GENERAL DYNAMICS
Armament and Technical Products

General Dynamics Armament and Technical Products – Lincoln Operations

Aerospace/Defense Structures

TUFFSHELL

NGV & Hydrogen Fuel Tanks

Oil & Gas Tubulars

Development of an All-Composite Tank for High Pressure Hydrogen Storage

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Product Lines

- Aerospace/Defense
  - Pressure Vessels
  - Rocket Motor Cases
    - Strategic
    - Tactical
    - Satellite
  - External Aircraft Fuel Tanks
  - Launch Tubes
  - Drive Shafts
  - Metal Bond HC
  - Missile/Satellite Structures
- Oil/Gas & Commercial
  - Offshore
    - Risers (Drill & Prod.)
    - Accumulator Bottles
    - Choke & Kill Lines
  - Other
    - Drill Pipe
    - Drillable Casing
    - Rolls & Shafts
- Natural Gas Vehicles
    - All Composite Tanks
    - Accessories
    - Hydrogen Applications

Pressure Vessel Experience

- Fabrication of Liners In-House and Outside
- Over 80 Configurations (all liner types)
- Over 75,000 Pressure Vessels Produced
- Water Volume from 4 ci to 600 cf
- Operating Pressures from 300 psig to 25,000 psig
- Contained Fluids: N_2, Hydrogen, Air, Oxygen, N_2O_4, Hydrazine, Xenon, Helium, Argon

Hydrogen Fuel Storage Technologies

- In what form (or feedstock) will Hydrogen be available?
- What are the key factors relating to Hydrogen fuel storage and retrieval?
- What onboard vehicle storage method will be used?
- The solution must be "agony neutral" or "transparent" to the consumer.

On-Board Storage Methods

- Direct Hydrogen Storage
  - Cryogenic Liquid
  - High-Pressure Gas
  - Solid-State Methods
    - Metal Hydrides
    - Adsorption (Carbon Nanotubules)
    - Glass Microspheres
- Indirect Hydrogen Storage
  - Methanol, LNG, CNG, Gasoline
  - Electrolysis

Why Direct Hydrogen Storage?

- Direct hydrogen vehicles are the most efficient and least complex.
  - ➢ Decouples energy sources from the vehicle
  - ➢ Simplifies vehicle systems (drive-train and fuel storage)
  - ➢ Provides acceptable range
- Gaseous storage is the most practical, especially for passenger vehicles.

Issues Relating to High-Pressure Gaseous Storage

- Storage pressures of 34MPa (5000 psi) to 70MPa (10,000 psi) are desired.
- High-Pressure components (valves, fittings) must be developed.
- High-Strength composite materials will be required to minimize weight.
- Fuel tank standard(s) will be required to help ensure safety and acceptance.

Hydrogen Fuel Tank Standard

- Currently, there are no formal regulations or standards that specifically address high pressure hydrogen storage for vehicles.
- ISO/CD 15869 is being developed to address the design, manufacture, and qualification of vehicle fuel tanks.
- The draft standard is based on ISO 11439, which addresses fuel tanks for compressed natural gas vehicles.

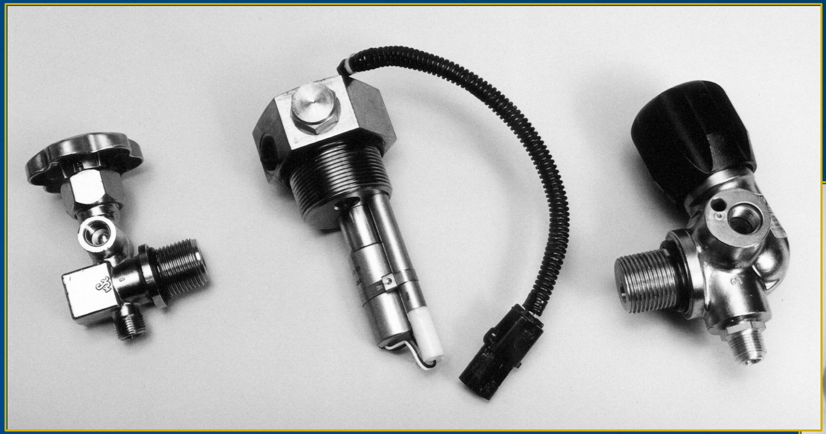
Proposed ISO* Tests for Hydrogen Storage Tanks

