetry and radar sensor data then flow back through the communications subsystem, are transmitted up to the satellite, and then are forwarded to NORAD for operational assessment. This level of detail helps ensure the architecture envisioned is addressing the essential interfaces connecting each subsystem to ensure the system as a whole can successfully function.

Having completed the above steps, the “Architecture Design” phase in Forsberg and Mooz’s systems engineering Vee model has now been accomplished, Kossiakoff’s formal “Concept Definition” actions have been completed, and Borky and Bradley’s “Logical Viewpoint” has been initiated using numerous airship subsystem parameters (see Figure 81).

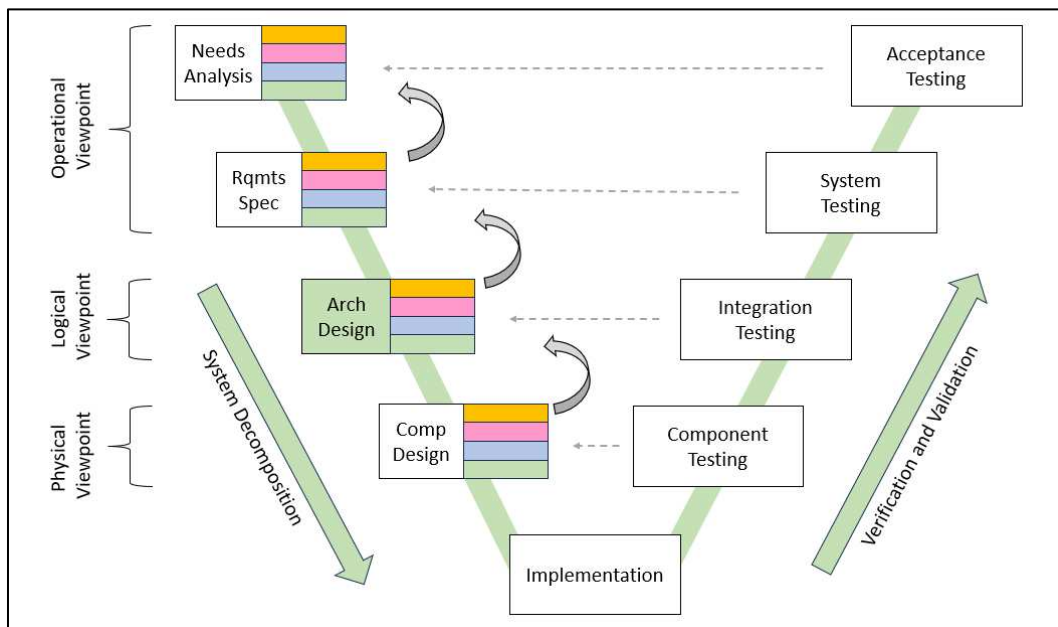


Figure 81: Project Systems Engineering Vee Model (Phase Completed)

4.4 Component Design

4.4.1 Design Parametric Sets

This phase now converted the previously derived requirements of "*what*" the system is to perform into specifications of generally "*how*" the required functions are to be implemented in actual hardware and software [118]. This process now moves from the "Logical Viewpoint" (LV) into the "Physical Viewpoint" (PV) [119].

Using the system composition developed in the above "Architecture Design" phase, the focus now shifted to identifying specific components that make up each subsystem. Parameter values were guided by published research results or examples of commercially available hardware identified during the literature review. Specifications were then grouped into twelve component design parametric sets:

Airship Dimensions. First, various combinations of airship length and "fineness ratios" (i.e., the airship length divided by its diameter) were examined. Those results determined the specific gas envelope volumes and surface areas for various airship configurations.

Airship Pressures. Next, a series of mission altitudes were selected for testing, ranging from 10,000 meters (32,800 ft) to potentially the top of the stratosphere (21,000 meters or 70,000 ft), and their associated air and hydrogen gas pressures.

Airship Volumes. Then, the applicable air and hydrogen gas volumes were then analyzed to include fractional percentages and the required hydrogen leakage into the atmosphere.

Airship Power Demand. Power requirements for propulsor motors; the guidance, radar, and communications payload subsystems; and the fuel cell assembly were also quantified. This determined the airship's estimated power demands under different operational modes.

Power Supply Mass. Next, the mass of the fuel cell assembly and the emergency battery assembly were derived.

Equipment Mass. This was followed by establishing the various masses of the propulsor motors and propellers; the guidance, radar, and communications payload subsystems; the miscellaneous support equipment; and finally, the payload equipment gondola.

Airship Mass. Using the envelope's material density, its mass was now derived. A "fill percentage" for the hydrogen gas was established and its mass calculated for varying volumes. Totaling all of the above elements, the airship's maximum takeoff mass was finally determined.

Airship Lift. Various air and hydrogen pressures, volumes, and masses were then developed to calculate the "useful lift" the hydrogen could produce. A check was then performed to verify the airship could successfully takeoff.

Altitude Winds. A look-up table was developed matching airship velocity with the expected windspeeds occurring between 10,000 to 21,000 meters altitude (e.g., up to 20 m/s or 45 mph) to ensure the airship could proceed against worst-case crosswinds.

Airship Cruise. Next, cruise velocities were tested to determine their effect on the airship's drag and the resulting electrical power demand placed on the fuel cell assembly.

Power Production. The consumption rate of both atmospheric air and hydrogen gas by the fuel cell assembly was then calculated, followed by determining the power generation limits of the compressors to meet the quantified power demand.

Mission Duration. Finally, based upon cruise velocities, crosswind occurrences, and associated hydrogen consumption rates, the maximum mission durations could be determined for a set of optimum mission altitudes. The resulting radar detection ranges were also computed.

To implement these component design sets, twelve separate Excel spreadsheets were constructed involving a total of 75 subsystem parameters (see Figure 82.)

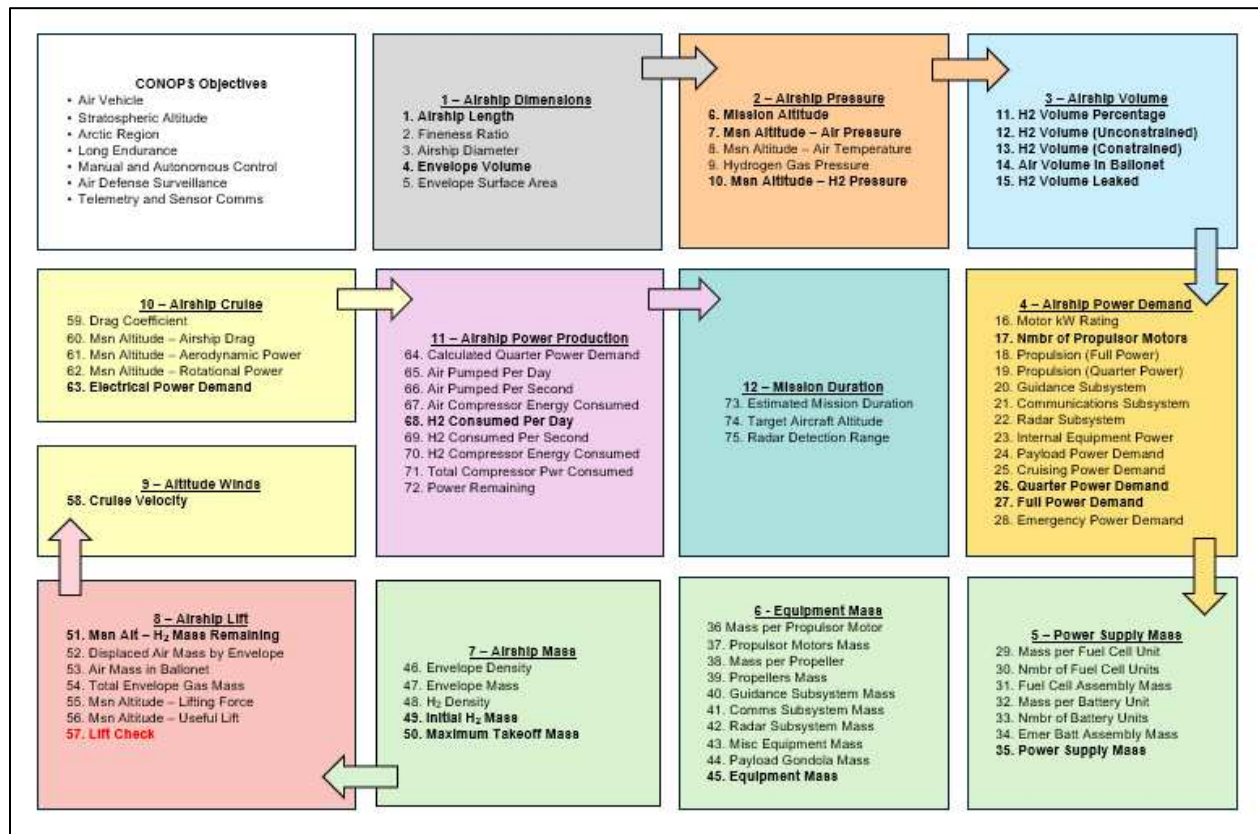


Figure 82: Component Design Parameters

Each of these spreadsheets received various inputs, performed the necessary (and often complex) internal calculations, and produced outputs for examination or as subsequent spreadsheet inputs, in an iterative process as multiple component designs were being designed and tested. Each of these twelve parametric spreadsheets and their calculations are now examined in detail.

4.4.2 Dimension Parameters

To illustrate the various calculations performed by each “Computational Analysis” (CA) block, an airship measuring 75 meters in length (e.g., the same size as the Goodyear Blimp [138])

was used as an example throughout this section. In addition, the desired mission altitude was set to 12,000 meters (39,400 ft) (this altitude choice is explained later in Sections 4.4.9 and 4.4.10).

To define the airship’s diameter, a “fineness ratio” value of 3 was chosen to ensure aerodynamic stability [36]. The resulting envelope volume was defined using the equation [59]:

$$\text{Envelope Volume (V}_E\text{)} = (1/6) * (3.14159) * (\text{Length}) * ((\text{Diameter})^2) \quad (24)$$

The envelope surface area was then calculated using the complicated equation [58]:

$$\begin{aligned} \text{Surface Area (A}_S\text{)} = & (4) * (3.14159) * ((((\text{Radius}) * (\text{Length}/2))^1.6) + \\ & ((2 * \text{Radius})^1.6) + ((\text{Length}/2) * (\text{Radius}))^1.6) / 3)^{1/1.6} \end{aligned} \quad (25)$$

These were incorporated into the “Airship Dimensions” Excel spreadsheet (see Table 22) forming the first CA block in the DSM (see Figure 83) and providing outputs to later CA blocks.

Table 22: Airship Dimensions Parameters

1 - Airship Dimensions CA	Inputs	Outputs
1. Airship Length (m)	75	
2. Fineness Ratio	3	
3. Airship Diameter (m)		25
4. Envelope Volume+ (m ³)		24,544
(Konstantinov - 2003)		24,544
(War Department - 1941)		24,158
5. Envelope Surface Area+ (m ²)		4,585

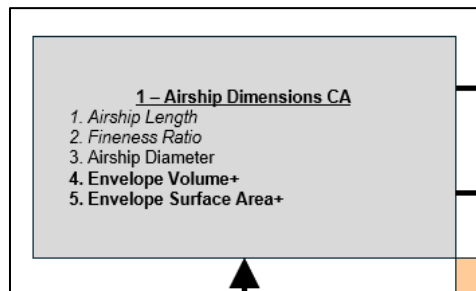


Figure 83: Airship Dimensions CA Block

4.4.3 Pressure Parameters

Airship calculations are highly sensitive to 1) the total envelope volume, 2) the desired mission altitude, and 3) the resulting atmospheric pressures. All of these design factors were initially defined prior to attempting to compute any subsequent requirements. Further, if design results proved insufficient, these were the first variables to be modified to achieve better results.

At sea level, the normal air pressure measures 101,325 Pascals at Standard Temperature and Pressure (STP) (e.g., 0 Celsius and 1 atmosphere) [52], while above 10,000 meters altitude, the air temperature stabilizes to 216.65 K due to continuous warming by the ozone layer [13].

By design, the airship uses hydrogen as its lifting gas based upon both the ease of which it can be manufactured and that it has the greatest buoyancy. This was a critical insight—it provided both the lift for the airship as well as providing a massive fuel supply for the power production subsystem (explained later in Section 4.4.12.)

Next, the airship design now implements an interesting new construct—combining two containers into a single airship envelope. First, the upper portion of the gas envelope was filled with hydrogen to 75% of its physical volume. Then, the lower 25% of the envelope was occupied by a separate, flexible “ballonet” bladder filled with air at takeoff. (Ballonets are well understood in the context of helium airships but have not been considered for hydrogen that has both lifting and fueling functions.) Prior to takeoff, the hydrogen was pressurized to 45,000 Pascals.

During ascent, the hydrogen gas (still at sea level pressure) begins to expand inside the envelope. At the same time, the ballonet begins venting its air, allowing the hydrogen gas to eventually expand to 100% of the envelope’s maximum physical volume. (For this airship example, it was estimated the ballonet would be completely vented by 9,000 meters [139].)

Then, as the airship continues to ascend, some of the hydrogen gas must now be “leaked” to the environment in order to protect the physical integrity of the balloon envelope. (Again, this is an innovative design, not seen in other research papers.)

Upon arriving at the desired mission altitude, the atmospheric air pressure was now computed using the formula [139]:

$$\text{Mission Altitude Air Pressure (P}_{A\text{-MA}}) = (101,325) * (1 - (2.25577 * 10^{(-5)} * (\text{mission altitude in meters}))^{5.25588}) \quad (26)$$

Finally, the hydrogen pressure was now the lesser of either the air pressure at that mission altitude plus 45,000:

$$\text{Mission Altitude H}_2 \text{ Pressure (P}_{H2\text{-MA}}) = \text{Min (P}_{A\text{-MA}} + 45,000) \quad (27)$$

These inputs and resulting calculations were incorporated into the “Airship Pressure” spreadsheet (see Table 23) forming the second CA block in the DSM (see Figure 84).

Table 23: Pressure Parameters

2 - Airship Pressure CA	Inputs	Output
(4. Envelope Volume+) (m3)	24,544	
6. Mission Altitude+ (m)	12,000	12,000
7. Mission Altitude - Air Pressure+ (Pa)		19,284
8. Mission Altitude - Air Temperature (K)		217
9. Hydrogen Lifting Gas Pressure (Pa)	45,000	
10. Mission Altitude - Hydrogen Pressure+ (Pa)		64,284

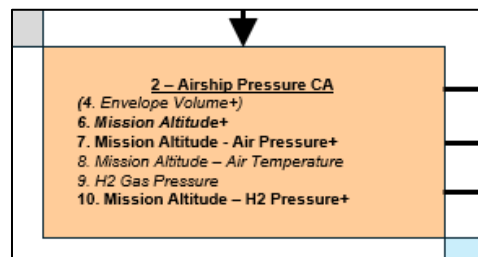


Figure 84: Airship Pressure CA Block

4.4.4 Volume Parameters

Typical air ballonets occupy from 25 to 50 percent of the envelope's gross volume [140]. For this project, 25 percent of the envelope's volume was occupied by a single air ballonet that filled the space beneath the hydrogen as a separate, flexible bladder. The ballonet's role is to limit the hydrogen to filling the remaining 75 percent of the volume (see Figure 85).

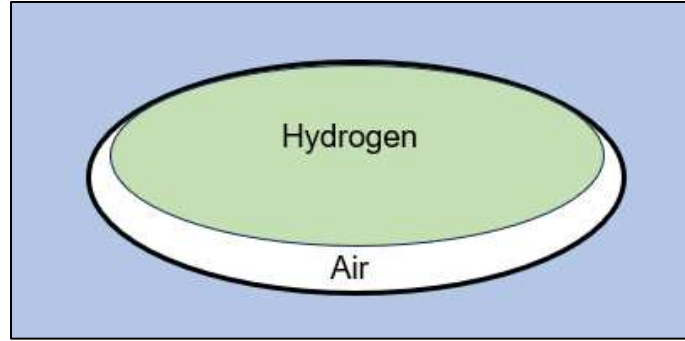


Figure 85: Air Ballonet Under Hydrogen Gas in Envelope (Side View)

If the airship envelope were flexible enough to expand unconstrained as it rose to its mission altitude (much like the NASA research weather balloons that expand to enormous sizes), its maximum hydrogen volume would be the initial 75 percent hydrogen volume times an expansion factor accounting for the great differences in altitude pressures [139]:

$$\begin{aligned} \text{Mission Altitude H}_2 \text{ Volume [Unconstrained]} (V_{\text{HU-MA}}) = \\ (\text{Envelope Volume}) * (0.75) * (101,325 / P_{\text{H}_2\text{-MA}}) \end{aligned} \quad (28)$$

(This is an important value. While the airship cannot actually expand to an enormous volume, it serves as the theoretical maximum hydrogen volume needed for the next calculations.)

In reality, the hydrogen gas initially fills its 75 percent volume and then (as the ballonet is emptied) eventually expands to fill 100 percent of the envelope. This is expressed as [139]:

$$\begin{aligned} \text{Mission Altitude H}_2 \text{ Volume [Constrained]} (V_{\text{HC-MA}}) = \\ \text{Min (Actual Envelope Volume, Unconstrained Volume)} \end{aligned} \quad (29)$$

The volume of air in the ballonnet was then defined as [139]:

$$\begin{aligned} \text{Mission Altitude Ballonet Volume (V}_{B\text{-MA}}) = \\ (\text{Actual Envelope Volume}) - (\text{Constrained Volume}) \end{aligned} \quad (30)$$

Finally, the amount of hydrogen leaked during the ascent was calculated by subtracting the actual envelope volume from the theoretical unconstrained volume [139]:

$$\text{Mission Alt H}_2 \text{ Volume Leaked (V}_{HL\text{-MA}}) = (V_{HU\text{-MA}}) - (V_E) \quad (31)$$

These various inputs and resulting calculations were incorporated into the “Airship Volume” spreadsheet (see Table 24) forming the third CA block in the DSM (see Figure 86) and providing five outputs to later CA blocks.

Table 24: Airship Volume Parameters

3 - Airship Volume CA	Inputs	Output
(4. Envelope Volume+) (m3)	24,544	
(7. Mission Altitude - Air Pressure+) (Pa)	19,284	
(10. Mission Altitude - Hydrogen Pressure+) (Pa)	64,284	
11. Hydrogen Volume Percentage+	0.75	0.75
12. Hydrogen Volume (Unconstrained) (m3)+		29,015
13. Hydrogen Volume (Constrained)+ (m3)		24,544
14. Air Volume in Ballonet+ (m3)		0
15. Hydrogen Volume Leaked+ (m3)		4,471

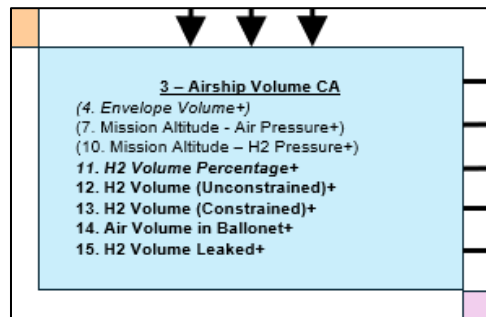


Figure 86: Airship Volume CA Block

4.4.5 Power Demand Parameters

To power the airship, the H3X HPDM-350 electric motor discussed in Section 2.5.1 was selected as an example [68]. With each motor turning very slowly at 90 RPM and at 90% efficiency, this resulted in an electrical power demand of approximately 9.5 kW [70].

