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Systems Considerations in Designing a Stratospheric Early Warning Airship

INCOSE WSRC · 2025

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PUBLICATION DATE

July, 2026

SUBMISSION #

16

INCOSE PUBLICATIONS

Systems Considerations in Designing a Stratospheric Early Warning Airship

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Abstract

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. NORAD's "North Warning System" consists of long-range remote radar sites positioned along the vast Canadian and Alaskan Arctic frontier. Because radio waves are broadcasted line-of-sight, signals transmitted at low angles 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 not be detectable. One solution to this 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 for long durations (e.g., 60+ days). During periods of required heightened readiness, this concept would offer greatly extended air surveillance coverage and enable early detection of any advancing hostile forces. Research to date has yet to uncover any examples of this proposed system concept, and thus would be a unique contribution to both the systems engineering and NORAD air defense communities.

Keywords

Stratospheric, Early Warning, Airship, Radar, NORAD.

Introduction

Because radio waves 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 1).

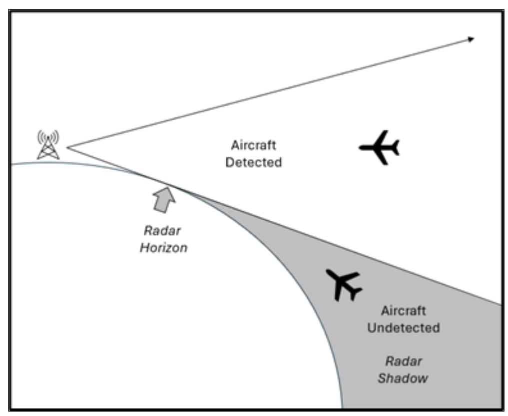

Figure 1. Radar Shadow Example.

The radar's signal transmission distance to the radar horizon (Dh) can be calculated using the following equation (Zolotkov, 2025):

$$Dh = \sqrt{(R + Hr)^2 - (R)^2} \qquad (1)$$

Given R is the radius of the Earth and Hr is the height of the radar. For current NORAD ground radars (tower height = 100 feet), the radar horizon distance equals 12 miles. Aircraft approaching at very low altitudes outside that range would be physically undetectable.

The solution to resolving this radar shadow dilemma is to raise the height of the radar substantially in order to look over the horizon more easily in order to detect approaching targets.

Employing an unmanned early warning airship capable of lofting a lightweight radar to stratospheric altitudes would be a suitable means to accomplishing this solution. Placing a radar at such a very high stratospheric altitude would push the radar horizon distance out to over 320 miles, thus allowing the observation of low flying aircraft previously undetectable, and resulting in greater early warning time.

Previous NASA studies have researched the feasibility of employing airships to conduct airborne surveillance operations off the coasts of the United States (Colozza and Dolce, 2005). This paper proposes implementing a similar early warning concept, but over the more challenging Arctic Region.

To date, this topic of research appears to be a wholly new application concept that has not been previously explored in research literature.

Methodology

The proposed airship is an example of a system with various subsystems having numerous requirements, conflicting design considerations, and requiring successful integration, verification, and validation activities. Successfully designing such a proposed vehicle requires a structured systems engineering approach.

During the 1990s, Forsberg and Mooz argued that heritage systems engineering approaches often presented an incomplete portrait of the actual engineering processes. To resolve these shortcomings, they proposed what is now known as the famous systems engineering *Vee* model (Forsberg and Mooz, 1996).

At that same time, Kossiakoff and Sweet developed their formal *systems engineering method* which provided a very logical, systematic application of the scientific method when engineering a complex system. It consists of four core activities applied during each engineering phase (Kossiakoff, et. al., 2020).

Finally, in 2019, Borky and Bradley introduced their Model-Based Systems Architecture Process. With digital Model-Based Systems Engineering (MBSE) software becoming more prevalent, they proposed systems engineers needed to incorporate a stronger *architectural* approach (Borky and Bradley, 2019).

Thus, management of this novel early warning airship project could be accomplished using a modified systems engineering Vee model that integrates all three of these engineering design approaches in order to provide a solid basis for systems analysis and to support technical digital engineering aspects (see Figure 2).

