Applications of Scientific Ballooning Technology to High Altitude Airships

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ABSTRACT

In recent years, the potential use of High Altitude Airships (HAA) as a platform for surveillance or communications operations has attracted growing interest. Many technical obstacles exist with regard to the successful launch, flight, and recovery of such systems.

Many decades of technological innovation in the field of scientific ballooning have resulted in a number of technologies that are directly applicable towards the success of the HAA platform. Among these are advances in materials, design, and launch methods. Discussed herein are potential applications of these technologies towards the development of a viable High Altitude Airship system.

HISTORICAL BACKGROUND

The concept of a buoyant stratospheric vehicle which can hover over one geographic location for long periods of time has been a "Holy Grail" in the LTA community for decades. The utility of such a vehicle is obvious. Lift would be provided by an envelope of lighter-than-air gas and would require no power. The only power requirement would be to power a propeller to push the vehicle against the wind, and to power the usable payload. If the vehicle were to be stationed high enough, very large areas on the ground could be in line-of-sight contact. The stratospheric vehicle could be used for a variety of purposes such as communications or surveillance.

Over the last thirty-five years, several programs have taken place that have attempted to develop stratospheric station-keeping airships for a variety of purposes. Several of these were paper studies which never resulted in the development of any flying prototypes. The only programs which had any success were started with modest goals for payload, duration, and station keeping capability.

Although it is out of the scope of this particular report, it is worth mentioning that several programs have also been undertaken which attempted to solve the general problem by using tethered aerostats at very high altitudes. Most of these programs were thwarted by problems associated with tether dynamics.

High Platform

In the late 1960's, Raven Industries was contracted to build a small stratospheric airship as a technology demonstrator.[1] The High Platform II vehicle was designed for a small payload of five pounds and a cruising altitude of 67,000 feet. Since it was designed as a technology demonstrator, the vehicle was programmed to track the sun during the flight. The demonstration flight was considered a success by flying for two hours under power. It also did not carry any batteries, so it could not operate at night. This is quite possibly the only airship ever to fly under power in the stratosphere.

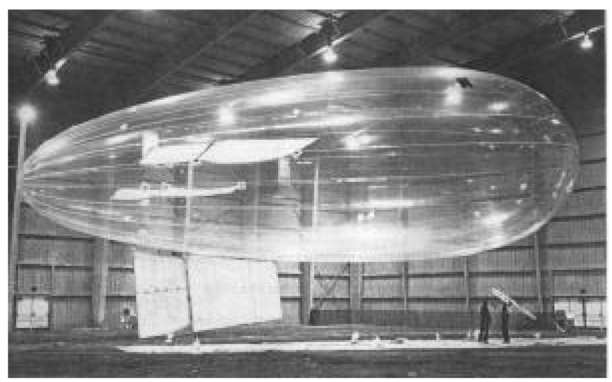

Figure 1 - High Platform II, The World's First Stratospheric Airship

The High Platform III design study in 1971 completed a design for an airship to carry 200 lbs to 70,000 feet, the study concluded that the concept was feasible, but further development work was not funded.[2]

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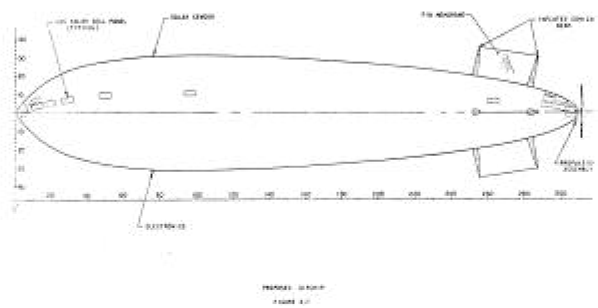

Figure 2 - The High Platform III Design

POBAL

The POBAL program began with a test of an experimental propulsion system at 60,000 feet using a natural shape balloon.[3] The twelve hour flight showed that there were problems with stability in controlling the direction of a natural shaped balloon's direction.

