NASA / GSFC

Systems Engineering Seminar

Balloon Flight and the ULDB Pumpkin Balloon Development

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May 6, 2008

CHAPTERS

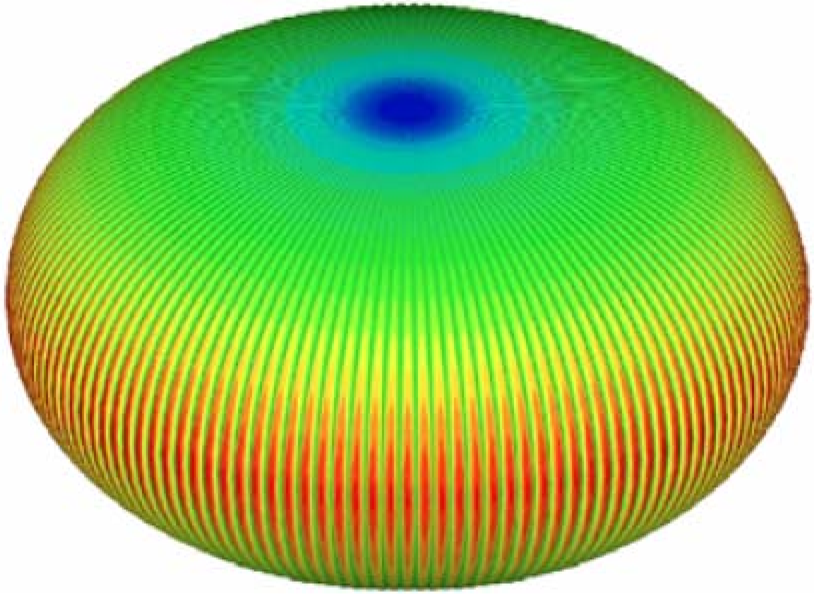
- NASA Balloon Program
- Balloons 101
  - Buoyancy
  - Force Balance
  - Gas Law
  - Energy/Heat Balance
  - Atmosphere & Winds
  - Typical Performance
  - Balloon Structure
  - Launch Ops
  - Day-in-the-life
- Environmental Models
- Super Pressure Balloons
- ULDB Test Flights
- Pumpkin Instabilities 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


BOOMERANG

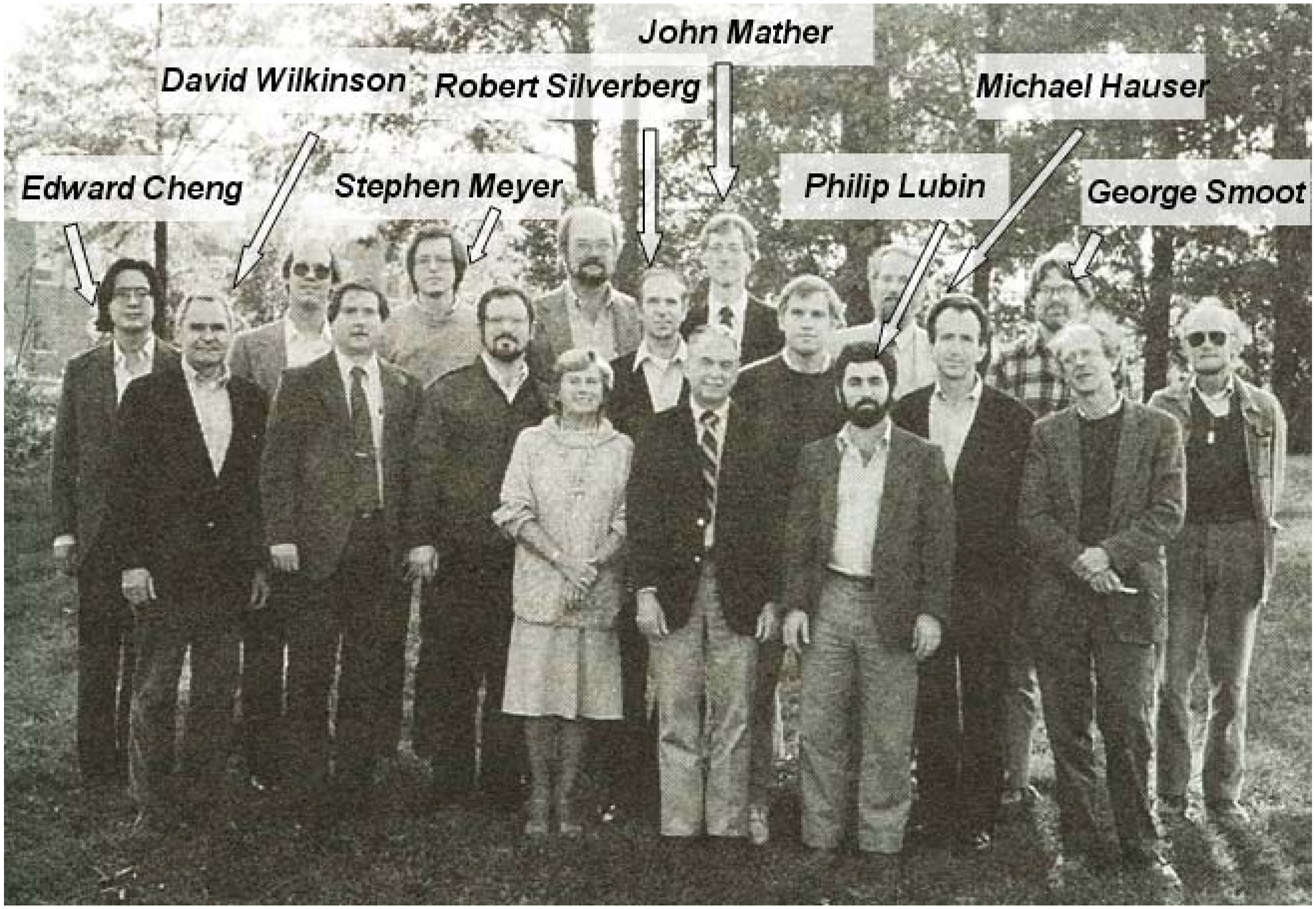

BLAST


HEFT


InFOCuS


TIGER / ANITA

2006 Nobel Prize in Physics
Congratulations to the CoBE Team



CoBE Science Team with balloon-payload scientists identified.

Balloon Program Capability

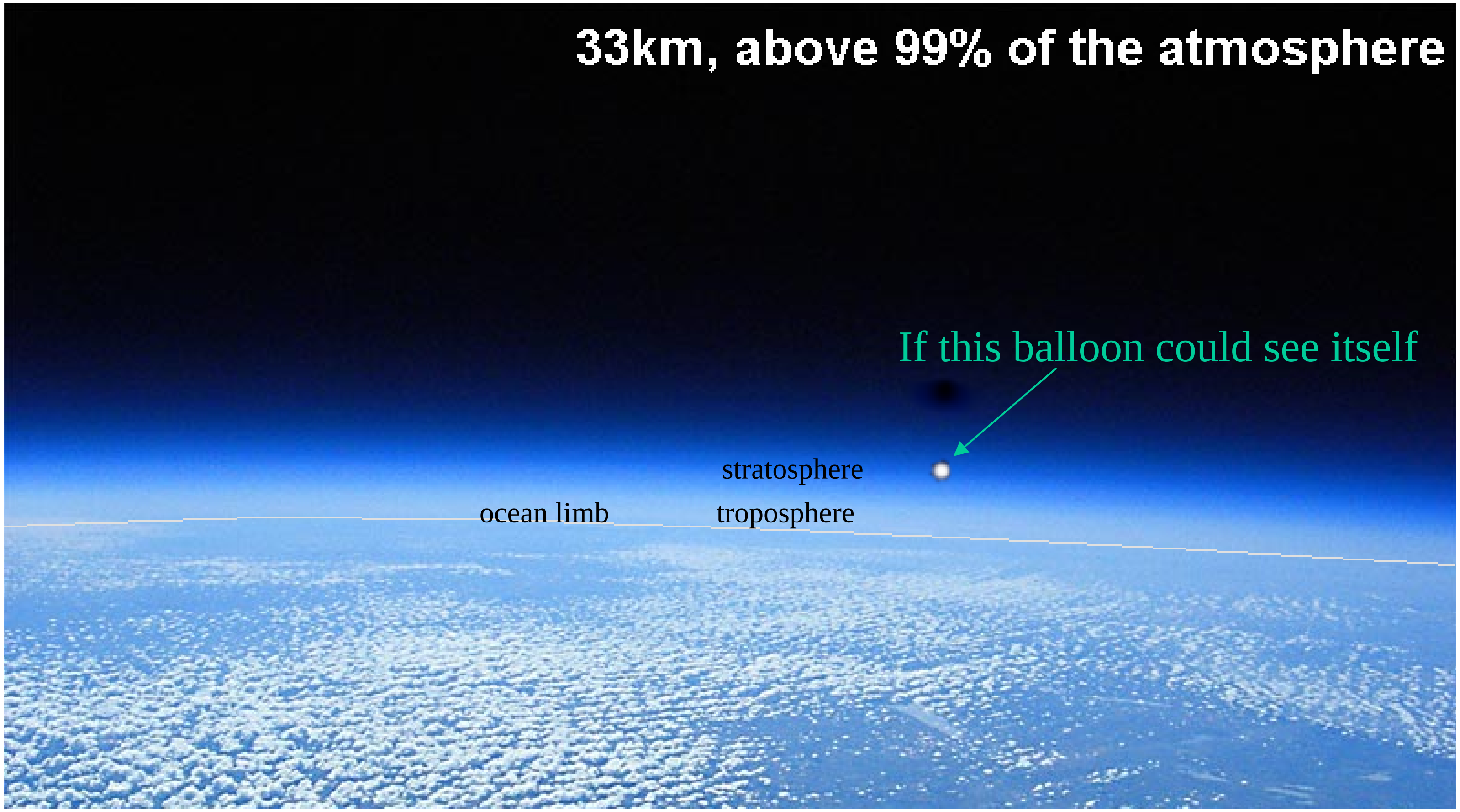
	Conventional	LDB	ULDB*
Duration	2 hours to 3 days	Up to 41+ days	Up to 100 days
Flight Opportunities	~20 per year	2-4 per year	1 per year
Suspended Capacity	1650-8000 lbs		6000 lbs
Float Altitude	Up to 160,000 ft (110,000 to 130,000 normal)		Up to 110,000 ft
Support Package	CIP •Line of Sight •300 kbps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

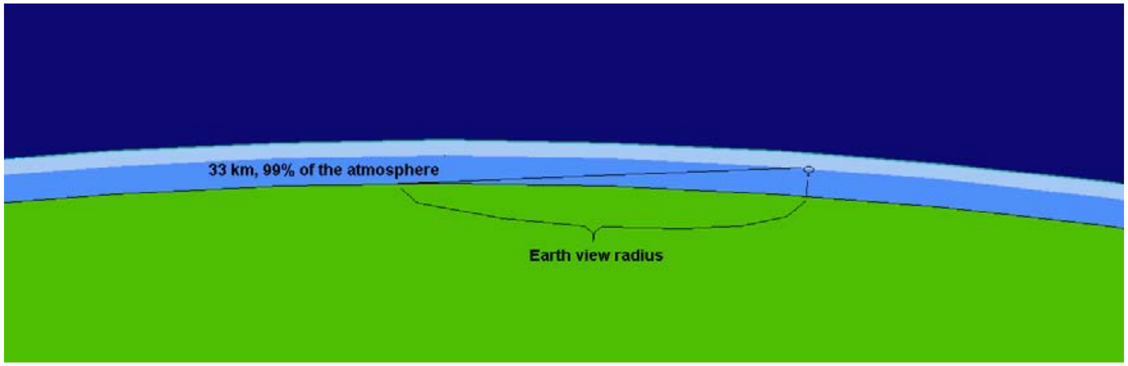
* Current development project

Monkey in balloon 1961

Balloon Primer 101

Where in the atmosphere to fly?





View Radius at:

2m Alt = 5km

33km Alt = 646km

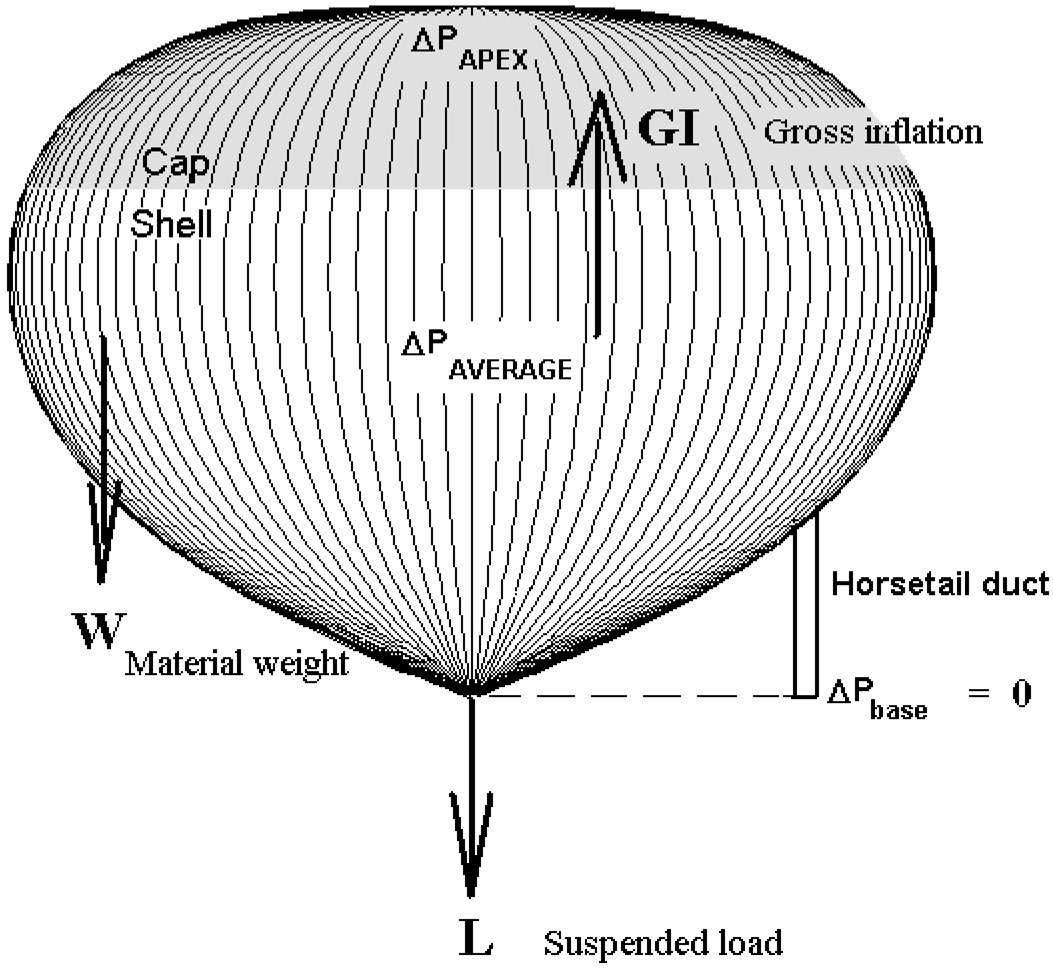
350km Alt = 2062km

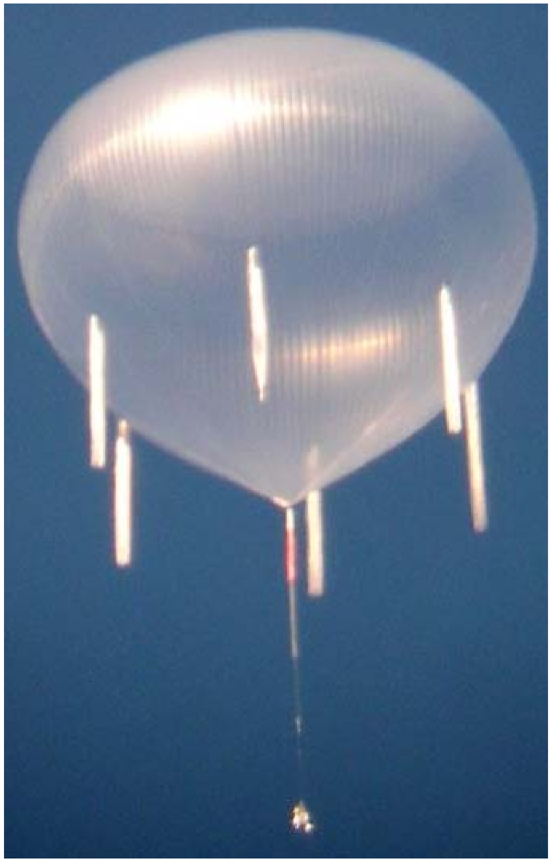
Balloon Definitions

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

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

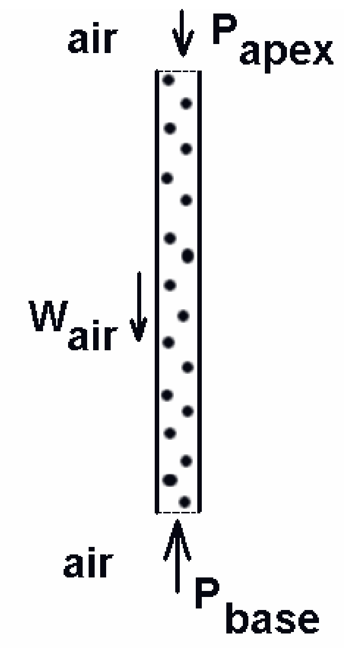
- Load tapes, tendons
- Gores
- Duct
- Valve
- Cap



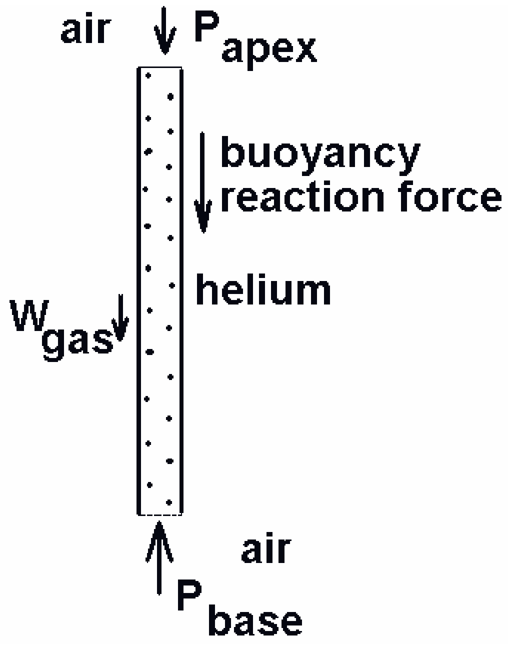


This is a 40 mcf zero pressure (ZP) balloon with "horse-tail" ducts

Nature of Buoyancy, part 1



$$W_{air} > W_{gas}$$



Set up two equilibrium equations:

$$P_{base} \cdot Area = W_{air} + P_{apex} \cdot Area$$

Divide by the volume, limit length to a differential:

→ Aerostatic Principle dP/dZ = g*Density

$$P_{base} \cdot Area = W_{gas} + P_{apex} \cdot Area + buoyancy_{reaction}$$

Subtract the two equilibrium equations, with **buoyancy = -buoyancy$_{reaction}$**

→ Archimedes Principle buoyancy = W_{air}-W_{gas}

Divide by the volume:

→ Specific buoyancy b, N/m^3

$$b = g \cdot \left(Density_{air} - Density_{gas} \right)$$

At sea level, b ~ 10 N/m^3

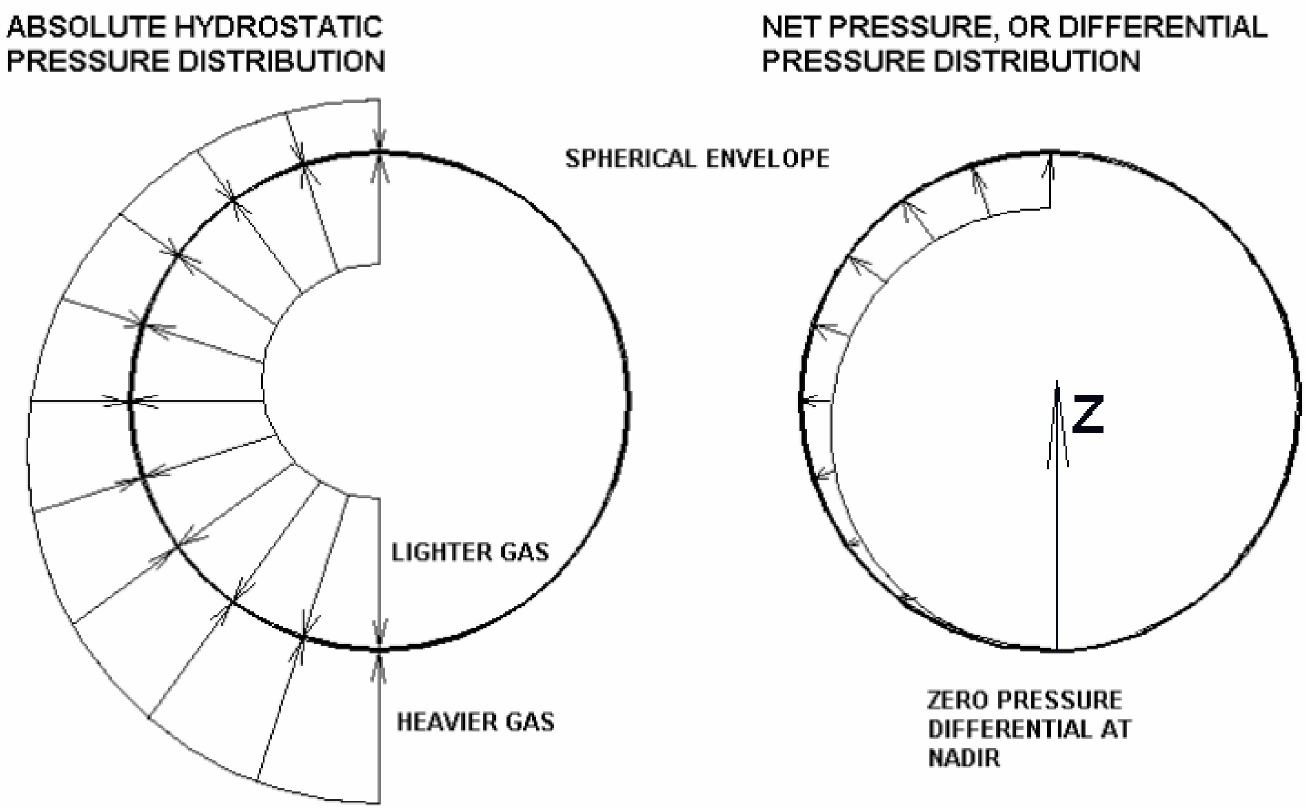
At 33km, b ~ 0.084

Nature of Buoyancy, part 2

Combine aerostatic principle for both air and lift gas:

