Bringing Science to Life

Evaluation of Large Tow-Size Carbon Fiber for Reducing the Cost of CNG Storage Tanks

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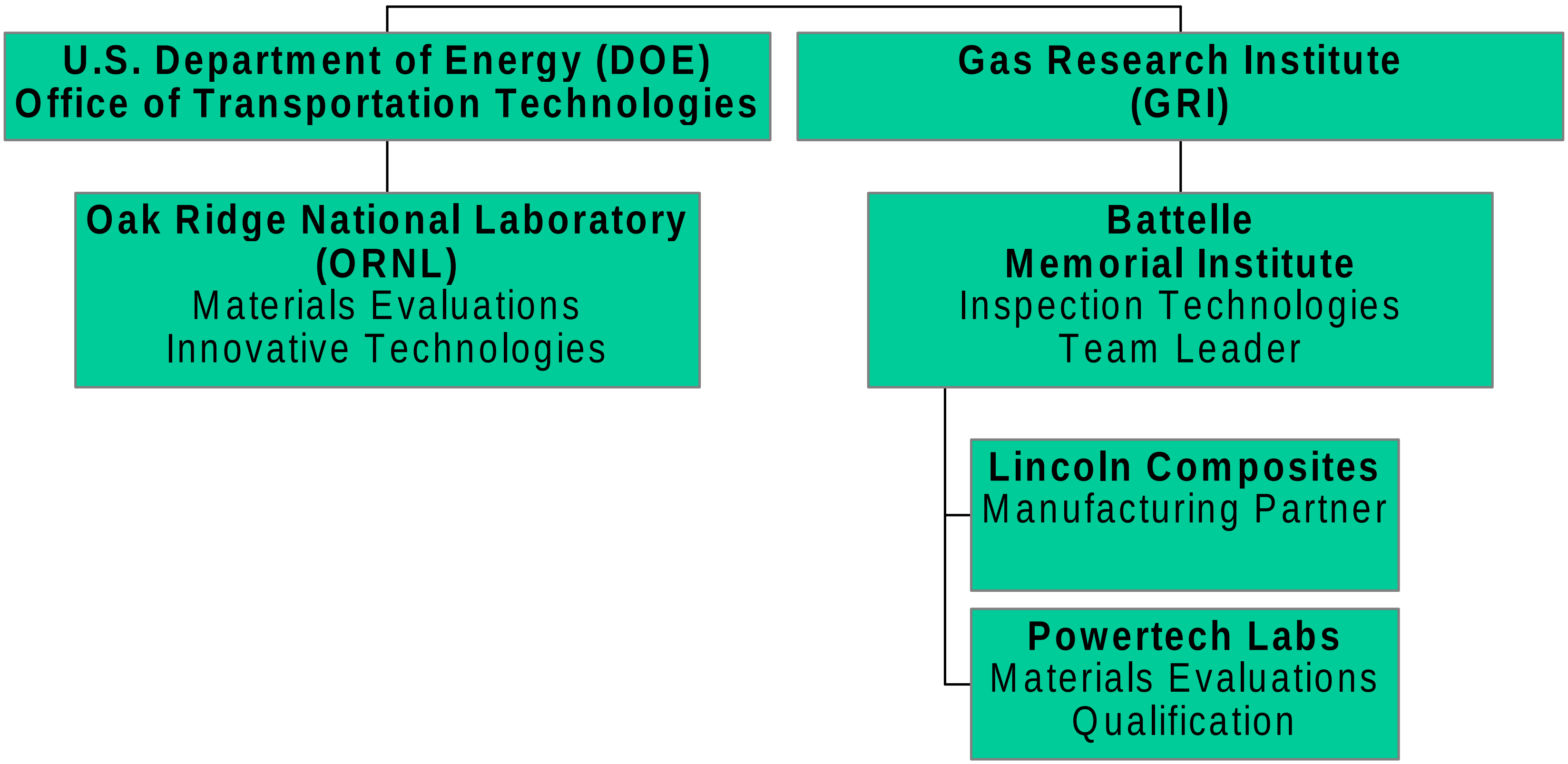
Outline