HASKV

Raven was once again contracted by the Air Force to conduct a design study on the problem of stratospheric station keeping.[4] The major outcome of the High Altitude Station Keeping Vehicle (HASKV) study was the detailed comparison of a variety of propulsion possibilities.

POBAL-S

The POBAL-S design study, by Raven, further refined the trade studies from HASKV.[5] Detailed designs for propulsion system mounting, empennage mounting, and launch operations were developed.

HASPA

After all of the design studies conducted under the High Platform III, HASKV, and POBAL-S, Martin was selected to build the first large scale stratospheric airship.[6] The project was not successful because of fabrication, material, and operational problems. Much of the design and operational concepts for HASPA came from the HASKV and POBAL-S studies. Although the payload for the HASPA test was only 200 pounds, the operational concept was developed for launching payloads of up to 6000 pounds.

HAPP

NASA conducted a large general study called High Altitude Powered Platform in the late 1970's.[7] This project studied both airship and airplane technology. The study was also the first to seriously study the feasibility of powering the platform by using high powered microwave energy beamed to the platform.

HI Spot

HI Spot was another study contract sponsored by the Navy for the purpose of developing an over-the-horizon fleet defense system. The study was centered on carrying huge radar systems to the stratosphere to detect low flying aircraft and cruise missiles. The payload for this project was also several tons. While feasibility was shown in the study, the system was extremely expensive and complex. No full scale development was funded.

Sky Station

Sky Station International was a for-profit venture which started with the goal of carrying a 10,000 pound communications payload to 100,000 feet for ten years.[8] Although millions of dollars were spent in design activities, the company never produced any airships.

Sounder

The Sounder Program, was only the second high altitude airship program to produce a flying stratospheric model. The system was designed to carry a usable payload of 20 pounds to 70,000 feet.[9] Propulsion was from a stern mounted propeller powered by an electric motor. The batteries for the motor were charged by an internal gimbaled solar array. The gimbaled solar array pointed directly at the sun during the daytime portion of the flight and greatly reduced the number of solar cells required.

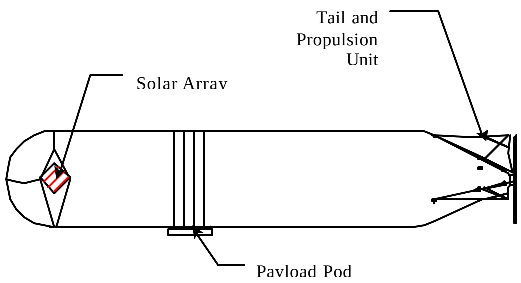

Figure 3 - Sounder Airship Configuration

The program had three full scale test flights. The first flight successfully reached superpressure float altitude, but failure of the empennage structure during ascent prevented successful operation of the propeller. The second flight identified deficiencies in the ability of the nylon film hull to be stored for long periods of time. The third flight failed during pressurization at float altitude. The cause of the failure of the third flight is under review.

PERFORMANCE REQUIREMENTS

Usable Payload Mass

As demonstrated in the historical review above, the mass requirements of the usable payload is the single most important driver in the design of a stratospheric airship vehicle. The size of the hull is driven by the payload size, thus material selection, fabrication methods, launch techniques, power requirements, etc. The mistake made in the development of previous airships was to go directly from small, hand launched systems to enormous payloads of several tons. The principle of incremental success was violated in scaling up the capabilities of the vehicles. As a result, the programs were all cancelled before any reasonable amount of success was achieved.

The reasonable approach to developing stratospheric airship capability is to begin with small hand launched systems. Systems would then be gradually increased in capability and operational experience while working up to the largest payloads. Along the way, practical uses will become evident for all of the intermediate vehicles.

Altitude

A rule of thumb in balloon design in stratospheric altitudes is that the balloon volume doubles for every ten thousand feet in required altitude for a given payload. With that in mind, it is obvious that the altitude of a station keeping platform must be carefully selected in order to minimize altitude while meeting operational objectives. An equally important factor in selecting an operational altitude is to minimize the amount of power required to station keep by selecting an altitude with the minimum winds. This minimum wind altitude generally exists between sixty and seventy thousand feet.

