# Conformable Pressure Vessels for Alternate Fuel Storage

A Case Study in Product Development

Richard K. Kunz, Ph.D., P.E.

Mercer University

March 30, 2006



# Introduction and Motivation

**There is a significant need for the development of alternatives to traditional- (gasoline- and diesel-) fueled vehicles**

- Geopolitical: dependence on foreign sources
- Environmental: carbon monoxide, NOx, ozone

**There are several potential alternative fuels**

- **Natural gas**
- **Hydrogen**
- Ethanol
- Propane

**There are a number of barriers to widespread acceptance of alternate-fuel vehicles**

- Cost
- Infrastructure
- **On-board storage**

# Steps toward Conformable Storage

**Identify a need**

**Understand the State of the Art**

**Develop a concept that potentially addresses the need**

**Quantify the benefits**

**Demonstrate feasibility of the concept**

**Address the details**

- Cost
- Safety
- Producibility
- Durability
- Functionality

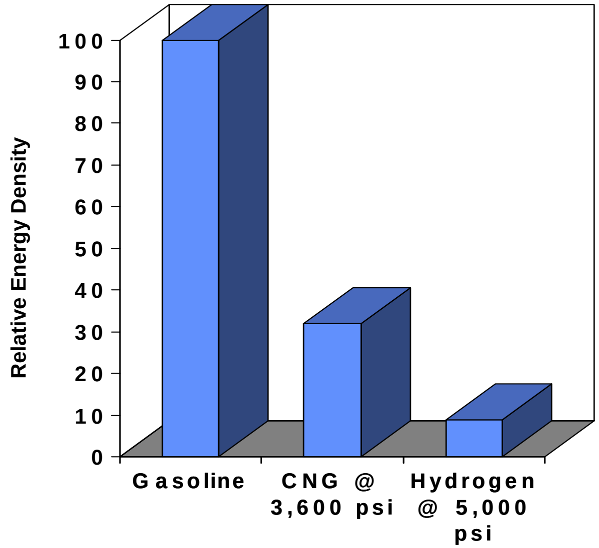
# The Need

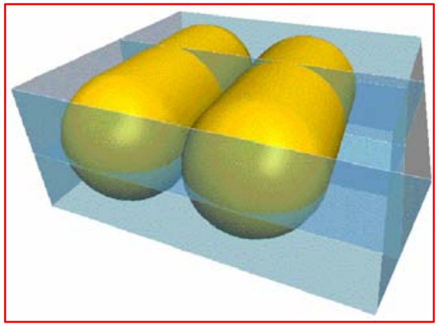
Gaseous fuels for alternative fuel vehicles have lower energy density than gasoline and diesel fuel

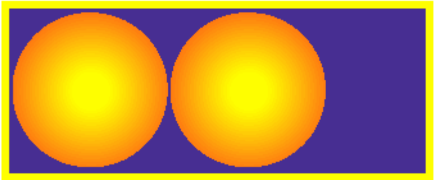
Cylindrical tanks do not package well within the substantially rectangular envelopes available on vehicles

Vehicle range is a significant limiting issue

There is a need for non-cylindrical pressure vessel technology





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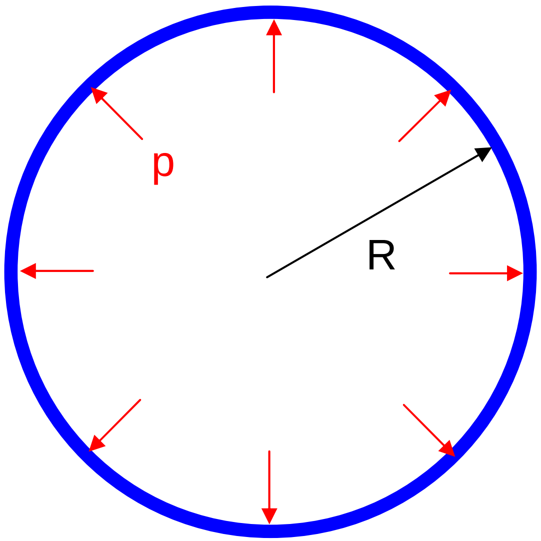
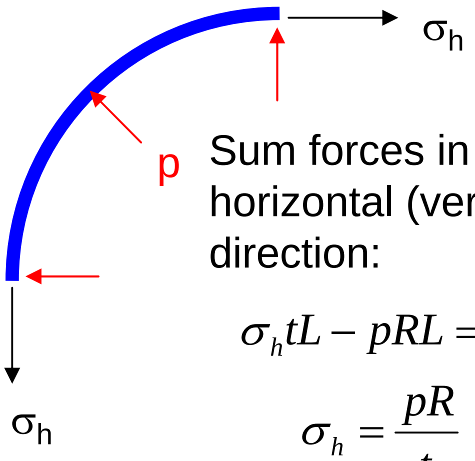
# State of the Art – Cylindrical Pressure Vessels

**Notation**

- p, internal pressure
- R, radius
- t, wall thickness
- σ, stress
- h, hoop direction
- a, axial direction

Consider a slice of length L:

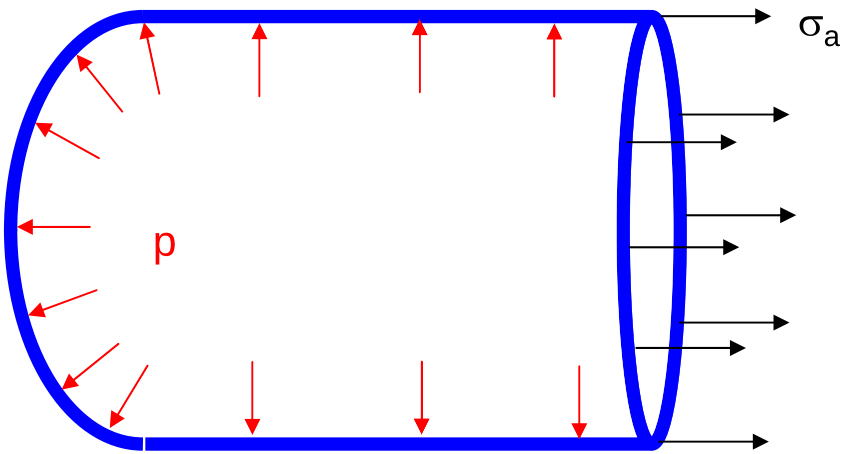



Sum forces in horizontal (vertical) direction:

$$\sigma_h tL - pRL = 0$$

$$\sigma_h = \frac{pR}{t}$$




Sum forces in horizontal direction:

$$\sigma_a (2\pi R)t - p(\pi R^2) = 0$$

$$\sigma_a = \frac{pR}{2t}$$

# Cylindrical Pressure Vessels – Design Considerations

**For thin-walled cylindrical pressure vessels:** $\sigma_h = \frac{pR}{t}$ $\sigma_a = \frac{pR}{2t}$

**Cylinder walls react the pressure load in a membrane state (no bending)**

- End domes can also be configured to minimize bending

**For cylindrical pressure vessels, hoop stress is twice the axial stress**

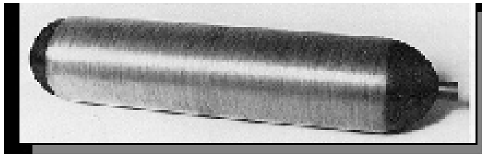
- This limits the structural efficiency (pV/W) of metal cylinders
- Metal spherical tanks have a higher efficiency than cylinders, but do not package as well

**Continuous fiber composite materials provide an ideal solution for optimizing the structural efficiency of cylindrical tanks**

- Higher strength-to-weight ratio than metals
- Efficiency can be further increased by structural tailoring – more fibers in hoop direction