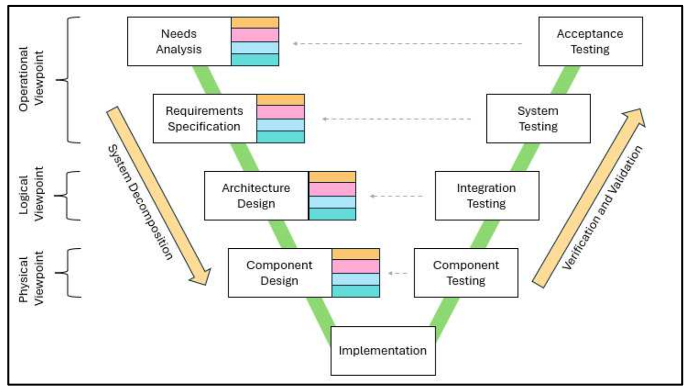

Figure 2. Modified Systems Engineering *Vee* Model.

Needs Analysis Phase

First, successful projects need to meet the various needs of stakeholders throughout the project's life cycle. Overall, this initial phase addresses *what* the system needs to provide and is the beginning of defining the system's *Operational Viewpoint* (Borky and Bradley, 2019).

Based upon presumed NORAD stakeholder needs, a proposed general Concept of Operations was developed (see Table 1.)

Stratospheric Early Warning Airship Concept of Operation
Construct an integrated air vehicle capable of operating at very high altitudes over the Arctic, maneuvering under both manual and autonomous flight control, performing strategic air defense surveillance continuously for a minimum of thirty days, and communicating both vehicle control telemetry and sensor data to NORAD for air vehicle operations and air defense assessment.

Table 1. Proposed Airship System CONOPS.

Requirements Specification Phase

Given this general CONOPS, numerous requirements were then derived. They were written to be simple, measurable, attainable, realistic, and time-bound (or *SMART*) (*Systems Engineering Handbook*, 2025). During this phase, concept exploration actions are accomplished, and the system's *Operational Viewpoint* is now further refined.

Some of the derived requirements were classified as Measures of Effectiveness (MOEs), which are operational measures of success that are closely related to achieving mission or operation objectives. These MOEs were developed to meet general CONOPS considerations. Other requirements were classified as Technical Performance Measures (TPMs) that measure specific technical attributes within the system to determine how well the system is meeting explicit requirements. (See Table 2 for examples.)

Type	Requirement	Class
Altitude	Shall be capable of ascending above 10,000 m (~32,800 ft.)	MOE
Duration	Shall be capable of operating aloft for 60 continuous days.	MOE
Environment	Shall be capable of operating over the Arctic Region.	MOE
Guidance	Shall be capable of autonomous flight path and velocity corrections.	MOE
Remote Control	Shall be capable of remote-controlled flight.	MOE
Sensor Data	Shall communicate sensor data to ground stations.	MOE
Vehicle Telemetry	Shall communicate vehicle telemetry to ground stations.	MOE
Temperature	Shall be capable of operating down to -60 C.	TPM
Reliability	Shall meet a MTBF rate of 2,200 hours (91.6 days).	TPM
Motor Power	Shall employ electrically-driven engines.	TPM
Propellers	Shall employ propellers rated for operation above 10,000 m.	TPM
Sensor Range	Shall have an aircraft detection range of 250 miles.	TPM
Radar Cross Section	Shall be capable of detecting 10-meter^2 sized targets.	TPM

Table 2. Derived Operational Requirements.

Architecture Design Phase

Next, this third phase marks the beginning of specific engineering efforts to define the functional and physical characteristics of the new system to meet operational requirements. The goal is to develop system functional specifications, a precisely defined system concept, and a detailed plan to ensure engineering program success. Accomplishing this phase completes various concept definition steps and now outlines the *Logical Viewpoint* of the system (Borky and Bradley, 2019).

