Test Flights of the Revised ULDB Design

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Development of the National Aeronautics and Space Administration's Ultra Long Duration Balloon has focused over the previous year on ground testing and analysis to understand the previously observed issue of balloon deployment. A proposed a new approach to the pumpkin balloon design and fabrication has been the subject of these ground tests and analytical efforts. This new approach should increase the probability of balloon deployment, does not require foreshortening, and will significantly reduce the balloon handling during manufacture reducing the chances of inducing damage to the envelope. The scaled models have provided a subset of the required information to determine if the deployment issue has been fully addressed. Analytical predictions demonstrate that the proposed flight balloon designs are stable and should fully deploy. The only way to fully assess the suitability of the proposed design approach is to actually build and fly flight structures. The test flight structures are intended to be increased in a stepwise development approach with successive test flight balloons increasing in both suspended weight carrying capability and in increased float altitude. This paper documents the first test flight of this revised Ultra Long Duration Balloon design; a short domestic test flight from Ft. Sumner, NM. A brief overview of the fabrication of these ~176,000 m^3 (~6.2 MCF) flight structures, based on knowledge gained from testing and analyses, will be presented. A description of the test flight balloon will be given. The test flight goals and success criteria for will be highlighted along with the test flight plans. An assessment of the balloon deployment will be given. Test flight results including flight performance will be presented. A brief lessons-learned and information on future Ultra Long Duration Balloon test flights will also be presented.

I. Introduction and Background

The NASA Ultra Long Duration Balloon (ULDB) project is managed by the Balloon Program Office at Wallops Flight Facility in Wallops Island, Virginia. The goal of the ULDB project is to develop a balloon vehicle capable of carrying a 2721 kg payload to 33.5 km for up to one hundred days. The project, established in 1998, has conducted a total of eight test flights. Each flight has provided valuable engineering data for the design team. It is important to point out that the weight limit for the previous generation of stratospheric superpressure balloons was approximately ninety kilograms. The advances in the level of technology brought about by the ULDB project are already benefiting balloon technology in standard zero-pressure balloons. A summary of test flights is presented in Table 1.

This summary of test flights shows that much has been learned about materials, fabrication methods, and design details. These design details include the method used for applying the tendons and shape of the individual gores in the balloon to maintain a stable shape. The failure modes encountered so far in the project have all been the types that would not allow for extended flight durations. As the program progresses to flying heavier payloads to higher altitudes, there is the potential to uncover further design challenges with these larger balloons. The design of these balloons is very new technology and should be viewed as such.

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Flight Date	Volume m3	Design Type	Launch Location	Flight Result
Oct. 1998	2350	Sphere with fabric/film composite shell.	Ft. Sumner, NM	Successfully pressurized and reached float altitude
Oct. 1999	60,000	Pumpkin with fabric/film composite shell and longitudinal tendons Foreshortened Tendon	Ft. Sumner, NM	Burst as it was pressurizing after reaching initial float altitude
June 2000	60,000	Pumpkin with polyethylene shell and longitudinal tendons Foreshortened Tendon	Ft. Sumner, NM	Successfully pressurized and reached float altitude - 30 hour flight.
Feb. 2001	510,000	Pumpkin with polyethylene shell and longitudinal tendons Foreshortened Tendon	Alice Springs, Australia	Failed to reach float - launch damage vulnerability of shell material revealed
Mar. 2001	510,000	Pumpkin with polyethylene shell and longitudinal tendons Foreshortened Tendon	Alice Springs, Australia	Successfully pressurized and reached float altitude - 30-hour flight. Shape stability problem first encountered with pumpkin balloon.
July 2002	594,000	Pumpkin with polyethylene shell and longitudinal tendons Foreshortened Tendon	Palestine, TX	Successfully pressurized and reached float altitude. Failed when an improperly attached tendon released.
Mar. 2003	594,000	Pumpkin with polyethylene shell and longitudinal tendons Foreshortened Tendon	Alice Springs, Australia	Successfully pressurized and reached float altitude. Shape instability observed. 20-hour flight.
Feb. 2005	176,000	Pumpkin with polyethylene shell and integrally sealed longitudinal tendons No foreshortening of tendons	Ft. Sumner, NM	Successfully pressurized, reached float altitude, and deployed. Failed soon after reaching float. Vulnerability of film to in-plant lighting discovered which caused an incomplete seal in the balloon.
Sept. 2005	168,000	Pumpkin with polyethylene shell and integrally sealed longitudinal tendons No foreshortening of tendons		To be flown in late Sept. 2005

