OPTIMUM DESIGNS FOR SUPERPRESSURE BALLOONS

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ABSTRACT

The elastica shape is now well known to be the best basic shape for superpressure balloon design. This shape, also known as the pumpkin, or natural shape for balloons, has been well understood since the early 1900's when it was applied to the determination of the shape of descending parachutes. The elastica shape was also investigated in the 1950's when high strength films were used to produce superpressure cylinder balloons. The need for uniform stress distribution in shells of early superpressure balloons led to a long period of the development of spherical superpressure balloons. Not until the late 1970's was the elastica shape revisited for the purpose of the producing superpressure balloons. This paper will review various development efforts in the field of superpressure design and will elaborate on the current state of the art with suggestions for future developments.

HISTORICAL BACKGROUND IN SUPERPRESSURE BALLOON DESIGN

The basic operation of the superpressure balloon is simple. As the balloon ascends and completely fills the envelope, the differential pressure increases as the ambient pressure decreases. The system reaches equilibrium when the weight of the balloon, payload, and lifting gas is equal to the weight of the displaced air. When the sun sets, the balloon gas cools, but the displaced volume of air remains the same. Thus, the lift of the balloon remains the same and the system remains at a constant altitude. The eternal challenge of designing of superpressure balloon system is to design it with sufficient strength to withstand the tremendous forces generated in the balloon shell and in the attachment points for the payload.

Cylinder Balloons

In the mid 1950's, the Air Force Cambridge Research Laboratory experimented with polyester film cylinder superpressure balloons. These balloons were successful in demonstrating the concept of the superpressure balloon, but the weight of the shell and the design of the end fitting termination became prohibitive. It is interesting to note that the first superpressure balloons were cylinders which were allowed to take on the natural shape. This shape minimizes the circumferential stresses in the shell material while transferring most of the loads to the longitudinal direction. The resulting forces at the ends of the gores are very high and increase with the square of the radius of the balloon. This rapid expansion in the material requirements with balloon size limited this type of design to very small balloons.

Spherical Balloons

The early 1960's began a new era in superpressure balloon design. Spherical balloons would generally carry the pressure created loads globally in the balloon material. The shells of spherical balloons were fabricated with very precisely cut gores which were joined at their edges with adhesive tape. The process of applying the adhesive tape required precision equal to that of the gore cutting process. Fabrication of these balloons was perfected by G.T. Sheldahl and Raven Industries in the

1960's. The required robustness of the fabrication process along with limitations of the materials used limited payload capability to less than 1000 lbs.

