# Parachute Materials and Stress Analysis

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Parachute Seminar

3rd International Planetary Probe Workshop

# Definitions

- **Fiber -** slender, threadlike structure; "tiny microscopic beams"
- **Filament -** a man-made fiber having great length compared to natural fibers
- **Staple -** a measure of length and/or fineness of a fiber
- **Yarn -** a generic term for continuous strands of textile staple fibers or continuous filaments in a form suitable for knitting, weaving, or otherwise intertwining to form a textile structure.

# Definitions (continued)

- **Denier -** term used to describe the weight and size of a fiber or yarn (weight in grams of 9000 meters of material). Difficult to measure diameter of fibers.
- **Tex -** term found more commonly in Europe - grams per 1000 meters of yarn
- **Selvage -** specially woven edge that prevents the fabric from raveling (or unraveling)

# Definitions (continued)

- **Tenacity -** strength of the fiber or yarn (units are grams per denier, gpd). Higher tenacity yarns must be of smaller denier to maintain adequate flexibility for weaving.

**Denier = weight (in grams) of 9000m of yarn**

**= Volume X Specific Gravity (S.G.)**

**= 9000m X $10^2$ cm/m X A ($cm^2$) X S.G.**

**Tenacity = g/d = g/[9*$10^5$ cm X A ($cm^2$) X S.G.]**

**Solving for Force vs. Area (stress)**

**Stress @ Break = g/A (g/$cm^2$) = 9*$10^5$ cm X Tenacity X S.G.**

**= F/A (psi) = 12,800 X specific gravity X tenacity (gpd)**

***Stress @ Break (psi) = 12,800 X specific gravity X tenacity (gpd)***

# Definitions (continued)

- **Warp -** refers to the direction in a fabric, tape or webbing that run in the length-wise direction when coming off the loom.
- **Fill -** refers to the direction perpendicular to the "Warp" direction. (Also referred to as the "weft" or "woof").
- **Picks per inch -** a measure of the yarn density in given direction (Warp or Fill) - number of threads per inch.
- **Fiber translation efficiency -** the ratio of the strength of the woven material to the total strength of the warp yarns.

# Types of Materials

- **Natural**
  - Wool
  - *Silk*
  - *Cotton*
  - Hemp
  - Flax
  - Others
- **Man-made**
  - Mineral Fibers
    - + *Glass*
    - + *Metal*
  - Organic Fibers
    - + *Rayon*
    - + *Nylon*
    - + Dacron
    - + *Teflon*
    - + *Nomex*
    - + *Kevlar*
    - + *Spectra*
    - + *Vectran*
    - + *Zylon*

# Nylon

- Developed shortly before WWII
- A primary parachute material (Nylon 6-6)
- Polyamide resin with high tenacity due to long highly oriented molecules and high intermolecular forces
- Tenacity is 2.5 to 9.5 grams/denier (6.6 for Nylon 6-6)

  Stress @ Break (psi) = 12,800 X specific gravity X tenacity (gpd)
  = 12,800 X 1.14 X 6.6 = 96 ksi

- Minimum elongation specified as 20%, actual elongation 30-40% at break
- Sensitive to ultraviolet light
- Does not burn readily, but melts at 480F

# Dacron

- **Polyester based man-made fiber**
- **Similar to nylon, but requires more treatment for stability**
- **Slightly lower elongation than nylon**
- **Better temperature resistance than nylon**
- **Slightly less weight and volume for comparable strength nylon, once making it attractive in sport parachutes**

# Polytetraflouroethylene, PTFE

- Telflon (DuPont), Fluor (ICI)
- Fluorocarbon based man-made fiber
- Very low friction coefficient
- Very expensive
- Used for deployment bag liners
- Used as buffer material where cotton cannot be used
- Expanded PTFE (Goretex) available as a slit film fiber with a tenacity of 3 grams per denier

# Nomex

- Polyamide man-made fiber
- Moderate tenacity of 5.4 grams per denier -> 90 ksi (s.g. = 1.38)
- Elongation at break about 16%
- Retains 50% of its strength at 500 F
- Used for flight suits and high-temperature buffers
- Has been used as cloth in parachutes in high temperature environments (e.g. F111 CEM stabilization parachute)

# Kevlar

- High strength, high modulus, para-aramid fiber developed for use in radial tires
- Version used for parachute materials identified as "Intermediate Modulus Para-Aramid"
- Each fiber is 0.00047 inches in diameter and is approximately 1.5 denier
- Tenacity is quoted to be 20-22 grams per denier -> 370 ksi! (s.g.=1.44) (Mild Steel ~100 ksi)
- Elongation at break is 3-5%
- Does not melt or burn, but sensitive to UV
- Abrasion resistant, but is very abrasive itself
- Cannot be hot cut or have the bitter ends seared

# Spectra

- **High-strength polyethylene fiber**
- **Tenacity 30-35 grams per denier -> 380-440 ksi !!!**
- **Elongation at break is 2.7%**
- **Subject to loss of strength at temperature (10 g/d @ 212 F)**
- **Low coefficient of friction**
- **Sometimes difficult to get good seam efficiencies**
- **Used extensively in sport parachutes for suspension lines**
- **Becoming common as a deployment bag material for high density packs**
- **For more information see** ***http://www.performancefibers.com/products/spectra.html***

