Development of the NASA Ultra-Long Duration Balloon

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Abstract

The National Aeronautics and Space Administration's (NASA) "Super-pressure Balloon" is designed to be capable of mid-latitude, long-duration flights at constant altitude even during day-night transitions. This first totally new balloon design in more than 50 years is commonly referred to as ULDB (Ultra Long Duration Balloon). This paper concentrates on the super-pressure balloon development by the NASA Balloon Program Office at Goddard Space Flight Center's Wallops Flight Facility. The goal of the NASA ULDB development project is to attempt to extend the potential flight durations for large scientific balloon payloads. Areas to be presented include the design approach, deployment issues that have been encountered and the proposed solutions, ground testing, and an analysis overview. Future plans for both ground testing and additional test flights will also be presented. Goals of the future test flights, which are staged in increments of increasing suspended load and altitude, will be presented. This will include the projected balloon volumes, payload capabilities, and test flight locations.

1. Introduction and Background

The desire for longer duration stratospheric flights at constant float altitudes for heavy payloads has been the focus of the development of the National Aeronautics and Space Administration's (NASA) Ultra Long Duration Balloon (ULDB) effort (Cathey, 2000). 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 weight limit for the previous generation of stratospheric super pressure balloons was approximately 90 kilograms. The project, established in 1998, has conducted a number of test flights. Each flight has provided valuable engineering data for the design team. The ULDB effort continues the development in incremental steps. To supplement the test flights, a number of ground test models have been used as part of this development effort.

The test flights and ground testing have expanded the knowledge of the 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.

Recent efforts have focused on ground testing and analysis to understand the previously observed issue of balloon deployment at float. A revised approach to the pumpkin balloon design has been tested through ground testing of model balloons, through two test flights, and additional model testing. The design approach does not require foreshortening, and will significantly reduce the balloon handling during manufacture reducing the chances of inducing damage to the envelope. Successful ground testing of model balloons lead to the fabrication and test flight of a ~176,000 m^3 (~6.2 MCF – Million Cubic Foot) balloon. Preflight analytical predictions predicted that the proposed flight balloon design to be stable and should fully deploy. The first test flight of the revised Ultra Long Duration Balloon design was a short domestic test flight from Ft. Sumner, NM, USA. This balloon fully deployed, but developed a leak under pressurization. After an extensive investigation to the cause of the leak, a second test flight balloon was fabricated. This ~176,000 m^3 (~6.2 MCF) balloon was flown from Kiruna, Sweden in June of 2006.

The deployment issues seen with previous test flights have lead to a new level of analysis and understanding of these types of super pressure balloons (Cathey, 2000 and 2001). Changes to the design approach were made to enhance the deployment of the flight balloons. A second round of ground model tests were designed, analyzed, built, and tested. With each step in the process, greater understanding of these types of balloons is gained. This paper presents the findings of the ground model testing, the two test flights flown over the past few years, and additional model testing and analyses, and future plans.

2. Initial Ground Model Testing

Ground testing of scaled model balloons has contributed greatly to the ULDB development effort. These model balloons have been used for deployment testing as well as analytical model validation. These model tests have included 48, 100, 145, and 200 gore model balloons. The smaller model balloons were used to explore the deployment behavior of the pumpkin shaped super pressure balloon using the Load Tape Tendon design approach. All of these balloons were built with a 1:1 tendon to film ratio. The larger balloons with 145 and 200 gores were used as design validation model test structures. Most of these tests were previously presented (Smith and Cathey, 2005). A total of 10 deployment and design validation model tests were completed.

The 14.3 m diameter, 200 gore model test balloons were designed to replicate the proposed flight balloon. They had the same equatorial lobe angle as flight structures. Both of the 200 gore model balloons demonstrated full deployment at almost no differential pressure. They were incrementally pressurized with air and valuable strain data obtained at each pressure step. Both of these structures demonstrated stability under pressure. Each of the models was purposely pressurized to failure. Test model #9 assumed a non-desired shape at 1344 Pa (0.195 psi). Test mode #10 was designed for the maximum design pressure of 1103 Pa (0.16 psi). Pre-test analysis predicted instability above 1379 Pa (0.2 psi). Test model #10 deformed and burst after pressure reached 1551 Pa (0.225 psi) level, ~40% above the maximum design pressure. Figure 1 presents a picture of the test structure #10.