Mission Duration

Perhaps the most common misconception about the technology requirements for stratospheric airships concerns the ability to fly missions lasting several months or even years. No stratospheric superpressure balloon system with a payload of more than a few ounces has ever flown reliably at middle latitudes for more than a month. There were a number of superpressure balloon programs conducted by NCAR in the U.S. and CNES in France.[10] These programs produced flights up to125 days at 78,000 ft, but average performance at these altitudes was less than a month. Zero pressure scientific balloons must drop ballast with each sunset, limiting their practical flight duration to only a few days.

NASA’s Long Duration Balloon (LDB) project employs zero pressure balloons to carry payloads up to four tons to over 120,000 feet.[11] These balloons have flown for durations over thirty days, but this is only possible in polar areas during the summer months when the solar heating on the balloon is almost constant. NASA’s Ultra Long Duration (ULDB) Project will develop large superpressure balloons that are not as susceptible to diurnal changes in balloon temperature.[12] Instead of being open to the surrounding atmosphere, the ULDB will increase in pressure after the balloon is fully inflated. After reaching an equilibrium, the systems flies at a constant density altitude while the pressure increases and decreases from day to night.

In order to achieve success in deploying a superpressure balloon, a careful balance of high strength, low weight, and (most importantly) appropriate solar absorptivity and emissivity must be achieved. The structure and materials must also be practically impermeable to the lifting gas. The achievement of stratospheric flight for months at a time is a goal that must be approached with serious understanding of the challenges faced. In order to achieve durations of months or years, the failure modes that keep vehicles from flying for weeks must first be mastered.

Station Keeping Capability

The system's station keeping capability is generally defined by two parameters: station accuracy and percentage of time on station. The accuracy requirement is driven by the system's application. If the system is to be used for subscription high speed internet access, then the system would need to be confined to a one thousand foot cube in the sky for the subscribers' dishes to be pointed correctly. A highly sophisticated control system would be needed to carefully control the airspeed and attitude of the airship to keep it in its assigned service area. A less demanding application, such as visual surveillance, would require the system to remain positioned in an area the size of a city. Variations in position due to wind fluctuations could be compensated for by the pointing system of the camera.

The percentage of time on station is a major driver for the power system of the airship. The system would need to be designed to remain within its desired accuracy for the highest winds encountered within the desired percentile at the altitude selected. Once again, the application of the system will determine the desired percentile. For the internet access application, the percentile could be as high as 99.9%. This could have a power requirement that is many times that of the surveillance platform that could have a desired percentile of 90%. Some studies have suggested that the minimum wind zone does not even exist in many areas of the world in winter time. In order stay on station, the study suggests that air speed capabilities of 80 knots would be necessary.[13]

AIRSHIP HULL

Aerodynamic Shape

A number of quite detailed studies have been conducted over the years to determine a shape that has minimum drag and maximum stability. It should be noted, however, that many of these studies were targeted at flight at low altitudes. When selecting a shape, consideration should be given to the fact that a stratospheric airship will operate at altitudes many times that of conventional airships with the correspondingly less dense atmosphere.

Buoyancy Control

At different phases of the flight, it may be necessary to adjust the altitude of the airship. This can be accomplished by pressurizing air inside an internal chamber in the balloon hull. By adding mass to the system in the form of pressurized air, the system can be made to descend. Likewise, releasing pressurized air or solid ballast will make the system rise. The main problems associated with buoyancy control is accomplishing altitude changes with the least amount of energy expenditure and with the least amount of permanent loss of lifting gas.

Materials

The materials used for a stratospheric airship hull would resemble the materials used in long duration stratospheric balloons. They would be very thin and light with the proper amount of strength to withstand the required internal pressure. Some of the strength may come from the fact that the system is operating at much lower temperatures than those near the ground. Most polymer materials have greatly enhanced strength lower temperatures. The materials should also have thermal properties which favor stratospheric flight. They should absorb little solar heat during the day and emit little infrared heat to space at night. This will ensure that diurnal temperature swings will be minimized.