- Motivation
- Manufacturing Process Trials
- Durability Testing
- Conclusions

DOE & GRI Project Team

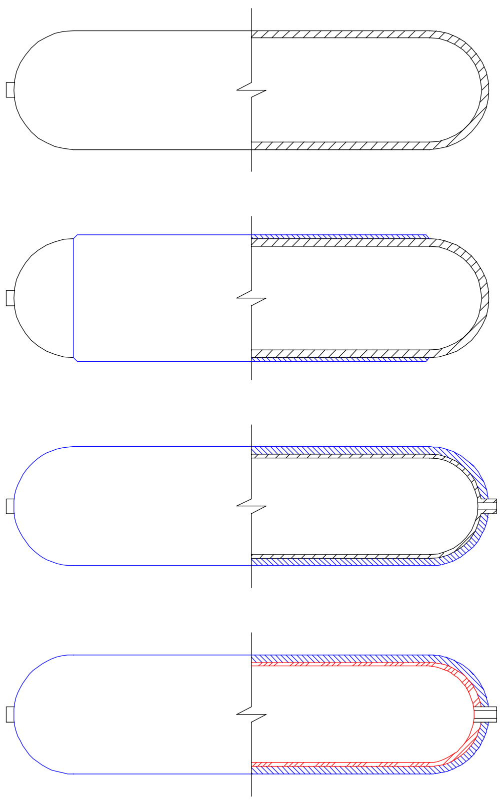
Enhanced CNG Composite Fuel Tank Study



Background

- Alternative fuels, such as CNG, can reduce the United States dependence on foreign oil with the potential added benefit of reducing emissions.
- CNG is an alternative fuel that is stored under high pressure on the vehicle (20.7- or 24.8 Mpa) (3000- or 3600-psi).
- Safety and cost are two factors that have prevented significant natural gas vehicle penetration in the automotive market.
- Composite materials are an enabling technology for reducing the weight of CNG fuel tanks

Types of CNG Storage Tanks



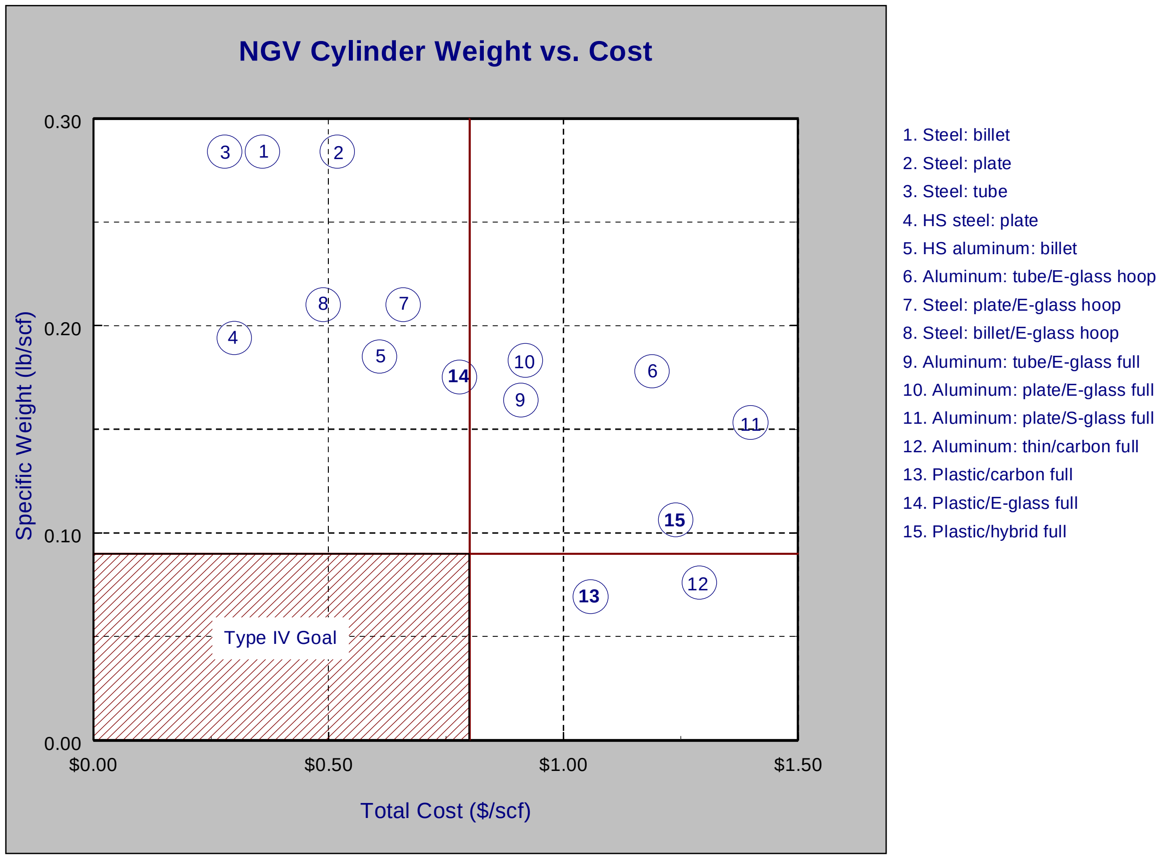
	Materials	Equivalent Gal. Gas/Weight Ratio
I	Metal	1 Steel
II	Metal lined Hoop wrapped w/ fiber composite	1.7 Steel/Glass fiber 2.1 Alum/Glass fiber
III	Metal lined Fully wrapped w/ fiber composite	2.3 Alum/Glass fiber
IV	Plastic lined Fully wrapped w/ fiber composite	4.0 Thermoplastic/ Carbon/Glass fiber