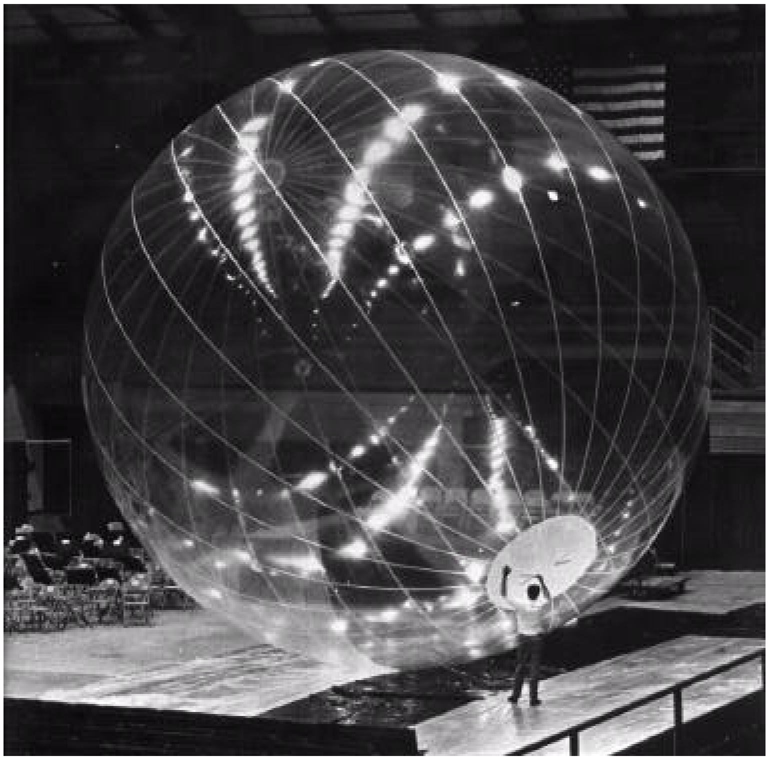

Figure 1 - Typical Polyester Superpressure Sphere

Spherical superpressure balloons were used extensively in the 1970's for global stratospheric wind circulation studies. These programs used superpressure balloons to carry transmitters which were tracked by a variety of means to develop better models of stratospheric circulation. These programs included GHOST (Global Horizontal Sounding Techniques), TWERLE (Tropical Wind Energy conversion and Reference Level Experiment), and GAMP (Global Atmospheric Measurements Program). These programs provided extremely valuable information in the development of global wind patterns. The developments of the GHOST program lead to very refined understanding of both the capabilities and limitations of spherical polyester superpressure balloons.

Early Treatment of the Elastica Shape

Knowledge of the longitudinally reinforced superpressure balloon dates back to the early 20th century when Taylor (Cambridge, 1963) used a rubber weather balloon surrounded by strings to validate his parachute shape calculations in 1919. This natural shape, shown in Figure 2, is essentially the same as the ULDB design used today.

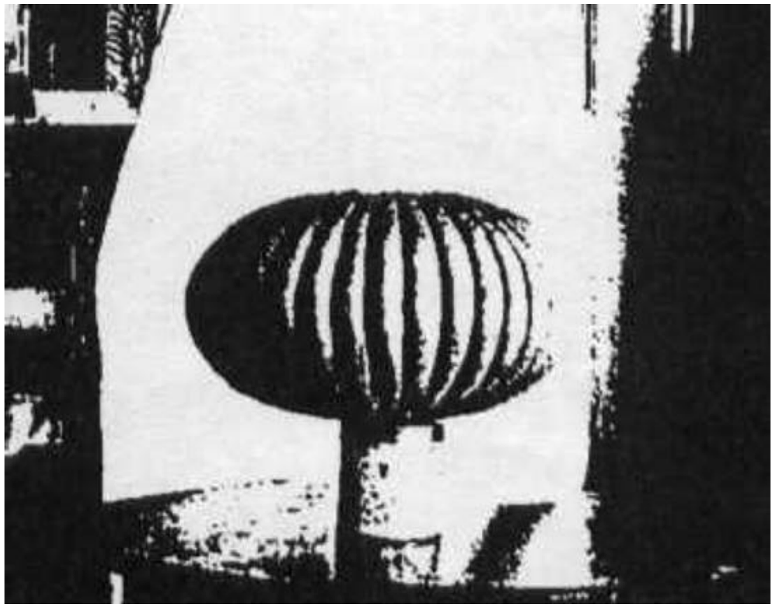

Figure 2 - Taylor Shape Validation Model CIRCA 1919 (courtesy Cambridge Press)

In the late 1960's fiber technology had progressed to the point where the large longitudinal forces created by superpressure natural shape balloons could be managed. Smalley (1970) introduced the "e" balloon which used glass fiber tapes and allowed the balloon gores to stretch both in the longitudinal and transverse directions to react to the differential pressures in the structure. The concept was tested with a small number of test flights with limited success. The limiting factor, as with the cylinder balloons of the 1950's, was the ability to hold the very large concentrated forces at the poles of the balloons.

In 1984, Julian Nott used a fabric elastica balloon with built-in lobing in the gores to reduce the stresses in the balloon material. The gores in this balloon were originally designed to have a full 180° radius between the load tapes. When the balloon was originally inflated, the balloon was found to have so much extra material between the load tapes, that it could not all deploy evenly, as shown in Figure 3. Four of the sixty-four gores in the balloon were removed in order to allow full deployment. During the flight, increasing pressure in the balloon caused the material to stretch and the onset of the buckling phenomenon was observed again.

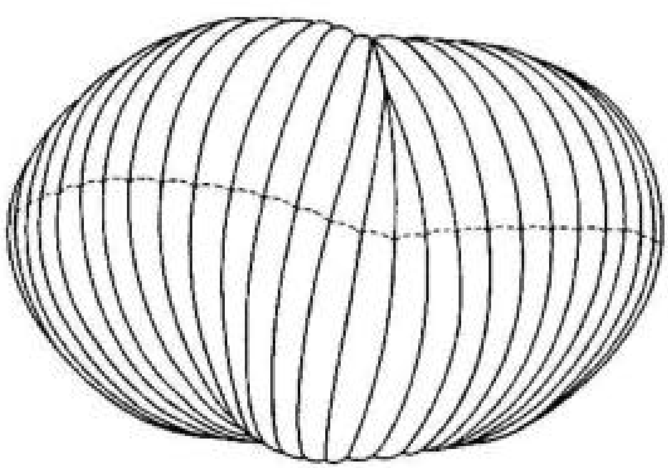

Figure 3 - Buckling of and Elastica Balloon with Lobed Gores
Due to Excess Material (courtesey Elsevier Science Publishers)