Table 1 - Summary of ULDB Test Flights

II. Summary of the Revised Design

The shell configuration used for all flights before the January 2005 flight used a constant lobe angle design with extra material gathered along each tendon. The revised design utilizes gores that are the same length as the tendons. The stiffness of the tendons prevents the film from straining beyond the yield limit in the longitudinal direction. The difference between the lobe configurations of the two design concepts is illustrated in Figure 1.

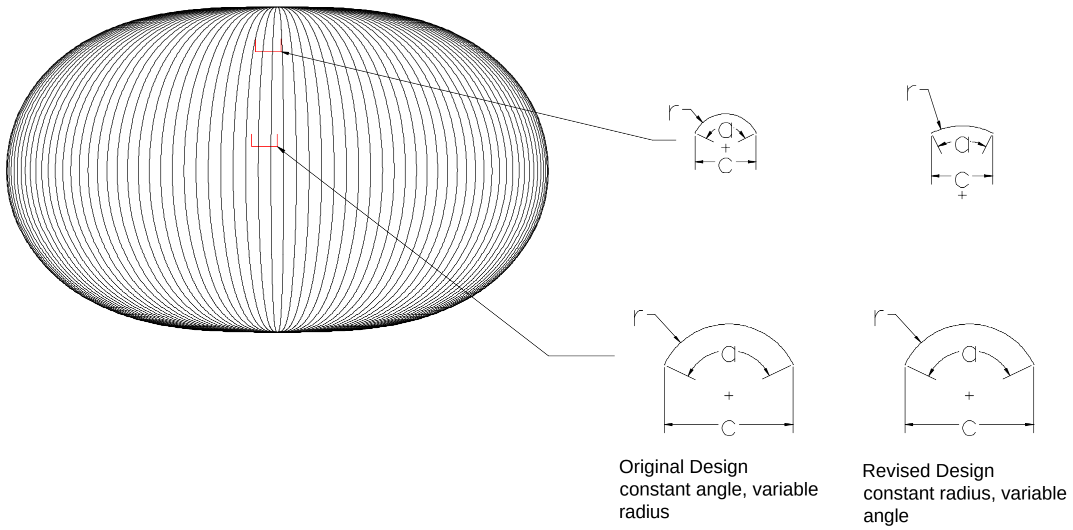

Figure 1 - Gore shape comparison of original and revised design ULDB. The revised design employs a constant lobe radius. The maximum angle occurs at the equator.

III. Incremental ULDB Development

Utilizing the new design approach of no foreshortening between the tendon and the film, an incremental development plan has been proposed. The specific steps increase the suspended load and float altitude toward the development of the balloon vehicle capable of carrying a 2721 kg payload to 33.5 km for one hundred days. These vehicles are presented in Table 2.

Suspended Load	Float Altitude	Balloon Volume	Number of Gores
1361 kg	30.5 km	~168,000 m3	200
1361 kg	33.5 km	~368,100 m3	~244
2721 kg	33.5 km	~631,500 m3	~290

Table 2 - Proposed ULDB Vehicles incrementally increase the suspended load and float altitude

The 1361 kg suspended mass was chosen to accommodate a payload and flight system that would be capable of extended flight duration at mid latitudes using existing systems in the NASA Balloon Program inventory. These flight systems include the structural support systems, power, communication, and control systems currently used on NASA Long Duration Balloon (LDB) flights as well as those unique to the ULDB flights such as the balloon differential pressure measurement and control system. The starting float altitude of 30.5 km was selected to initially limit the resulting balloon volume to a manageable size that can be fabricated and flown more easily.

