Storage of high pressure hydrogen as a fuel for vehicles

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The team of the High Pressure Vessels and Composites Laboratory

Testing methods:
- Universal testing machines (static, dynamic and fatigue)
- Creep
- Pressure test up to 2400 bar
- Climatic chamber (high and low temperatures)
- Microscopic analysis
- Acoustic emission
- Thermography
- Non-standard tests

Technologies:
- Filament winding
- Pultrusion
- Hand lay-up
- Vacuum Infusion (VI)
- Resin Transfer Moulding
Centrifugal moulding

Military pontoon (floating) bridge concept
Zalety kompozytów w porównaniu z metalami

PZL W-3RM Anakonda (PZL W-3 Sokół) 1992
Which way to choose?

- Gasoline
- Diesel oil
- Natural gas
- Fuel cells (hydrogen)
- Solar energy
- Biofuels
- Methanol
- Under investigation

Wood gas vehicles

Gasifier is visible in the rear, the fuel storage on the roof. Along the roof and pillars, hot wood gas runs to the cooler mounted in the front of the vehicle.
CNG-fuelled passenger and utility cars

All of the automotive producers offer CNG car models

Fiat Ducato 140 Natural Power

Number of CNG-fuelled vehicles in the world

Total ~2.3 million

14,883

Canada 20,000

USA 120,000

Columbia 12,000

Bolivia 6,000

Argentina 120,000

Venezuela 41,000

Brazil 120,000

Egypt 24,600

Bolivia 8,48

Russia 35,000

Indonesia 3,000

New Zealand 12,000

Canada

USA

Columbia

Bolivia

Argentina

Venezuela

Brazil

Egypt

Bolivia

Russia

Indonesia

New Zealand
INTERVIEW: III Industrial Revolution a solution for crysis

Jeremy Rifkin: To defend European quality of life and European social model a vision of a new European project is needed.

The Third Industrial Revolution is the plenitude of small energy sources from: wind, sun, water, geothermal, heat pumps, biomass etc.

Hydrogen-fuelled vehicles - Berlin
Hydrogen-fuelled forklift trucks

Hydrogen-fuelled vehicles (CNG and CH2)

Hydrogen Test Vehicles
Hydrogen-fuelled vehicle
(fuels with water while driving to fire)

Future car equipped with hydrogen fuel cells
Concept of placement of components of a hydrogen-fuelled vehicle (AUTOnomy) - fuel cells in the chassis

Pressure Vessel Components
Co-operation in StorHy project:

- **testing** of high pressure vessels
  - Cyclic tests at ambient and extreme temperatures
  - Burst tests
- concept of „on-line” **monitoring** sensor system for high pressure vessels (optical fiber sensor based)
- **creep test** of NOL-type composite specimens
- **modelling** of running damage process and current damage level
StorHy Vision

... introduce and for cars, busses
and trucks as quickly as possible

Gas

Liquid

Solid

Source: Dynetek
Source: SIP Cryo
Source: FZK

Transport of hydrogen

Tube Trailer

Composite Trailer

Source: Dynetek
Source: SIP Cryo
Source: FZK
**Definition of composite materials**

- Fibers: Carbon, Aramid, Glass
- Resin: Epoxy, Polyester, Vinyl-ester
- REINFORCEMENT: strength, stiffness
- Load direction: Fiber coating, Fiber orientation
- Composite

**Reinforcing fibers characteristics**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Glass fiber</th>
<th>Basalt fiber</th>
<th>Aramid fiber</th>
<th>Carbon fiber</th>
</tr>
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<tbody>
<tr>
<td>Strength</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Impact strength</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Fatigue strength</td>
<td>-</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Creep resistance</td>
<td>-</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Resistance to acidic, basic, damp environment</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
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<tr>
<td>Radiation resistance</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td>Fire resistance</td>
<td>-</td>
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<tr>
<td>Prica</td>
<td>-</td>
<td>+</td>
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</table>
Carbon fiber production