Composite Materials

- For weight sensitive applications (transit bus and passenger cars) Type 4 composite tanks are attractive.
- Reinforcement used in over-wrapping a tank is typically either a carbon fiber or glass fiber
- Advantages
  - low weight
  - corrosion resistance
  - fatigue resistance
- Disadvantages
  - carbon fiber is relatively expensive
  - carbon fiber has a poor resistance to impact damage

Goals

- Lower Cost
- Lighter weight
- More durable
- Improved safety



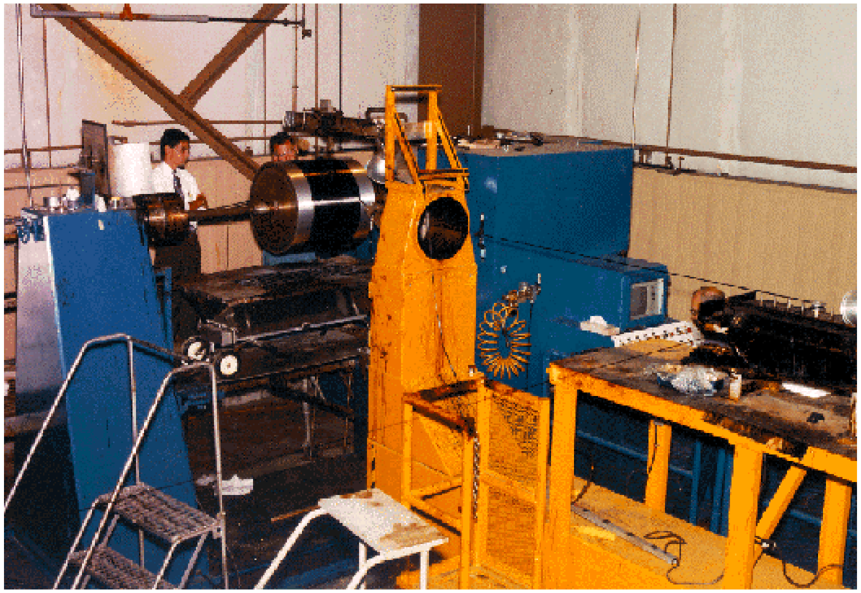
Ref. "Compressed Natural Gas Storage Optimization for Natural Gas Vehicles" Final Report, Dec., 1996, Prepared by IGT and Powertech Labs for GRI

Cost Reduction

- Cost analysis of a typical Type 4 tank showed that 40% of the total cost is attributed to the carbon fiber raw material cost.
- Cost of large tow-size carbon fiber is approximately 1/2 the cost of conventional tow-size carbon fiber.
- Manufacturing processes and test procedures need to be developed for large tow-size carbon fiber.
- As-manufactured performance of large tow-size carbon fiber needs to be evaluated to ensure safe designs.