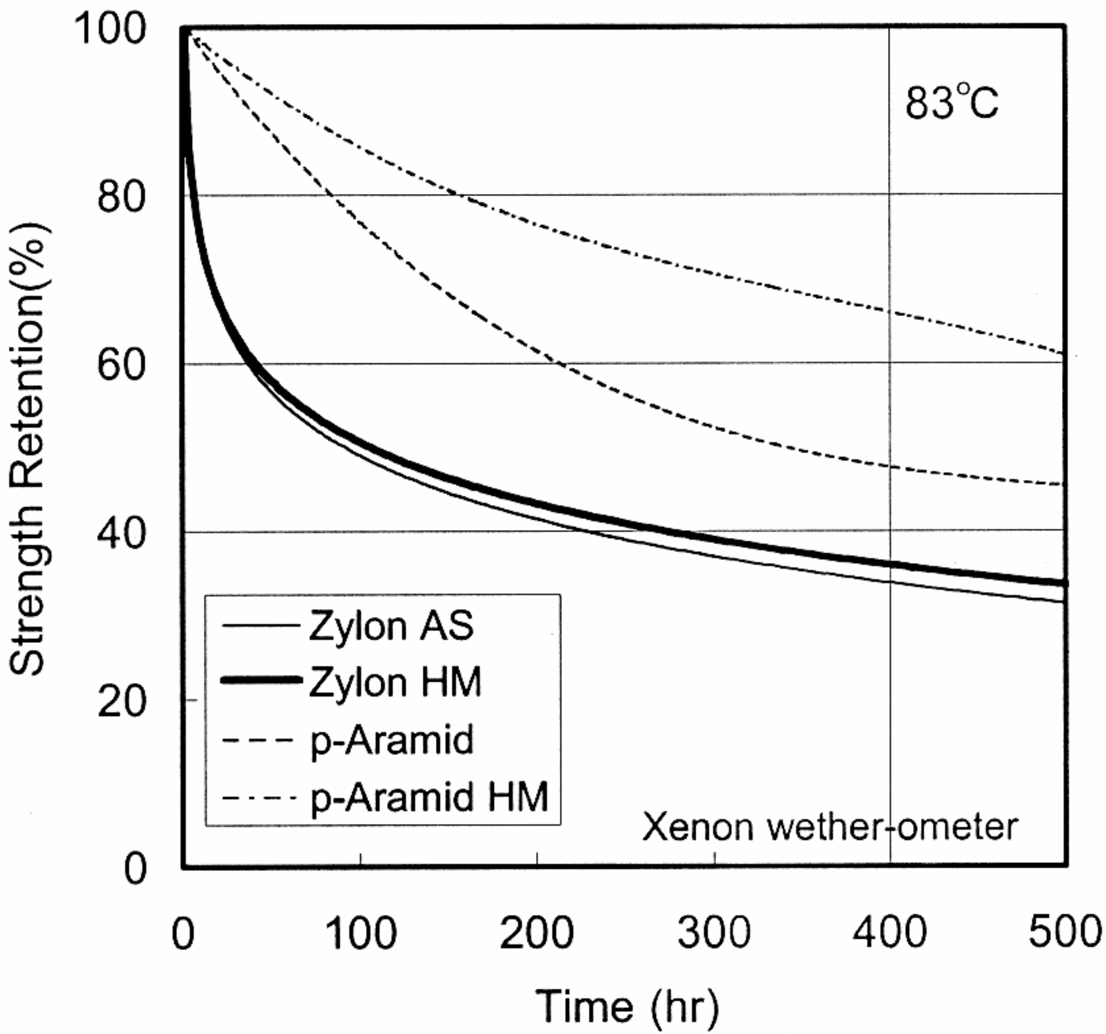
# Vectran-LCP

- LCP - Liquid Crystal Polymer
- Tenacity- 23 g/d => tensile strength = 300 ksi
- Elongation - 2-3%
- Friction properties similar to Spectra
- Immune to acids and UV
- Specific Gravity slightly less than 1.0
- Experiences zero creep under constant load
- Just entering the field of parachutes

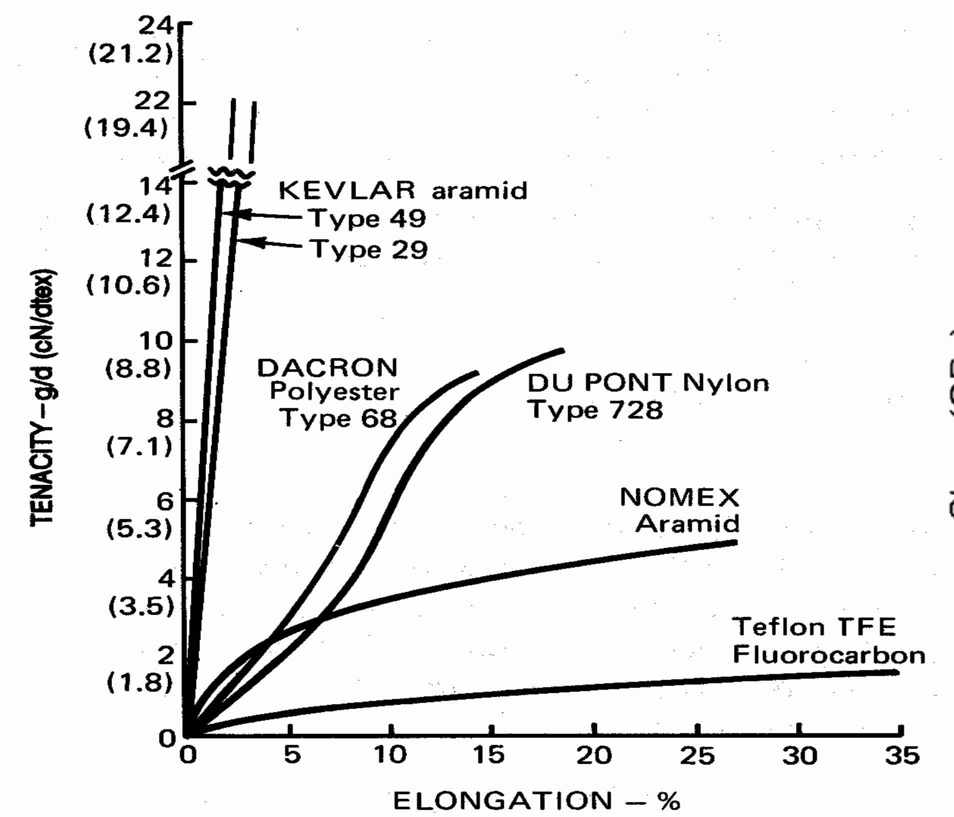
# Zylon

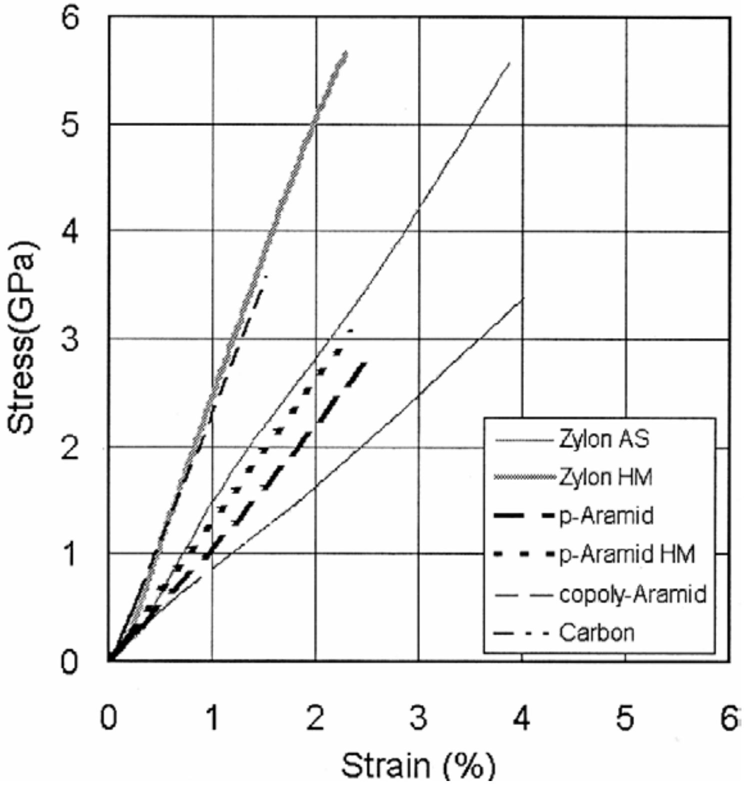
- **New fiber from TOYOBA (Japanese firm)**
- **"Rigid-rod chain molecules of poly(p-phenylene-2,6-benzobisoxazole) (PBO)**
- **Tenacity - 43 gpd => 840 Ksi !!!**
- **Elongation at break - 3.5/2.5**
- **"Decomposition Temperature in Air" - 650 $^{o}$C**
- **Much lower friction coefficient than Kevlar**
- ***Significant strength reductions with prolonged exposure to light (65% reduction in 6 months)***
- **For more info see *http://www.toyobo.co.jp/e/seihin/kc/pbo/main.html***