Vessel mass comparison according to vessel type
Filament winding

Braiding of a vessel at TU Dresden
Vessels made at the Institute

Liners made in the Institute
Gas storage for CNG engines

Focus on WP5: Vehicle Performance Assessment
Crashworthiness for Side Pole Impact

Safety: Testing of CH2 Cylinders

- B1 Tensile Test
- B2 Softening/Melting Temperature Test
- B3 Glass Transition Temperature Test
- B4 Resin Shear Strength Test
- B5 Coating Test
- B6 Coating Batch Test
- B7 Hydrogen Compatibility Test
- B8 Hardness Test
- B9 Burst Test (minimal burst pressure value 164.5 MPa)
- B10 Ambient Temperature Pressure Cycling Test (45k pressure cycles 2 - 87.5 MPa)
- B11 LBB Performance Test
- B12 Bonfire Test
- B13 Penetration Test
- B14 Chemical Exposure Test
- B15 Composite Flaw Tolerance Test
- B16 Accelerated Stress Rupture Test
- B17 Extreme Temperature Pressure Cycling Test (-40°C and 85°C, relative humidity 95%)
- B18 Impact Damage Test
- B19 Leak Test
- B20 Permeation Test
- B21 Boss Torque Test
- B22 Hydrogen Gas Cycling Test
- B23 Hydraulic Test

* Draft ECE Compressed Gaseous Hydrogen Regulation, Revision 12b, 12.10.03, GRPE Informal Group: Hydrogen/Fuel Cell Vehicles
**High-pressure Vessels Laboratory**

**Burst tests**

WUT tests characteristics:
- Max. test pressure - 3000 bar
- Rate of pressurization - max 5 bar/s
- Working medium - degassed water

Burst pump  
Control panel  
Pneumatic engine
Hydraulic Burst Test at ambient temperature

Burst Test Results:
- maximum burst pressure more than 1645 bar
- optical sensors registered strain changes during pressurization
- slope of a green curve changed during pressurization

Accelerated stress rupture test setup

Stress rupture test procedure (in accordance with ECE R110):
1. A cylinder shall be immersed in water at 65 °C.
2. Then cylinder shall be pressurized to 260 bar and held at this pressure and temperature for 1000 hours (~6 weeks).
3. Burst test – the minimum burst pressure shall exceed 85% of designed burst pressure.
A.18. High temperature creep test – test procedure

One finished cylinder was tested as follows:

a) The cylinder was pressurised to 26 MPa and held at a temperature of 100 °C for not less than 200 hours.

b) Following the test, the cylinder shall be put to the hydrostatic expansion test A.11, the leak test A.10, and finally the burst test A.12.

Cycling tests

WUT tests characteristics:

- Max. cyclic pressure - 1400 bar
- Min. cyclic pressure - 0 bar
- Number of cycles - < 10 cycles / min (depending on vessel capacity, cyclic pressure, etc.)
- Working medium - oil, glikol

Hydraulic equipment for cycling tests

Shape of the pressure-time curve can be modified. During the whole cycle increase and decrease time of the pressure is controlled.

Control panel
Extreme Temperature Pressure Cyclic Tests

**Extreme temperature test characteristics:**

- Min. chamber temperature – 52 °C
- Max. chamber temperature + 90 °C
- Max. humidity 100%

Cyclic test at extreme low temperature (2 cycles/minute)

Test vessel inside the climatic chamber
Type-3 hydrogen vessel during a fatigue test
Test of vessel notch resistance

a) Placement of the notch  
b) Vessel rupture  
c) Damage site

Fire test - 200atm, natural gas
Destructive tests of a vessel using gas

Dynamic strength tests
Impact damage test procedure (in accordance with ECE R110 – for CNG):

1. Cylinder shall be dropped in a horizontal position with the bottom 1.8 m above the surface.
2. Cylinder shall be dropped vertically on each end at a sufficient height above the floor or pad so that the potential energy is 488 J, but in no case shall the height of the lower end be greater than 1.8 m.
3. One cylinder shall be dropped at a 45° angle onto a dome from a height such that the centre of gravity is at 1.8 m, if the lower end is closer to the ground than 0.6 m, the drop angle shall be changed to maintain a minimum height of 0.6 m and a centre of gravity of 1.8 m.
4. Cylinders shall be pressure cycled (20 + 260 bar for 1,000 cycles x specified service life in years). The cylinders may leak but not rupture, during the cycling.