Material Tests	Non-Destructive Tests	Destructive Tests
Tensile tests for steel and aluminum tanks and liners	Extreme temperature pressure cycling	Environment test
Impact test for steel tanks and liners	Coating tests	Bonfire test
Corrosion tests for aluminum	Leak test	Penetration (gunfire) test
Sustained load cracking tests for aluminum	Hydraulic test (volumetric expansion or proof)	Composite flaw tolerance tests
Brinnell hardness test	Ambient temperature pressure cycling	Accelerated stress rupture test
Tensile properties of plastics	Permeation test	Drop test
Softening temperature of plastics	Hydrogen gas cycling test	Leak Before Break test
Resin shear strength	Boss torque test	Hydrostatic pressure burst test
	High temperature Creep test	

* ISO/CD 15869

Fuel Tank Hardware

- Valves and Pressure Relief Devices must be evaluated for higher pressures and hydrogen compatibility.



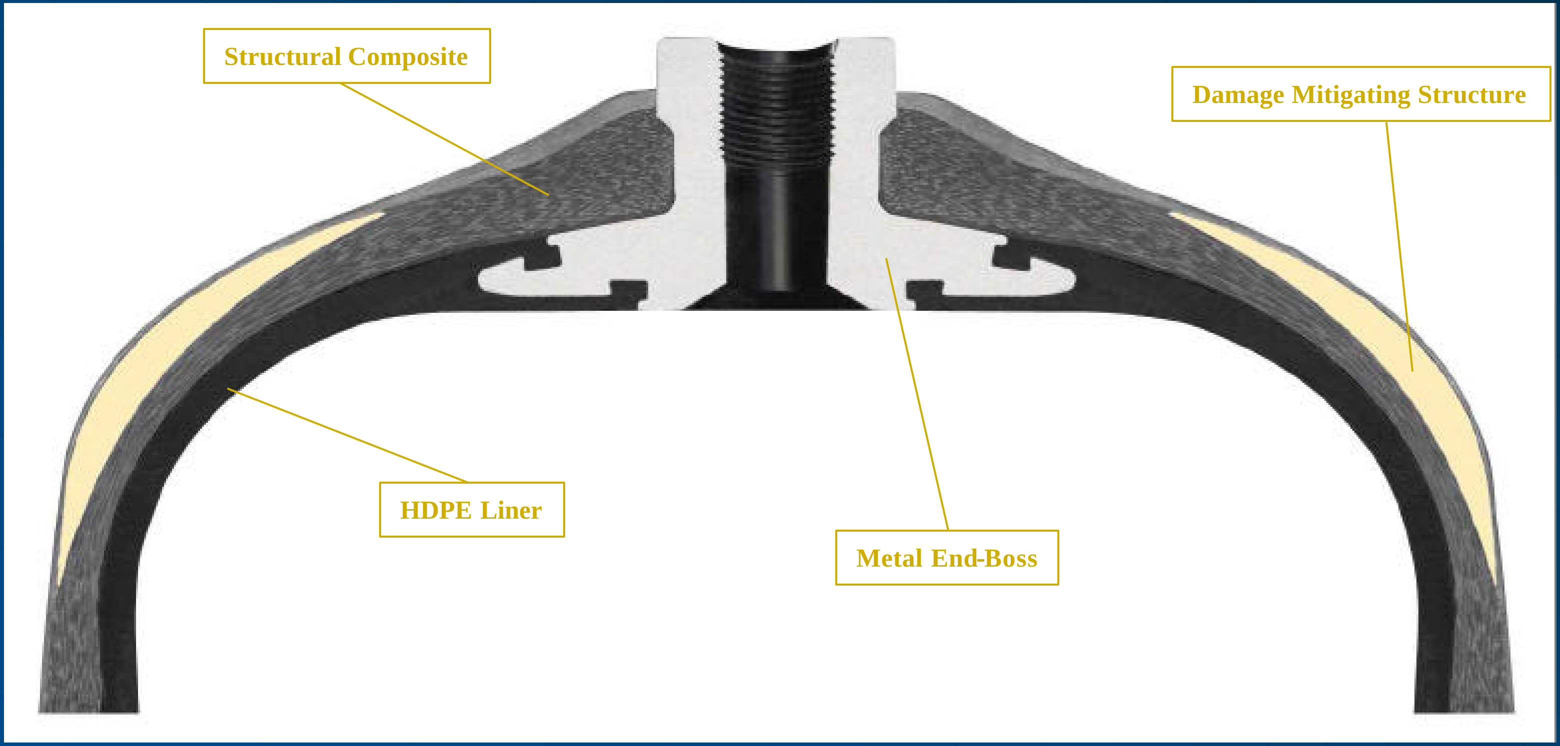
Comparison of Hydrogen Fuel Containers

Criteria	Carbon fiber, HDPE liner (Type 4)	Carbon fiber, aluminum liner (Type 3)	Comments
Weight	5	5	
Cost	3	2	Cost of aluminum is greater than that of HDPE.
Cycle life	5	2	Carbon fiber provides excellent cycle life, as does HDPE, but aluminum has a lower fatigue life.