EVOLUTION OF THE ULTRA LONG DURATION BALLOON DESIGN

NASA's Ultra Long Duration Balloon (ULDB) project started in the mid 1990's with a series of material and seaming method studies at Raven and NASA's Wallops Flight Facility. The original design goal of the ULDB was to carry a 1500 kg payload above 30 km for a three month mission. This requirement exceeded any previous superpressure balloon payload by nearly ten times. The other major factor affecting the design was the requirement to have a launch operation that was as close to standard balloon operations as possible. This meant that the payload would be attached at the bottom pole of the balloon and standard inflation tubes would be used.

The First Concept – High Strength Sphere

The original design concept for the ULDB, shown in prototype form in Figure 4, was a classic sphere design with the payload attachment at the base. This design showed difficulties during the initial test flight phase. Since one of the design requirements was for the payload to be attached at the base, management of the combined pressure and payload forces at the base of the balloon was very difficult.

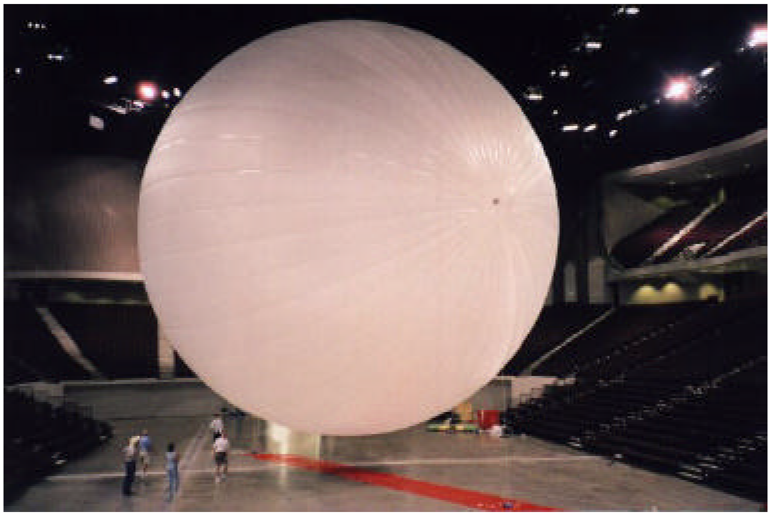

Figure 4 - ULDB Sphere Designed with High Strength Fabric

Second Concept – Lobed Elastica with High Strength Material Shell

Having experienced difficulties with the spherical balloon, the elastica concept was revisited. The first elastica balloon built in the ULDB project was made with the same high strength laminated fabric as the first sphere. The overall shape followed the elastica and the gores were constructed with a constant lobe angle down the length of the gore. This design resulted in decreasing lobe radius from the equator of the balloon to the poles. This design required the use of high strength tendons along the seams because most of the pressure loads in the balloon were transferred to the longitudinal direction. The difficulty in attaching the tendons to the fabric shell was apparent in the test flight of this design. The tendons slipped from their attachments along the length of the balloon and allowed a large amount of material to bulge out between, negating the effect of the lobing. As the pressure in the balloon increased, the balloon burst.

Third Concept – Constant Angle Lobed Elastica with Polyethylene Shell

Further analysis during the ULDB project showed that if the lobing in the balloon was not allowed to move, and a very high modulus tendon material was used, the shell material strength requirements were greatly reduced. The next design concept utilized a polyethylene shell with the tendons sealed in place on each seam. This balloon also had a constant lobe radius design. The test flight of the first balloon with this design was a complete success. The volume of the test balloon was 60000 m^3.

The next balloon to use this design was flown from Alice Springs Australia in March of 2001. The balloon had a volume of 441000 m^3. In order to keep the skin stresses to a minimum, the lobe angle on the gore design was increased. This extra material caused the same kind of incomplete deployment that Julian Nott experienced. The deployed shape of the balloon is shown in Figure 5.

