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Deliverable Report

WP7
Report on recommendations for design and testing

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1. Executive summary

1.1 Summary of deliverable content and initial objectives

The purpose of this deliverable is to propose recommendations for Industry regarding the design and testing of composite pressure vessels (CPVs). In this deliverable, focus has been given to recommendations intended for Industry: composite cylinder manufacturers and end-users (gas supplier). We will detail here lessons learned from HyCOMP project (experimental results and conclusions), and highlight the real meanings for Industry.

1.2 Partners involved

All partners were involved in this Work Package, especially: Air Liquide, Hexagon, Faber, CAQ CCS and academic partners.

1.3 Relation with others WPs / Tasks

This deliverable is one of the final deliverable of the HyCOMP project, whose status is public. It makes the link with all final WP deliverables (D2.4, D3.4, D4.4, D5.3, D6.4).

2. Recommendations for Industry

In the first part, we will focus on recommendations intended to composite cylinder manufacturers. We will present again the main results obtained on specimens and cylinders, and identify important parameters that need to be considered for the design and manufacturing of composite pressure vessels (CPVs). Then, in the second part we will focus on load conditions in service in order to demonstrate that a detailed discussion of conditions for reduction of safety factor should be possible.

2.1 Recommendations for cylinder manufacturers

Testing performed on specimens and cylinders were rich in conclusions that can be of high interest for the Industry, cylinders manufacturers mainly, in order to improve reliability of their products.

- **Carbon fibers**

Fibre breakage is the primary damage mechanism in unidirectional carbon-epoxy laminate under monotonic tensile loading (see HyCOMP public deliverable D2.4). Mechanical properties of carbon fibers are thus of prime importance. Testing carried out on the effect of the variability of fiber characteristics (replacement of T700 fiber with T300) has shown, as expected, that lower mechanical characteristics have a very important effect in both type 3 and type 4 cylinders. This results in a lower burst pressure (see HyCOMP public deliverable D4.4).

Even if the burst test prescribed by present regulations, norms and standards would detect such variation, **attention must be brought to the careful choice of carbon fiber**. Scattering of carbon fiber is also an important topic.

- **Resin**

Testing carried out at a specimen scale has demonstrated that resin is of prime importance in the damage accumulation rate in the composite laminates over the long-term (see HyCOMP public deliverable D2.4). Indeed the damage process is time-dependent, which is associated to viscoelasticity property of epoxy matrix, which affects the growth rate of fibre rupture clusters in the composite materials. Viscoelastic properties of the epoxy resin are governed by its glass transition temperature (T_g) and its degree of curing.

Furthermore, temperature is an important parameter influencing damage accumulation (fibre breaks) in the composite wrapping. As operational conditions (like maximum temperature in service, T_{max}) can't be changed, it is important to ensure that difference between T_{max} and T_g is sufficient so that damage does not accumulate too quickly when temperature is getting close to T_{max}. As a consequence, the choice of the resin by the manufacturer is of great importance.

This has lead to a recommendation especially addressed to cylinder manufacturers, and translated in standards by **specifications on the glass transition temperature** of the epoxy resin:

Example: T_g must be higher than T_{max} + 30°C (based on composite specimens tested in HyCOMP)

In direct link with the resin glass transition temperature is the **curing step in the manufacturing process of CPVs**. Indeed epoxy resin properties can vastly differ depending on the curing process, curing temperature, and time cured. A good curing is essential to reach the highest thermal performance characteristics of the resin.
HyCOMP has demonstrated in WP4 (see HyCOMP public deliverable D4.4) that a very low degree of curing (no curing at all) leads to poor performance of cylinders: low cyclic performance for type 3 cylinders and high scattering of burst pressure for type 4 cylinders.

Therefore, it is necessary that all attention of manufacturers must be brought to this delicate step. A control of process parameters is necessary at this stage. Therefore, there is a need of introducing a specific control of this characteristic in regulations and standards, by specifying additional requirements to verify the proper curing of the resin mix. It is then recommended to cylinder manufacturers to **control the resin mixture and curing process (by monitoring temperature, time…)**. If any, **tests in standard must be considered to verify the good curing of the resin**, like for example a Barcol hardness test to evaluate resin hardness and by consequent degree of curing.

Note: For further details, the reader must refer to the HyCOMP public deliverables D2.4, D3.4, D4.4 and D6.4.

2.2 From an end-user point of view

In WP5 "Characterization of service life", pressure loads that are likely to occur in service have been identified and quantified for each application: stationary, on-board and transportable storage. In this part, focus is given to transportable and on-board application. Stationary cylinders are not covered.

For transportable cylinders, that require a TPED approval, small cylinders that can be handled by an operator, must be differentiated from large containers that are permanently mounted or mounted in bundles (that cannot by manipulate with hands).

It has been demonstrated in the final WP deliverable D5.3, that pressure loads are very similar between on-board and transportable cylinders (small and large cylinders). A synthesis of operating conditions expected for each application is proposed in the table below for a quick comparison. Definitions in regulations use the phrase "cylinder" for containments up to 150 litres, while larger containments, up to 3000 liters, are called tubes. Beside this, the following table separates cylinders by differing criteria.