Thus, when employing all four motors (e.g., during takeoff and landing operations or during persistent crosswinds), the full power demand equals approximately 38 kW.

Next, the power for the mission components (i.e., guidance, communications, and radar subsystems), the fuel cell assembly, the landing gear assembly, the subsystem heaters (required due to the stratospheric cold), and miscellaneous support equipment totaled 8.0 kW.

Therefore, the total airship power demand was estimated to be approximately 46 kW.

Finally, a separate emergency battery assembly was added to provide 50 kW to power the minimum essential subsystems for one hour in order to accomplish an quick emergency landing.

These inputs and resulting calculations were incorporated into the “Power Demand” spreadsheet (see Table 25) forming the fourth CA block in the DSM (see Figure 87).

Table 25: Airship Power Demand Parameters

4 - Airship Power Demand CA	Inputs	Output
16. Motor Rating (kW)	9.42	
17. Number of Propulsor Motors+	4.00	4.00
18. Propulsion Subsystem (kW)		37.68
19. Guidance Subsystem (kW)	0.55	
20. Communications Subsystem (kW)	0.35	
21. Radar Subsystem (kW)	3.60	
22. Fuel Cell Assembly (kW)	1.00	
23. Landing Gear Assembly (kW)	1.00	
24. Subsystem Heaters (Kw)	1.00	
25. Misc Equipment (kW)	0.50	
26. Payload Power Demand (kW)+		8.00
27. Estimated Full Power Demand (kW)		46.00
28. Emergency Power Demand (Kw)		43.00

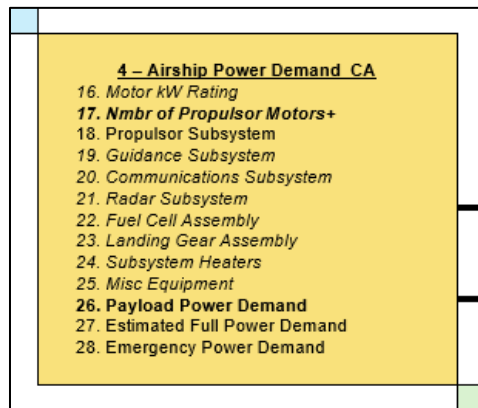


Figure 87: Airship Power Demand CA Block

4.4.6 Power Supply Mass Parameters

Next, the mass of the Toyota fuel cell unit [83] and the emergency battery unit [77] were obtained from the literature research. One fuel cell assembly was installed capable of generating 65 kW of power, thus enough to power all airship components. Including the emergency battery assembly, the complete Power Supply Mass equaled 435 kg.

These inputs and resulting calculations were incorporated into the “Power Supply Mass” spreadsheet (see Table 26) forming the fifth CA block in the DSM (see Figure 88) and providing one output to later CA blocks.

Table 26: Power Supply Mass Parameters

5 - Power Supply Mass CA	Inputs	Outputs
29. Mass per Fuel Cell Unit (kg)	235	
30. Number of Fuel Cell Units	1	
31. Fuel Cell Assembly Mass (kg)		235
32. Mass per Battery Unit (kg)	200	
33. Number of Battery Units	1	
34. Emergency Battery Assembly Mass (kg)		200
35. Power Supply Mass+ (kg)		435

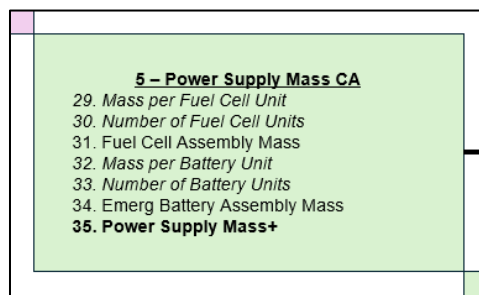


Figure 88: Power Supply Mass CA Block

4.4.7 Equipment Mass Parameters

The mass of the remaining airship equipment (e.g. motors, propellers, payload subsystems, miscellaneous equipment, and the payload gondola) were then estimated to total 947 kg.

These various inputs and resulting calculations were inserted into the “Equipment Mass” spreadsheet (see Table 27) forming the sixth CA block in the DSM (see Figure 89).

Table 27: Equipment Mass Parameters

6 - Equipment Mass CA	Inputs	Output
(17. Number of Propulsor Motors+)	4	
36. Mass per Propulsor Motor (kg)	50	
37. Propulsor Motors Mass (kg)		200
38. Mass per Propeller (kg)	96	
39. Propellers Mass (kg)		384
40. Guidance Subsystem Mass (kg)	29	29
41. Communications Subsystem Mass (kg)	30	30
42. Radar Subsystem Mass (kg)	104	104
43. Misc Equipment Mass (kg)	100	100
44. Payload Gondola Mass (kg)	100	100
45. Equipment Mass+ (kg)		947

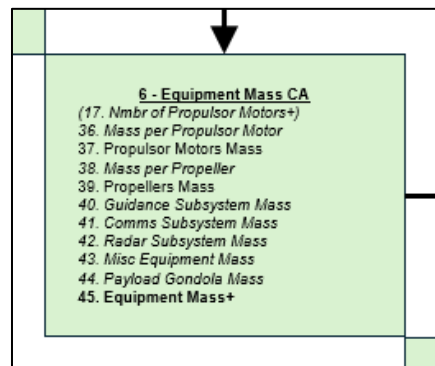


Figure 89: Equipment Mass CA Block

4.4.8 Airship Mass Parameters

Given the airship uses an envelope material weight of 0.113 kg/m^2 [42], the combined masses resulted in a Maximum Takeoff Mass totaling 3,631 kg. (Note: At this stage, this airship design is notably lighter than those proposed in previous NASA studies for non-polar airships.)

These numerous inputs and resulting calculations were combined into the “Airship Mass” spreadsheet (see Table 28) forming the seventh CA block in the DSM (see Figure 90).

Table 28: Airship Mass Parameters

7 - Airship Mass CA	Inputs	Output
(35. Power Supply Mass+) (kg)	435	435
(45. Equipment Mass+) (kg)	947	947
(5. Envelope Surface Area+) (m^2)	4,585	
46. Envelope Material (kg/m^2)	0.113	
47. Envelope Mass (kg)		596
(4. Envelope Volume+) (m^3)	24,544	
(11. Hydrogen Volume Percentage+)	0.7500	
48. Hydrogen Density (kg/m^3)	0.0898	
49. Initial Hydrogen Mass+ (kg)		1,653
50. Maximum Takeoff Mass+ (kg)		3,631

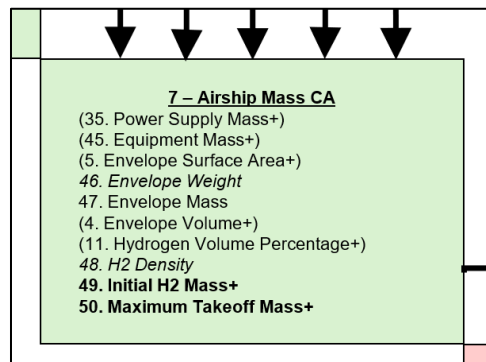


Figure 90: Airship Mass CA Block

4.4.9 Lift Parameters

The Archimedes Principle states: “any body completely or partially submerged in a fluid (e.g., gas or liquid) at rest is acted upon by an upward, or *buoyant, force*, the magnitude of which is equal to *the weight of the fluid displaced by the body*” (author’s italics) [141]. This section proceeds through several steps to compute the airship’s overall buoyancy force.

First, the initial hydrogen mass was computed by multiplying the initial envelope volume times the ballonnet percentage, then times the density of hydrogen (i.e., 0.0898 kg/m³) [142]:

$$\text{Initial H}_2 \text{ Mass (M}_{H-I}) = (V_{H-I}) * (0.75) * (0.0898) \quad (32)$$

Next, upon reaching the desired mission altitude, the remaining envelope hydrogen mass was computed in three steps:

1. First, the fraction of hydrogen leaked was determined by dividing the volume of hydrogen leaked by the total unconstrained volume of hydrogen.
2. This fraction was subtracted from “1” to determine the remaining percentage.
3. Finally, this percentage was multiplied by the initial hydrogen mass to determine the remaining hydrogen mass.

These three steps are captured in the following equation [139]:

$$\begin{aligned} \text{Mission Altitude H}_2 \text{ Mass Remaining (M}_{HR-MA}) = & (1 - (\text{H}_2 \text{ volume leaked} / \\ & \text{H}_2 \text{ volume unconstrained}) * (M_{H-I}) \end{aligned} \quad (33)$$

Then, based upon Archimede’s Principle, the displaced air mass in the atmosphere produced by the airship’s envelope must be determined. This was calculated using the actual envelope volume times the density of air at the mission altitude (again times a factor accounting for the great pressure differences compared to that at sea level of 101,325 Pa [52]) [139]:

$$\text{Displaced Air Mass (M}_{AD}) = (V_E) * (\text{air density}) * (P_{A-MA} / 101,325) \quad (34)$$

(Above 9,000 meters, the air in the ballonnet will have been completely emptied, so the total envelope gas mass was simply the mass of the hydrogen that now remained.)

Having completed the above calculations, the “Lifting Force” (the amount of force, measured in Newtons) was now computed using the gravitational constant of 9.81 [139]:

$$\text{Lifting Force (F}_L) = (\text{displaced air mass} - \text{remaining gas mass}) * (9.81) \quad (35)$$

The critical “Useful Lift” (the amount of mass the resulting buoyancy can loft, measured in kg) could then be calculated [55]:

$$\text{Useful Lift (L}_U) = (\text{lifting force}) / 9.81 \quad (36)$$

Finally, a “Lift Check (Difference)” was accomplished to verify sufficient buoyancy had been generated to lift the airship’s Maximum Takeoff Mass (used in Section 4.5).

The flow of these pressure, volume, mass, and force elements is shown in Figure 91 to allow the reader to better follow the sequence of the aerodynamic lifting force calculations.

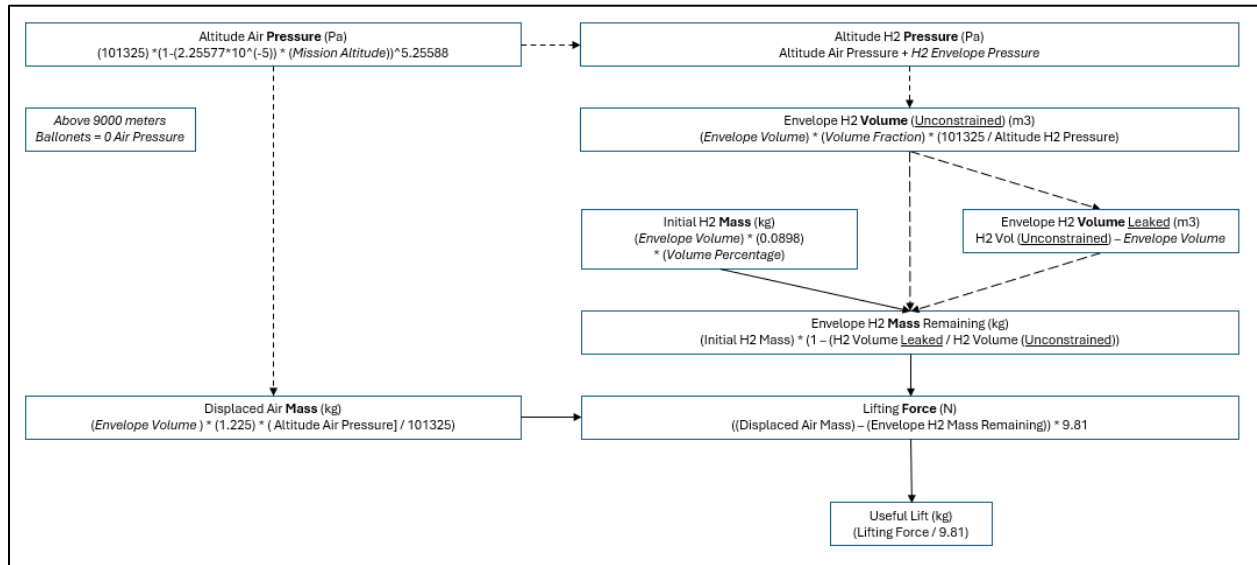


Figure 91: Aerodynamic Lifting Force Calculations

Overall, the Useful Lift of 4,324 kg exceeds the Maximum Takeoff Mass of 3,631 kg by only 693 kg, indicating the airship has nearly reached its highest attainable altitude.

Each of these numerous calculations were then incorporated into the “Airship Lift” spreadsheet (see Table 29) forming the eighth CA block in the DSM (see Figure 92).

Table 29: Airship Lift Parameters

8 - Airship Lift CA	Inputs	Output
(7. Mission Altitude - Air Pressure+) (Pa)	19,284	
(10. Mission Altitude - Hydrogen Pressure+) (Pa)	64,284	
(12. Hydrogen Volume (Unconstrained)+) (m ³)	29,015	
(13. Hydrogen Volume (Constrained)+) (m ³)	24,544	
(14. Air Volume in Ballonet+) (m ³)	0	
(15. Mission Altitude - Hydrogen Volume Leaked+) (m ³)	4,471	
(49. Initial Hydrogen Mass+) (kg)	1,653	
51. Mission Altitude - Hydrogen Mass Remaining+ (kg)		1,398
52. Displaced Air Mass by Rigid Envelope (kg)		5,722
53. Air Mass in Ballonet (kg)		0
54. Total Envelope Gas Mass (kg)		1,398
55. Mission Altitude - Lifting Force (N)		42,416
56. Mission Altitude - Useful Lift+ (kg)		4,324
(50. Maximum Takeoff Mass+) (kg)	3,631	
57. Lift Check (Difference)+		693



Figure 92: Airship Lift CA Block

4.4.10 Altitude Winds Parameters

Crosswind Calculations. Upon launching, it is proposed the airship will ascend to its mission altitude and then drift along with the counter-clockwise air flow around the North Pole, using the propulsor motors occasionally to adjust the airship's heading as it travels. However, if significant crosswinds began to challenge the airship's forward travel, it was necessary to include calculations addressing that eventuality.

As the crosswinds became stronger, the airship would need to “tack” against them, slowly zigzagging back and forth in order to make forward progress. At a minimum, this would require the airship's speed to match the wind speed being confronted at each proposed mission altitude.

Recalling from Section 2.2.1, Arctic wind speeds between 10,000 and 20,000 meters typically top off at 20 meters/second (45 mph) (see Figure 93).

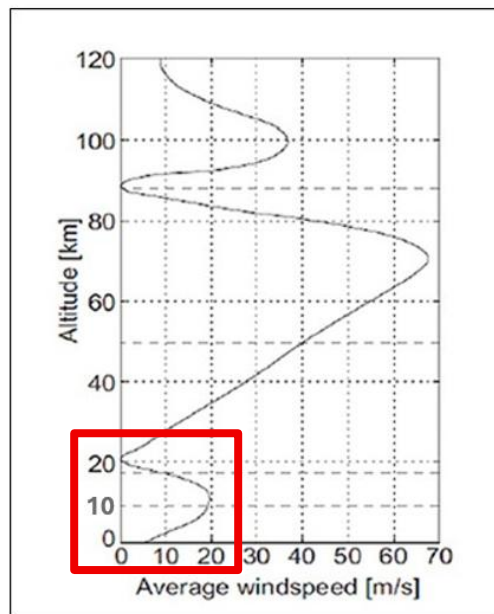


Figure 93: Typical Wind Velocity Profile [19]

Using this information, an Excel spreadsheet reference table was built reflecting the various crosswinds expected from 10,000 to 21,000 meters at 1,000-meter intervals (see Table 30). For example, assuming the airship was operating at 12,000 meters altitude, crosswinds gusting up to 20 meters/second (45 mph) could be expected.

(Note: Wanting the maximum crosswind value possible for testing purposes was the other reason 12,000 meters altitude was selected for the design example.)

Table 30: Altitude Wind Velocities

Altitude (km)	Velocity (m/s)	Altitude (km)	Velocity (m/s)	Altitude (km)	Velocity (m/s)
10 to <11	19	14 to <15	19	18 to <19	10
11 to <12	20	15 to <16	17	19 to <20	8
12 to <13	20	16 to <17	15	20 to <21	4
13 to <14	19	17 to <18	13	21	2

These values were then incorporated into the “Altitude Winds” spreadsheet (see Table 31) forming the ninth CA block in the DSM (see Figure 94) and an output to the next CA block.

Table 31: Altitude Winds Parameters

9 - Altitude Winds CA	Input	Output
(6. Mission Altitude+) (m)	12,000	
7. Cruise Velocity+		20

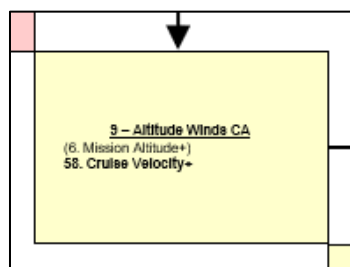


Figure 94: Altitude Winds CA Block

4.4.11 Cruise Parameters

Once airborne, it was necessary to calculate the amount of electrical energy required to power the propulsor motors. Previously in Section 4.4.5, it was estimated whenever the airship used all four motors, the maximum airship power demand equaled 46 kW. This was helpful for initial equipment planning.

However, based upon the actual atmospheric conditions at the surveillance mission altitude (e.g., air pressure, air density, gas envelope volume, airship velocity, etc.), the actual power demand could now be calculated more precisely.

The overall airship drag (a force in Newtons) at mission altitude was calculated using a standard airship drag coefficient of “0.02” [37] and the following complicated equation [139]:

$$\begin{aligned} \text{Mission Altitude Airship Drag at } (D_{MA}) = & (\text{sea level air density} * \\ & \text{mission altitude air pressure} / \text{sea level air pressure} / 2) * \\ & ((\text{cruise velocity in m/s})^2) * (0.02) * (\text{original envelope volume})^{(2/3)} \end{aligned} \quad (37)$$

(Notice this equation is very sensitive to cruising velocity. The faster the airship is required to travel, the greater the airship drag being produced.)