# Types of Cylindrical Tanks

Type 1: All metal

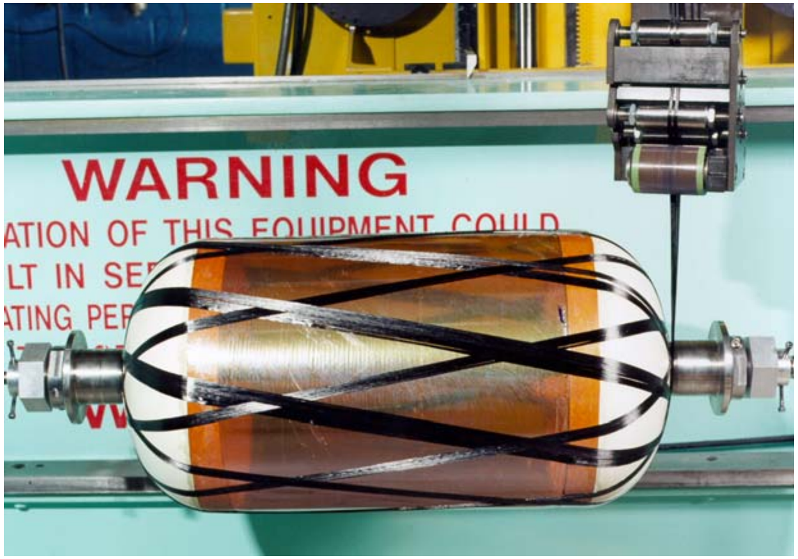


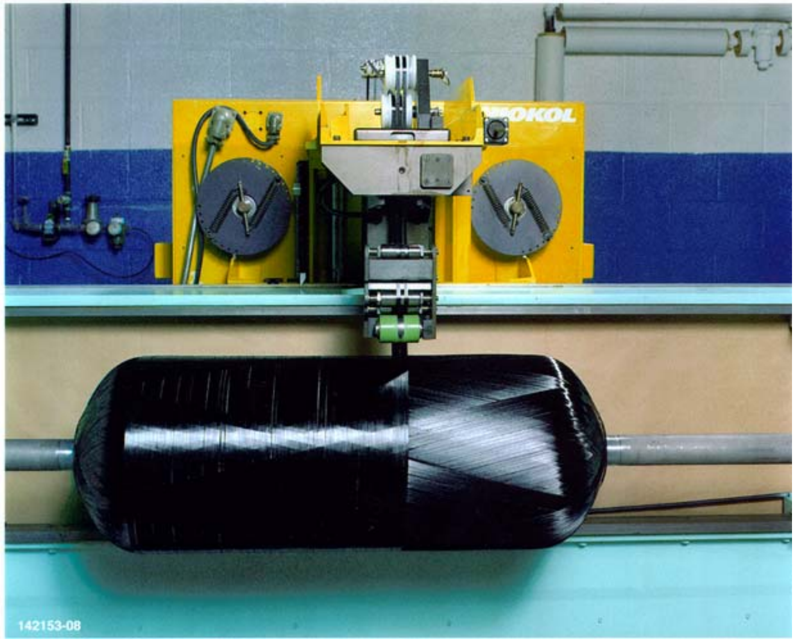
Type 2: Metal with composite hoop wrap

Type 3: Metal liner with full composite wrap


Type 4: Plastic liner with full composite wrap

# Composite Tank Fabrication: Filament Winding




**Continuous fibers under tension are applied to a mandrel**

**Carbon fiber bundles (tows) consist of 12k fibers provided on a spool; four tows constitute a band**

**Wet-winding vs. pre-preg winding**

**Helical layers cover cylinder plus domes**

**Hoop plies cover cylinder section only**

**Oven curing to harden the resin follows winding**

**Mandrel doubles as an impermeable barrier to the stored high-pressure gas**

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# Conformable Tank Constraints/Concepts

**Must more efficiently conform to a rectangular envelope than cylinders**

**Tank walls under pressure must be cylindrical or consist of cylindrical segments**

- Require primarily membrane loading
- The laws of physics prevail

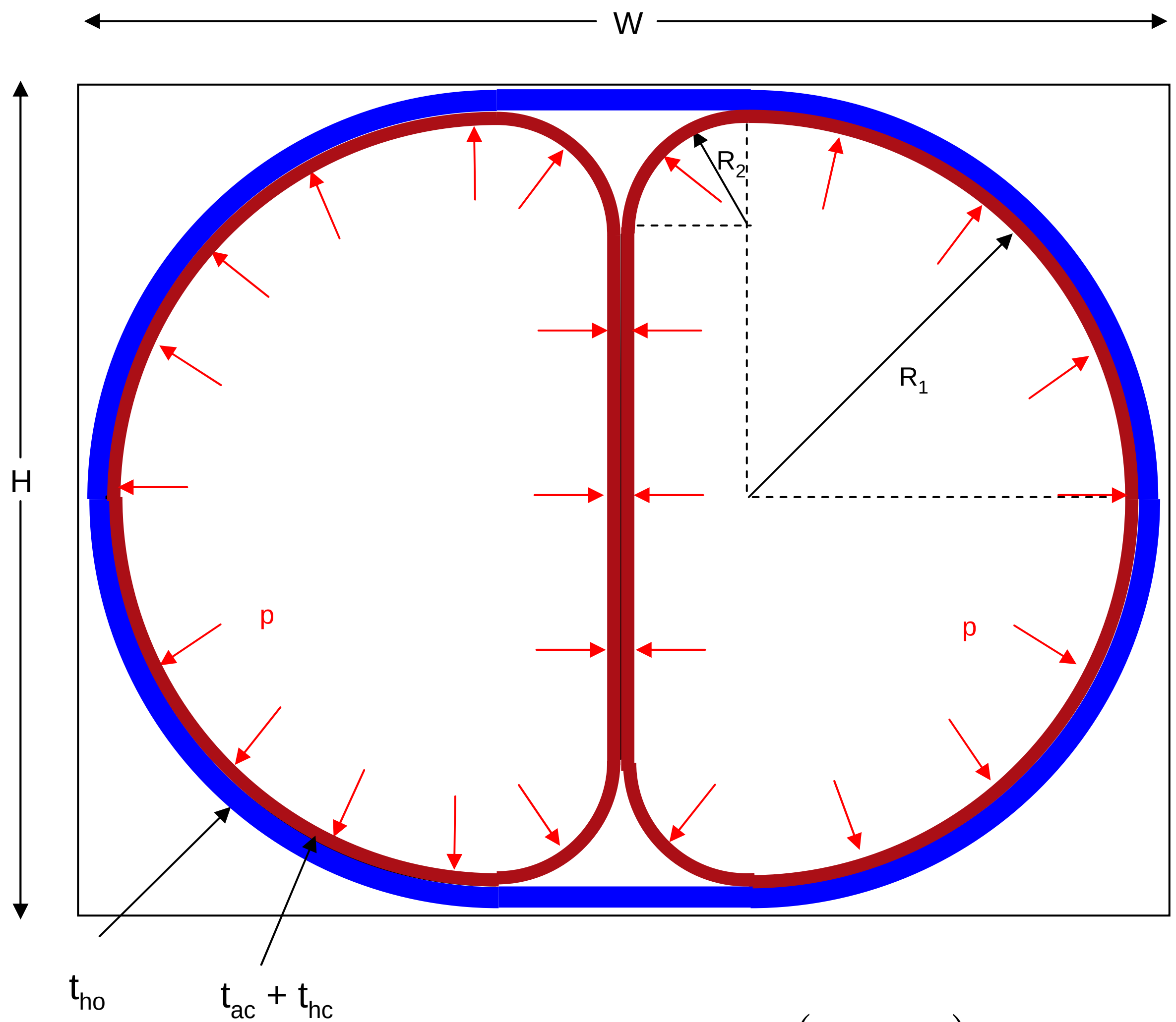
**Should be able to be fabricated by filament winding**

