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14. ABSTRACT
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Report Title

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List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

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(d) Manuscripts

Design and Fabrication of Exo- and Endoskeleton Framed Envelopes for Air Platforms by Raghu Panduranga, Robert Sadler and Kunigal Shivakumar

Number of Manuscripts: 1.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Final Report is attached

Technology Transfer

Report

Feasibility Study of Endo- and Exo-skeletal Framed Structures with Envelopes for LTA Platforms

Grant #: W911NF-10-1-0020

Short Term Innovative Research

To

Col. Young Reed, Program Manager
Army Research Office
Research Triangle Park, NC
and
Mr. Harris Edge
Army Research Laboratory
Proving Ground, MD

Submitted by

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February 15, 2011

Abstract

A pathway for design and fabrication of Endo- and Exoskeleton framed elliptical envelopes was demonstrated. Envelope sizes of 2 ft x 0.5 ft and 5 ft x 1.25 ft were successfully fabricated and their buoyancy and lifting capability were assessed. A technique of filling the envelope with helium was demonstrated. The weight of 2 ft by 0.5 ft envelope before and after filling with helium was 0.082 lb (37 g) and 0.018 lb (8 g), respectively. Using the concepts developed for the 2ft x 0.5ft envelope, the fabrication was successfully scaled to 5 ft x 1.25 ft. The weight of the 5 ft x 1.25 ft envelope before filling with helium was 0.48 lb (218 grams). After it was filled with helium the envelope carried a payload of 0.32 lb (143 grams). Frame member sizes are not structurally designed and optimized because the loadings and their conditions were not available, if provided the structure could be designed to meet the optimal operational conditions.

1. Introduction

Lighter Than Air (LTA) flying platform concepts have been studied intermittently ever since the desire to fly evolved. That interest continued to expand utilizing helium filled and hot air balloons for recreational applications. Because of limited buoyancy, size and low altitude use, these concepts have not replaced the interest in powered aircrafts. In 2008 Army Science Board report [1] entitled “Platforms for Persistent Communications, Surveillance and Reconnaissance” (CSR), the board revisited and investigated the capabilities of the platforms deployed in space, near space and lower altitudes and assessed the tradeoffs among benefits, weaknesses, costs and logistics burdens associated with each platform type. Based on this study, the army notes [1, 2] that the medium altitude LTA airships offer a promising capabilities for CSR based on time on station, all weather capability, flying hour cost and vulnerability. The report also notes that high altitude LTA platform permits the offloading of communication traffic from high-cost commercial satellites and future military satellites. The report concludes that “the maturation and potential payoff of LTA technology warrants for their investment in experimentation and potential acquisition because of persistence time-on-station”. In this regard, Edge et al. [3] proposed “Pressurized Structure Based (PSB) - technology for stealthy UAV’s using the concepts of lighter and partially buoyant systems”. These concepts have potential for significant reduction in weight as well as smaller, quieter and energy-efficient propulsion system. Potential pressurized envelopes concepts are shown in Figure 1.

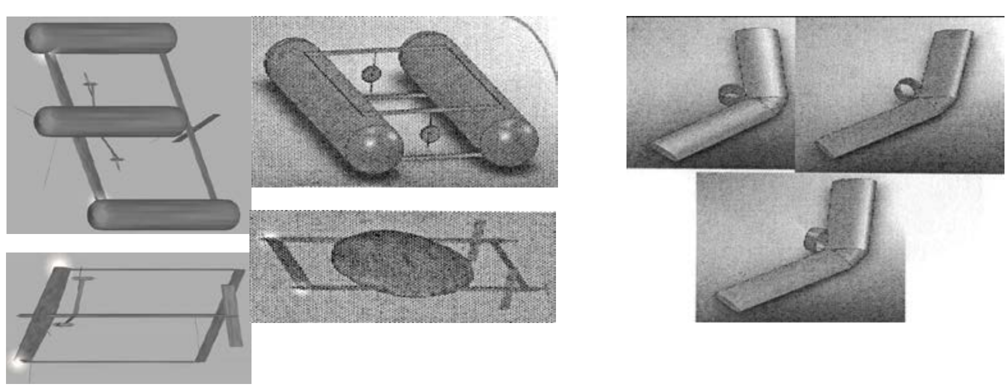

Figure 1. Pressurized Envelopes for LTA Platforms

The configurations chosen in the present study is an endoskeleton envelope with the outer envelope containing the lighter-than-air gas attached to internal ultra lightweight frame with aerodynamic control surfaces and propulsion systems mounted on an external exoskeleton. Although the configurations appear to be simple and doable, the challenges are many. Are these platforms self buoyant? What is the payload? How far they could lift? Lower air density at high altitude may counteract the density of low density gas. What are design limits? Challenges also include choice of material and the choice of fabrication techniques that meets the demands of size, weight, stiffness and durability are formidable. Objective of this short term innovative research was to conduct a feasibility study of design, fabrication and lift test studies of an endo- exo-Skelton framed envelops using the real materials and a proven knowledge of fabrication techniques. This study would potentially show a pathway to build complicated geometrical systems.

2. Objectives of the Research

The overall objective of this exploratory research is to demonstrate through design, analysis, fabrication, and testing of endoskeleton structures/envelopes that potentially address the needs of the LTA platforms for the Army. Then show potential pathways to extend the technology to other configurations. The endoskeleton concept would maintain the shape even after the helium has lost due to a skin puncture possibly by enemy action. The research focus is to fabricate 5ft x 1.25ft ellipsoidal saucer envelope. A sub-scale model of one-half will be utilized for the initial developmental program. Here, we assume that all envelopes are filled with helium gas to provide buoyancy with and without the endoskeleton structural frame, then it will lift or partially support itself in air. The technology developed in this program is generic and broad and that can be extended to other inflatable shapes. The availability of large exposed surface area can be exploited for solar power generation and management and embedment of communication antennas.

3. Approach

The approach followed consists of the following two steps.

1. Design of ellipsoidal envelopes sizes for buoyancy/lift
2. Fabrication of endo and exoskeleton framed envelope.

The concept of endo and exoskeleton framed envelope is shown in Figure 2. It consists of a very light weight endoskeleton frame (Fig. 2b) that maintains the shape of the envelope. The endoskeleton frame is covered by an ellipsoidal envelope (Fig. 2c). The envelope was filled with helium to provide the buoyancy to the structure. Then the endoskeleton structure was attached to a exoskeleton frame (Fig. 2d) that potentially could be used to mount propulsion and control systems. The fabrication of each of the item and their integration is explained in the next sections.

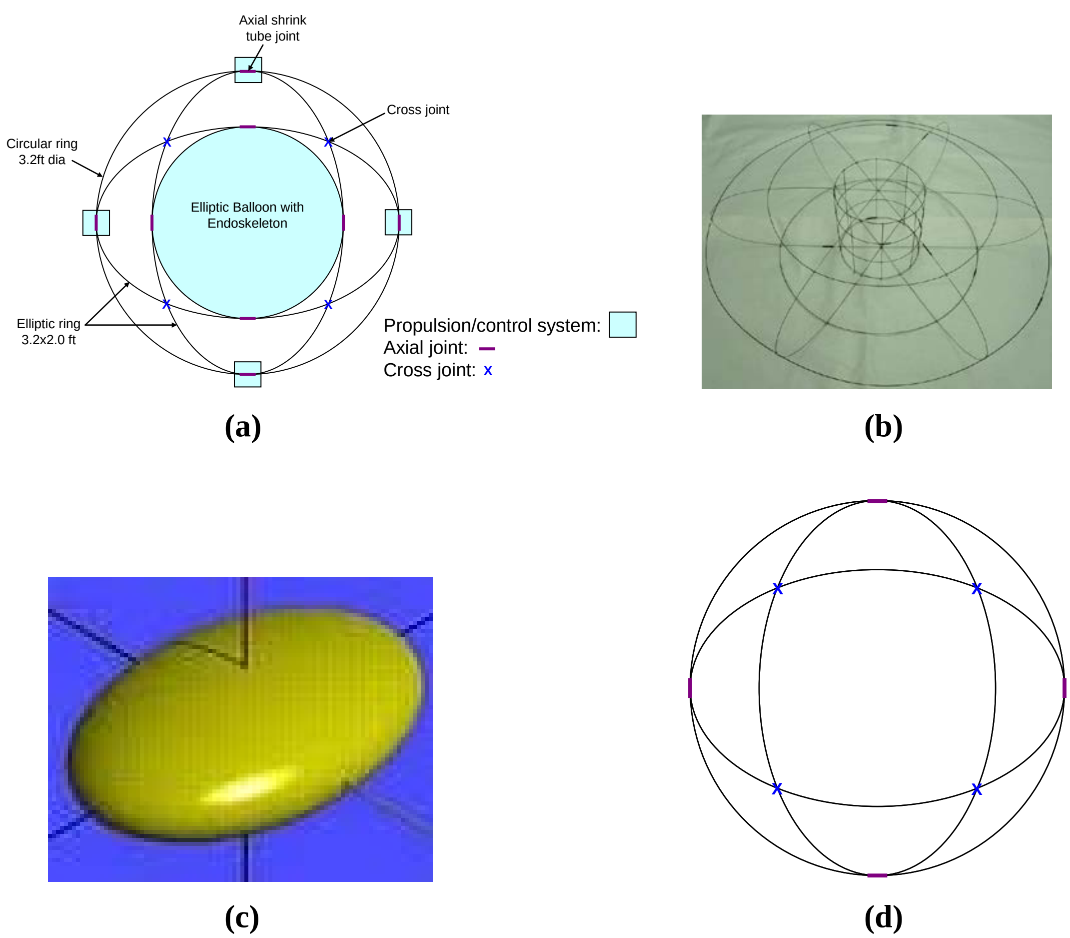

Figure 2. Concepts of Fabrication of Endo- and Exoskeleton Framed Envelope

4. Design Studies

The lift design calculations were performed for 2 ft, 4 ft, 5 ft and 8 ft diameter envelopes using a simple buoyancy equation.