The ~386,100 m3 balloon will use the same flight systems as the ~168,000 m3 balloon but will fly at the projects target altitude of 33.5 km. Again, this represents an incremental step in increasing the balloon by approximately doubling the volume. The next step will be to increase the suspended load to the projects desired level at the desired float altitude. This again will result in a balloon that is approximately double the volume of the previous one.

Test flight durations for these three designs will vary depending on the launch locations chosen. The desire will be to fly one of each size balloon in a short US domestic test flight for up to a day, and then to fly a longer duration flight with a second balloon. These longer test flights would be similar in nature to the highly successful LDB flights, but would demonstrate altitude stability and potentially longer durations. The desire will be to fly each of these balloons as long as possible.

The characteristics of the first balloon flown utilizing the new design approach of no foreshortening between the tendon and the film is presented in Table 3.

Nominal Payload	1360.5 kg
Nominal Float Altitude	30,511 m
Volume	175,720 m^3
Theoretical Gore Length	104.9 m
Cap Length	43.59 m
Diameter	79.9 m
Inflated Height	48.28 m
Height/Diameter	0.60426
Number of Gores	200
Max Gore Width	1.45 m
Shell Thickness	38.10 micron
Shell Area	17,199.21 m^2
Cap Thickness	20.32 micron
Tendon Denier	48,000
Lobe Radius	0.79 m
Equator Lobe Angle	0.0º
Max Pressure	240 Pa
Max Film Stress	4.98 Mpa
Max Tendon Load	6,084 N

Table 3 – February 2005 Test Balloon Characteristics

IV. Most Recent Test Flight Results

The latest test flight of the revised design ULDB was conducted on February 4, 2005. The general objective of this flight was to fully deploy the structure under low pressure and then incrementally increase the pressure inside the balloon to the maximum extent possible via dropping ballast or until failure. The general flight plan was to launch the balloon in the early morning with ~10% free lift. The balloon would be vented during ascent above ~18.3 km. The balloon would then be "eased" into float at a relatively low ascent rate and the balloon allowed to deploy with a minimal pressurization. Ballast drops would then be made to increase the differential pressure up to the design level and then beyond.

This plan would allow for the verification of finite element analysis that predicted the initial deployment behavior and structural response of the ULDB. It would also allow for data to be gathered that can be used to assess both the thermal models and flight performance models of the balloon. Below are the test flights mission objectives and success criteria.

Primary Mission Objectives of Test Flight

1. Successful inflation and launch of a flight pumpkin balloon.
2. Deploy a flight pumpkin balloon using the new Load Tape Tendon
3. Pressurize a flight pumpkin balloon
4. Collect data that will aid in the assessment of the performance of super pressure pumpkin balloons.

5. Demonstrate altitude stability of a super pressure pumpkin balloon
6. Demonstrate that the materials and fabrication issues with building a large super pressure pumpkin balloon using the new Load Tape Tendon approach have been successfully addressed and that the manufacturing processes used to fabricate this balloon are acceptable.
7. Demonstrate that the ground preparation and launch operations aspects for the super pressure balloon pumpkin design proposed for ULDB have be successfully addressed including the lessons learned from the ground model tests and previous test flights.

Secondary Mission Objectives of Test Flight

1. Demonstrate the performance of the differential pressure control system
2. Explore the limits of the pumpkin design by pressurizing the system to a level up to and beyond the design limits

Minimum Mission Success Criteria for Test Flight

1. Successful inflation and launch operation
2. Successful deployment of the balloon

Comprehensive Mission Success Criteria for Test Flight

1. Positive balloon pressurization through flight float phase
2. Stabilization of the balloon at a constant pressure altitude for the flight duration (flight required valve downs for safety or possible trajectory control excepted)
3. Verification of proper response from balloon pressure control autovalve algorithm (ascent and float)
4. Data from one differential pressure gage or load cell data for 75% of flight
5. Pressurization of the balloon to the maximum extent possible via ballast drops at the end of the flight
6. Balloon destruct device operation
7. Post flight recovery of the balloon carcass

As shown in Figure 2, the inflation of the system was very similar to other ULDB launches. The crew from the National Scientific Balloon Facility (NSBF) has developed the ULDB launch procedure into a very efficient process. An auxiliary tow balloon first lifts the apex fitting and then inflation of the main balloon begins. Inflation is through the valves in the apex of the balloon. The inflation tubes are released from the balloon just before launch.