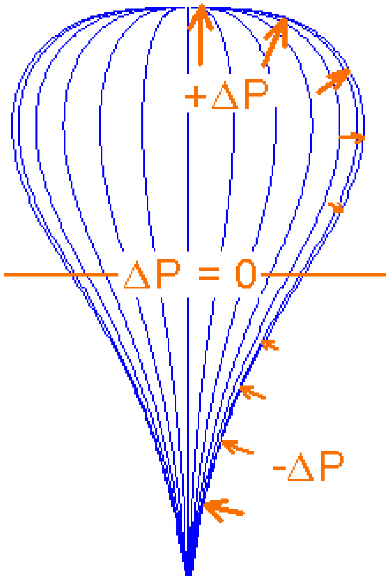
Buoyancy gradient pressure, N/m^2

$$\Delta P_{buoyancy} = b*Z$$



Like a hot air balloon…

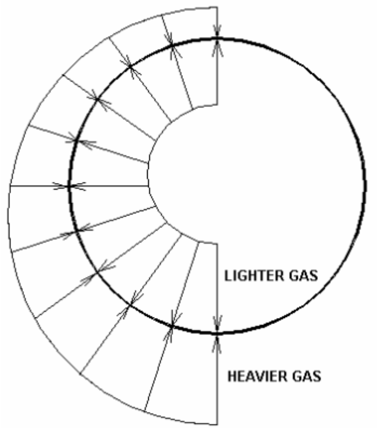
Under-pressurized shape



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

Balloon Force Equilibrium Equations

Gross Lift capacity, N

$$GrossInflation = b \cdot Volume$$

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

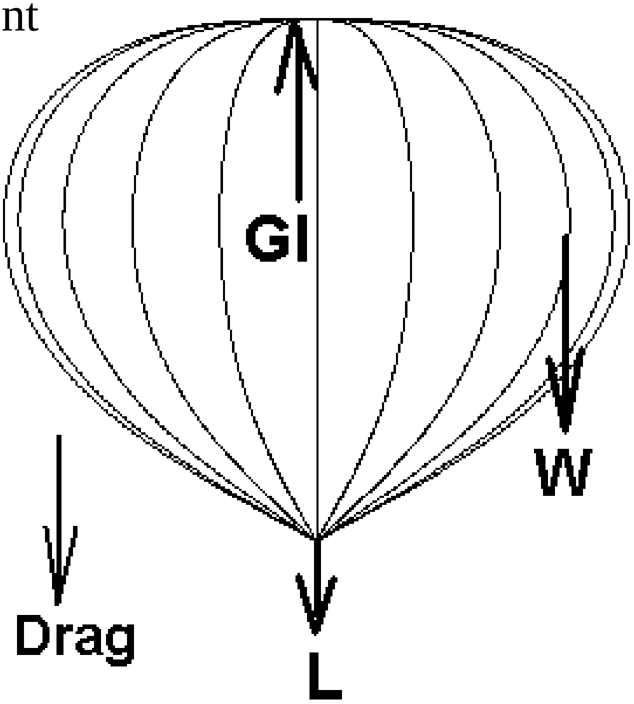
GrossWeight = Balloon weight + suspended load

GrossInflation = GrossWeight + freelift

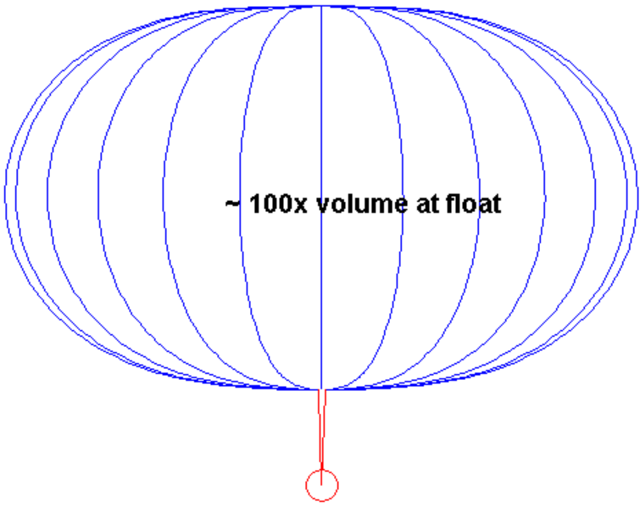
GrossInflation = GrossWeight + Drag @ equilibrium ascent

Drag = free lift @ equilibrium ascent

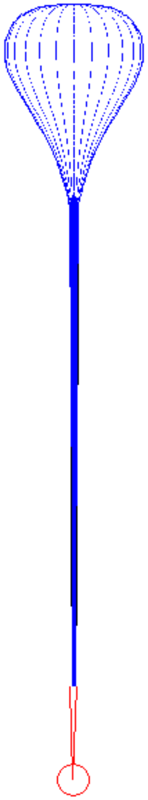
GI	Gross Inflation	
G	Gross weight = W + L	
W	Balloon weight (not including gas)	
L	Suspended Load	
F	Free lift	Free lift ratio = 1+F/G



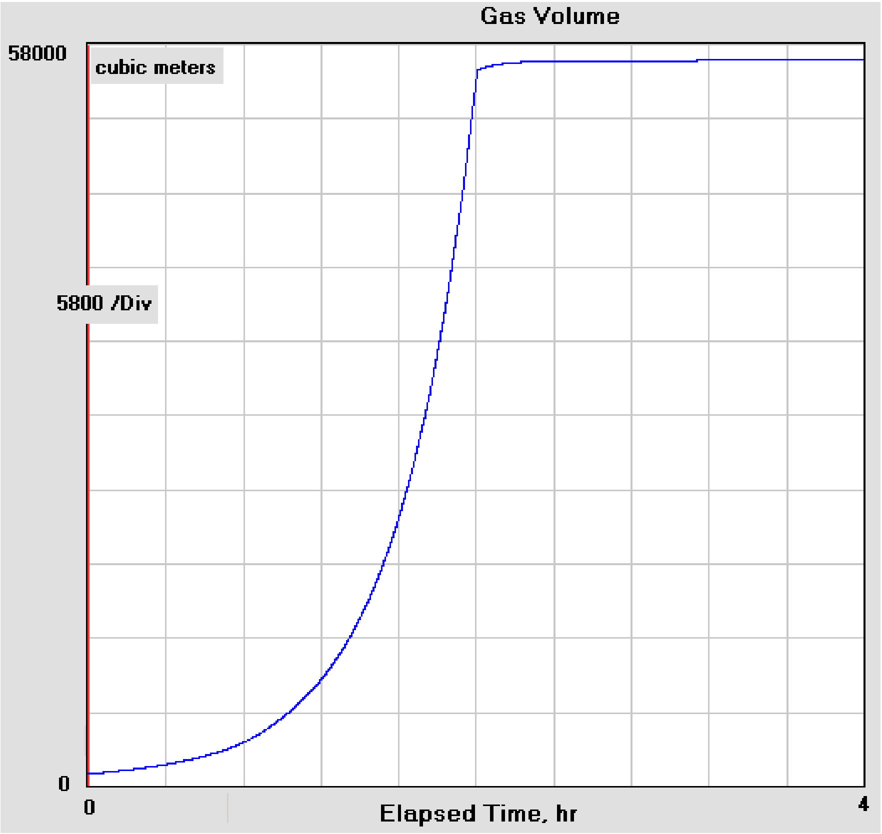
Volume change during ascent



PUMPKIN AT FLOAT



PUMPKIN AT SEALEVEL



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

$$P = n \cdot R \cdot \frac{T}{V}$$

General equation

Kinetic energy proportional to temperature

$$P = \rho \cdot R_{gas} \cdot T$$

Using specific gas constants, Rgas = 8314.5/molecular weight

$$R_{air} = 287.1$$

$$R_{helium} = 2077.2$$

$$R_{H_2} = 4148.7$$

Specific gas constants, Joules/kg/°K

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

Combining Ideal Gas Law with buoyancy relationships yields:

Super temperature

$$\Delta T = T_{gas} - T_{air}$$

$$\Delta P = P_{gas} - P_{air}$$

Super pressure

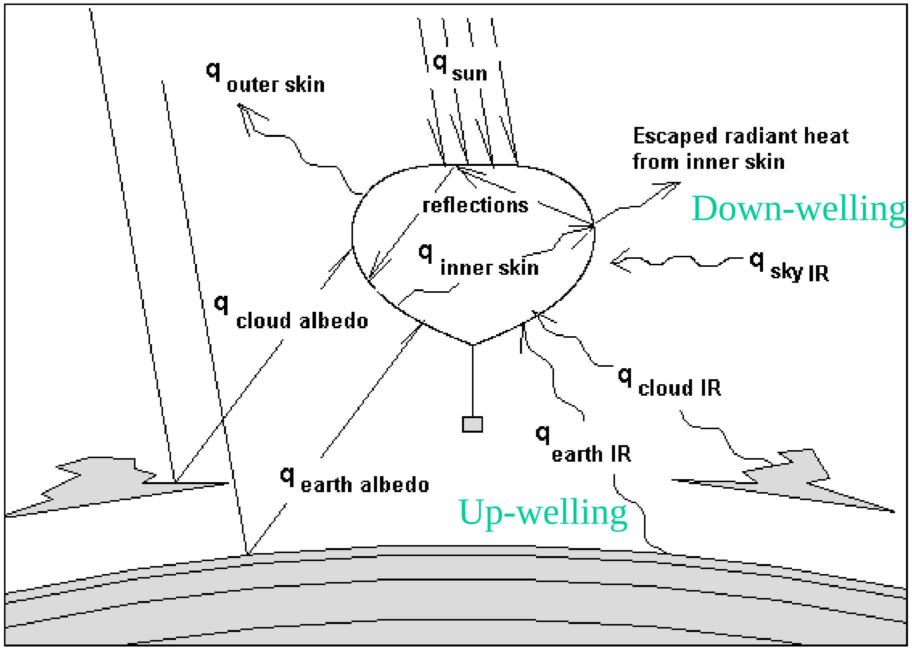
$$FreeLift_{ratio} = \frac{M_{gas}}{M_{gross}} \cdot \left[\frac{\left(1 + \frac{\Delta T}{T_{air}}\right)}{\left(1 + \frac{\Delta P}{P_{air}}\right)} \cdot \frac{R_{gas}}{R_{air}} - 1 \right]$$

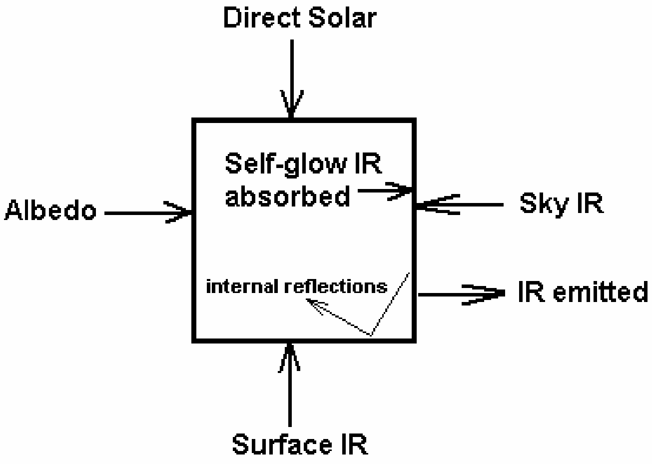
Free lift ratio = 1+F/G

G = g * Mgross

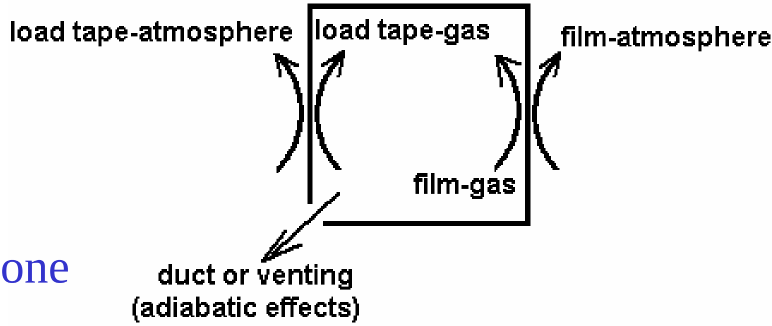
Energy Balance

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





Convection and Venting Effects



Use 1st law for both film and gas

Energy IN = Energy OUT + Energy stored + Work done

q = energy flux, Watts/m^2
Q = energy, Watts

Energy stored = Mass*specificheat*dT/dt

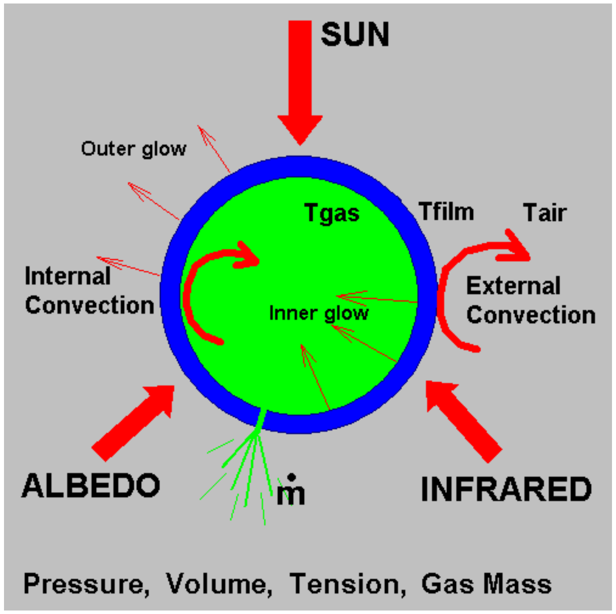
Film and Lift Gas Heat Balance

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

$$\overbrace{Q_{Sun}+Q_{Albedo}+Q_{IRplanet}+Q_{IRsky}+Q_{IRfilm}+Q_{ConvExt}}^{\text{Energy IN}} = \overbrace{Q_{ConvInt}+Q_{IRout}}^{\text{Energy OUT}} + \overbrace{c_f \cdot M_{film} \cdot \frac{dT_{film}}{dt}}^{\text{Energy stored}}$$

Flux q = σ*emissivity*T^4, watts per square meter

Energy Q = q*Area*Viewfactor*absorptivity, watts

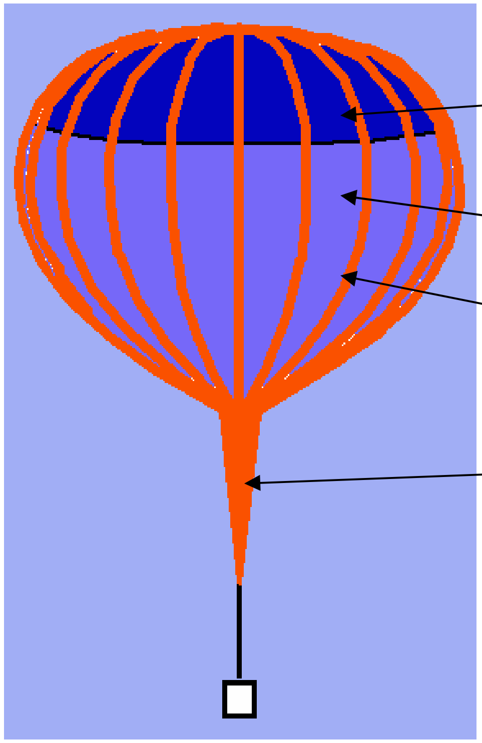


Apply 1st law and ideal gas law to lift gas:

$$\frac{dT_{gas}}{dt} = \overbrace{\frac{(Q_{ConvectionInternal}+Q_{burner})}{c_v \cdot M_{gas}}}^{\text{Energy IN}} + \overbrace{(\gamma-1)\cdot\frac{T_{gas}}{\rho_{gas}}\cdot\frac{d\rho_{gas}}{dt}}^{\text{Adiabatic Expansion}}$$

$$\gamma = \frac{c_p}{c_v}$$

Optical Property Effects



Cap + Shell

Shell

Load Tapes

Un-expanded portion

α absorptivity

e emissivity = α_{IR}

τ transmittance

τ_{IR} IR transmittance

Properties weighted according to ratio of surface area in the bubble

	1 layer
α	0.024
ε	0.184
τ	0.914
τIR	0.81
α/ε	0.130

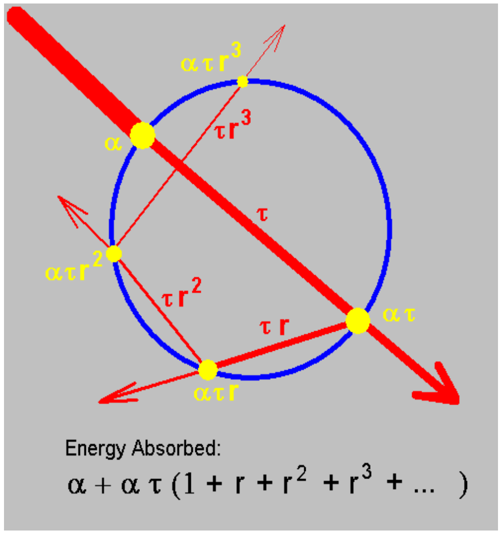
ULDB Material
SF420, 1.5 mil

	1 layer
α	0.023
ε	0.102
τ	0.916
τIR	0.866
α/ε	0.225

ZPB Material
SF372, 0.8 mil

Killer is the balloon geometric effects

Many internal bounces create an effective reflectivity

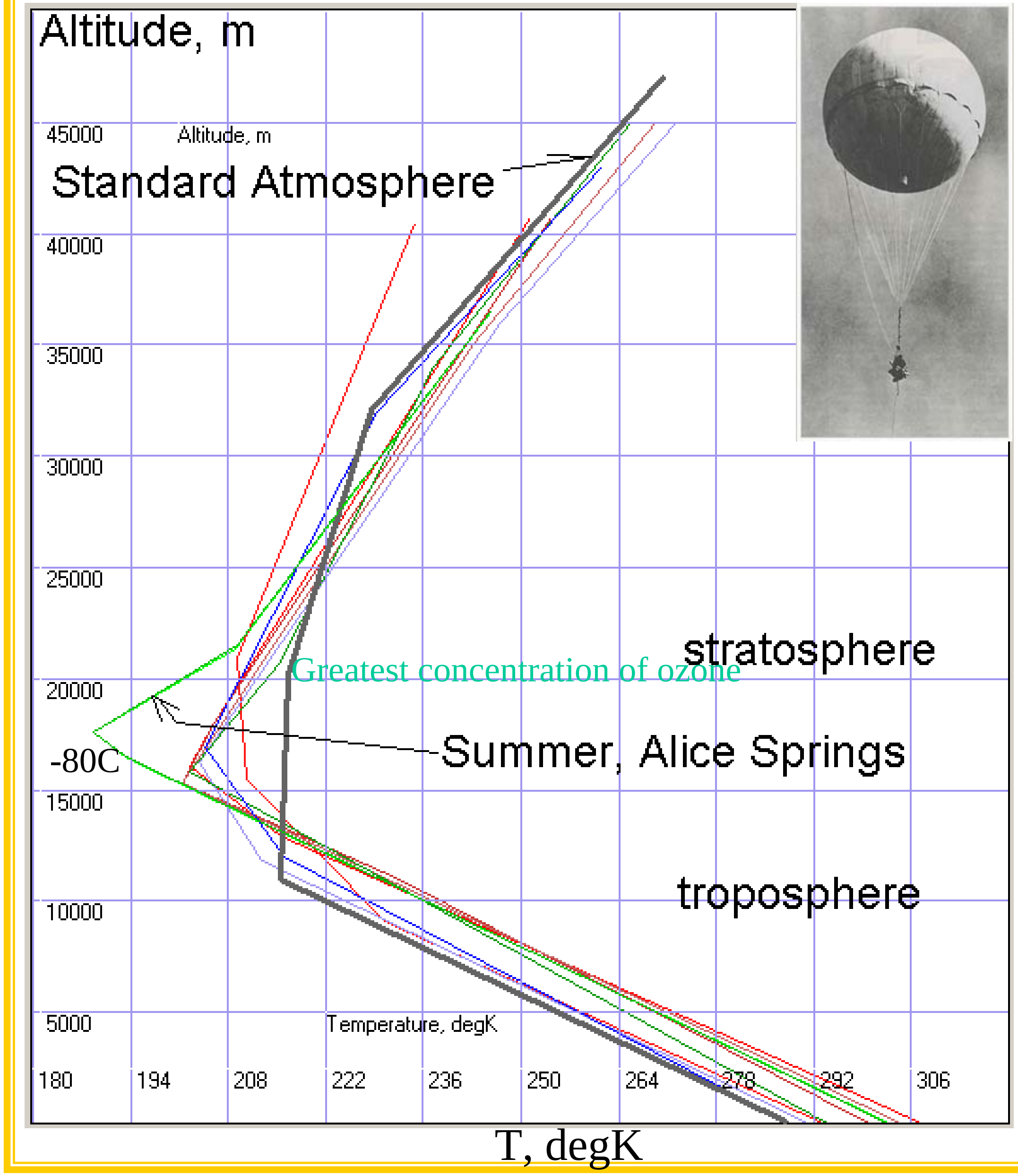


Energy Absorbed:

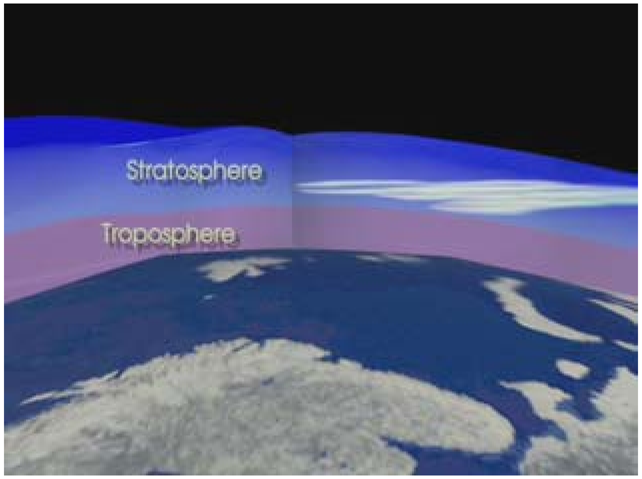
$\alpha + \alpha\tau\,(1 + r + r^2 + r^3 + \ldots)$

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



Balloon Bobbing

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

For a zero-pressure balloon, the bobbing factor

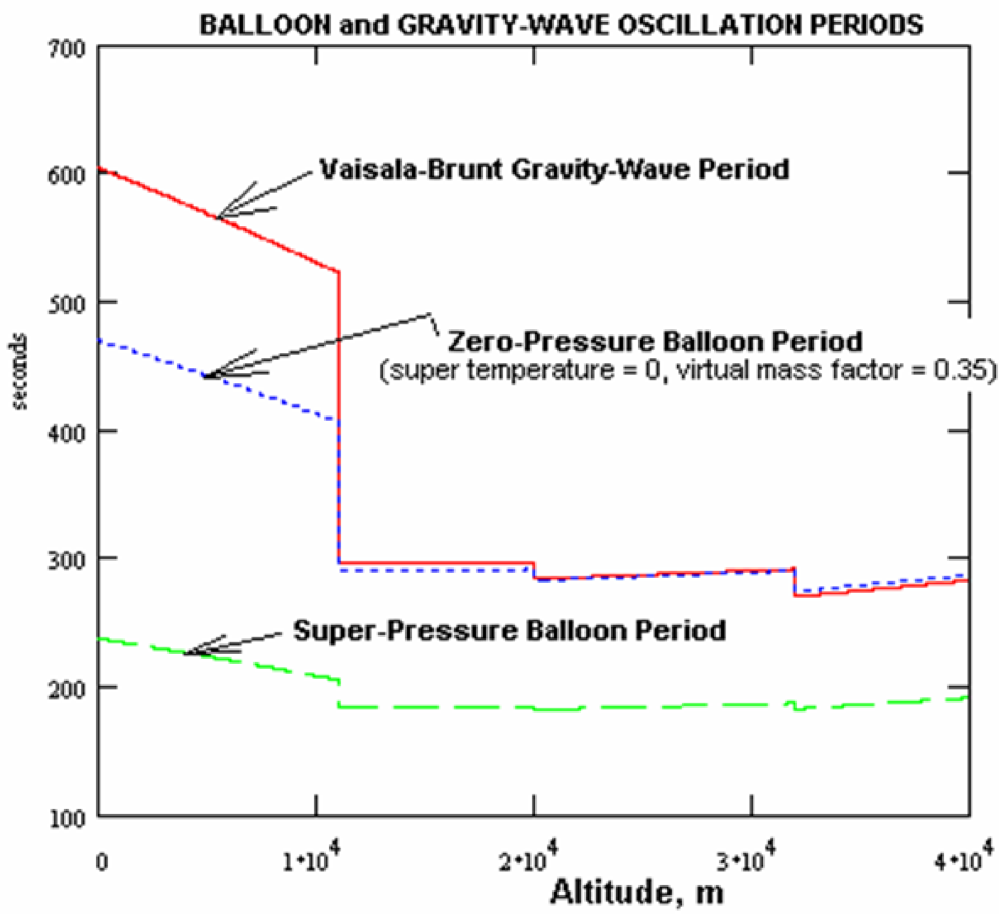
$$\text{KoverM}_{zpb} = g \cdot \frac{\left[\left[\frac{\frac{d}{dz}P_{air}}{R_{gas}\cdot T_{air}\cdot \gamma_{g}}\right]\cdot \frac{\rho_{air}}{\rho_{gas}} - \frac{d}{dz}\rho_{air}\right]}{\rho_{air}\cdot\left(1 + C_B\right)}$$

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

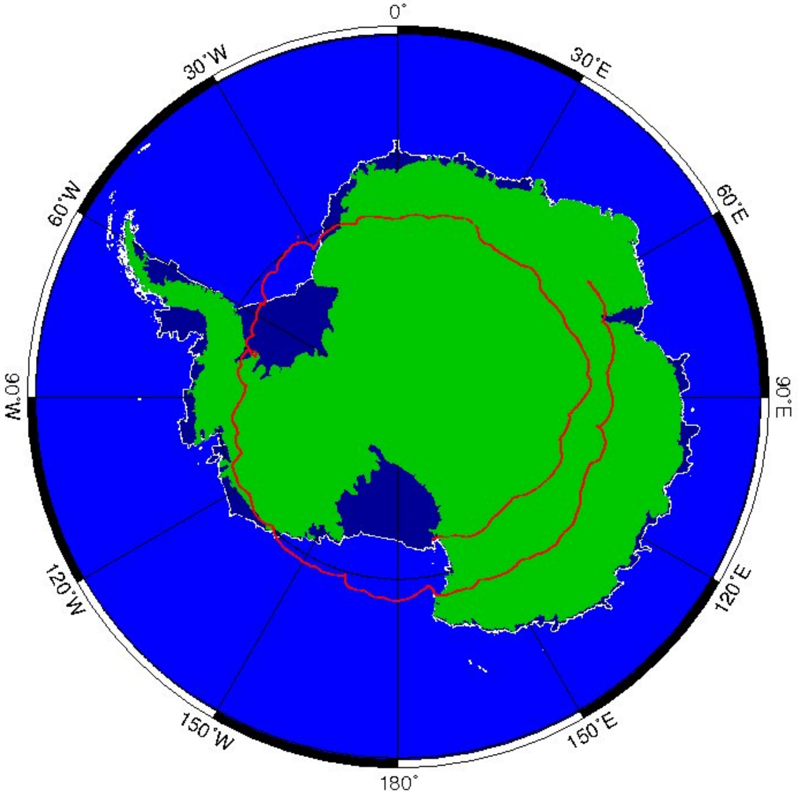
$$\text{KoverM}_{spb} = g \cdot \frac{-\left(\frac{d}{dz}\rho_{air}\right)}{\rho_{air}\cdot\left(1 + C_B\right)}$$

Bobbing Period

$$\text{Period} = \frac{2\cdot\pi}{\sqrt{\text{KoverM}}}$$



Ground track in Antarctica



Long Duration Balloon in
the Polar Vortex

CREAM circled for
42 days

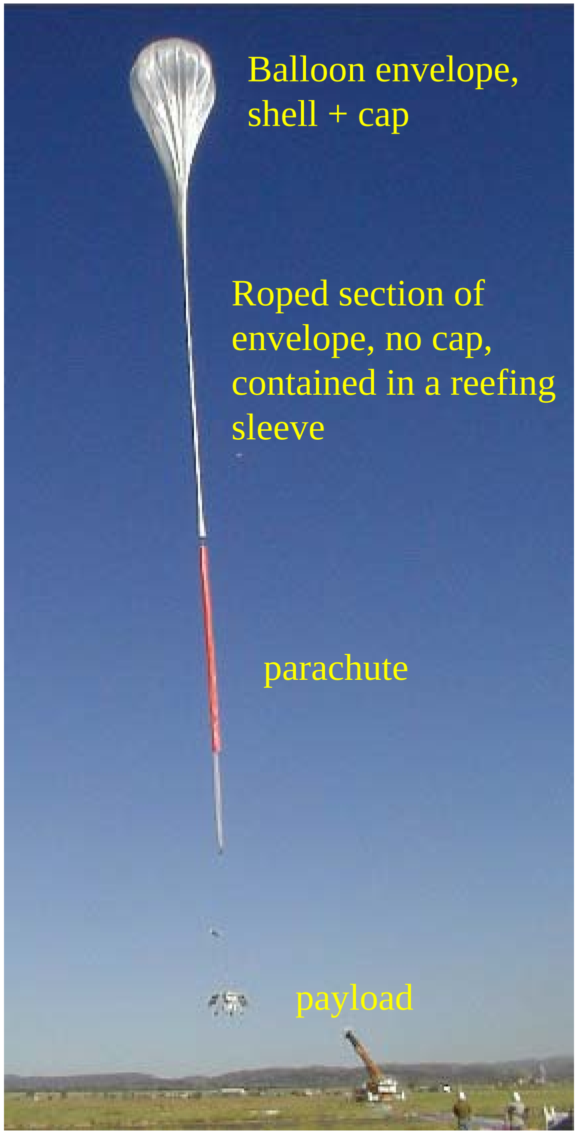
Typical Dynamic Launch

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

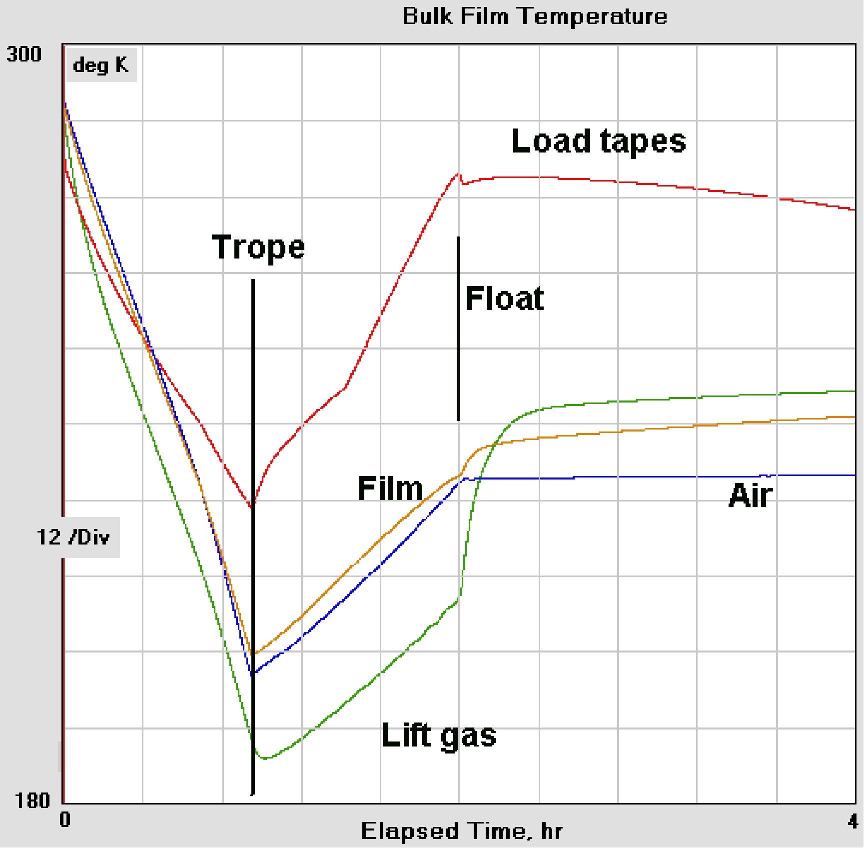
Static Launch Technique


USS Valley Forge 1960

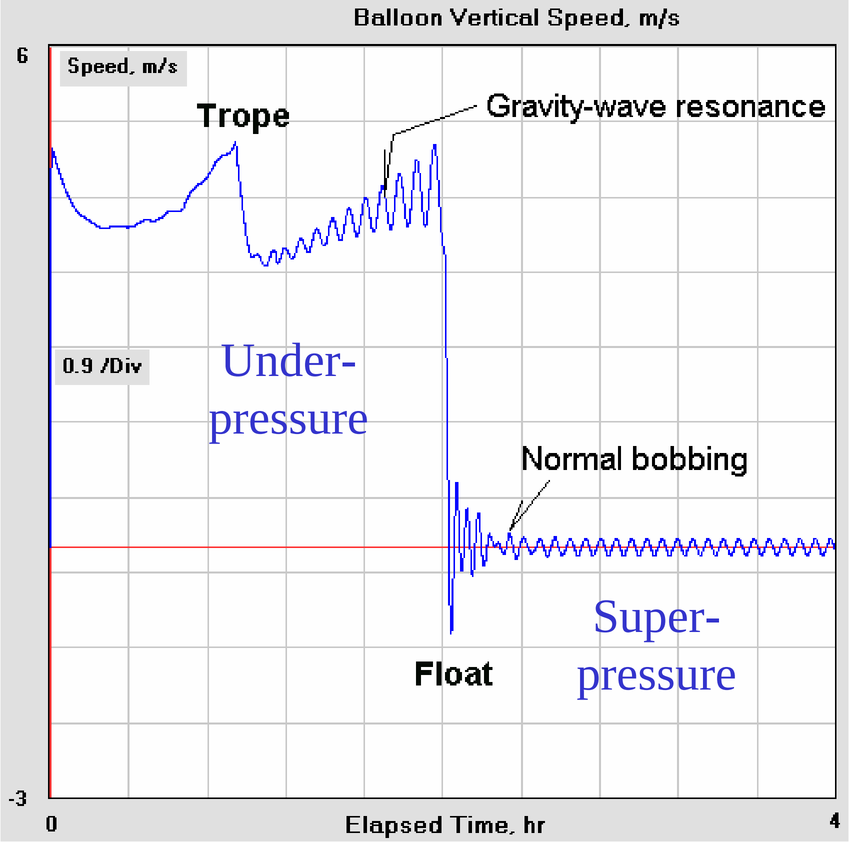
When balloons were used for spy missions, with many UFO sightings

Basic performance during ascent

Temperatures

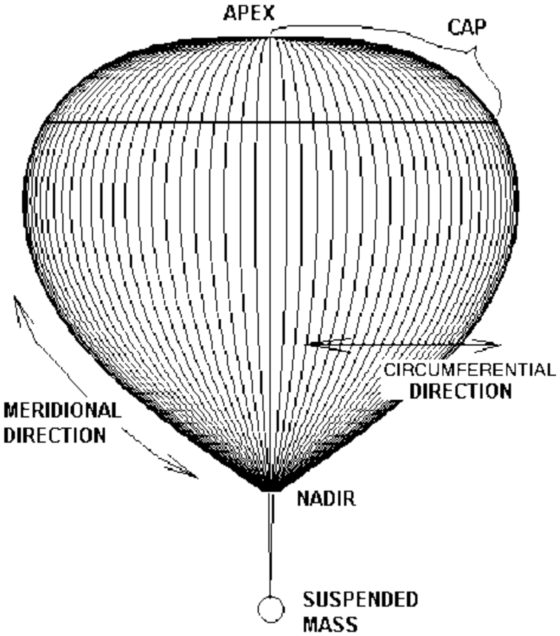


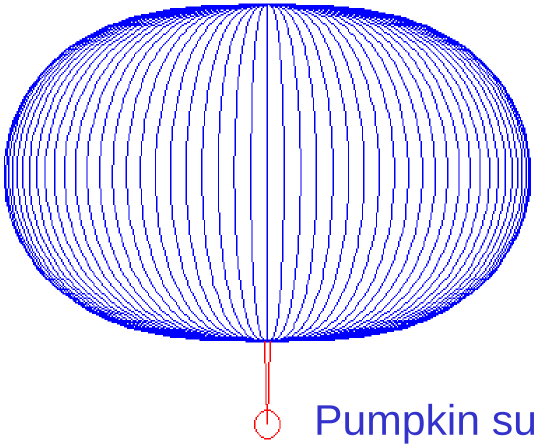
Ascent Speed



Meridionally-Reinforced Membrane Structures

Zero-pressure Balloon

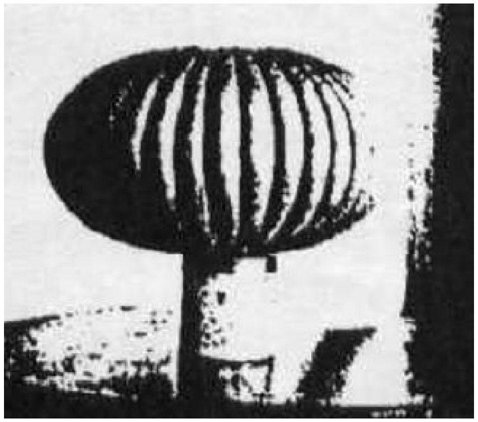




Pumpkin super-pressure

"Natural Shape"

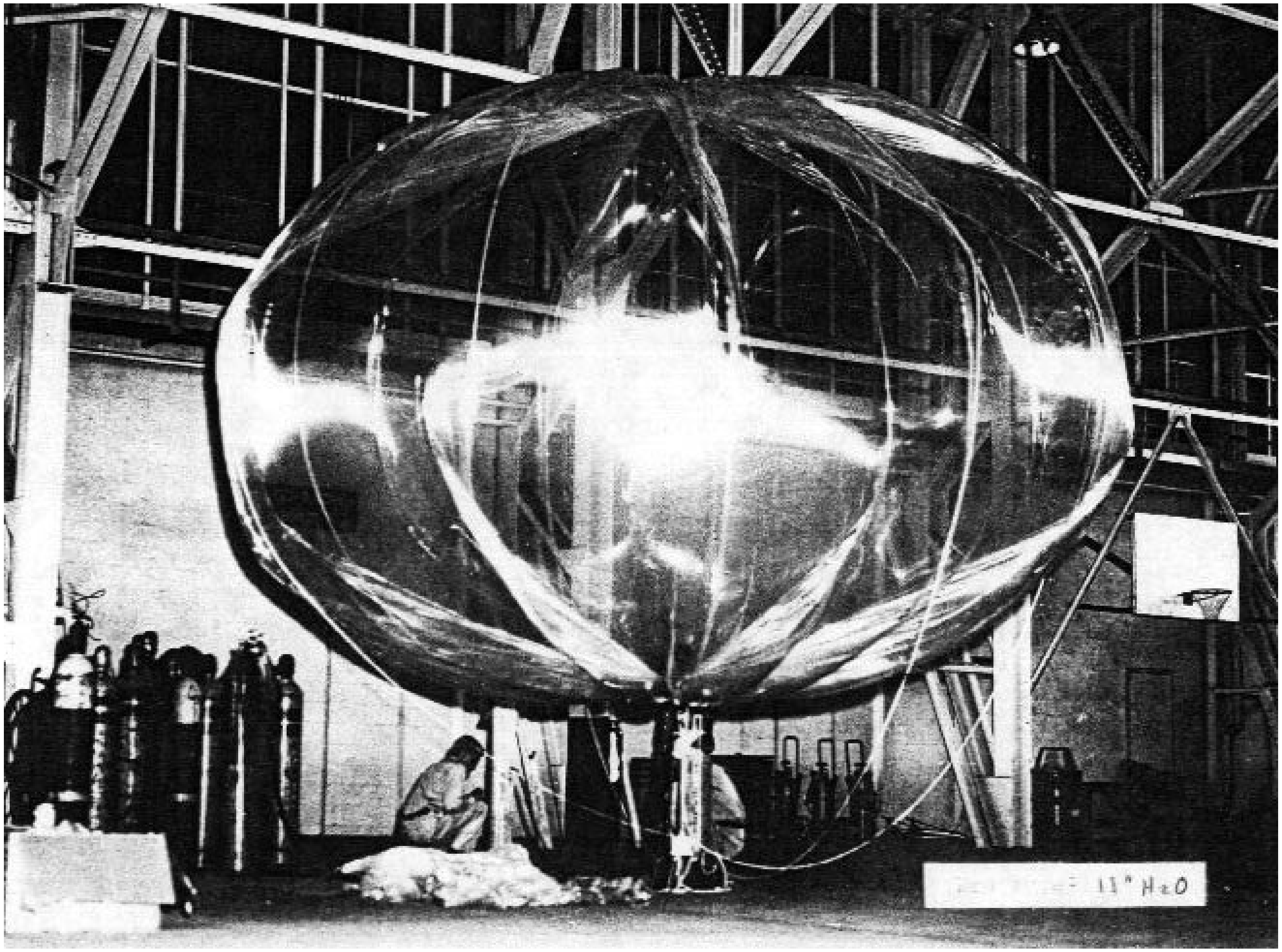
Vast majority of load reacted in the meridional (longitude) direction, with little or no load in the circumferential (latitude) direction



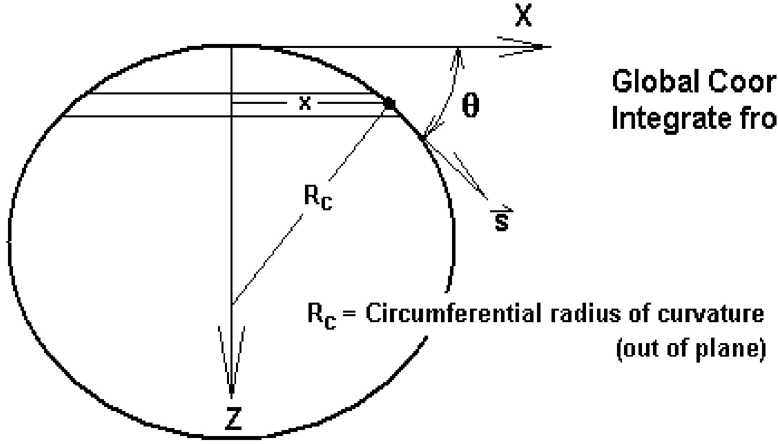
Taylor parachute shape validation model, 1919