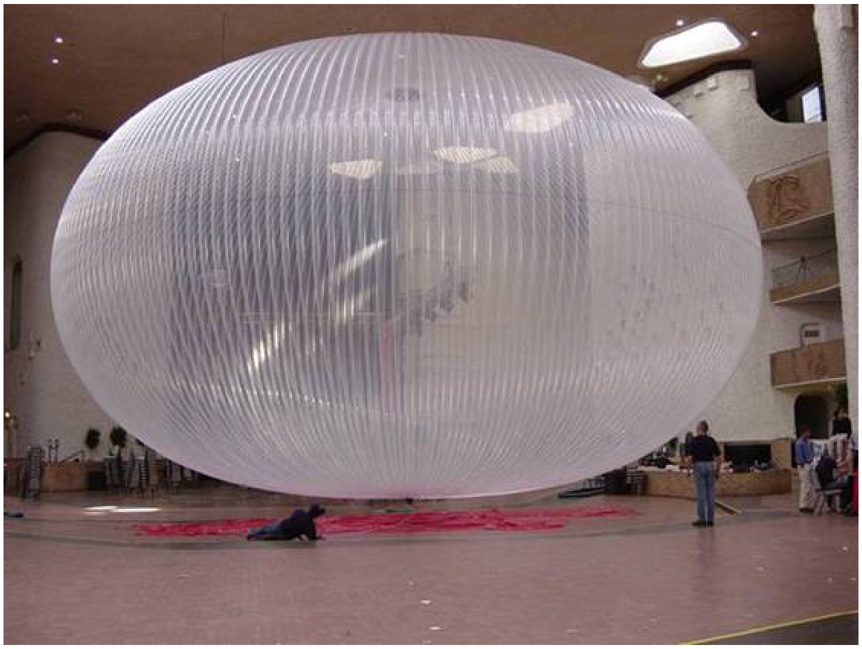

Figure 1. 14.3 m diameter, 200 gore model test balloon #10

3. From Ground Models to Flight Balloons

Full deployment of the balloon at float had been an issue with some of the previous ULDB test flights. Design changes were made to address the issues that had previously been seen. The focus of these design changes was the implementation of the Load Tape Tendon and fabrication of the balloon with a 1:1 tendon to film ratio. Coupled with the ground test models, material testing was completed to better understand the materials. The results of the material testing fed into new material model development for input into the analytical tools. The final piece of this progression was the extensive analysis completed of both ground model balloons and flight balloons (Wakefield and Rand, 2006). With the newly obtained material properties, updated material model, analytical verification, and the successful deployment testing of the model balloons, the transition to a flight balloon was made. Based on a suspended load ~1,360 kg (3,000 lbs), a float altitude 30.4 km (~100,000 ft), and the same design characteristics as ground test models #9 and #10, a balloon was deigned. The nominal design generated was for a ~176,000 m^3 (~6.2 MCF), 200 gore balloon.

4. Test Flight 540NT

A test flight of the revised ULDB design was conducted on February 4, 2005 from Ft. Sumner, New Mexico, USA. The balloon was a 176,000 m^3 (~6.2 MCF) pumpkin design with a polyethylene shell and integrally sealed longitudinal tendons. Details of this test flight including flight plots were previously presented (Smith and Cathey, 2005). The ULDB test flight, Flight 540NT, was launched early in the morning on February 4, 2005 with ~10% free lift. The desire was to “ease” the balloon into float at a relatively low ascent rate to allow the balloon to gently deploy with minimal pressurization.

The balloon reached a float altitude of 30.5 km in 2.7 hours. The balloon began pressurizing and the valves opened as planned when the pressure reached 50 Pa with a slight overshoot in differential pressure expected. Video survey of the balloon using a camera mounted in the base of the balloon and looking into the interior of the balloon showed that the shell was completely deployed in the upper section of the balloon with only two small areas remaining to be deployed. These two areas were completing their deployment as the balloon was pressurizing. Figures 2 and 3 show the launch and deployment of 540NT.

Figure 2. Launch of ULDB test flight 540NT

As the balloon reached 55 Pa differential pressure, the bottom 10 m of the closing seal in the balloon came open. The on-board camera captured the failure as it happened. It was clear that the seal that had opened up was the closing seal of the balloon. 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 m of the balloon’s closing seal was found to have peeled open.

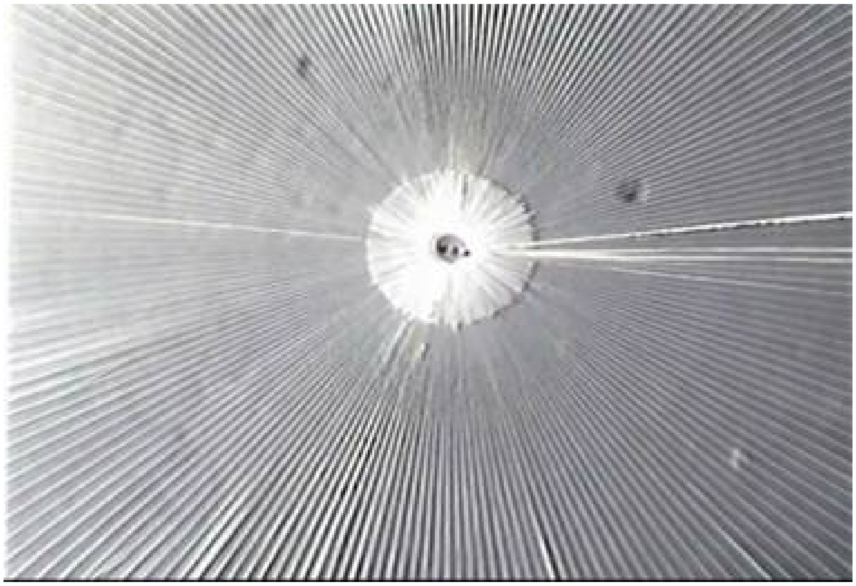

Figure 3. Internal camera view of 540NT at float with the upper section fully deployed

In summary, ULDB test flight 540NT was successfully launched, ascended, reached float altitude, and started to pressurize. The balloon was fully deployed in the upper section of the balloon with only two small areas in their final deployment. The balloon failed soon after reaching float along the bottom section of the closing seal. A thorough investigation was undertaken with NASA, Aerostar, and PSL participating. Many of the details and specific aspects of the investigation that followed the test flight are covered by Smith and Cathey (2005) and Seely (2006).

The root cause was determined to be surface oxidation of material from long-term plant light exposure that created a bad seal. This issue has never been seen before in a balloon. This vulnerability of the film to extended exposure to in-plant lighting was discovered and was the problem that caused an incomplete seal in the balloon. The surface energy of the film was found to have increased with this exposure and reduced the seal quality. Through the investigation, it was found that higher sealing temperatures would prevent reoccurrence and ensure a proper seal. Additional material and quality checks were added to the fabrication and production procedures to present this in the future. 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.

