Balloon Flight and the ULDB Pumpkin Balloon Development

Rodger Farley  Code 543

May 6, 2008
CHAPTERS

• NASA Balloon Program

• Balloons 101
  – Buoyancy
  – Force Balance
  – Gas Law
  – Energy/Heat Balance
  – Atmosphere & Winds
  – Typical Performance
  – Balloon Structure
  – Launch Ops
  – Day-in-the-life

• Environmental Models

• Super Pressure Balloons

• ULDB Test Flights

• Pumpkin Instabilities and the S-cleft

• Pumpkin Design Methodology

• Flight Simulations

Many Thanks!
Deb Fairbrother, Henry Cathey, Dave Pierce
Jim Rand, Dave Wakefield, Danny Ball
Gabe Garde, Leyland Young, Jerry Sterling
Balloon Program Supports Cutting Edge Science

- The NASA Balloon Program provides low-cost, quick response, near space access to NASA’s science Community for Heavy payloads conducting Cutting Edge Science Investigations
  - Observatory-class Payloads With Advanced Technologies and Large Aperture/Mass
  - Serve as a technology development platform
  - Instrument/Subsystem development for NASA Spacecraft Missions
- Provide hands-on training of Young Scientists and Engineers

CoBE, WMAP, RHESSI, ACE, EOS inst, SWIFT, GLAST
2006 Nobel Prize in Physics

Congratulations to the CoBE Team

CoBE Science Team with balloon-payload scientists identified.
## Balloon Program Capability

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>LDB</th>
<th>ULDB*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duration</strong></td>
<td>2 hours to 3 days</td>
<td>Up to 41+ days</td>
<td>Up to 100 days</td>
</tr>
<tr>
<td><strong>Flight Opportunities</strong></td>
<td>~20 per year</td>
<td>2-4 per year</td>
<td>1 per year</td>
</tr>
<tr>
<td><strong>Suspended Capacity</strong></td>
<td>1650-8000 lbs</td>
<td>6000 lbs</td>
<td></td>
</tr>
<tr>
<td><strong>Float Altitude</strong></td>
<td>Up to 160,000 ft</td>
<td>(110,000 to 130,000 normal)</td>
<td>Up to 110,000 ft</td>
</tr>
<tr>
<td><strong>Support Package</strong></td>
<td>CIP</td>
<td>SIP</td>
<td>CDM</td>
</tr>
<tr>
<td></td>
<td>• Line of Sight</td>
<td>• Over the Horizon</td>
<td>• Over the Horizon</td>
</tr>
<tr>
<td></td>
<td>• 300 kbps direct return</td>
<td>• 6-8 kbps TDRSS downlink</td>
<td>• 100 kbps TDRSS downlink</td>
</tr>
<tr>
<td><strong>Launch Locations</strong></td>
<td>Fort Sumner, NM; Palestine, TX; Lynn Lake, Canada; Alice Springs, Australia</td>
<td>Antarctica; Kiruna, Sweden; Alice Springs, Australia; Fairbanks, Alaska</td>
<td></td>
</tr>
</tbody>
</table>

* Current development project
Balloon Primer 101
Where in the atmosphere to fly?

33km, above 99% of the atmosphere

If this balloon could see itself

View Radius at:

- 2m Alt = 5km
- 33km Alt = 646km
- 350km Alt = 2062km
Balloon Definitions

- Specific buoyancy
- Zero pressure balloon
- Super pressure balloon
- Super temperature
- Super pressure

- Gross inflation
- Gross weight
- Free lift
- Differential pressure
- Suspended Load

- Load tapes, tendons
- Gores
- Duct
- Valve
- Cap

This is a 40 mcf zero pressure (ZP) balloon with “horse-tail” ducts.
Nature of Buoyancy, part 1

\[ W_{\text{air}} > W_{\text{gas}} \]

Set up two equilibrium equations:

\[ P_{\text{base}} \cdot \text{Area} = W_{\text{air}} + P_{\text{apex}} \cdot \text{Area} \]