**The low transverse strength of composites must be considered**

**Think of an air mattress . . .**

**. . . or bubbles that stick together . . .**

# Multi-cell concept




**Cross-section of multi-cell tank is shown**

**Each individual cell (c) is wound with both hoop (h) and helical (a) plies**

**An overwrap (o) of entirely hoop (h) plies is applied to the assembly of cells**

$$W = 2R_1 + 2R_2 + 4(t_{ac} + t_{hc}) + 2t_{ho}$$
$$H = 2R_1 + 2(t_{ac} + t_{hc}) + 2t_{ho}$$

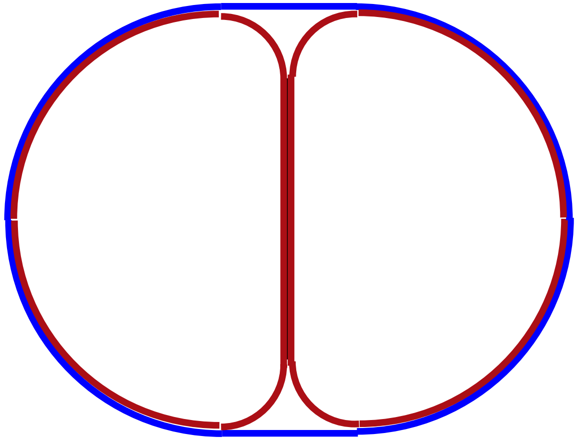
# Preliminary Prototype Design Considerations

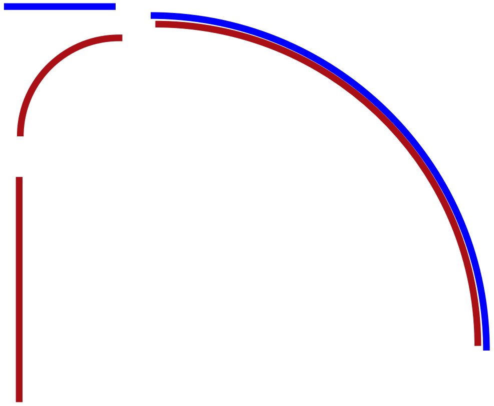
**How are loads distributed among the tank components?**

**How do we determine the thicknesses of the cell wrap and overwrap?**

**Approximations for preliminary design/analysis**

- Hoop plies carry all the hoop loads
- Helical layers carry all the axial loads
  - $E_1/E_2 \approx 10$
  - Helical fibers are not in axial direction ($\alpha \approx$ 15-20º)