Process Trials

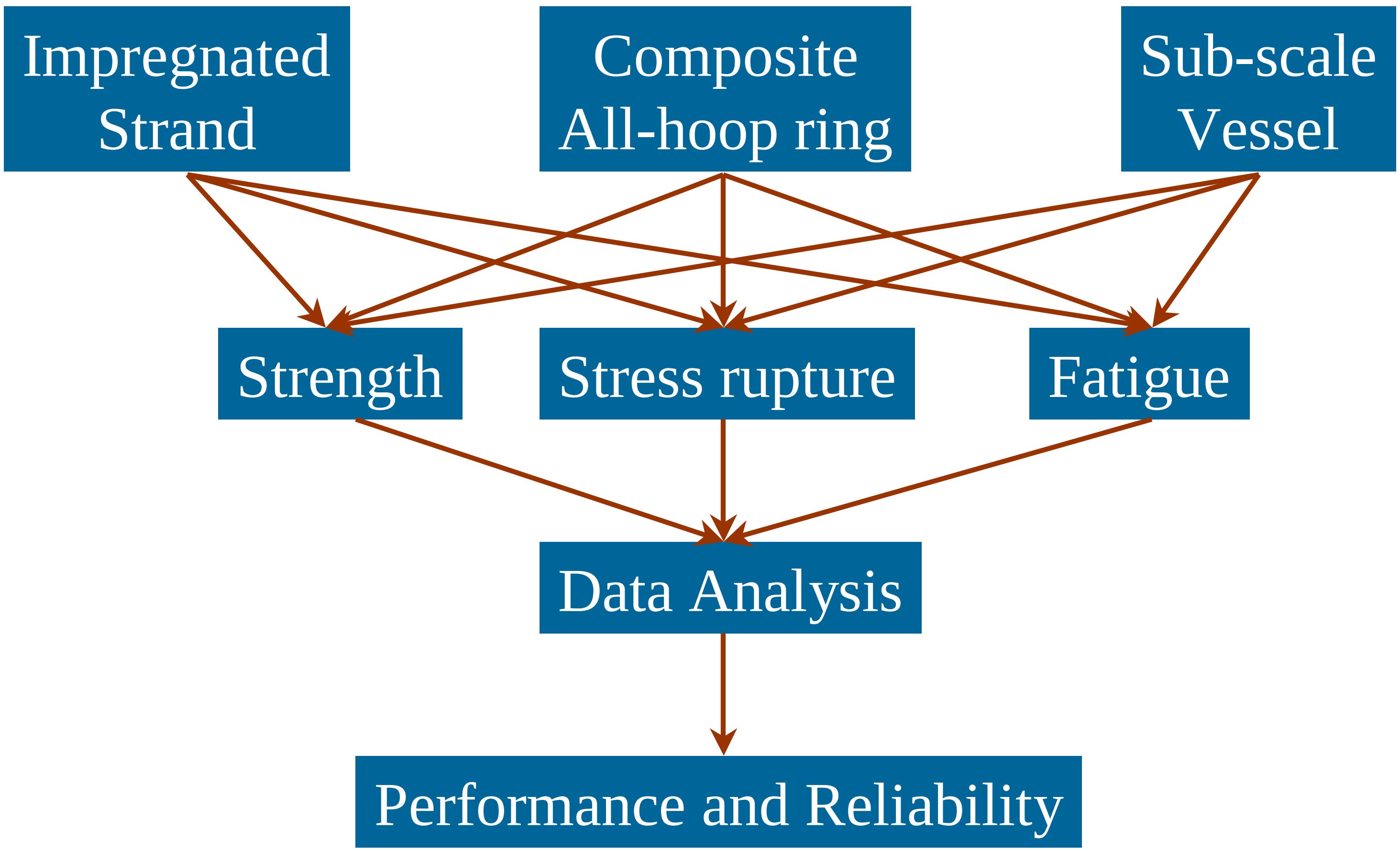
- Akzo Fortafil 3C large tow carbon fiber
- Union Carbide ERL-2258/mPDA epoxy resin
- Wet-filament winding parameters
  - compaction
  - fiber tension
  - bandwidth
- Composition
  - fiber content
  - resin content
  - void content