# Effects of Light on Zylon

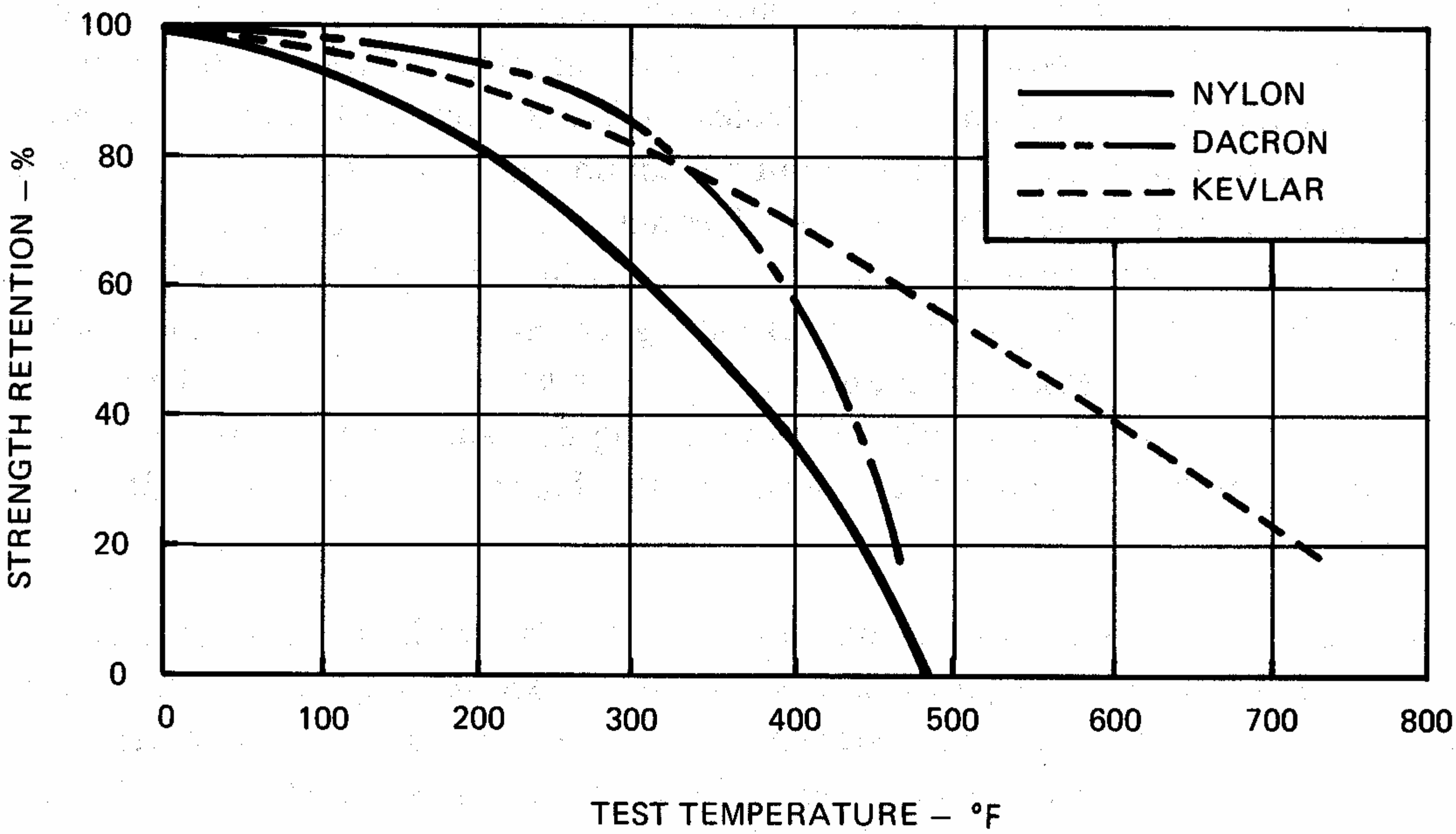


# Comparison of Some Materials



# Temperature Effects



# Specifications

- **Military Specifications**
  - Have been deactivated but are still commonly used to specify materials in purchases
- **Commercial Specifications**
  - Supplier
  - National organizations (e.g. SAE, PIA)
- **Customer Specifications**
- **Detailed vs. Performance Specifications**
  - Suppliers prefer performance specs
  - Must make sure all necessary properties are specified in specifications

# Specifications (continued)

- **Performance**
  - Strength
  - Weight
  - Elongation
  - Permeability
  - UV resistance
  - Allowable defects
  - Color, etc.

- **Detailed**
  - Threads per inch
  - Weave pattern
  - Yarn twist
  - Width, etc.

**See Knacke, Sections 6.6.3 and 6.6.5.3 for an extensive (but not exhaustive) list of material specifications**

# Products of Weaving

- **Broad-goods**
- **Narrow-goods**
- **Cord**

# Broad-goods

- **Produced on looms**
  - Shuttle
  - Rapier
  - Water-and-air jet
- **Woven in 36-, 48-, 60-, and 72-inch widths and different weave patterns**
  - Plain
  - Twill
  - Taffeta
  - Satin
  - Ripstop
  - Selvage Edge

# Finishing

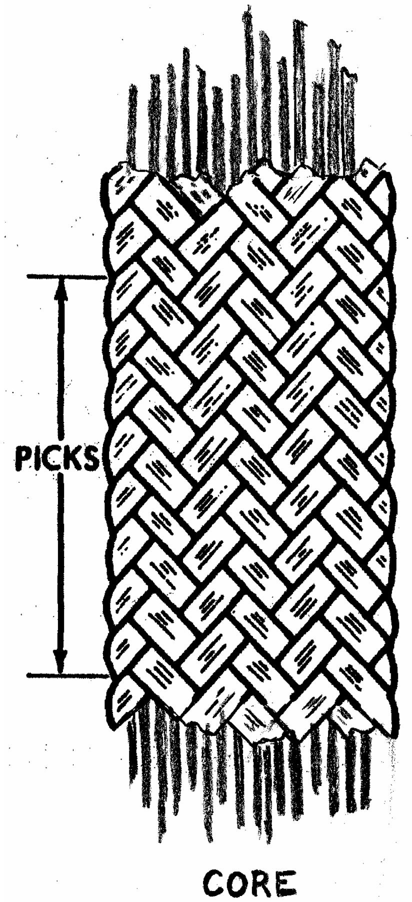
- **Greige goods**
- **Finishing processes(Converters)**
  - *Washing/Bleaching*
  - *Dyeing*
  - *Calendering*
  - *Coating*

# Narrow Goods

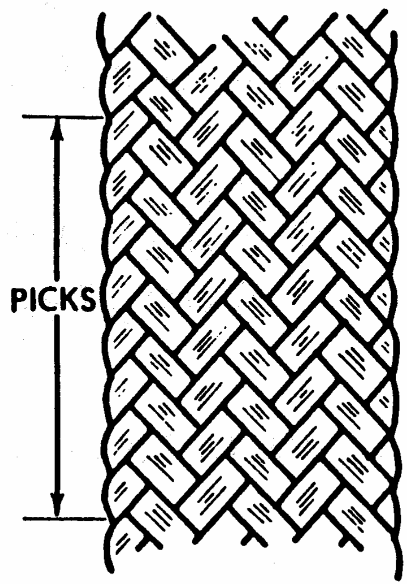
- **Usually less than 12 inches wide**
- **Weavers very skilled in developing new weaves**
  - Compromise between fiber translational efficiency and joint efficiency
- **Used in parachute systems for**
  - Suspension lines
  - Radials
  - Reinforcements
  - Risers
  - Bridles, etc.

# Braided Cord

- **With Core**




- **Coreless**



# Thread

- **Obviously used for sewing joints**
- **Twist can confound use in sewing machines**
- **Used to tie or tack textile components together for various reasons**
- **Many times waxed when used for tacking**
- **Generally use the same type thread material as being sewn (e.g. Kevlar in Kevlar, Nylon in Nylon)**
- **Nylon thread can melt in sewing machines if precautions are not taken**

# Textile Drawings

- **Different than more common solid modeling drawings**
  - **Thickness depicted only by a single line for fabric, tapes, or webbing. (Cord can be shown as circular or elliptical in cross-section)**
  - **No cross hatching of textile components in "cutaway" views**
  - **Hidden edges not depicted**
  - **Dashed lines used to show stitching**
- **Defined in ANSI/AIAA-S-017-1991**

# Outline

- Stress Analysis Methods
- Stress Analysis Code Examples
- Simplified Stress Analysis Examples

# Parachute Stress Analysis Tools

- Simplified methods
- CANO code
- CALA code
- Commercial finite element codes

# Simplified Methods

- Load carrying structure – suspension lines, radials or other reinforcements
  - **Estimated distribution of total load in parallel elements**
  - **Estimates based on geometry, shape from photographs, material stiffness**
- Pressurized structure – canopy
  - **Membrane theory – load/unit length = (K) (pressure) (radius of curvature)**
    - **K = 1.0 for cylinder**
    - **K = 0.5 for hemisphere**
  - **Radius of curvature from photograph or characteristic length**

# CANO Code

- Developed by Northrop Ventura in 1960s
- Initial solutions used desk calculators
- Used for stress analysis of Apollo parachutes
- Many modifications now exist
- Good users manual written by University of Minnesota
- Version exists that includes verticals in ribbon parachutes
- Non-vertical solutions take seconds on modern PCs

# CANO Code

- Early “finite element” code
- Original convergence algorithm not sophisticated
  - **May require patience**
- Modified algorithm developed by University of Minnesota
- Solutions starts at skirt and converges at vent
- Models parachute canopy gore
- Inputs
  - **Element geometry, parachute load, normalized pressure distribution, load/strain tables for materials**

# CALA Code

- Developed at Sandia in the 1980s
- More modern numerical formulation than CANO
- Solution starts at vent and converges at skirt
- Models parachute canopy gore
- More general boundary conditions
  - **Pull-down vent**
  - **Attached pilot chute**
- More complicated input than CANO
- Input
  - **Element geometry, dynamic pressure, pressure coefficient distribution load/strain curves for materials**

# Commercial Finite Element Codes

- Several commercial PC-based finite element software packages exist
- Specialized input/output formats for parachute stress analysis needed to make them user friendly for parachute engineers
- Potential for analysis of more general parachute canopy shapes and types of construction than CANO and CALA
- Potential for dynamic inflation modeling

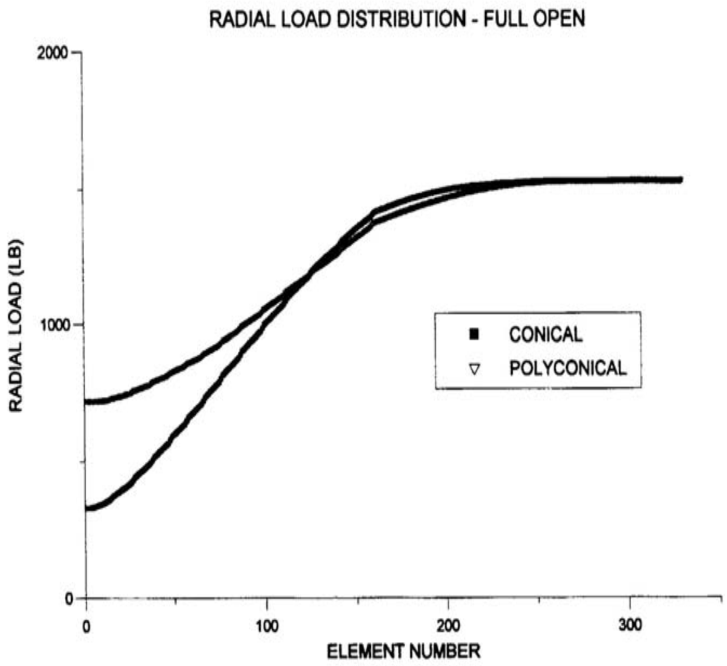
# Stress Analysis Examples

- SRB lightweight main parachute
- Space Shuttle Orbiter main parachute
- Space Shuttle Orbiter pilot parachute
- X-38 pilot parachute
- First stage floor panels for X-38 parafoil
- Fabric foam container

# SRB Lightweight Main Parachute

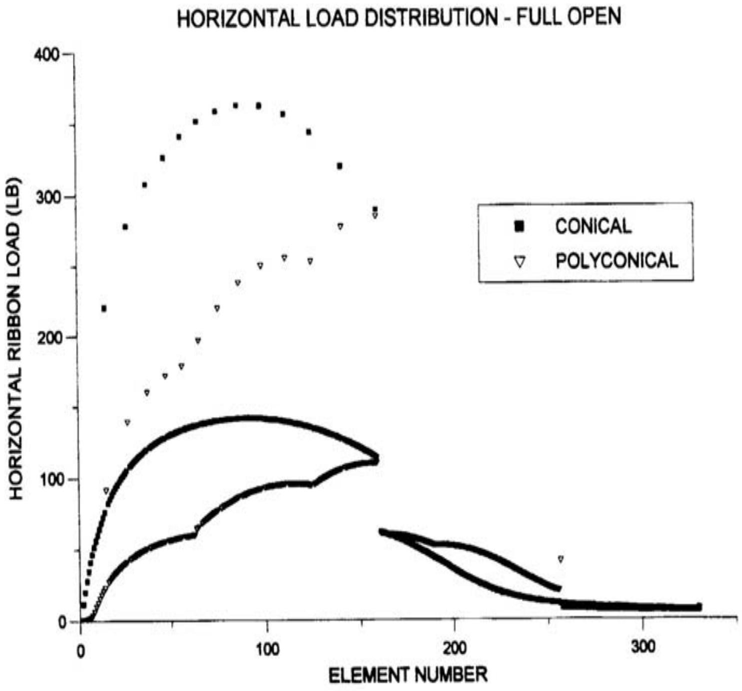
- **New main parachute designed to reduce weight and increase Shuttle payload**
  - Existing parachute weight = 2150 lb
  - New parachute weight =850 lb
- **124-ft Kevlar/Nylon ribbon parachute with solid cloth material near the skirt**
- **Design load increased from 175,000 lb to 210,000 lb**
- **Canopy design was polyconical (5 section) approximation to a quarter spherical shape**
  - Primarily to reduce canopy loads and reduce material weight