5. Test Flight 555NT

5.1 ULDB Test Flight Directions

Following the 540NT investigation and the identification of a root cause for the balloon failure, an assessment was made on the next steps. The upper section of 540NT balloon was fully deployed. The video showed two small folds in the lower section of the balloon, but these were slowly deploying as the differential pressure increased. These folds were unlike the ‘S’ shaped clefts that created shape instability in previous ULDB models and flight balloons. A program decision was made and direction was given to move toward a longer duration test flight of a similar size balloon.

Additional material testing has been part of this overall project development. Improved materials properties were developed after the 540NT test flight. Post flight analyses were completed using these updated material properties. The analyses, using these updated properties, showed higher stresses in the area where the seal peeled. To address this and to incorporate updated coefficient of thermal expansion information, a new balloon design pattern was generated. This new balloon design was very similar to the previous pattern with only minor changes.

5.2 June 2006 ULDB Test Flight 555NT

Test Flight 555NT took place in Kiruna, Sweden on June 12, 2006. This was the second test flight of a pumpkin balloon fabricated with no foreshortening of the tendons relative to the shell of the balloon. This 6.2 MCF Ultra Long Duration Balloon (ULDB) balloon incorporated all of the findings from the post 540NT investigation. Minor changes were made in the balloon design based on subsequent material testing, material modeling, and analysis. The flight performance was covered in a paper by Smith and Cathey (2006)

The nominal flight scenario is that with a successful launch operation, the balloon will ascend to a float altitude and fully deploy. It was desired to fly for at least 24 hours. Within the comprehensive success criteria, the desire was to have an extended float phase and then to pressurize the balloon incrementally to as high a differential pressure as possible. It was desired to pressurize it to the maximum extent possible near the end of the flight. The design limit for the balloon was 240 Pa. Depending on the amount of venting on ascent and the environmental inputs, it could be possible to push the balloon beyond this level with the ballast available. The initial maximum expected differential pressure that has been targeted during this flight was ~80 Pa. The desire was to have the balloon at a stable float altitude before any additional ballast drops would occur.

The ULDB test flight took place on June 12, 2006. The inflation and launch operations were nominal. It was desired to reach float at an ascent rate of less than 2 m/s (400 ft/min). The ascent rate was to be controlled by opening and closing the valves. The atmospheric sounding for the day of the launch showed a cold, rather isothermal temperature profile. This colder atmosphere lead to a slower ascent rate. Combined with the winds and safety restrictions, it was desired to ascend at this slower rate until the balloon reached an altitude where the winds pushed it back toward a more favorable trajectory.

The electronically logged flight data was rather extensive for this flight. It was similar to the data normally gathered for a NASA LDB flight with the addition of data for the balloons pressure monitoring and increased video. Figures 3 and 4 represent some of the flight performance data colleted for ULDB Test Flight 555NT.

The balloon was eased into float via the flight control. The balloon approached float with an ascent velocity of less than ~2.03 m/s (~400 ft/min). The differential pressure control system automatically controlled the pressure back down to between 75 and 80 Pa.

There were a number of undeployed areas in the balloon as it ascended. These areas, except for one, reduced in both number and size as the balloon got higher. When the balloon reached float, one large area was not deployed. This area is shown in Figure 6. The area was covered in detail with the onboard video cameras to document the issue. Both the payload mounted and internal balloon mounted pan/tilt/zoom cameras were used to document the feature. Assessment of the up-looking video placed the undeployed material between gores 138 and 149. The rest of the balloon was deployed.

Flight rules precluded crossing the Recovery Limit Line with a balloon that was not fully deployed. As part of the flight plan, small ballast drops were allowed to try to force the balloon to deploy. In an effort to try to deploy the balloon fully, incremental ballast drops were made. Ballast drops were coordinated with Columbia Scientific Balloon Facility (CSBF) flight operations to ensure that they were done safely and over an acceptable area. The timing of the ballast drops were verified with flight operations before each drop. After the initial ballast drops, it was clear that the balloon would not fully deploy with the increasing differential pressure.