$$L_e = V(\rho_{Air} - \rho_{He}) \tag{1}$$

Where, L_e = lift of the envelope, V = volume of the envelope, ρ_{Air} = density of the air, and ρ_{He} = density of the helium.

At sea level the density of air, ρ_{Air} = 0.0752 lb/ft^3 and it changes with altitude (see data in ref. 4). The density of helium, ρ_{He} = 0.0104 lb/ft^3. Using the equation 1 the lift versus altitude was calculated for the four envelopes and are listed in Table 1. The envelope volume and surface area are calculated from:

$$V = \frac{4}{3}\pi abc \tag{2}$$

$$SA = 4\pi\left[\frac{a^p b^p + a^p c^p + b^p c^p}{3}\right]^{1/p} \tag{3}$$

Where, a, b, and c are semi axis lengths in length, width and thickness directions, respectively and the value of p is 1.6075. The Table 1 also shows that the envelopes of size 4ft x 1ft and above will have enough lift to carry some payload and the size 2ft x 0.5ft and below will not carry any payload by the buoyancy alone.

Table 1. Lift Calculations for Envelopes of Various Sizes

Balloon Size, Dia x ht, ft	Surface Area, ft^2	Volume, ft^3	Lift, lb
2 x 0.5	7.2	1.0	0.07
4 x 1	28.7	8.4	0.54
5 x 1.25	44.8	16.4	1.06
8 x 2	114.6	66.9	4.33

The figure 3 shows the plot of lift against the altitude for the four envelopes. Because the density of the air falls as the altitude increases, the lift also decreases with altitude. The slope of the curve is a function of volume of the envelope as seen in equation (1).

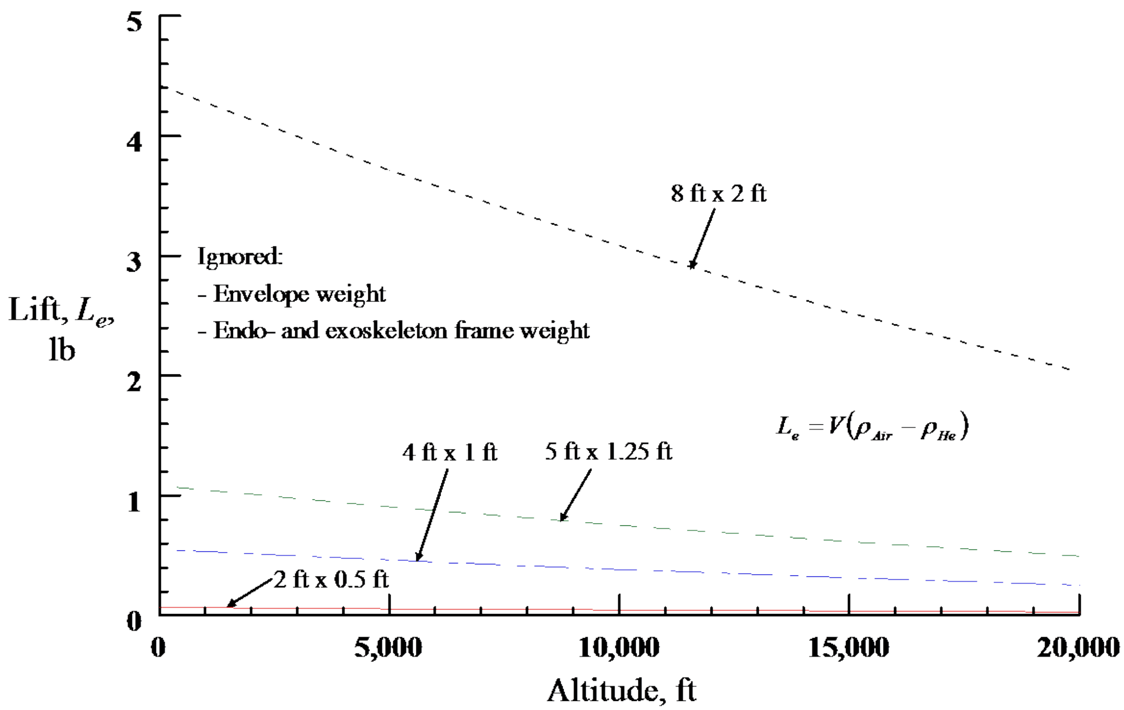

Figure 3. Plot of Lift vs. Altitude for various Envelope Size

For the 4 ft diameter envelope, detailed lift calculations were performed for the case of envelope with and with out the endoskeleton frame and the covering membrane (film). The lift design calculations were performed using a simple buoyancy equation.

$$L_M = V(\rho_{Air} - \rho_{He}) - W_{frame} - W_{envelope} \qquad (4)$$

Where, W_{frame} = weight of the endoskeleton frame and $W_{envelope-}$= weight of the envelope film. Table 2 shows the lift calculations for 4 ft x1 ft envelope at different altitudes for the three different designs using the equation (4). Figure 4 shows the plot of lift versus altitude for 4 ft x1 ft envelope for various cases. From the Figure 4, we can observe that the lift is decreasing with increase in altitude for all the cases. The inclusion of endoskeleton frame to the envelope resulted only marginal reduction of lift. If we assume the payload to be 0.2 lb, the 4 ft x1 ft envelope can carry this payload to an altitude of 10,000 ft by buoyancy alone.

Table 2. Lift Calculations for 4 ft x 1 ft Envelope

Altitude, ft	Atm Pressure, in. Hg	Air Density, lb/ft^3	Lift, lb				
			with out film	with film	with film + frame (6 divisions)	with film + frame (8 divisions)	with film + frame (12 divisions)
0	29.92	0.0765	0.553	0.380	0.367*	0.366	0.363
5,000	24.89	0.0659	0.464	0.292	0.279	0.277	0.275
10,000	20.57	0.0565	0.385	0.213	0.200	0.199	0.196
15,000	16.88	0.0481	0.315	0.143	0.130	0.129	0.126
20,000	13.74	0.0408	0.254	0.081	0.068	0.067	0.065

* includes 10% wt. of endoskeleton structure for joints

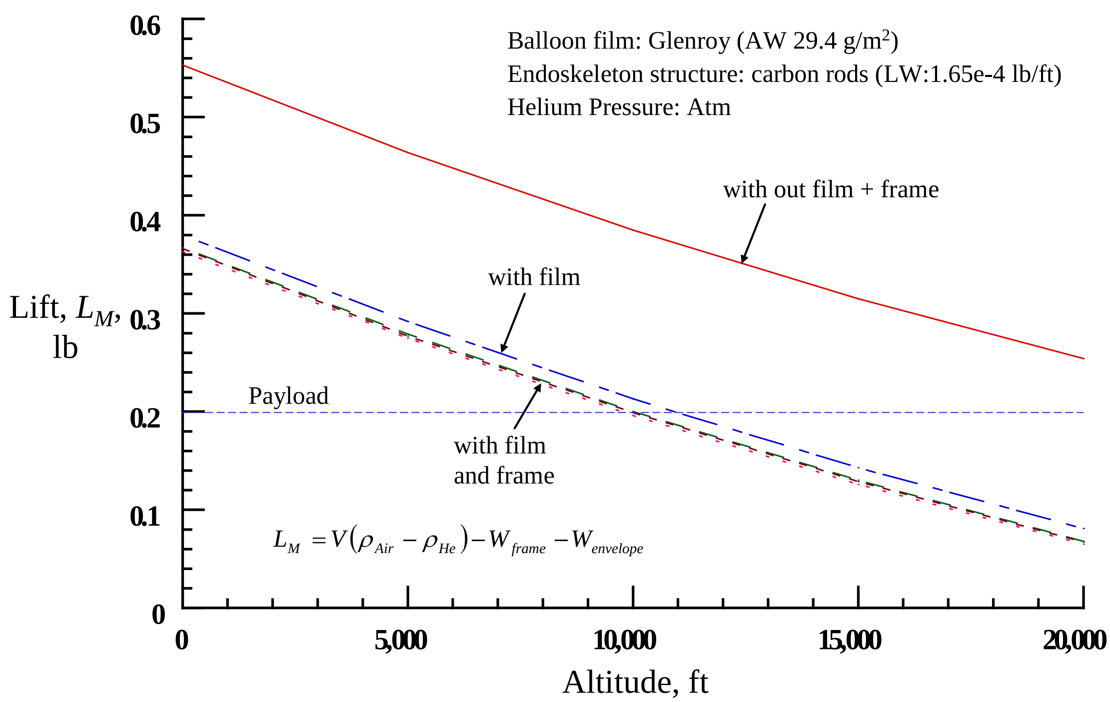

Figure 4. Plot of Lift vs. Altitude for 4 ft x 1 ft Envelope

The following data were used in the lift calculation of 4 ft x 0.5 ft envelope.