Divide by the volume, limit length to a differential:

\[ \Rightarrow \text{Aerostatic Principle} \quad \frac{dP}{dZ} = g \cdot \text{Density} \]

\[ P_{\text{base}} \cdot \text{Area} = W_{\text{gas}} + P_{\text{apex}} \cdot \text{Area} + \text{buoyancy}_\text{reaction} \]

Subtract the two equilibrium equations, with \( \text{buoyancy} = -\text{buoyancy}_\text{reaction} \)

\[ \Rightarrow \text{Archimedes Principle} \quad \text{buoyancy} = W_{\text{air}} - W_{\text{gas}} \]

Divide by the volume:

\[ \Rightarrow \text{Specific buoyancy} b, \text{N/m}^3 \]

\[ b = g \cdot (\text{Density}_{\text{air}} - \text{Density}_{\text{gas}}) \]

At sea level, \( b \sim 10 \text{ N/m}^3 \)

At 33km, \( b \sim 0.084 \)
Nature of Buoyancy, part 2

Combine aerostatic principle for both air and lift gas:
Buoyancy gradient pressure, N/m^2

\[ \Delta P_{\text{buoyancy}} = b \cdot Z \]

Under-pressurized shape

Like a hot air balloon…
Nature of Buoyancy, part 3

What does a lift gas do for you?

• Why not a “vacuum balloon”?
  • buoyancy increases from 10 to 11.4 N/m^3
• Lift gas provides the majority of reaction pressure
• Allows gossamer construction

Normal float (110k ft) ambient 700 Pa, normal gradient 6 Pa
Force Balance

Gross Lift capacity, N

\[ \text{GrossInflation} = b \cdot \text{Volume} \]

System density (all mass/displaced volume) = atmospheric density @ equilibrium

GrossWeight = Balloon weight + suspended load

GrossInflation = GrossWeight + freelift

GrossInflation = GrossWeight + Drag @ equilibrium ascent

Drag = free lift @ equilibrium ascent

<table>
<thead>
<tr>
<th>GI</th>
<th>Gross Inflation</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>Gross weight = W + L</td>
</tr>
<tr>
<td>W</td>
<td>Balloon weight (not including gas)</td>
</tr>
<tr>
<td>L</td>
<td>Suspended Load</td>
</tr>
<tr>
<td>F</td>
<td>Free lift</td>
</tr>
</tbody>
</table>

Free lift ratio = 1+F/G
Volume change during ascent

What to do with the free lift at float altitude?

1) Suddenly weigh more (not likely)
2) Vent excess lift gas (ZPB)
3) Pressurize (SPB)
4) Burst (latex weather balloon)
Ideal Gas Law

\[ P = \frac{n \cdot R \cdot T}{V} \]

General equation

\[ P = \rho \cdot R_{\text{gas}} \cdot T \]

Using specific gas constants, \( R_{\text{gas}} = 8314.5/\text{molecular weight} \)

\[ R_{\text{air}} = 287.1 \]

Specific gas constants, Joules/kg/°K

\[ R_{\text{helium}} = 2077.2 \]

Helium being mono-atomic is a good ideal gas for lift

\[ R_{\text{H}_2} = 4148.7 \]

Combining Ideal Gas Law with buoyancy relationships yields:

\[ \Delta T = T_{\text{gas}} - T_{\text{air}} \]

Super temperature

\[ \Delta P = P_{\text{gas}} - P_{\text{air}} \]

Super pressure

\[ \text{Free Lift ratio} = \frac{M_{\text{gas}}}{M_{\text{gross}}} \cdot \left[ \frac{1 + \frac{\Delta T}{T_{\text{air}}}}{1 + \frac{\Delta P}{P_{\text{air}}}} \right] \cdot \frac{R_{\text{gas}}}{R_{\text{air}}} - 1 \]

Free lift ratio = 1+F/G

\[ G = g \cdot M_{\text{gross}} \]
Energy Balance

Balloons live in a radiant-energy dominated environment where the gas volume and/or pressure are sensitive to changes.