In turn, the aerodynamic power (now measured in Watts) required to achieve that desired airship velocity against that drag equals [139]:

$$\text{Mission Alt Aerodynamic Power } (P_{A-MA}) = (D_{MA}) * (\text{cruise velocity}) \quad (38)$$

(Again, the cruise velocity directly affects the aerodynamic power requirement.)

Then, the motor rotational power (again in Watts) required to achieve that aerodynamic power, assuming a 75 percent motor efficiency, was calculated [139]:

$$\text{Rotational Power } (P_{R-MA}) = P_{A-MA} / 0.75 \quad (39)$$

Finally, the electrical power demand (again in Watts) required to power the motors to that velocity against that drag, assuming 90 percent fuel cell efficiency, was determined [139]:

$$\text{Full Power Demand (P}_{E\text{-MA}}) = P_{R\text{-MA}} / 0.90 \quad (40)$$

Traveling at 20 m/s, the calculated electrical power demand was now only 23.3 kW – actually half of the previously estimated 46 kW! Thus, using the actual velocity, airship drag, mission altitude, and rotational parameters were critical to obtaining a more accurate result.

Each of these inputs and calculations were then incorporated into the “Airship Cruise” spreadsheet (see Table 32) forming the tenth CA block in the DSM (see Figure 95).

Table 32: Airship Cruise Parameters

10 - Airship Cruise CA	Inputs	Output
(4. Envelope Volume+) (m ³)	24,544	
(7. Mission Altitude - Air Pressure+) (Pa)	19,284	
58. Cruise Velocity+ (m/s)	20	
59. Drag Coefficient	0.02	
60. Mission Altitude - Airship Drag (N)		788
61. Mission Altitude - Aerodynamic Power (W)		15,752
62. Rotational Power (W)		21,002
63. Calculated Electrical Power Demand+ (W)		23,336

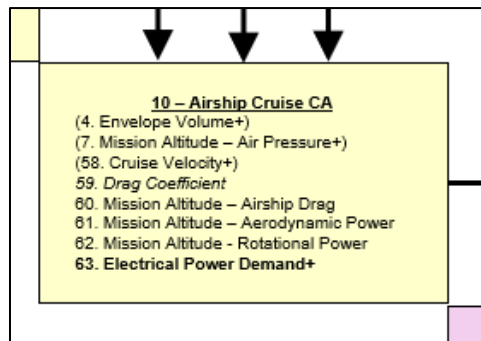


Figure 95: Airship Cruise CA Block

4.4.12 Power Production Parameters

Quantifying the amount of electrical power to be produced required calculations involving both atmospheric air and hydrogen compressor operations being conducted at very high altitudes (i.e., involving very thin air.)

Air Calculations. The mass of the air required to be pumped daily into the fuel cell assembly at high altitude was determined using the complicated formula [139]:

$$\begin{aligned} \text{Air Pumped Per Day (M}_{A-D}\text{)} = & ((0.000000357 * 2 * (\text{power demand} / 0.65) \\ & * 3600 * 24) - ((0.000000357 * 2 - 0.0000000829) * (\text{power demand} / 0.65) \\ & * 3600 * 24) \end{aligned} \quad (42)$$

Then, the volume of air pumped per second was established [139]:

$$\begin{aligned} \text{Air Pumped Per Second (V}_{A-S}\text{)} = & (\text{M}_{A-D} / \text{altitude air density} / 24 \text{ hours} / 3600 \\ & \text{seconds per hour}) \end{aligned} \quad (43)$$

Finally, the energy consumed by the air compressor itself pulling in extremely thin air existing at high altitudes was now calculated [139]. (Note: Atmospheric temperatures from 11,000 to 25,000 meters remain at a constant 216.65 Kelvin due to the heating of the ozone layer [20].)

$$\begin{aligned} \text{Air Compressor Energy Consumed (E}_{AC}\text{)} = & (\text{V}_{A-S}) * (216.65) * (1.4 / 0.4) * \\ & (101,000 / 273) * ((101,000 / \text{altitude air pressure})^{(0.4 / 1.4)} - 1) \end{aligned} \quad (44)$$

Hydrogen Calculations. As previously noted, 1 kg of hydrogen can produce 33.3 kW of electrical power [88]. The mass of the hydrogen being consumed by the fuel cell assembly can now be more accurately defined [139]:

$$\begin{aligned} \text{Hydrogen Mass Consumed Per Day (M}_{H-D}\text{)} = & (\text{power demand}) * \\ & (24 \text{ hours}) / (33,300 \text{ watts of energy per kg}) / (0.50 \text{ efficiency}) \end{aligned} \quad (45)$$

(Note: This is the critical factor that eventually drives overall Mission Duration.)

Next, the volume of hydrogen consumed per second is determined [139]:

$$\text{Hydrogen Consumed Per Second (V}_{H-S}) = (M_{H-D}) / (H_2 \text{ density}) / (24 \text{ hours}) / (3600 \text{ seconds per hour}) \quad (46)$$

Finally, the energy consumed by the hydrogen compressor itself is calculated [139]:

$$\text{Hydrogen Compressor Energy Consumed (E}_{HC}) = (V_{H-S}) * (216.5) * (1.4 / 0.4) * (101,000 / 273) * ((101,000 / P_{H2-MA})^{(0.4 / 1.4)-1}) \quad (47)$$

Total Electrical Power Demand. Now the total electrical power demand for both the air and hydrogen compressors at 80% efficiency can now be established [139]:

$$\text{Total Compressor Power Consumed (P}_C) = (E_{AE} + E_{HC}) / 0.8 / 0.8 \quad (48)$$

All of these air and hydrogen compressor mass, volume, and wattage equations are summarized in Figure 96 to allow the reader to better follow the sequence of these calculations.

(Note: This is a novel implementation of a high-altitude fuel cell model and is one of the first Proton-Exchange Membrane (PEM) fuel cell models proposed to operate at stratospheric altitudes. To date, no other studies have outlined PEM fuel cells using a similar approach.)

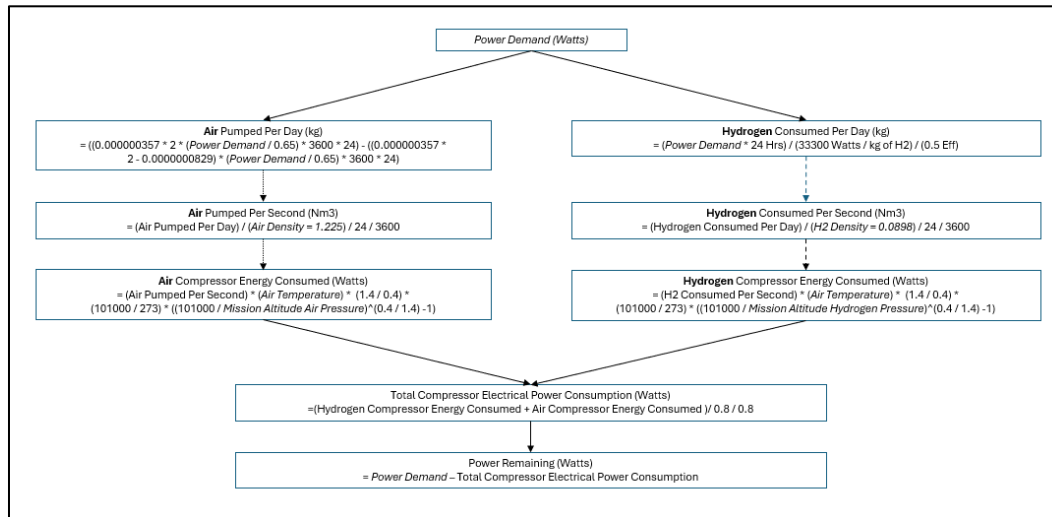


Figure 96: Sequential Compressors Calculations

Finally, a key assumption has been the airship will float along with the counter-clockwise winds present in the stratosphere and thus would not require constant use of its propulsor motors. Therefore, the calculated electrical power demand was divided in half to more accurately reflect this “reduced operation” concept. As a result, traveling at 20 m/s but actually employing the motors less often now resulted in an adjusted power demand of 11.7 kW. And since both compressors only consume 459 Watts, the remaining 22.9 kW is more than sufficient to power the 8.0 kW needed for the remaining payloads and airship equipment.

These complicated calculations were incorporated into the “Airship Power Production” spreadsheet (see Table 33) forming the eleventh CA block in the DSM (see Figure 97).

Table 33: Power Production Parameters

11 - Airship Power Production CA	Inputs	Output
(4. Envelope Volume+ (m3)	24,544	
(6. Mission Altitude+ (m)	12,000	
(63. Calculated Electrical Power Demand+ (W)	23,336	
64. Adjusted Power Demand (W) (reduced operation)		11,668
(7. Mission Altitude - Air Pressure+ (Pa)	19,284	
65. Air Pumped Per Day (kg)		129
66. Air Pumped Per Second (Nm3)		0.001240
67. Air Compressor Energy Consumed (W)		210
(10. Mission Attitude - Hydrogen Pressure+ (Pa)	64,284	
68. Hydrogen Consumed Per Day+ (kg)		16.8
69. Hydrogen Consumed Per Second (Nm3)		0.002168
70. Hydrogen Compressor Energy Consumed (W)		84
71. Total Compressor Power Consumed (W)		459
72. Remaining Airship Power (W)		22,876

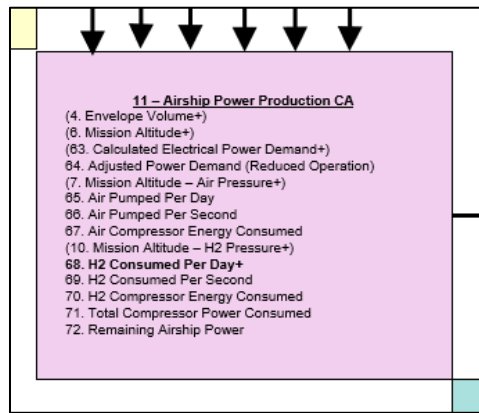


Figure 97: Airship Power Production CA Block

4.4.13 Radar Detection Parameters

Having previously examined the Radar Range Equation in Chapter II, specific power parameters for the proposed radar were now developed (see Table 34).

Table 34: Proposed Radar Range Equation Parameters

INPUTS				CONVERTED VALUES	
Peak Power	$P_t =$	1,400	kilowatts	1.40E+06	watts
Transmit Gain	$G_t =$	33	dB	1,995	linear
Receive Gain	$G_r =$	33	dB	1,995	linear
Frequency Wavelength	$\lambda =$	0.0375	meters		
	$\lambda^2 =$			0.0014	meters ²
Radar Cross Section	$\sigma =$	125	meters ²	125	meters ²
Radiation Area	$(4\pi)^3$	1984	---	1984	---
Range to Target	$R =$	250	miles	402,250	meters
	$R^4 =$			2.62E+22	meters ⁴
Boltzmann's Constant	$k =$	1.38E-23	watts/Hz-K	1.38E-23	watts/Hz-K
Standard Temperature	$T_s =$	950	K	950	K
Receiver Bandwidth	$B_n =$	1.67	MHz	1.67E+06	Hz
Total System Losses	$L_s =$	8	dB	6.3	linear
Pulse SNR =				0.13653863	dB
Minimum Pulses per Dwell	$\eta_p =$	150	pulses	20.5	dB
Dwell SNR =				13.1	dB

From Section 2.8.1, when operating an X-band radar (8 GHz) transmitting 150 pulses per dwell period, the total linear radar SNR equaled [99]:

$$\text{SNR}_{\text{TOTAL(LIN)}} = (150) (0.136) = 20.4 \quad (49)$$

Converting total linear SNR back into decibels:

$$\text{SNR}_{\text{TOTAL(dB)}} = 10\log_{10} (20.4) = 13.1 \text{ dB} \quad (50)$$

This signal strength should be sufficient to detect bomber-sized aircraft at 250 miles.

4.4.14 Mission Duration Parameters

This final Excel spreadsheet captures the concluding values and estimates the mission duration and radar range obtained at the designated mission altitude.

As a simplistic estimate, it first divides the hydrogen mass remaining (once the airship has achieved the mission altitude) by the previously calculated daily hydrogen consumption rate. Understanding this was a general estimate, it then multiplies that derived value times 0.50 to establish an approximated number of days duration.

Finally, it also calculates the radar detection range based upon the mission altitude and the equation previously introduced in Section 1.2.

Using this approach, the mission duration was calculated to be 31 days (which does not meet the NORAD 60-day derived requirement.)

These computations were then inserted into the “Mission Duration” spreadsheet (see Table 35) forming the twelfth and final CA block in the DSM (see Figure 98).

Table 35: Mission Duration Parameters

12 - Mission Duration CA	Inputs	Output
(56. Mission Altitude - Useful Lift+) (kg)	6,399	
(50. Maximum Takeoff Mass+) (kg)	3,930	
(57. Lift Check (Mass Difference+)	2,469	
(51. Mission Altitude - H2 Mass Remaining+) (kg)	1,445	
(68. Hydrogen Consumed Per Day+) (kg)	23.1	
73. Estimated Mission Duration (days) (based on hydrogen supply)		31
(6. Mission Altitude+) (m)	10,000	
74. Target Aircraft Altitude (feet)	2,000	
75. Radar Detection Range (miles)		275

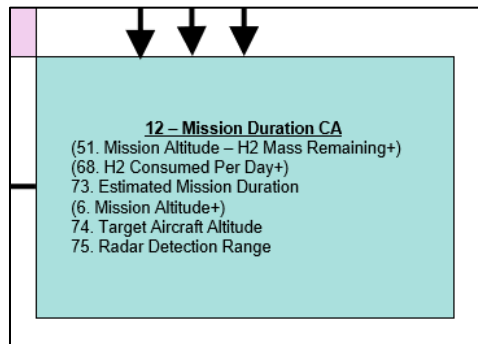


Figure 98: Mission Duration Parameters

Need for Optimization Modeling. While the airship example used throughout this discussion was helpful in demonstrating the numerous CA block elements involved in the system designing process, it actually did not produce a successful design.

Apparently, randomly choosing the 75-meter length, the 12,000 meters altitude, traveling at 20 m/s, using 75% hydrogen at 45000 Pascals, etc., were incorrect values. So, how does one determine the correct values to use to actually improve design performance?

Answer: Using specialized design optimization modeling software will resolve this problem, and is introduced in the next section.

4.5. Design Optimization

4.5.1 Optimization Approach

Design Structure Matrix (DSM). As previously shown, each CA block contains a custom Excel spreadsheet with inputs, calculations, and outputs tailored to their specific design parameters and used to model the altitude and operational sensitivities of each airship design. These CA blocks were then interconnected to form the DSM for this project (see Figure 99).

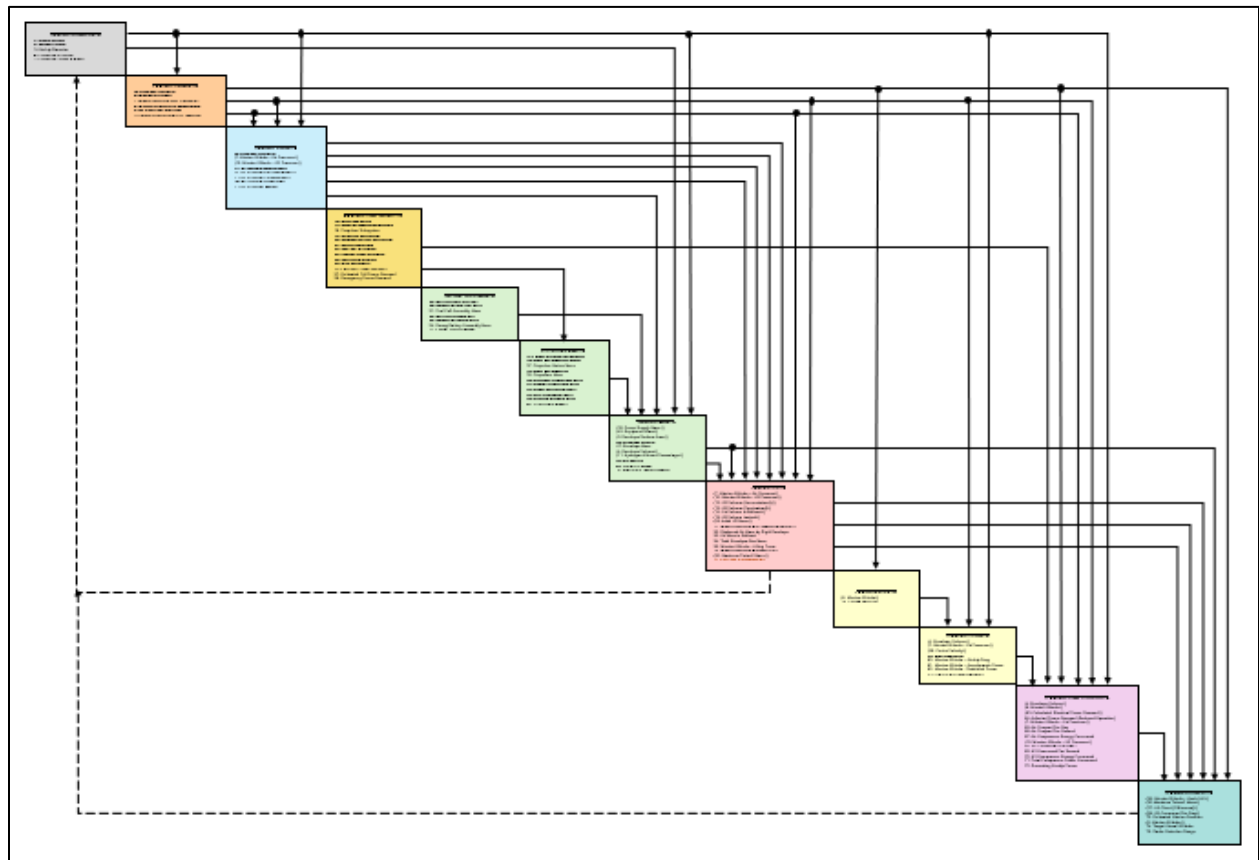


Figure 99: Project Design Structure Matrix (DSM)

Optimization Software. The commercial ModelCenter® Optimizing Tool is a special application that connects to the DSM model and uses appropriate Objective, Constraint, and Design Variable parameters from the main Project Component Tree. Lines running from the Optimizing Tool up to various CA blocks indicate these control connections (see Figure 100).