Stress rupture life	5	5	Carbon fiber provides excellent stress rupture performance.
Lead time	4	2	Aluminum products for making liners are often long lead items.
Permeation resistance	3	4	Aluminum liner offers better permeation resistance.
Damage tolerance	4	4	
Overall (Total)	**29**	**24**	
Notes: 5 = best performance, 3 = acceptable performance, 1 = unacceptable performance			

Material Compatibility Issues

- Hydrogen “embrittlement” is a major concern for most tank materials.
- Materials used in All-Composite tank are not susceptible to hydrogen attack.
  - Carbon/Epoxy Laminate
    - No homogenous structures
    - Carbon fiber is inert
    - Epoxy resin not affected
  - HDPE Liner has well-documented resistance
  - Aluminum is one of the few metals with only minimal susceptibility

All-Composite Tank Features



U.S Patents 5,429,845 and 5,476,189

All-Composite Tank Design

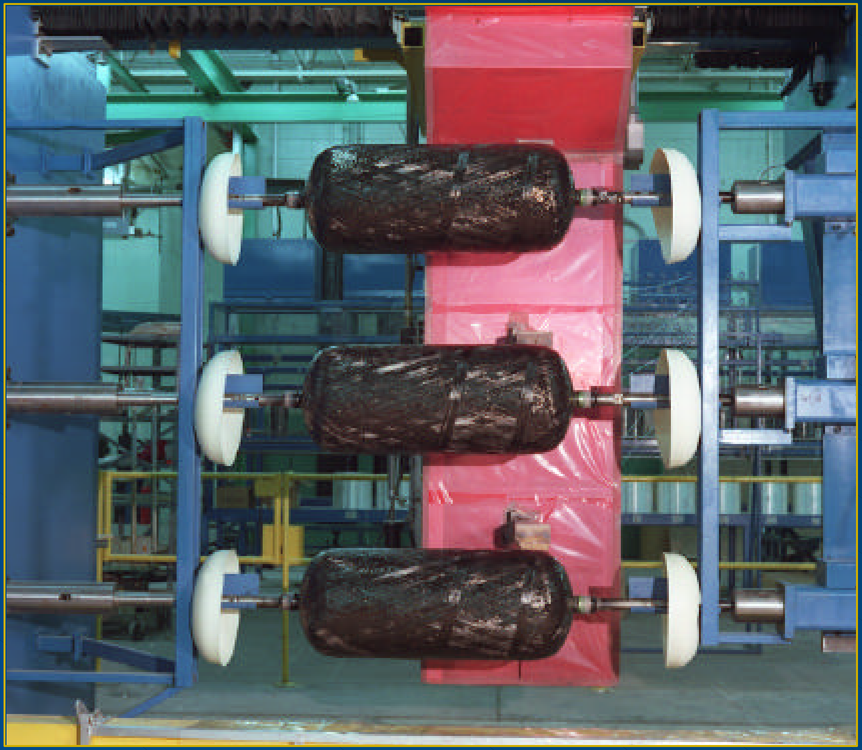
- Structural Analysis
  - ➢ Finite element analysis (FEA) and netting analysis
    - Axi-symmetric FEA model
    - Commercial Code (ANSYS) with customized pre-post processors
  - ➢ Post-processor converts to fiber stresses
- Fracture Performance
  - ➢ Cyclic Fatigue life far exceeds the use-life requirement
  - ➢ Stress Rupture (at 20 years predicted reliability is .999999