Use 1st law for both film and gas:

\[ \text{Energy IN} = \text{Energy OUT} + \text{Energy stored} + \text{Work done} \]

- \( q \) = energy flux, Watts/m\(^2\)
- \( Q \) = energy, Watts

\[ \text{Energy stored} = \text{Mass} \times \text{specific heat} \times \frac{dT}{dt} \]
Film and Lift Gas Heat Balance

Apply 1st law to gore film: (Similar applies to the load tapes)

\[
\begin{align*}
\text{Energy IN} & \quad \text{Energy OUT} & \quad \text{Energy stored} \\
Q_{\text{sun}} + Q_{\text{albedo}} + Q_{\text{IR planet}} + Q_{\text{IR sky}} + Q_{\text{IR film}} + Q_{\text{Conv Ext}} & = Q_{\text{Conv Int}} + Q_{\text{IR out}} + c_f \cdot M_{\text{film}} \frac{dT_{\text{film}}}{dt} \\
\end{align*}
\]

Energy IN

Energy OUT

Energy stored

Flux \( q = \sigma \cdot \text{emissivity} \cdot T^4 \), watts per square meter

Energy \( Q = q \cdot \text{Area} \cdot \text{Viewfactor} \cdot \text{absorptivity} \), watts

Apply 1st law and ideal gas law to lift gas:

\[
\frac{dT_{\text{gas}}}{dt} = \left( \frac{Q_{\text{Convection Internal}} + Q_{\text{burner}}}{c_v \cdot M_{\text{gas}}} \right) + (\gamma - 1) \cdot \frac{T_{\text{gas}}}{\rho_{\text{gas}}} \cdot \frac{d\rho_{\text{gas}}}{dt}
\]

\( \gamma = \frac{c_p}{c_v} \)
Optical Property Effects

Cap + Shell
Shell
Load Tapes
Un-expanded portion

Properties weighted according to ratio of surface area in the bubble

<table>
<thead>
<tr>
<th></th>
<th>1 layer</th>
<th></th>
<th>1 layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.024</td>
<td>$\alpha$</td>
<td>0.023</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>0.184</td>
<td>$\varepsilon$</td>
<td>0.102</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.914</td>
<td>$\tau$</td>
<td>0.916</td>
</tr>
<tr>
<td>$\tau\varepsilon$</td>
<td>0.81</td>
<td>$\tau\varepsilon$</td>
<td>0.866</td>
</tr>
<tr>
<td>$\alpha/\varepsilon$</td>
<td>0.130</td>
<td>$\alpha/\varepsilon$</td>
<td>0.225</td>
</tr>
</tbody>
</table>

ULDB Material
SF420, 1.5 mil

ZPB Material
SF372, 0.8 mil

$\alpha$ absorptivity
$\varepsilon$ emissivity = $\alpha_{IR}$
$\tau$ transmittance
$\tau_{IR}$ IR transmittance

Killer is the balloon geometric effects

Many internal bounces create an effective reflectivity

Energy Absorbed:
$\alpha + \alpha \tau (1 + \tau + \tau^2 + \tau^3 + ...)$
The Atmosphere

Variation in temperature from “standard”

- The “trope” (tropopause) varies in altitude with season and location
- Jet streams form at the trope
- High altitude zonal winds in the stratosphere blow E to W in the summer, and W to E in the winter. During the equinoxes there is a period of calming called “turn-around”
- Meridional winds move towards equator
- During the solstices over the poles, a polar vortex sets up to orbit balloons at 32km or higher every 11 to 14 days

Temperature, degK

Altitude, m

45000
40000
35000
30000
25000
20000
15000
10000
5000
180 194 208 222 236 250 264 278 292 306

-80°C

Greatest concentration of ozone

Summer, Alice Springs

stratosphere

troposphere
Balloon Bobbing

Forced by Gravity-wave Vaisala-Brunt oscillations (vertical wind)