- Surface area of the 4 ft x 1 ft envelope : 28.65 ft^2
- Volume of the envelope : 8.36 ft^3
- Areal weight of the Glenroy film : 0.00602 lb/ft^2 (29.4 g/m^2)
- Linear weight of the carbon rod (0.02" dia) : 0.000166 lb/ft (0.075 g/ft)
- Total length of the carbon rod for endoskeleton frame : 92.2 ft
- Total weight of the Glenroy film required : 0.173 lb
- Total weight of the carbon rod required : 0.017 lb
- Density of the helium at sea level (0 ft) : 0.01039 lb/ft^3

5. Fabrication Concepts for 2 ft x 0.5 ft Envelope

As previously explained the fabrication consists of three parts and assembly. Each of these steps are explained in the following sections.

5.1 Endoskeleton Frame

(a) Materials

The material selected for frame construction is Carbon/Epoxy pultruded rods because they have the greatest specific mechanical properties of any material commercially available. These rods are composed of carbon fibers with an epoxy matrix. Carbon fiber pultruded rods are readily available from a number of sources. We purchased the carbon/epoxy rods from Goodwinds, Inc., Washington. We purchase the rods in rolls where we could cut them to the lengths required for the job. The rods are actually manufactured by Diversified Structural Composites at Erlager, KY but they only sell large quantities and refer smaller customers like ourselves to Goodwinds. The rods used for this project were 0.020, 0.030 and 0.040 inches in diameter. The properties of the rods composed of standard modulus carbon fibers are listed in Table 3. The other factors considered in the selection of pultruded carbon rod is weight per unit length and the bend radius. The carbon rods, which has minimum weight/unit length and allow maximum bend radius, were selected. The linear density of the selected carbon/epoxy pultruded rods are given in Table 4.

Table 3. Physical and Mechanical Properties of the Carbon/Epoxy Pultruded Rods

Property	Value
Fiber Volume Fraction, %	67
Tensile Strength, ksi (GPa)	320 (2.3)
Tensile Modulus, msi (GPa)	19.5 (134)
Ultimate Tensile Strain, %	1.3
Compression Strength, ksi (GPa)	270 (1.9)
Compression Modulus, msi (GPa)	19 (131)
Glass Transition (Tg), ^{o}C	100
Diameter Tolerance, %	± 5

Table 4. Linear Density of Selected Carbon/Epoxy Pultruded Rods

Outside Diameter, in	Linear Density, grams/ft
0.02	0.075
0.03	0.125
0.04	0.275
0.06	0.925

(b) Fabrication

Two types of endoskeleton frames of reduced scale (2ft dia x 0.5 ft height) were fabricated. The smaller size mock up is selected to understand the know-how of the material and fabrication methods and to prove the fabrication concept. The preliminary design of the endoskeleton frame consists of central tubular grid structure, an outer equatorial circular ring, and a number of meridional elliptic rings which connects the central tubular structure with the outer equatorial ring. The frame also consists of top and bottom latitudinal circular rings to provide additional stability. A diagram of the endoskeleton frame design is shown in Figure 5.

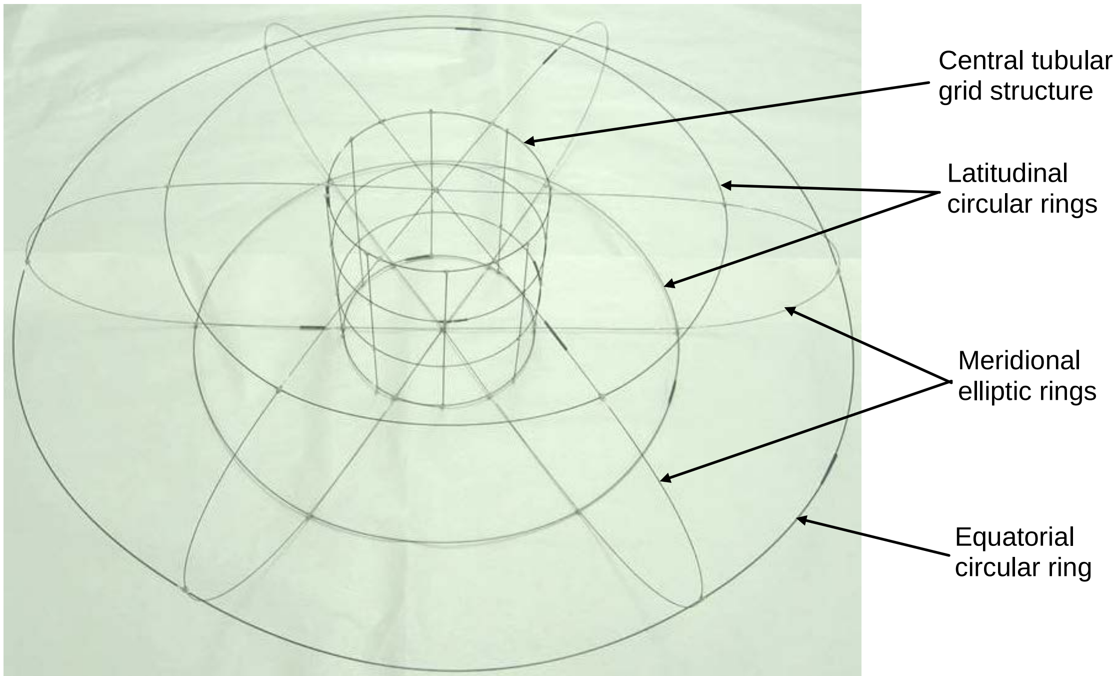

Figure 5. Design of the Endoskeleton Frame

The envelope configuration was a solid ellipse with a diameter four times the height at the center axis. The initial construction was for a diameter of 24 inches and a height of 6 inches. It is actually a series of rings joined together a various points. The rings were constructed using shrink tubing to join the two ends into a ring configuration. It was planned for the tubing to be shrunk with heat to provide the joints but the high temperature required to shrink the tubing also tended to damage the pultruded rods. Perhaps this problem could have been solved by using the right shrink tubing and the right heating conditions but it was decided to use adhesive with the tubing. The use of adhesive worked quite well so we didn't continue to develop the heat shrink technique.

The endoskeleton frame is fabricated from pultruded solid carbon rods of various diameter. The details of the carbon rod dimensions used for constructing various frame members are listed in Table 5. The carbon rods of required lengths were cut using scissors. The joint locations were marked using white ink. The circular rings of various diameters were made by joining the ends of the rods using adhesive coated PVC heat shrink tubes. Four circular rings of 6 in diameter, two circular rings of 15 in diameter and one circular of 24 in diameter were made for fabricating central tubular grid structure, latitudinal rings, and an outer equatorial ring, respectively. Three meridional elliptic rings were fabricated from 18.3 in dia circular rings. First, the central tubular grid structure is fabricated by tying the vertical rods to the 6 in dia circular rings with cotton thread at marked locations using square lash type of knot design. Second, the meridional rings were tied to the outer equatorial ring using the same knot design. Finally, the equatorial outer ring structure is tied to the central tubular grid structure using the same knot design. The meridional elliptic rings were aligned in vertical planes using square edge. Then the top and bottom latitudinal rings were tied to the frame structure at the marked locations. A drop of "Bondo" polyester adhesive is applied at all joints to impregnate the knot. To minimize the weight of the adhesive, the excess was removed with a wiper. The joints were allowed to cure at room temperature for 24 hours. The photograph of the endoskeleton frame is shown in Figure 6. The weight of the 24 in dia endoskeleton frame was around 0.018 lb (8 grams).

