HyCOMP

Enhanced Design Requirements and Testing Procedures for Composite Cylinders intended for the Safe Storage of Hydrogen

HyCOMP dissemination workshop

AFNOR, Paris, France

Speaker: Clémence DEVILLIERS

March 5th 2014

Coordinator: Ms Clémence DEVILLIERS, AIR LIQUIDE

Partners: Armines, BAM, WUT, CEA, JRC, CAQ, Faber, HEXAGON, CCS

HyCOMP is supported by the European Union through the Fuel Cell Hydrogen Joint Undertaking (FCH JU)

Agenda *(morning)*

Time	Topic	Speaker
9h30 – 9h45	Welcome	H. Barthélémy, *Air Liquide*
9h45 – 10h15	Project presentation	C. Devilliers, *Air Liquide*
10h15 – 10h55	Damage accumulation in the composite wrapping: impact, rate and measurement (30 min presentation + 10 min questions)	K. Chou / S. Joannès, *Armines*
10h55 – 11h15	*Break*	
11h15 – 11h55	Fatigue failure of cylinders (30 min presentation + 10 min questions)	G. Mair, *BAM*
11h55 – 12h30	Characterization of service life (20 min presentation + 10 min questions)	P. Heggem, *Hexagon*
12h45 – 14h00	*Lunch and coffee (*)*	

(*) Lunch is served at the cafeteria. The price is 12€/person, including coffee.

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Agenda *(afternoon)*

Time	Topic	Speaker
14h00 – 14h40	Manufacturing Quality Assurance: effect of variability of fiber and matrix characteristics (30 min presentation + 10 min questions)	A. Agnoletti, *Faber*
14h40 – 15h20	Design requirements and testing procedures (30 min presentation + 10 min questions)	C. Devilliers, *Air Liquide*
15h20 – 15h30	*Break*	
15h30 – 17h00	Q&A session, discussions	All

Overview of the project

- HyCOMP is a Pre-Normative Research project on composite pressure vessels
- Started in January 2011 and will finish on **March 31st 2014** (39 months)
- Budget: **3 802 542 €** of which **1 380 728 € (36 %)** is funded by FCH JU
- Partnership:

• 3 manufacturers:

T4 cyl: CAQ, HEX

T3 cyl: Faber

• 3 academics:

BAM, Armines, WUT

• 2 research institutes:

JRC, CEA

• 1 gas supplier: *AL*

• 1 expert in RCS: *CCS*

• 1 management expert: *ALMA*

Content

- Context
- Key issues in current standards and regulations
- General objectives of the project and expected outcomes
- Approach followed
- Materials and cylinders tested

Context

- Hydrogen storage is a key issue for the extensive use of H_2 as an energy vector & for the success of the whole hydrogen value chain

- Need to support market deployment of hydrogen energy: 2015-2020
  - Different technologies for H2 storage:
    - In a cryo-compressed form, or solid storage in metal hydrid materials, etc…
  - But the most mature technology for storing hydrogen is **in compressed form** in high-pressure cylinders

Context

- Composite cylinders are already used to store H2 for different functions
  - Onboard storage
    - Automotive
    - Public transport
    - Material handling (forklifts)
  - Transportable storage
    (Cylinders, bundles and tube trailers)
    - Back-up power supply
    - Off-grid power supply
    - Mobile power generation
  - Stationary storage
    - HP buffers for hydrogen refueling station
    - Storage of H2 produced from intermittent sources

Material Handling

Fuel cell vehicles

Hydrogen buses

Off-grid equipment

Mobile generator

Context

- Need to improve the performance of storage vessels
  - Performance objectives in terms of cost efficiency, safety and improved logistics (high quantity transported and low compacity)
    - Gravimetric storage capacity = m_{H2} / (m_{system}+m_{H2}) (in wt.% hydrogen) **≥ 4,8%**
    - Volumetric storage capacity = m_{H2} / V_{system} (in g_{H2}/L) **≥ 23g_{H2}/L**