For a zero-pressure balloon, the bobbing factor

\[
K_{\text{zpb}} = g \frac{\frac{d}{dz} \frac{P_{\text{air}}}{R_{\text{gas}} T_{\text{air}}} - \frac{\rho_{\text{air}}}{\rho_{\text{gas}}} \frac{d}{dz} \rho_{\text{air}}}{\rho_{\text{air}} (1 + C_B)}
\]

For a super-pressure constant volume balloon, the bobbing factor

\[
K_{\text{spb}} = g \frac{- \left( \frac{d}{dz} \rho_{\text{air}} \right)}{\rho_{\text{air}} (1 + C_B)}
\]

Bobbing Period

\[
\text{Period} = \frac{2\pi}{\sqrt{K_{\text{zpb}}}}
\]
Ground track in Antarctica

Long Duration Balloon in the Polar Vortex

CREAM circled for 42 days
Typical Dynamic Launch

1) Tow balloon to raise the main balloon for inflation

2) Balloon ready for launch

3) Bubble released from spool

4) Payload released from L.V.

Ascend with ~10% more lift than the weight then vent at max volume condition
Static Launch Technique

When balloons were used for spy missions, with many UFO sightings
Basic performance during ascent

Temperatures

Ascent Speed

Graphs showing temperature and ascent speed over time with labels for different phases of ascent:
- Load tapes
- Float
- Film
- Air
- Lift gas
- Trope
- Under-pressure
- Super-pressure
- Gravity-wave resonance
- Normal bobbing
Meridionally-Reinforced Membrane Structures

Zero-pressure Balloon

“Natural Shape”
Vast majority of load reacted in the meridional (longitude) direction, with little or no load in the circumferential (latitude) direction

Parachute

Taylor parachute shape validation model, 1919

Pumpkin super-pressure
Air Force cylinder balloon pressurized to a smooth pumpkin shape
Membrane Shape Formulation

- **P** is linear pressure loading
- **Q** is linear gravity loading
- **T** is the meridional tension
- **tc** is the transverse linear loading
- **tm** is the meridional linear loading

From equilibrium equations:

\[
\frac{d}{ds} = \frac{-2 \cdot \pi \cdot t_c \cdot \sin(\theta) - Q \cdot \cos(\theta) + P}{T}
\]

\[
\text{and} \quad \frac{dT}{ds} = 2 \cdot \pi \cdot t_c \cdot \cos(\theta) - Q \cdot \sin(\theta)
\]
Day-in-the-life of a ZP balloon

- Bubble with 10% more lift than it weighs
- It launches and rises at equilibrium speed where drag = free lift
- It expands, filling out the envelope, catching the sun and warming at the same time it is cooling due to adiabatic expansion
- Hit the tropo, and it slows momentarily going into a rapidly diminishing air density
- Convection is having less effect, it warms from the sun, earth albedo and infrared to a rapidly increasing surface area (IR 45%, direct solar 33%, albedo 13%)
- It hits the float altitude, where the volume can no longer expand, and the free lift gas whooshes out the ducts
- The adiabatically-cooled gas warms up as the sun rises higher and comes into thermal equilibrium with the radiant environment
- Sun goes down, the gas contracts, and ballast has to be dropped (now it weighs less)
- Morning comes, sun heats up the gas, the envelope expands, and it floats up to a higher altitude where it has too much gas which vents out
- 1 or 2 diurnal cycles, no more ballast
Environmental Models
Direct Solar Model

\[ I_{\text{Sun}} = \frac{1358}{R_{AU}^2} \cdot \left[ \frac{1 + e \cdot \cos(TA)}{1 - e^2} \right]^2 \]

Solar Irradiance at the top of the atmosphere, watts/m²

mean orbital radius \( R_{AU} \), astronomical units

orbital eccentricity \( e \)

true anomaly \( TA \)