Parachute

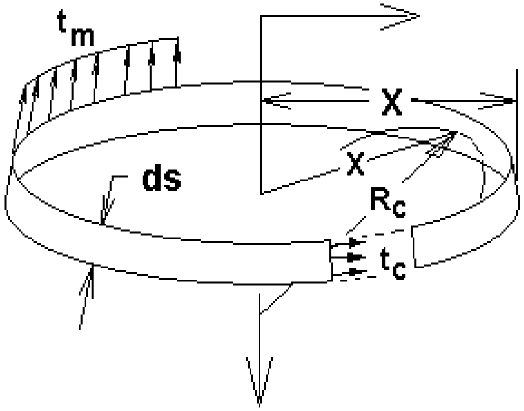
Air Force cylinder balloon pressurized to a smooth pumpkin shape



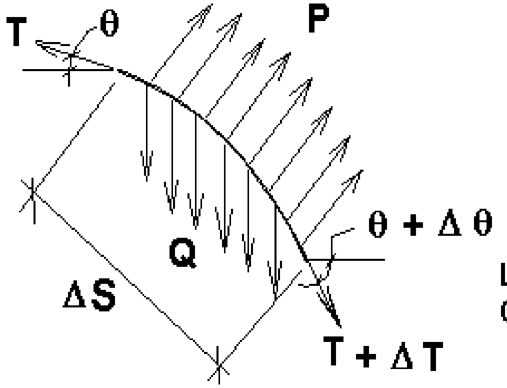
Membrane Shape Formulation



Global Coordinates
Integrate from top to bottom



Circumferential
Annulus



Local Meridional Forces on the
Circumferential Annulus

P is linear pressure loading

Q is linear gravity loading

T is the meridional tension

tc is the transverse linear loading

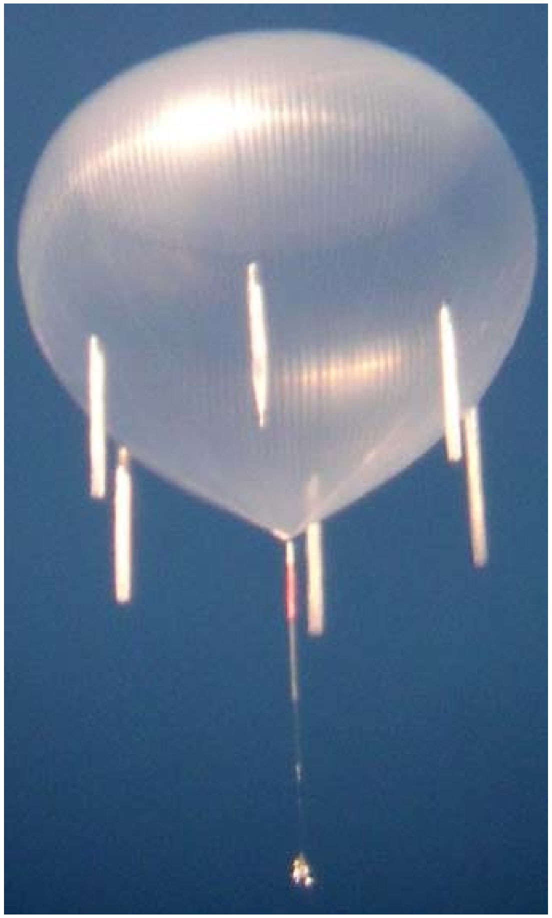
tm is the meridional linear loading

From equilibrium equations:

$$\frac{d}{ds}\theta = \frac{-2\cdot\pi\cdot t_c\cdot\sin(\theta) - Q\cdot\cos(\theta) + P}{T} \quad \text{and} \quad \frac{d}{ds}T = 2\cdot\pi\cdot t_c\cdot\cos(\theta) - Q\cdot\sin(\theta)$$

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 trope, 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

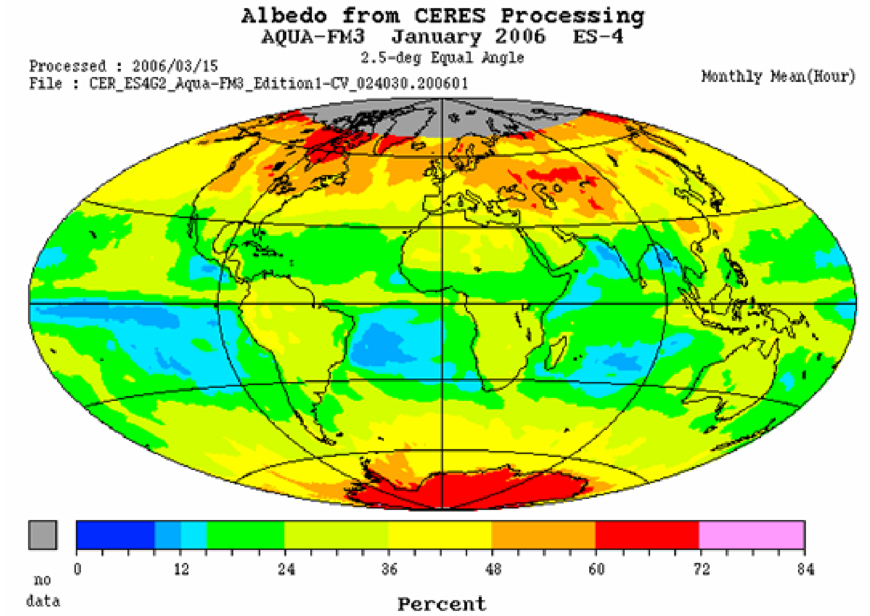


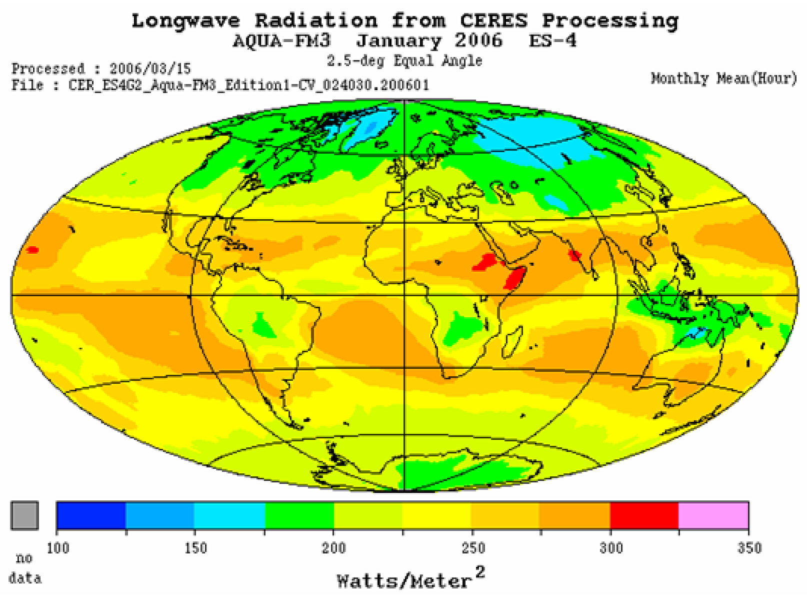
Environmental Models

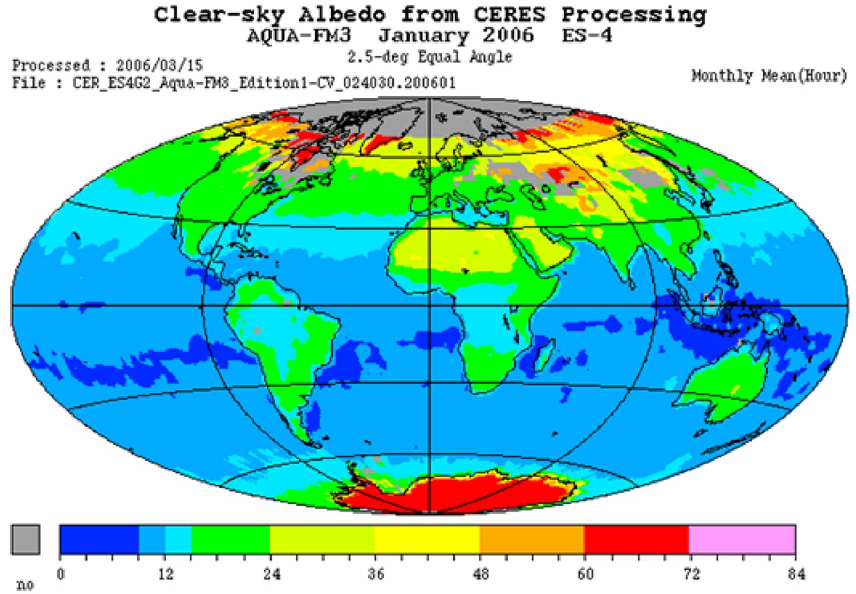
EOS monthly average data

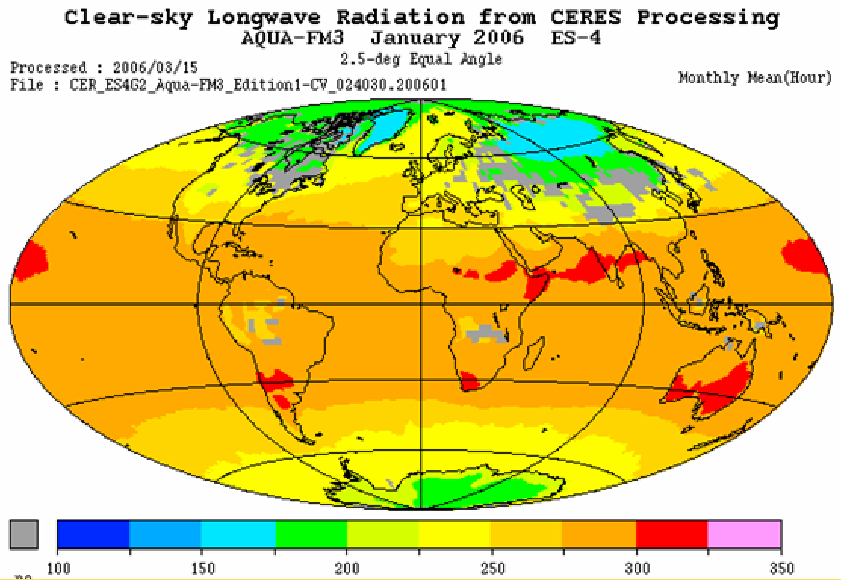
Albedo

Up-welling IR









Direct Solar Model

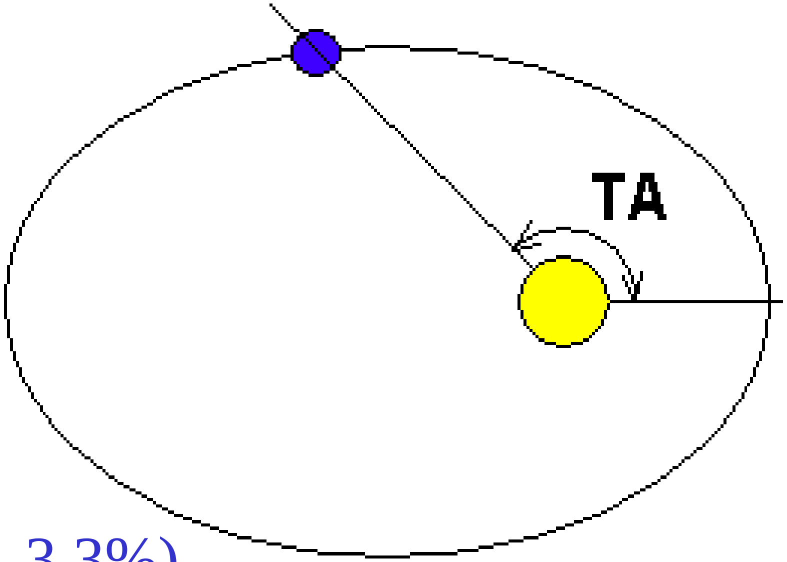
$$I_{Sun} = \frac{1358}{R_{AU}{}^{2}} \cdot \left[\frac{1 + e \cdot \cos(TA)}{1 - e^{2}} \right]^{2}$$

Solar Irradiance at the top of the atmosphere, watts/m^2

mean orbital radius R_{AU}, astronomical units

orbital eccentricity e

true anomaly TA



For Earth

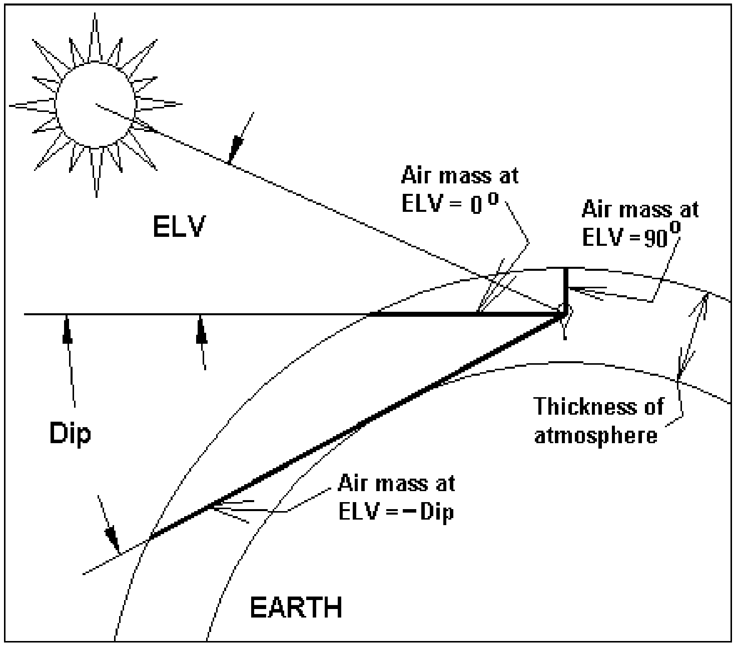
Isun = 1358 +/- 45 watts/m^2 (+/- 3.3%)

Atmospheric Solar Attenuation

Direct Solar Transmittance Factor

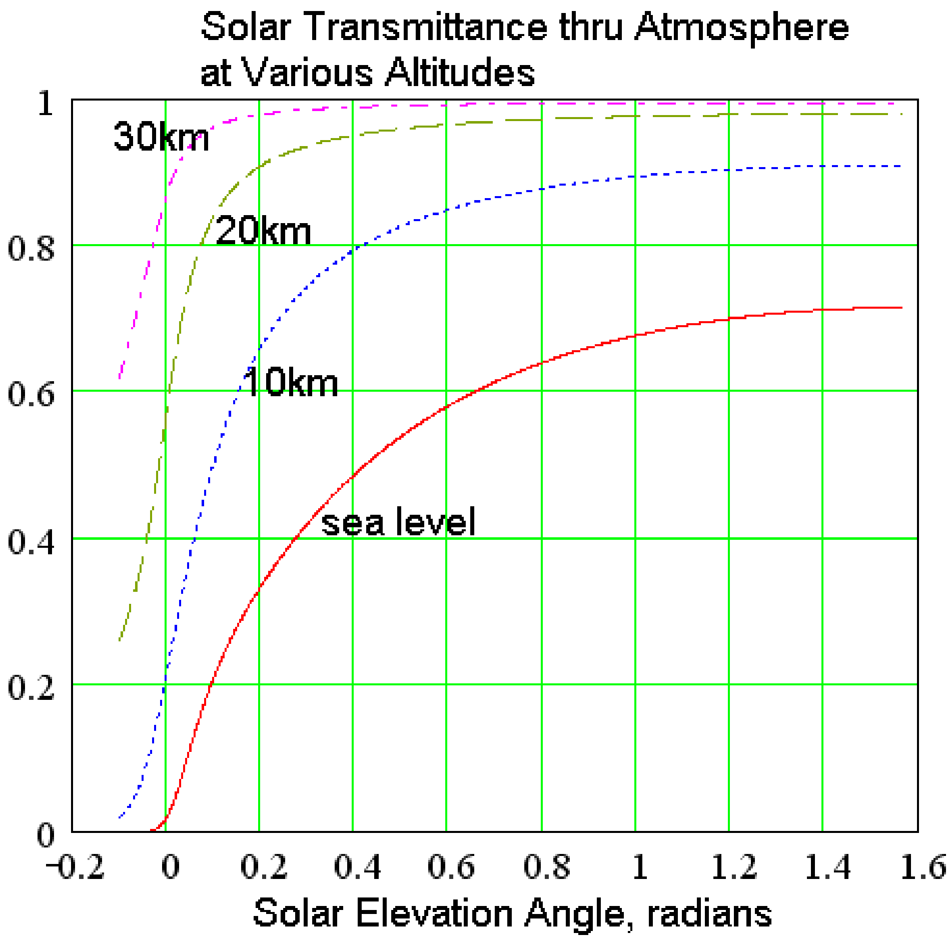
$$AirMass = CF_{airmass} \cdot \left(\frac{P_{air}}{P_o}\right) \cdot \left[\sqrt{1229 + (614 \cdot \sin(ELV))^2} - 614 \cdot \sin(ELV)\right]$$

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

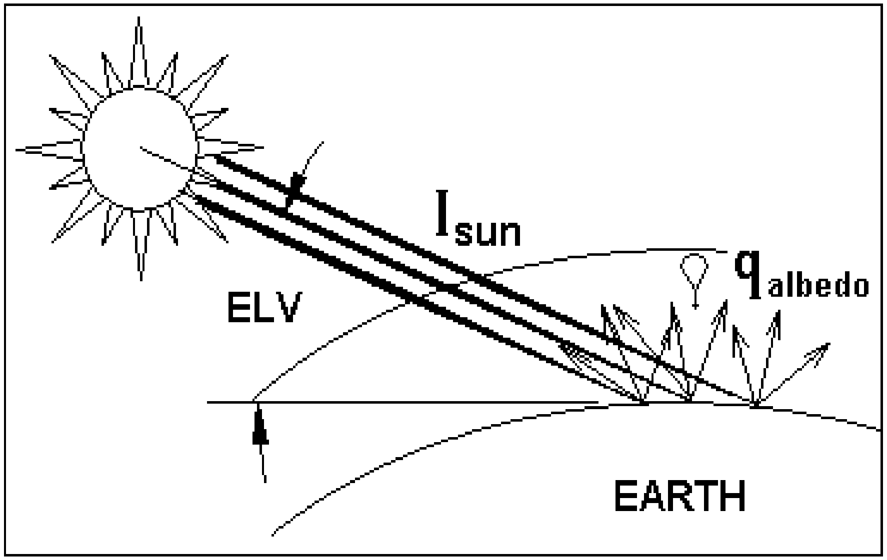


$$I_{SunZ} = I_{Sun} \cdot \tau_{atm}$$

Solar Irradiance at the balloon altitude



Albedo Model



Simple diffuse model

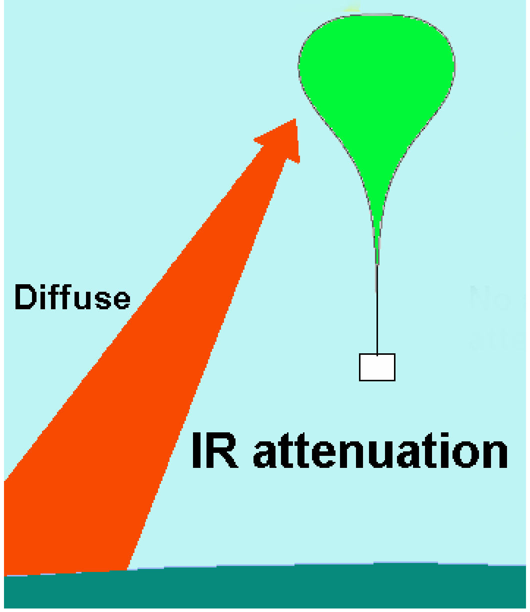
$$q_{albedo} = Albedo \cdot I_{Sun} \cdot \sin(ELV)$$ Watts/m^2

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 ε_{ground} and ground temperature T_{ground} (°K):

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



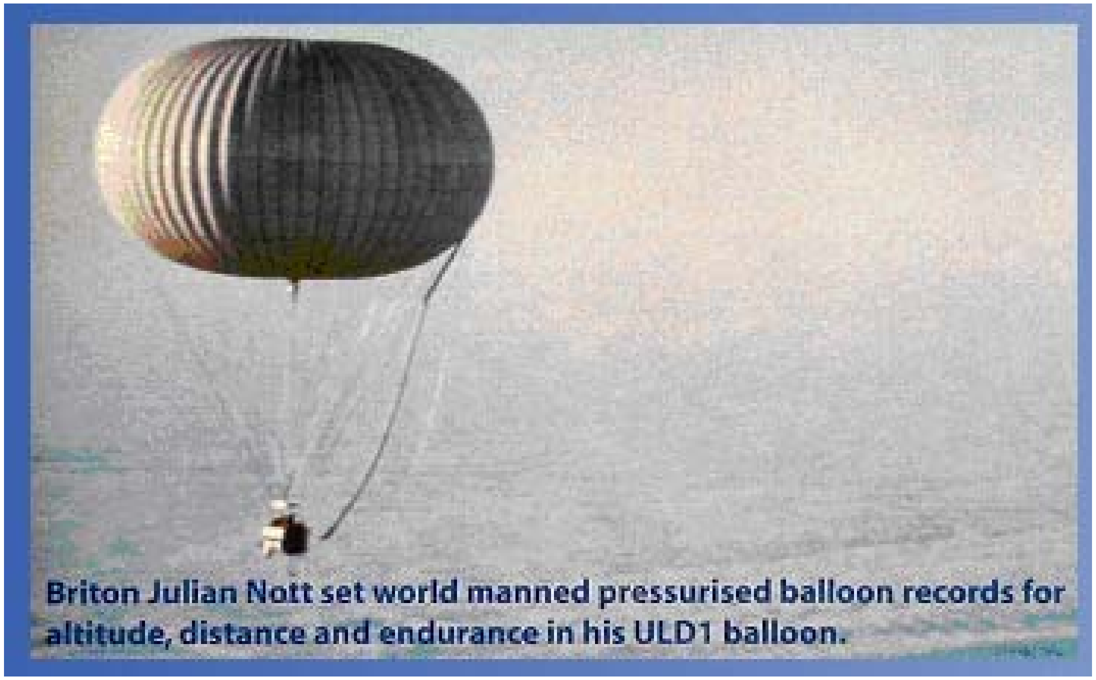
$$\text{Attenuation} = A_{IR} \cdot \left(\frac{P_{air}}{P_{sealevel}} - 1 \right) + 1$$