# SRB Lightweight Main Parachute



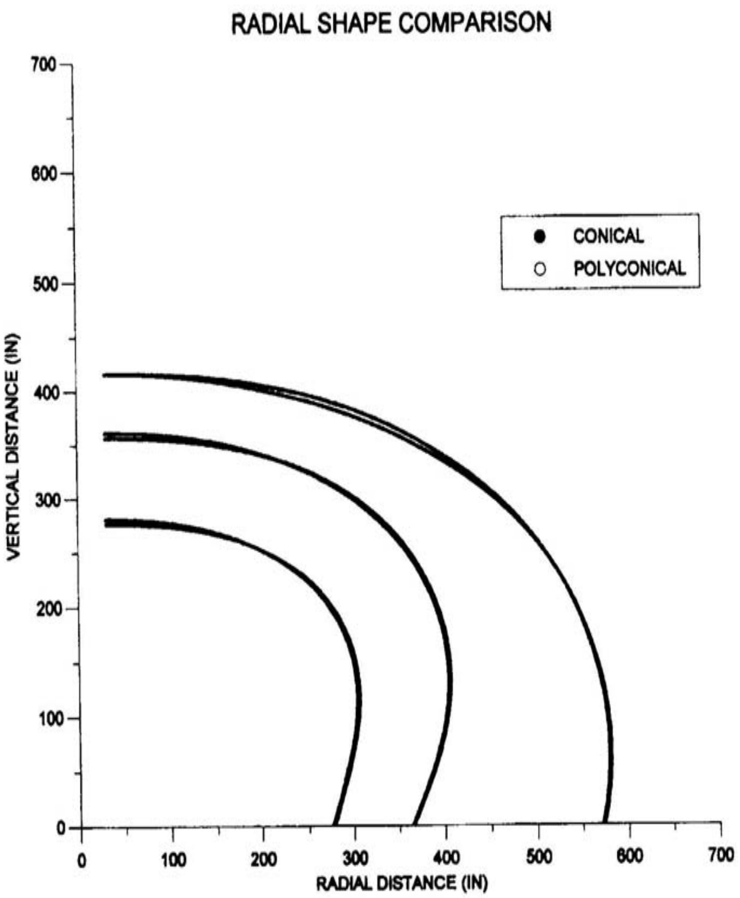

- CANO analysis used to support decision to use polyconical design
- Comparison with traditional 20 degree conical design
- Loads in primary load carrying structure were shown to be similar for both designs

# SRB Lightweight Main Parachute



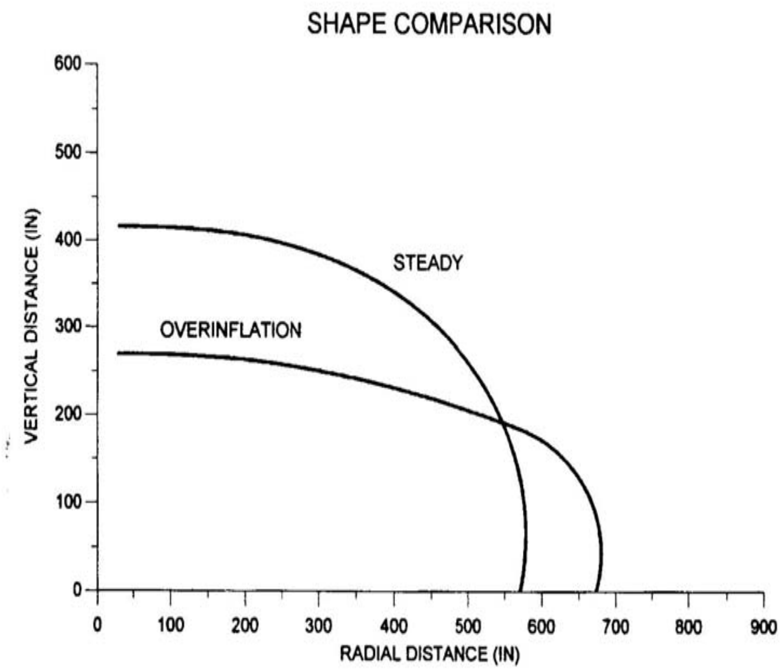

- Horizontal ribbon loads were shown to be significantly lower for the polyconical design
  - **Higher points are for ripstops**
  - **Lower curves are for ribbons and fabric**
- Lower loads allowed use of lighter materials

# SRB Lightweight Main Parachute



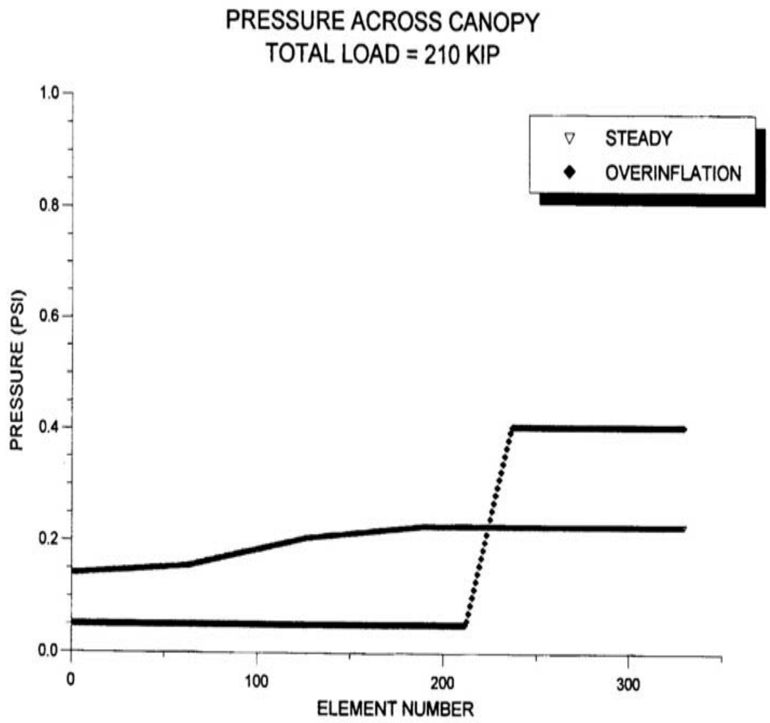

- CANO results were also used to show that inflated shapes would not be much different than for conical canopy
  - **Conical canopy performance experience would still be valid**
  - **Reefing data for conical canopies could be used**