For Earth

\[ I_{\text{sun}} = 1358 +/- 45 \text{ watts/m}^2 \ ( +/- 3.3\% ) \]
Atmospheric Solar Attenuation

Direct Solar Transmittance Factor

\[ I_{SunZ} = I_{Sun} \cdot \tau_{atm} \]

Solar Irradiance at the balloon altitude

\[ \tau_{atm} = 0.5 \left[ e^{-0.65 \cdot AirMass} + e^{-0.95 \cdot AirMass} \right] \]

Solar Transmittance thru Atmosphere at Various Altitudes

\[ \text{AirMass} = CF_{airmass} \cdot \left( \frac{P_{air}}{P_o} \right) \cdot \left[ \sqrt{1229 + (614 \cdot \sin(ELV))^2} - 614 \cdot \sin(ELV) \right] \]
The albedo factor is measured from orbit, and so represents a top-of-the-atmosphere number.
Up-welling IR Environment

Infrared diffuse flux at ground level with ground emissivity $\varepsilon_{\text{ground}}$ and ground temperature $T_{\text{ground}}$ ($\degree\text{K}$):

$$q_{\text{IR ground}} = \varepsilon_{\text{ground}} \cdot \sigma \cdot T_{\text{ground}}^4 \quad \text{Watts/m}^2$$

Attenuation:

$$A_{\text{IR}} = 0.35 \quad \text{For normal temperate air masses}$$

$$A_{\text{IR}} = 0.30 \quad \text{For very dry air masses (Antarctica, deserts)}$$

Ground IR diffuse radiation at balloon altitude, watts/m$^2$

$$q_{\text{IR groundZ}} = q_{\text{IR ground}} \cdot \text{Attenuation}$$
Super-Pressure Ballooncraft

Briton Julian Nott set world manned pressurised balloon records for altitude, distance and endurance in his ULD1 balloon.
Performance Comparison

**Super-Pressure**: Constant volume, variable pressure $\rightarrow$ constant altitude
- Good for flying at any latitude

**Zero-Pressure Balloon**: Ambient pressure, variable volume
- Good for lengthy summer polar flights, or 1-2 days mid latitude (diurnal cycles)
Types of Superpressure Balloons

**Spherical Design**

- Spherical balloon would have much higher stresses.

**Pumpkin Design**

- A pumpkin divides the jobs into gas containment (film) and structure (tendons, load tapes).
- A sphere has both jobs simultaneously.

Skin Stress:

\[
\text{Skin Stress} = \frac{1}{2} \cdot \frac{R_{\text{SPHERE}} \cdot \Delta P}{t}
\]

Hoop Stress:

\[
\text{Hoop Stress} = \frac{R_b \cdot \Delta P}{t}
\]

\(R_b = \) bulge radius of curvature

\(\Delta P = \) differential pressure

\(t = \) film thickness
ULDB Super Pressure-Pumpkin

- ULDB is basically a two part system:
  - PBO Tendon “zylon”
  - Polyethylene Film, LLDPE 3-layer co-extruded

- Over past 6 years, BPO implemented an integrated approach toward development of the ULDB:
  - MATERIALS - Characterize ULDB materials, Film & Tendon.
  - ANALYTICAL MODELING - Develop design tools, and create test data correlated models.
  - MODEL TESTS – Conduct scaled model tests and incorporate data into design tools.
  - FLIGHT TESTS – Conduct incremental sized Flight tests that meet long term ULDB objectives.

100 day flight makes this a sub-satellite vehicle!
Design Features  some good, one not so good…

Inherent strain arrest features!

Large radius of curvature

Small radius of curvature

Structural-geometric self-limiting feedback

Pressurization involves running the gauntlet with much extra material
Materials Characterization

Non-linear visco-elastic constitutive modeling, materials models with a “memory” of previous stress-strain history (Schapery formulation)

Testing indicating stress ratios of ~1:1 are very beneficial, even with high stresses

Tertiary Creep Limit defined as a loading that survives 24 hours

Tremendous effort in:
- Photogrametry Testing
- LLDPE Math modeling
- Creep Compliance
  \( \text{strain} = C \times \text{stress} \)
- Creep Relaxation
  \( \text{stress} = K \times \text{strain} \)
Bulge Design

Constant radius bulge
Constant angle bulge
Constant hoop stress

“Tightness” of a pumpkin described by the bulge angle at the equator

- Stress
- Stress ratio
- “tightness”
Scale Effects

Scale Factor SF

\[ SF = \frac{S_{gore_2}}{S_{gore_1}} \]  
Gore length ratio

\[ \frac{R_{bulge_2}}{R_{bulge_1}} = SF \]

\[ \frac{N_{gore_2}}{N_{gore_1}} = 1.0 \]

\[ \frac{GI_2}{GI_1} = SF^3 \]

\[ \frac{M_{suspend_2}}{M_{suspend_1}} = SF^3 \]

Good for low pressure shape effects

To maintain the relationship between buoyancy and gravity effects to match shape effects (which will not give similar balancing to stresses and strains)

\[ \frac{b_2}{b_1} = 1.0 \]

\[ \frac{t_2}{t_1} = SF \]

\[ \frac{Denier_2}{Denier_1} = SF^2 \]

\[ \frac{\Delta P_2}{\Delta P_1} = SF \]

Same bulge radius

Same hoop stress

4x area

2x number of gores

Result 2x meridional tension
Required Super Pressure at Design Float Altitudes

\( \Delta T = \text{max gas day temperature} - \text{min gas night temperature} \)

- Antarctica \( \Delta T \approx 20^\circ C \) if spiraling off to ocean, \( \approx 55^\circ C \)
- Australia desert \( \Delta T \approx 60-75^\circ C \)
- Ft Sumner \( \Delta T \approx 50^\circ C \)

Quick Design Reference

Antarctica \( \Delta T \approx 20^\circ C \) if spiraling off to ocean, \( \approx 55^\circ C \)
Australia desert \( \Delta T \approx 60-75^\circ C \)
Ft Sumner \( \Delta T \approx 50^\circ C \)
• 10/1998  Fabric-film spherical balloons - 16.5 meter diameter
• 10/23/1999 1.817 MCF fabric-film pumpkin – Flight 474NT
• 6/4/2000 2.421 MCF co-extruded pumpkin – Flight 485NT
• 2/24/2001 18.38 MCF co-extruded pumpkin – Flight 495NT-leaker
• 3/9/2001 18.38 MCF co-extruded pumpkin – Flight 496NT-cleft
• 7/6/2002 21.56 MCF modified co-extruded – Flight 1580PT-loose tendons
• 3/16/2003 21.56 MCF modified co-extruded – Flight 517NT - cleft
• 2/4/2005 6.2 MCF modified co-extruded LTT pumpkin – Flight 540NT-peeled seal
• 6/12/2006 6.2 MCF modified co-extruded LTT pumpkin – Flight 555NT-cleft

ULDB Test Flights
Flight 496 NT: Anomalous Shaped Balloon Flight

Flight 496 NT experienced an anomalous float shape, yet flew through one complete diurnal cycle.

Volume: 520,483 m$^3$ (18.38 MCF)
Material weight: 37.7 g/m$^2$
Number of gores: 290
Gore length: 152.7 m (501 ft)
Weight: 2,155 kg (4,740 lb)
Inflated height: 68.9 m (226 ft)
Inflated diameter: 114.9 m (377 ft)
Float Altitude: ~34,110 m (111,900 ft)
Suspended Load: 2,045 kg (4,500 lbs)
Launch Date: March 9, 2001
Location: Alice Spring, Australia
Flight Duration: 24 hours 42 minutes
Flight 517-NT – Images