Composition Data

Process Number	Tension (kg)	Compaction (kg/type)	Bandwidth (cm)	Density (g/cc)	Fiber content (%)	Resin content (%)	Void content (%)
1	11.3	9.1/DSS	1.079	1.5920	69.30	27.79	2.91
2	11.3	9.1/DSS	1.105	1.5834	69.17	27.29	3.54
3	11.3	9.1/DSS	1.118	1.5786	68.10	28.45	3.45
4	9.1	9.1/DSS	1.123	1.5575	66.05	29.72	4.23
5	13.6	9.1/DSS	1.123	1.5780	68.98	27.13	3.89
6	13.6	9.1/SSS	1.123	1.5772	68.50	27.75	3.74
7	11.3	18.1/DSS	1.118	1.5844	67.05	30.44	2.51
8	11.3	18.1/DSS	1.123	1.5629	65.06	31.60	3.34
9	13.6	18.1/DSS	1.123	1.5728	67.05	29.50	3.44
10	15.9	18.1/DSS	1.123	1.5636	63.16	34.42	2.42
11	13.6	9.1/DSS	1.123	1.5756	66.14	31.05	2.80

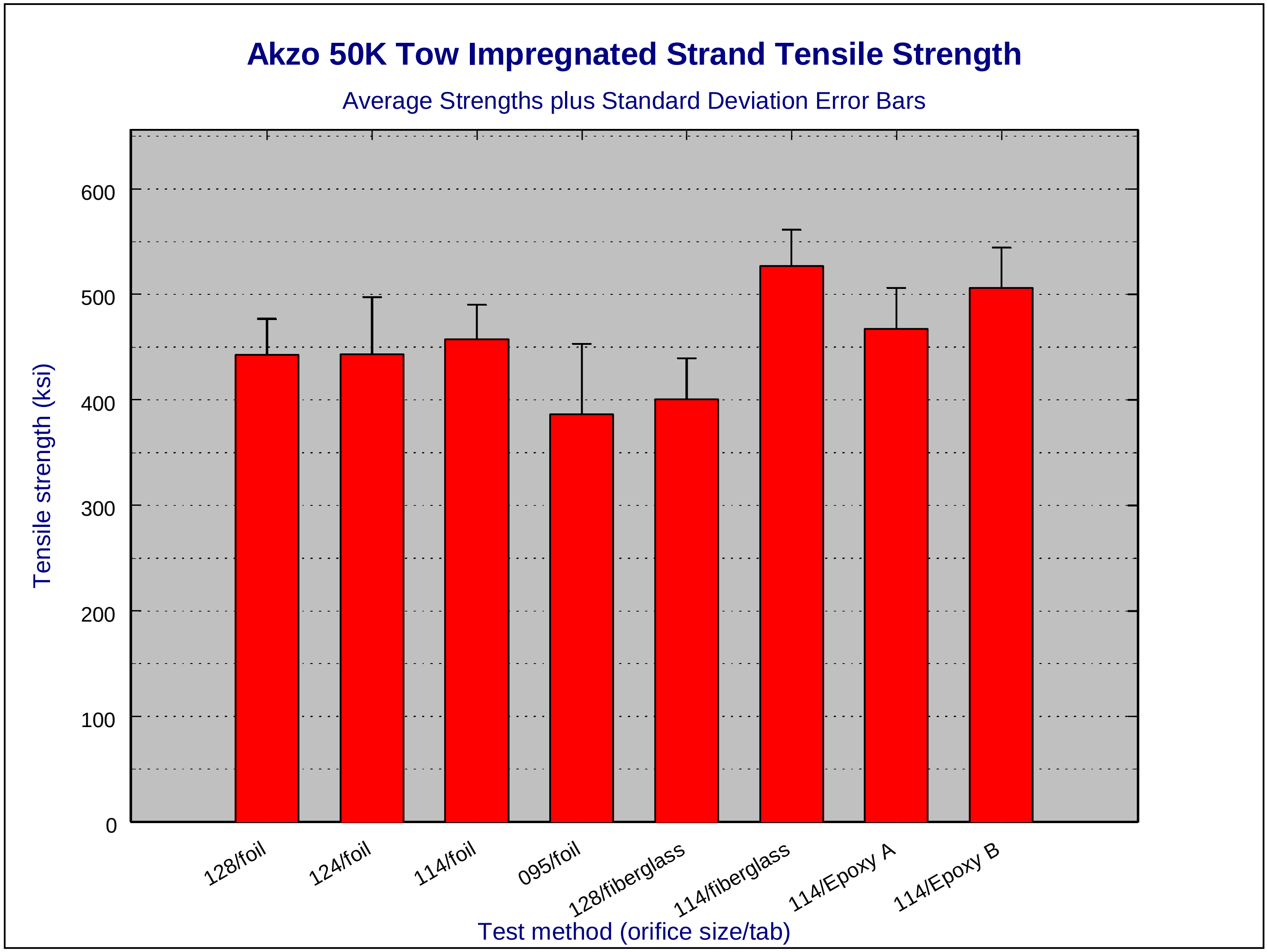
Durability


Impregnated Strand
Composite All-hoop ring
Sub-scale Vessel
Strength
Stress rupture
Fatigue
Data Analysis
Performance and Reliability