Based upon the CONOPS and the numerous derived requirements, it is proposed the airship system should consist of seven key subsystems:

- Structural Subsystem, which provides the physical airframe.
- Propulsion Subsystem, consisting of two electric motors and their controls.
- Guidance Subsystem, providing the navigation, guidance, and control functions.
- Detection Subsystem, which conducts the strategic air surveillance operations.

- Communications Subsystem, providing two-way communication capability.
- Power Subsystem, which powers the airship and the payloads.
- Control Subsystem, providing ground-based airship control and surveillance sensor displays.

Next, the process to identify key parameters that influence airship design and performance of these subsystems was started. This was a very recursive effort, as new design elements were often discovered that relied on previously defined parameters, thus needing to return to previously accomplished steps for closer analysis and revision. For this project, 76 different subsystem parameters were eventually identified for the air vehicle and are illustrated using a block diagram chart for reference (see Figure 3).

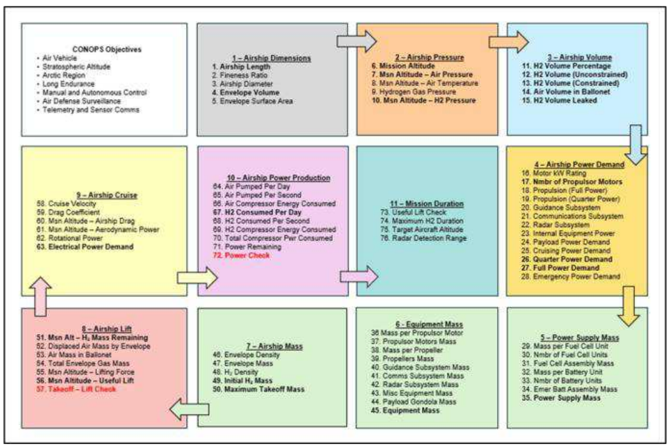

Figure 3. Block Diagram Chart Example.

These identified input/output subsystem parameters were then outlined using a Design Structure Matrix. Using the DSM allows system designers to examine the specific input variables required for each Computational Analysis (CA) block, and their subsequent calculated outputs which then cascade into succeeding CA blocks until all air vehicle design elements are met (see Figure 4) *(Design Structure Matrix,* 2012).

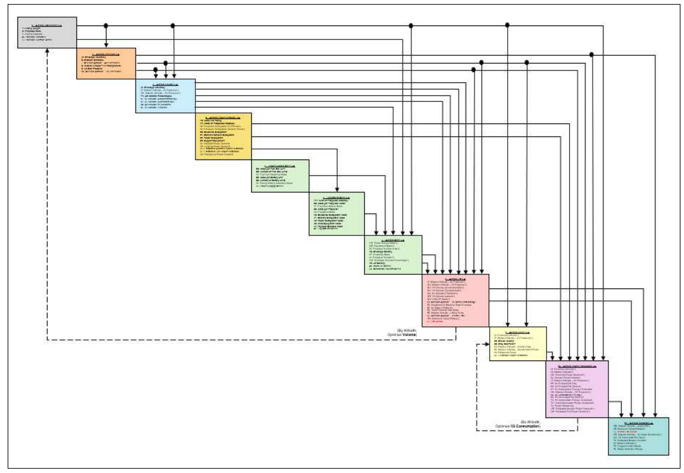

Figure 4. Airship Design Structure Matrix.

For example, initial airship length and diameter dimension inputs were developed. If the *fineness ratio* (e.g., airship length to diameter) was too large (indicating the airship might be difficult to maneuver), the process flowed backwards, the airship's length was increased, and the data flow was reaccomplished. Also, hydrogen was selected to be the lifting gas as it was easy to manufacture and could serve as a main supply source for the fuel cells.

Power is the critical enabler to this new airship concept. Based upon commercially available components, the power needs of the propulsor engines; the guidance, radar and communications subsystems; and the fuel cells assembly were determined. This established the Airship Power Demand inputs.

Later, total Airship Power Production capabilities were analyzed. Parameters included air and hydrogen consumption rates of the fuel cells and the resulting power they produced. An internal Power Check was then performed to ensure sufficient total power was being produced. If not, the process flowed backwards to increase the number of fuel cells until satisfactory power was generated.