22 mcf pumpkin, 290 gores, Alice Springs, Australia

Nominal bulge angle = 114 deg
Test Flight 540NT, 6mcf

- Ft. Sumner Test Flight, February 4, 2005, was eased into float by venting helium during the ascent
- Unlike some of the previous pumpkin flights, the top region of the balloon fully deployed
- During the pressurization, the bottom region of the closing seal opened
- A video survey of the balloon was conducted and the flight terminated
- Test Flight 540NT Post Flight Investigation
  - 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
  - Higher sealing temperature would prevent reoccurrence and ensure a proper seal
  - Subsequent design analyses with updated material properties and updated CTE values showed higher stress regions near poles. Design change required before next test flight. Minor changes made to the pattern.

95 deg bulge angle, just missed clefting
ULDB Test Flight 555, 6mcf

ULDB Sweden - June 12, 2006.

Pan Tilt Camera

Altitude ~30.8 km ~101,000 ft

98 deg bulge angle, clefted
Pumpkin Instabilities and S-Cleft

10m model
Pumpkin Shapes and Instabilities

1) Desired pumpkin shape at pressure
2) Buckled pumpkin at threshold pressure
3) Buckled pumpkin at zero pressure
4) S-clefted pumpkin at low pressure

Manifests at high pressure (when designed correctly)

Pressure-Shape Instability

- Differential Pressure
- Material Properties
- Gore Pattern
- Launch-Induced Perturbations?
- Buoyancy Friction?

Single S-Cleft

S-cleft: sheared halves with single baseball s-shaped stitch transitioning between the two halves. Global helical distortion

RELATIVE INFLUENCES
Before the 27m test balloons, we could not answer the basic question:

**INHERENT?** Deterministic

- Gore Pattern
- Buoyancy, weight
- Temperature
- Material properties

**Or** **PROCESS DEPENDENT?** Lady Luck

- Launch induced perturbation
  - Roping
  - Sailing / Pac-man ingestion
- Friction or static cling
- Tendon locking or twist-gripping

*When your in the dark, you see monsters everywhere*
27m Scale model testing

T-com facility Eliz. City NC  WWII blimp hangar

Mission: record an s-cleft in captivity
Inflation of s-cleft

In the zero-pressure shape, s-cleft runs N to S
27m Model Designed to S-cleft
same as FLT 555

Used scaling laws to ratio forces similar

99 deg bulge angle
S-cleft side, top, bottom views

27m Test (Top View)

Sweden 555NT (Bottom View)

Side view, 27m
Internal Camera Shots of S-cleft

Flt 555

27m Test

Courtesy: Henry Cathey
So, what’s an S-Cleft?

Model tests were conducted with properly scaled 27m diameter pumpkins

• An inherent feature of the specific pumpkin design
• The gore pattern (excess material) is the major contributor with buoyancy playing a role
• Deformed shape in stable equilibrium that cannot be popped-out with pressure
• Requires diagonal wrinkling (non-symmetric stiffness) and contact forces
• Triggered when the envelope cannot exercise enough global circumferential load to pull out cleft, dependent on bulge angle and number of gores

The s-cleft can be avoided by designing the bulge angle low to kick-in enough global circumferential tightness
Cleft-free 27m model

Suspecting that for 200 gores a 90 degree bulge angle was just this side of good to avoid a cleft:

55 deg bulge angle

Conducted “magic hands” experiment

Morning at the T-COM hangar

- Flt 555 simulant with 99 deg bulge cleft
- 55 deg model no cleft
- 90 deg model no cleft
- 33 deg “flat facet” no cleft
27m pumpkin bursting!