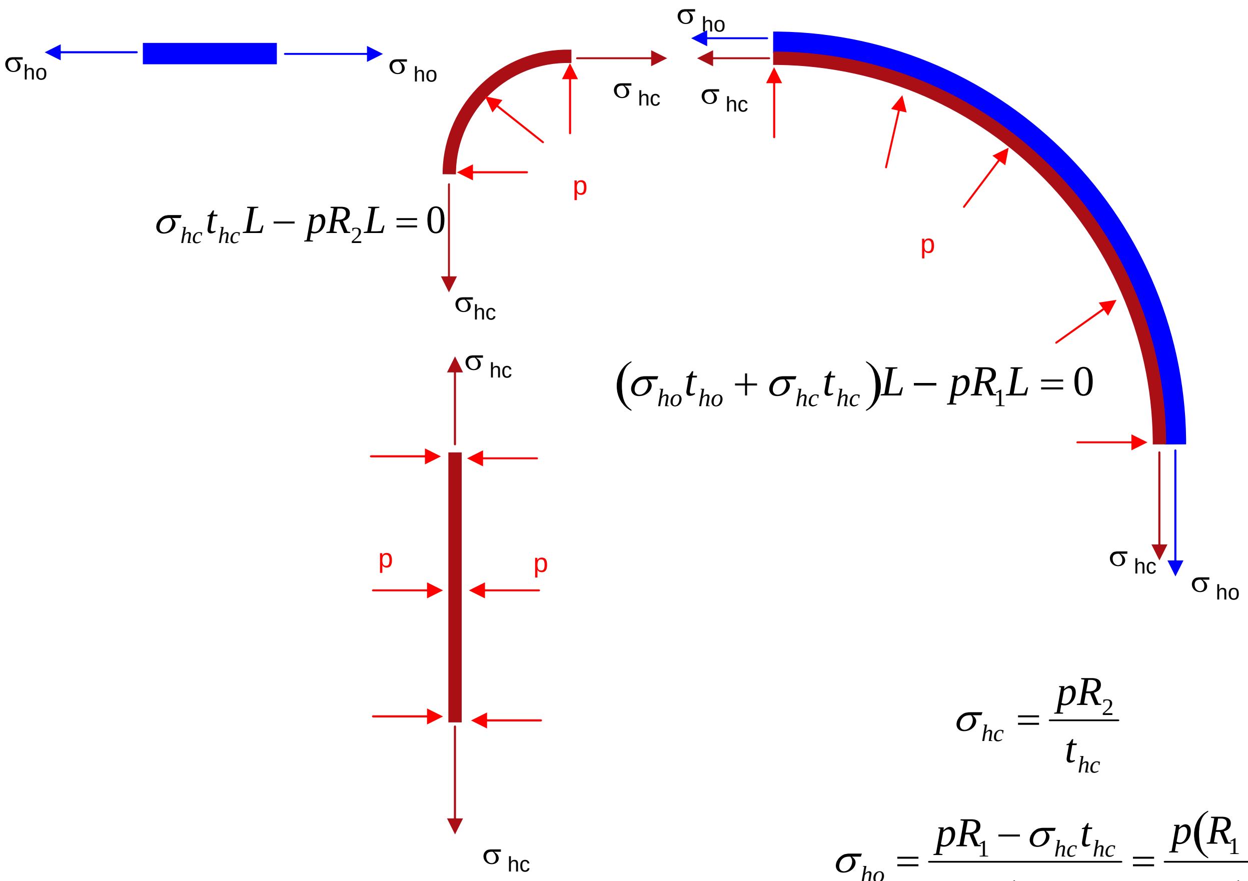




**Methodology**

- Draw free-body diagrams of tank components
- Examine loads and equilibrium
- Determine thicknesses by equating strains

# Hoop Loads



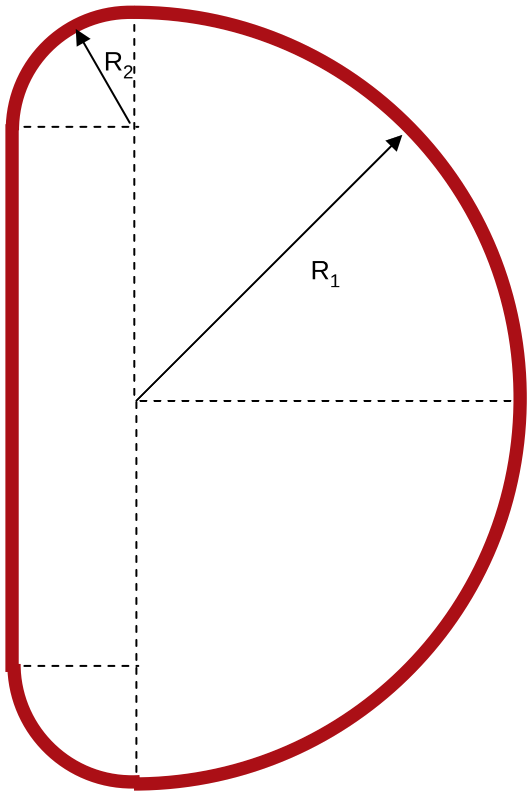

$$\sigma_{hc} t_{hc} L - p R_2 L = 0$$

$$(\sigma_{ho} t_{ho} + \sigma_{hc} t_{hc}) L - p R_1 L = 0$$

$$\sigma_{hc} = \frac{p R_2}{t_{hc}}$$

$$\sigma_{ho} = \frac{p R_1 - \sigma_{hc} t_{hc}}{t_{ho}} = \frac{p(R_1 - R_2)}{t_{ho}}$$

# Axial Loads




$$\sigma_{ac}\left(\pi R_1 + \pi R_2 + 2\left(R_1 - R_2\right)\right)t_{ac} - p\left(\frac{\pi R_1^2}{2} + \frac{\pi R_2^2}{2} + R_2\left(R_1 - R_2\right)\right) = 0$$

$$\sigma_{ac} = \frac{p}{t_{ac}}\,\frac{\frac{\pi R_1^2}{2} + \frac{\pi R_2^2}{2} + R_2\left(R_1 - R_2\right)}{\pi R_1 + \pi R_2 + 2\left(R_1 - R_2\right)}$$