The Power Supply, Equipment, and Airship masses were subsequently calculated to determine the airship's maximum takeoff weight. The overall Useful Lift was then computed using the air density, air pressure, and air temperature for each mission altitude being tested.

As can be seen, airship performance parameters are extremely interconnected; a change in one often can affect several others. To implement the DSM, the design process uses *Multidisciplinary Design Optimization*, a field of engineering that uses adjusting methods to help solve problems involving numerous, simultaneously interacting elements (Martins and Lambe, 2013). Using MDO, these various airship parameters can then be manipulated to determine the optimum combination of Size, Weight, and Power (SWaP) characteristics.

If there was insufficient lift, and the payload weight could not be further reduced, the process would flow back to Structure inputs to increase the envelope's length, which then increases the envelope volume and thus the airship's buoyancy. Then the full MDO process is repeated.

One uncomplicated means of conducting MDO analysis is to use an Excel spreadsheet and link the numerous airship parameters together from tab to tab (see Figure 5). As the length of the airship is adjusted, changes in the fineness ratio and overall buoyancy values are recalculated. Changing the solar array size then directly affects the power production totals, which then drives the need for additional fuel cells, which increases the overall airship weight, thus requiring further adjustments in the airship length. A key objective is avoiding a recursive design problem that becomes unresolved.

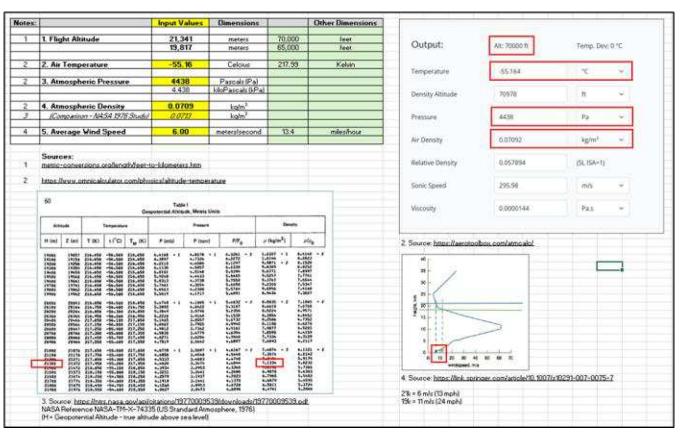

Figure 5. Airship MDO Excel Spreadsheet Example.

Component Design Phase

During this phase, actions convert the previously derived requirements of *what* the system is to perform into specifications of *how* the required functions are to be implemented in hardware and software. Overall, it can be viewed as now moving from the *Logical Viewpoint* to the *Physical Viewpoint* (Borky and Bradley, 2019).

Design Results

By following the systems engineering Vee model process, stakeholder requirements can be determined, the overall system architecture can be developed, subsequent subsystems can be designed, and all elements successfully tested, verified and validated. The tentative results for those activities are highlighted below.

Environmental Considerations

As one ascends into the stratosphere, the atmospheric temperature drops to nearly −60 °C (−76 °F). At this very high altitude, the atmosphere is a thousand times thinner than at sea level (only ~ 1.4 millibars). This extremely thin air is very dry, contains very little water vapor, and thus few clouds form within this layer (Pidwirny, 2024).

In addition, a 1975 NASA study determined wind speeds typically peaked at 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). It would appear the region between 10 km and 20 km should be reasonably calm for long duration airship operations (Beemer, et al., 1975.)

Structural Subsystem Design

The gas envelope forming the shape of the airship is a critical element to the vehicle design. Most gas envelope airship designs being proposed have been low-drag, axisymmetric 2-dimensional bodies of revolution (see Figure 6 for a typical example) (Manikandan and Pant, 2021).

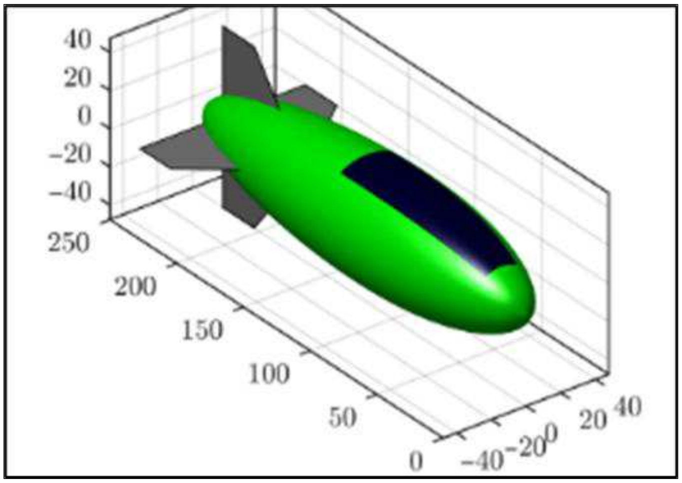

Figure 6. Airship Envelope Design (in feet.)

In 2007, NASA's Langley Research Center conducted an Analysis of Alternatives study of various high altitude long endurance unmanned aerial vehicles configurations. Their study developed several conservative factors for consideration during airship design (see Table 3) (Nickol, et al., 2007).

Factor	Value
Endurance	180 days
Takeoff Gross Mass	28,870 lbs
Maximum Length	140 m (469 ft)
Maximum Diameter	40 m (134 ft)
Gas Envelope Volume	124,000 m^3 (4,398,300 ft^3)
Technical Risk Estimate	TRL 6

Table 3. 2007 NASA AoA Study Results.

Based upon NASA studies and numerous airship design articles, the initial Structural parameters for airship length and diameter were calculated using the MDO spreadsheet. The maximum length, width, volume, and surface area were then computed (see Table 4). Additional modeling and physical prototype development is clearly necessary here to ensure these estimates are workable.

1 - Airship Dimensions CA	Inputs	Outputs
1. Airship Length (m)	***100.0***	
2. Fineness Ratio	***3***	
3. Airship Diameter (m)		33.3
4. Envelope Volume+ (m^3)		**58,178**
(Konstantinov - 2003)		*58,178*
(War Department - 1941)		*57,264*
5. Envelope Surface Area+ (m^2)		**8,142**

Table 4. Structural Parameters Example.

Propulsion Subsystem Design

Based upon the derived system CONOPS, the airship must remain airborne for weeks at a time. Therefore, a propulsion design using fuel-powered engines was not deemed practical. Instead, it was envisioned a tail-mounted, electrically-driven motor and propellor unit would be suitable.

Figure 7 provides an example of the H3X HPDM-350 electric motor (*HPDM-350,* 2025). Each motor turning very slowly at 90 RPM and at 90% efficiency, this results in an electrical power demand of approximately 9.5 kW. When using six motors (e.g., during critical takeoff and landing phases), the motor power demand would equal 57 kW.

Figure 7. Airship Electric Motor Example.

Detection Subsystem Design

For this project, specific radar parameters were developed (see Table 5.)

Parameter	Value
P_t	20 kW
G_t	30 bd (= 1000 linear)
G_r	30 bd (= 1000 linear)
λ	0.0375 m
σ	Large Bomber (=125 m^2)
n_p	21 (integrated pulses per dwell)
$(4\pi)^3$	= 1984
R	320 NM = 592,640 meters
k	1.38 x 10^{-23} watt-sec/K
T_0	950 K
B_n	1.67 MHz
L_s	8 bd (= 6.3 linear)

Table 5. Radar Parameters Example.

These parameters were then inserted into the *Radar Range Equation* to compute the overall Signal-to-Noise (SNR) ratio of the subsystem to determine the viability of the design. An SNR measurement exceeding 13 dB is considered sufficient for target detection (Richards, Scheer, & Holm, 2010):

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

$$\frac{(0.02\,x\,10^6)\,(1000)\,(1000)\,(0.0375)\,(0.0375)\,(125)\,(21)}{(1984)\,(592{,}640)^4\,(1.38\,x\,10^{-23})\,(950)\,(1.67\,x\,10^6)\,(6.3)}$$

$$= 13.22 \text{ dB}$$

As shown, these proposed surveillance radar parameters appear to produce a reasonable SNR for detecting large bomber aircraft at long distance.