33 deg bulge angle

Final burst at 500Pa differential pressure with 66,200 lbs of tendon load at fittings
S-cleft Design Envelope

Equatorial Bulge Angle, deg

Number of Gores

Data point from 27m tests

Marked sensitivity to bulge angle and number of gores
S-cleft analytical efforts

Dr. Frank Baginski’s structural, fluid interaction, contact, wrinkled, friction, finite element method
Pumpkin Design Methodology
<table>
<thead>
<tr>
<th>Parameter Trade Space for ULDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Number of gores</td>
</tr>
<tr>
<td>• Max bulge angle</td>
</tr>
<tr>
<td>• Max gore width</td>
</tr>
<tr>
<td>• Hoop stress, stress ratio</td>
</tr>
<tr>
<td>• Film thickness, shell &amp; cap</td>
</tr>
<tr>
<td>• Tendon denier</td>
</tr>
<tr>
<td>• Suspended mass</td>
</tr>
<tr>
<td>• Float altitude, minimum night altitude</td>
</tr>
<tr>
<td>• Date &amp; location</td>
</tr>
<tr>
<td>• Film optical properties</td>
</tr>
<tr>
<td>• Film mechanical properties</td>
</tr>
<tr>
<td>• Freelift, ascent venting, ballast</td>
</tr>
<tr>
<td>• Super pressure</td>
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<td>• Super temperature</td>
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<tr>
<td>• Environment, atmosphere</td>
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<tr>
<td>• Ascent speed</td>
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<td>• Manufacturing capability</td>
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<table>
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<tr>
<th>Concerns / Issues</th>
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<td>Trajectory control</td>
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<td>Diurnal performance</td>
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Find the sweet spot to make it all work!
Enveloping the Albedo and IR Environment

Design cases by worst-case pairing between albedo and the upwelling IR environment

*Antarctica*
- (IR=165, albedo =50%), (IR=190, albedo =72%)
- (IR=210, albedo =55%), (IR=195, albedo =35%)

*Southern Oceans*
- (IR=195, albedo =35%), (IR=210, albedo =55%)
- (IR=260, albedo =40%), (IR=250, albedo =10%)

*Equatorial Zones*
- (IR=250, albedo =10%), (IR=260, albedo =40%)
- (IR=300, albedo =38%), (IR=295, albedo =9%), (IR=320, albedo =28%) (desert)
Simplified Design Flow

Environment + Optical properties \( \rightarrow \Delta T \)

\( \Delta T \) + Altitude \( \rightarrow \Delta P \)

\( \Delta P \) + Balloon diameter + Ngores + Tendon stiffness \( \rightarrow \) Meridional strain

Meridional strain + Meridional film modulus E \( \rightarrow \) Meridional stress

\( \Delta P \) + Balloon diameter + Ngores + Hoop stress \( \rightarrow \) Bulge radius

Hoop stress + Meridional stress + Meridional strain \( \rightarrow \) Hoop strain

Hoop strain + Meridional strain + Bulge radius + Ngores + Diameter + Temperature strain effects \( \rightarrow \) Gore pattern

Flight Simulations for diurnal effects

Finite Element Stress-Strain Analysis
Flight Sims

Super-Pressure Diurnal Cycle with Ballast Drop

Predicted behavior for June 7 2008 flight of 2mcf pumpkin
Mars Balloon Simulation

A super-pressure balloon on Mars will actually float upwards at night!

A Mars balloon operates at the bottom of the atmosphere, which explains this effect

AND

da 30K diurnal swing
Venus Balloon Simulation

Altitude

Super-pressure

Zero-pressure

Binary Altitude Behavior

Temperature
### 2008 Milestones

- **2 MCF Fabrication**: April 30
- **2 MCF MRR**: May 8
- **2 MCF Test Flight**: June (Ft. Sumner)

- **7 MCF Fabrication**: May
- **7 MCF Test Flight #1**: Aug (Ft. Sumner)

- **7 MCF Fabrication**: July
- **7 MCF Test Flight #2**: Dec (Antarctica)

### Calendar Years

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<td>7 MCF Test Flight</td>
<td>14 MCF Test Flight</td>
<td>22 MCF Science Flight</td>
<td>22 MCF Test Flight</td>
<td>22 MCF Test Flight</td>
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- ▲: Scaled Models
- △: Test Flight

The schedule includes milestones for fabricating and testing models, with specific dates for each event.