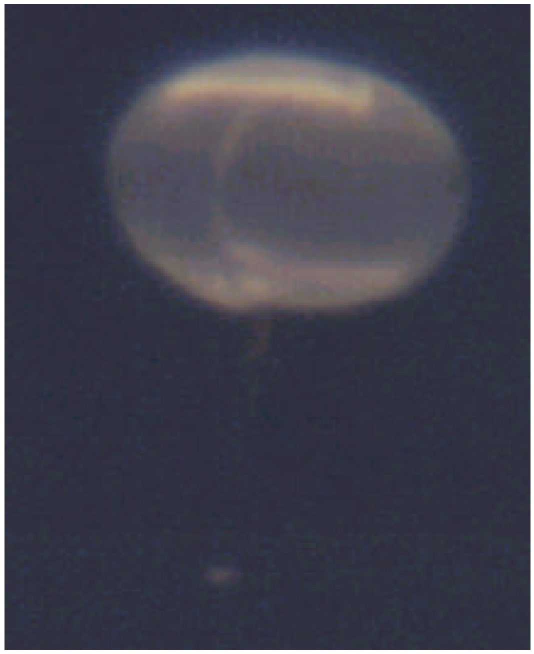

Figure 5 - Incomplete Deployment of Full Scale ULDB Test Balloon in March of 2001

Current Concept – Constant Radius Lobed Elastica with Polyethylene Shell

In order to develop a full understanding of the phenomenon of incomplete deployment, a series of model tests was conducted. The models with constant lobe angles, like the balloons test flown previously, confirmed the analysis conducted by Calladine (1980). Dr. Calladine's work showed that for a lobed balloon with constant lobe angle, there was a limit to the amount of built-in lobing that could be obtained for a given number of gores. The lobe geometry, as shown in Figure 6, consists of a half lobe angle α, tendon to tendon distance c, lobe radius r, and manufactured gore width s.

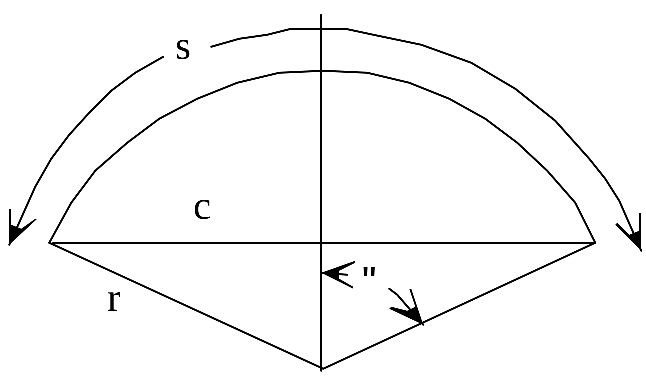

Figure 6 - Lobed Gore Geometry

Calladine developed a semi-empirical relationship for the maximum gore width angle for balloons with constant lobe angles down their lengths. Smith later rearranged this relationship for a maximum ratio of s/c. The relationship for the maximum half lobe angle and gore width ratio is presented in Eq. (1) and (2). In these equations, α_{max} is in radians.

$$\alpha_{max} = (47/n)^{0.4} \quad (1)$$

$$s/c_{max} = \alpha_{max}/\sin\alpha_{max} \quad (2)$$

The resulting relationship, shown in Figure 7, is compared to several of the 48 gore models and flight test balloons. The balloons with a constant lobe angles, thus a varying lobe radius, behaved as suggested by the Calladine relationship. As suggested by Schur, the balloon can be built with a constant lobe radius and the maximum lobe angle can be increased significantly. This allows the balloon to be built with deep lobes in the areas where they are needed the most – in the equatorial regions of the balloon.