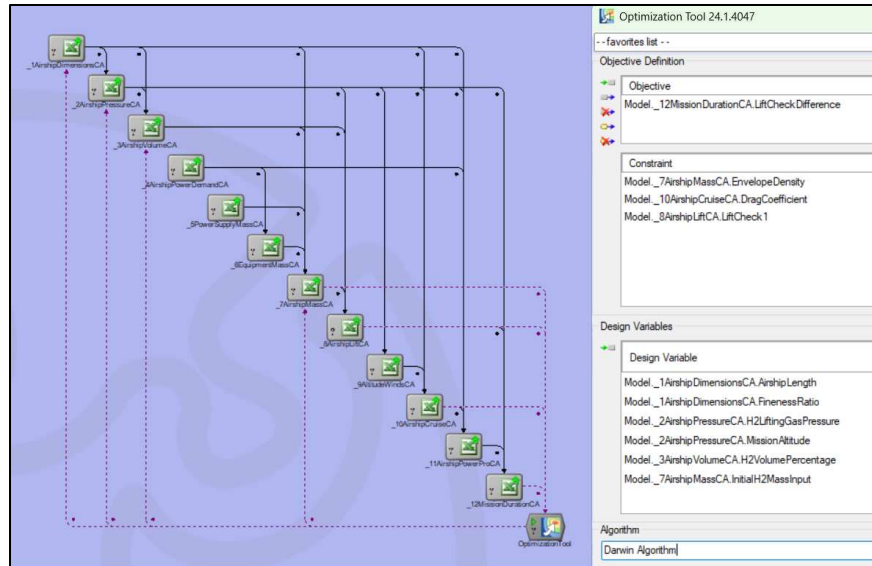


Figure 100: ModelCenter® Optimization Tool (Example) [122]

Parameter data is then optimized using the “Darwin Algorithm,” a genetic search algorithm developed specifically for solving engineering optimization problems [143]. It selects the worst design from the child population and replaces it with the best design from the parent population.

During each simulation run the optimizer produces thousands of random values, eventually determining the best combination of values producing the best results (see Figure 101).

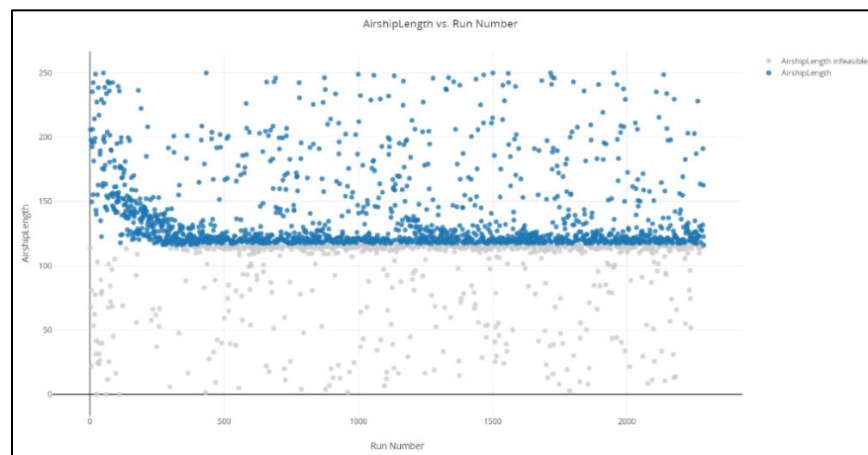


Figure 101: ModelCenter® Optimization Tool Scatter Plot (Example) [122]

Automating the Duration Calculation. The reason the airship remains aloft is the generated “Useful Lift” by the hydrogen exceeds its “Maximum Takeoff Mass” (discussed in Section 4.4.9.)

However, as the hydrogen in the envelope is rapidly being consumed by the compressors, not only is the airship’s total mass decreasing, the Useful Lift produced by the remaining hydrogen also is decreasing – and at a faster pace. As a result, at some equilibrium point, the airship will no longer have sufficient hydrogen to generate lift (although it will still have a significant amount of hydrogen still remaining in its envelope.) Thus, duration is not dependent upon how much hydrogen remains, but rather the remaining Useful Lift being generated by that hydrogen.

Thus, a mathematical approach was needed to enable the ModelCenter® Optimization Tool to maximize the days aloft. This was accomplished by repeatedly calculating the numerical difference between the airship’s initial “Maximum Takeoff Mass” and the changing “Useful Lift” mass that was continuously decreased over time as the hydrogen was being consumed. The software was then instructed to maximize this numerical difference as it tested thousands of modeling combinations.

The result: the greater the *numerical difference* between those two mass values, the greater the *physical distance* occurring on the “Altitude & Operations Sensitivity Calculator” spreadsheet [139], and thus the greater number of days spent aloft (see Table 36.) (This specialized calculator spreadsheet is explained in greater detail later in Section 4.5.6.)

Table 36: Airship Duration Calculation (Example)

	Airship Pressure Calculations					Airship Volume Calculations					Airship Lift Calculations							
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	
	Mission Altitude (m)	Mission Altitude Air Pressure (Pa)	Mission Altitude Air Temperature (K)	Total Airship Volume m3	Mission Altitude Hydrogen Pressure (Pa)	Hydrogen Volume Percentage at Takeoff	Hydrogen Volume (Unconstrained) (m3)	Hydrogen Volume (Constrained) (m3)	Air Volume in Ballonet (m3)	Hydrogen Volume Leaked (m3)	Initial Hydrogen Mass (kg)	Hydrogen Mass Remaining (kg)	Displaced Air Mass by Rigid Envelope (kg)	Air Mass in Ballonet (kg)	Total Envelope Gas Mass (kg)	Lifting Force (N)	Useful Lift (kg)	
18																		
Day	12000	19284	216.65	24544	64284	0.7500	29015	24544	0	4471	1653	1398	5722	0	1398	42416	4324	
0		19284	216.65	24544	64284	0	29015	24544		4471	1398	1398	5722	0	1398	42416	4324	
1		19284	216.65	24544	64284	0	29015	23954		4471	1398	1365	5722	135	1500	42416	4223	
2		19284	216.65	24544	64284	0	29015	23363		4471	1398	1331	5722	270	1601	42416	4121	
3		19284	216.65	24544	64284	0	29015	22773		4471	1398	1297	5722	405	1702	42416	4020	
4		19284	216.65	24544	64284	0	29015	22182		4471	1398	1264	5722	539	1803	42416	3919	
5		19284	216.65	24544	64284	0	29015	21592		4471	1398	1230	5722	674	1904	42416	3818	
6		19284	216.65	24544	64284	0	29015	21001		4471	1398	1196	5722	809	2006	42416	3717	
7		19284	216.65	24544	64284	0	29015	20411		4471	1398	1163	5722	944	2107	42416	3615	
8		19284	216.65	24544	64284	0	29015	19821		4471	1398	1129	5722	1079	2208	42416	3514	
9		19284	216.65	24544	64284	0	29015	19230		4471	1398	1096	5722	1214	2309	42416	3413	
10		19284	216.65	24544	64284	0	29015	18640		4471	1398	1062	5722	1348	2410	42416	3312	
11		19284	216.65	24544	64284	0	29015	18049		4471	1398	1028	5722	1483	2512	42416	3211	
12		19284	216.65	24544	64284	0	29015	17459		4471	1398	995	5722	1618	2613	42416	3109	
13		19284	216.65	24544	64284	0	29015	16869		4471	1398	961	5722	1753	2714	42416	3008	
14		19284	216.65	24544	64284	0	29015	16278		4471	1398	927	5722	1888	2815	42416	2907	
15		19284	216.65	24544	64284	0	29015	15688		4471	1398	894	5722	2023	2916	42416	2806	
16		19284	216.65	24544	64284	0	29015	15097		4471	1398	860	5722	2157	3018	42416	2705	
17		19284	216.65	24544	64284	0	29015	14507		4471	1398	826	5722	2292	3119	42416	2603	
18		19284	216.65	24544	64284	0	29015	13916		4471	1398	793	5722	2427	3220	42416	2502	
19		19284	216.65	24544	64284	0	29015	13326		4471	1398	759	5722	2562	3321	42416	2401	
20		19284	216.65	24544	64284	0	29015	12736		4471	1398	726	5722	2697	3422	42416	2300	
21		19284	216.65	24544	64284	0	29015	12145		4471	1398	692	5722	2832	3524	42416	2199	
22		19284	216.65	24544	64284	0	29015	11555		4471	1398	658	5722	2966	3625	42416	2097	
23		19284	216.65	24544	64284	0	29015	10964		4471	1398	625	5722	3101	3726	42416	1996	
24		19284	216.65	24544	64284	0	29015	10374		4471	1398	591	5722	3236	3827	42416	1895	
25		19284	216.65	24544	64284	0	29015	9783		4471	1398	557	5722	3371	3928	42416	1794	
26		19284	216.65	24544	64284	0	29015	9193		4471	1398	524	5722	3506	4030	42416	1693	
27		19284	216.65	24544	64284	0	29015	8603		4471	1398	490	5722	3641	4131	42416	1591	
28		19284	216.65	24544	64284	0	29015	8012		4471	1398	456	5722	3776	4232	42416	1490	
29		19284	216.65	24544	64284	0	29015	7422		4471	1398	423	5722	3910	4333	42416	1389	
30		19284	216.65	24544	64284	0	29015	6831		4471	1398	389	5722	4045	4434	42416	1288	
31		19284	216.65	24544	64284	0	29015	6241		4471	1398	356	5722	4180	4536	42416	1187	
32		19284	216.65	24544	64284	0	29015	5651		4471	1398	322	5722	4315	4637	42416	1085	
33		19284	216.65	24544	64284	0	29015	5060		4471	1398	288	5722	4450	4738	42416	984	
34		19284	216.65	24544	64284	0	29015	4470		4471	1398	255	5722	4585	4839	42416	883	
35		19284	216.65	24544	64284	0	29015	3879		4471	1398	221	5722	4719	4940	42416	782	
36		19284	216.65	24544	64284	0	29015	3289		4471	1398	187	5722	4854	5042	42416	681	
37		19284	216.65	24544	64284	0	29015	2698		4471	1398	154	5722	4989	5143	42416	579	
38		19284	216.65	24544	64284	0	29015	2108		4471	1398	120	5722	5124	5244	42416	478	
39		19284	216.65	24544	64284	0	29015	1518		4471	1398	86	5722	5259	5345	42416	377	
40		19284	216.65	24544	64284	0	29015	927		4471	1398	53	5722	5394	5446	42416	276	
41		19284	216.65	24544	64284	0	29015	337		4471	1398	19	5722	5528	5548	42416	174	

Key Modeling Parameters and Values. Reviewing all of the available design parameters

identified in the DSM, seven key modeling parameters were selected for modeling (see Table 37).

Table 37: Key Modeling Parameters and Values

Lift Check Difference:	$M(x) = \text{Useful Lift (kg)} - \text{Maximum Takeoff Mass (kg)}$
Objective:	$f_{\text{OBJ}}(x) = \text{Maximize } M(x)$
Constraints:	$x_1 = 0.113$ (latest technology envelope material)
	$x_2 = 0.02$ (standard airship drag coefficient)
Design Variables:	$1 \text{ meter} < x_3 \text{ (airship length)} < 200 \text{ meters}$
	$3 < x_4 \text{ (fineness ratio for best maneuverability)} < 6$
	$10,000 \text{ meters} < x_5 \text{ (mission altitude)} < 21,000 \text{ meters}$
	$0.60 < x_6 \text{ (hydrogen percentage)} < 0.75$
	$40,000 \text{ Pa} < x_7 \text{ (hydrogen pressure)} < 50,000 \text{ Pa}$

Using the ModelCenter® Optimization Tool will help determine the optimum values for each of these key design parameters that were unsuccessfully estimated in Section 4.4.

4.5.2 Design Study 1

For this initial modeling effort, numerous simulations were conducted to establish a baseline understanding of optimum airship lengths (and hence gas envelope volumes) needed to reach increasingly higher altitudes. No requirement was levied to remain airborne for any specific mission duration period.

Modeling Results. See Figure 102 and Table 38.

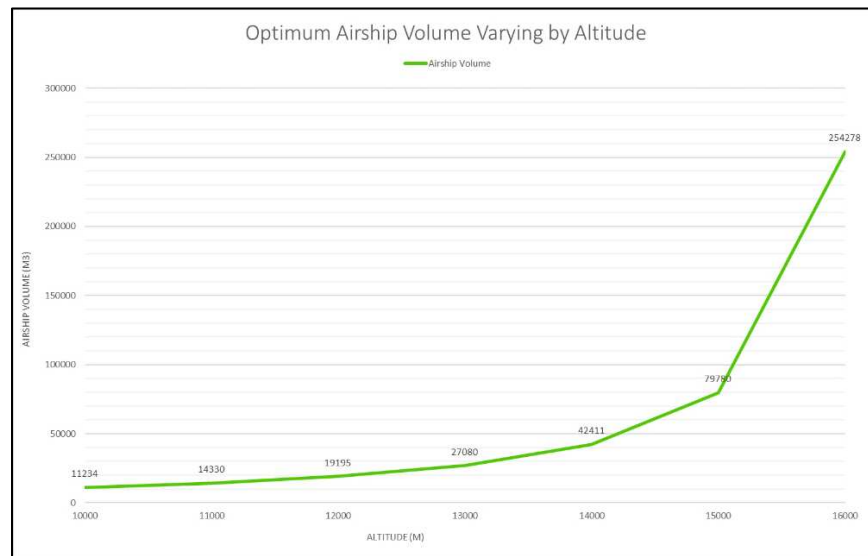


Figure 102: Optimum Airship Volumes Varying By Altitude – Design Study 1

Table 38: Design Study 1 Optimum Results

Altitude (m)	Length (m)	Volume (m ³)	H ₂ Percentage	Mass (kg)	Lift (kg)	Cycles	Run Time
10,000	57.8	11,234	0.65	2,899	2,904	5,929	2:16
11,000	62.7	14,300	0.62	3,104	3,128	8,038	3:01
12,000	69.1	19,195	0.62	3,464	3,467	7,354	2:44
13,000	77.5	27,080	0.60	3,984	4,000	5,758	2:10
14,000	90.0	42,411	0.60	5,031	5,047	5,929	2:13
15,000	111.1	79,780	0.60	7,493	7,503	7,468	2:48
16,000	163.5	254,278	0.60	18,415	18,426	7,696	3:26

Modeling Analysis. Seven simulation modeling runs were successfully accomplished, each lasting 2 to 3 hours. The results were then plotted and observed for trends (see Figure 102).

First, to reach ever-increasing altitudes, the airship's gas envelope volume needed to continuously grow in order to contain greater amounts of hydrogen to generate the required lift.

Second, at 16,000 meters, the required envelope volume (hence the airship's length) suddenly increased dramatically due to the very thin atmosphere now being confronted at that very high altitude. While the simulation model was successful in attaining this altitude, the airship's length was now nearly three times its original size.

The next modeling design study further explored higher altitudes and volume expansion.

4.5.3 Design Study 2

Modeling Results. By manually stepping through six sequential optimization efforts up to 16,500 meters, Table 39 illustrates how unreasonably large the airship's length eventually became.

Table 39: Design Study 2 Optimum Results

Altitude (m)	Length (m)	Volume (m ³)	H ₂ Percentage	Mass (kg)	Lift (kg)
16,000	163	251,952	0.65	2,899	2,904
16,100	169	280,812	0.62	3,104	3,128
16,200	181	344,978	0.62	3,464	3,467
16,300	197	444,789	0.60	3,984	4,000
16,400	217	594,477	0.60	5,031	5,047
16,500	246*	866,086	0.60	7,493	7,503

(*Note: The massive Hindenburg airship, the largest airship ever built, measured 245 meters [47].)

Modeling Analysis. As an envelope progressively grew to hold more hydrogen, the mass of the envelope itself increasingly grew, as well. Eventually, the overall mass of the airship became heavier than any amount of useful lift the massive envelope could possibly generate. Even when using a super lightweight envelope material measuring 0.113 kg/m² [42], the optimizing model was unable to produce any successful design capable of achieving 17,000 meters.

4.5.4 Design Study 3

Given this baseline understanding, during the third design study, the airship length was set to 75 meters and the windspeed to 20 m/s, as previously used. But now, the remaining five design factors were to be determined by the ModelCenter® Optimization Tool.

Modeling Results. See Figures 103 through 106.

The screenshot displays the 'Optimization Tool 24.1.4047 - Model.OptimizationTool' window. It is configured for an optimization study with the following settings:

- Objective Definition:** A single objective is defined: 'Model._12MissionDurationCA.LiftCheckDifference' with a value of 2469.04, a weight of 1, and a goal to 'maximize'.
- Constraint:** Four constraints are listed:
 - 'Model._7AirshipMassCA.EnvelopeDensity' with a value of 0.113, lower bound of 0.113, and upper bound of 0.113.
 - 'Model._10AirshipCruiseCA.DragCoefficient' with a value of 0.02, lower bound of 0.02, and upper bound of 0.02.
 - 'Model._8AirshipLiftCA.LiftCheck1' with a value of 1, lower bound of 1, and upper bound of 1.
 - 'Model._1AirshipDimensionsCA.AirshipLength' with a value of 75, lower bound of 75, and upper bound of 75.
- Design Variables:** Four design variables are defined:
 - 'Model._1AirshipDimensionsCA.FinnessRatio' (continuous) with a value of 3, start value of 3, lower bound of 3, and upper bound of 6.
 - 'Model._2AirshipPressureCA.H2LiftingGasPressure' (continuous) with a value of 40000, start value of 40000, lower bound of 40000, and upper bound of 50000.
 - 'Model._2AirshipPressureCA.MissionAltitude' (continuous) with a value of 10000, start value of 10000, lower bound of 10000, and upper bound of 21000.
 - 'Model._3AirshipVolumeCA.H2VolumePercentage' (continuous) with a value of 0.6558, start value of 0.75, lower bound of 0.6, and upper bound of 0.75.
- Algorithm:** The 'Darwin Algorithm' is selected.
- Status:** The 'Elapsed Time' is 01:26:38.