# SRB Lightweight Main Parachute



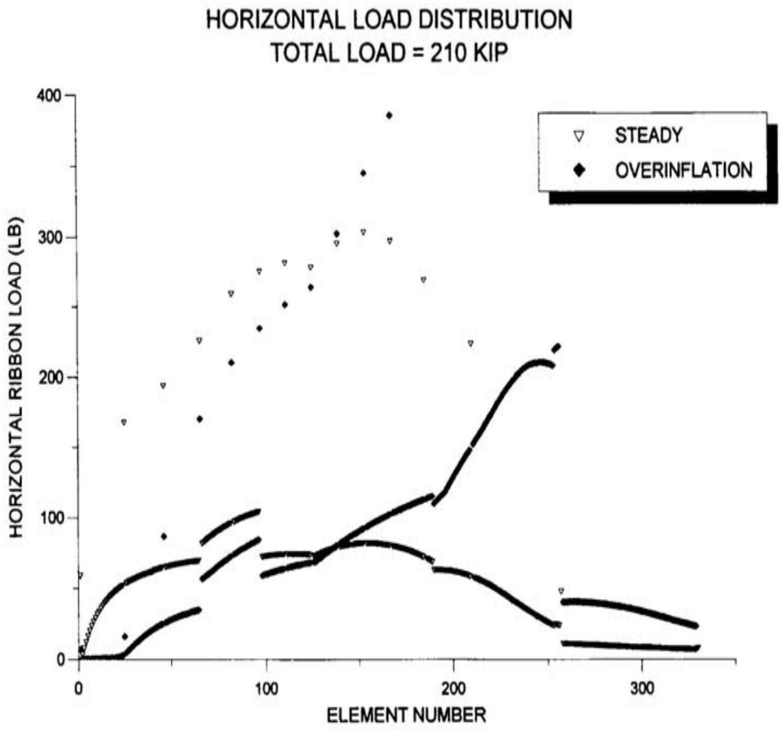

- 1st test showed some fabric failures near the skirt during canopy overinflation
- CANO results were used to study the fabric loads in an overinflated canopy

# SRB Lightweight Main Parachute



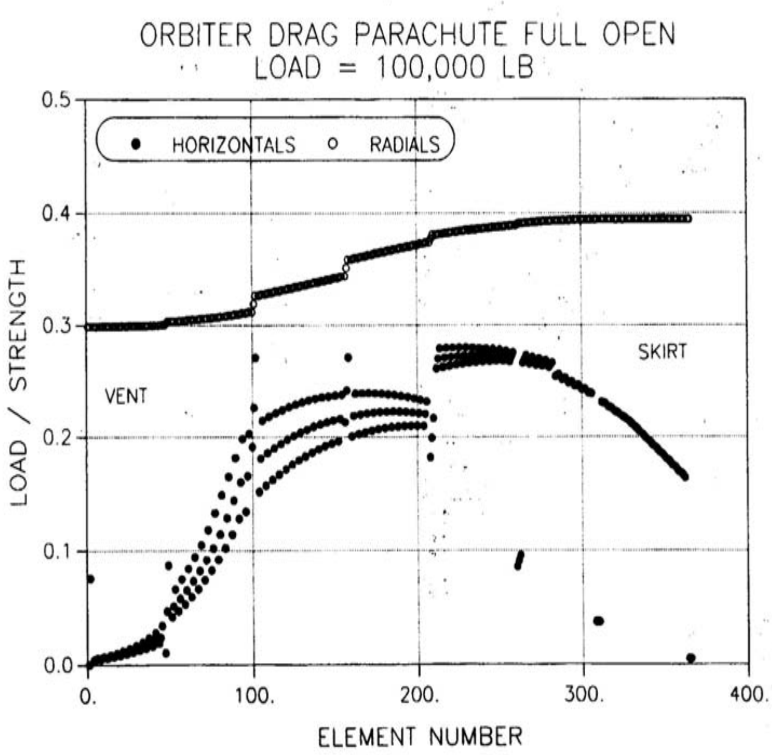

- A pressure distribution was derived that produced the same CANO shape as that observed during the 1st test

# SRB Lightweight Main Parachute



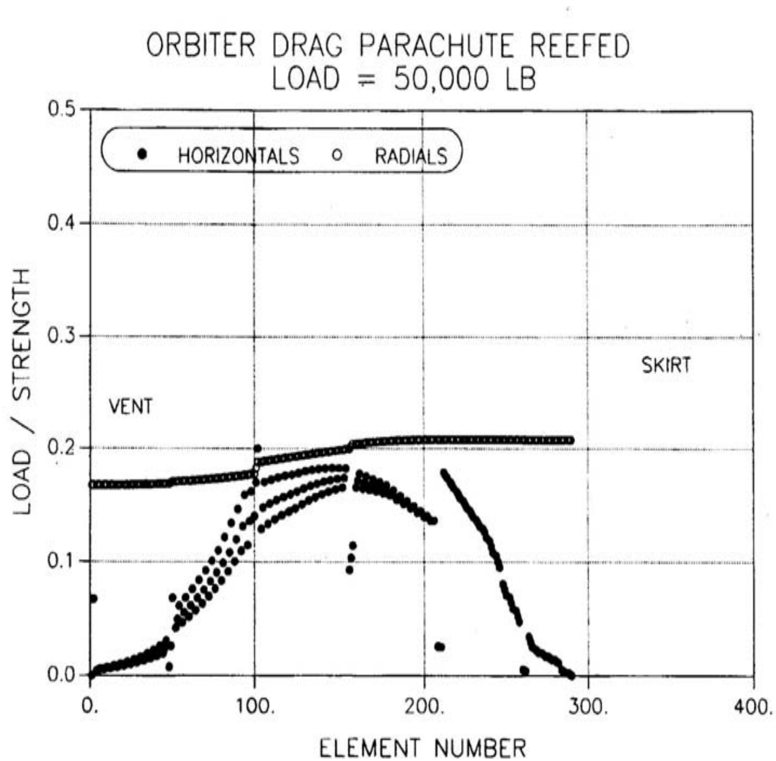

- CANO loads for the overinflated shape were not sufficient to cause failure of undamaged fabric
- The very lightweight fabric near the canopy skirt was being damaged during deployment at the high SRB bag strip velocities

# Orbiter Drag Parachute




- Decision to reuse the Orbiter drag parachute required detailed loads analysis
- A CANO analysis provided the loads data necessary for inspection and repair work at the KSC PRF

# Orbiter Drag Parachute

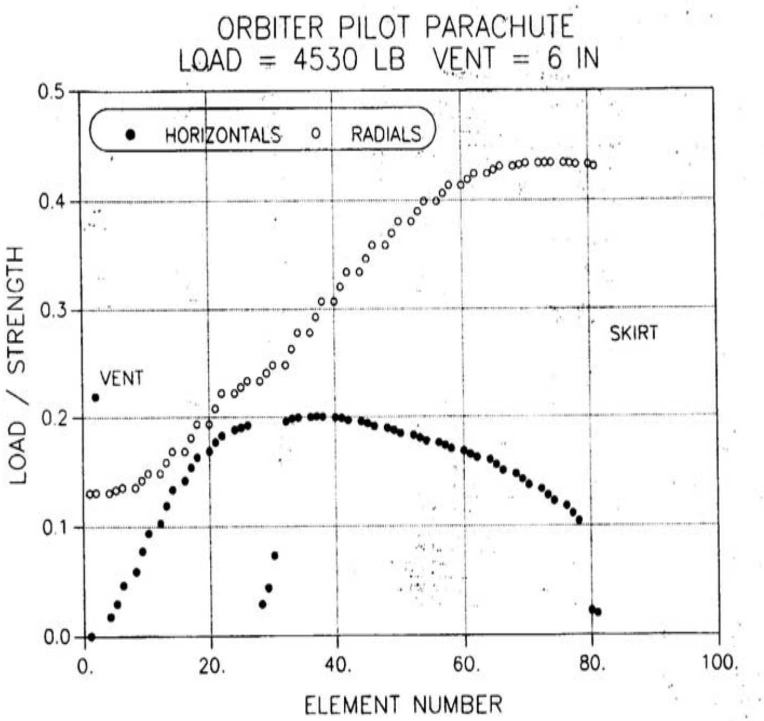



- Load/strength ratio provides the inverse of available design factor in structure
- Parachute was originally designed without reefing so reefed loads are low