	On-board	**Small transportable cylinders**	**Large transportable cylinders**
Volume range	/	20 to 100L	50 to 10 000L
Refueling	3 min, up to 125% of service pressure	Idem	Moderate fill time (limited by delivery system performance)
	-40°C → +85°C	Temperature during and just after fill is expected to be higher than the ambient conditions.	Temperature during and just after fill is expected to be higher than the ambient conditions.
Depressurization	Can be as short as 1h Can vary from several hours to days	Several hours (1-2h to 24 hours)	Moderate depressurization rate is expected Can be as quick as or even quicker than the fill rate of the cylinders onsite
Number of cycles	7300 cycles over 20 years (one fill per day) Can be up to 21 900 cycles (3 fills per day)	Around one filling per week or per month	7300 cycles over 20 years (one delivery per day) Can be up to 15 000 cycles (2 deliveries per day)
Exposure at high pressure	Difficult to quantify, can be exposed for long periods at higher pressures Filling at cold nights and just thereafter car parked in a hot garage or hot/sunny outdoor location for a long period... In average, the cylinder pressure will be slightly above ½ the service pressure of the cylinder during its service life.	Pressure is expected to be constant at high level (100% service pressure) most of the lifetime	Pressure is expected to be higher than the service pressure (gradually reduced to rated service pressure during the transport) for ½ of the rated service life and at low pressure during the return to the production site or waiting for next loading

The main difference between these two applications is related to external mechanical impacts that are likely to occur. By impacts, we mean here real mechanical impacts (fall of a tool on the cylinder for example, or repetitive shocks between cylinders) or a fall of the cylinder itself.

- For automotive applications, it is assumed that cylinders are permanently integrated into the structure of the vehicle. Crash testing of the vehicle with cylinders onboard must demonstrate finally that the cylinder behave safe under all known conditions throughout the lifetime of the vehicle.

- For transportable applications, here again difference must be made between small and large cylinders.
  - Small portable cylinders: all kinds of mechanical impact are likely to occur: drop of a cylinder from the roof of a building or from a workbench.
  - Large cylinder permanently mounted: in this case, a limited number of scenarios are envisaged: mainly the fall of a bundle from a truck or a forklift during handling.
    - Bundles can sometimes be designed with protection plates that act as cylinder protection from external mechanical impacts.
    - Furthermore, a drop of the bundle with mounted and pressurized cylinders is required to get bundle approval. No leak of cylinder must occur.

In all cases, the external impact coming from handling of the cylinder at the production stage (cylinder drops to the floor for example) must be considered.

From this analysis, it is shown up that **utilization profile and accidental conditions of permanently mounted transportable cylinders are close to on-board storage**, rather than small and manually handled cylinders for gas transport.
For the on-board storage, Safety Factor is defined as 1.8 above the Maximum Developed Pressure, instead of 2 times test pressure P_h for transportable storage. Therefore, **there can be a potential to reduce Safety Factor of permanently-mounted transportable composite cylinders from 2, above the Maximum Developed Pressure.** , as it was done in regulations for automotive application (refer to ISO 11439, ASME, EU 406/2010, JARI S001, GTR).

The value of 1.4 demonstrated on flat panels with specific materials and specific loading (sustained load only) is a **theoretical absolute minimal Safety Factor**. It covers intrinsic properties of composite materials. For composite cylinders, others factors shall be taken into account to cover other aspects.

Note: Limitations related to the 1.4 value are largely described and discussed in the HyCOMP public deliverables D2.4 and D6.4

3. Conclusions

As conclusion, this deliverable presents lessons learned from the project in a different way, with a special focus on recommendations from industry for Industry, especially for cylinder manufacturers. Indeed, some conclusions coming from HyCOMP and related to manufacturing parameters are very useful for the industry and must be shared. These lessons have been turned into recommendations for RCS (for further details, see HyCOMP public deliverable D6.4), to address the different points of vigilance in cylinder design and manufacturing, that need a particular attention and control.
These recommendations deal mainly with the choice the epoxy resin (specifications on glass transition temperature) and its curing process (control of curing parameters).
It turned out that the control of the manufacturing process of composite cylinders is of prime importance in the reliability of the product.

Finally, from an end-user point of view, a parallel has been drawn between operation loads in service and accidental conditions of on-board storage and permanently-mounted transportable cylinders. Pressure profile in service, but also possible mechanical impact that are likely to occur, are very similar. The Safety Factor for automotive applications has been reduced to 1.8 over the maximum developed pressure. This is an additional argument to discuss the potential and relevant conditions for a decrease of Safety Factors of transportable cylinders (at least for permanently mounted cylinders that cannot be handled).

4. List of HyCOMP public deliverables

The following reports are public and available for consultation at the following address: http://www.hycomp.eu

- **D2.4: Final WP2 report**: “Damage accumulation rate in the composite wrapping: impact, rate and measurement”
- **D3.4: Final WP3 report**: “Fatigue failure of cylinders”
- **D4.4: Final WP4 report**: “Manufacturing Quality Assurance: effect of variability of fiber and matrix characteristics”
- **D5.3: Final WP5 report**: “Characterization of service life”
- **D6.4: Final WP6 report**: Design requirements and testing procedures”

5. References

- **TPED**: Transportable Pressure Equipment Directive
- **Global Technical Regulation No. 13**, EC/TRANS/180/Add.13, Global technical regulation on hydrogen and fuel cell vehicles, United Nations, July 2013
- **79/2009/EC** and **EU 406/2010** of 26 April 2010 implementing Regulation (EC) No 79/2009 of the European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles