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Deliverable Report
D7.4
Preliminary WP7 Report

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1. Executive summary

1.1 Summary of deliverable content and initial objectives

The HyCOMP project concerns enhanced design requirements and testing procedures for composite cylinders intended for the safe storage of compressed hydrogen in on-board, transportable and stationary applications.

The objective of this final report is to provide an introduction of the HyCOMP project, an outline of the work done in the different work packages (Section 2.1) and the project outcomes in terms of recommendations for enhanced design and testing procedures and Regulations, Codes and Standards (RCS) recommendations and roadmap. Finally, the report summarizes the work done to disseminate the project results to the FCH community and international RCS bodies.

At this time, all the work of HyComp WP2-6, i.e. D2.4, D3.4, D4.4, D5.3 and D6.4 have been completed. They have been reviewed and a brief summary of their findings has been reported (see Section 2.2).

Also included in this report are summaries of WP7 reports including the preliminary and final reports (D7.1 and the present report which is D7.4), the Industry report on recommendations for design and testing (D7.2), the summary report on RCS recommendations to support initiatives (D7.3) and the dissemination workshop (D7.5).

This report represents the consensus of the HyComp group regarding RCS and industry recommendations.

1.2 Partners involved

All partners were involved in this work package including, work package leaders: Air Liquide, Armines, BAM, CCS, Faber and Hexagon. It is important to note that the WP leaders also worked in conjunction with the other HyCOMP partners CEA, CAQ, WUT and JRC-IE in different WPs and also contributed to this report.

1.3 Relation with other WPs / Tasks

The results of the work of all WP2-6 of the project were taken into account in this report.

2. Introduction

Hydrogen storage is a key enabling technology for the extensive use of H_2 as an energy vector. Currently, the most mature technology for storing hydrogen in compressed form is high-pressure cylinders. This technology has already been used for many decades for industrial gases in metallic cylinders at 20 MPa. However, the use of hydrogen as an energy vector places new constraints on compressed gas storage in cylinders. In order to improve the gravimetric and volumetric performance of the storage in cylinders, there is a strong need for lightweight, highly safe and reliable designs of pressure vessels for hydrogen storage in a variety of applications, in particular:

- on-board vehicles
- transportable cylinders: hand held or in bundles (frames)

- stationary storage, for example in fuelling station stations

The major technological route for these designs is the application of composite materials, in particular carbon fibre composites.

There are a number of issues that remain to be addressed in current RCS for hydrogen storage in high-pressure composite cylinders (so called type 3 and type 4 cylinders according to whether the liner material is fully metallic or polymeric.)

- Current RCS do not allow one to exploit the full potential of composite cylinders. According to field data, safety factors relative to burst pressure ratio and number of cycles for a given lifetime appear to be conservative, which increases the cost of a cylinder without necessarily improving safety.
- Requirements for type approval and batch testing, as well as requalification of cylinders in service are still based on approaches developed for steel cylinders, which are not the most appropriate for composite cylinders.
- Composite materials demonstrate different failure behavior when compared with metallic cylinders.

Therefore new rationale for defining and justifying the service life (such as the number of load cycles) of composite cylinders need to be developed based on a detailed understanding of the degradation mechanisms affecting the carbon composite and for each application.

This project develops a better understanding of the damage accumulation processes in composite cylinders as well as quantitative data on the degradation rate as a function of the type of load and environmental conditions. This provides the comprehensive scientific and technical basis for fully justifying as well as improving the full set of requirements defined for ensuring the structural integrity of the cylinders throughout their service life, covering design type approval, manufacturing quality assurance, and in-service inspection. The outcome of the project is in the form of recommendations gathering broad support for improving the applicable European and international RCS on high-pressure hydrogen cylinders for automotive, transport and stationary applications, as well as defining a strategy for implementing these changes.

3. Description of work done (including difficulties encountered and solutions)

3.1 Objectives

The work plan was constructed with the objective of generating all the data that is necessary to define and scientifically justify performance-based design requirements. From an improved understanding of the causes and consequences of the degradation mechanisms taking place in a carbon fibre composite under load, improved performance-based design requirements and conditions of type approval and batch testing as well as RCS recommendations were defined.

The work of each work package (WP) began with a review and update of the state of the art in the field. The experimental program focused on loads associated with normal use (combination of static and cyclic loads) over a range of conditions (temperature, humidity, etc.).

3.1.1 WP2. Damage accumulation in the Composite Wrapping: Impact, Rate and Measurement

WP leader is Armines.

To better understand the degradation phenomena taking place in the composite material (accumulation of fibre ruptures), the rate of damage accumulation as a function of sustained pressure loading (static, cyclic, and combined) and environmental loading are determined by testing sample specimens. Also to develop damage accumulation prediction models for calculating residual lifetime and instability. In this WP, plate specimens made of unidirectional carbon-epoxy laminate were used. Acoustic Emission (AE) is already a proven method for measuring damage accumulation in composite materials and it was largely used in the HyCOMP test program, WP2-4.

3.1.2 WP3. Fatigue Failure of Cylinders

WP leader is BAM.

To assess the effect of pressure (cyclic, static and hybrid) loads on cylinder strength, it is necessary to evaluate the parameters relative to failure mode, after preconditioning. Destructive tests are performed after preconditioning to evaluate the evolution of cylinder strength. The most damaging loads are studied at cylinder level in order to determine the conditions required for the different types of possible failure to occur. For type 3 cylinders, the typical failure mode is cracking of the metallic liner leading to a leak of the cylinder. It is thus important to quantify cylinder strength by a cycling test. On the other hand, type 4 cylinders are not sensitive to fatigue cycling. In this case the failure mode is the wrapping or liner failure caused by burst test.