Unless an elegant method for redistributing material stresses in an airship hull can be developed, such as in NASA's ULDB project, it is unlikely that polyethylene could be used by itself for a stratospheric airship hull. The strength of polyethylene is not high enough to withstand the stresses of superpressure flight. Table 1 presents a summary of materials used for the development of long duration scientific balloons.

Material	Use
Polyethylene	The "Work Horse" of scientific ballooning. Limited to use on zero pressure balloons until the ULDB project. Elastica shape and stress distribution allows the use of polyethylene.

Polyester (Mylar)	Highly oriented polyester film commonly referred to as Mylar. Susceptible to microscopic pin hole leaks created in material manufacture and in handling during balloon fabrication.[10]
Laminated Polyester	Pin hole problems were addressed by using two or three sheets of Mylar laminated together to cover pinholes. This material was used successfully on many NCAR superpressure programs [10]
Polyester film with fiber scrim	In an attempt to increase the strength to weight ratio of balloon materials, scrims were developed by Raven and Sheldahl. The resulting performance of these balloons was not a clear cut success. Problems included development of equivalent seam strength and leaking seams.[10]
Laminated Fabric	Composite materials of very light weight fabric film were developed under the NASA ULDB project. The development was discontinued after structural changes allowed the use of polyethylene[14]
Biaxially Oriented Nylon Film	Selected for High Platform III and Sounder. Possesses excellent thermal and barrier properties. May have viscoelastic problems.

Table 1 – General Summary of Scientific Balloon Materials

In the list of materials above, most were less than 2.5 oz/yd². Many are less than 1.0 oz/yd². Compare this to the typical weights for low altitude airships and tethered blimps of over 7 to 10 oz/yd².

It is important to note in any discussion of stratospheric balloon materials the fact that the radiation environment on a stratospheric balloon is very intense. Experimental results have shown that the breakdown of materials in the stratosphere could possibly be abated by the decreased concentration of oxygen atoms in the stratosphere.[15] **NCAR flights** showed a marked decrease in balloon life with increasing altitude. This suggests that some degradation mechanism is at work in the stratosphere.[10]

Thermal Balance at Cruising Altitude

As stated above, it is advantageous to minimize the swing in temperature between day and night of the airship hull. If the hull becomes too hot during the day, added strength will be necessary to compensate for the increased pressure. One advantage of the airship over a free floating stratospheric balloon is the fact that the moving airship will have forced convection over its hull to damp diurnal temperature swings. Proper thermal modeling of the system will be necessary to calculate daytime stresses and select materials.

Fabrication Methods

Like long duration scientific balloons, the methods used to assemble the panels in the airship hull must produce joints that are as strong or stronger than the panels themselves. The adhesives or other compounds used in the fabrication method must also be compatible with the panels in the full range of operating temperatures of the airship. Many adhesives work quite well at room temperature but become very brittle at the temperatures that stratospheric airships must operate in.

Attachment Points

The attachment points for the payload and other accessories on the hull must be compatible with the hull materials and be capable of surviving the full operating temperature range of the system. The attachment points must also be designed in such a way that the stresses are properly distributed around the hull of the airship and not introduce excessive point loads on the thin hull materials.

AIRSHIP CONTROL

Power System

A stratospheric airship will be expected to stay on station at night as well as during the day. Power systems must be designed to both power the on-board electrical systems and charge batteries during the day. The charged batteries will then be used to power on-board electrical systems during the night. The design of the power system will be effected by the latitude, time of year, and cost of the solar cells.

Propulsion

The design of the propulsion system, which is driven by the station keeping requirements, should be optimized to operate at the specific altitude selected for the mission. The popellers and the structural components supporting them should be sized for the amount of torque that will be developed in providing the maximum speed specified by the station keeping requirements.

Directional Stability and Control

Low altitude airships have significant pitch and yaw control capabilities. High altitude airships do not require the pitch capabilities required by traditional airship launch and landing operations. In order to simplify design requirements, it is expected that the flight of a stratospheric airship will be controlled only in the yaw axis. Up and down motion would be carried out with buoyancy control methods.