Figure 2 - ULDB Inflation aided by an auxiliary tow balloon attached to the apex fitting

The balloon release took place without incident and the payload was released normally. The balloon ascended at a rate of 4-6 m/s during the initial part of the ascent. The flight plan called for entering float altitude at a very low ascent rate to allow for a gentle pressurization after reaching float altitude. The helium valves were opened at an altitude of 18.3 km to slow the ascent rate from 3 m/s to 1.5 m/s. The valves were opened four times to regulate the ascent rate. This system of opening the valves when the ascent rate exceeded 3 m/s and closing them when the ascent rate fell below 1.5 m/s worked very well as shown in Figure 3.

The valves were closed in manual mode at an altitude of 26.6 km. At that time, they were put in automatic mode. They were set to open when the differential pressure inside the balloon reached 50 Pa. Upon reaching the float altitude of 30.5 km, the balloon began pressurizing and the valves opened when the pressure reached 50 Pa. The balloon shell was completely deployed in the upper section of the balloon with only two small areas remaining to be opened up. These two areas were completing their deployment as the balloon was pressurizing. With the valving during ascent, the balloon reached float altitude in 2.7 hours. Plots of altitude and differential pressure are shown in Figures 4 and 5.

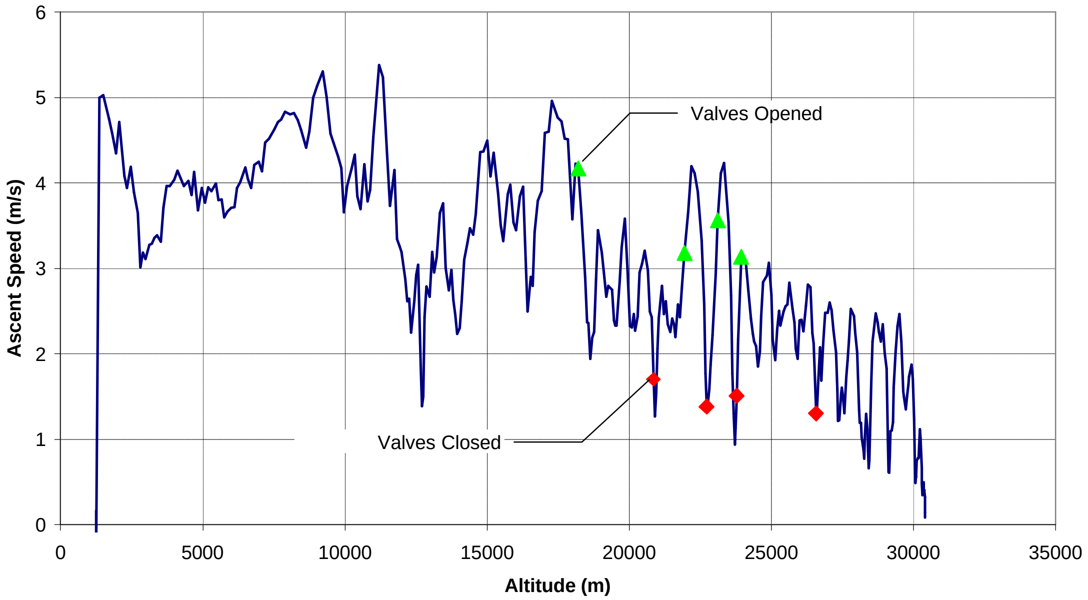

Figure 3 - Balloon Ascent Rate vs. Altitude. The balloon valves were opened four times during the ascent to allow a gentle entry into float altitude

As the balloon reached 55 Pa differential pressure, the bottom 10 meters of the closing seal in the balloon came open. It was easy to identify the seal that failed because an on-board camera captured the failure as it happened. The flight was terminated shortly after the failure occurred. The system descended safely in an area north of Amarillo, Texas. The balloon was recovered and returned to the Ft. Sumner facility the next day. The base area where the balloon failed was carefully examined. The bottom 10 meters of the balloon's closing seal was found to have peeled open. This is highly unusual since specific steps are taken in the production plant to prevent this from happening. The most unusual aspect of this failure was that it took place on the closing seal of the balloon. This seal is the most rigorously tested and inspected seal in the entire balloon.