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

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

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

$$q_{IRgroundZ} = q_{IRground} \cdot \text{Attenuation}$$



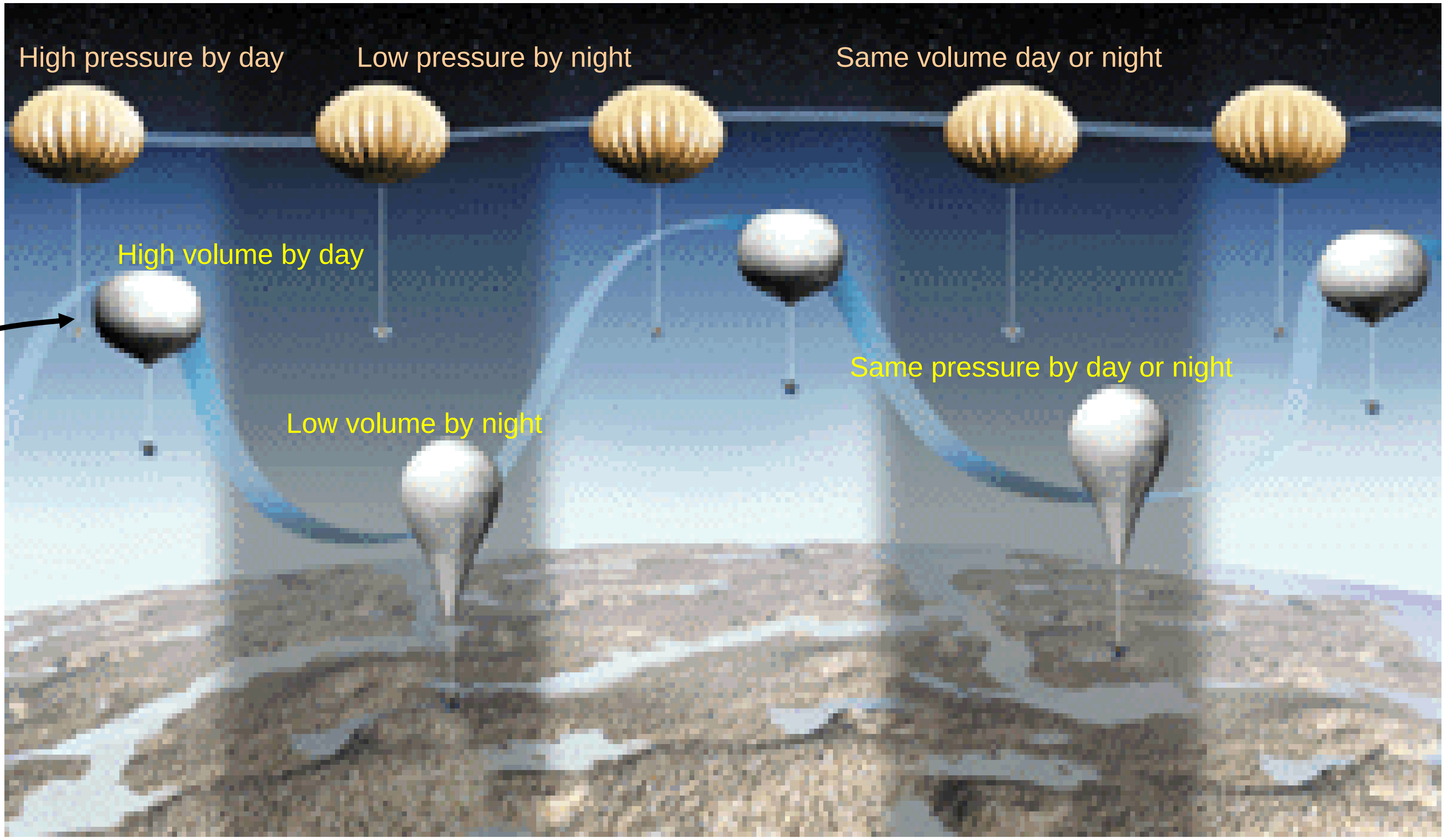
Briton Julian Nott set world manned pressurised balloon records for altitude, distance and endurance in his ULD1 balloon.

Super-PressureAllooncraft

Performance Comparison

Super-Pressure : Constant volume, variable pressure → constant altitude

Good for flying at any latitude



Zero-Pressure Balloon: Ambient pressure, variable volume

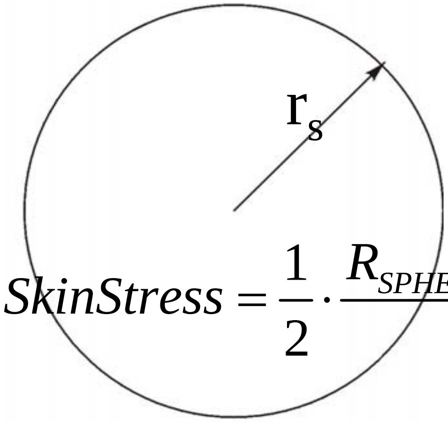
Good for lengthy summer polar flights, or 1-2 days mid latitude (diurnal cycles)

Types of Superpressure Balloons

Spherical Design

Spherical balloon would have much higher stresses

1960’s polyester super-pressure sphere



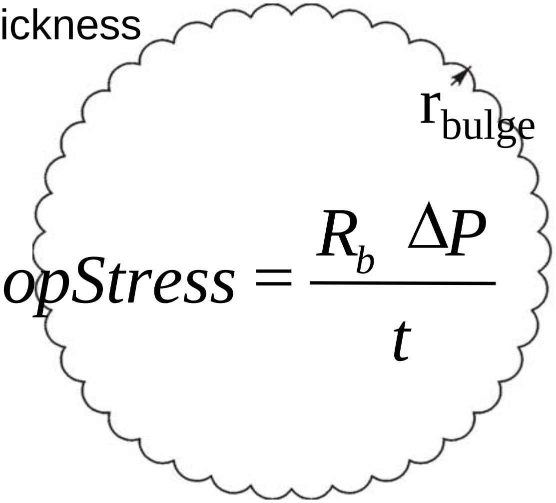
$$SkinStress = \frac{1}{2}\cdot\frac{R_{SPHERE}\cdot\Delta P}{t}$$

Pumpkin Design

Rb = bulge radius of curvature

ΔP = differential pressure

t = film thickness

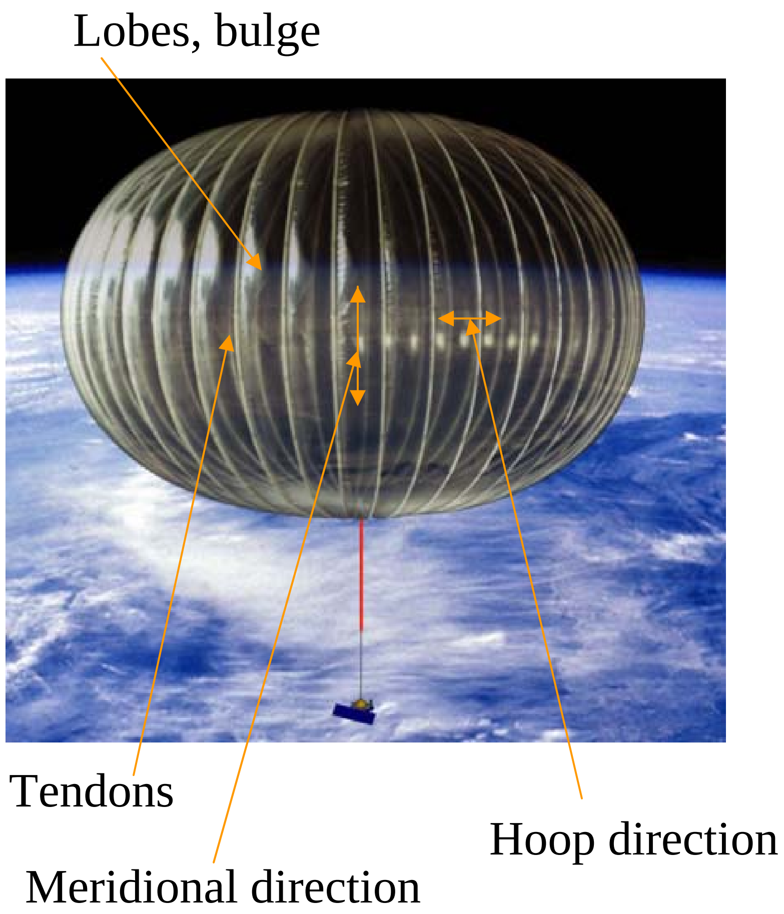


$$HoopStress = \frac{R_b\ \Delta P}{t}$$

A pumpkin Divides the jobs into gas containment (film) and structure (tendons, load tapes)

A sphere has both jobs simultaneously

ULDB Super Pressure-Pumpkin



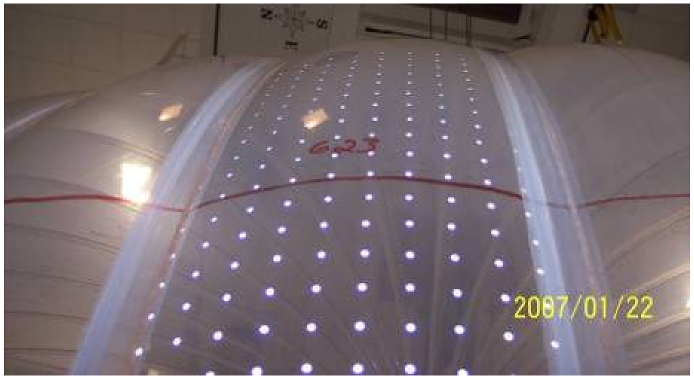
- ULDB is basically a two part system:
  - PBO Tendon “zylon”
  - Polyethylene Film, LLDPE 3-layer co-extruded

- 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

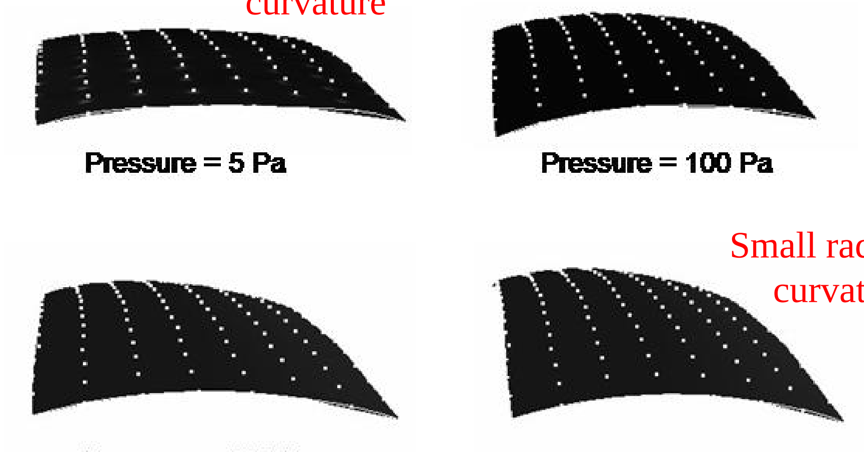
100 day flight makes this a sub-satellite vehicle!

Design Features some good, one not so good…

Inherent strain arrest features!



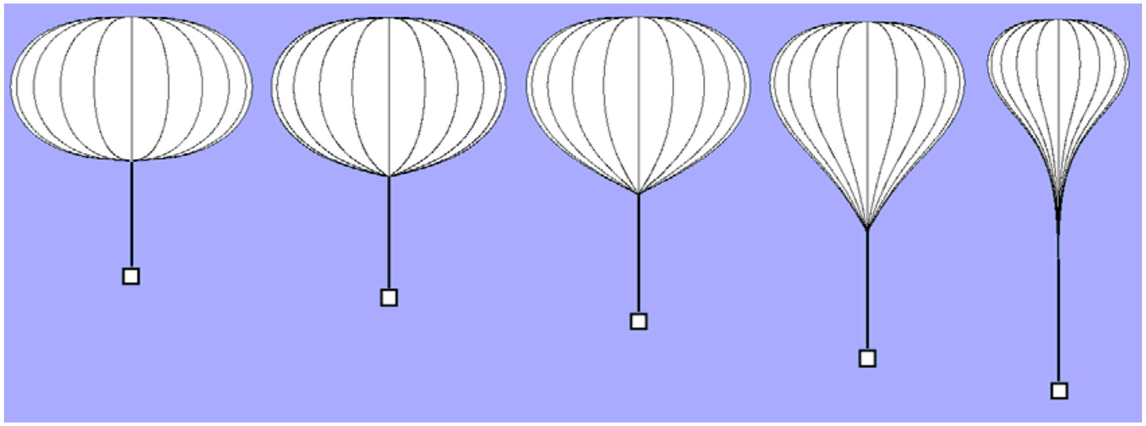
Large radius of curvature


Pressure = 5 Pa
Pressure = 100 Pa
Pressure = 200 Pa
Pressure = 300 Pa

Small radius of curvature

Structural-geometric self-limiting feedback

Pressurization involves running the gauntlet with much extra material

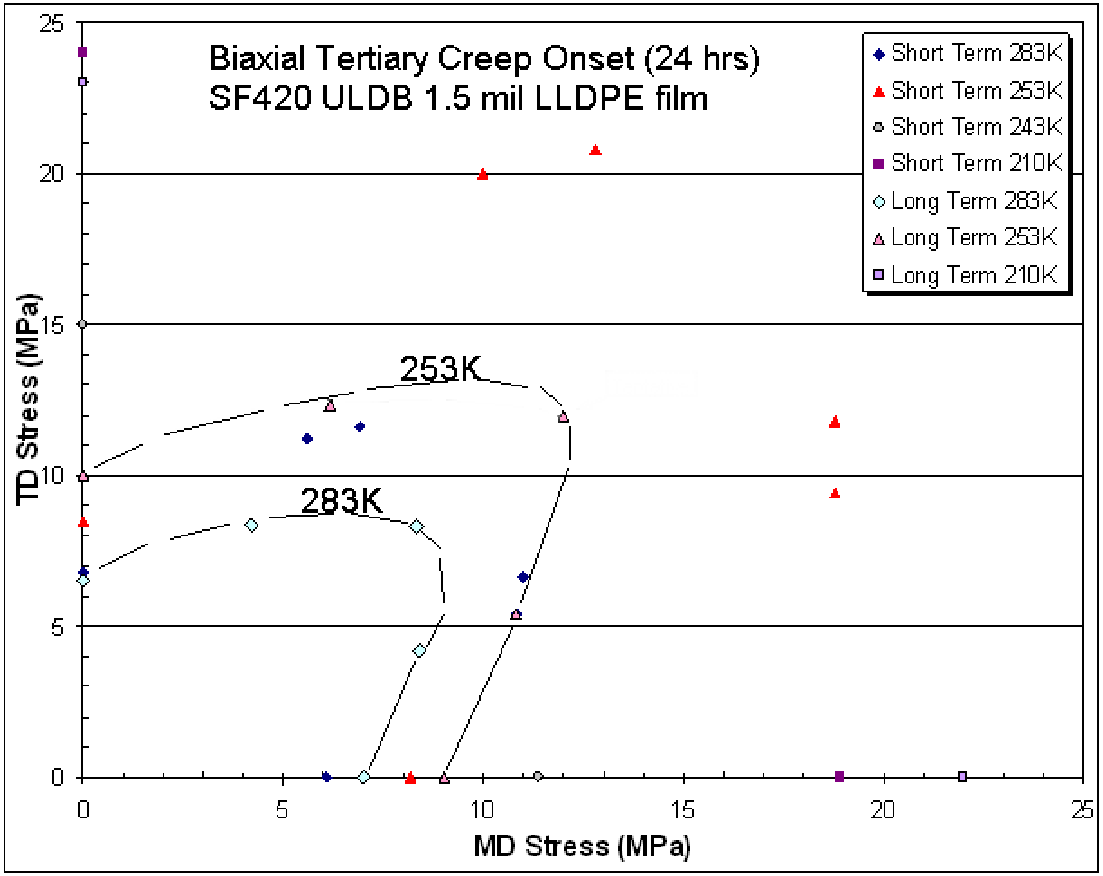


Materials Characterization

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

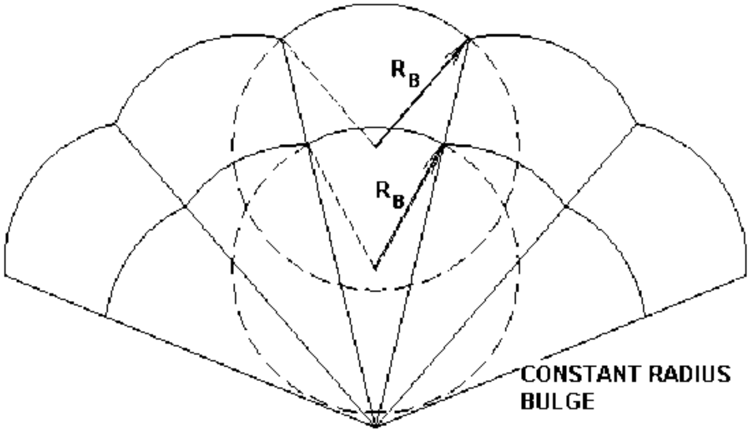
Creep Compliance

(strain = C*stress)

Creep Relaxation

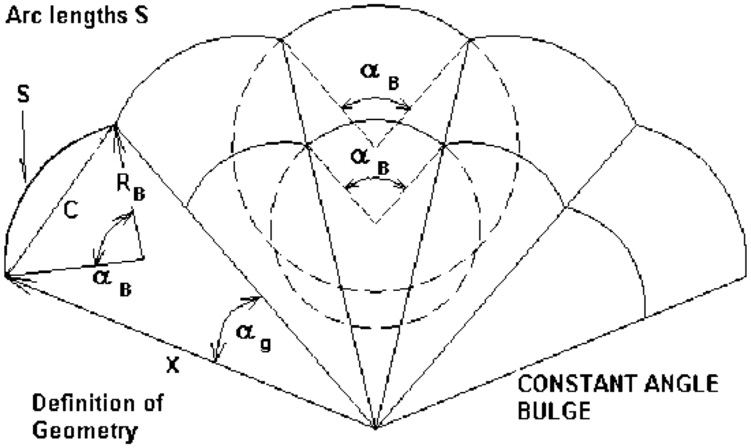
(stress = K*strain)

Bulge Design

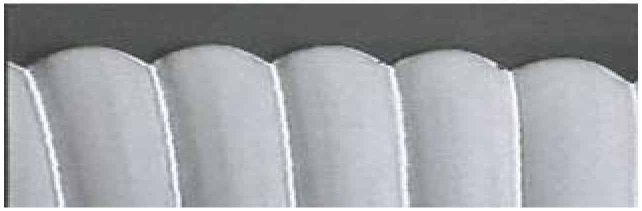


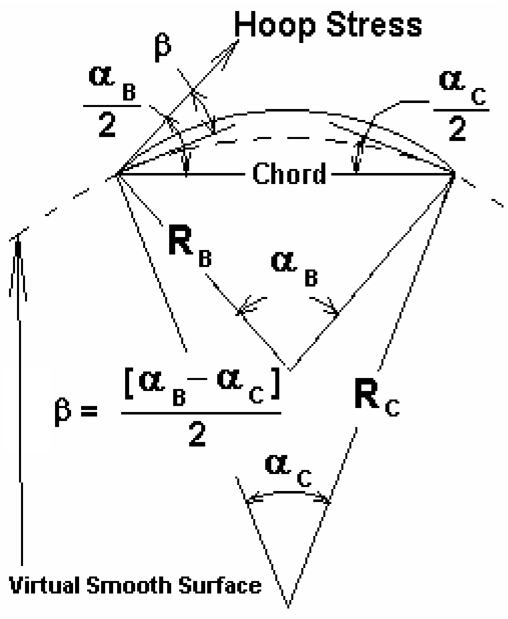
Constant radius bulge
Constant angle bulge
Constant hoop stress

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



- Stress
- Stress ratio
- “tightness”





Bulge Geometry in the Local Plane of the Bulge

Scale Effects

Scale Factor SF

$$SF = \frac{Sgore_2}{Sgore_1}$$

Gore length ratio

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

$$\frac{R_{bulge2}}{R_{bulge1}} = SF$$

$$\frac{b_2}{b_1} = 1.0$$

$$\frac{N_{gore2}}{N_{gore1}} = 1.0$$

$$\frac{t_2}{t_1} = SF$$

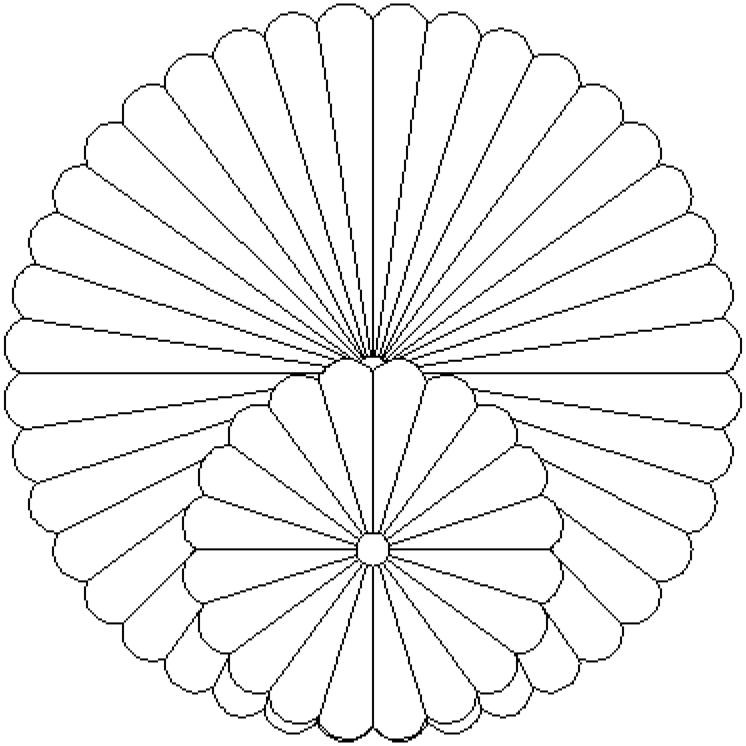
$$\frac{GI_2}{GI_1} = SF^3$$

$$\frac{Denier_2}{Denier_1} = SF^2$$

$$\frac{M_{suspend2}}{M_{suspend1}} = SF^3$$

$$\frac{\Delta P_2}{\Delta P_1} = SF$$

Good for low pressure shape effects



Same bulge radius

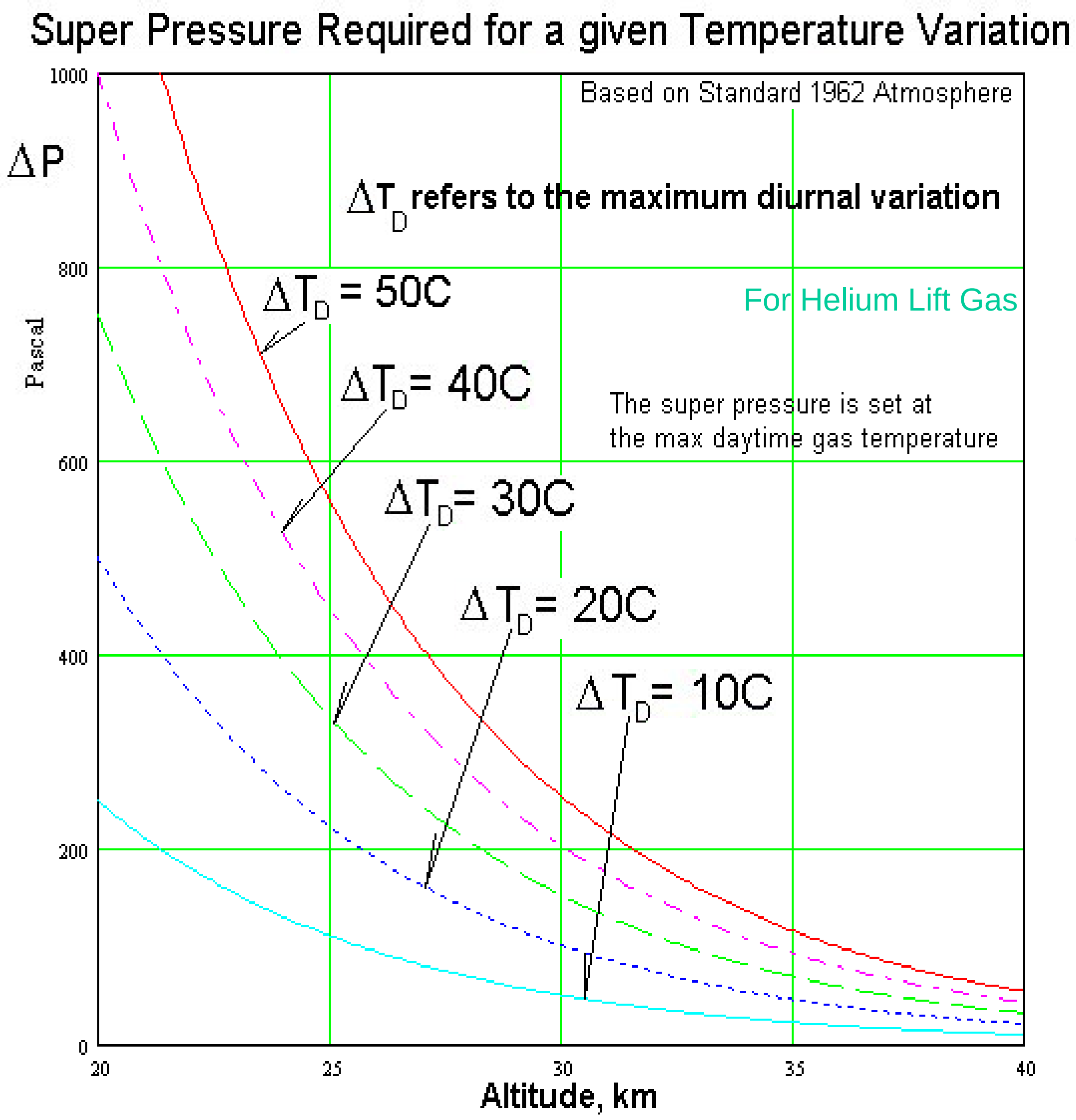
Same hoop stress

4x area

2x number of gores

Result 2x meridional tension

Required Super Pressure at Design Float Altitudes



ΔT = max gas day temperature

–min gas night temperature

$$P_{gas} = Density_{gas} \cdot R_{gas} \cdot T_{gas}$$

$$\frac{dP}{dT} = Density_{gas} \cdot R_{gas}$$

The higher the altitude, easier it gets…

… smaller ΔP change for same ΔT

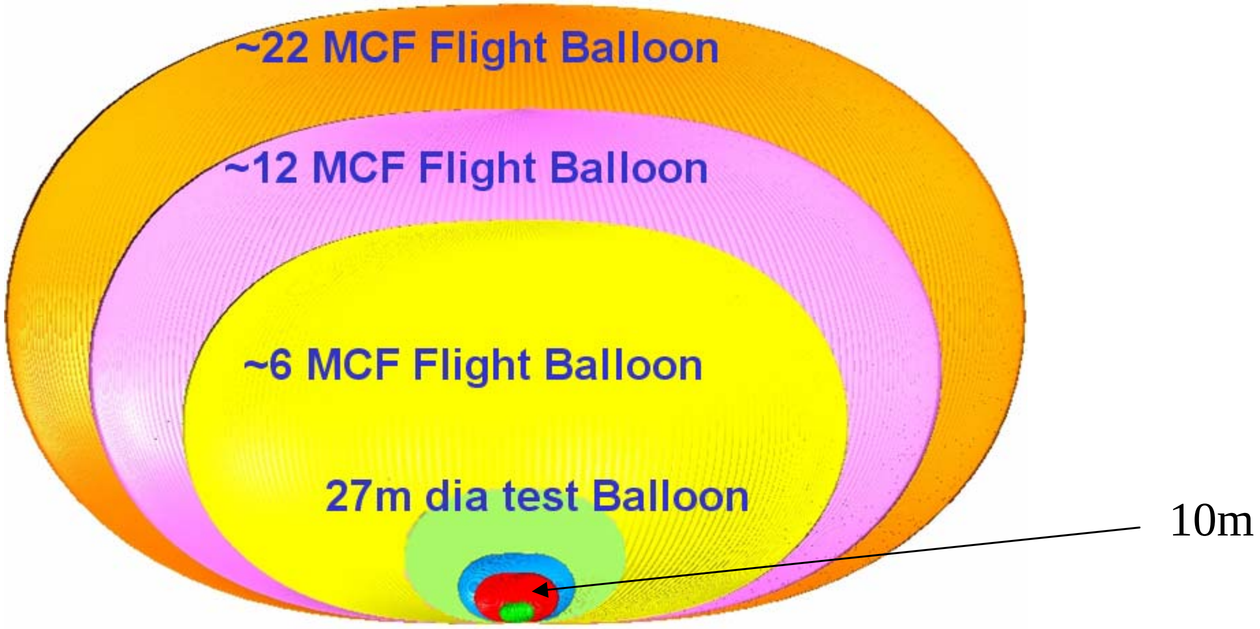
Quick Design Reference

Antarctica ΔT~ 20C if spiraling off to ocean, ~55C

Australia desert ΔT~ 60-75C

Ft Sumner ΔT~ 50C

ULDB Test Flights

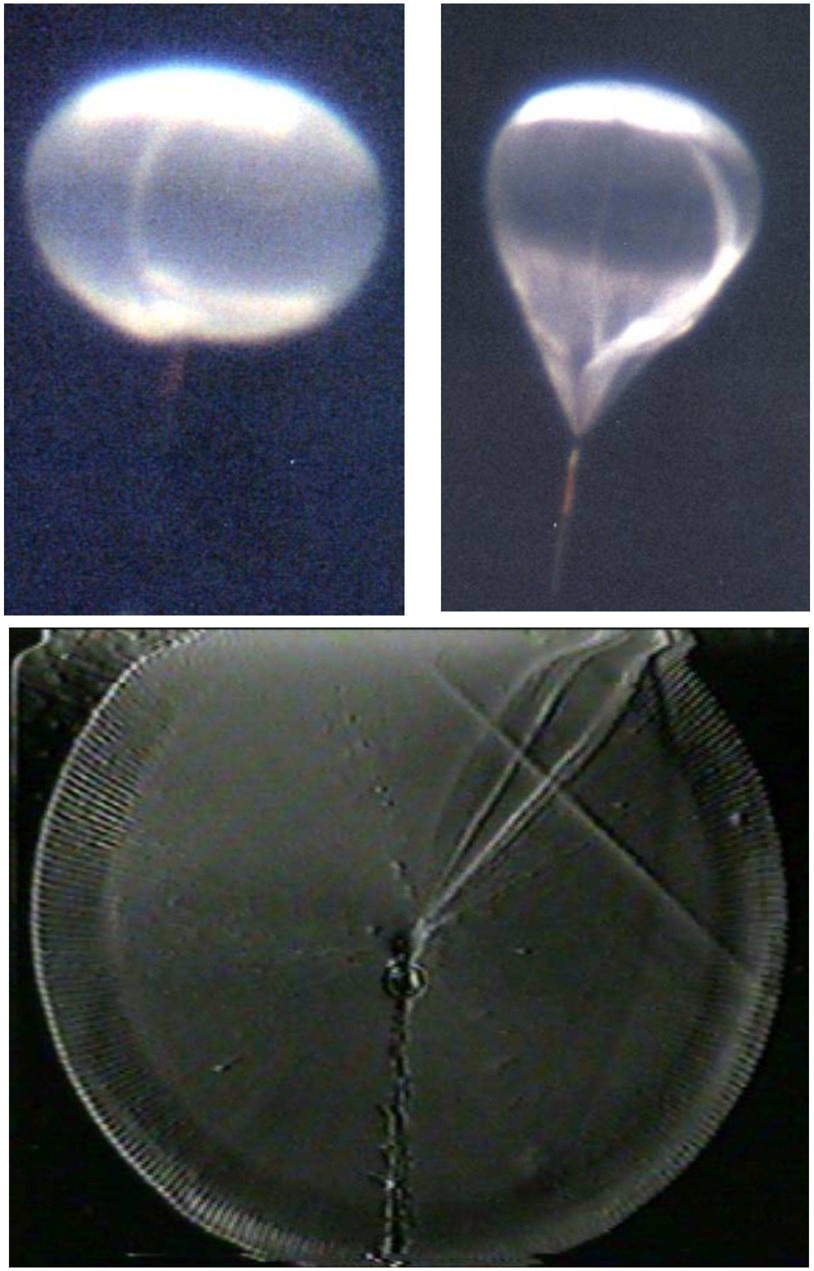


10/1998	Fabric-film spherical balloons - 16.5 meter diameter
10/23/1999	1.817 MCF fabric-film pumpkin – Flight 474NT
6/4/2000	2.421 MCF co-extruded pumpkin – Flight 485NT
2/24/2001	18.38 MCF co-extruded pumpkin – Flight 495NT-leaker
3/9/2001	18.38 MCF co-extruded pumpkin – Flight 496NT-cleft
7/6/2002	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

Foreshortened tendons

Load tape tendons

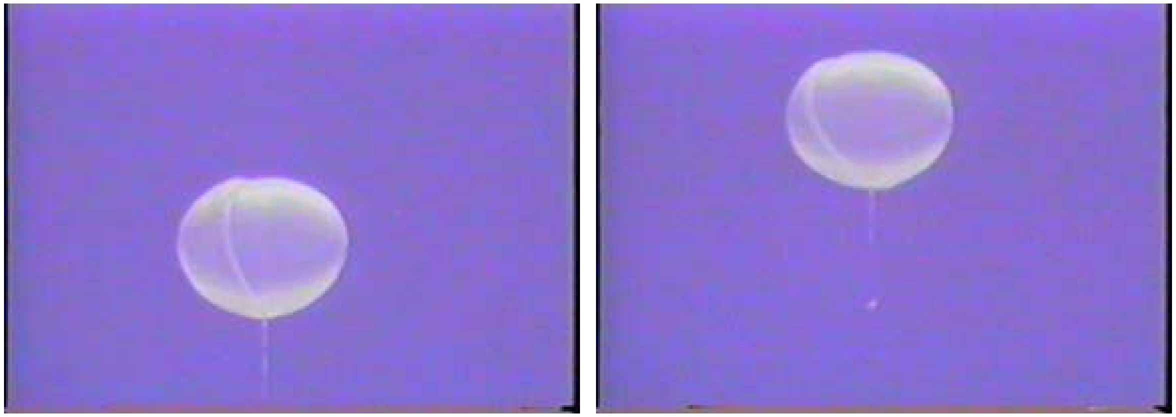
Flight 496 NT: Anomalous Shaped Balloon Flight



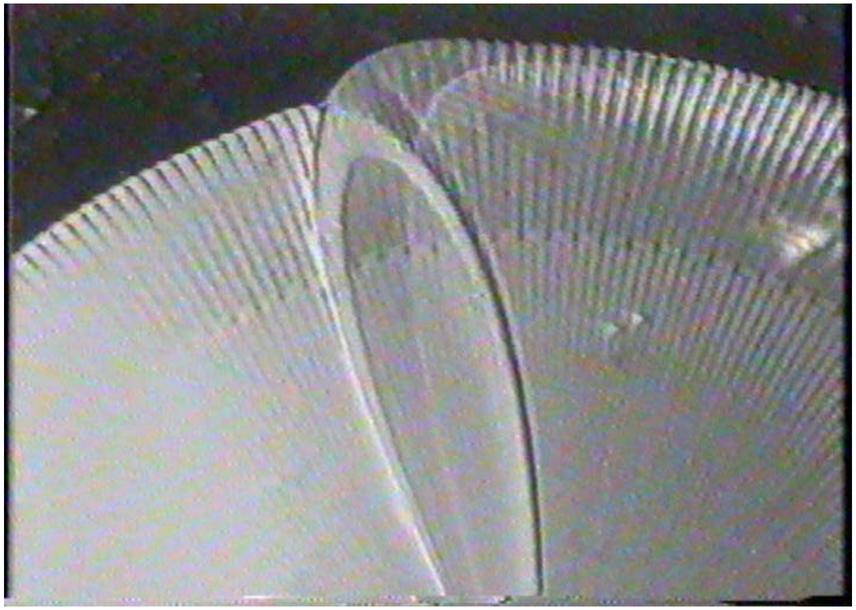
Flight 496 NT experienced an anomalous float shape, yet flew through one complete diurnal cycle.

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

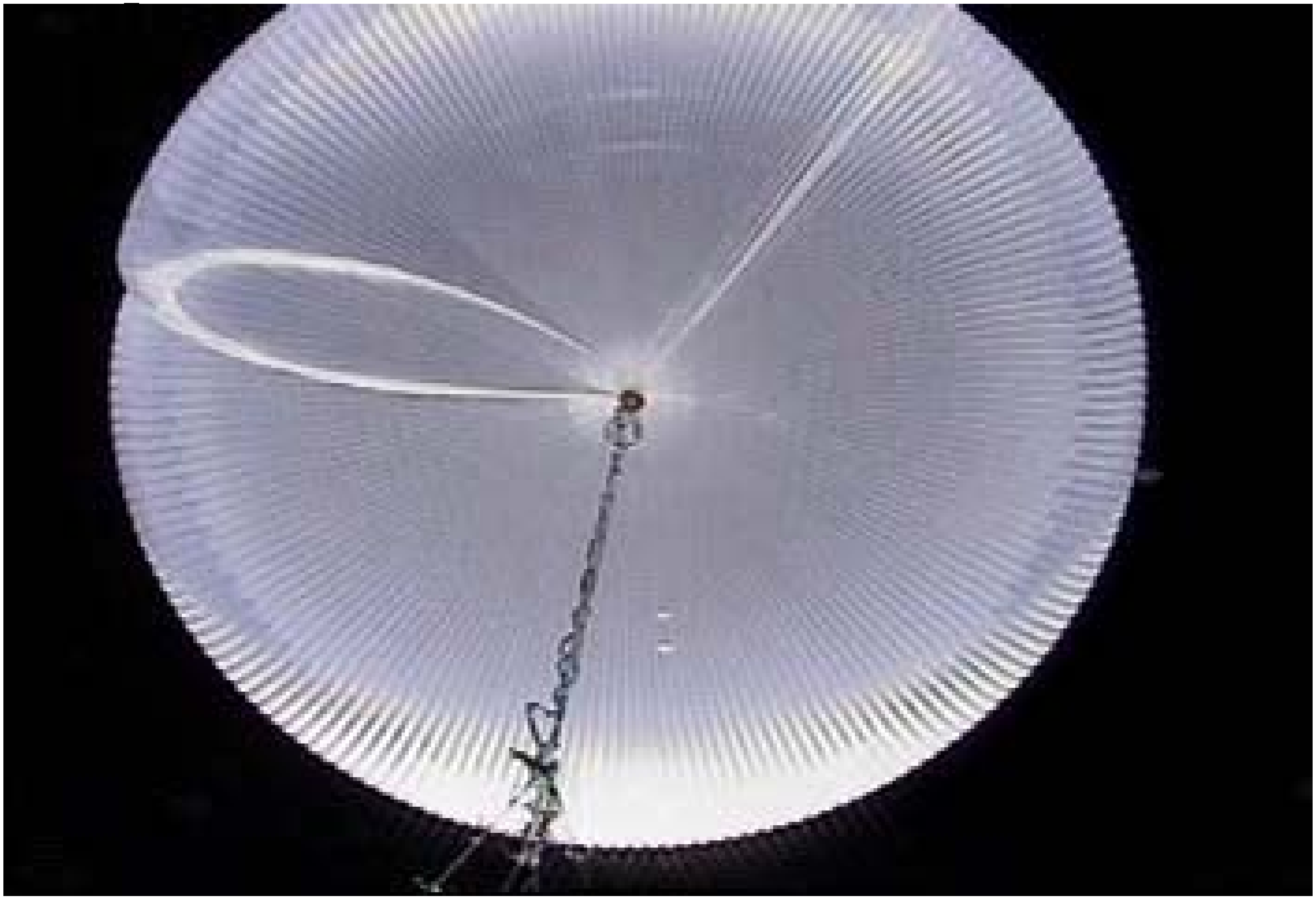
- Ft. Sumner Test Flight, February 4, 2005, was eased into float by venting helium during the ascent
- Unlike some of the previous pumpkin flights, the top region of the balloon fully deployed
- During the pressurization, the bottom region of the closing seal opened
- A video survey of the balloon was 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.


FTS 6MCF Uplooking FM.avi

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

10m model

Pumpkin Instabilities and S-Cleft

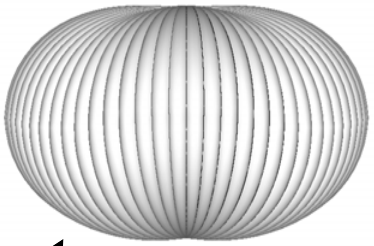
Pumpkin Shapes and Instabilities

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)

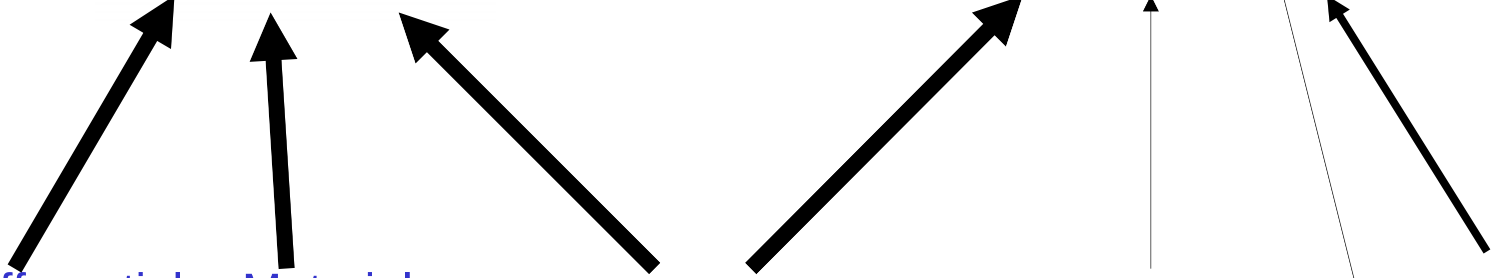
Manifests at low pressure

Pressure-Shape Instability



Single S-Cleft

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



Differential Pressure

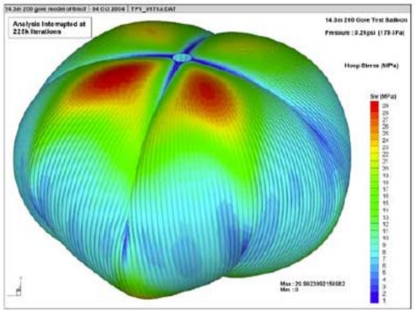
Material Properties

Gore Pattern

Launch-Induced Perturbations?

Friction?