Table 5. Details of Carbon Rods used for fabricating Endoskeleton Frame#1

Structural Element	Carbon Rod Diameter, in	Numbers Used
Meridional elliptic rings	0.02	3
Circular rings	0.03	2
Central columns	0.03	8
Equatorial circular ring	0.04	1

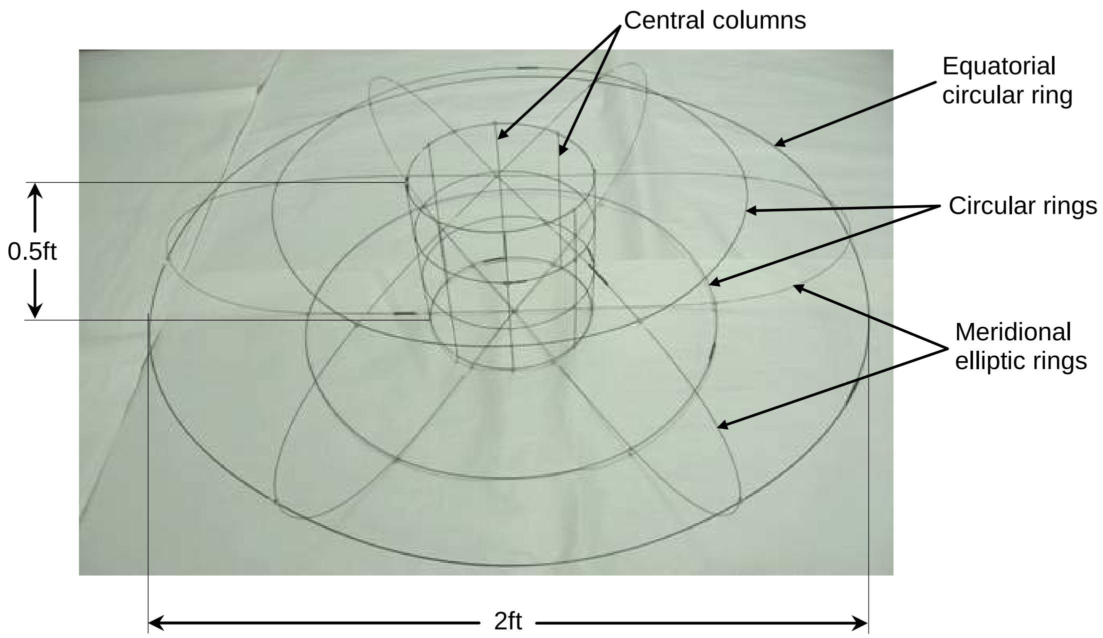

Figure 6. Photograph of the Endoskeleton Frame#1

It is realized that the endoskeleton frame with three meridional rings was not stable when the balloon envelope is laid over the frame. In addition, this arrangement was creating wrinkles in the balloon envelope. Therefore, it was decided to add three more meridional rings to the frame in order to improve the structural stability. The modified endoskeleton frame is fabricated with six meridional rings using the same fabrication procedure as outlined above. The photograph of the modified endoskeleton frame is shown in Figure 7. The weight of the modified 24 in dia endoskeleton frame was around 0.02 lb (9 grams). The modified endoskeleton frame was stronger and stiffer with only a small weight difference in 0.018 lb (8 grams) versus 0.02 lb (9 grams) for the total frame. The details of the carbon rod dimensions used for constructing modified endoskeleton frame are listed in Table 6.

Table 6. Details of Carbon Rods used for fabricating Endoskeleton Frame#2

Structural Element	Carbon Rod Diameter, in	Numbers Used
Meridional elliptic rings	0.02	6
Circular rings	0.03	2
Central columns	0.03	8
Equatorial circular ring	0.04	1

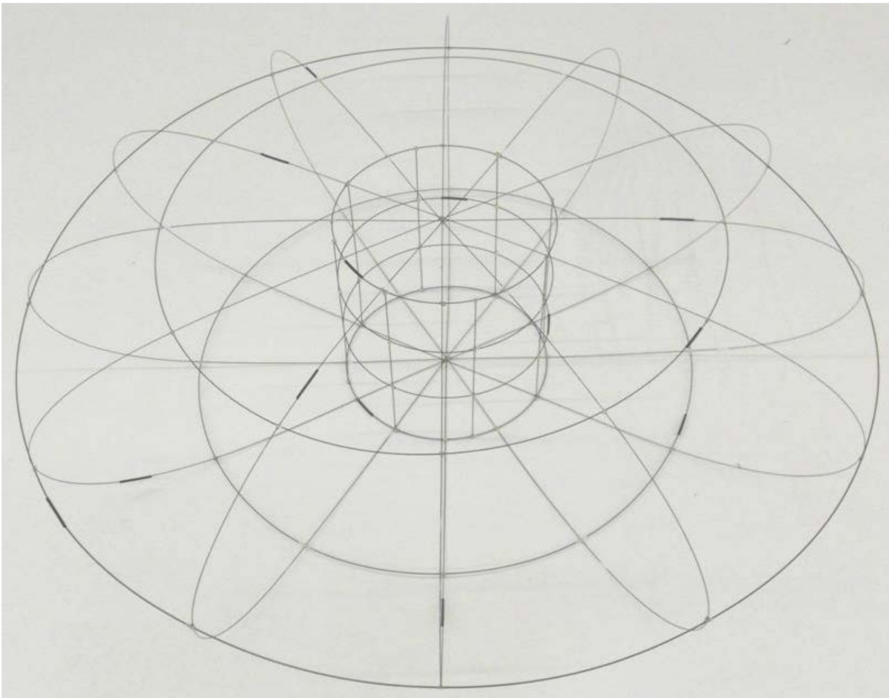

Figure 7. Photograph of the Endoskeleton Frame#2

Challenges

- All the members except central vertical columns were pre-stressed since they are fabricated by bending the straight carbon rods.
- Thermal post-forming of carbon/epoxy rods resulted in breaking of the rods instead of shaping when heated above the glass transition temperature.

Possible Solutions

- In order to fabricate the stress free endoskeleton frame we need to have pultruded rods made out of thermoplastic materials such as Spectra fibers and a thermoplastic matrix which could be shaped to required contour upon application of heat.

5.2 Balloon Envelope

(a) Material

The construction the balloon envelope requires the film material which is both heat sealable and commercially available in small quantities. The criteria used for the selection of the film for balloon envelope are;

- Low helium permeability
- Commercial availability
- Good strength
- Good toughness (puncture resistance)
- Good heat sealing

Based on the above criteria a number film candidates were selected and is listed in Table 7. For this project it was decided that fabrication by heat sealing was necessary. The balloon film down selected for this study was Glenroy N00 001. The film is a multilayer material consisting of three layers; metallic gas barrier layer, strength layer and heat sealing layer. The schematic of the multilayer film is shown in Figure 8. Glenroy N00 001 is metalized biaxially stretched Nylon 6 with a low melt point polyethylene (LLDPE) coating for heat sealing. It is especially produced for helium filled

Table 7. Properties of Balloon Film Candidates

Properties	Dupont MYLAR 48A	Honeywell CAPRAN 1200	Honeywell CAPRAN MEDALLION MT1000	Glenroy N00 001	Toray LUMLIFE
Type	PET	Biaxial Nylon 6	Metallized biaxial Nylon 6	Metallized biaxial Nylon + LLDPE	Metallized PET
Use	Industrial	Packaging	Packaging + Balloons	Balloons	Balloons
Density, g/cc	1.39	1.38	1.38		1.4
Area Weight, g/m^2				29.4	
Gauge, 0.00001-in (microns)	48 (12)	47 (12)	40 (10)	48 (Nylon) + 65 (LLDPE)	48 (12)
Elongation @ Break MD, %	110	60 - 90	90 - 110		
Elongation @ Break TD, %	70	60 - 90	60 - 80		
Tensile Strength MD, ksi	26	34 - 42	35 - 45		
Tensile Strength TD, ksi	32	34 - 42	45		
Tensile Modulus MD, ksi	507	350 - 450			
Tensile Modulus TD, ksi		350 - 450			
Yield (nominal), in^2/lb	41,300	51,000	60,450	24,000	
Gas Transmission Rate, $cc/100in^2/day$			0.07 (O_2)		
OTR (oxygen transmission rate), $cc/100in^2/day$		3.5 - 4.5 (77^oF, 0% RH)			
HTR (helium transmission rate), $cc/100in^2/day$			3 (73^oF, 0% RH)		
Heat Seal Range, ^oF					
Heat Seal Strength @350^oF/ 40psi/1-sec dwell, g/in				3,600	
Shrinkage MD, %	2				
Shrinkage TD, %	1				
Availability		1000-lb lots	1000-lb lots	37.25" x 100'	Pallet lots

foil balloons. None of the other film candidates had both metallization and a heat sealing layer and were not also available in the small quantities required.