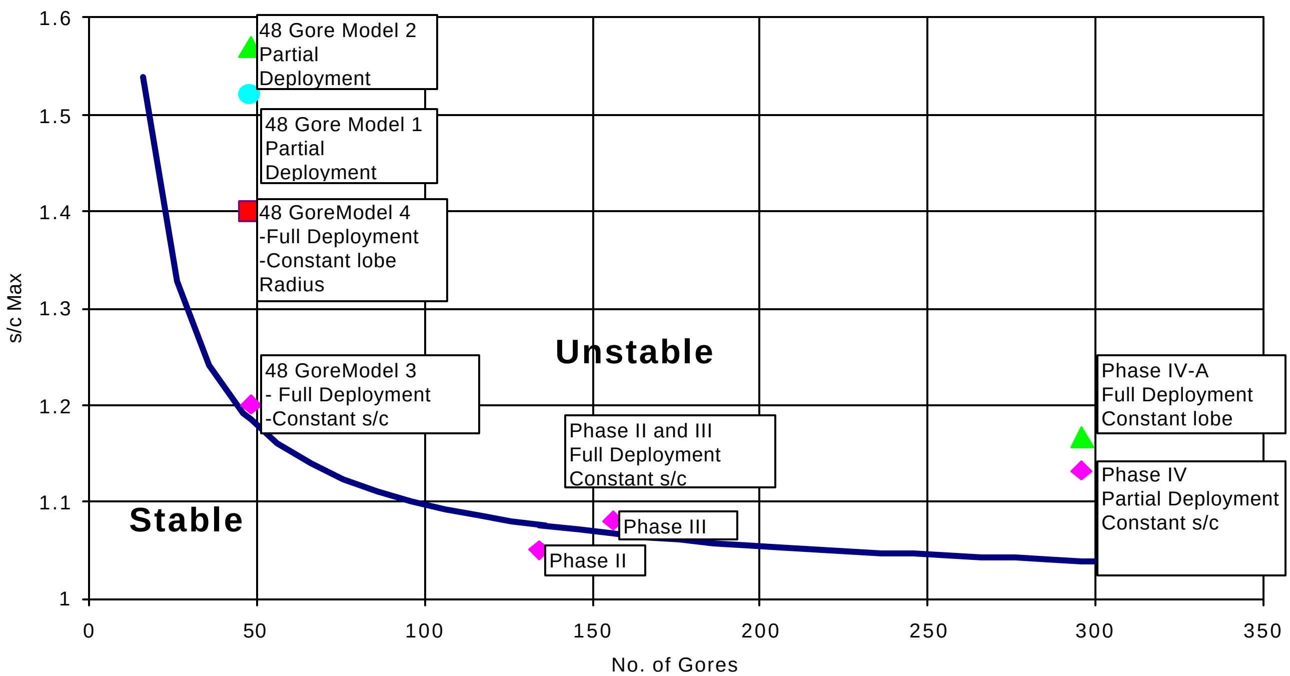

Figure 7 - Test Balloons Compared to the Calladine Relationship. The thick line is the limit of s/c per Eq. (2). Balloons with a constant s/c will not deploy completely if s/c is above the line. Balloons with constant lobe radius will deploy completely if above the line.

From the data shown in Figure 7, it is clear that the balloons with constant lobe radius are not subject to the limit defined by Calladine. The balloons that completely deployed were either constant s/c balloons that were very close to the Calladine limit, or balloons with constant lobe radius. The phase IV-A balloon, with a s/c of 1.17 at the equator, had a complete deployment during its test flight in July of 2002 although it was designed significantly above the Calladine limit. The fact that the majority of the balloon was below the Calladine limit in terms of s/c ratio gave the balloon the ability to deploy properly.

DEVELOPMENT OF OPTIMUM DESIGNS APPRORIATE FOR VARIOUS PLATFORMS

The ULDB project has allowed the development of the specialized design features and fabrication techniques that will allow fabrication of natural shaped superpressure balloons. Armed with the more complete understanding of the behavior of lobed balloons, opportunities now exist to apply the technology toward optimum designs. When one considers the concept of an “optimum” design, the definition of optimum is in the eye of the beholder. The structural analyst may consider optimum to be the design that yields the lowest stresses. The accountant may consider the optimum design to be the one that yields the lowest per-unit cost. The reliability engineer may prefer the design that has the fewest difficult production operations. In actuality, the most optimum design is the one that provides the highest levels of reliability without being overly expensive. This section reviews some applications of ULDB technology that will potentially allow some previously impractical design concepts to become more practical.

Fully Tailored Overpressure Zero Pressure (OZP) Balloons

In the early 1990's, NASA experimented with a natural shape balloon that was designed to be slightly pressurized during the daytime. The design was not a true superpressure balloon since it was not intended to be pressurized during the whole night time. By maintaining a slight overpressure, the size of sunset ballast drops could be decreased. Test flights using shell designs of previously proven zero pressure balloons were conducted with some success. Later failures in the project prompted a search for stronger shell fabrication methods, and eventually, the ULDB project.