Buoyancy



RELATIVE INFLUENCES

S-Cleft Quandary

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

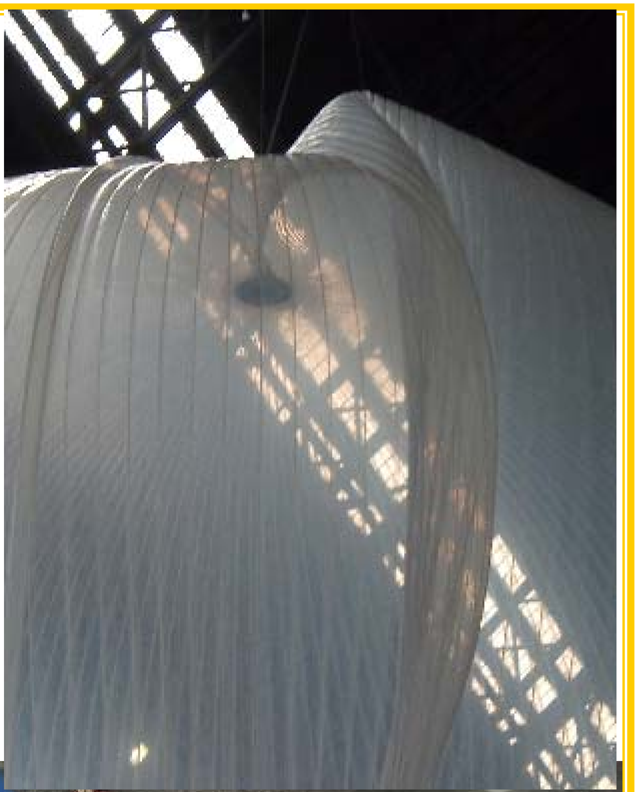
27m Scale model testing

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

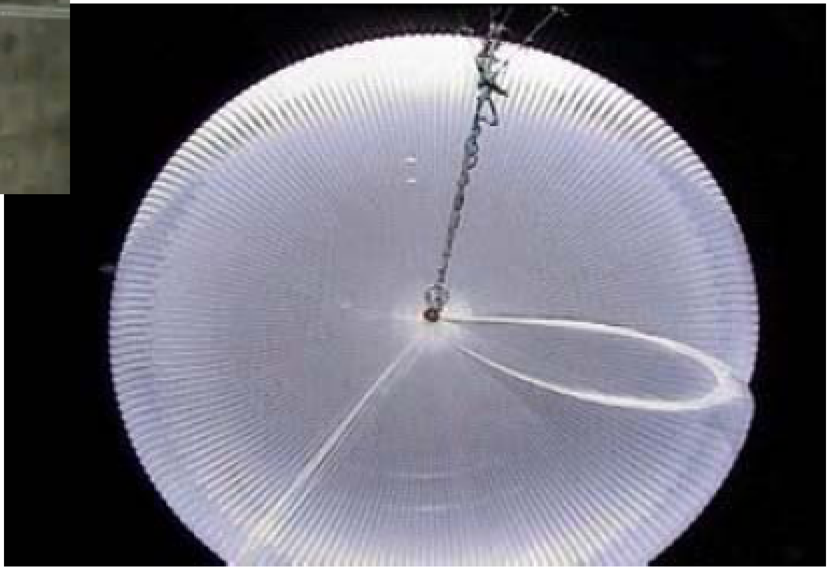
Used scaling laws to ratio forces similar

99 deg bulge angle

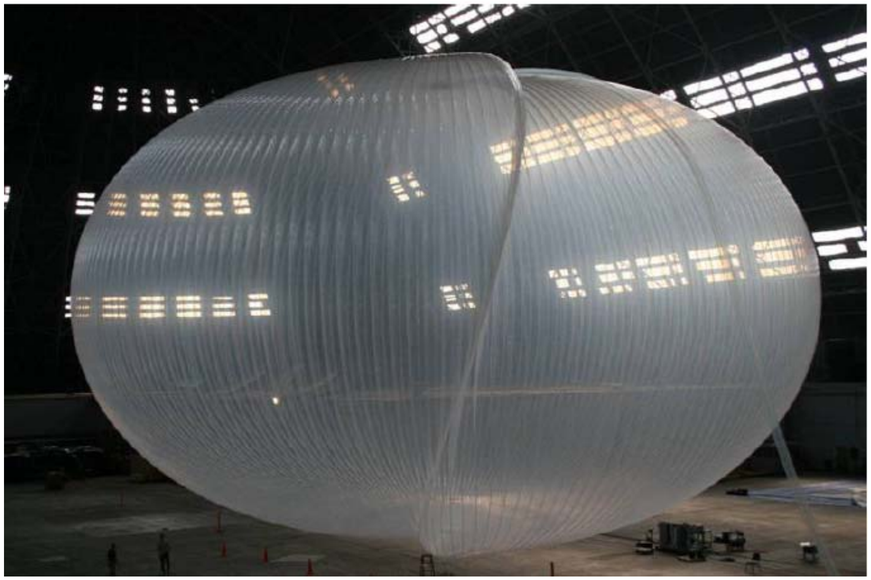
S-cleft side, top, bottom views

27m Test (Top View)

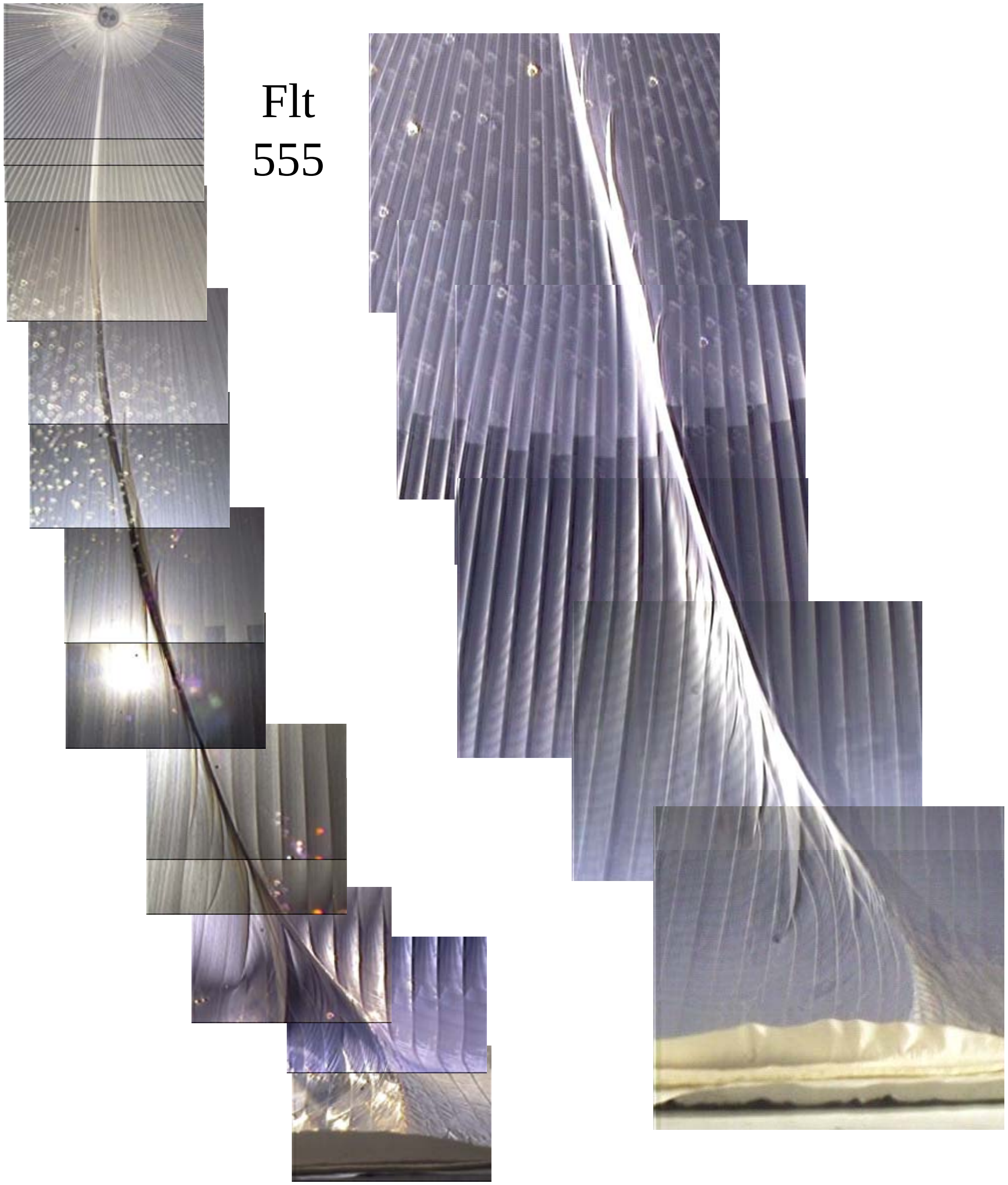
Sweden 555NT (Bottom View)



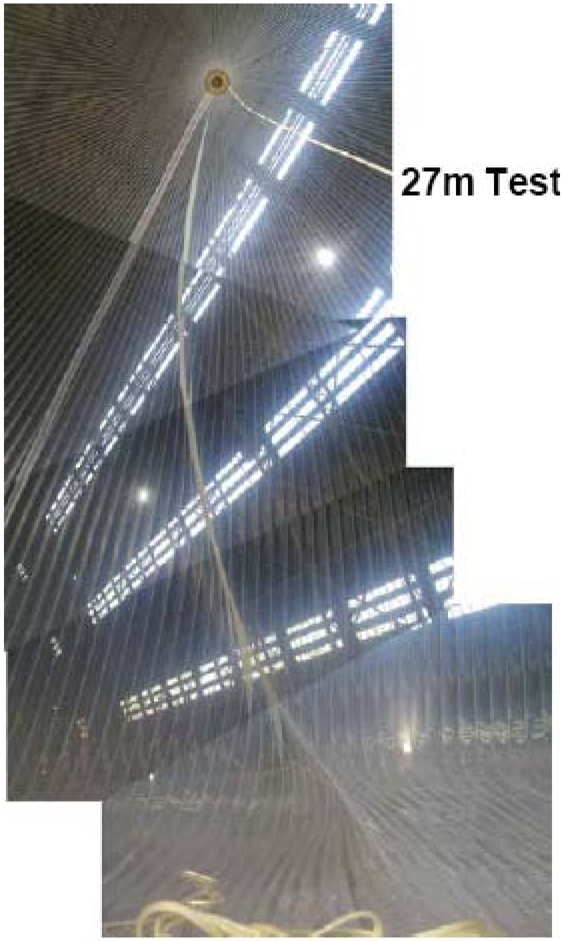
Side view, 27m



Internal Camera Shots of S-cleft



Flt 555



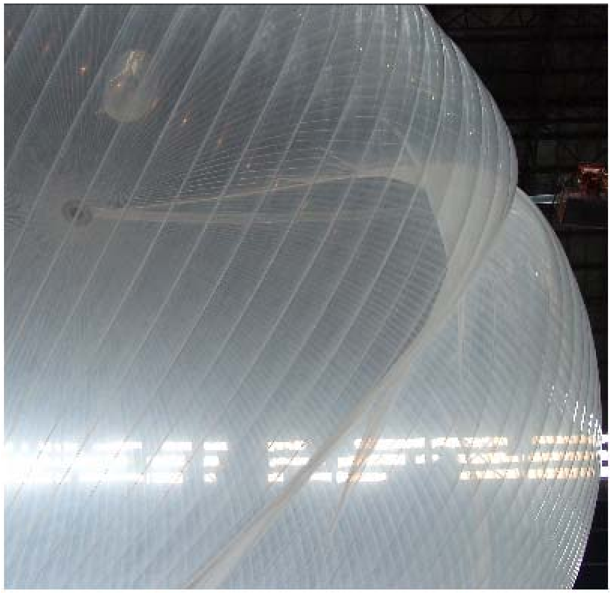
27m Test

Courtesy: Henry Cathey

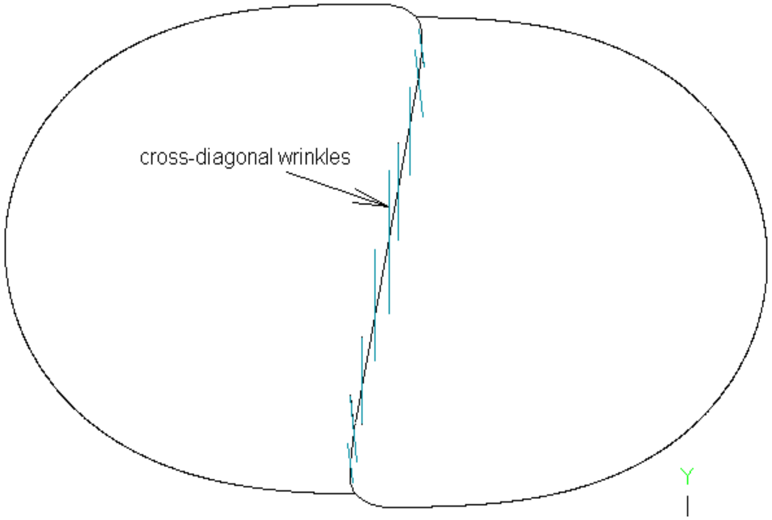
So, what’s an S-Cleft?

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

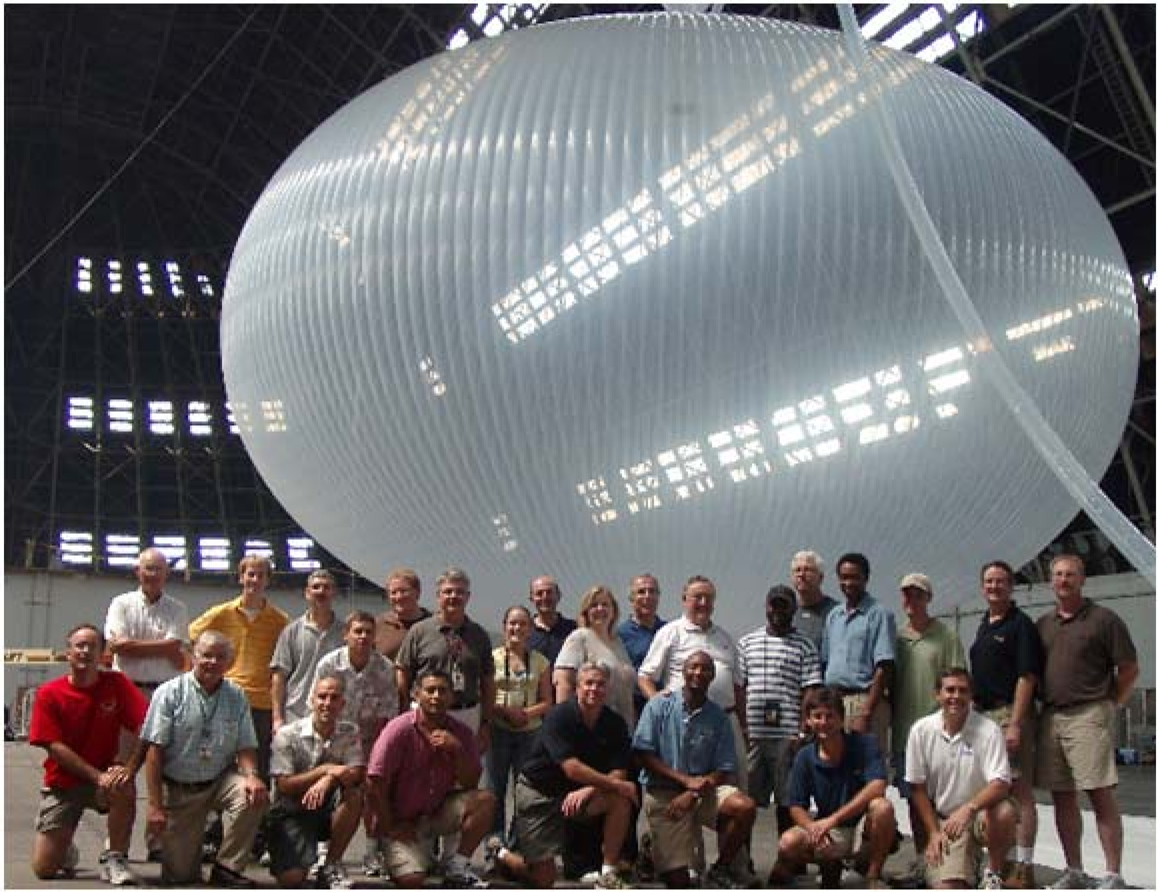


Cleft-free 27m model

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



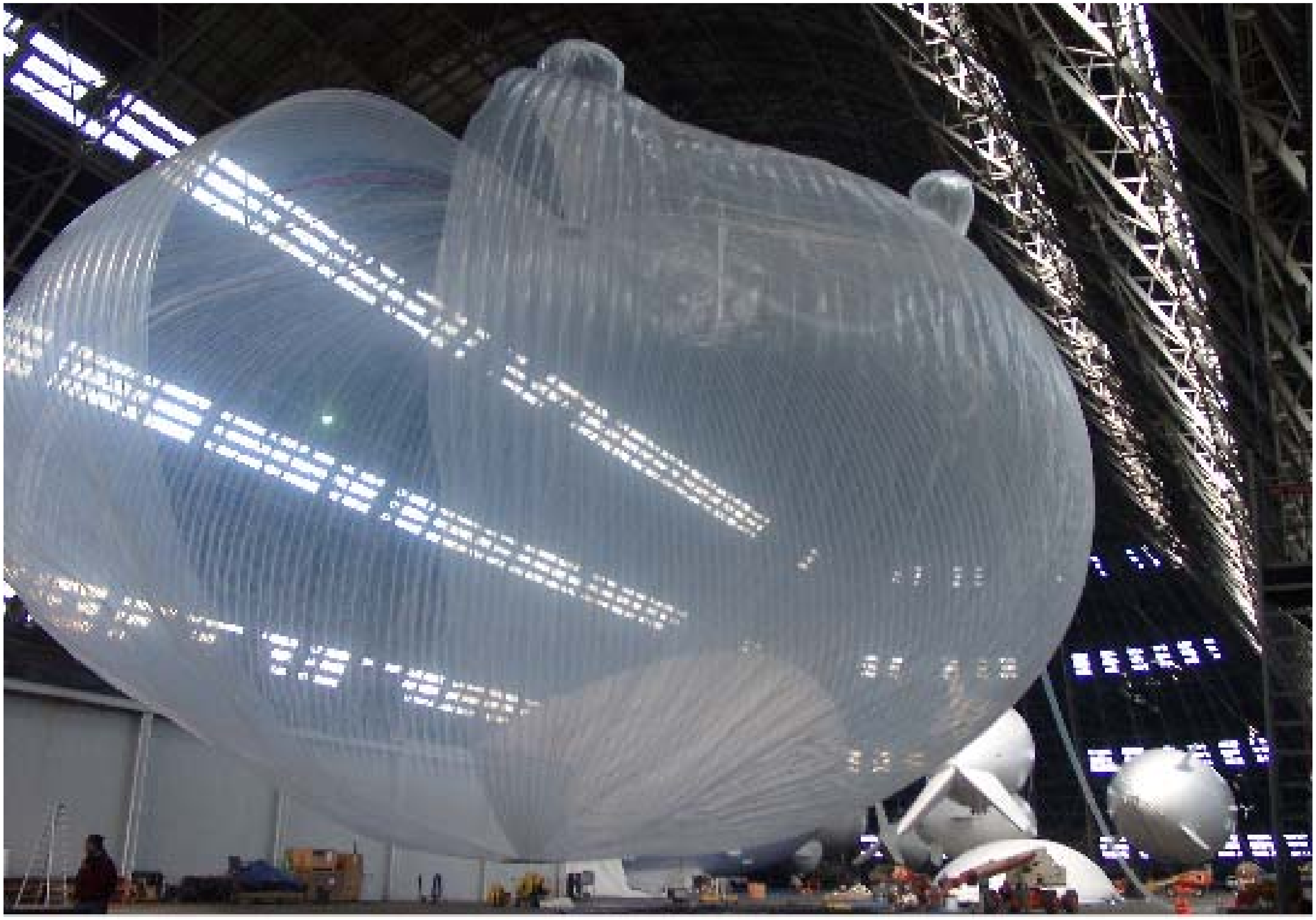
Morning at the T-COM hangar

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!