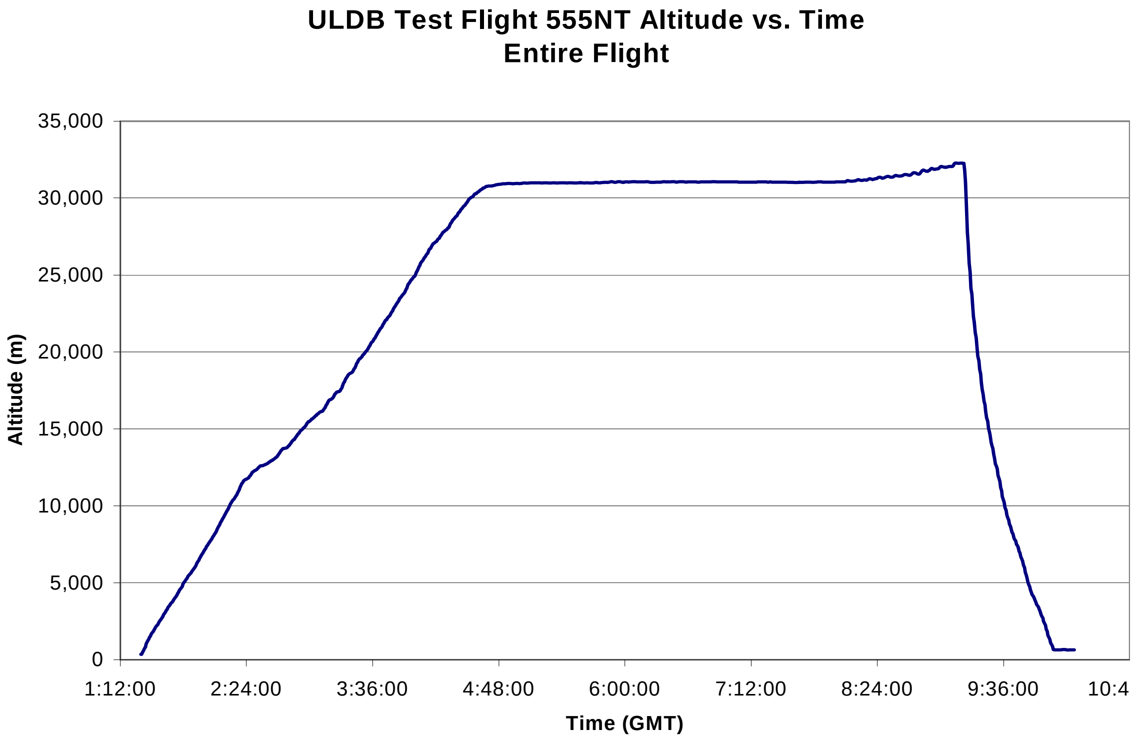

Figure 4. Flight 555NT flight profile

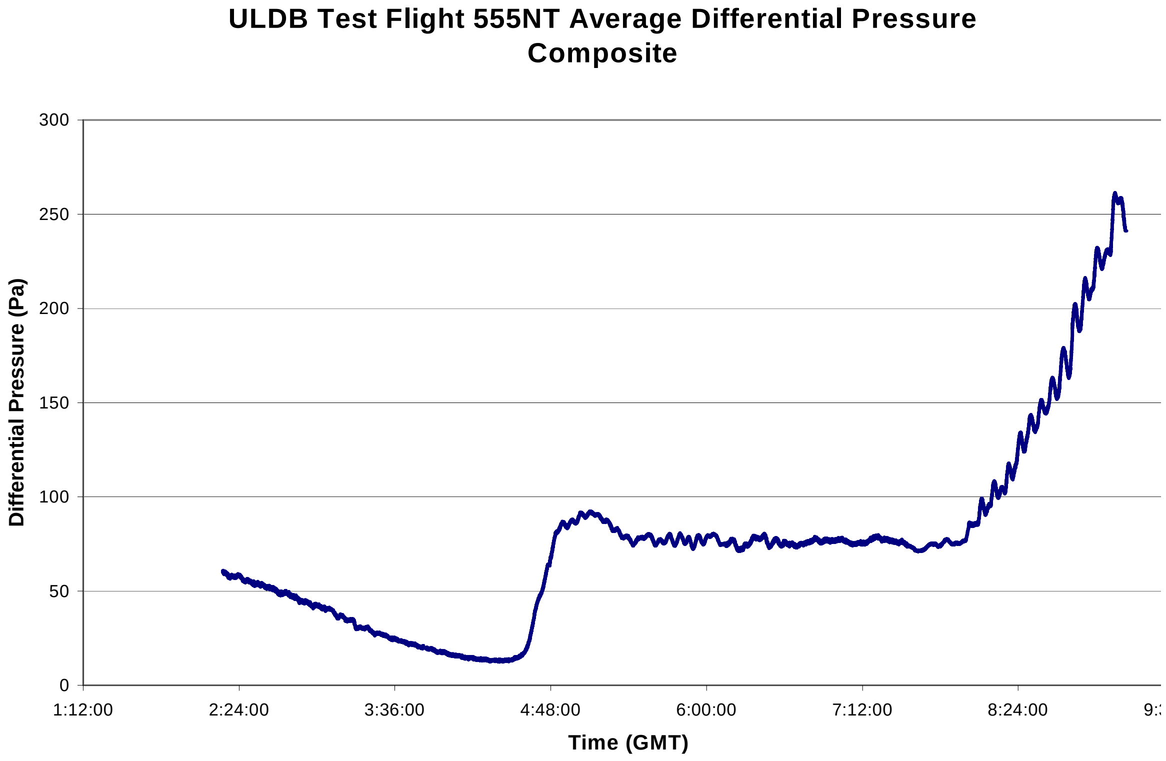

Figure 5. Flight 555NT differential pressure profile

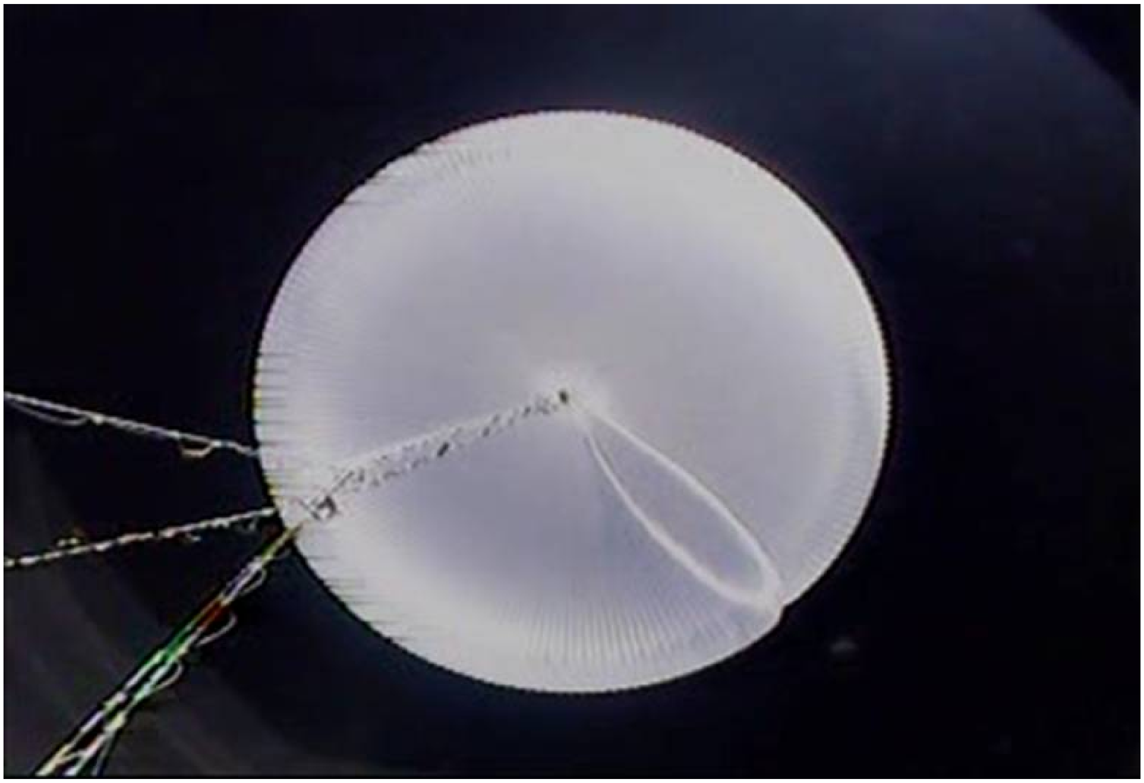

Figure 6. Flight 555NT undeployed at float

At this point, with a balloon that was not fully deployed, the flight would need to be terminated before reaching the Recovery Limit Line. Two of the pre-flight comprehensive success criteria were to pressurize the balloon up to the maximum design differential pressure, and to pressurize the balloon above that point to the maximum extent possible with the available ballast.

A total of 12 ballast drops were made, each increasing the differential pressure by ~10 Pa or ~20 Pa. With all of the ballast expended, the balloon's final maximum differential pressure was ~265 Pa. It was desired to terminate the flight in the best possible recovery location. This was accomplished within the desired time frame before the Recovery Limit Line. At this point a video view was made of the balloon and the undeployed area, and the balloon was turned over to CSBF flight operations for termination. The flight was successfully terminated and both the balloon and payload landed safely. The total flight time for test flight 555NT was approximately 8 hours and 50 minutes.

6. Comparison Of Ingested Gores Investigation

After 555NT, there were a number of unanswered questions related to the balloon deployment. The assessment of the deployment and the process was broken into two separate and complimentary approaches. The two approaches were to perform additional deployment testing on small balloons, and to review the deployment process for all previous ULDB flights.

6.1 Balloon Deployment Using Model Balloons and Different Initial Conditions

The ULDB project has made and tested a number of small model balloons for various purposes as part of the development effort. Previous test articles had built in lobing in the structure. The idea of employing a balloon with no built in lobing has been discussed and a project decision made to test such a structure. A 4 m, 48 gore flat faceted (gore width = tendon spacing) hangar pumpkin balloon was fabricated. This ULDB flat faceted test structure, along with a previously built 4 m, 48 gore balloon with 180 degree lobe angle at the equator were used for tests to explore deployment and “S” cleft formation.