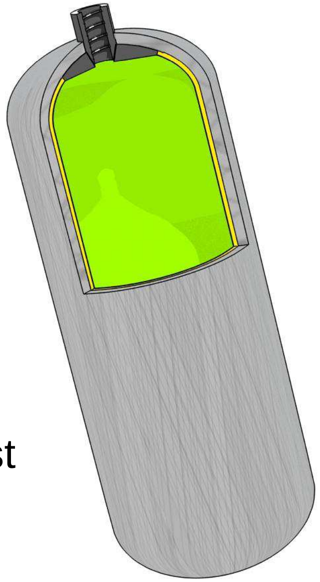
Targets fixed by the FCH-JU by 2015-2016

High pressure storage of H_2 (700 bar) in **carbon fiber composite cylinders** => most suitable technology at this stage

9L cylinder especially designed for HyCOMP

Fully wrapped composite cylinders are made of:

1. A metallic boss
2. A liner: load sharing (type III) or non load sharing (type IV)
3. A filament wound composite wrapping (most often carbon fibers and epoxy resin)



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Context

- Beyond the improvement of gravimetric and volumetric performance of cylinders, there is a strong need to have composite pressure vessels that are:
  - Reliable and safe
  - Cost competitive

- Means of action to ensure safe and cost competitive composite cylinders:
  1. Optimize CPV design → demonstrate that a **reduction of safety factor** is possible while ensuring structural integrity of CPV
     - Safety Factor ↔ Composite thickness ↔ Quantity of Carbon Fibers ↔ Cylinder cost
     - **Need to have a well-defined safety factor**
  2. Propose **testing procedures adapted to specific features of composite materials**, for:
     - Type approval
     - Manufacturing quality assurance
     - In-service inspection

Key issues in current standards and regulations

1. **Damage mechanisms** in composites materials are different from metals

- **Metals**: failure due to cracks initiation and propagation until reaching a critical size

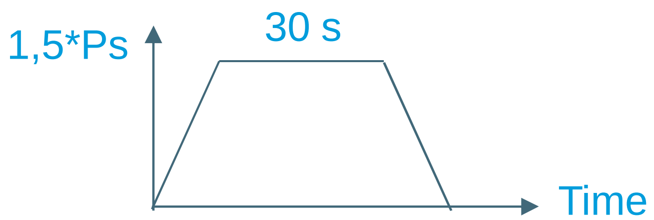
- **Carbon fiber composites**: accumulation of fiber breaks
  - Damage initiation when weaker fibers break
  - Stress transferred over time to intact fibers via the viscoelastic matrix, which can the break under the increased load
  - Formation of clusters of broken fibers
  - Critical size then rupture of the composite

Mechanism active under static load

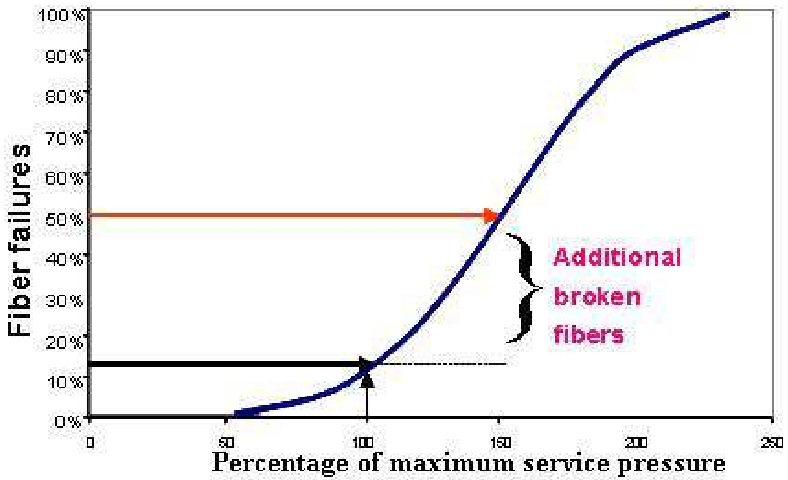
→ **Potential stress rupture** of the composite

Key issues in current standards and regulations

2. Therefore, tests and requirements in current standards need to be improved to better address structural integrity of composite cylinders, e.g.:
   - Requirements in **burst pressure ratio** for type approval
   - **Hydraulic proof test** for batch approval and inspection test