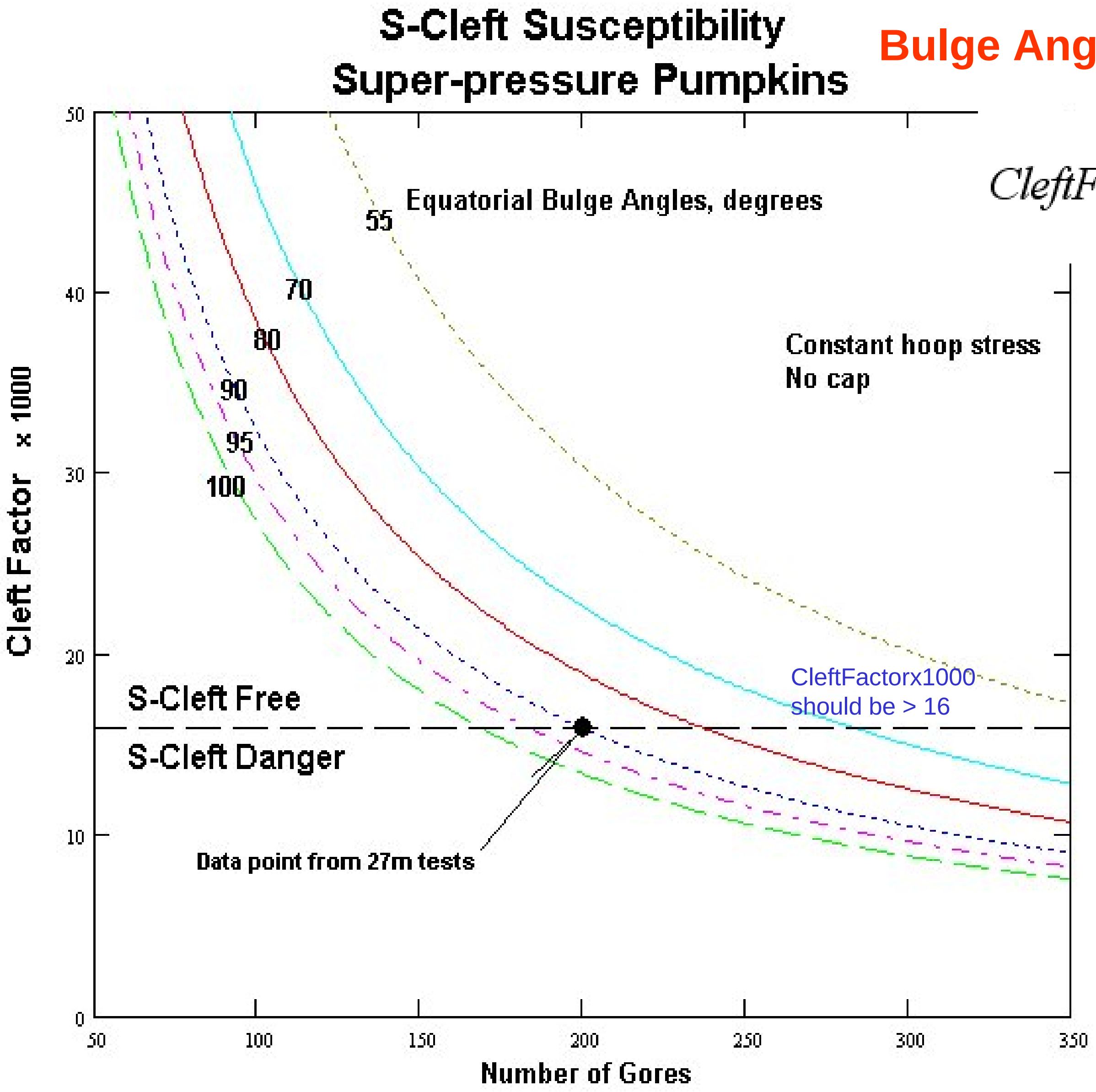
33 deg bulge angle

Final burst at 500Pa differential pressure with 66,200 lbs of tendon load at fittings



S-cleft Design Envelope

Bulge Angle AND Number of Gores



CleftFactorx1000 should be > 16

$$CleftFactor = \frac{\sin(\pi / N_{gore})}{\sin(\alpha_B / 2)} \cdot \cos(\beta)$$

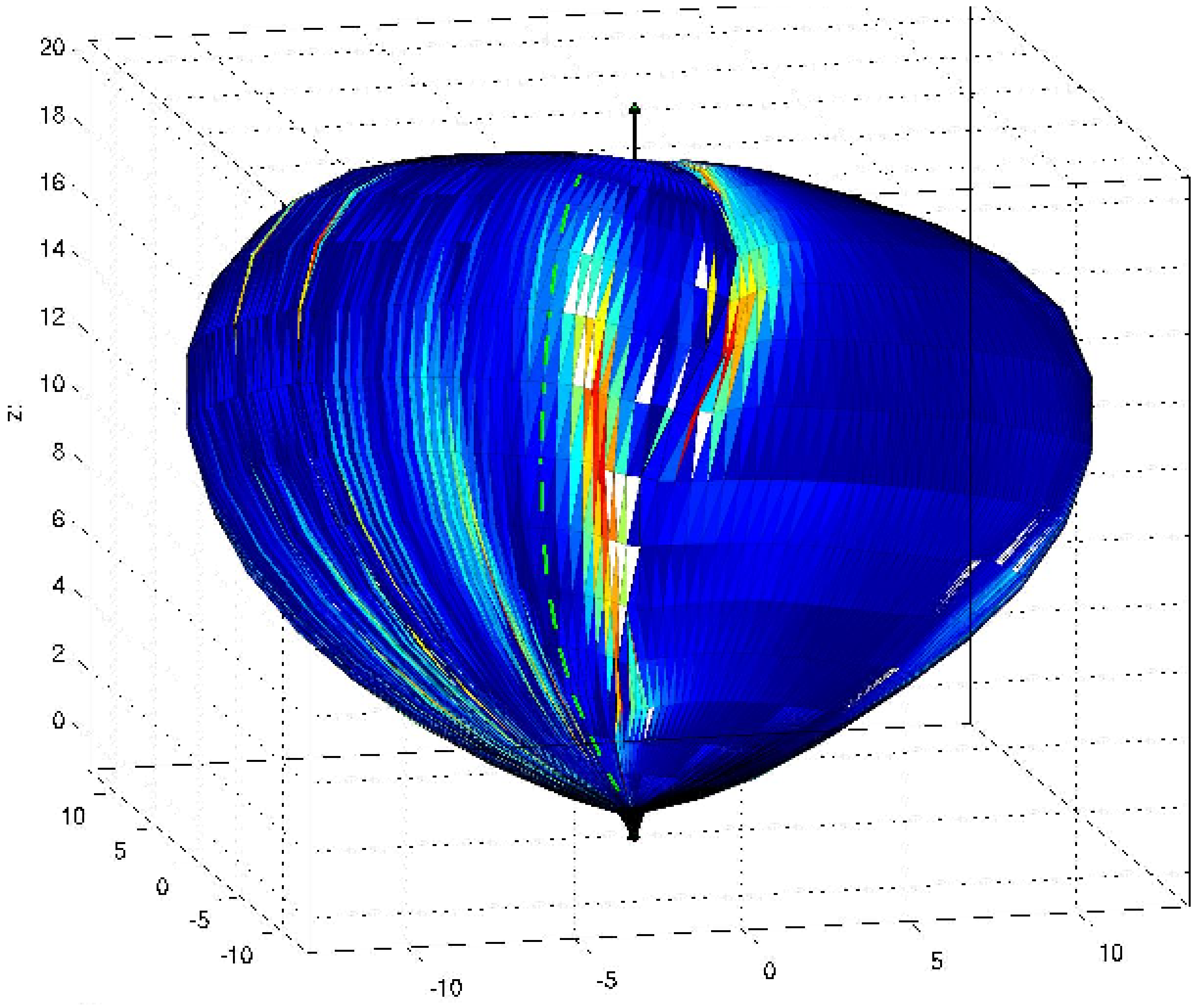
Recommendations

Number of Gores	Equatorial Bulge Angle, deg
100	130
150	107
200	90
250	77
290	68
300	67
350	59

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

Parameter Trade Space for ULDB

- Number of gores
- Max bulge angle
- Max gore width
- Hoop stress, stress ratio
- Film thickness, shell & cap
- Tendon denier
- Suspended mass
- Float altitude, minimum night altitude
- Date & location
- Film optical properties
- Film mechanical properties
- Freelift, ascent venting, ballast
- Super pressure
- Super temperature
- Environment, atmosphere
- Ascent speed
- Manufacturing capability

Concerns / Issues

Deployment

Film UV degradation

PBO degradation

PBO creep rupture

Thermal knife of LTT

Thermal gradient

Temperature measurements

Spool damage

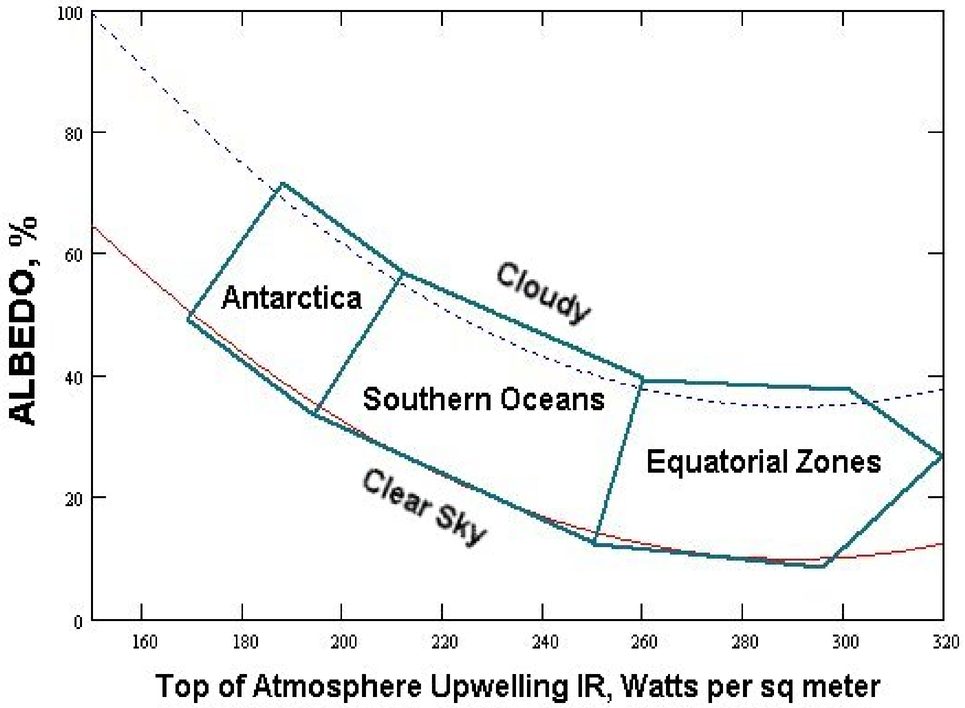
Reliability

Trajectory control

Diurnal performance

Find the sweet spot to make it all work!

Enveloping the Albedo and IR Environment



From ERBE data

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

(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 → ΔT

ΔT + Altitude → ΔP

ΔP + Balloon diameter + Ngores + Tendon stiffness → Meridional strain

Meridional strain + Meridional film modulus E → Meridional stress

ΔP + Balloon diameter + Ngores + Hoop stress → Bulge radius

Hoop stress + Meridional stress + Meridional strain → Hoop strain

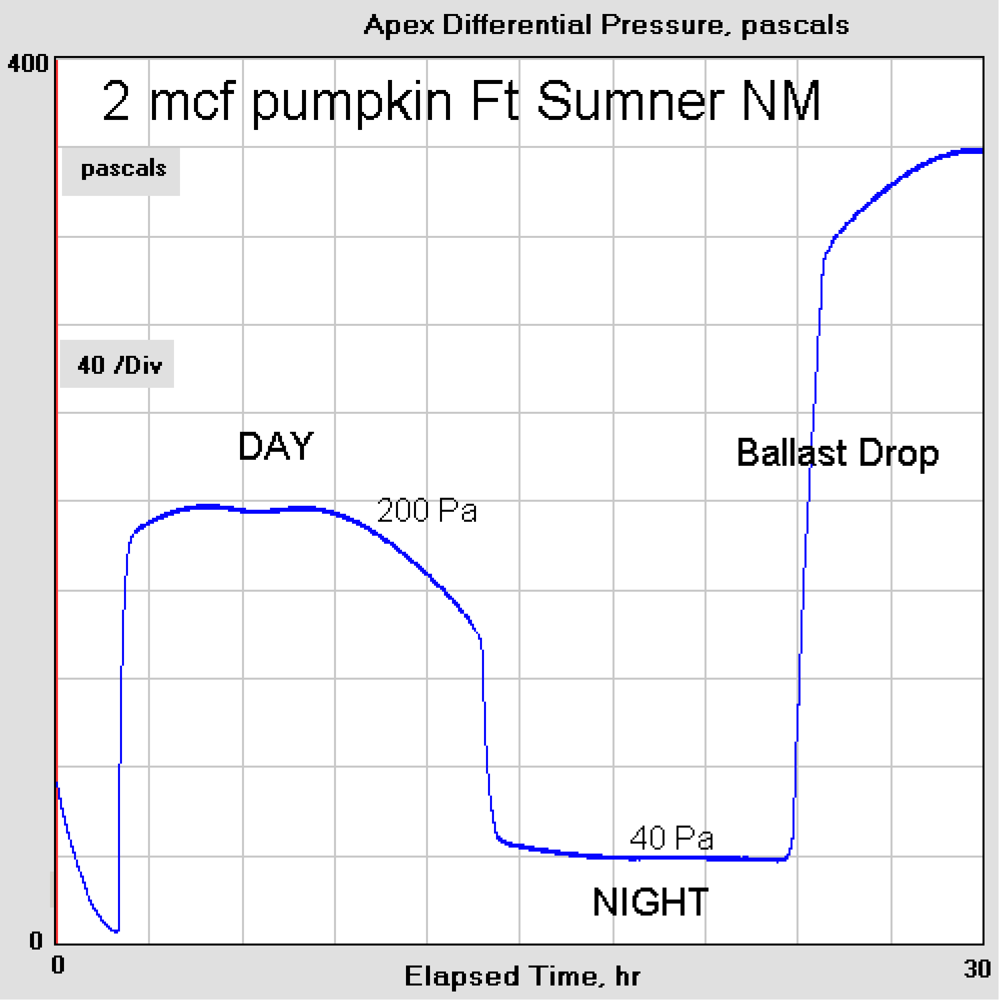
Hoop strain + Meridional strain + Bulge radius + Ngores + Diameter + Temperature strain effects → Gore pattern

Flight Simulations for diurnal effects

Finite Element Stress-Strain Analysis

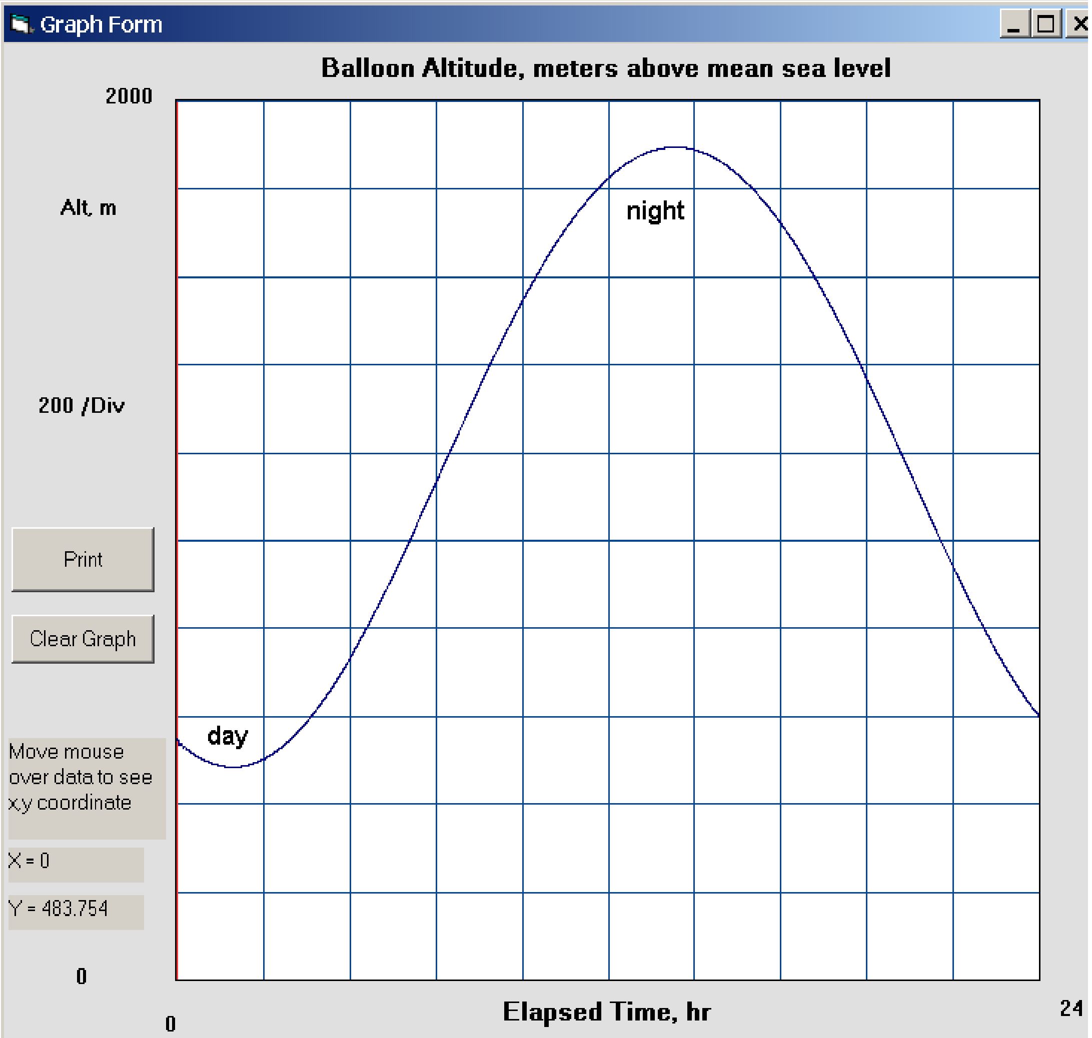
Flight Sims

Super-Pressure Diurnal Cycle with Ballast Drop



Predicted behavior for June 7 2008 flight of 2mcf pumpkin

Mars Balloon Simulation



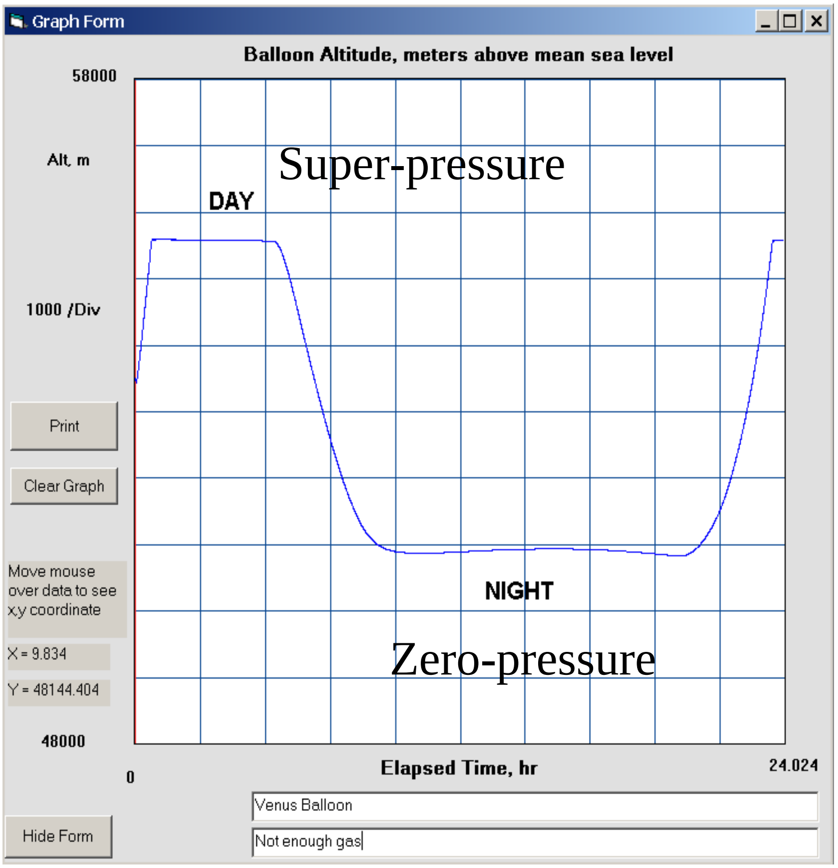
A super-pressure balloon on Mars will actually float upwards at night!

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

AND

a 30K diurnal swing

Venus Balloon Simulation



Super-pressure

DAY

NIGHT

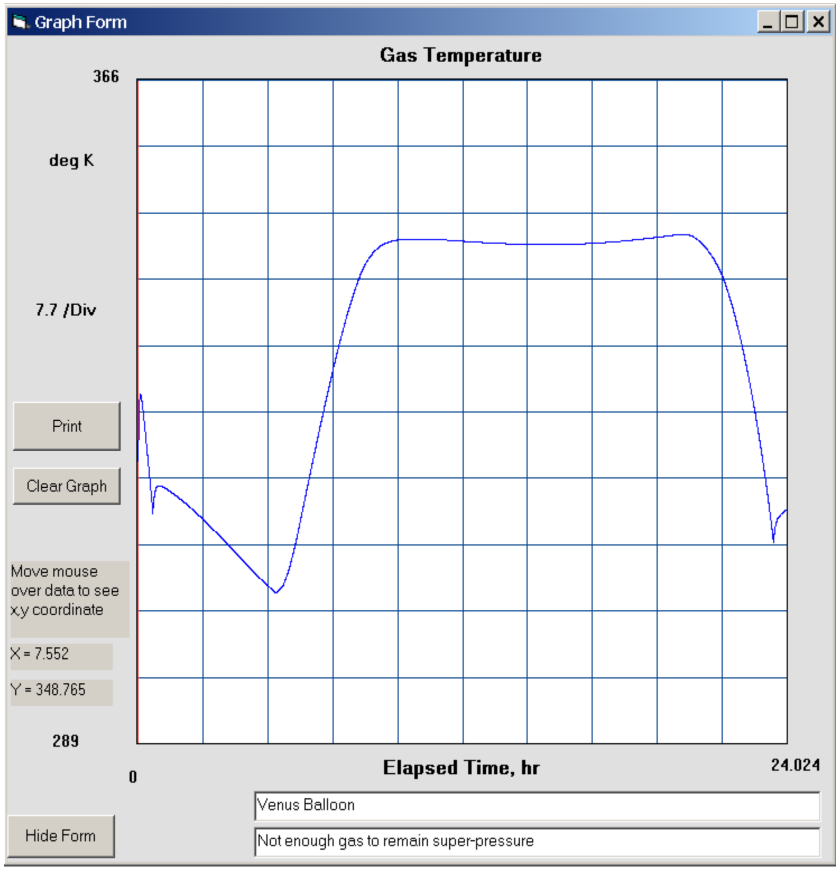
Zero-pressure

X = 9.834

Y = 48144.404

Venus Balloon

Not enough gas



X = 7.552

Y = 348.765

Venus Balloon

Not enough gas to remain super-pressure

Altitude

Temperature

Binary Altitude Behavior

ULDB Test Flight 555 – Post Cards from Space

Pumpkin Superpressure Development Schedule

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)