Eleven test inflations were conducted on the two 4-meter pumpkin balloons to explore the deployment behavior of the pumpkin balloon from different folding/stacking methods and initial conditions. Some of the inflations with the 180 degree lobe angle balloons did exhibit an “S” shape during the inflation process. It was clear that the balloons final deployment was a function of the path it followed. From these tests, there were several different potential end points for the balloon. Some of the tests ended up with the balloon being essentially fully deployed, and others had some distinct features like widow’s peaks and undeployed gores. It was felt that these features would have been more pronounced on a balloon with a greater number of gores. Comparing to a 200 gore balloon, each gore on these 48 gore balloons was equivalent to over 4 gores on the larger balloon.

The tests with the 4 m, 48 gore balloon with flat facets for the gores was somewhat similar to the previous tests, but there were some marked differences. The sub pressure region in the balloon was similar to the lobed balloon. Even with the “sucked in” areas in the lower portion of the balloon, the balloon was very neatly deployed in the upper section of the balloon. The full deployment line moved down the balloon as the air was being introduced, and it essentially followed along the zero pressure line. There were essentially no odd shapes present during these inflations and essentially all of the tendons and gores were where we expected them to be for the duration of the test. At no time during the inflation was an “S” shape observed with this balloon except in a few areas where the balloon was “sucked in” due to the sub pressure regionvacuum. In summary, the flatter gores lead to a much better deployment. This balloon deployed easily regardless of the initial conditions. This has very positive implications for ULDB.

6.2 Review of Previous ULDB Test Flights

A review of previous ULDB test flights was competed to investigate the formation of the cleft as the balloon stands up from the spool. Launch and ascent videos were reviewed to determine the location of the “undeployed” areas of the balloon from the launch spool, through the balloon stand-up, and through ascent. The desire of this effort was to determine if there was any correlation among these flights with what was observed on test flight 555NT. A total of seven ULDB test flights were reviewed and included the following:

485 NT – Ft. Sumner, June 4, 2000
495 NT – Australia, February 24, 2001
496 NT – Australia, March 9, 2001
1580 PT – Palestine, July 6, 2002
517 NT – Australia, March 16, 2003
540 NT – Ft. Sumner, February 4, 2005
555 NT – Sweden, June 12, 2006

A Zero Pressure 37Heavy test flight was also reviewed for comparison.