Impregnated Strand

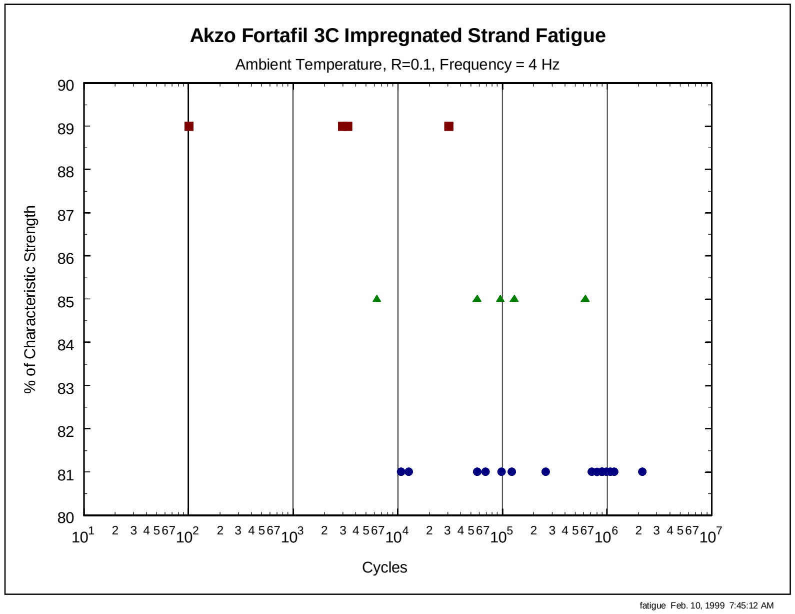
- Conventional manufacturing and test methods were determined to be inadequate
- Process development
  - Orifice size
  - Wider pulleys
- Test development
  - Tab method
    - foil, co-cured
    - fiberglass with adhesive film
    - epoxy, potted
  - Grip method
    - rubber-face, pneumatic
    - serrated, self-tightening mechanical

Impregnated Strand Static Tensile Strength



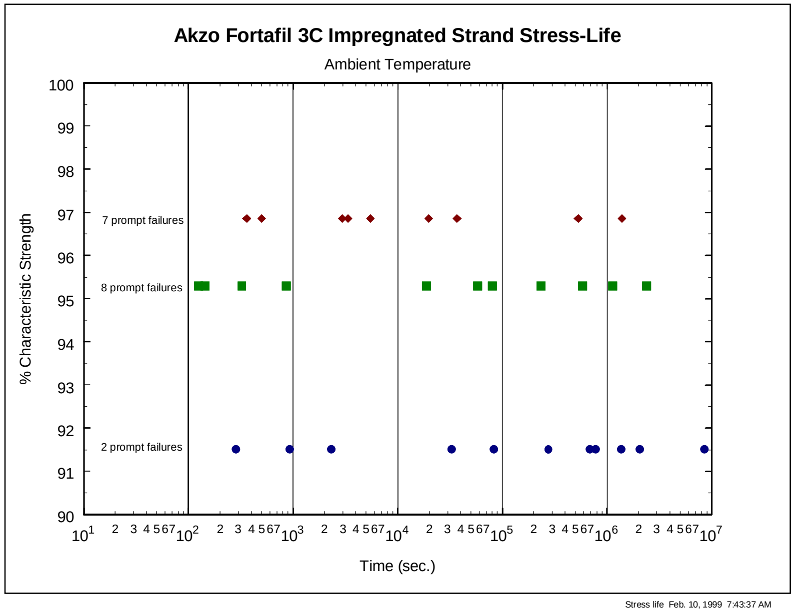
Impregnated Strand Tension-Tension Fatigue

- Scale parameter = 3735 MPa (Characteristic strength)
- Shape parameter = 20.0
- Tab failures using fiberglass tabs
- Epoxy B potting method used
- Decade increase in cycles to failure for a 4% reduction in stress