# Preliminary Thicknesses

**Determine approximate thicknesses**

- Equate hoop stress in cell and overwrap to ultimate stress in fiber-direction, $\sigma_f$
- Equate axial stress to $\sigma_f$ times Stress Ratio (SR)
  - Knockdown factor in recognition of non-uniform dome stresses
  - Desired failure mode is hoop failure in cylinder section
  - SR = 0.6 to 0.8
- Adjust for actual layer thicknesses

$$\sigma_{hc} = \frac{pR_2}{t_{hc}}$$

$$\sigma_{ho} = \frac{p(R_1 - R_2)}{t_{ho}}$$

$$\sigma_{ac} = \frac{p}{t_{ac}} \frac{\frac{\pi R_1^2}{2} + \frac{\pi R_2^2}{2} + R_2(R_1 - R_2)}{\pi R_1 + \pi R_2 + 2(R_1 - R_2)}$$

$$t_{hc} = \frac{pR_2}{\sigma_f}$$

$$t_{ho} = \frac{p(R_1 - R_2)}{\sigma_f}$$

$$t_{ac} = \frac{p}{SR \cdot \sigma_f} \frac{\frac{\pi R_1^2}{2} + \frac{\pi R_2^2}{2} + R_2(R_1 - R_2)}{\pi R_1 + \pi R_2 + 2(R_1 - R_2)}$$

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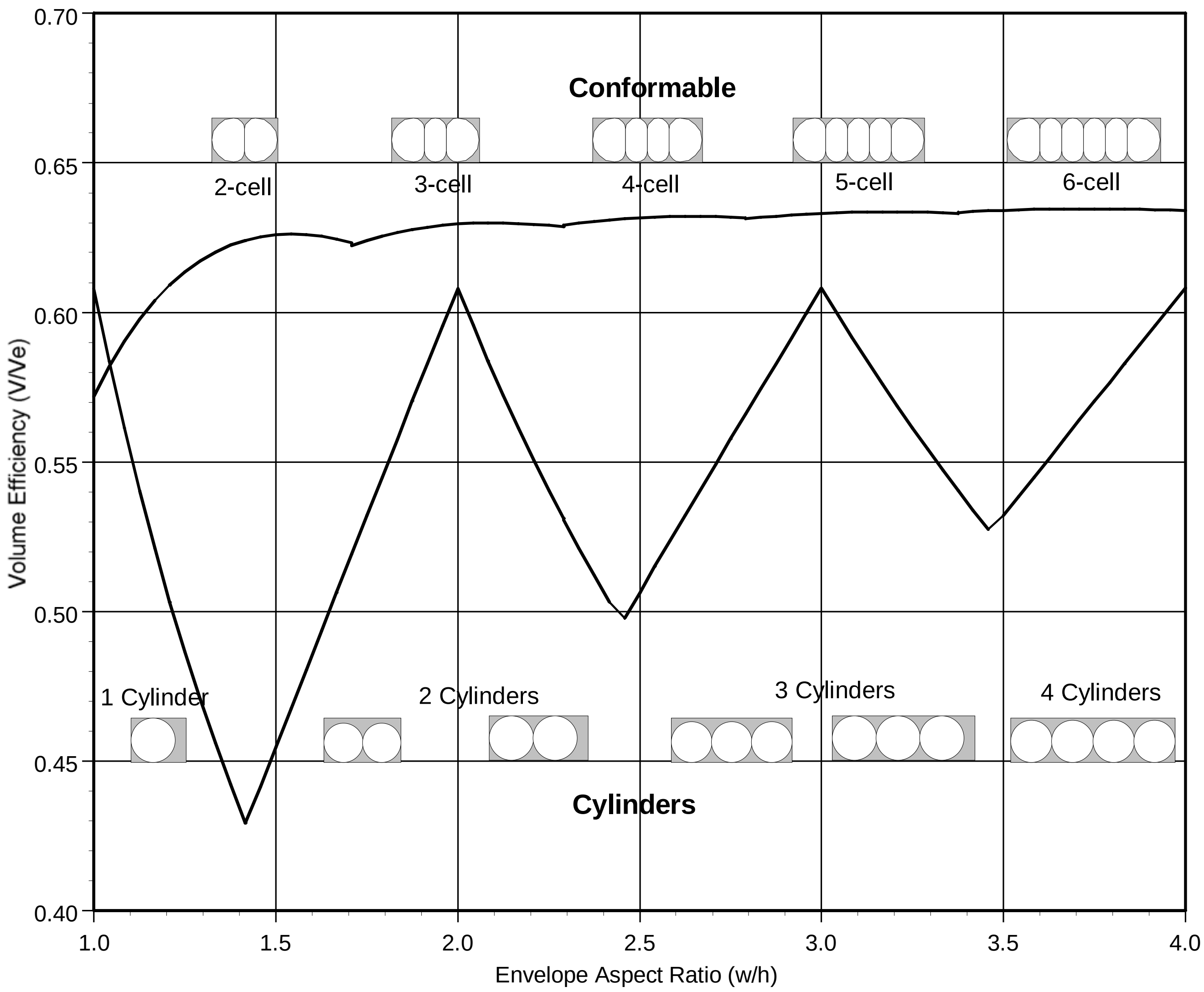
# Potential Benefits of Conformable Storage Concept