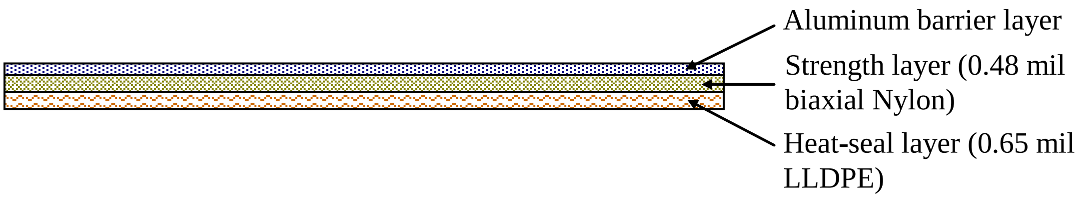

Figure 8. Schematic of the Glenroy N00 001 multilayer film

(b) Fabrication

The brief procedure for fabrication of balloon envelope is explained here. The Glenroy N00 001 film is cut to two pieces of size 34 in x 34 in. The envelope size and location of the helium inlet and outlet tabs were marked. The film were laid over the card board panel covered with a Teflon coated glass fabric. The film were tightly secured by using adhesive tapes along the edges. Two pieces of 6 in x 0.25 in Teflon coated glass fabric were cut and secured at the helium inlet and outlet location using adhesive tape on the Glenroy film as shown in the Figure 9. Figure 9 also shows the placing of arc shaped Teflon strips of width 1/16" for inserting the members of the exoskeleton frame in later stage. A template fabricated from corrugated box board is placed over the films and a Teflon film is laid at the periphery of the template as shown in Figure 10 to ease the heat sealing operation. A Hot Iron set at approximately 110^{o}C is moved back and forth under hand pressure over the area to be heat sealed. First, the semicircular periphery is heat sealed to form a bag like envelope. Second, the endoskeleton frame is inserted carefully into envelope. Finally, the envelope is carefully stretched over the endoskeleton frame and temporarily locked in place using binder clips. Then the heat sealing operation is performed sector-by-sector over the remaining semicircular periphery of the film.

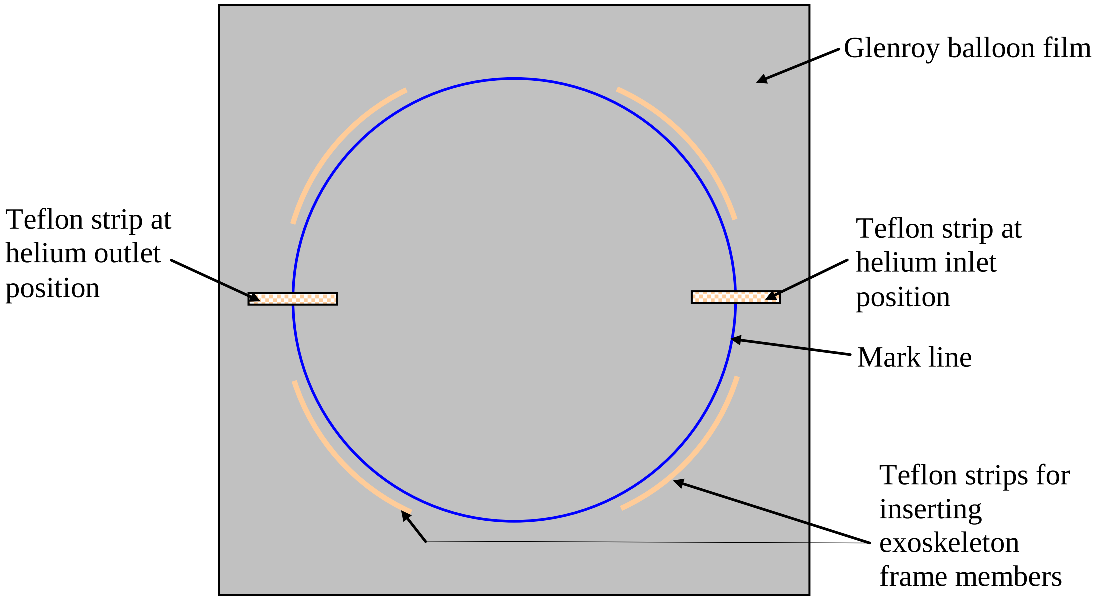

Figure 9. Inlet and Outlet Tab Making using Teflon Film Strips

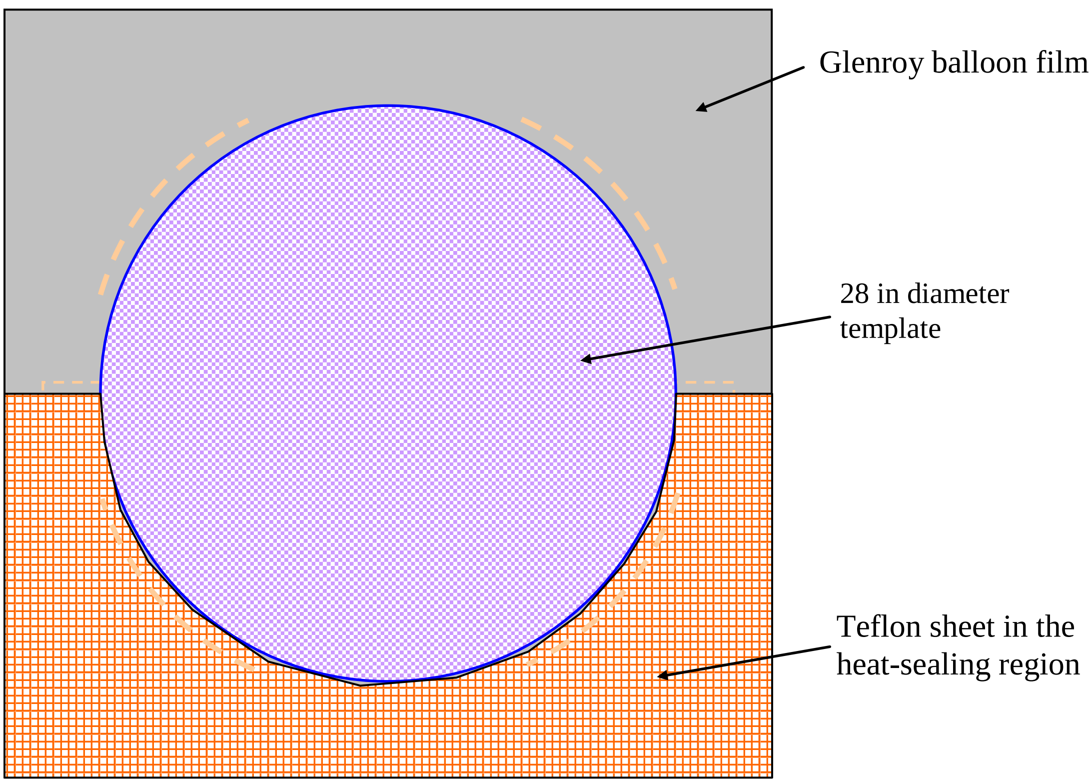

Figure 10. Preparations Required for Heat Sealing of Balloon Envelope

(c) Envelope Filling

The helium filling operation for envelopes containing an endoskeleton was thought to be a problem because of the presence of air in the envelope. The air needs to be replaced to achieve a helium fill. Normally envelopes are supplied in the collapsed form and it is not necessary to remove the air. Before starting helium filling operation, the envelope with the endoskeleton frame was weighed. The pressure regulator is adjusted to release the helium gas at a pressure of 2.1 - 2.3 inch column of water. The envelope was held vertically and the helium gas was allowed to pass through the top of the envelope for 4 minutes and the air was allowed to escape from an opening at the bottom. After 4 minutes, the envelope inlet and outlet tabs were sealed and weighed. This procedure was repeated at every 4 minute interval until the envelope reached a minimum weight. The weight of envelope and helium filling time is listed in Table 8. This process would tend to use more helium to accomplish a complete fill but it seemed to work quite well. For one example, the envelope weighed 35 grams before filling and 2 grams after filling. After 44 minutes, additional helium flushing did not reduce the envelope weight. Therefore, it is assumed that the filling was pretty much 100%. The photograph of the helium filled envelope with endoskeleton frame is shown in Figure 11.

Table 8. Details of Helium Filling Time and Envelope Weight

Time, min	Balloon Weight, grams
0	35
4	24
8	21
12	16
16	12
20	9
24	7
28	5
32	4
36	3
40	2
44	2

Figure 11. Photograph of the Helium Filled Envelope with Endoskeleton Frame

Challenges

- Formation of wrinkles on the surface of the envelope near the circumferential edges.
- Film is available in 3ft width. Due to width limitation, fabrication of the envelope of size more than 2ft diameter requires joining of the film with a seam.
- Filling of envelope containing endoskeleton frame with helium is challenging because the air needs to be flushed from the envelope.

Possible Solutions

- To avoid wrinkles in the balloon film envelope and to maintain aerodynamic shape, thermoforming of the film can be considered.
- For fabricating larger envelopes, locate suppliers of film in wider rolls.
- Helium flushing technique needs further development.
- Balloon film can be cut into pie sections and the seams sealed to form required configuration.

5.3 Exoskeleton Frame

An exoskeleton frame is designed to support the propulsion and control equipments. The exoskeleton frame basically consists of two elliptical rings which orthogonal to each other and outer circular ring of diameter 3.2 ft. All the rings were made of carbon/epoxy pultruded rods of outside diameter 0.04 in. The two elliptical rings connects the periphery of the envelope with an outer circular ring. The design details of the exoskeleton frame is shown in Figure 12.

6. Integration of Endoskeleton Frame, Envelope and Exoskeleton Frame

The fabrication of integrated endo and exoskeleton framed structure with envelope consists of the following steps. The steps are the list of items performed in previous sections.

1. The endoskeleton frame (Fig. 6) was fabricated using carbon/epoxy pultruded rods as explained in the section 5.1.
2. The balloon envelope was formed from Glenroy N00 001 film as explained in section 5.2.
3. The endoskeleton frame was inserted into the half-sealed envelope bag and the remaining half of the envelope was hand stretched over the frame and heat sealed.
4. The balloon envelope was filled with helium as described in section 5.2.
5. The exoskeleton frame (Fig. 2d) is fabricated as explained in section 5.3 and attached to the balloon envelope at its periphery.

Some of the photographs of the integrated endo- and exoskeleton framed envelope shown in Figures 13a to 13d. Frame member sizes are not designed and optimized because of lack of knowledge of required loadings and their conditions. Once it is known it can be easily designed, optimized and fabricated. We have a concept of fabrication and knowledge of designing.