Figure 103: ModelCenter® Optimization Tool Settings – Design Study 3

Table - Trade Study 1 - Data Explorer

File

Chart

Help

Add View
 Finder
 Plug-Ins

Legend:

input

valid output

invalid output

modified value

AUTO SCROLL	4641	4642	4643	4644	4645
objective(Model. 12MissionDurationCA.LiftCheckDifference)	-2986.43	2454.39	2465.28	2348.34	2469.04
constraint(Model. 7AirshipMassCA.EnvelopeDensity)	0.113	0.113	0.113	0.113	0.113
constraint(Model. 10AirshipCruiseCA.DragCoefficient)	0.02	0.02	0.02	0.02	0.02
constraint(Model. 8AirshipLiftCA.LiftCheck1)	0	1	1	1	1
constraint(Model. 1AirshipDimensionsCA.AirshipLength)	75	75	75	75	75
design variable(Model. 1AirshipDimensionsCA.FinenessRatio)	3	3	3.001	3	3
design variable(Model. 2AirshipPressureCA.H2LiftingGasPressure)	49400	40000	40010	40000	40000
design variable(Model. 2AirshipPressureCA.MissionAltitude)	17440	10010	10000	10110	10000
design variable(Model. 3AirshipVolumeCA.H2VolumePercentage)	0.6536	0.6574	0.656	0.6554	0.6558

Figure 104: ModelCenter® Optimization Tool Simulation Runs – Design Study 3

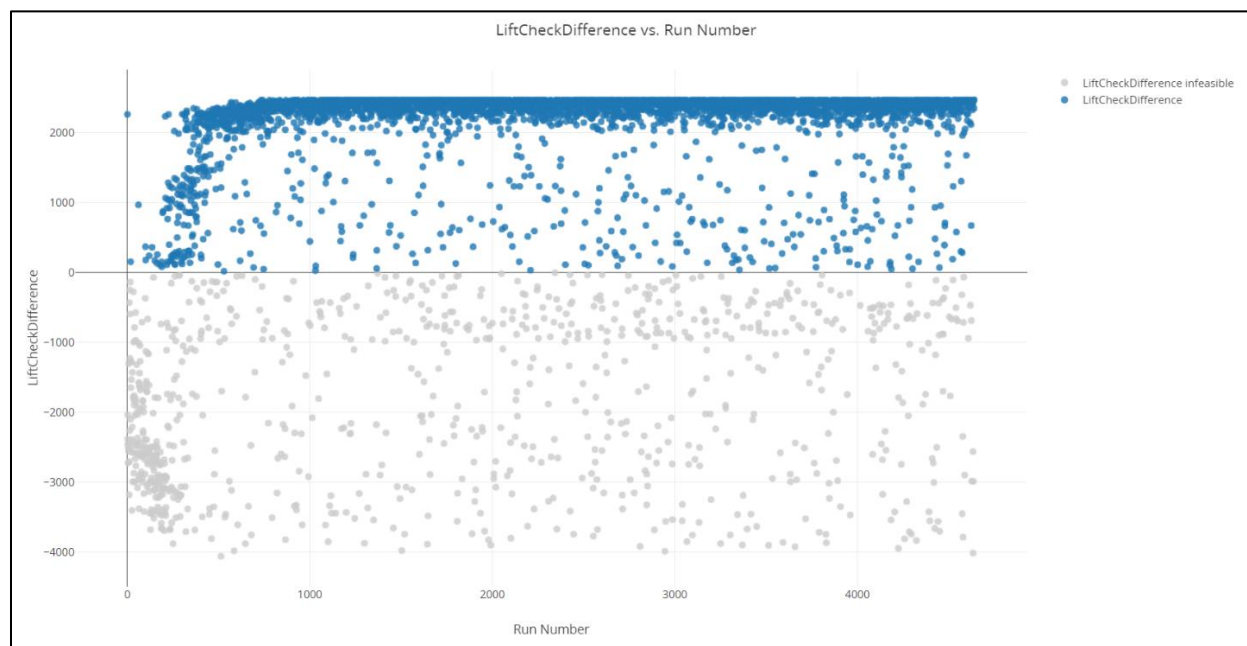


Figure 105: ModelCenter® Optimization Tool Scatter Plot – Design Study 3

Component Tree	
Name	Value
Model	
_1AirshipDimensionsCA	
_2AirshipPressureCA	
EnvelopeVolume	24543.7
MissionAltitude	10000
H2LiftingGasPressure	40000
MissionAltitudeOut	10000
MissionAltitudeAirPressure	26436.2
MissionAltitudeH2Pressure	66436.2
_3AirshipVolumeCA	
_4AirshipPowerDemandCA	
_5PowerSupplyMassCA	
_6EquipmentMassCA	
_7AirshipMassCA	
_8AirshipLiftCA	
_9AltitudeWindsCA	
Altitude	10000
Velocity	20
_10AirshipCruiseCA	
_11AirshipPowerProCA	
_12MissionDurationCA	
MissionAltitudeUsefullLift	6399.26
MaximumTakeoffMass	3930.22
LiftCheckDifference	2469.04
H2ConsumedPerDay	46.1126
EstimatedMissionDurationDays	30.3
TargetAirshipAltitudeDefect	2000
MissionAltitudeMeters	10000
RadarDetectionRangeMiles	274.986
OptimizationTool	

Figure 106: ModelCenter® Optimization Tool Results – Design Study 3

Modeling Analysis. Overall, modeling results demonstrated an airship measuring 75 meters had sufficient lift to reach the lowest stratospheric altitude of 10,000 meters, but the total mission duration still only lasted 30 days (similar to the manually calculated duration in Section 4.4).

It appeared the airship had an insufficient supply of hydrogen. This generated two areas of investigation:

1. Perhaps the airship's length (volume) needed to be increased to hold more hydrogen?
2. Perhaps the continuous windspeed velocity of 20 m/s was incorrect, therefore the model was generating higher airship drag and thus consuming more hydrogen than was realistic?

The next modeling design study would test these observations.

4.5.5 Design Study 4

First, during this fourth design study, the airship’s original length was maintained at the original 75 meters in order to adjust and observe the other design variable.

Then, actual National Weather Service meteorological windspeed data was collected for the northernmost city of Barrow, Alaska [144]. After accessing over 4,500 windspeed readings taken every six hours during 2025, it was determined the average windspeed at 34,000 ft (10,400 meters) actually measured 30 knots (i.e., 16 m/s) versus the 20 m/s formerly used..

As a result, a new “Altitude Winds” parameter was now added as third design constraints:

Constraint: $x_8 = 16$ m/s (average wind velocity) (see Figure 107.)

Modeling Results. See Figures 107 through 110.

Objective Definition

Objective	Value	Weight	Goal
Model_8AirshipLiftCA.LiftCheckDifference	2469.04	1	maximize

Constraint

Constraint	Value	Lower Bound	Upper Bound
Model_7AirshipMassCA.EnvelopeDensity	0.113	0.113	0.113
Model_10AirshipCruiseCA.DragCoefficient	0.02	0.02	0.02
Model_8AirshipLiftCA.LiftCheck1	1	1	1
Model_1AirshipDimensionsCA.AirshipLength	75	75	75
Model_9AltitudeWindsCA.Velocity	16	16	16

Design Variables

Design Variable	Type	Value	Start Value (Explicit value)	Lower Bound	Upper Bound	Edit
Model_1AirshipDimensionsCA.FinenessRatio	continuous	3	3	3	6	...
Model_2AirshipPressureCA.H2LiftingGasPressure	continuous	40000	45000	40000	50000	...
Model_2AirshipPressureCA.MissionAltitude	continuous	10000	10000	10000	21000	...
Model_3AirshipVolumeCA.H2VolumePercentage	continuous	0.6558	0.75	0.6	0.75	...

Algorithm

Darwin Algorithm Choose...

Status

Elapsed Time: 01:33:13 View Output...

Figure 107: ModelCenter® Optimization Tool Settings – Scenario 4

Table - Trade Study 1 - Data Explorer

File

Chart

Help

Add View

Finder

Plug-Ins

Legend:

input

valid output

invalid output

modified value

AUTO SCROLL	5019	5020	5021	5022	5023
objective(Model. 8AirshipLiftCA.LiftCheckDifference)	2348.04	2423.11	2451.2	2409.17	2469.04
constraint(Model. 7AirshipMassCA.EnvelopeDensity)	0.113	0.113	0.113	0.113	0.113
constraint(Model. 10AirshipCruiseCA.DragCoefficient)	0.02	0.02	0.02	0.02	0.02
constraint(Model. 8AirshipLiftCA.LiftCheck1)	1	1	1	1	1
constraint(Model. 1AirshipDimensionsCA.AirshipLength)	75	75	75	75	75
constraint(Model. 9AltitudeWindsCA.Velocity)	16	16	16	16	16
design variable(Model. 1AirshipDimensionsCA.FinenessRatio)	3	3.01	3	3	3
design variable(Model. 2AirshipPressureCA.H2LiftingGasPressure)	40010	40030	40020	40040	40000
design variable(Model. 2AirshipPressureCA.MissionAltitude)	10000	10000	10000	10050	10000
design variable(Model. 3AirshipVolumeCA.H2VolumePercentage)	0.7106	0.6541	0.6637	0.6574	0.6558

Figure 108: ModelCenter® Optimization Tool Simulation Runs – Design Study 4

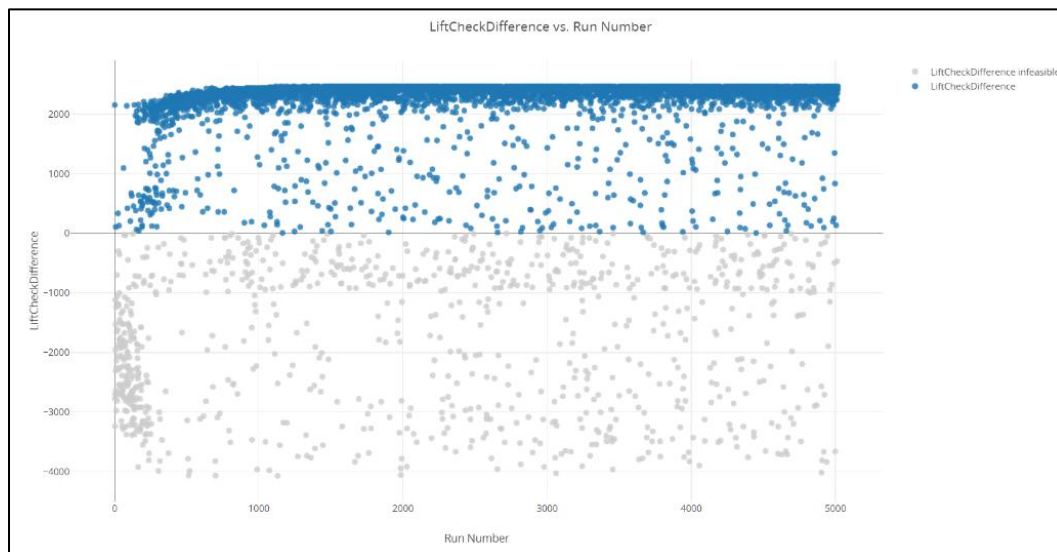


Figure 109: ModelCenter® Optimization Tool 2D Scatter Plot – Design Study 4

Component Tree	
Name	Value
Model	
_1AirshipDimensionsCA	
AirshipLength	75
FinenessRatio	3
AirshipDiameter	25
EnvelopeVolume	24543.7
EnvelopeSurfaceArea	4584.98
_2AirshipPressureCA	
EnvelopeVolume	24543.7
MissionAltitude	10000
H2LiftingGasPressure	40000
MissionAltitudeOut	10000
MissionAltitudeAirPressure	26436.2
MissionAltitudeH2Pressure	66436.2
_3AirshipVolumeCA	
_4AirshipPowerDemandCA	
_5PowerSupplyMassCA	
_6EquipmentMassCA	
_7AirshipMassCA	
_8AirshipLiftCA	
_9AltitudeWindsCA	
Altitude	10000
Velocity	16
_10AirshipCruiseCA	
_11AirshipPowerProCA	
_12MissionDurationCA	
MissionAltitudeH2MassRemaining	1445.12
Difference	2469.04
H2ConsumedPerDay	11.8051
EstimatedMissionDurationDays	61.2
TargetAircraftAltitudeFeet	2000
MissionAltitudeMeters	10000
RadarDetectionRangeMiles	274.986
OptimizationTool	

Figure 110: ModelCenter® Optimization Tool Results – Design Study 4

Modeling Results. Success! Optimized modeling results demonstrated a 75-meter airship now operating against 16 m/s crosswinds was capable of remaining aloft at 10,000 meters altitude for 61 days. A summary of the optimization results is provided on Table 40.

Table 40: ModelCenter® Optimization Tool Results – Scenario 4

Elapsed Time	1:33 hrs
Simulation Cycles	5,023
*Envelope Material (Constraint)	0.113 kg/m ²
*Drag Coefficient (Constraint)	0.02
*Airship Length (Constraint)	75 meters
*Cruise Velocity (Constraint)	16 meters / second (36 mph)
*Fineness Ratio	3
Volume	24,545 m ³
*Mission Altitude	10,000 meters
*Envelope Hydrogen Pressure	40,000 Pa
*Envelope Hydrogen Percentage	0.6558
Useful Lift	6,400 kg
Maximum Takeoff Mass	3,930 kg
Total Power Demand (Reduced Operations)	8.19 kW
Daily Hydrogen Consumption (Reduced Operations)	11.8 kg
Estimated Mission Duration	61 days
Target Altitude	2,000 feet
Radar Detection Range	274 miles
(*Key Modeling Parameters)	

4.5.6 Results Validation

Having produced what appears to be an optimized solution using the ModelCenter® software, these results were then validated manually. This was accomplished using the specialized “Altitude & Operations Sensitivity Calculator,” briefly introduced in Section 4.5.1 [139].

Constructed using an integrated Excel spreadsheet, this innovative calculator implemented all of the complicated air and hydrogen pressures, volumes, masses, and force calculations previously outlined in Sections 4.4.8 through 4.4.12.

Altitude Sensitivity. First, the optimized mission altitude of 10,000 meters was selected. Next, the 75-meter airship’s gas envelope volume measuring 24,545 m³ was inserted, filled with hydrogen now to 65.68 percent, and pressurized to 40000 Pascal for takeoff (see Table 41).

Table 41: Altitude Sensitivity Calculations (Part 1)

			40000						
Airship Pressure Calcs					Airship Volume Calcs				
A	B	C	D	E	F	G	H	I	J
Mission Altitude (m)	Mission Altitude Air Pressure (Pa)	Atm Air Temperature (K)	Total Airship Volume (m3)	Hydrogen Pressure (Pa)	Hydrogen Volume Percentage at Takeoff	Hydrogen Volume (unconstrained) (m3)	Hydrogen Volume (constrained) (m3)	Air Volume in Ballonet (m3)	Hydrogen Volume Leaked (m3)
0	101325	288.15 (15 C)	24545	101325	0.6558	16097	16097	8448	0
1000	89875	281.65	24545	101325		16097	16097	8448	0
2000	79495	275.15	24545	101325		16097	16097	8448	0
3000	70109	268.65	24545	101325		16097	16097	8448	0
4000	61640	262.15	24545	101325		16097	16097	8448	0
5000	54020	255.65	24545	94020		17347	17347	7198	0
6000	47181	249.15	24545	87181		18708	18708	5837	0
7000	41061	242.65	24545	81061		20121	20121	4424	0
8000	35600	236.15	24545	75600		21574	21574	2971	0
9000	30742	229.65	24545	70742		23055	23055	1490	0
10000	26436	216.65	24545	66436		24550	24545	0	5
11000	22632	216.65	24545	62632		26041	24545	0	1496

Following Archimede's Principle, the displaced air mass caused by the airship's envelope produced a Useful Lift of 6,399 kg, capable of lofting the 3,930 kg airship (see Table 42).

Table 42: Altitude Sensitivity Calculations (Part 2)

Airship Lift Calcs						
K	L	M	N	O	P	Q
Initial Hydrogen Mass (kg)	Hydrogen Mass Remaining (kg)	Displaced Air Mass by Rigid Envelope (kg)	Air Mass in Ballonet (kg)	Total Envelope Gas Mass (kg)	Lifting Force (N)	Useful Lift (kg)
1445	1445	30066	10349	11794	179250	18272
	1445	26669	9179	10625	157391	16044
	1445	23589	8119	9565	137577	14024
	1445	20803	7161	8606	119657	12197
	1445	18291	6296	7741	103491	10550
	1445	16029	4701	6146	96957	9883
	1445	14000	3329	4775	90501	9225
	1445	12184	2196	3642	83801	8542
	1445	10564	1279	2724	76906	7840
	1445	9122	554	1999	69879	7123
	1445	7844	0	1445	62778	6399

Operational Sensitivity. Now the focus shifted to examining the “operational sensitivity” of the airship’s cruising and power parameters and their effect on mission duration.

Setting the airship velocity to 16 m/s and dividing the cruise power demand by two (implementing the “reduced operations” concept), the amount of hydrogen consumed per day was now just 11.8 kg (see Table 43).

Table 43: Hydrogen Consumption Calculations (Reduced Operations)

Airship Cruise Calculations						Airship Power Calculations				
R	S	T	U	V	W	Y	Z	AA	AB	AC
Cruise Velocity [m/s]	Airship Drag Coeff	Airship Drag (N)	Aero Power Required at Cruise [W]	Rotational Power Required at Cruise [W]	Electrical Power Required at Cruise (W)	Power Demand (Welec)	Air Pumped Per Day (kg) @ Stoich of 2	Air Pumped Per Sec (Nm3)	Air Compressor Energy Consumed (W)	Hydrogen Consumed Per Day (kg) @ 50% eff
16	0.02	691	11056	14742	16380					
				Reduced Operations	8190	8190	90.25	0.00087	114	11.8

As a result, over a 60-day period, a total of 708 kg of hydrogen would have been consumed, eventually reducing the airship’s initial mass of 3,930 kg down to 3,222 kg by “End of Mission.”

As the hydrogen was being consumed, the airship’s Useful Lift was rapidly decreasing. Again, “Mission Duration” is that point where the Useful Lift mass roughly equals the airship’s “End of Mission” mass. At that point, there would no longer be sufficient lift to maintain the airship at the desired mission altitude, and the airship would begin to slowly descend each day.

By physical inspection, airship Useful Lift was maintained until Day 62 (see Table 44). This confirmed the ModelCenter® duration calculation of 61 days proved to be very accurate.