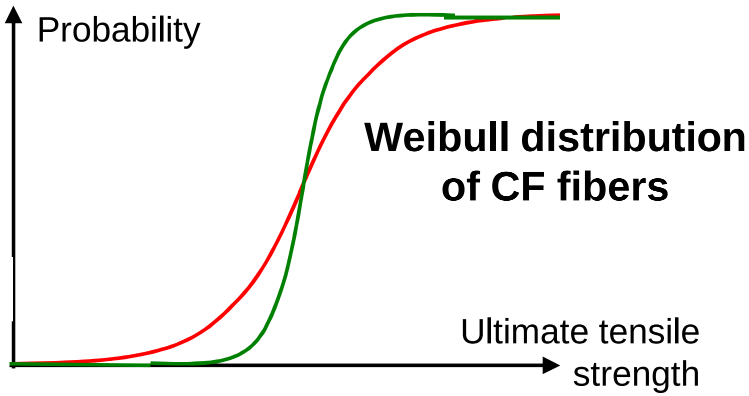
- <u>For metals</u>: limit crack propagation by yielding at crack tip
- <u>For composites</u>: Does not reveal the real state of damage of composite cylinders



Key issues in current standards and regulations

3. Additionally, manufacturing quality assurance methods adapted to composite need to be developed:

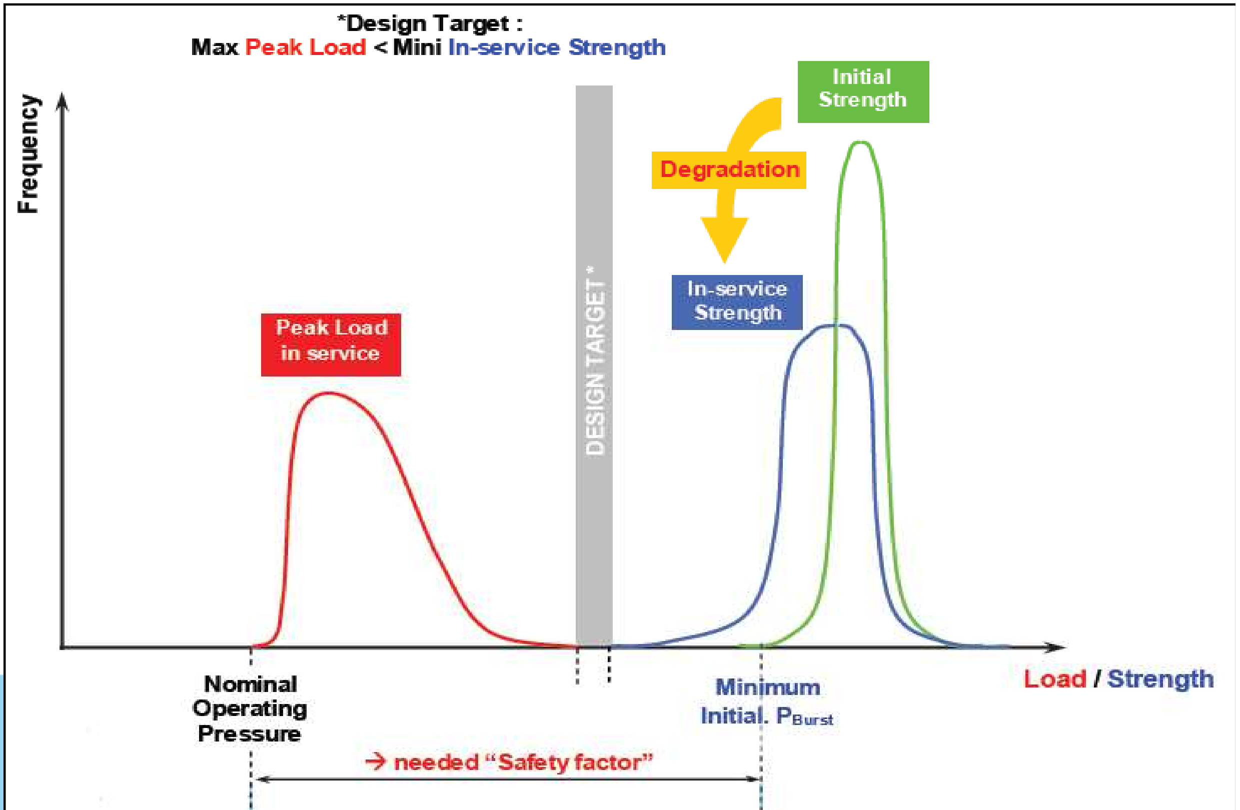
- Need to quantify the impact of **CF tensile strength distribution** on cylinder performances
- Need to quantify the impact of **process parameters variability** on cylinder performances