Airship hulls do not naturally point into the free air stream. A properly sized and positioned vertical stabilizer must be attached to the rear of the hull to move the center of pressure far enough aft of the centers of gravity and buoyancy to allow stable flight in a straight line.

Telemetry and Control

For ascent, high speed position, attitude, and hull "health" data must be relayed to a ground control station. During the cruising phase of the flight, this data can be relayed at a much slower rate, thus conserving power for propulsion. During long term cruise phases, autonomous control of position and buoyancy is expected.

OPERATIONAL CONCEPTS

Traditional Airship Operations

Under the term "traditional airship operations", the airship would launch from the ground fully inflated, carry out its mission, and then descend and land like a traditional airship. This operational concept is the most complicated and requires the most amount of ground handling equipment. After a very long flight, the hull may not be able to withstand the rigors of descent and landing. It also requires the use of blowers to inflate air chambers in the hull as the helium contracts during descent. With modest payload requirements, the size and cost of the hull would allow for disposable hull operations. As the size and cost of the hull increases, the cost of the hull may justify intact recovery and refurbishment for reflight. The economics of such as system would be decided in a carefully executed trade study.

Flaccid Launch with Disposable Hull

The flaccid launch concept is the most like the typical scientific balloon launch. The amount of helium at ground level is put in the balloon and the rest of the envelope is left uninflated. This type of launch is well developed and the potential difficulties are well understood. In application to stratospheric airships, the most difficult aspect is in the last portion of ascent as the hull becomes fully inflated. Scientific balloons simply deploy and stop ascending as they reach equilibrium. Elongated airships tend to pitch down violently as the center of buoyancy moves aft. This can cause unforeseen stresses on the empennage. To counteract this affect, some concepts have developed movable payload pods, or carried extra ballast in the tail to keep the center of gravity aft long enough for the balloon to reach equilibrium.

The biggest advantage of the flaccid launch is that it requires the least amount of ground handling facilities for the airship. Like a scientific balloon, it is inflated and launched outdoors at an airport or specialized launch facility.

The major disadvantage of the flaccid launch concept is that there is no way to know if the envelope is "healthy" until it is at its operational altitude. Even if it is fully inflated and checked out before launch, there is still uncertainty about possible damage that could be introduced during the deflation and packing process after check-out.

Once the system has completed its mission, the payload would be released from the envelope and would be parachuted back to the ground. This concept is also very consistent with scientific balloon operations and has been proven reliable over thousands of flights.

Fully Inflated Launch with Disposable Hull

Like the traditional airship operation, this concept would allow the complete system to be integrated and checked out inside a hangar. Once weather conditions are favorable, the system would be walked outside and launched. Small amounts of ballast would be dropped to give the system positive buoyancy and allow it to reach cruising altitude without the oscillations observed in flaccid launches. The initial inflation would be with helium in an expandable chamber with air making up the majority of the volume of the hull on the ground. The air would be expelled through a valve by the pressure of the expanding helium.

Like the flaccid hull launch, the payload could be brought down to the ground by parachute and possibly even returned to a designated area by a steerable parachute.

CONCLUSIONS AND RECOMMENDATIONS

There have been numerous design studies centered around the problem of stratospheric station keeping. Only a few programs have attempted to build flying models and only one has resulted in a completely successful flight. Unfortunately that one successful flight probably would not have flown through a day/night cycle even if it had be equipped with enough storage batteries to power the propulsion system. Based on this limited amount of success, the next twenty years were spent trying to rapidly scale up without having the advantage of any operational experience with stratospheric airships. The concept has been plagued with attempts to "run before learning to walk". By combining experience from scientific ballooning and low altitude airship design, a reasonable development program can be established. Over time, the development program can gain operational experience with smaller systems and then build on that experience to increase payload capability and other operational requirements.