# Orbiter Drag Parachute
## Comparison of Ribbon Load Estimates

- Full Open Design Load F = 100,000 lb and Projected Area A = 628 $ft^2$
- Average Pressure p = F/A = 159 $lb/ft^2$
- Hoop Tension Formulas
  - $T/\ell = (\delta p)\,R$ for cylinder
  - $T/\ell = (\delta p)\,R / 2$ hemisphere
- From CANO Analysis Maximum $T/\ell$ = 38 lb/in
- For Hemisphere $T/\ell$ = 93 lb/in - Too High
- For Cylinder With R = Gore Width, $T/\ell$ = 40 lb/in

# Orbiter Pilot Parachute

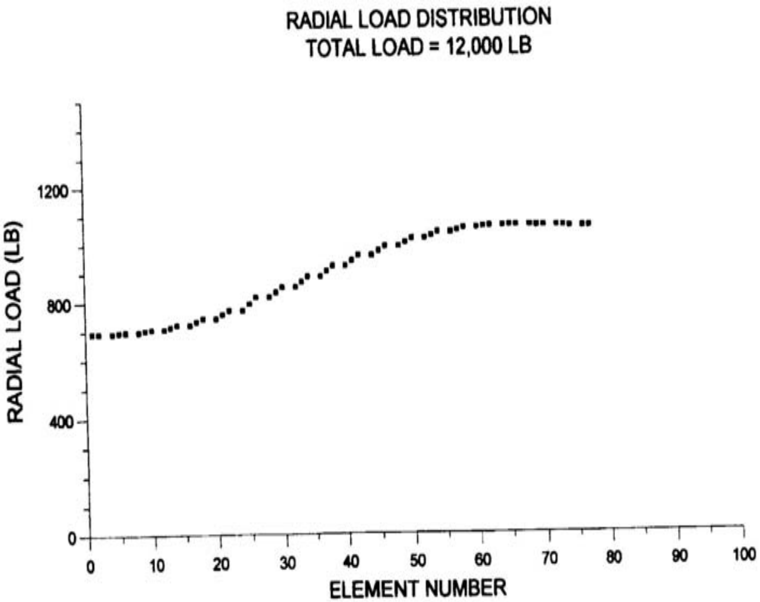



- Decision to reuse the Orbiter pilot parachute also required CANO loads analysis to support inspection and repair
- Radial strength not robust

# X-38 Pilot Parachute

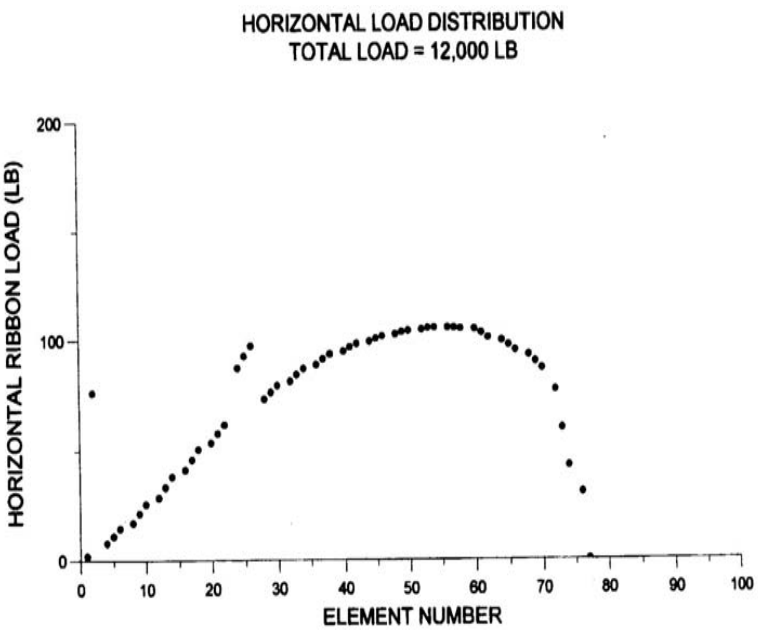
- X-38 Project wanted to use Orbiter mortar and pilot chute to reduce development costs
- A much higher design load was required for the pilot parachute
  - **12,000 lb for X-38**
  - **4500 lb for Orbiter**
- Kevlar suspension line and radial overlay was added to the existing canopy to provide the required strength
- Total weight was slightly less than all Nylon chute

# X-38 Pilot Parachute




- Radial load distribution in modified Orbiter pilot parachute
- Required strength in Kevlar load carrying structure

# X-38 Pilot Parachute




- Horizontal load distribution in modified Orbiter pilot parachute
- Adequate strength in existing horizontals
- Stiff radial structure keeps loads in horizontals low

# X-38 Parafoil First Stage Floor Panel

- During the X-38 parachute development program, a "zero" reefed stage was tried to promote inflation symmetry in the first reefed stage
  - **The "zero" stage reefing was suspension line reefing that pulled the parafoil corners down into a semi-round configuration**
- Unfortunately, disreef from the "zero" stage was very rapid and dynamic
  - **A parafoil floor failure occurred**
  - **The very large radius shape at failure suggested a membrane stress calculation**

# X-38 Parafoil First Stage Floor Panel

- Hoop Tension $T/\ell = (\delta p)\, R$
  - $\delta p$ = pressure across fabric
  - R = radius of curvature
- Unsteady Pressure $\delta p = \delta C_p\, C_k\, Q$
  - $\delta C_p$ = steady pressure coefficient across fabric
  - $C_k$ = shock factor
  - Q = dynamic pressure
- Estimate $\delta p = (1.2)(2)(10\ lb/ft^2) = 24\ lb/ft^2 = 0.17\ lb/in^2$
- Maximum Radius = Suspension Line Length = 767 in
- Hoop Tension $T/\ell = (0.17\ lb/in^2)(767\ in) = 130\ lb/in$

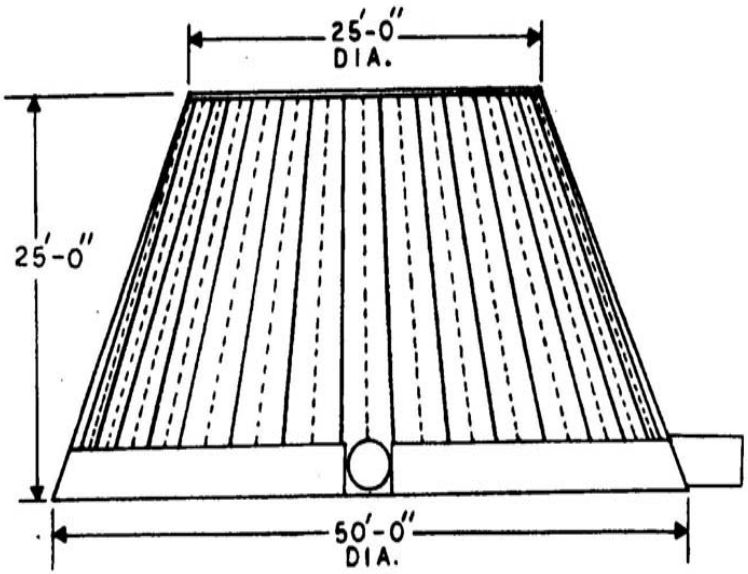
# X-38 Parafoil First Stage Floor Panel

- Floor Panel Fabric Strength was $T/\ell = 100$ lb/in so Decision was Made to Increase Fabric Strength
- Under Steady State Conditions the Radius of Curvature was Proportional to the Cell Width Because All Suspension Lines Were Loaded
- Maximum Radius = 3 Times Cell Width = 144 in
- Hoop Tension $T/\ell = (0.17 \text{ lb/in}^2)(144 \text{ in}) = 25$ lb/in
- Original Design was Adequate Under Steady State Conditions