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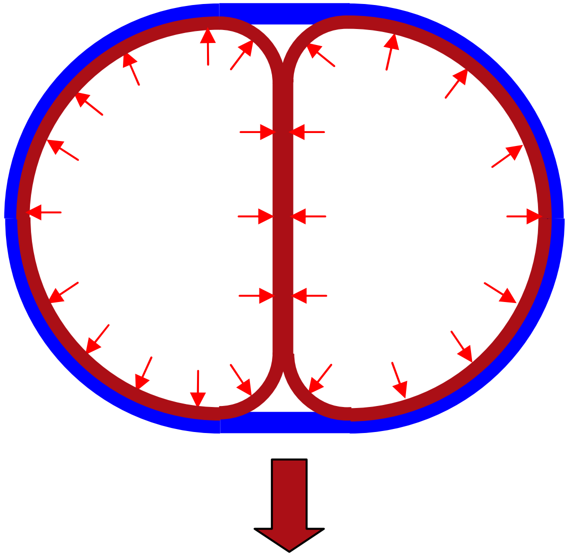
# Proof-of-Concept Prototype

**Goal**

- To demonstrate the capability of the conformable design concept to sustain pressure

**Ground Rules**

- No expensive tooling or hardware required
- Burst pressure should be “substantial” and predictable
- A path to full-scale production processes should be evident
- No need to optimize the design for weight or cost
- Overall size of the tank is not important
- A low burst could signal an end to the program



# Prototype Design

**Establish a target burst pressure**

- 5000 psig

**Establish overall tank dimensions**

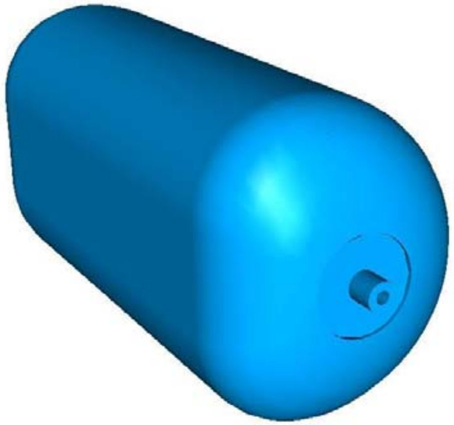
- 11 x 16 x 20 in

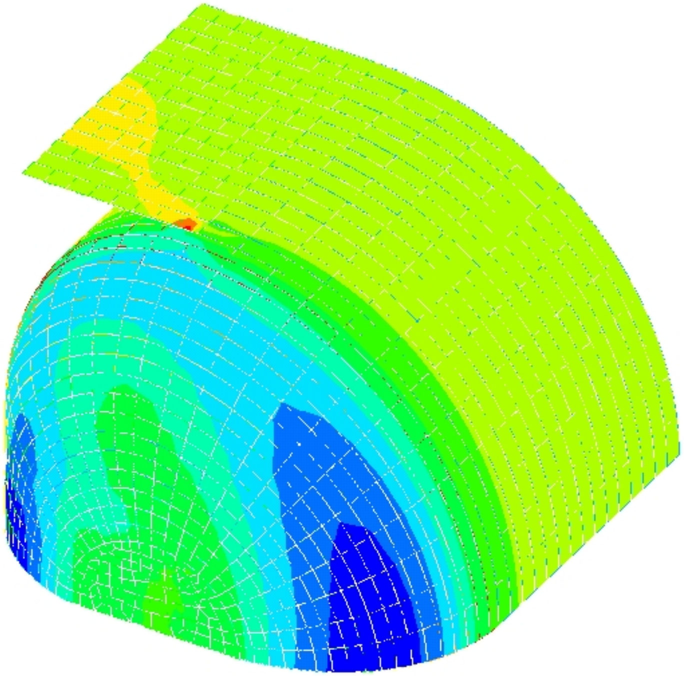
**Dome design**

- Location of polar boss – at centroid of section
- Dome geometry – adapt cylinder geometry

**Detailed design/analysis**

- Finite element shell model
- Estimate materials properties and thicknesses in dome
- Adjust number of hoop, helical plies





# Fabrication Considerations

**Tooling**

- Mandrels
  - Molds packed with sand/binder
  - When set, encase in thin rubber bladder
  - Following winding and cure, sand is washed out
- Special tooling
  - Polar boss
  - Fixturing cells for winding overwrap