The ULDB project was an indirect result of the needs identified in the OZP program. The OZP balloons required high strength shell designs and new ways to manage the tremendous forces generated by the small differential pressures acting over very large areas. The balloon designs, materials, and fabrication techniques are all applicable to the production of OZP balloons. The shell of an OZP balloon could be constructed in the same way as a ULDB, except the gore material would not be shortened along the tendon to form the longitudinal lobes in the gores. The OZP would be designed using extra gore width in the transverse direction, but longitudinal lobing would be formed by material strain. The amount of material strain for an OZP balloon with 290 gores would be less than 1%. A comparison of the OZP gore design with ULDB gore design is presented in Figure 8.

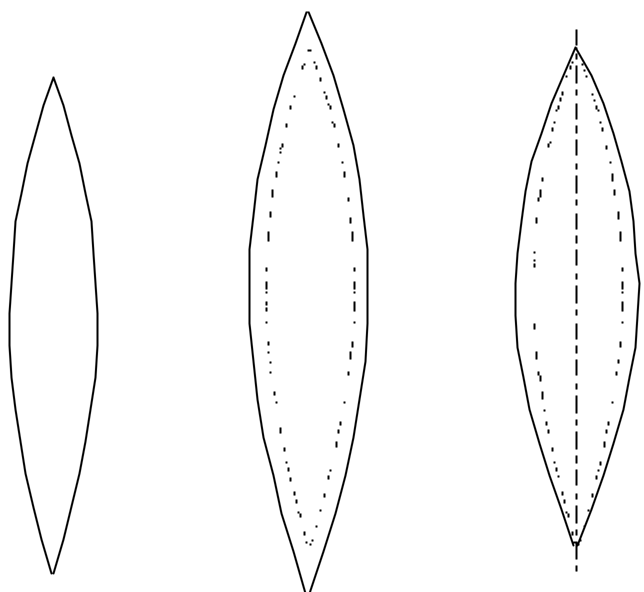

Figure 8 - Gore Design Comparisons

The design of previous OZP balloons used a shape that was originally intended for a zero pressure balloon. This design used a gathered base fitting in which the sum of the gore widths at the base of the balloon was much greater than the circumference of the fitting. In the proposed OZP design, no gathering would be used and the tendons would bear almost all of the longitudinal stresses in the balloon. The The shapes of zero pressure balloon is compared to the shape of a proposed new OZP balloon design is presented in Figure 9. The balloon design parameters are identical except for the use of an initial superpressure of 0.6 mb on the OZP shape. They were both designed for 1800 kg to 35 km. The balloons have volumes of 0.51 million cubic m^3. From observation of the shapes, it is clear that the zero pressure balloon shape was not suitable for use as an OZP balloon. It is also interesting to note that the balloon shapes are almost identical in their upper halves.

While an OZP balloon is not intended to perform in the same way as a ULDB, the cost of such a balloon would be less than one half of the cost of a comparably sized ULDB. For certain applications, where altitude stability is not as critical, and duration is not expected to be measured in months, a natural shape OZP would provide the optimum combination of cost and performance.

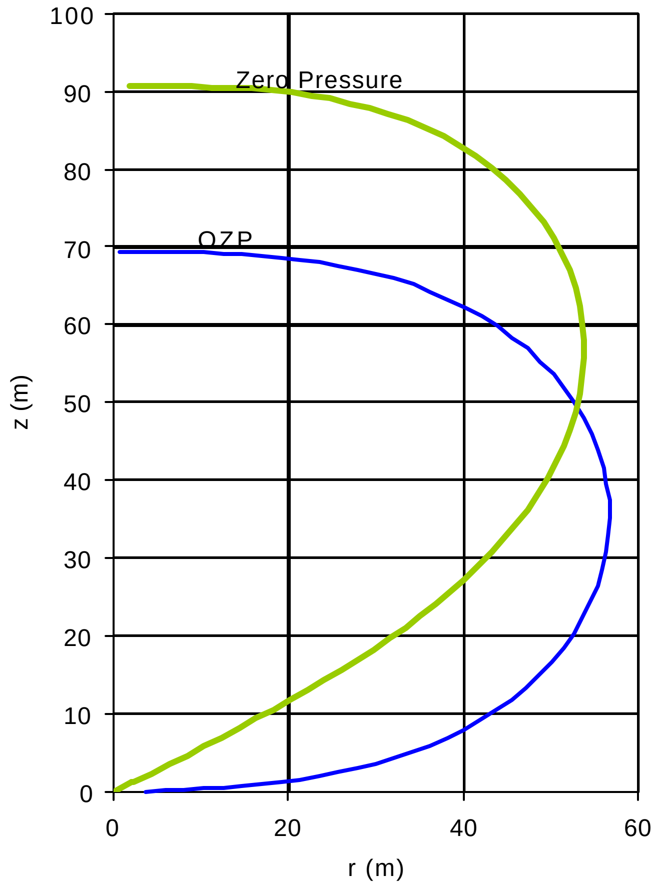

Figure 9 – Comparison of calculated balloon shapes for 0.51 million m^3 balloon designs with zero differential pressure and with 0.6 mb overpressure.