An example of a commercially available radar unit that could be suitable for this project is the *Leonardo Seaspray 7500E V2* radar, currently employed on General Atomics MQ-9 *Reaper* UAVs (see Figure 8 and Table 6) (*Leonardo Corporation*, 2024).

Figure 8. Seaspray 7500E V2 Radar.

Frequency	X-Band
Type	Active Electronic Scanned Array
Max Range	320 NM (368 miles)
Size	1.1 (45”) x 0.5 m (22”)
Weight	104 kg (230 lbs)
Power	3.3 kW
MTBF	2,000 hrs

Table 6. Detection Subsystem Characteristics.

Communication Subsystem Design

A Tactical Data Link (TDL) is an electronic data transmissions means allowing participating military units to transmit tactical data to each other using UHF radio. The TDL commonly used today is *Link-16* (General Accountability Office, 1990).

To maximize detection timing, it is proposed airships would fly out and establish patrol flights up to 1,500 miles off the northern coast of the North American continent (see Figure 9.) Unfortunately, these extreme distances are too great for normal UHF radio transmissions for ground-to-airship communications, as UHF works best at a maximum line-of-sight transmission limit of approximately 300 miles (Seybold, 2005).

Figure 9. Long Distance Communications.

In 2023, U.S. Space Force announced it had successfully demonstrated the first-ever two-way transmission of Link-16 data using a low earth orbit satellite network (Space Development Agency, 2023).

As these early warning airships will be operating over the North Pole region, they cannot transmit their data to geostationary satellites. The solution would be to transmit their data to highly elliptical *Molniya* satellites that spend the majority of their time orbiting overhead the Arctic (McGraw, et. al., 2017).

Thus, using commercially available, highly elliptical satellites to send and receive both vehicle system telemetry and radar sensor data via Link-16 would seem to be a reasonable solution to overcome this long distant communications challenge.

Power Subsystem Design

A suitable means for providing airship power during daylight hours can be accomplished using thousands of photovoltaic (PV) cells that convert sunlight into electrical energy. As sunlight photons strike the PV cell, electrons are ejected from the semiconductor material creating both free electrons and vacancy holes. When influenced by an electric field, negatively charged electrons drift toward the positively charged holes resulting in direct current flow (Bosio, et. al., 2020).

Using PV panel arrays to provide airship power has been successfully demonstrated on numerous commercial prototype airships over the past several years. One example of these arrays is shown on the 270-ft Sceye airship during its 24-hour test flight (see Figure 10) (*Sceye*, 2024).

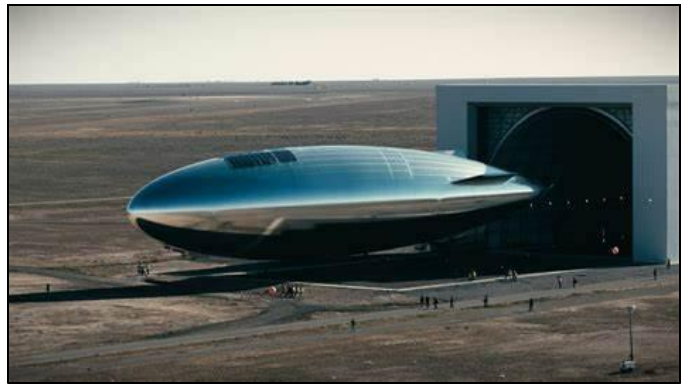

Figure 10. Sceye Airship with Solar Arrays.

Unfortunately, collecting solar energy while positioned over the North Pole becomes very problematic. The available sunlight at the North Pole ranges from continual sunlight in summer to continual darkness during wintertime (*Daylight*, 2024).

Interestingly, it was determined for an airship to remain within line-of-sight of the sun while precisely over the North Pole in winter, the airship would need to be situated 349 miles in space (see Figure 11) (Furth, 2024). Clearly not feasible in an airship! Thus, using fuel cell power became mandatory.