Table 44: Design Study 4 Validation

	40000																
	Airship Pressure Calculations					Airship Volume Calculations					Airship Lift Calculations						
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
	Mission Altitude (m)	Mission Altitude Air Pressure (Pa)	Mission Altitude Air Temperature (K)	Total Airship Volume m3	Mission Altitude Hydrogen Pressure (Pa)	Hydrogen Volume Percentage at Takeoff	Hydrogen Volume (Unconstrained) (m3)	Hydrogen Volume (Constrained) (m3)	Air Volume in Ballonet (m3)	Hydrogen Volume Leaked (m3)	Initial Hydrogen Mass (kg)	Hydrogen Mass Remaining (kg)	Displaced Air Mass by Rigid Envelope (kg)	Air Mass in Ballonet (kg)	Total Envelope Gas Mass (kg)	Lifting Force (N)	Useful Lift (kg)
16	Day	10000	216.65	24544	66436	0.6558	24549	24544	0	5	1445	1445	7844	0	1445	6	6399
0		26436	216.65	24544	66436	0	24549	24544		5	1445	1445	7844	0	1445	62778	6399
1		26436	216.65	24544	66436	0	24549	24344		5	1445	1433	7844	63	1496	62778	6348
2		26436	216.65	24544	66436	0	24549	24143		5	1445	1422	7844	126	1547	62778	6297
3		26436	216.65	24544	66436	0	24549	23943		5	1445	1410	7844	188	1598	62778	6246
4		26436	216.65	24544	66436	0	24549	23742		5	1445	1398	7844	251	1649	62778	6195
5		26436	216.65	24544	66436	0	24549	23542		5	1445	1386	7844	314	1700	62778	6145
6		26436	216.65	24544	66436	0	24549	23341		5	1445	1374	7844	377	1751	62778	6094
7		26436	216.65	24544	66436	0	24549	23141		5	1445	1363	7844	439	1802	62778	6043
8		26436	216.65	24544	66436	0	24549	22940		5	1445	1351	7844	502	1853	62778	5992
9		26436	216.65	24544	66436	0	24549	22740		5	1445	1339	7844	565	1904	62778	5941
10		26436	216.65	24544	66436	0	24549	22539		5	1445	1327	7844	628	1955	62778	5890
11		26436	216.65	24544	66436	0	24549	22339		5	1445	1315	7844	691	2006	62778	5839
12		26436	216.65	24544	66436	0	24549	22138		5	1445	1303	7844	753	2057	62778	5788
13		26436	216.65	24544	66436	0	24549	21938		5	1445	1292	7844	816	2108	62778	5737
14		26436	216.65	24544	66436	0	24549	21737		5	1445	1280	7844	879	2159	62778	5686
15		26436	216.65	24544	66436	0	24549	21537		5	1445	1268	7844	942	2210	62778	5635
16		26436	216.65	24544	66436	0	24549	21336		5	1445	1256	7844	1004	2261	62778	5584
17		26436	216.65	24544	66436	0	24549	21136		5	1445	1244	7844	1067	2312	62778	5533
18		26436	216.65	24544	66436	0	24549	20935		5	1445	1233	7844	1130	2363	62778	5482
19		26436	216.65	24544	66436	0	24549	20735		5	1445	1221	7844	1193	2414	62778	5431
20		26436	216.65	24544	66436	0	24549	20534		5	1445	1209	7844	1255	2464	62778	5380
21		26436	216.65	24544	66436	0	24549	20334		5	1445	1197	7844	1318	2515	62778	5329
22		26436	216.65	24544	66436	0	24549	20133		5	1445	1185	7844	1381	2566	62778	5278
23		26436	216.65	24544	66436	0	24549	19933		5	1445	1174	7844	1444	2617	62778	5227
24		26436	216.65	24544	66436	0	24549	19732		5	1445	1162	7844	1507	2668	62778	5176
25		26436	216.65	24544	66436	0	24549	19532		5	1445	1150	7844	1569	2719	62778	5125
26		26436	216.65	24544	66436	0	24549	19331		5	1445	1138	7844	1632	2770	62778	5074
27		26436	216.65	24544	66436	0	24549	19131		5	1445	1126	7844	1695	2821	62778	5023
28		26436	216.65	24544	66436	0	24549	18930		5	1445	1115	7844	1758	2872	62778	4972
29		26436	216.65	24544	66436	0	24549	18730		5	1445	1103	7844	1820	2923	62778	4921
30		26436	216.65	24544	66436	0	24549	18529		5	1445	1091	7844	1883	2974	62778	4870
31		26436	216.65	24544	66436	0	24549	18329		5	1445	1079	7844	1946	3025	62778	4819
32		26436	216.65	24544	66436	0	24549	18128		5	1445	1067	7844	2009	3076	62778	4768
33		26436	216.65	24544	66436	0	24549	17928		5	1445	1056	7844	2072	3127	62778	4717
34		26436	216.65	24544	66436	0	24549	17727		5	1445	1044	7844	2134	3178	62778	4666
35		26436	216.65	24544	66436	0	24549	17527		5	1445	1032	7844	2197	3229	62778	4615
36		26436	216.65	24544	66436	0	24549	17326		5	1445	1020	7844	2260	3280	62778	4565
37		26436	216.65	24544	66436	0	24549	17126		5	1445	1008	7844	2323	3331	62778	4514
38		26436	216.65	24544	66436	0	24549	16925		5	1445	997	7844	2385	3382	62778	4463
39		26436	216.65	24544	66436	0	24549	16725		5	1445	985	7844	2448	3433	62778	4412
40		26436	216.65	24544	66436	0	24549	16524		5	1445	973	7844	2511	3484	62778	4361
41		26436	216.65	24544	66436	0	24549	16324		5	1445	961	7844	2574	3535	62778	4310
42		26436	216.65	24544	66436	0	24549	16123		5	1445	949	7844	2636	3586	62778	4259
43		26436	216.65	24544	66436	0	24549	15923		5	1445	938	7844	2699	3637	62778	4208
44		26436	216.65	24544	66436	0	24549	15722		5	1445	926	7844	2762	3688	62778	4157
45		26436	216.65	24544	66436	0	24549	15522		5	1445	914	7844	2825	3739	62778	4106
46		26436	216.65	24544	66436	0	24549	15321		5	1445	902	7844	2888	3790	62778	4055
47		26436	216.65	24544	66436	0	24549	15121		5	1445	890	7844	2950	3841	62778	4004
48		26436	216.65	24544	66436	0	24549	14920		5	1445	878	7844	3013	3892	62778	3953
49		26436	216.65	24544	66436	0	24549	14720		5	1445	867	7844	3076	3943	62778	3902
50		26436	216.65	24544	66436	0	24549	14519		5	1445	855	7844	3139	3994	62778	3851
51		26436	216.65	24544	66436	0	24549	14319		5	1445	843	7844	3201	4044	62778	3800
52		26436	216.65	24544	66436	0	24549	14118		5	1445	831	7844	3264	4095	62778	3749
53		26436	216.65	24544	66436	0	24549	13918		5	1445	819	7844	3327	4146	62778	3698
54		26436	216.65	24544	66436	0	24549	13717		5	1445	808	7844	3390	4197	62778	3647
55		26436	216.65	24544	66436	0	24549	13517		5	1445	796	7844	3453	4248	62778	3596
56		26436	216.65	24544	66436	0	24549	13316		5	1445	784	7844	3515	4299	62778	3545
57		26436	216.65	24544	66436	0	24549	13116		5	1445	772	7844	3578	4350	62778	3494
58		26436	216.65	24544	66436	0	24549	12915		5	1445	760	7844	3641	4401	62778	3443
59		26436	216.65	24544	66436	0	24549	12715		5	1445	749	7844	3704	4452	62778	3392
60		26436	216.65	24544	66436	0	24549	12514		5	1445	737	7844	3766	4503	62778	3341
61		26436	216.65	24544	66436	0	24549	12314		5	1445	725	7844	3829	4554	62778	3290
62		26436	216.65	24544	66436	0	24549	12113		5	1445	713	7844	3892	4605	62778	3239
63		26436	216.65	24544	66436	0	24549	11913		5	1445	701	7844	3955	4656	62778	3188
64		26436	216.65	24544	66436	0	24549	11712		5	1445	690	7844	4017	4707	62778	3137
65		26436	216.65	24544	66436	0	24549	11512		5	1445	678	7844	4080	4758	62778	3086

Modeling Analysis. Overall, Design Study 4 successfully demonstrated a 75-meter airship, operating at 10,000 meters, facing 16 meters/second (36 mph) crosswinds, and employing its propulsors using reduced operations, would have sufficient hydrogen to provide both lift and power to operate for 61 days, thus exceeding the derived NORAD 60-day requirement. And by achieving 10,000 meters altitude, it enabled a radar to detect targets out to 270 miles.

4.5.7 Optimization Results

Having completed numerous optimization modeling simulations, the various parameters identified during Component Design activities have now been successfully scoped to specific Size, Weight and Power (SWaP) values (see Table 45), and could now be used in subsequent fabrication, testing, and integration activities. Overall, this effort produced excellent design results.

Table 45: Optimized Airship Parameters – Final Component Design

Mission Altitude: 10,000 meters (32,800 ft)		Mission Duration: 61 Days	
Useful Lift: 6,400 kg		Average Velocity: 16 m/s (36 mph)	
Maximum Takeoff Mass: 3,930 kg		Radar Detection Range: 274 miles	
End-Of-Mission Airship Mass: 3,222 kg		Target Altitude: 2,000 ft	
Structural Subsystem		Propulsion Subsystem	
Airship Length:	75.0 meters	Number of Propulsor Motors:	6
Fineness Ratio:	3	Mass per Propulsor Motor:	50 kg
Airship Diameter:	25.0 meters	Total Propulsor Motors Mass:	300 kg
Envelope Volume:	24,544 m ³	Mass per Propeller:	96 kg
Envelope Surface Area:	4,585 m ²	Total Propellers Mass:	576 kg
Envelope Material:	0.113 kg/m ²	Envelope Mass:	596 kg
Hydrogen Percentage:	0.6558	Drag Coefficient:	0.02
Hydrogen Pressure:	40000 Pa	Initial Hydrogen Mass:	1,445 kg
Power Demand		Power Production Subsystem	
Electrical Demand:	16.38 kW	Fuel Cell Unit Output:	65 kW
H2 Consumption:	11.8 kg/day	60-Day Hydrogen Consumption:	708 kg
Equipment Mass			
Fuel Cell Assembly Mass:	470 kg	Comms Subsystem Mass:	30 kg
Battery Mass:	180 kg	Radar Subsystem Mass:	104 kg
Power Supply Mass:	650 kg	Misc Equipment Mass:	100 kg
Payload Gondola Mass:	100 kg	Total Equipment Mass:	1,239 kg

4.6 Reliability Analysis

Traditional design analysis and test methods include vibration and shock analysis, thermal analysis and measurement, electrical stress analysis, and wear-out life prediction. Reliability, Availability, and Maintainability (RAM) failure analysis includes Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and various systems modeling and simulations [145].

A general attempt was made to identify the key reliability measures useful for this project and to quantify their values. This analysis produced several Technical Performance Measures (TPMs) that describe specific system expectations or minimum requirements (see Table 46).

Table 46: System Technical Performance Measures

Categories	Equations	Results
Mean Time Between Failures (θ)	$\theta = \frac{\text{Total Hours of Operation}}{\text{Total Number of Failures}}$	1,440 hours (60 days) / 1
Failure rate (λ)	$\lambda = 1 / \theta$ $= 1 / 1440$	.00069 or 0.069%
Reliability (R_t)	$= e^{-\lambda t}$ $= 2.718^{(-.00069)(60 \text{ days})}$	.9594 or 95.94%
Maintainability (M_t)	$MTTR = \frac{\text{Total Hours of Maintenance}}{\text{Total Number of Repairs}}$ (Mean Time To Repair)	40 hours (1 week)
Availability (A_t)	$= \frac{MTBF}{MTBF + MTTR} = \frac{1440}{1480}$	.9730 or 97.30%

4.7 Risk Management

Project risk analysis consists of estimating the *likelihood* (i.e., the probability of occurrence) a specific risk event will occur, and then the *consequential effect* in terms of cost, schedule, or performance impact. Risk analysis typically follows a structured analysis process, as outlined below [146, 147, 148].

Establish Risk Probability Criteria. First, objective criteria must be established on which to base probability estimates. Table 47 provides an example of typical criteria used in assessing the likelihood that an event might occur and its corresponding likelihood rating.

Table 47: Risk Probability Criteria [149]

Likelihood	Probability of Occurrence	Rating
Near Certainty	81 – 99%	5
High Likelihood	61 – 80%	4
Likely	41 – 60%	3
Low Likelihood	21 – 40%	2
Not Likely	5 – 20%	1

Establish Risk Consequence Criteria. Next, criteria is established in assessing the cost, schedule, or performance impact if an identified risk were to actually occur, and its corresponding consequence rating (see Tables 48 to 50).

Table 48: Risk Consequence Criteria – Cost [149]

Costs Criteria	Risk Level
Greater than 10% increase in programmed program costs.	5
5% to <10% increase in programmed program costs.	4
3% to <5% increase in programmed program costs.	3
1% to <3% increase in programmed program costs.	2
<1% increase in programmed program costs.	1

Table 49: Risk Consequence Criteria – Schedule [149]

Scheduling Criteria	Risk Level
Major schedule slip; requires modification to key milestones > 12 months.	5
Significant schedule slip; requires modification to key milestones < 12 months.	4
Program schedule slip; requires modification to critical path dates.	3
Program schedule slip; still able to meet key milestone dates.	2
Minimal program schedule slip.	1

Table 50: Risk Consequence Criteria – Performance [149]

Performance Criteria	Risk Level
Severe degradation: jeopardizes program success.	5
Significant degradation: technical performance is below threshold values.	4
Performance shortfall: technical performance approaching unacceptable limits.	3
Minor impact: technical performance will be reduced, but still within limits.	2
Minimal impact: technical performance will still be met.	1

Identify Project Risks. In reviewing the subsystems design concepts developed during the Component Design phase, the following were judged as potential “Performance Risks”:

- Arctic Operations. Airship fueling, launching, and recovery operations will be conducted under often dark, freezing, and/or windy Arctic conditions.
- Hydrogen Handling. Airship operations are dependent on producing, storing, and transferring highly flammable hydrogen gas.
- Very Low Temperatures. Operating above 10,000 meters exposes external airship components to 216 K (-70 F) temperatures for weeks at a time.
- Stratospheric Winds. Operating above 10,000 meters introduces potential crosswinds increasing to 34 m/s (76 mph).

- Envelope Fabric. The long-term effects of pressure, cold, and ozone exposure on extremely thin envelope fabric employed at stratospheric altitudes are unknown.
- High Altitude Air Compressors. At stratospheric altitudes, the air pressure is a thousand times less than at sea level. Air compressors servicing the fuel cells or refilling the empty air ballonnet during descent may not be effective.
- Motor Overheating. At stratospheric altitudes, natural convection heat dissipation of motor heat becomes more difficult, leading to component superheating.
- High Altitude Propellers. At stratospheric altitudes, employing 12-meter propellers may not be effective due to the very low air density.
- Satellite Data Link. Link-16 data link transmission over satellite relay processes is still a relatively new operational capability.

Conduct Risk Assessment. Next, the likelihood and consequences of the above potential risks were assessed, then multiplied, and then rank ordered by their overall severity (see Table 51).

Table 51: Program Risk Assessment (Performance).

Identified Risks	Likelihood	Consequence	Risk Severity	Ranking
Arctic Operations	5	5	25	1
Hydrogen Handling	4	5	20	2
High Altitude Air Compressors	3	5	15	3
Very Low Temperatures	3	4	12	4
High Winds	2	5	10	5
High Altitude Propellers	2	4	8	6
Motor Overheat	2	3	6	7
Satellite Data Link	1	4	4	8
Thin Envelope Fabric	1	2	2	9

Plot on Risk Matrix. The likelihood and consequence values for each risk were then plotted on a "5 x 5" risk matrix to portray the relative priorities of all low, medium, and high risks for program management awareness and subsequent resource prioritization (see Table 52).

Table 52: Program Risk Matrix.

LIKELIHOOD	5					1-Arctic Operations
	4					2-Hydrogen Handling
	3				4-Very Low Temps	3-Air Compressors
	2			7-Motor Overheating	6-High Altitude Propellers	5-Stratospheric Winds
	1		9-Envelope Fabric		8-Satellite Data Link	
		1	2	3	4	5
		CONSEQUENCE				

Develop Risk Handling Strategies. Having analyzed the likelihood and impact consequences of each risk, proactive risk handling strategies were developed to help drive down the likelihood of each risk occurring, thus ensuring project development success (see Table 53.)

Table 53: Risk Mitigation Strategies

Identified Risks	Risk Handling Strategies
1 – Arctic Operations	- Research dirigible handling procedures and lessons learned during inclement weather conditions. - Research techniques used when constructing and operating the Alaska Pipeline. - Visit Alaskan airports to document winter weather airfield management lessons learned.

2 – Hydrogen Handling	- Contact commercial gas companies to obtain lessons learned about aircraft hydrogen handling. - Research dirigible fueling procedures used in 1930s for hydrogen-based airships. - Investigate hydrogen production lessons learned from Norwegian prototype demonstration
3 – High Altitude Air Compressors	- Conduct altitude chamber testing of air compressors down to components down to 9,000 Pa to determine correct sizing and power needs of appropriate air compressor units.
4 – Very Low Temperatures	- Conduct temperature chamber testing of external components down to 216 k (-70 F) to verify reliability. - Test external components wrapped in heating blankets to determine effects, and the resulting increase in airship power demand.
5 – Stratospheric Winds	- Conduct wind chamber testing of airship prototypes to verify aerodynamic stability and mobility under expected wind conditions. - Conduct high-altitude testing of prototype models.
6– High Altitude Propellers	- Conduct evacuation chamber testing of prototypes to ensure propellers can successfully “grab” extremely thin atmosphere. - Conduct high-altitude testing of prototype models.
7 – Motor Overheating	- Conduct temperature chamber testing of motor components down to 216 k (-70 F) to determine heat dissipation effects, and the required approach for enhanced motor cooling due to superheating.
8 - Satellite Data Link	- Conduct data link testing with commercially available satellites to verify Link-16 can be transmitted over satellite communication links.
9 – Envelope Fabric	- Test candidate fabrics for operational resiliency. - Identify contractors to pursue parallel development.

Plot Impact of Risk Handling Strategies. Finally, for each identified risk, detailed handling activities and milestones are plotted on a “waterfall” diagram. This diagram illustrates how, as each risk mitigation event is being accomplished, the overall project risk is being subsequently reduced (see Figure 111 for a notional example).

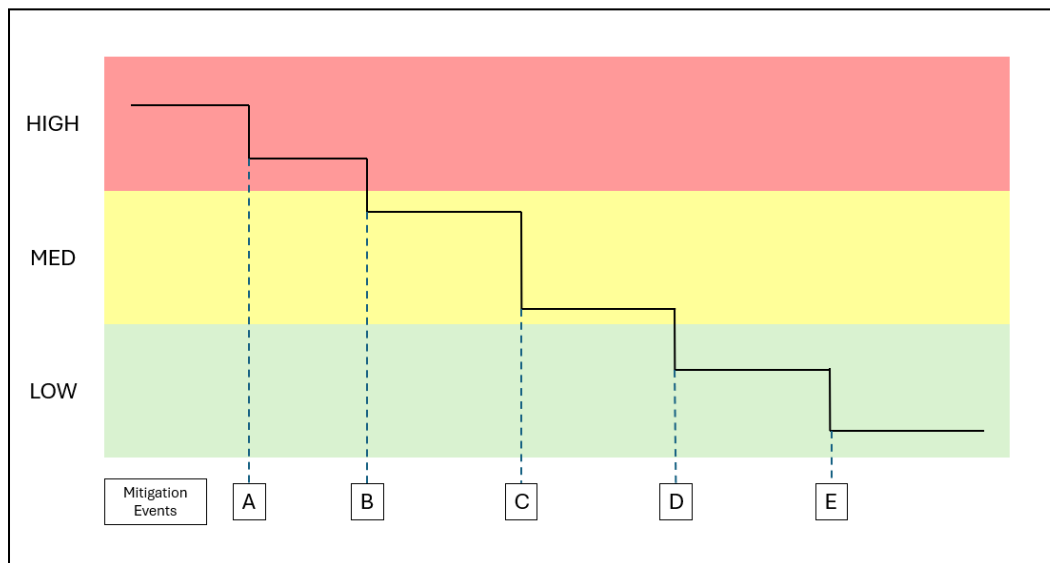


Figure 111: Risk “Waterfall” Diagram (Example)

4.8 Summary

To effectively design this airship required the use of an integrated systems engineering methodology. This Chapter followed such a united design approach by:

- Incorporating Forsberg and Moos’s basic systems engineering Vee model.
- Applying Kossiakoff and Sweet’s four iterative design activities in each phase.
- Following Borky and Bradley’s model-based systems architecture methodology.
- Implementing a Design System Matrix to document key input and output values.
- Employing a Model-Based Systems Engineering software tool to optimize values.
- And using Multidisciplinary Design Optimization to obtain optimum results.