**Winding**

- Fiber slippage
- Gaps and overlap

# Prototype Testing

Hydroburst test conducted remotely

Painted white with stripes for visibility

Instrumented with strain gages on overwrap and domes

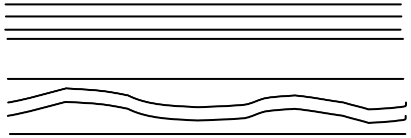
Filmed with high-speed camera

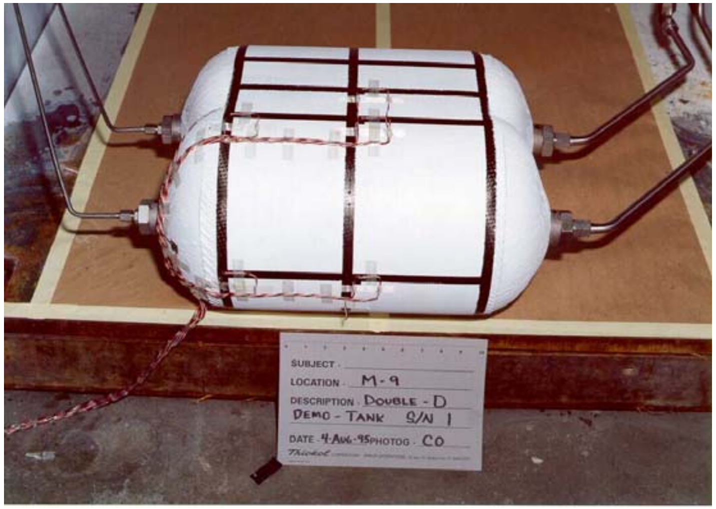
Burst at 4530 psi (90% of target)

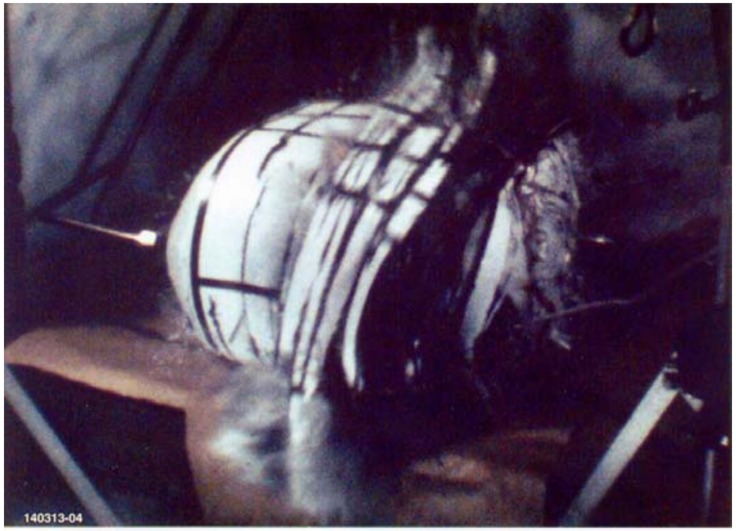
Failure initiated in overwrap near one end

Both cells ruptured in cylinder region, extending to the dome

Examination of carcass revealed some waviness in fibers of overwrap





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# Liners

**Requirements**

- Permeability
- Rigidity
- Thermal stability

**Material**

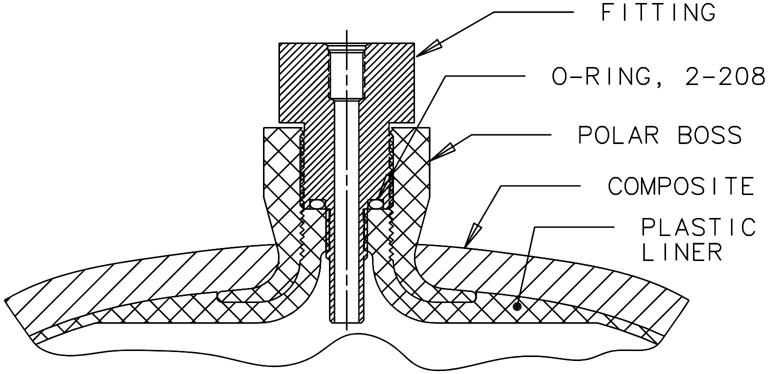
- Plastic vs. metal
- High density polyethylene

**Fabrication process**

- Rotational molding
- Injection molding

**Integration with polar boss/fill fitting**

- O-ring seal
- Fill tube extension



# Design/Process Modifications

**Durability – resistance to cuts and abrasion**

- Two layers of glass hoop fibers on outside of hoop overwrap

**Performance – eliminate fiber waviness**

- Pressurize liner during winding
- Foam insert in “Y-Joint” region between the cells

**Pressure equalization between cells**

- External manifold

**Damage tolerance**

- External foam on domes


# Safety Testing

**Safety requirements dictated by industry standard ANSI-NGV2**

- Burst pressure
- Cycle life
- Bonfire
- Bullet impact
- Pendulum impact
- Drop
- Environmental exposure (temperature, chemicals)
- Permeation
- Flaw tolerance

# General Observations

**There are potential show-stoppers at each step of the development process**

- Early identification is beneficial

**The last step of the process can easily consume the majority of resources**

- The definition of “details” is a matter of perspective

**The flow of the product development process is dependent on:**

- Budget
- Staffing level
- Management commitment

**In the automotive industry, cost is paramount**

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