Tests of resistance to chemically-aggressive environment (battery acid)
Reaction on ballistic penetration

Collision under the viaduct

- Ciśnienie 200 barów, zerwana i zniszczona osłona
- jeden zbiornik został rozszczelniony
- w pozostałych nastąpiło uszkodzenie płaszcza nośnego
Auto Fire with Compressed Natural Gas (CNG) Fuel Tank Explosion

March 2007, Seattle, USA
- Honda Civic CNG

The explosion hazard for CNG and CH2 pressure vessels

Ranges of flight path of splinters (the assumptions are based on gaseous burst experience of BAM)

Source: BAM
Hydrostatic expansion test - Water jacket test

Water jacket test procedure:
1. A test vessel shall be filled with a nearly incompressible liquid (usually water or oil).
2. Then test vessel shall be immersed in another cylinder fully filled with water.
3. Then cylinder shall be pressurized to 300 bar and held at this pressure for at least 30 seconds and depressurized again.
4. The water level in the graduated glass is then examined.

CH2 vessel, over 1640 bar burst pressure
The scheme of the burdening composite pipe in any system principal stresses:
1 - pump, 2 - apparatus for measuring the effects of EA,
3 - Pressure transmitter, 4 - tested composite pipe,
5 - testing machine, 6 - security guard,
7 - control computer, 8 - strain gauge bridge

Pressure tests of tubular specimens

Test emplacement
Slow tensile tests

Increase of loading force in a function of the duration of the experiment (1.75 N/sec, 17.5 N/sec and 175 N/sec)

NOL specimens during the slow tensile test

Creep test (Static fatigue) of composite for high pressure H2 vessels

- Creep strength of composite material for high pressure vessels evaluation.
- Specimen load level responds to the load in vessel’s composite layer (when it is filled with CH2).
- The ring NOL (Naval Ordnance Laboratory, USA) specimen was assumed:
  - fiber continuity (without breaks),
  - ring shape specimen corresponds to the strain state in cylindrical part of vessel,
  - NOL specimens dimensions were obtained by FEM modeling and tensile tests

NOL specimens (photo and FEM model) as well as innovative displacement sensor heads
Acoustic emission recorded during fatigue testing of the tank

1 - the location of the event, 2 - RMS time,
3 - amplitude of events in time, 4 - pressure course.

Temperature distribution at the surface of a vessel during fatigue test.
Burst vessels after pressure tests

Fatigue test using elastoric filling

MTS hydraulic pulsator

Pipe specimen

Thermographic system
VarioCAM hr head
Thermal images show probable fault zones in fatigue test

Stan próbki przed rozerwaniem

Moment rozerwania próbki

Stan próbki po rozerwaniu

Próbka po rozerwaniu

Thermal images show probable fault zones in fatigue test (cylindrical part of filament winding pressure vessel)

Stan spoczynkowy próbki

Stan próbki przed rozerwaniem

Moment rozerwania próbki

Stan próbki po rozerwaniu
Tests of the cylindrical part filament winding pressure vessel

<table>
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<tr>
<th>Numer architekturny</th>
<th>Liczba przepływów</th>
<th>Udział pustek [%]</th>
<th>Grubość ścianki [mm]</th>
<th>Odkształcenie objętościowe [cm³]</th>
<th>Udziały węglowe wiertnia sztucznego</th>
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