Impregnated Strand Stress Rupture

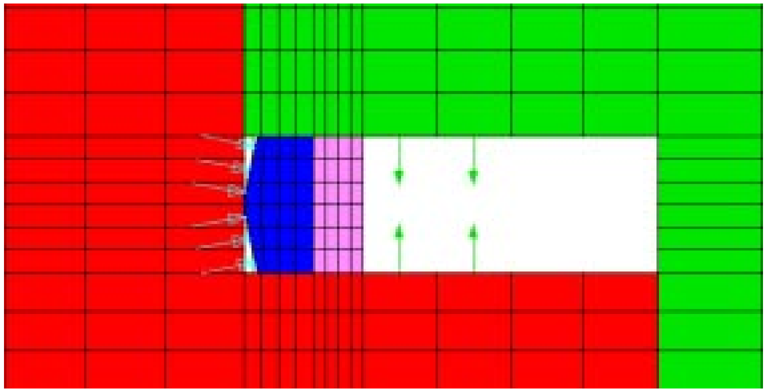
- Scale parameter = 3735 MPa (Characteristic strength)
- Shape parameter = 20.0
- Fiberglass tab method was acceptable
- Fewer prompt failures occurred as the stress level was reduced
- More tests needed!

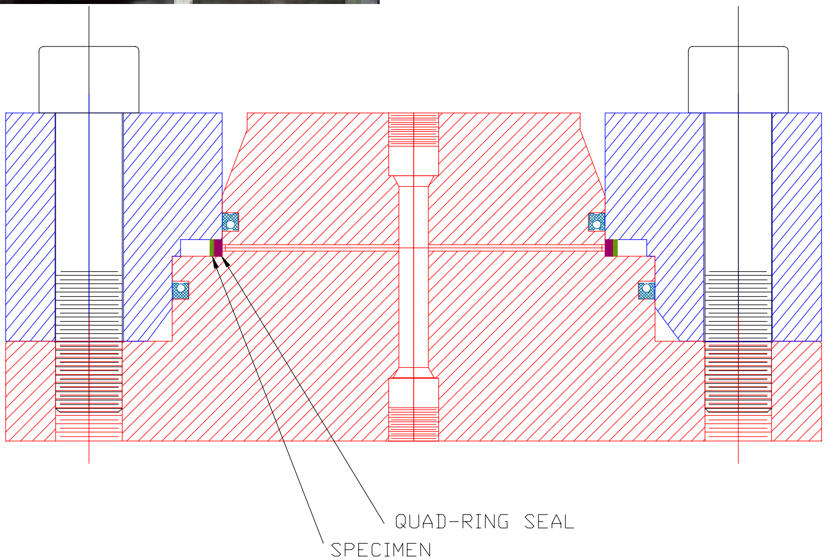


Composite Ring

- Test development
  - Split-disk (NOL) method
    - non-uniform stress distribution
    - significant bending and shear stresses
    - friction becomes a major issue for fatigue testing
  - Hydroburst
    - internal pressure results in uniform stress state
    - seal design
    - limited pressure capability
  - Designed a hydroburst fixture for testing 15.2 cm diameter rings with an axial height of 0.635 cm