Recommended Development Roadmap

Based on the overall recommendation to reduce the initial requirements for a stratospheric airship, a roadmap for development is presented below:

1. Set a modest payload and mission time requirement of less than 20 pounds and less than one week
2. Develop a demonstrator that would first fly under battery power, without solar panels
3. Conduct at least five flights with the demonstrator. The last two or three flights would last 24 hours to gain thermal performance data.
4. Add solar cells to increase duration ability and fly multi-day missions
5. Once operational mastery has been achieved, increase payload and speed capability in manageable increments

Even though the major end user community wants payloads of over 1000 pounds, the prudent development cycle is to work up that that capability incrementally. As the intermediate systems are developed. Uses for them will be identified. Some of the intermediate uses may actually render the ultimate specification obsolete.

Recipe for Disaster

Even with the recommended development plan, unforeseen engineering problems will be encountered. It is important to remember that a major failure with a one hundred thousand dollar vehicle is called a learning experience. A major failure with a ten million dollar vehicle is a career killer. In order to avoid major failures with huge experimental vehicles in unforeseen failure modes, a set of "program killer" specification is offered:

- Start with over 1,000 pounds for the target payload
- Set the station altitude above 80,000 feet
- Set the initial duration requirement at more than two weeks
- Require that the system station-keep inside an area the size of a football field
- Set payload power requirements equal to that of a small city
- Require the system to carry people
- Schedule a full-scale demonstration flight in two years (with any of the above requirements)

REFERENCES

In addition to the traditional bibliographic entries, the GSFC Balloon Technology Library access number is provided at the end of each citation, where applicable.

1. Rupp, D. T., Beemer, J.D., Swindern, L.R.; High Platform II Final Report, August 14, 1970; Raven Industries, Inc.. (BT-2150)
2. Beemer, J.D. , Swinden, L.R., Rupp, D.T.; High Platform III Design Study, Final Report; August 31, 1971; Raven Industries, Inc. (BT-2154)
3. Munson, James B.; Design and Manufacture of a 670,000 Cubic Foot Natural ShapeBalloon for Project POBAL; September 15, 1972; G.T. Schjeldahl Co. (BT-1204)
4. Beemer, J.D. et.al; Study of High Altitude Station Keeping Vehicles, March 15, 1973 (BT-2178
5. Beemer, J.D. et.al; POBAL-S, The Analysis and Design of a High Altitude Airship, Final Report; February 15, 1975; AFCRL-TR-75-0120 (BT-2197)
6. Scales, S.H.., McComas, C.B., High Altitude Superpressured Powered Aerostat (HASPA) Demonstrator Program, Final Report; September 30, 1977; Martin Marietta Corporation. (BT-2776)
7. Proceedings of the High Altitude Platform Workshop, Washington D.C., 26-27 July, 1978.

Presentation by Norman Mayer, NASA , P 141 (BT-2497)
8. Sky Station International Web Site.
9. Smith, M.S., Perry, B.P., Lew, T.L.; Development of a Small Stratospheric Station Keeping System; Proceedings, ISTS, 2000; Morioka, Japan; ISTS-2000-k-15
10. Proceedings of the High Altitude Platform Workshop, Washington D.C., 26-27 July, 1978. Presentation by Vincent Lalley , NCAR P 122 (BT-2497)
11. Nock, Robert, Kubara, Robert; The NASA Long Duration Balloon Project; Presented at: AIAA 32nd Aerospace Sciences Meeting, Reno, NV, 10-13 January 1994 (BT-2464.17)
12. Cathey, H.M.; The NASA Ultra Long Duration Balloon Vehicle; Presented at: AIAA International Balloon Technology Conference, June 28, 1999, Norfolk, VA AIAA-99-3867
13. Proceedings of the High Altitude Platform Workshop, Washington D.C., 26-27 July, 1978. Presentation by Maynard Hill, Johns Hopkins University , P 257 (BT-2497)
14. Smith, M.S., Schallenkamp, R.S.; The Development of Revolutionary Balloon Materials; Presented at: AIAA 34th Aerospace Sciences Meeting, Reno, NV, 15-18 Jan 1996 (BT-2518.03)
15. Rainwater, E.L.; McLaughlin, Joe; The Effects of Oxygen Upon Strength Degradation of PBO Cordage; Presented at the AIAA 3rd Aviation Technology, Integration, and Operations (ATIO) Technical Forum, Denver, Colorado, November 17-19, 2003.