After review of hundreds of pictures and many hours of video, there were a number of conclusions. Deployment of the balloon is a function of a number of different factors. This work looked at essentially only one of these aspects. The configuration in the spool is not necessarily a direct indicator of how the balloon will deploy when it is released from the spool and as the balloon stands up. There are two considerations for the balloon configuration in the spool; potential to damage the balloon due to roping, and final deployment. Balloon damage in the spool was not assessed as part of this effort. The balloon can (and does) “shake itself out” as it goes through the dynamic event of spool release and stand up. In some cases, the balloons configuration was completely different in the “pin release” configuration than it was in the "in-spool" configuration. The balloons that did not deploy appeared to have redistributed the balloon material after spool release and during the time the balloon is standing up. As the balloon stands up after spool release, the "sailing of the balloon" above the reefing sleeve and collar can produce a "scoop like" indentation, or it can also form a "pocket" on the back side of the balloon. Either one can be bad. Figure 7 shows a balloon as it forms a "scoop" during stand up. Figure 8 is what is called the "Pac-Man" configuration for a balloon with undeployed material located in a single cleft.

Figure 7. Balloon forming "scoop" on stand up

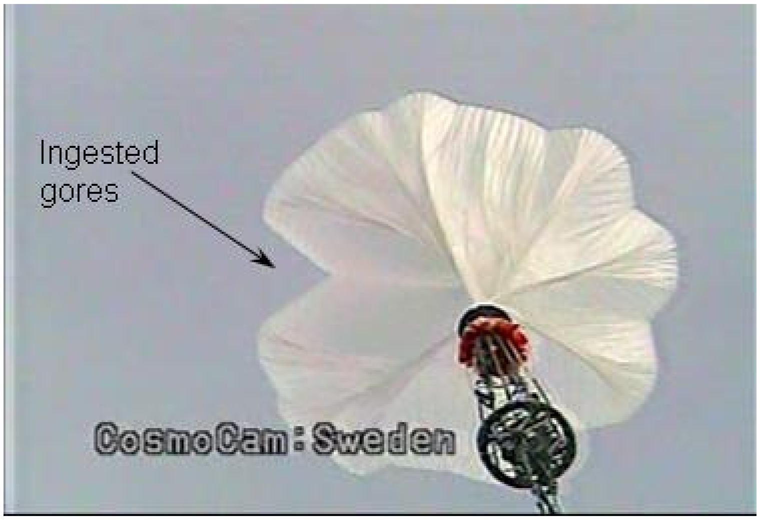

Figure 8. Balloon with most of its undeployed material in a "Pac-Man" configuration

In a number of cases, this "scoop" or "pocket" allowed the balloon material to redistribute itself into this one location forming either a single large clefted area, or a clefted area that was significantly larger than any of the others. In many of the cases, the balloon formed an asymmetric shape with much of the excess material located in one location. In the cases where the balloon assumed an asymmetric shape, the clefted area ran very close to the apex fitting. From what could be extracted from the videos and still pictures, in all cases, if this asymmetric shape formed from spool release to balloon stand up ("scoop" or "pocket"), then this was the location for the final cleft. An undesired in-spool configuration for the balloon may exacerbate the issue of the balloon being able to form a "scoop" or "pocket" and thereby end up in the asymmetric clefted configuration. The balloon may end up forming a "scoop" or "pocket" anyway regardless of the in-spool configuration.

7. Materials, Models, and Analysis

Parallel to the efforts described above have been ones focused on expanding our knowledge of the materials used in the balloons, developing material models, and balloon analysis. A large number of material tests have been completed. These have included testing on uniaxial samples of material, and cylinder tests. A key to this testing and data collection has been the use of photogrammetry. The photogrammetry (Young), material model development (Rand and Sterling), and analyses (Wakefield) efforts have been recently documented and are leading the way toward solutions for ULDB. Additional balloon analyses have been completed at the University of Cambridge (Gerngross, Pagitz, and Pellegrino).

Additional testing was completed using the 4 m, 48 gore flat faceted (gore width = tendon spacing) hangar pumpkin balloon that had been fabricated. This ULDB flat faceted test structure was previously used to explore deployment and "S" cleft formation. The next steps with this balloon were to explore strain arresting in a flat faceted balloon, and to measure strain in pumpkin balloon using photogrammetry. This testing took place in the Balloon Laboratory at NASA's Wallops Flight Facility between January 16, 2007 and February 15, 2007. These tests were an "exploration of strain arresting in a flat faceted balloon". The testing was conducted on the same balloon, took place in three separate incremental tests, and with each subsequent test the structure was pressurized to higher test levels. Measurements were made of the actual strains on the structure as a function of time and differential pressure via photogrammetry. Hand measurements were also made for reference.

The testing was broken down into three different "sub-tests". The first test of the balloon was to pressurize to a very low initial differential pressure and then back down again. These two pressurization levels allowed the entire test procedure to be run through and all aspects of the testing to be checked. This test also allowed the post processing procedure to be vetted. The second test took the structure in four steps to half of the desired maximum test differential pressure level. The third test took the structure in six steps to the desired maximum test differential pressure level. At the end of each test, the differential pressure was taken back down to a very low level and an additional set of measurements taken. All of the data was then post processed. After each inflation, the balloon was carefully deflated and prepared for the next test. The data collected includes the differential pressure, hand measured strain/displacement measurements, photogrammetry photographs, and some video.

These tests were successful in demonstrating both the capabilities of the balloon design as well as the data collection techniques. A number of follow up tests will be completed with this structure to take it to higher pressurization levels and to explore the longer term creep behavior of the materials. Knowledge gained from these efforts was used to design a scaled model balloon for and indoor test. This model balloon, represented the largest ground model test that has been fabricated and tested as part of the ULDB effort and is covered in the following section.