Hydroburst Fixture

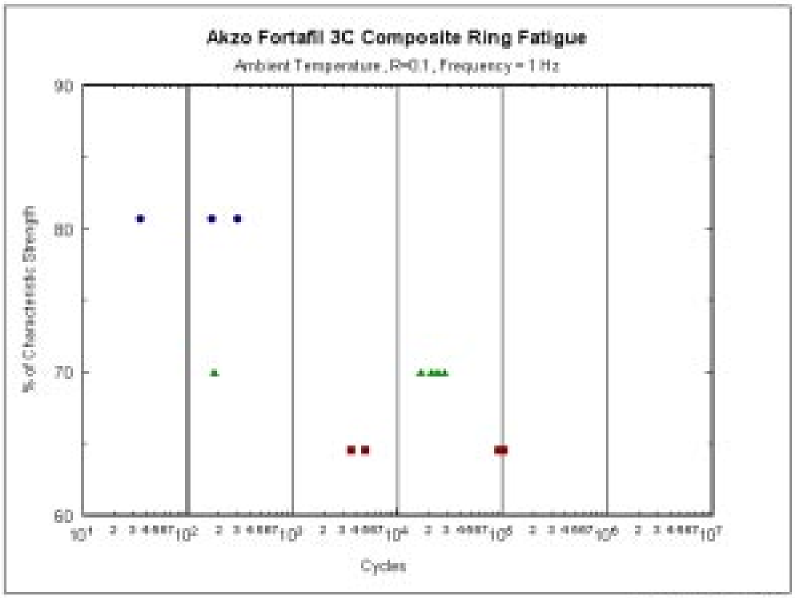


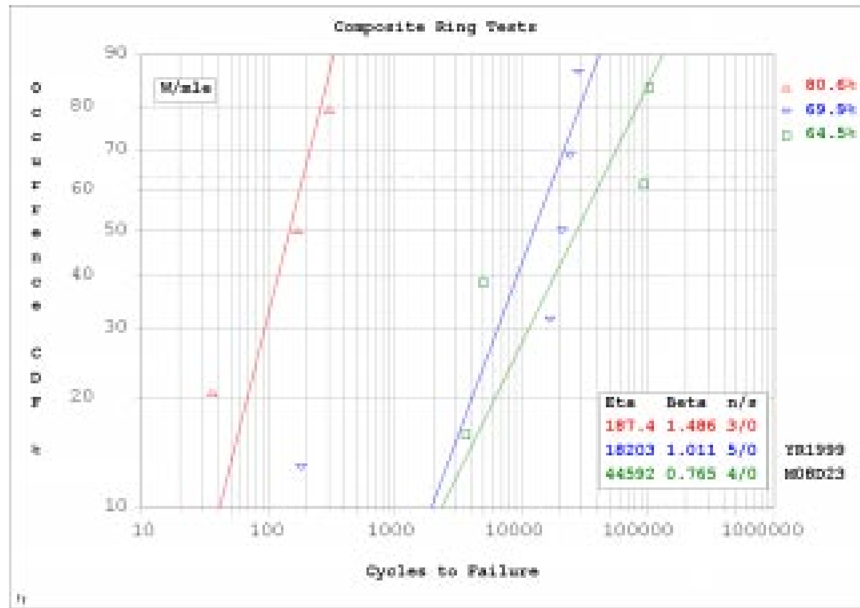


Composite Ring Hoop Tensile Strength

- Akzo Fortafil 3C/ERL2258 ring composition
  - V_f = 66.2%
  - V_r = 31.5%
  - V_v = 2.3%
- Average strength
  - 1248 MPa (hydroburst) w/ 5.76% CV
  - 1206 MPa (split-disk) w/ 6.17% CV
- Strength translation
  - 51% for the large tow-size Akzo carbon fiber
  - 85% typically achieved using the wet-filament winding method with aerospace grade 12K tow-size carbon fiber

Composite Ring Tension-Tension Fatigue





Based on a Weibull analysis of the fatigue data, a design safety factor of 2.25, and a 15,000 cycle life it does not appear that fatigue will be a critical failure mode.

Subscale Pressure Vessels

- Fabricated by Lincoln Composites
  - 22.9-cm diameter Type 4 cylinders
  - Reduced wall thickness
  - Design failure pressure of 27.6 MPa
  - Grafil 34-600 (48K tow) carbon fiber
- Cylinders were pressurized using hydraulic oil at a rate of 70-kPa/second
- Elevated temperature tests were conducted by preheating the oil and the circulating the oil through the vessel until equilibrium was reached

Subscale Pressure Vessel Burst Tests

Test No.	Burst @ 23C (MPa)	Burst @ 82C (MPa)
1	27.0	27.3
2	25.9	26.7
3	24.8	25.4
Average	25.9	26.5

Summary

- Cost and durability of Type 4 CNG storage tanks are major factors that have inhibited the growth of CNG as an alternative fuel
- Introducing lower cost, large tow-size carbon fiber has the potential for tremendous cost savings
- Manufacturing and durability studies were conducted on the Akzo Fortafil 3C carbon fiber to evaluate its performance and to identify any design impacts
- Required manufacturing modifications included larger pulley widths, increased fiber tension, and larger bandwidths

Summary Continued

- Additional process trials are needed to achieve lower void contents and to increase the strength translation
- New test methods were developed for conducting impregnated strand tests and hydroburst tests of composite rings
- Strength data was generated for designing CNG tanks with the required safety factor
- Fatigue was identified as not being a critical failure mode
- Additional data is needed for stress rupture of large tow-size carbon fiber composites