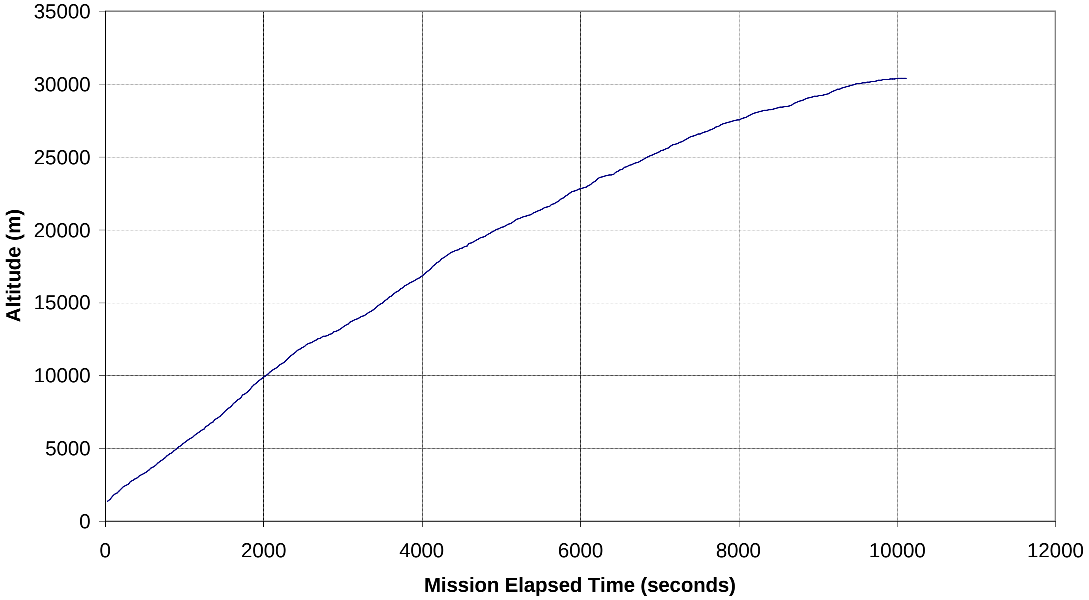

Figure 4 - Altitude vs. Mission Elapsed Time

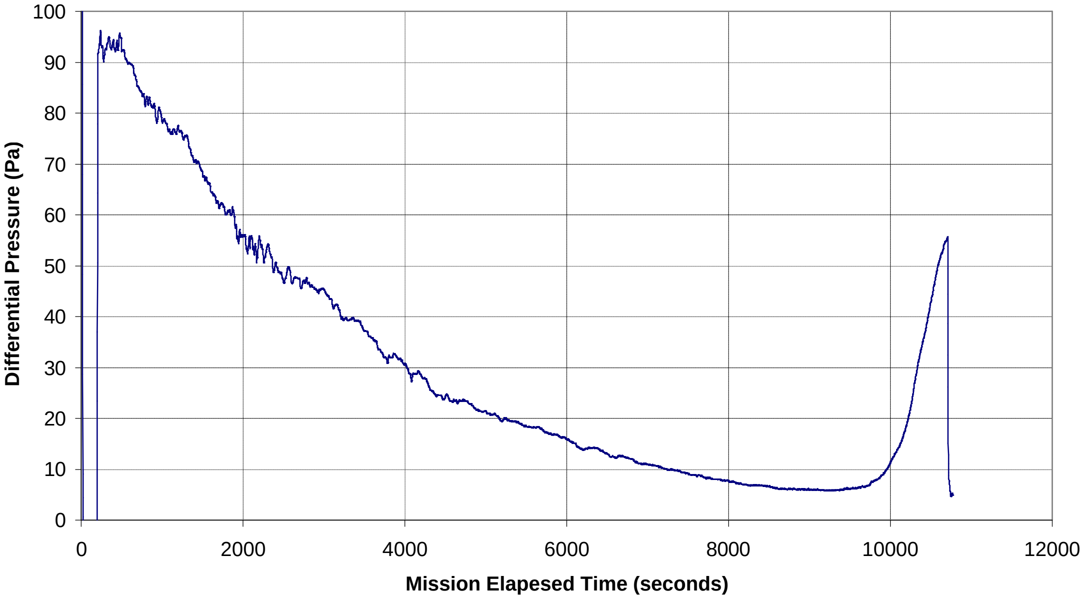

Figure 5 - Differential Pressure vs. Mission Elapsed Time

A thorough investigation was undertaken with NASA, Aerostar, and PSL participating. The four main areas of study in the investigation were: verification of the sealing equipment, testing the materials used in the balloon, testing of the seals in the remains of the balloon, and inspection of the seals using various methods. The investigation team studied the surface of the seals in the areas where they peeled apart. No evidence of surface contamination was found. Sample seals were run with almost ridiculous amounts of different contaminants between the layers and satisfactory seals were produced in all cases. Every sample seal produced with the sealing equipment used on the balloon was found to be satisfactory. The detailed examination of the closing seal showed that peeled seals could be found not only in the base area of the balloon, but in the top ten meters of the same seal. It should be noted that it was quite difficult to make the seal peel. It took a significant applied load in a concentrated area to make the seal peel. Sample seals run with the material from the same seal also peeled when the material came from the top and bottom ten meters of the first gore in the balloon. The last seal in the balloon joins the first and last gores produced. The balloon material in the first gore in these areas was closely tested and was found to be oxidized by the lighting in the production plant. During the production of a ULDB, the first gore of the balloon will remain on the table for two months. During this time, it is exposed to the plant lighting during the first and last ten meters of the balloon. The center section of the balloon is covered by the other gores and is not exposed to plant lighting. The reason this is not a problem on standard zero pressure balloons is because they are not left on the table for extended periods of time like ULDB. This failure mode was not anticipated and is new to all the people involved with the ULDB.