8.0 Indoor Inflation and Launch – Replication of the "Sweden Cleft" and Design Solutions

Combining all of the information gathered from the model testing, materials testing, analyses, and post flight reviews, it was desired to attempt to replicate the "S" Cleft configuration seen on ULDB test

Flight 555NT with a model balloon. It was desired to build a balloon of a size that was as large as possible to be tested indoors and as small as possible to be a flight article. For direct comparison, this same size balloon, and if possible the exact same balloon, can then be flown to a comparable ULDB flight altitude with a small payload. The balance of making a balloon as large as possible for an indoor test and one as small as possible for a test flight was the driver for the balloon design. The resulting balloon that was used for these tests was a ~27 meters diameter structure when fully inflated. It should carry at least 20 kg to 30.5 km in altitude.

The primary purpose of this testing was to explore the balloon deployment and to experimentally demonstrate the “S” cleft seen in the Sweden balloon with a scaled structure. The balloon was scaled as much as possible to the Sweden balloon. The design was generated to replicate the amount of excess material at the float condition for the Sweden test flight. There were a number of secondary objectives to this test. It was desired to simulate the launch process with Helium inflation, spool release, and balloon stand up. This would allow the balloon/spool interaction to be documented. To replicate ascent and allow the deployment evolution to be observed, the balloon volume was filled out with air. Observations of deployment during the filling out of the structure were made.

The testing took place in an old airship hangar in Elizabeth City, North Carolina between March 27, 2007 and March 29, 2007. This testing was focused on exploring balloon deployment. The testing included, replicating the inflation, launch and ascent of the balloon to explore the impact of this on the ultimate balloon deployment. The testing did experimentally demonstrate the “S” cleft seen in the Sweden balloon with a scaled structure. A second standing inflation of the balloon confirmed the balloons deployment configuration. The bulk of the information collected from this test included photos, video from numerous angles, and witness observations. This testing was recently documented by Cathey(2007). Figures 9 and 10 demonstrate that the testing was able to match the cleft seen in Flight 555NT.

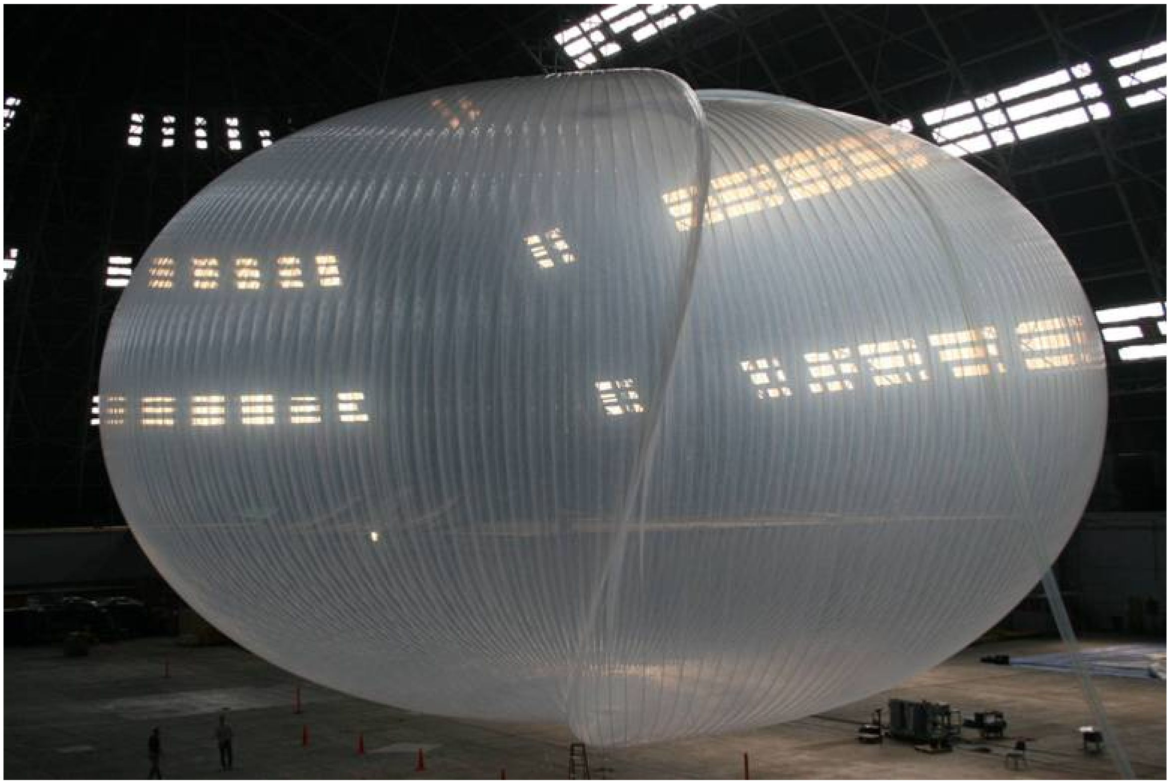

Figure 9. ~27m diameter balloon test replicating the “S” cleft seen in flight 555NT