- Need to develop the approaches to demonstrated that all manufactured cylinders have the expected performances

General objectives of the project

- Provide a comprehensive basis for specifying performance-based requirements for high-pressure composite cylinder, allowing to optimize design
  - Better understanding of damage accumulation mechanisms in composite cylinders
  - Assessment of the damage accumulation rate as a function of:
    - the type of load (cyclic, static),
    - the level of load (pressure)
    - and environmental conditions (temperature, humidity)
  - Definition of a damage accumulation limit for preserving structural integrity



Expected outcomes

- **Recommendations to Industry** for design and testing of high-pressure hydrogen cylinders for automotive, transport and stationary applications
  - Fully **performance-based design criteria** (including acceptable stress ratios for carbon fibers) for composite cylinders allowing to optimize design
  - More specific **qualification test programs** for an improved cylinder **manufacturing quality control**
  - A common rationale and **improved inspection methods** to determine the level of damage in the cylinder composite wrapping
- Recommendations to support **Regulations, Codes & Standards** (RCS)

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WP1 – Air Liquide
Executive Committee / Project management

Approach followed

Material scale

WP2 - Armines
Damage accumulation in wrapping : Rate, damage limits & measurement

Cylinder scale

WP3 - BAM
Effect of static and cyclic load
T3 : load distribution
T4 : temperature and cycle depth

WP4 - Faber
Production Quality Assurance

WP5 - Hexagon
Characterization of service life

WP6 – Air Liquide
Design criteria and testing procedures

WP7 - CCS
Findings & Recommendations for industry & RCS

Materials tested

- Focus on **carbon fiber only**!
- Two different fiber/matrix systems studied:

		Plate specimens CAQ's & Faber's cylinders (Reference system)	***Hexagon's cylinders (Specific system)***
Carbon fiber		**T700** (E = 230 GPa, ε = 2,1%, UTS = 4,9 GPa)	
Epoxy resin	Commercial reference	Huntsman resin	Hexagon proprietary
	Glass transition temperature T_g	Measured around 115°C	**110°C**

All results and conclusions presented today are valid for these specific materials exclusively !!

Specimens tested

- Plate specimens
  - Unidirectional and cross-ply plates.
  - Dimensions: 300 mm x 300 mm x 1 mm in thickness
  - Manufactured by filament winding in similar conditions as cylinders
- Cylinders:

	Type III thin wall cylinder	**Type IV thin wall cylinder**	**Type IV thick wall cylinder**
Manufacturer	Faber	CAQ	Hexagon
Volume (L)	**9**		**19**
Length (mm)	635	583	920
External diameter (mm)	158	179	235
Safety factor	**2.25**		
Nominal working pressure (bar)	**300**		**700**
Min burst pressure (bar)	675		1575

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Specimens tested

- Definition of the composite pattern:
  - For Hexagon's cylinders: **commercial pattern** slightly modified and disclosed to laboratories for modeling
  - For Faber's and CAQ's cylinders: **proposed by CEA**, and deliberately simplified

9L CAQ cylinder, especially designed for the HyCOMP project

Proto n°3		
réservoir 9L Hycomp type IV		
2012 02 02_9L_CEA_HYCOMP		
couche	angle	épaisseur
L1	8,8	0,3
L2	8,8	0,3
L3	10,3	0,3
L4	10,3	0,3
L5	90	0,3
L6	90	0,3
L7	9,9	0,3
L8	9,9	0,3
L9	14,9	0,3
L10	14,9	0,3
L11	9	0,3
L12	9	0,3
L13	90	0,3
L14	90	0,3
L15	27,5	0,3
L16	27,5	0,3
L17	32,5	0,3
L18	32,5	0,3
L19	70	0,3
L20	70	0,3
L21	TR 70--> 90	0,11
L22	90	0,3
L23	90	0,3
L24	90	0,3
		7,01

THANK YOU FOR YOUR ATTENTION.

ANY QUESTION?