All-Composite Tank Manufacture

- Liner
  - End-bosses machined from bar stock or impact extrusions
  - Domes are injection molded
  - Mid-section is extruded pipe
  - Domes are welded to pipe section
- Composite Laminate
  - Carbon and glass fibers
  - Proprietary epoxy resin

Liner Manufacture

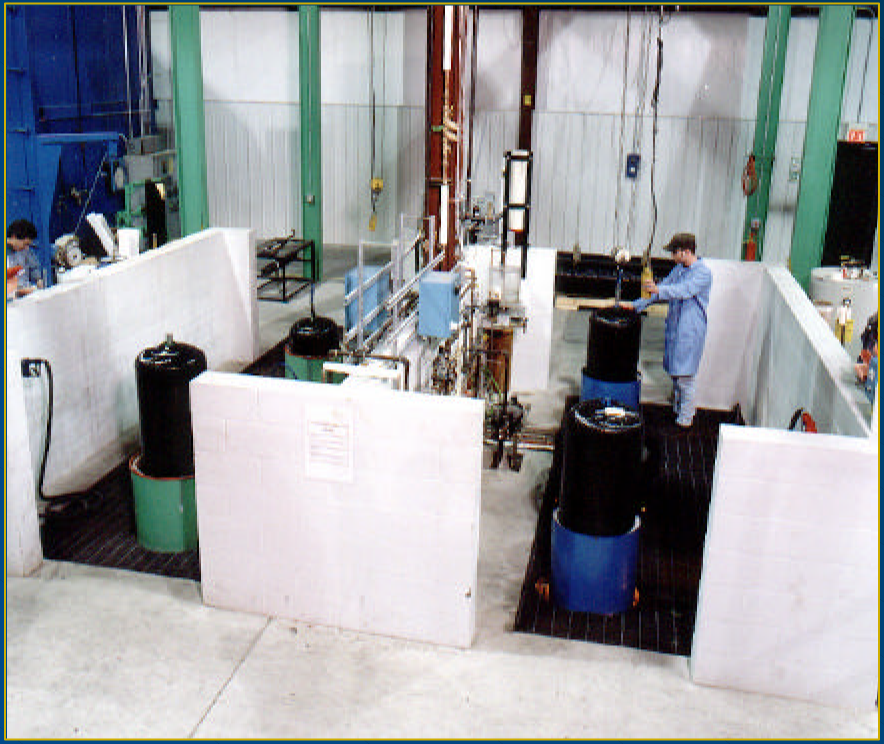
High-Speed Filament Winding



Acceptance Testing

- Hydrostatic Pressure Test
  - 1.5 times Service Pressure
  - Elastic Expansion evaluated
- Gaseous Leak Test
  - Valve(s) installed
  - Test @ Service Pressure
  - Trace Gas detected and measured
- Lot Sample Destructive Testing
  - Cycle Test
  - Burst Test

Pressure Testing



Development and Qualification Testing

- A variety of tests have been conducted on 35 MPa (5,000 psi) tanks.