In addition to the discovery made concerning the film, the speed and temperature controls on the sealing equipment were upgraded to allow digital control and logging. This improvement has caused a marked decrease in the number of flaws requiring reinforcement in the balloon shells. While not a structural concern, the improvement allows more efficient production flow and additional data that can be used to assess production efficiency.

V. Lessons Learned and Future Plans

A. Lessons Learned

Although the most recent test flight of the ULDB was not a complete success, it validated several design features. These included:

- Complete deployment of the balloon material at low pressure in the upper section of the balloon. The deployment of the balloon film was observed to be very similar to that observed during indoor tests of scaled models of the balloon design.
- Excellent control authority in regulating the ascent rate of the balloon using the apex mounted helium valves. The ascent rate was regulated to allow a gentle initial pressurization of the balloon upon reaching initial float.

As with other previous ULDB test flights, the results revealed previously unknown areas for improvement. The advances in the level of technology brought about by the ULDB project are already benefiting balloon technology in standard zero-pressure balloons. These included:

- Decreasing the vulnerability of the film to long term exposure to UV light
- Improvement of the balloon sealer speed control and temperature control
- Significant reductions in thickness variations in the balloon film to allow greater reliability

B. Future Plans

Using the improvements noted from the results of the February 2005 test flight, a 168000 m^3 ULDB prototype has been fabricated and is scheduled for flight in September of 2005. This design is a hybrid which has a constant lobe radius through most of the length of the gore. Near the ends, the lobe radius is linearly reduced in order to decrease hoop stresses in the two ends of the balloon.

There is a desire from the science community to further increase the float altitudes of these super pressure balloons to 36.5 km and above. This potential step would again result in a nearly doubling of the balloon volume above the projected size of this current efforts goal. There are active efforts related to planetary ballooning. These efforts may also take advantage of the advancements made through the ULDB Vehicle development.

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