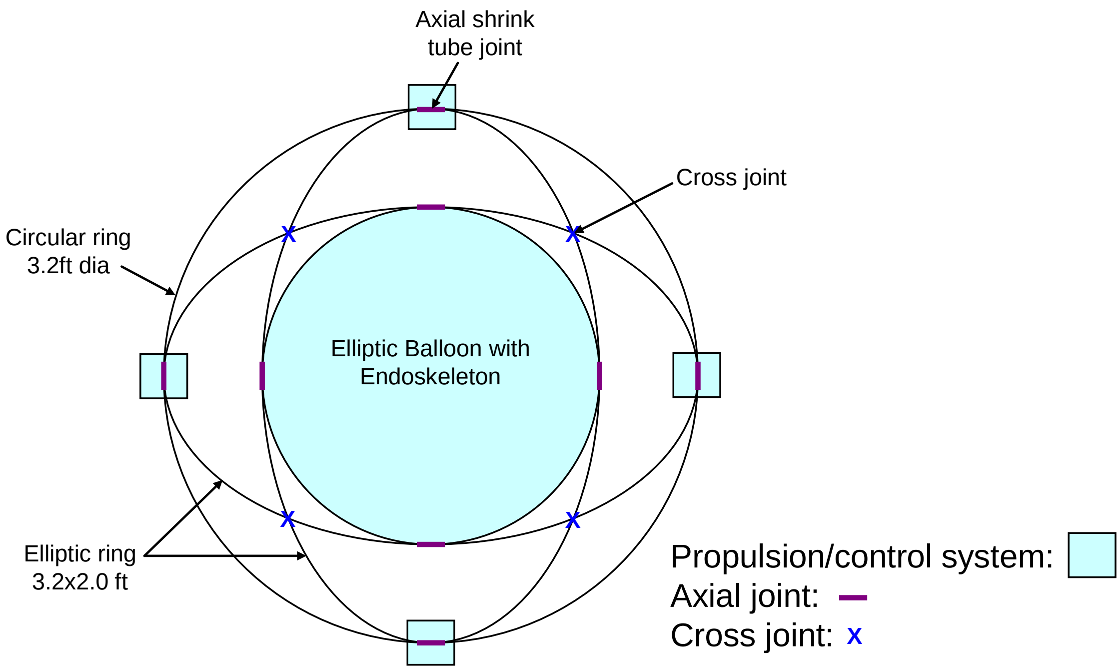

Figure 12. Design Details of an Exoskeleton Frame

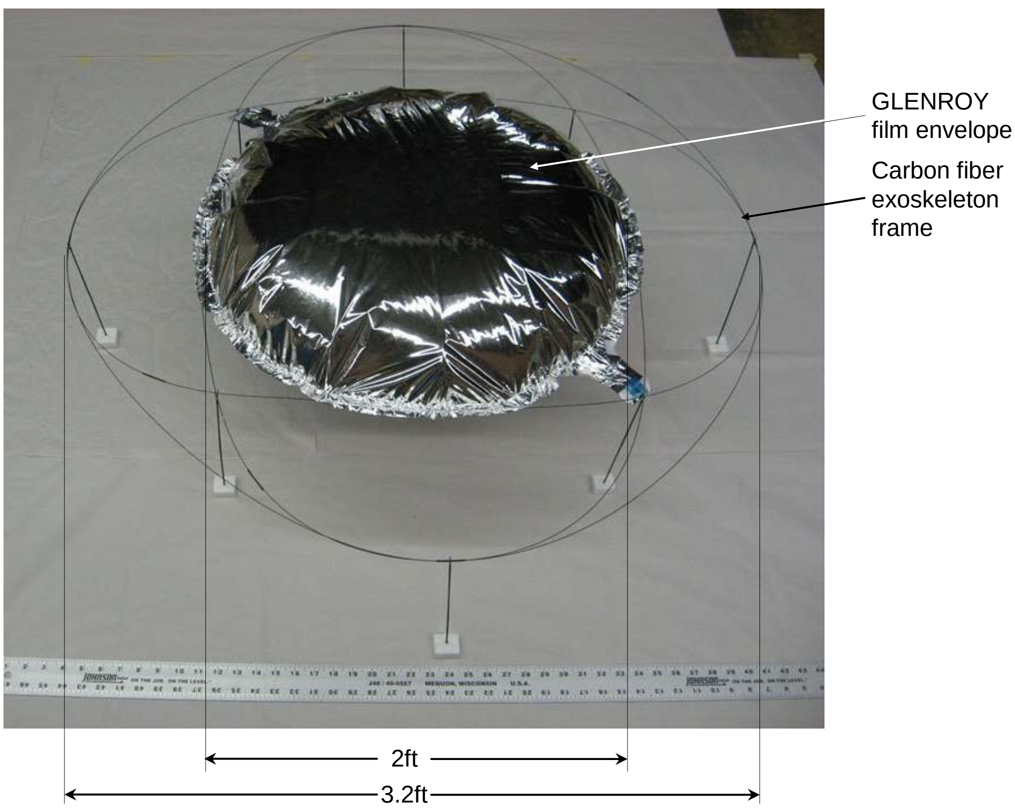

Figure 13a. Photograph of Envelope with Endo- and Exoskeleton Frame

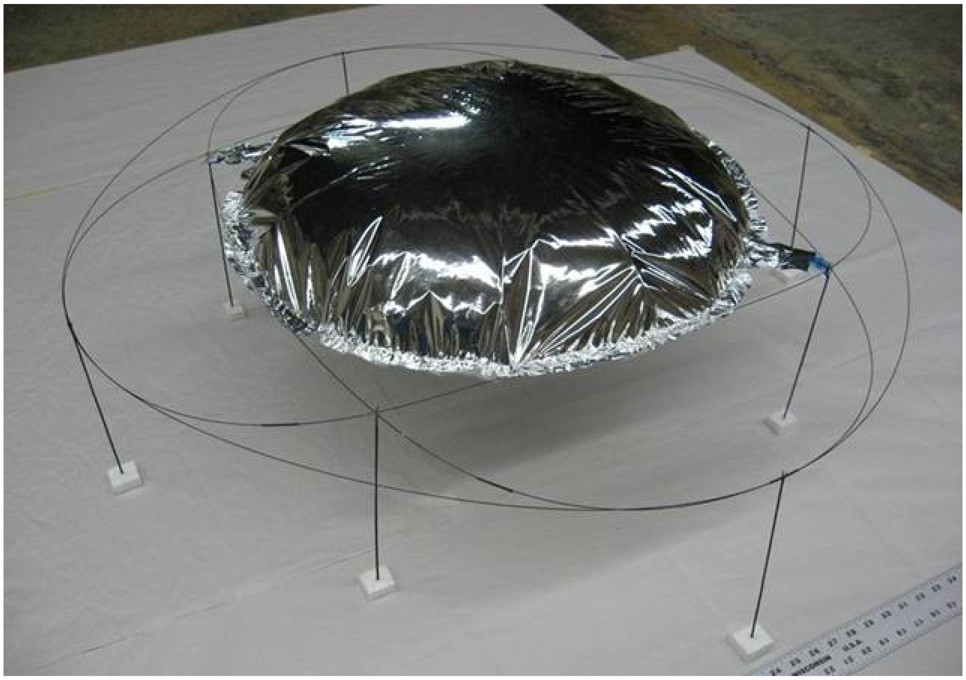

Figure 13b. Photograph of Envelope with Endo- and Exoskeleton Frame

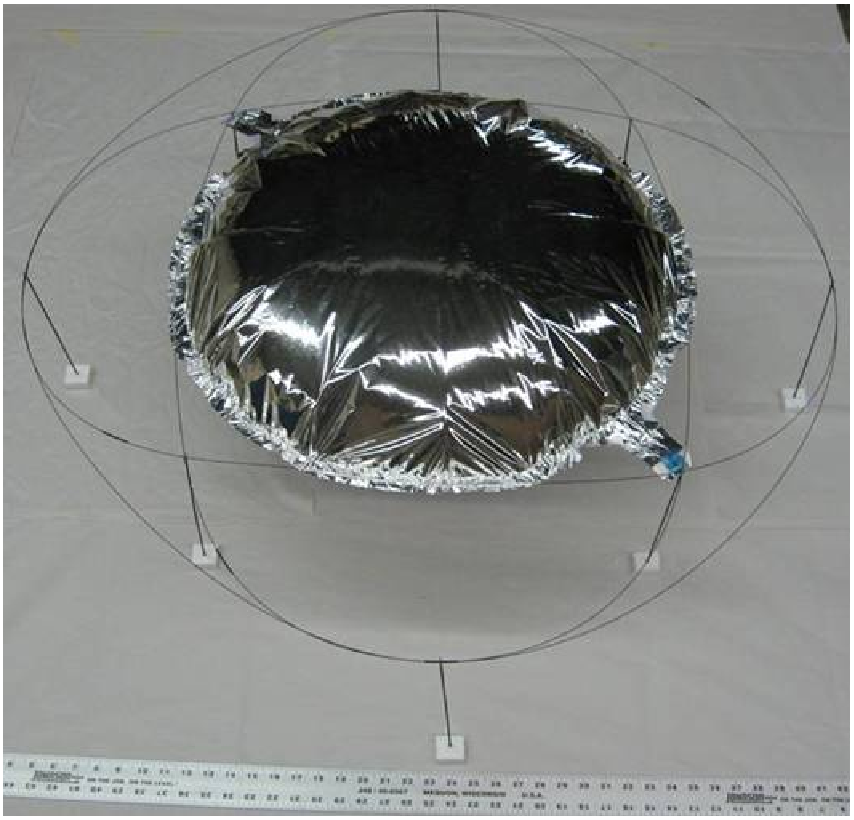

Figure 13c. Photograph of Envelope with Endo- and Exoskeleton Frame (Top view)

Figure 13d. Photograph of Envelope with Endo- and Exoskeleton Frame (Side view)

7. Scale-up to 5ft x 1.25ft Envelope

The design and fabrication procedures developed for the 2ft x 0.5ft envelope were scaled up to fabricate 5ft x 1.25ft envelope. The detailed design and fabrication procedures employed for manufacturing 5ft x 1.25ft envelope with endo- and exoskeleton structures is described below.

7.1 Endoskeleton Frame

The endoskeleton frame is fabricated from pultruded solid carbon rods of various diameter using the same procedure as outlined in section 5.1. The details of the carbon rod dimensions used for constructing various frame members are listed in Table 9. The photograph of the endoskeleton frame is shown in Figure 14. The weight of the 5 ft in dia endoskeleton frame was around 0.093 lb (42 grams).

Table 9. Details of Carbon Rods used for fabricating Endoskeleton Frame5ft#1

Structural Element	Carbon Rod Diameter, in	Numbers Used
Meridional elliptic rings	0.03	6
Circular rings	0.03	10
Central columns	0.03	12
Equatorial circular ring	0.06	1

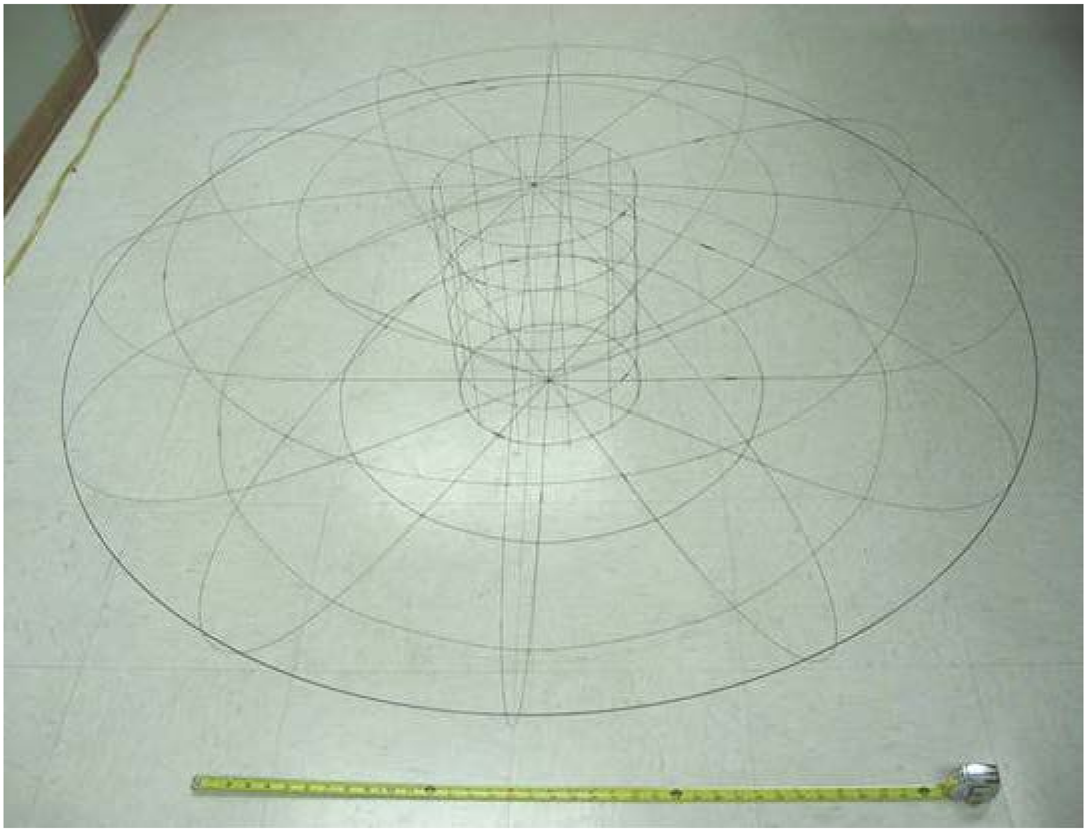

Figure 14. Photograph of the Endoskeleton Frame5ft#1

It was observed that the fabricated endoskeleton frame was too flexible and not stable when the balloon envelope is laid over the frame. Therefore, it was decided to add two more tubular grid structures at the location shown in Figure 15 in order to improve the structural stability. The weight of the modified 5 ft dia endoskeleton frame was around 0.137 lb (62 grams). The details of the carbon rod dimensions used for constructing modified endoskeleton frame are listed in Table 10.

Table 10. Details of Carbon Rods used for fabricating Endoskeleton Frame5ft#2

Structural Element	Carbon Rod Diameter, in	Numbers Used
Meridional elliptic rings	0.03	6
Circular rings	0.03	15
Central columns	0.03	36
Equatorial circular ring	0.06	1