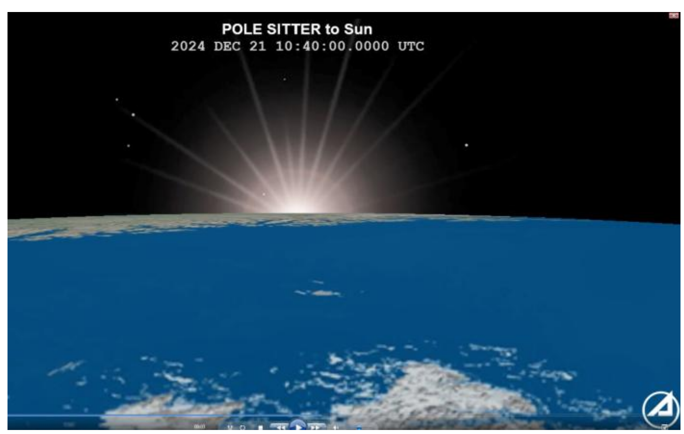

Figure 11: View of the Sun Over the North Pole on Winter Solstice.

To simplify the airship design, one option was to eliminate using solar panels completely and power the airship using only fuel cells. These cells convert the chemical energy of a fuel (e.g., hydrogen gas) and an oxidizing agent (e.g., oxygen gas) into electricity. Fuel cells offer the cleanest power generation possible, are quiet in operation, and are best used as a steady energy source of power rather than for dynamic power demands (*Fuel Cells*, 2015).

During power production, the excess water produced by the fuel cell chemical reaction can be run through an electrolyzer where it is broken down into hydrogen and oxygen components and resupplied into reagent tanks for reuse (Liao, et al., 2018).

Several commercially available *Proton-Exchange Membrane* (PEM)-based fuel cell assemblies using a platinum catalyst and Nafion^{tm} electrolyte can generate up to 550 kW of power at 80% efficiency (see Figure 12) (Alaswad, et. al., 2008).

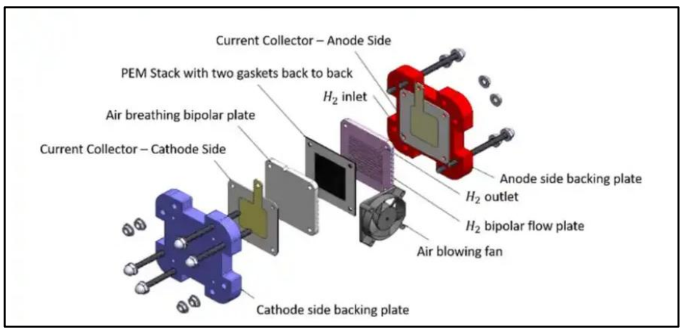

Figure 12: PEM Fuel Cell Elements.

Totaling the power estimates for the propulsion, guidance, detection, communications, and power subsystems resulted in a total power demand of 85.5 kW (see Table 7). This amount of power seems quite reasonable for the fuel cell assembly to supply.

Propulsion	76 kW
Guidance	550 W
Communications	350 W
Detection	3.6 kW
Support Equipment	5 kW
Total Demand	85.5 kW

Table 7: Estimated Total Power Requirement.

Final Lift Check

Finally, Lift Checks were performed to test if each proposed airship mass could be successfully launched to various altitudes (see Figure 13).

8 - Airship Lift CA	Inputs	Output
(7. Mission Altitude - Air Pressure+) (Pa)	26,436	
(10. Mission Altitude - Hydrogen Pressure+) (Pa)	71,436	
(12. Hydrogen Volume (Unconstrained)+) (m3)	61889	
(13. Hydrogen Volume (Constrained)+) (m3)	58178	
(14. Air Volume in Ballonet+) (m3)	0	
(15. Hydrogen Volume Leaked+) (m3)	3712	
(49. Initial Hydrogen Mass+) (kg)	3,918	
51. Mission Altitude - Hydrogen Mass Remaining+ (kg)		3,683
52. Displaced Air Mass by Rigid Envelope (kg)		18,594
53. Air Mass in Ballonet (kg)		0
54. Total Envelope Gas Mass (kg)		3,683
55. Mission Altitude - Lifting Force (N)		146,275
56. Mission Altitude - Useful Lift+ (kg)		14,911
(50. Maximum Takeoff Mass+) (kg)	7,025	
57. Lift Check		1

Figure 13: Final Lift Check.