In addition, this Component Design phase developed a novel Proton-Exchange Membrane (PEM) fuel cell model capable of operating at stratospheric altitudes. To date, no other studies have used fuel cells in these atmospheric conditions.

Finally, the modeling simulations produced a successful airship design meeting the NORAD derived mission duration requirement, plus identified two new research findings:

- Achieving 17,000 meters using a medium-sized airship appears to be infeasible using current technology.
- Huge airships are not necessary to be successful; the goal should be to design the smallest possible airship that meets performance requirements.

Overall, Forsberg and Mooz’s systems engineering Vee model has been closely followed, Kossiakoff’s formal “Advanced Development” activities have been finalized, and Borky and Bradley’s “Physical Viewpoint” has been outlined in significant detail. The project can now move into the “Implementation” engineering phase for manufacturing and assembly (see Figure 112.)

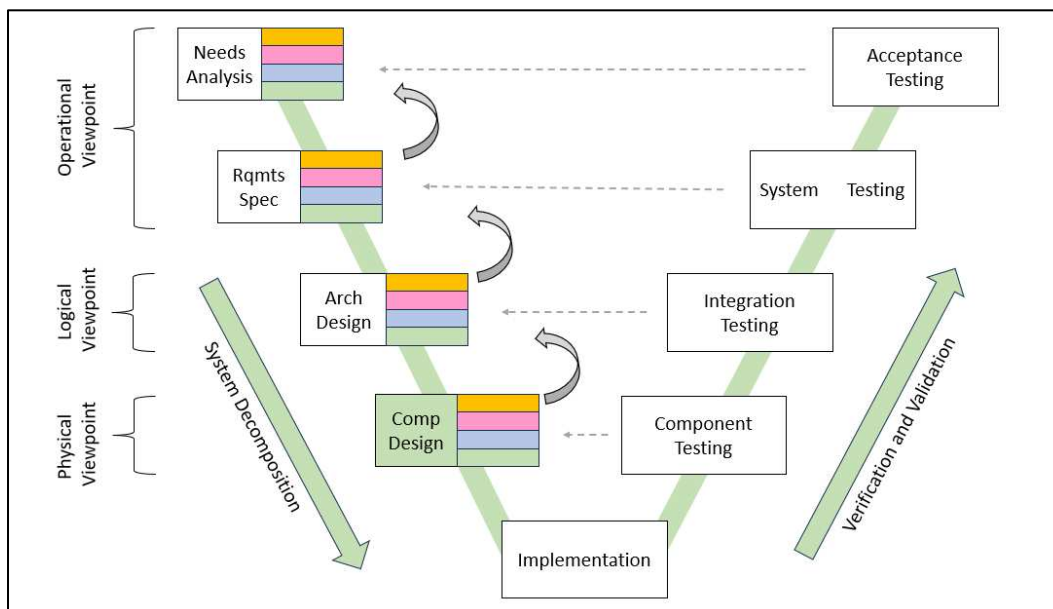


Figure 112: Project Systems Engineering Vee Model (Phase Completed)

CHAPTER V. OPERATIONAL EMPLOYMENT

5.1 Airship Basing

Given the CONOPS requirement to operate the airship across the Arctic Region, it would seem logical to base the airship fleet along the northern coast of either Alaska or Canada. One possible location next to the Arctic Ocean is Utqiagvik (UUT-kee-ah-vik”), Alaska (formerly known as Barrow) [150] (see Figures 113 and 114).

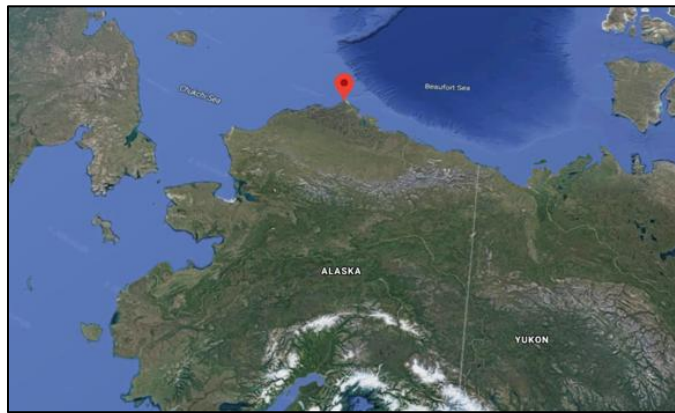


Figure 113: Location of Utqiagvik, Alaska [151]



Figure 114: Utqiagvik, Alaska [152]

This village of 4,400 is supported by the nearby Wiley Post/Will Rogers Memorial Airport which has a runway length of 6,500 feet (see Figure 115) [153] and receives regular commercial and air cargo services provided by Alaska Airlines (see Figure 116) [154].



Figure 115: Wiley Post-Will Rogers Memorial Airport [153]



Figure 116: Alaska Air Cargo Delivery [154]

In addition, there is a regularly scheduled ocean barge service that operates from April to October along the Alaskan coastline. Typical cargo deliveries include building and construction materials, heavy equipment, and vehicles (see Figure 117) [155].



Figure 117: Arctic Regional Barge Service [155]

Having determined a reasonable geographic location for the new NORAD airship base, the next major requirement would be to construct a large airship hangar. An instructive example comes from the Goodyear Tire and Rubber Company which houses its 75-meter blimp fleet in a massive 800-foot hangar built in Akron, Ohio [156] (see Figure 118). A similar sized structure built in Alaska could reasonably support a fleet of similarly sized 75-meter NORAD airships.



Figure 118: Interior of Goodyear Blimp Maintenance Hangar [156]

The question could be asked: could a similar airship hangar be constructed in the Arctic? In fact, back in 1928, a 30-person construction team deployed to the remote island of Svalbard, Norway, to construct a large hangar for the airship “Norge” whose mission was to explore the Arctic from the sky. Two supply ships later arrived by sea at the island with cement, steel poles, 600 cubic meters of timber, 50 tons of iron, and enough supplies to support the construction team.

After just five months, the team had completed a wooden framework which was covered by a giant canvas tarp to provide wind and snow protection. The hangar measured 110 meters (361 ft) long and 30 meters (98 ft) high (see Figure 119) [157]. (Note: These dimensions would easily accommodate one of the proposed 75-meter NORAD airships.)

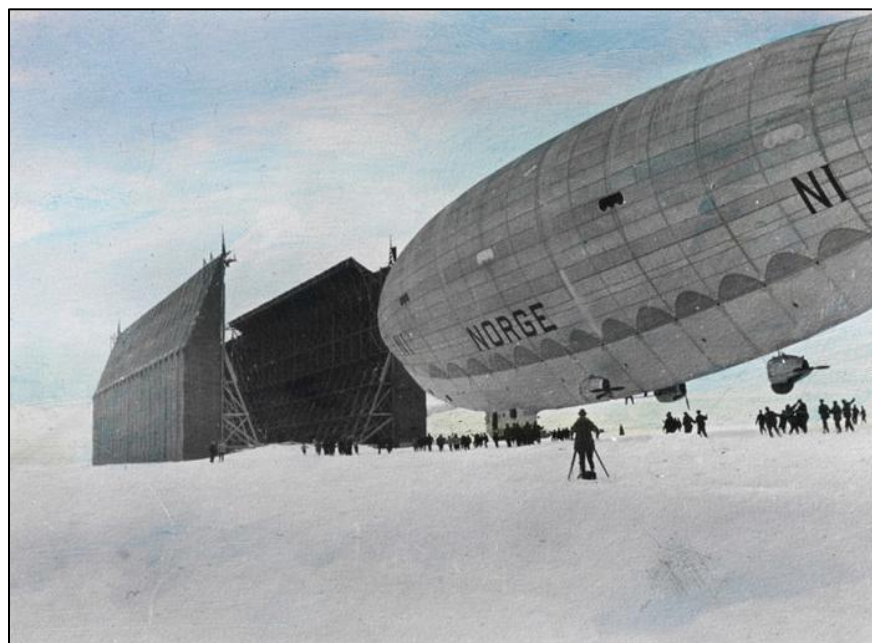


Figure 119: Airship and Arctic Hangar Built in 1928 [157]

Given modern building materials, advanced construction technology, and dependable logistical support now available one hundred years later, it would seem building a similar large airship hangar in the Arctic could be successfully accomplished yet again.

5.2 Hydrogen Production

Using hydrogen as the lifting gas eliminates the need to transport thousands of cubic meters of helium to the airship base. Instead, hydrogen could be manufactured on-site using a unit called an “electrolyzer” plant (see Figure 120) [158].



Figure 120: Electrolyzer Plant (Example) [159]

Generally, it takes 60 kW-h of electricity to generate 1 kg of hydrogen. Given it takes approximately 1,500 kg of hydrogen to fill an airship, that would require a total of 90 MW-h of power to fill an airship every 2 months, or roughly 1.5 MW of power per day.

One solution would be to harness wind power from the Arctic environment. The “Haeolus” project, conducted from 2018 to 2023 in Norway, effectively powered a 2.5 MW electrolyzer plant using a nearby 45 MW “wind park” (see Figure 121) [160].



Figure 121: 45 MW Wind Park in Norway [161]

5.3 Operational Flights

Airship Fleet Size. It is proposed the NORAD Airborne Early Warning Airship fleet consists of five airships. This would allow one airship to undergo preparations for launch, the second airship to be flying an active surveillance mission, a third airship having just returned from its mission, and two other airships undergoing routine maintenance. All five of these airships would easily fit inside a single hangar the same size as the Goodyear Blimp hangar in Ohio, which would protect operations and maintenance efforts from Arctic weather conditions.

Surveillance Loop. Launched from Alaska, an airship would proceed along the Canadian frontier, drifting with the counter-clockwise air flow, conducting surveillance enroute to Greenland. The airship would then turn left and circle around the North Pole. It would then proceed westbound, heading back towards Alaska, again turning left, and repeating the surveillance loop. This flight pattern resembles a box formation (see Figure 122).



Figure 122: Surveillance Loop and Radar Detection Rings [162].

The distance from Alaska to Greenland is approximately 3,200 km (2,100 miles) [163]. Drifting with a wind velocity of 16 m/s (35 mph), it would take about 60 hours (about 2 1/2 days) to reach the Greenland turn point. To traverse the entire Arctic surveillance loop would therefore take approximately 10 days (assuming no challenging headwinds were experienced.)

Given the 60-day NORAD surveillance goal, the airship should be able to accomplish six of these surveillance loops before needing to return to base. And having a 270-mile radar detection radius (indicated by the red rings on Figure 123), this pattern would provide excellent surveillance coverage over most of the Arctic while patrolling.

Air Traffic Deconfliction. As the airship proceeds along its surveillance path, it must avoid all North America to Asia cross-polar commercial airliner routes (e.g., “Polar 1, 2, 3, and 4”) shown on Figure 123 [164].

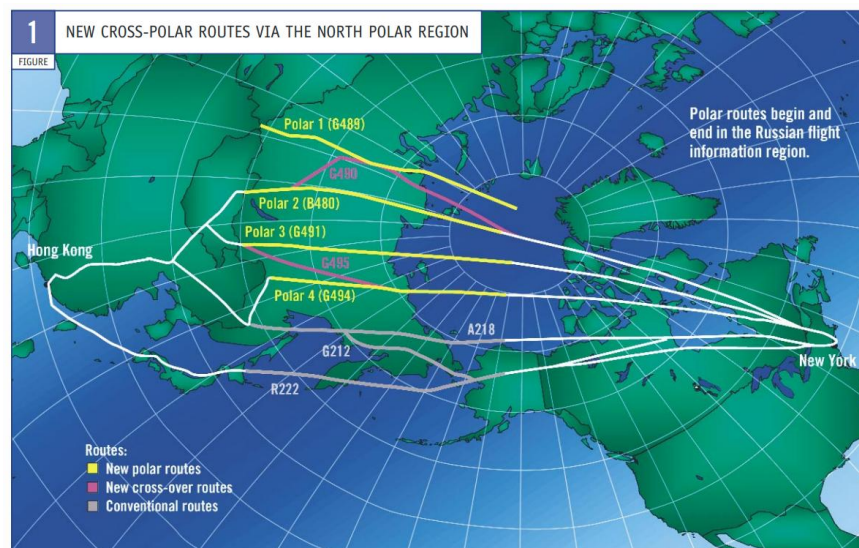


Figure 123: Cross-Polar Airliner Flight Routes [164].

International airliner flights typically fly at very high altitudes where the air is less dense, thus allowing their aircraft to be more fuel efficient. The polar altitudes routes range from 36,000 to 41,000 ft [164]. Because the optimum NORAD airship altitude was set at 10,000 m (32,800 ft), the airship should be operating well below all international air traffic flying overhead.

Crosswind Concerns. As outlined in the CONOPS, the general requirement was to develop an “unmanned air vehicle operating at stratospheric altitudes over the Arctic Region.” This does not specifically state the airship must travel out to the North Pole and remain directly overhead.

Instead, the proposed approach is to coast along with the prevailing counter-clockwise winds, applying propulsion at reduced speeds as needed to conduct occasional course correction maneuvers against any crosswinds in order to remain in international airspace.

“Wind barbs” are meteorological symbols used to indicate wind speed (measured in knots) and their direction. Generally, two barbs indicate speeds in the twenties, three barbs indicate speeds in the thirties, etc. (see Figure 124) [165].

Observed wind speed	0-2 kts (0-2 mph)	3-7 kts (3-8 mph)	8-12 kts (9-14 mph)	13-17 kts (15-20 mph)	18-22 kts (21-25 mph)	23-27 kts (26-31 mph)	28-32 kts (32-37 mph)	33-37 kts (38-43 mph)	48-52 kts (55-60 mph)
Rounded to the nearest 5	0 kts	5 kts	10 kts	15 kts	20 kts	25 kts	30 kts	35 kts	50 kts
Plotted as									

Figure 124: Wind Barb Symbols [165].

As background, the National Oceanographic and Atmospheric Agency (NOAA) measures altitudes using atmospheric pressure readings shown in “millibar” (MB) values. The higher the altitude, the lower the millibar value [166].

To examine typical high altitude Arctic wind velocities occurring over the North Pole, NOAA satellite imagery was obtained for analysis (see Figures 125 through 127.)

In general, the Arctic winds occurring from 400 MB (7200 m) up to 100 MB (15800 m) (e.g., winds indicated by pink barbs) appeared to travel counter-clockwise around the North Pole at approximately 20 to 40 knots (10 to 20 m/s) [167].

(Note: These high altitude windspeeds are consistent with those used in the Altitude Winds [Section 4.4.9] and Mission Duration [Section 4.4.12] velocity calculations.)

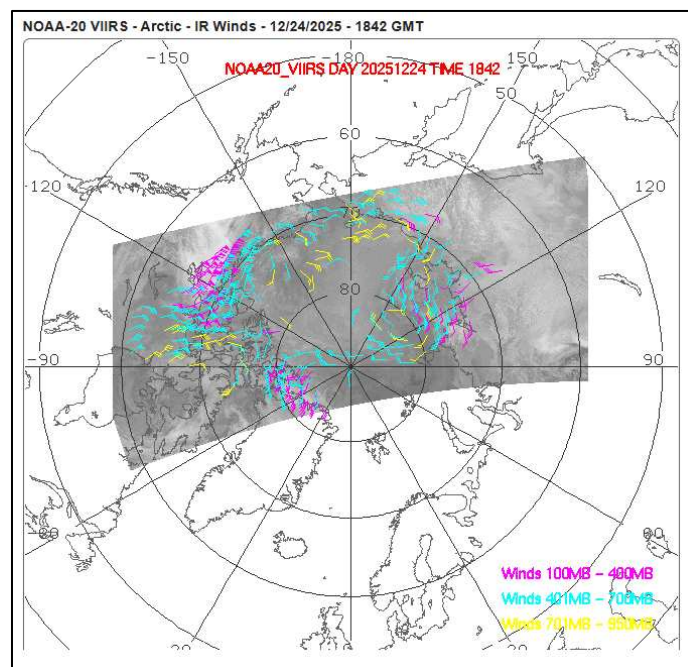


Figure 125: North Pole Winds (24 Dec 25) [167]

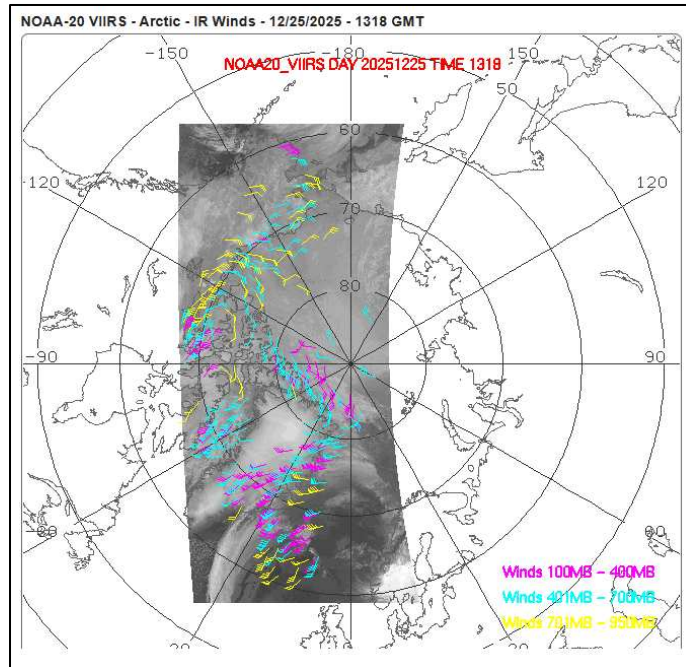


Figure 126: North Pole Winds (25 Dec 25) [167].