Tandem Systems

In the 1970's tandem balloon systems were developed to increase the flight duration capability of zero pressure balloons. A tandem system, shown in Figure 10, uses a zero pressure main balloon which is filled with helium. A polyester superpessure balloon filled with air would be suspended from the base of the zero pressure balloon. The principle of the operation of the tandem or "sky anchor" system was the anchor balloon would dampen or eliminate diurnal altitude oscillations by virtue of its constant volume. If the system descended, the anchor balloon would weigh less because it displaced an equal volume of increasingly dense air with its constant mass of pressurized air. Problems with Sky Anchor systems were mainly with the polyester anchor balloons. The anchor balloons would leak or fail to pressurize at all. Launching such systems proved to be a challenge for operational crews. Previous sky anchor systems used complicated load skirts to introduce the loads into the spherical shells.

Revisiting tandem systems under the context of ULDB technology would yield anchor balloons of much lighter weight and greater volume. The ability of the system to hold a base mounted ballast hopper is inherent to the design of the ULDB. Tandem systems using natural shaped anchor balloons would be an excellent choice for long duration flights that would require more altitude stability than an OZP, but would fly for up to two months.

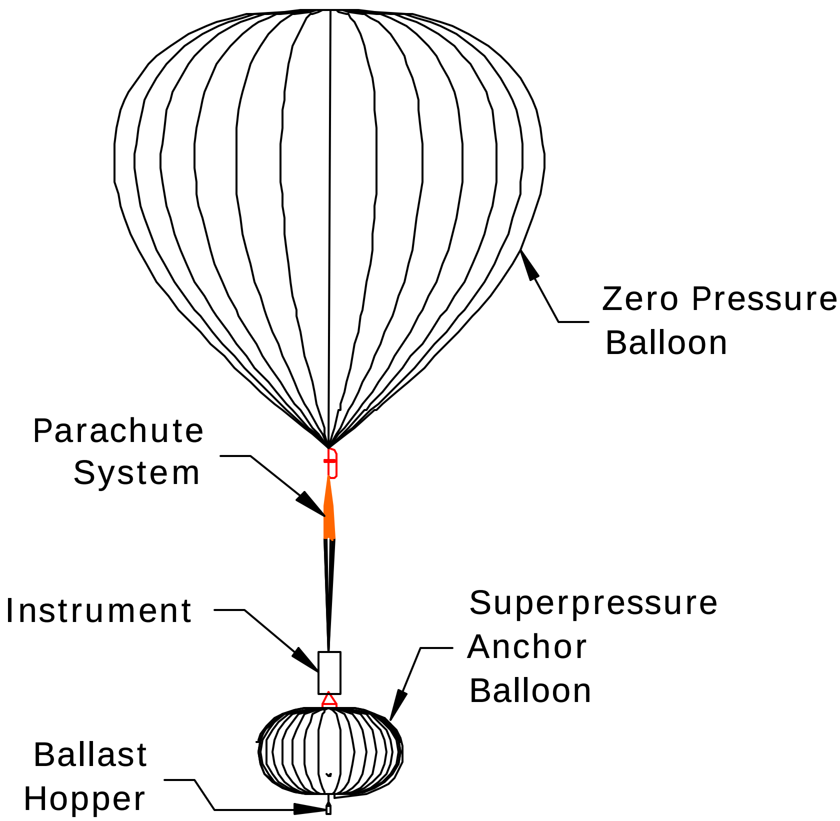

Figure 10 - Tandem Sky Anchor System Using a Natural Shape Anchor Balloon

CONCLUSIONS

The utility of the ULDB technology is not limited to single cell superpressure balloons. By using some or all of the innovations from this project, less demanding applications can be addressed in more cost effective ways. The use of ULDB technology in other applications could also be used to improve the design and fabrication of single cell ULDB envelopes.

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