If the Lift Check failed and the payload's mass could not be further reduced, the gas envelope volume was expanded to increase the airship's buoyancy. This was accomplished by increasing the airship's length and repeating the entire DMO process.

Using this iterative DMO process, system modeling demonstrated as the mission altitude was raised, the total mass the airship was capable of lifting continuously decreased due to the rapidly decreasing air density at higher altitudes.

After accomplishing numerous simulation scenarios, it was eventually shown all altitudes above 13,650 meters resulting in the airship mass increasing faster than the lift being generated by increasing the volume of envelope material and adding more hydrogen, resulting in insufficient lift being generated (see Figure 14).

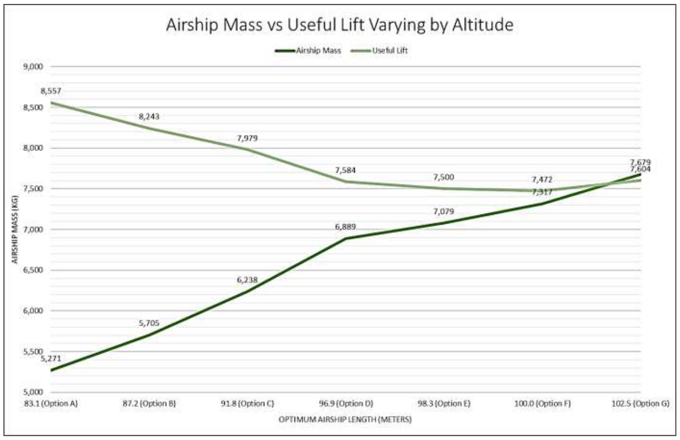

Figure 14: Airship Mass Versus Useful Lift.

Further optimization efforts were conducted, with the final results determining the prototype airship should measure 98.3 meters, have an envelope volume of 55,261 m^3, a takeoff mass of 6,787 kg, and operate at a mission altitude of 11,000 meters (36,000 feet.) At this altitude, the radar detection range would be 270 miles.

Areas of Concern

- High Altitude Propellers. At this extreme stratospheric altitude, the air pressure is a thousand times less than at sea level. Employing electrically-driven propellers in this extremely thin atmosphere would require further testing.
- Envelope Fabric**.** Another area of concern is the harsh environment an airship would experience at stratospheric altitudes. The effects of long-term extreme cold and ozone exposure on airship elements at this altitude are concerning. This topic would require extra research and experimentation during gas envelope fabric material design.
- Satellite Data Link**.** Finally, while data link transmission over satellite relay was recently demonstrated, this is still a new capability. Using prototype testing using commercially available satellite services would reduce the uncertainty of this method.

Conclusion

Designing a high-altitude airship can be viewed in systems engineering terms: the proposed airship is a system consisting of various subsystems each having numerous requirements, there are design considerations that have conflicting perspectives, and a key consideration must be conducting continuous component verification and validation testing throughout development.

As outlined in this paper, using both the Vee model approach and the Kossiakoff systems engineering method results in successfully identifying the key subsystems needed for this proposed airship and the viability of each of the subsystem components.

Numerous NASA technical studies and real-world airship prototypes are demonstrating airships will soon become a reality. The elements that make up this proposed early warning airship are realistic and are based upon both scientific analysis and real-world capabilities.

This concept offers greatly extended air surveillance coverage and could act as a tripwire for the early detection of any advancing hostile forces. Based upon the research conducted to date, this stratospheric early warning airship approach has yet to be proposed in any research paper.

In summary, developing this novel early warning airship would serve as a unique contribution to both the systems engineering profession and the NORAD air defense community.

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