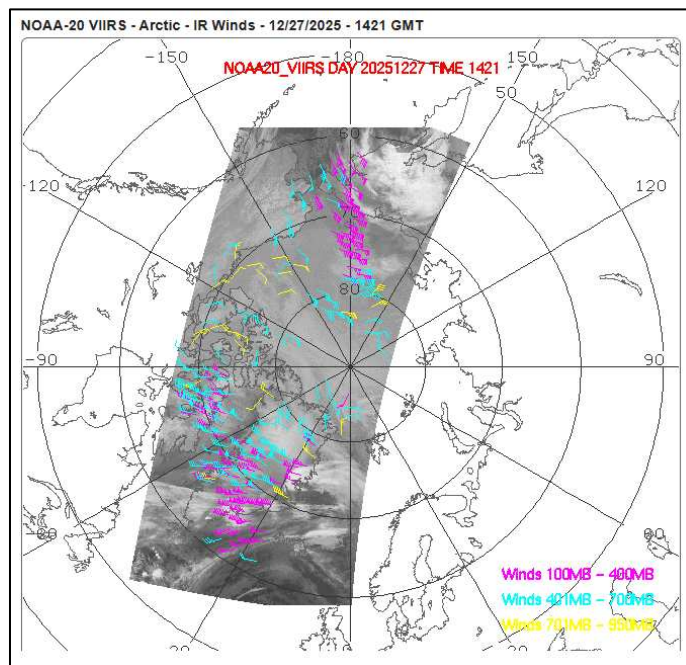


Figure 127: North Pole Winds (27 Dec 25) [167].

These NOAA satellite images provide a clear sense of the counter-clockwise wind currents occurring around the North Pole. Also, it should be noted that several of the images do not indicate any significant high-altitude wind (pink wind barbs) occurring at all in this region. This confirms the literature review research indicating that above 10,000 meters, wind speeds drop off to significantly lower strengths (see Figure 93).

Operational Tradeoff Considerations:

- Fewer Number of Airships. Operating five airships allows operational flexibility. As a tradeoff, constructing fewer airships would definitely reduce the overall development timeline and overall system cost, but it would also affect mission readiness by reducing the number of ready spares available for operational employment.
- Alternate Hangar Location. Literature research indicated building a hangar large enough to hold five airships on the northern coastline of Alaska seems completely feasible. An alternative option would be to construct a similar hangar farther south in the city of Anchorage. This location would require airships to travel an additional 1200 km (725 miles) north to arrive in the Arctic Ocean. Traveling at 35 mph, it would take almost two days to arrive at the Arctic Ocean, and an additional two days to return to Anchorage. This tradeoff would significantly consume the available hydrogen aboard the airship and thus keep it from meeting the 60-day mission goal.
- Direct Flight to North Pole. Instead of conducting wide-area surveillance of the Arctic Region, an alternative option would be to travel from Utqiagvik directly to the North Pole. This should take approximately 1 1/2 days but would provide much more limited radar coverage.
- Station Keeping Option. The design optimization simulations were all conducted using an average crosswind velocity of 16 m/s. How would hydrogen consumption be affected by constantly matching the prevailing crosswinds in order to constantly remain over one location?

To analyze this tradeoff, optimized airship parameter values from Table 46 were first inserted into the “Altitude & Operations Sensitivity Calculator” [139] (see Table 54.)

Table 54: Altitude Sensitivity – Airship Parameter Inputs.

						40000					
	Airship Pressure Calculations					Airship Volume Calculations					
	A	B	C	D	E	F	G	H	I	J	
	Mission Altitude (m)	Mission Altitude Air Pressure (Pa)	Mission Altitude Air Temperature (K)	Total Airship Volume m3	Mission Altitude Hydrogen Pressure (Pa)	Hydrogen Volume Percentage at Takeoff	Hydrogen Volume (Unconstrained) (m3)	Hydrogen Volume (Constrained) (m3)	Air Volume in Ballonet (m3)	Hydrogen Volume Leaked (m3)	
Day	10000	26436	216.65	24544	66436	0.6558	24549	24544	0	5	

Then, randomly-occurring crosswind velocity data taken at Barrow/Utqiagvik over a 30-day period during March 2026 [144] were sequentially inserted (See Table 56 for data).

To station keep, the airship would need to employ continuous propulsor power (and thus full hydrogen consumption) to maintain its position against the wind (see Table 55.)

Table 55: Operations Sensitivity – Station Keeping Calculations.

Airship Cruise Calculations						Airship Power Calculations				
R	S	T	U	V	W	Y	Z	AA	AB	AC
Cruise Velocity [m/s]	Airship Drag Coeff	Airship Drag (N)	Aero Power Required at Cruise [W]	Rotational Power Required at Cruise [W]	Electrical Power Required at Cruise (W)	Power Demand (Welec)	Air Pumped Per Day (kg) @ Stoich of 2	Air Pumped Per Sec (Nm3)	Air Compressor Energy Consumed (W)	Hydrogen Consumed Per Day (kg) @ 50% eff
15	0.02	607	9110	12147	13496					
				Station Keeping	13496	13496	148.72	0.00143	188	19.5

Based upon continuously employing its propulsor motors, at the end of 30 days the airship had only 348 kg of hydrogen remaining (see Table 56). As can be seen, maintaining an airship over a specific location quickly exhausts the airship’s hydrogen supply.

(Note: The average wind velocity during this particular 30-day period measured 15.2 m/s, reinforcing the validity of using 16 m/s in the optimization simulation model.)

Table 56: Operations Sensitivity – Station Keeping Hydrogen Consumption.

Day	knots	m/s	H2 Consumed	H2 Remaining
				Initial = 1,445.0
1	50.7	26	101.3	1,343.7
2	3.8	11	7.7	1,336.0
3	2.1	9	4.2	1,331.8
4	1.5	8	3.0	1,328.8
5	2.1	9	4.2	1,324.6
6	0.2	4	0.4	1,324.2
7	0.4	5	0.7	1,323.5
8	6.3	13	12.7	1,310.8
9	5	12	10.0	1,300.8
10	14.2	17	28.3	1,272.5
11	11.8	16	23.6	1,248.9
12	7.9	14	15.8	1,233.1
13	5	12	10.0	1,223.1
14	9.7	15	19.5	1,203.6
15	26.7	21	53.4	1,150.2
16	7.9	14	15.8	1,134.4
17	7.9	14	15.8	1,118.6
18	0.6	6	1.2	1,117.4
19	14.2	17	28.3	1,089.1
20	7.9	14	15.8	1,073.3
21	45	25	90.1	983.2
22	77.8	30	155.6	827.6
23	50.7	26	101.3	726.3
24	123.6	35	247.1	479.2
25	3.8	11	7.7	471.5
26	39.8	24	79.7	391.8
27	2.9	10	5.8	386.0
28	9.7	15	19.5	366.5
29	3.8	11	7.7	358.8
30	5	12	10.0	348.8
	Average =	15.2		

5.4 NORAD Control

Finally, using Equation 6 from Section 1.2, using a mission altitude of 10,000 meters (32,800 feet) for the airship's radar height and 610 meters (2,000 feet) for any approaching target aircraft, the airship's radar should be able to detect bomber-sized aircraft cresting the horizon as far as 274 miles away (see Table 57 and Figure 129).

Table 57: Horizon Visibility Distance Calculation

R	Radius of the Earth	6,300,000 m
H _r	Height of the radar above the Earth's surface	10,000 m
H _t	Height of the target above the Earth's surface	610 m

$$D_v = \sqrt{2RH_r} + \sqrt{2RH_t} = 274 \text{ miles} \quad (53)$$

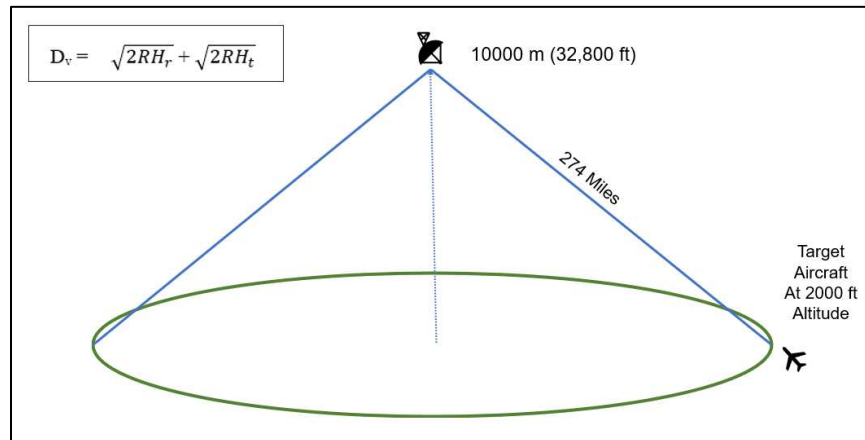


Figure 128: Radar Detection Range at 10,000 Meters

This radar surveillance data would then be sent via satellite to NORAD air defense operation centers for tactical and strategic assessments (see Figures 129 and 130).



Figure 129: NORAD Air Surveillance Technician's Displays [168]



Figure 130: NORAD Command Center Strategic Displays [169]

5.5 Summary

The logistics involved in the construction of an airbase in northern Alaska appear to be reasonable. Material can arrive both by air cargo and by ocean barge transport. Building a suitable hangar would be very challenging, but as history has demonstrated, it can be done. A single very large hangar could accommodate a fleet of five 75-meter airships satisfactorily.

Likewise, hydrogen production using a wind-powered electrolysis plant was demonstrated in Norway and would provide a local hydrogen fuel supply on demand for airship operations.

Launching from Alaska, an airship would then proceed to patrol across the Arctic region. It is estimated it would take roughly two days to reach the first patrol turn point near Greenland, and 10 days to traverse the full Arctic surveillance loop. The winds aloft appear to be manageable.

And because the optimum airship altitude has now been set at 10,000 m (32,800 ft), the airship would fly below all international air traffic transiting overhead at 36,000 ft and above. Also, this mission altitude would enable radar detection of any approaching potentially hostile aircraft at ranges out to 270 miles.

Overall, this proposed airship concept would offer greatly extended air surveillance coverage over the Arctic region where none currently exists, and could, during an increased alert posture, act as an operational “tripwire” for the early detection of any advancing hostile forces.

CHAPTER VI. CONCLUSION

6.1 Introduction

The broad goal of this research was to determine if the proposed concept of a remotely controlled stratospheric Arctic early warning airship is theoretically possible. Designing such a vehicle was viewed in systems engineering terms: the proposed concept was a classic system with various subsystems having numerous requirements, conflicting design considerations, and requiring successful component integration and validation activities. Using an integrated systems engineering methodology ensured system architecture and component design phases stayed on track. The results produced an integrated airship design that was optimized for size, weight, power, and mission duration. Finally, a brief operational appraisal was conducted regarding airship basing, hydrogen production, flight consideration, and NORAD command and control.

This project's research was guided by three primary research questions and nine associated research taskings. While this dissertation is the overall result of that entire research effort, summary answers to each of the specific research tasks are provided below.

6.2 Research Question 1

Research Question 1 is restated here: "Can the Geometry, Performance, Mass, Power Requirements, and Payload Systems Required of the Airship be Represented Parametrically Within An Integrated and Optimizable Mission System Model?"

As outlined in Chapter 4, a set of models were derived from the literature review to represent airship dimensions, pressures, volumes, power, mass, lift, velocity, and duration. These models were identified, mathematically modeled, and parameterized resulting in 75 different design variables across a broad set of multi-disciplinary contributing analyses.

Twelve computational analysis (CA) blocks were then iteratively developed and integrated into Ansys ModelCenter® MBSE software and linked together to form an integrated Design Structure Matrix formatted multidisciplinary analysis (MDA). The MDA enabled variations of length, volume, altitude, mass, and other factors to be repeatedly tested. Several hundred simulations were conducted using this software to develop aircraft models for further refinement and development in subsequent tasks.

Design exploration was used to verify and validate the modeling and optimization tools. The Ansys ModelCenter® Optimization Tool was connected to eight key parameters and allowed to run to determine optimum Size, Weight, and Power (SWaP) characteristics. Simulation run times to determine the optimum airship length per designated altitude often took up to 4 hours per problem to finish calculations.

Overall, the answer to this research question is that, indeed, the geometry, performance, and mass of the proposed airship were successfully represented in a set of interrelated models. The resulting analyses were demonstrated to work together through an MDO framework that optimized the performance of a baseline long-endurance, high-altitude polar airship.

6.3 Research Question 2

Research Question 2 is restated here: “What Are the System Performance Characteristics that Make this Arctic Early Warning Airship System Feasible?”

Having satisfactorily developed each general functional airship component using systems engineering approaches, specific optimization of critical dimensions, operational altitudes, power supply and demands, airship and crosswind velocities, and resulting mission durations required an intensive effort to identify ideal system performance attributes.

A key design element was the decision to employ hydrogen to serve as both the airship lifting gas as well as the fuel supply for the fuel cell assembly. This creative solution resulted in the airship achieving remarkably long mission durations exceeding 60 days.

Finally, after completing four optimization scenarios, it was possible to determine the ideal mission performance characteristics for optimum airship length, volume, hydrogen pressure, airship and payload mass, power supply and demand, useful lift, cruising velocity, mission altitude, mission duration, and radar range. (A summary of the final optimization results was provided at the end of Chapter IV as a reference.)

In summary, the answer to this research question is that specific system performance characteristics were successfully derived by using MBSE modeling, thus making this novel airship design entirely feasible.

6.4 Research Question 3

Research Question 3 is restated here: “What Combination of Achievable Technology and Operational Scenarios Produce Optimal Airship Surveillance and Make it Performance-Preferred?”

Regarding airship technology issues, operating five airships would allow one to undergo preparations for the next launch, the second to be flying an active surveillance mission, the third recovering from its recent mission, and the other two undergoing routine maintenance, as required. Construction of fewer airships would definitely reduce the overall system development cost but would also affect the readiness of the mission by reducing the number of ready spares. And while the airship concept itself is unique, research indicated building a hangar large enough to hold five airships on the northern coastline of Alaska seems completely feasible.

Producing a sufficient supply of hydrogen in the Arctic was successfully demonstrated by the Norwegians as late as 2023. However, establishing a similar production plant in Utqiagvik would require a significant construction effort. Certainly not on the scale of constructing the Alaskan oil pipeline, but undoubtedly a considerably expensive endeavor.

Regarding operational mission scenarios, research also demonstrated the winds at 10,000 meters are relatively calm. Thus, the airship should be able to conduct a counter-clockwise surveillance loop around the North Pole and back in approximately 10 days. Given the 60-day NORAD surveillance goal, the airship should be able to complete six of these surveillance loops, then return to base. And because airship's optimum mission altitude was set at 10,000 meters (32,800 ft), they would operate well below airliner traffic flying overhead in the Polar region.

Also, the estimated radar detection range was over 270 miles, exceeding the derived requirement of 250 miles. This early warning surveillance capability would provide NORAD an additional hour of warning if fighter aircraft were needed to conduct air defense interceptions.

Finally, the key requirement underlining this entire research effort was the need to conduct long-duration surveillance operations for 60 days. As was previously discussed, the U.S. Navy's Triton UAV has an impressive service ceiling of 55,000 ft, a range of 7,400 miles, and carries a radar with a 200 NM range. What it lacks is persistence—it can remain airborne for only 30 hours. Thus, the challenge for this project was to demonstrate 1) that it was actually feasible, and 2) that it had better operational utility than current airborne systems. As shown by this dissertation, this unique airship concept can maintain a surveillance watch for at least 60 days, scan the horizon out to 270+ miles, and provide real-time warning to NORAD in case large aircraft suddenly appear across the Arctic where no other surveillance sensors are located.

Overall, this system is performance-preferred, as clearly proven by this dissertation.

6.5 Key Findings

- Arctic missions lasting 60 days are possible using this novel airship concept.
- Sufficient missions durations can be achieved using moderately sized vehicles.
- Attempting to reach the top of stratosphere using an airship is very difficult using current materiel technology and is actually unnecessary.
- The overall airship design goal should be to achieve the smallest-sized airship that meets the performance requirements.
- The resulting optimized airship design is significantly smaller and lighter than those proposed in NASA studies for non-polar airships.
- Using hydrogen gas resolves both airship lift and power production challenges, eliminating the need for numerous solar panels or transporting heavy batteries.
- Using a combined hydrogen-air ballonnet concept enables high altitude realization.
- The design employs one of the first Proton-Exchange Membrane fuel cell system models capable of operating at stratospheric altitudes.
- No other studies have used fuel cells under these high atmospheric conditions.
- Probabilistic modeling of stratospheric winds produces a more accurate design.

6.6 Research Contributions

Upon completion of this research project, the research contributions of this dissertation are:

- A scholarly review of the literature including stratospheric environmental conditions; historic examples of successfully designed high-altitude airships developed over the last 50 years; and detailed examples of design factors to include gas envelope and lifting gas issues, propulsion concerns, propeller design attributes, power supply options, and various payload considerations.

- A brief review of key system engineering approaches to include the classic “Vee” model, a more detailed scientific method, and a model-based systems architecture process. Each of these approaches were combined to form a new integrated systems engineering approach that benefitted from the strengths of the previous three. This newly devised approach helped ensure the airship project would be successfully developed.

- An example of an effective systems engineering effort involving formal needs analysis, requirements specification, architecture design, and component design actions, resulting in the identification of 75 various design parameters.

- The creation of a specialized “Altitude and Operations Sensitivity Calculator” capturing the applicable factors involved in the operating a novel, high-altitude fuel cell concept.

- A successful application of Model-Based Systems Engineering (MBSE) by developing a complicated Design Structure Matrix (DSM) which enabled specialized parameter optimizing software to produce ideal values for key airship design parameters.

- And finally, a first-of-its-kind early warning airship design capable of filling a strategic warning radar gap currently facing the NORAD air defense community.

6.7 Future Work

During both the literature research and component design, numerous technological risks became apparent. Technology gaps included concerns over conducting large airship operations under Arctic conditions, storing and handling hydrogen gas, long-term effects on airship components from cold and ozone exposure, compressors and propellor operations in very thin atmospheres, and potential motor overheating due to low atmospheric pressures. Many of these concerns may have been resolved. However, developing such an innovative airship would require additional work to ensure an airship prototype could be successfully constructed.

6.8 Conclusion

This research proposed to use systems engineering approaches to develop a remotely controlled airship capable of carrying a lightweight radar set aloft to very high altitudes in the stratosphere over the Arctic region for long durations. This innovative concept would offer greatly extended air surveillance coverage and could act as a “tripwire” for the early detection of any advancing hostile forces.

Research explored how new model-based system engineering tools could be used in conjunction with traditional system engineering processes to capture program requirements, assist component design activities, and conduct validation efforts to successfully realize this proposed early warning airship concept.

Model-Based Systems Engineering (MBSE) was employed to develop numerous airship design parameters, integrate them, and then optimize them to determine their ideal characteristics. Numerous modeling scenarios were then run resulting in an optimized set of airship design parameters.

The elements making up this proposed early warning airship are realistic and are based upon both scientific analysis and real-world capabilities. And employing a formal system engineering process was fundamental to successfully designing the project.

In conclusion, research to date has yet to uncover any examples of this proposed early warning airship system and thus would be a unique contribution to both the systems engineering and the NORAD air defense communities.

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