# Fabric Foam Containers

- Aqueous foam has been used as an effective medium for the mitigation of explosive effects
- Lightweight portable fabric structures were developed to contain the aqueous foam around the explosive charge
- Several different containment structures were developed and tested under realistic deployment conditions
- Containers were designed to hydrostatic pressure using membrane equation

# 50-ft Conical Container




- Sketch with dimensions of 50-ft conical container

# 50-ft Conical Container


- 50-ft conical container filled
- Conical containers were filled from top

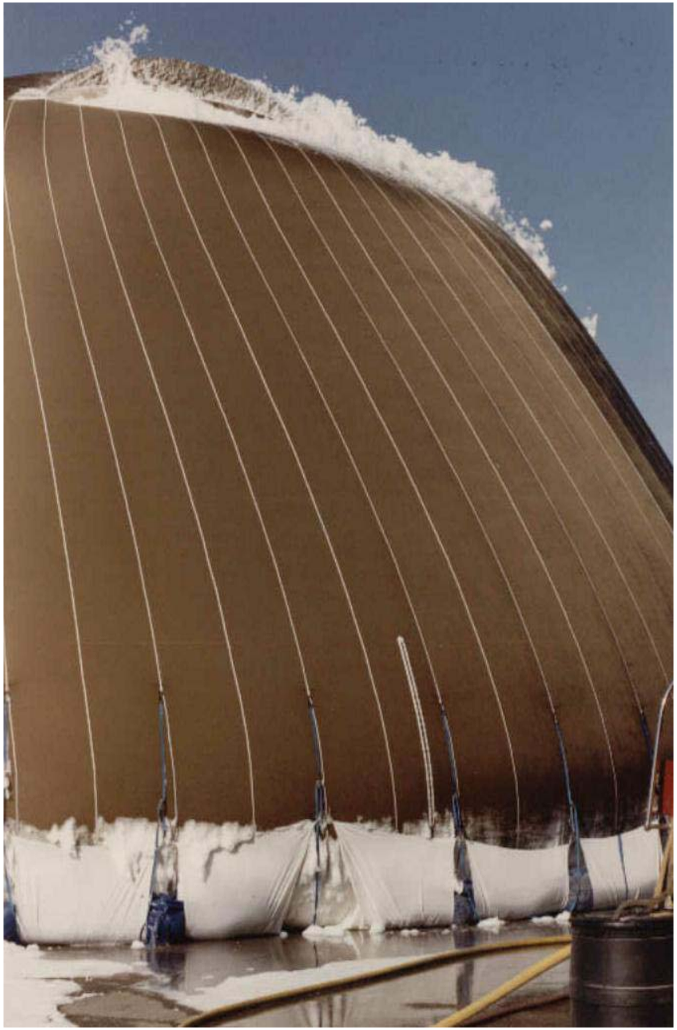
# 50-ft Conical Container

- 50-ft conical container personnel access opening
- Access openings were closed with heavy duty zippers

# 70-ft Conical Container

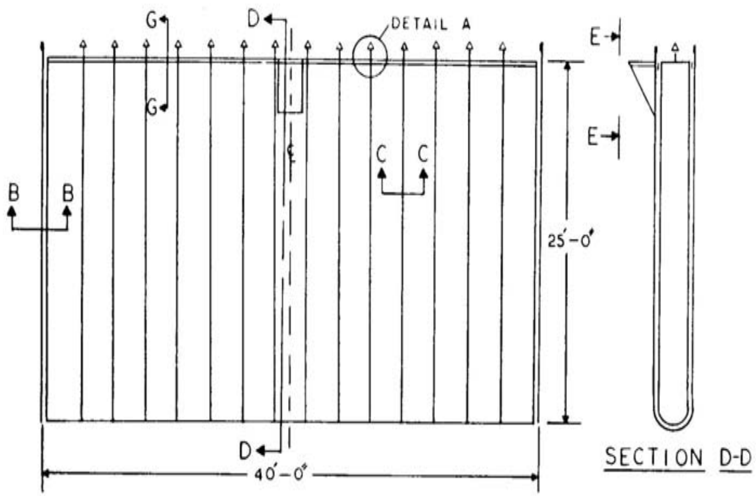
- 70-ft conical container filled
- Container deliberately overfilled to test structure

# 70-ft Conical Container



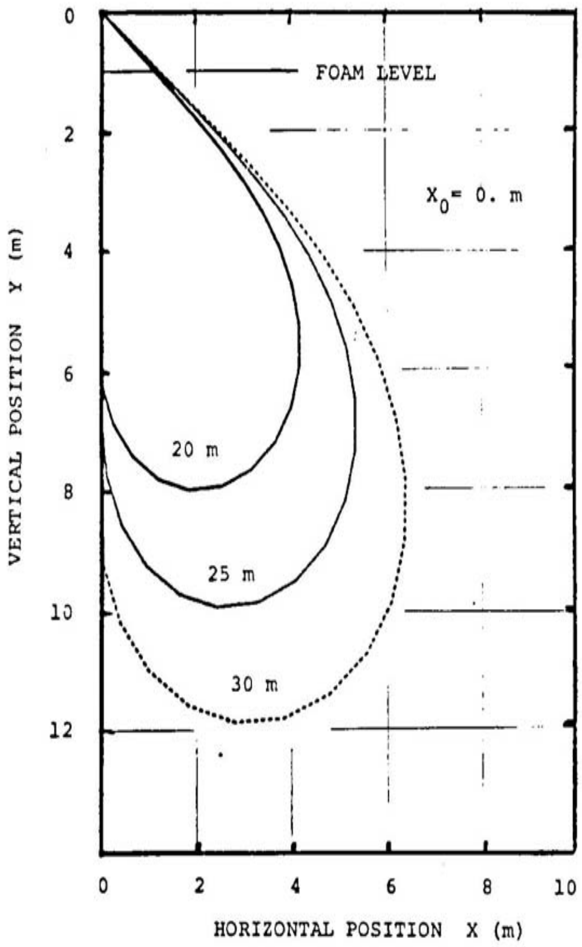
- Close up of 70-ft conical container filled
- Personnel access opening zipper at base in center

# Vertical Wall Container




- Sketch with dimensions of vertical wall container

# Vertical Wall Container




- Predicted shapes of different sized vertical wall containers
- Membrane theory use to predict shape

# Vertical Wall Container

- Vertical wall container filled
- Vertical wall container filled from top