Permeation	Drop Impact
Environmental	Accelerated Stress Rupture
Bonfire	Penetration (Gunfire)

- Approvals have been received from MITI (Japan).
- Limited testing has been completed on a 70 MPa (10,000 psi) tank design.

Permeation Testing

- Pressurized with hydrogen to Service Pressure.
- Sealed in chamber for a minimum of 500 hours and monitored for permeation and leakage.
- Permeation limit is based on tank water volume.

Hydrogen Permeation Requirement

- Draft version of standard specifies 1.0 cc/hr/liter (derived from NGV tank standard).
- Proposal has been made by various groups to change requirement to 10 cc/hr/liter.
  - Draft requirement could increase tank weight and cost without providing safety.
  - Proposal (10 cc/hr/liter) is based on conservative calculations.

540L Tank	34 MPa Service Pressure
Elevated temperature	30 m^3 enclosed garage
4.1% flammability limit	Margin of Safety of 2

Permeation Test Results

- Multiple test methods employed
  - ➢ Gas Chromatography, Pressure Decay, Mass Spectrometer
- Test results varied depending on method and liner "formulation"
  - ➢ Permeation rates for "standard" liners ranged from 0.54 to 1.48 scc/hr/L.
  - ➢ Permeation rates for "formulated" liners ranged from 0.19 to 0.26 scc/hr/L.
- Special attention required for valves and fittings!

Vent Test

- This is not a standard qualification test.
- Pressurized with hydrogen to Service Pressure.
- Maintained at pressure for 500 hours.
- Vented (uncontrolled release) and inspected for liner buckling and deterioration of boss-to-liner seal.
- Tank was leak tested and then liner was dissected.

Drop Impact Testing

- Drops performed at various heights and orientations.
- Tank pressure cycled to 43 MPa (6250 psi) more than 15,000 times.
- Burst pressure was greater than 82 MPa (12,000 psi).

Bonfire Testing

- Pressurized with hydrogen to Service Pressure.
- Equipped with valve and pressure relief device.
- Horizontal orientation over the fire source.
- Tank must vent contents without rupture.

Penetration (Gunfire) Testing

- Pressurized with hydrogen to Service Pressure.
- 7.62mm projectile shall penetrate at least one tank wall @ 45º angle.
- Tank shall not fragment.

Hydrogen Vehicle Applications

- Neoplan Hybrid Bus in Germany
  - Two (2) buses in operation
  - Each bus carries four (4) tanks
  - Tanks operate at 20 MPa service pressure
- California Fuel Cell Partnership
  - Supporting auto manufacturers with new lightweight, high-pressure (35 Mpa) tank configuration
- Work with other vehicle OEM's that cannot be mentioned.

Higher Pressures?

- Numerous inquiries about pressures as high as 70 MPa (10,000 psi).
- 70 MPa is “not an issue” for All-Composite tank.
  - ➢ Cycle life is not affected
  - ➢ Composite technology is proven
  - ➢ Lead-time is minimal
- Lincoln Composites has already developed a 70 MPa (10,000 psi) tank.

70 MPa (10,000 psi) Tank

Service Pressure	70 MPa (10,000 psi)
Burst Pressure	175 MPa (25,400 psi)
Dimensions	434 x 1308 mm (17.1 x 51.5 in.)
Weight	81 kg (178 lb.)
Water Volume	112 liters (6822 in^3)
Capacity H2	4.4 kg (9.7 lb.)

Summary

- Key issue remains: How to provide hydrogen to the fuel cells?
  - ➢ Store it onboard the vehicle (direct hydrogen option)
  - ➢ Produce the hydrogen onboard (onboard fuel processor option)
- Direct hydrogen option provides the best near-term solution.
- Technology already exists for high-pressure gas storage onboard vehicles.

NGVs: A Pathfinder for Hydrogen

- Technology Development
- Component Standards
- Fuel Infra-structure
- Economics