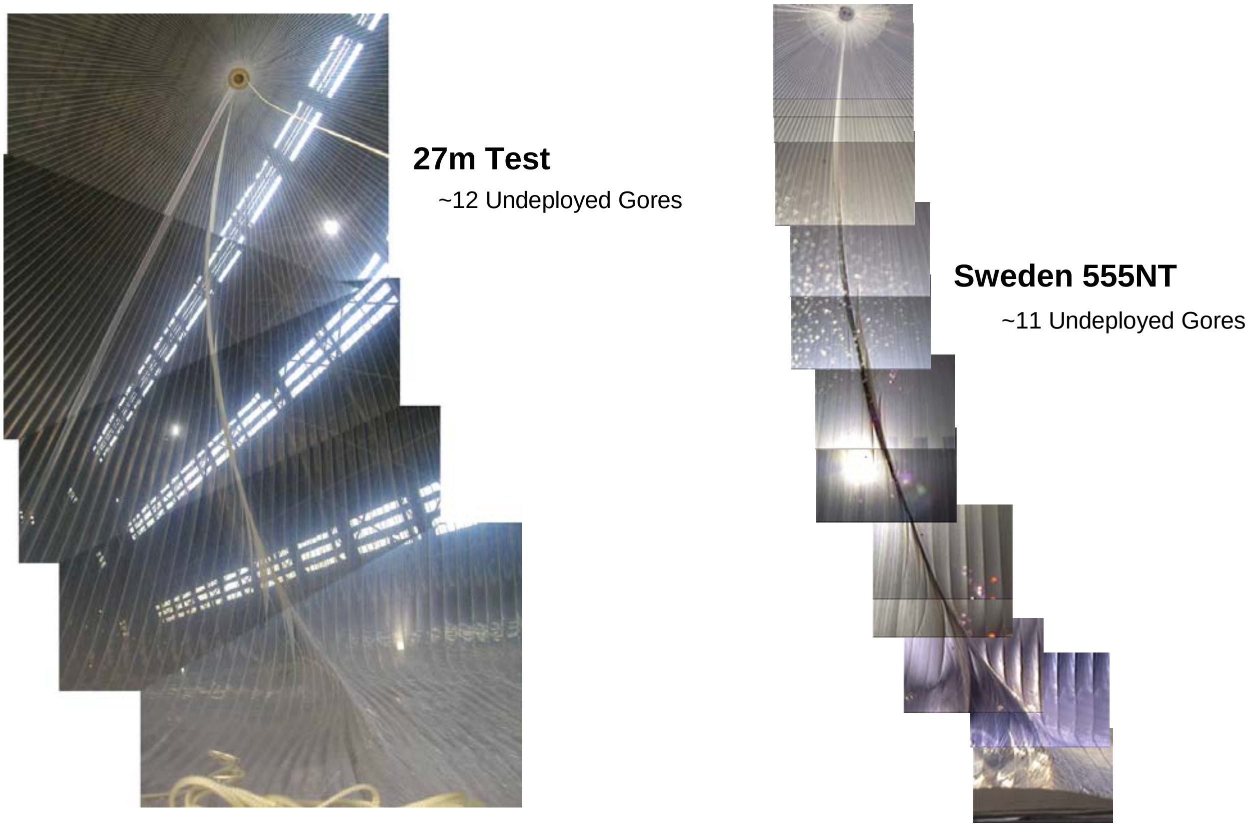

Figure 10. Internal views of test model and flight 555NT demonstrating match of “S” cleft configurations. Shape and amount of undeployed material very similar.

This test was a great success. The test logic set out before the test carefully followed. It was successful in experimentally replicating the “S” cleft observed in Sweden balloon with a scaled structure. A number of excellent observations were made by the team. The “launch” and “inflation” process used for this test were excellent to replicate what was desired. It was found that the ~27m scaled balloon proved to be a good test bed There were several indications on the source of the “S” cleft. The launch spool configuration (twisting) and launch dynamics are not the root cause of clefting. The folding of the balloon, which is different from a zero pressure balloon, is not the cause of this problem. The Pac-Man ascent shape is not the cause of clefting. The launch spool configuration, folding, and Pac-Man shape have nothing to do with whether a cleft will form or not, but undoubtedly play a role in determining where the cleft will form. There was little friction between the halves of the clefted material. It was surmised that the design determines the balloon’s susceptibility to S-cleft buckling. This is a function of the excess material as the balloon reaches float.

9. Incremental ULDB Development

Utilizing the new design approach of no foreshortening between the tendon and the film, an incremental development plan has been proposed. Additional ~27 m indoor model balloons will be fabricated and tested. The results of these tests, coupled with the improved material model and photogrammetry results will help dictate the trade space for the next flight balloon design. It is desired to fly another ~168,000 m^3 in 2008. From there additional test flights will be completed. The specific steps increase the suspended load and float altitude toward the development of the balloon vehicle capable of carrying a 2,721 kg payload to 33.5 km for one hundred days. These vehicles are presented in Table X.

Suspended Load	Float Altitude	Balloon Volume	Number of Gores
1,361 kg	30.5 km	~168,000 m^3	200
1,361 kg	33.5 km	~368,100 m^3	~244
2,721 kg	33.5 km	~631,500 m^3	~290

Table 1 - Proposed ULDB Vehicles incrementally increase the suspended load and float altitude

The 1,361 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 m^3 balloon will use the same flight systems as the ~168,000 m^3 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. Possible flight locations include launches from Sweden, Australia, and Antarctica.

10. Conclusions

The development of the National Aeronautics and Space Administration's Ultra Long Duration Balloon has made significant strides in addressing the deployment issues experienced in the scaling up of the balloon structure. The ground testing and tests flights have provided significant input into the design process. It is clear that there are unique challenges with producing a super pressure pumpkin balloon. Test Flight 540NT fully deployed, but developed a leak that was attributable to a manufacturing issue. Test Flight 555NT did not fully deploy, but held pressure to a point above the maximum design level. These test flights spurred a number of investigations and advancements for this project. The development path has pursued some new approaches in the design, analysis, and testing of the balloons. Small model testing and indoor inflation tests have provided significant knowledge. New issues have been identified through both analysis and testing. These items will be addressed in the design stage before the next flight balloon construction will begin.

The ULDB team continues to investigating the deployment issue. Photogrammetry is being used to obtain better biaxial material properties, especially at low temperatures. Updates to the material model will be made, and additional analyses will be completed using the updated material model. Additional subscale ground model testing will also be completed. The plan for future ULDB efforts is under development.

11. Acknowledgements

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