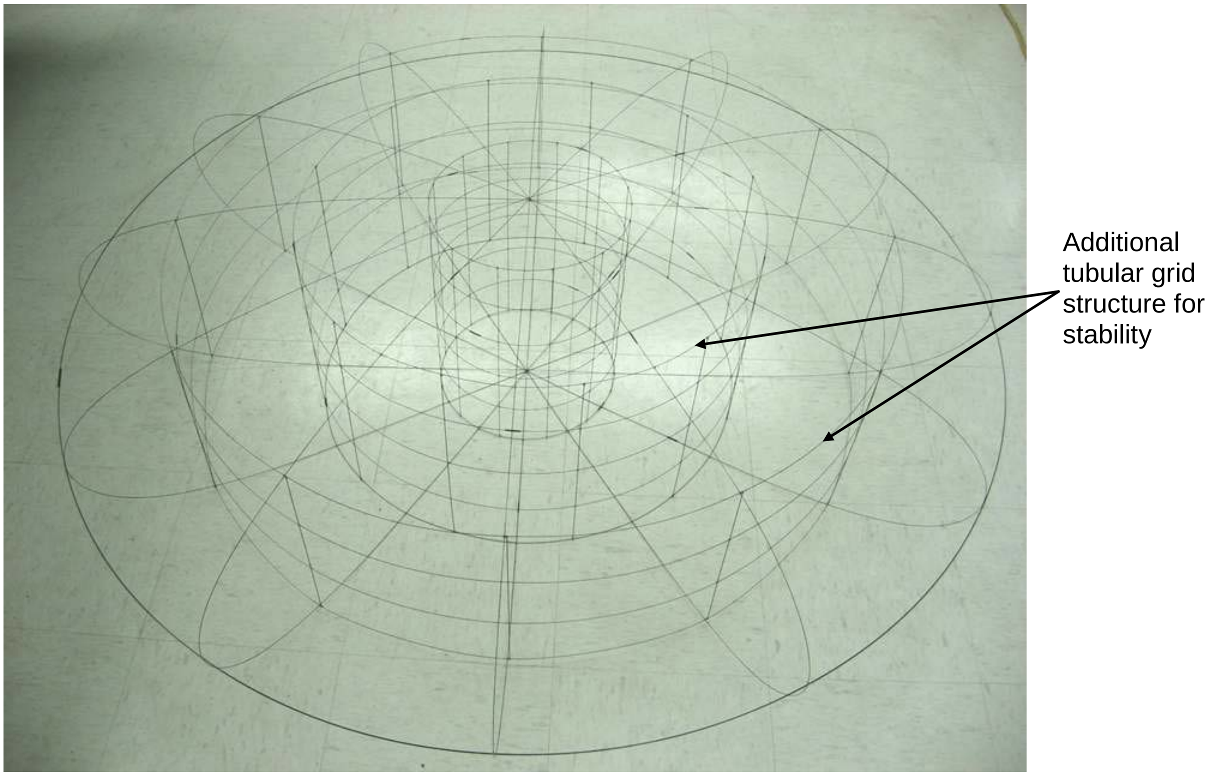

Figure 15. Photograph of the Endoskeleton Frame5ft#2

Challenges

- All the members except central vertical columns were pre-stressed since they are fabricated by bending the straight carbon rods.

Possible Solutions

- In order to fabricate the stress free endoskeleton frame it may be possible to pultrude rods composed of thermoplastic materials such as Spectra fibers and a thermoplastic matrix which could be shaped to required contour upon application of heat.

- Configuration could be molded to shape using carbon fiber and epoxy resin but tooling would be required.

7.2 Balloon Envelope

The Glenroy N00 001 film was available in 3ft wide rolls. Therefore, to fabricate 5 ft wide envelope, two Glenroy N00 001 films were joined together using heat sealing technique to form a seam in machine direction. After joining, the balloon envelope is fabricated using the same procedure as outlined in section 5.2. Figure 16 shows the preparations required for fabrication of balloon envelope before heat sealing operation.

Figure 16. Preparations Required for Heat Sealing of 5ft Balloon Envelope

Challenges

- Formation of wrinkles on the surface of the envelope near the circumferential edges.
- Film is available in 3ft width. Due to width limitation, fabrication of the envelope of 5ft diameter requires joining of the film with a seam. Joining created additional wrinkles which could possibly be avoided with additional experience.
- After insertion of the endoskeleton frame, sealing of the remaining half of the envelope bag is very difficult with out fixture.

Possible Solutions

- To avoid wrinkles in the balloon film envelope and to maintain aerodynamic shape, thermoforming of the film can be considered.
- For fabricating larger envelopes, locate suppliers of film in wider rolls.
- Design and fabricate heat sealing fixture to ease the sealing operation.
- Balloon film can be cut into pie sections and the seams sealed to form required configuration.

7.3 Envelope Filling

The helium filling operation for envelopes containing an endoskeleton was thought to be a problem because of the presence of air in the envelope. The air needs to be replaced to achieve a helium fill. Before starting helium filling operation, the envelope with the endoskeleton frame was weighed. The pressure regulator is adjusted to release the helium gas at a pressure of 2.1 - 2.3 inch column of water. Based on the filling experience of 2 ft diameter envelope, the envelope was held vertically and the helium gas was allowed to pass through the top of the envelope for 2 hours and air was allowed to escape from an opening at the bottom. After 2 hours not much buoyancy was observed. The envelope inlet and outlet tabs were sealed and weighed. The weight was 0.27 lb (122 grams). The envelope was kept overnight in the sealed condition to allow the air to settle down and the air outlet was opened after 12 hours. The helium filling operation is continued for 1 hour and then air outlet is closed and air is allowed to settle down. This procedure was repeated at every 1 hour interval until the envelope become buoyant and carried a weight of 0.32 lb (143 grams). The photograph of the helium filled envelope with endoskeleton frame is shown in Figure 17.

Challenges

- Filling of envelope containing endoskeleton frame with helium is challenging because large volume of air needs to be flushed from the envelope.

Possible Solutions

- Stepwise helium flushing technique improves the filling operation. The helium and air are mixed as the helium flows into the envelope and some time factor is required for gas separation. This knowledge could be used to fill the envelope using the least helium as well as time.

Figure 17. Photograph of the Helium Filling Operation

7.4 Exoskeleton Frame

An exoskeleton frame of 8ft diameter is fabricated from pultruded solid carbon rods of 0.06in diameter using the same procedure as outlined in section 5.3.

Challenges

- Bending stiffness of the frame members needs to be increased

Possible Solutions

- The frame members can be designed and made from tubular cross-sections, or structural shapes with greater stiffness than rods or tubes. Even sandwich sections could be used to significantly improve the bending stiffness.

7.5 Integration of Endoskeleton Frame, Envelope and Exoskeleton Frame

The fabrication of integrated endo and exoskeleton framed structure with envelope consists of the same procedure as outlined in section 6. Some of the photographs of the integrated endo- and exo-skeleton framed envelope shown in Figures 18a to 18c.

Figure 18a. Photograph of 5ft dia Envelope with Endo- and Exoskeleton Frame

Figure 18b. Photograph of 5ft dia Envelope with Endo- and Exoskeleton Frame

Figure 18c. Photograph of 5ft dia Envelope with Endo- and Exoskeleton Frame

8. Summary

A pathway for design and fabrication of Endo- and Exoskeleton framed elliptical envelopes was demonstrated. Envelope sizes of 2 ft x 0.5 ft and 5 ft x 1.25 ft were successfully fabricated and their buoyancy and lifting capability were assessed. A technique of filling the envelope with helium was demonstrated. The weight of 2 ft by 0.5 ft envelope before and after filling with helium was 0.082 lb (37 g) and 0.018 lb (8 g), respectively. Using the concepts developed for the 2ft x 0.5ft envelope, the fabrication was successfully scaled to 5 ft x 1.25 ft. The weight of the 5 ft x 1.25 ft envelope before filling with helium was 0.48 lb (218 grams). After it was filled with helium the envelope carried a payload of 0.32 lb (143 grams). Frame member sizes are not structurally designed and optimized because the loadings and their conditions were not available, if provided the structure could be designed to meet the optimal operational conditions.

9. Possible Future Research and Development

- Explore the packaging concepts for portability and compactness. For example, movable joints, collapsible frame, foldable envelopes, etc.
- Explore the possibility of applying this technology for micro robotics.

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3. Edge, H., Nixon, M., Janas, A., Ross, W., and Collins, J., “Pressurized Structure Technology for UAVS”, Army Science Conference, 2008.
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5. APPENDIX

The appendix contains list of various experimental trials conducted for fabricating endoskeleton frame, envelope and exoskeleton frame.

Trial #	Part No.	Remarks
1	Endoskeleton Frame#1	2 ft diameter frame with 3 meridional rings
2	Balloon Envelope#1	1 ft dia balloon envelope made to understand heat sealing process
3	Balloon Envelope#2	2 ft dia balloon envelope made but frame could not be inserted
4	Balloon Envelope#3	2.2 ft dia balloon envelope made and frame succesfully inserted
5	Envelope-Endoskeleton Frame#1	2 ft dia envelope with endoskleton frame
6	Endoskeleton Frame#2	2 ft diameter frame with 6 meridional rings
8	Balloon Envelope#4	2.2 ft dia balloon envelope made and frame succesfully inserted
9	Envelope-Endoskeleton Frame#2	2 ft dia envelope with modified endoskleton frame
10	Endoskeleton Frame#3	2 ft diameter frame with 3 meridional rings as show piece
11	Endoskeleton Frame#4	2 ft diameter frame with 6 meridional rings for making balloon with Exoskeleton frame
12	Balloon Envelope#5	2.2 ft dia balloon envelope made with in built grooves in heat sealed periphery for inserting exoskeleton frame members
13	Envelope-Endoskeleton Frame#3	2 ft dia envelope with modified endoskleton frame
14	Exoskeleton Frame#1	3.2 ft diameter exoskeleton frame
15	Envelope-Endo-Exoskeleton Frame#3	2 ft dia envelope with endo- and exoskeleton frame
16	Endoskeleton Frame5ft#1	5 ft diameter frame with 6 meridional rings
17	Endoskeleton Frame5ft#2	5 ft diameter frame with 2 additional tubular grid structures to improve stability
18	Balloon Envelope5ft#1	5.25 ft dia balloon envelope
19	Balloon Envelope5ft#1	5.3 ft dia balloon envelope
20	Exoskeleton Frame#2	8 ft diameter exoskeleton frame
21	Envelope-Endo-Exoskeleton Frame5ft#1	5 ft dia envelope with endo- and exoskeleton frame