3.1.3 WP4. Manufacturing Quality Assurance: Effect of Variability of Fibre and Matrix Characteristic

WP leader is Faber.

Improved approaches for demonstrating that all manufactured cylinders meet a specified performance criterion (e.g. minimal initial burst pressure) despite known factors of variability in the manufacturing process are studied. Four parameters considered as the most affecting cylinder performance were chosen: winding geometry, improper resin mix, improper resin curing and carbon fibre mechanical properties. One artificial defect is introduced by cylinder simulating an extreme variation in the manufacturing parameters. For type 3 and type 4 cylinders, initial performance was evaluated by a burst test, whereas long-term performance was assessed by a cycling test for type 3 cylinders and a burst test for type 4 cylinders after a preconditioning (sustained load simulating service life).

List of materials and cylinders (type 3 and type 4) tested in WP2-4: The experimental program that has been developed to produce the necessary data from WP2 to WP4 involves the testing of a large number of UD carbon-epoxy specimens and around 200 gas cylinders. Materials used are carbon fibre.

3.1.4 WP5. Characterization of Service Life

WP leader is Hexagon.

The objective of the work package was to characterize the service life of the carbon fibre composite cylinders in the automotive, transportable and stationary application.

Hence, the cylinder Accidentology of the carbon fibre composite cylinders was analyzed. Bibliography, industrial databases and demonstration project results has been studied to collect data about incidents involving the composite cylinders used for hydrogen or natural gas storage. As a summary, the causes, effects, and resulting damages have been assessed and classified and mitigation measures were identified respectively proposed.

Furthermore, the operational loads as specified/expected by European automotive makers (based on latest revisions of specifications from selected automotive makers, refuelling station makers and bulk providers of compressed hydrogen) have been identified. Last but not least, on-going discussions / activities / argumentations noted from automotive makers, gas providers and regulators were analyzed and added to the conclusions as well.

3.1.5 WP6. Design Requirements and testing procedures

WP leader is Air Liquide.

The first task was to review published and draft RCS for all applications covered by HyCOMP (stationary, transportable and on-board). Based on this review, requirements were analyzed and compared in order to identify specific information (or gaps) that HyCOMP has to address.

The other task was to summarize the results of WP2-WP5 and to make recommendations to cover design requirements, testing procedures for type approval, manufacturing quality assurance and in-service inspection.

3.1.6 WP7. Findings and Recommendations for Industry and RCS

WP leader is CCS.
The findings of the project were summarized and recommendations to support RCS initiatives extracted, prioritized and disseminated. As a first task, a list of active and published RCS was prepared and kept up-to-date throughout the duration of the project. Also, in conjunction with WP6, the RCS gaps report was updated several times throughout the project. Also WP7 prepared a list of questions (**Annex A** attached) for WP2-6 which were considered in their test program. These questions were answered by the WP2-6 in their final reports.

Challenges:
The project was faced a couple of challenges such as delay in getting the test program started due to planning while the other challenge was related to a lack of cooperation from the automotive OEMs.

Planning: At the start of the project, there was a delay in getting the test program started due to planning which involved defining materials, plate specimen and cylinders and ordering materials. This caused an estimated 6-9 months of delay in the test program. Steps were taken in conjunction with the Program Office to revise the project plan including the test program with the help of the members. An extension of three months was granted by the PO which allowed HyCOMP members to complete all testing and research work. The final WP2-6 reports were available at the end of the project. Finally, there were some interesting design and testing recommendations as well as RCS recommendations. A dissemination workshop was held successfully where there was good support received for HyCOMP results from the stakeholders and RCS experts alike.

Automotive Advisory Group (AAG): With CRF, the only automotive OEM on HyCOMP, leaving the group early in the project, the formation of the Automotive Advisory Group (AAG) was a difficult proposition Nonetheless, OEMs like Daimler, Opel, Volkswagen and BMW were consulted. Daimler and Opel finally accepted the invitation and participated in an AAG meeting which was held in M20. As it turned out, the extent to which they were willing to actively contribute and liaise with relevant activities at their companies was quite low

As a result, this matter of the AAG was brought forward to the PO by the Coordinator. In agreement with the PO, the AAG task has been “suspended” and the information exchange was planned to take place during a dissemination workshop at the end of the project.

Unfortunately, only representatives from Opel attended the meeting by teleconference. In summary, after the withdrawal by CRF, it was very difficult to establish an information interchange with the automotive industry.

Completion:
The main challenges were handled by the project beginning with a good understanding of the state of the art and then developing and carrying out the test program. The final WP2-6 reports were available at the end of the project. Finally, there were some interesting design and testing recommendations as well as RCS recommendations. A dissemination workshop was held successfully where there was good support received for HyCOMP results from the stakeholders and RCS experts alike.

3.2 Conclusion

Following is a brief summary of findings of the WP2-5 as well as recommendations from the work of HyCOMP for enhanced design requirements and testing procedures (WP6) and RCS initiatives (WP7).

3.2.1 WP2 – Summary of findings

Refer to Final WP2 Report – D2.4

The WP2 concludes that large-scale fibre rupture clusters are the most critical damage to the structural integrity of composite materials dedicated to cylinders. It was determined that the strength of the laminates was dependent on the total content of fibre rupture clusters developing in the material. It was found that fibre rupture clustering process was more favourable in the laminate containing one thick 0° ply than multiple thin 0° plies.

The long-term damage processes of composites, which are time-dependent, are governed by the visco-elastic properties of the matrix that are themselves dependent on the type of epoxy resin used and the curing condition applied. There are other factors that can affect the growth rate of damage clusters such as, applied stress level and environmental conditions (for example temperature and humidity).

Testing at a material scale shows that temperature is an important parameter influencing damage accumulation (fibre breaks) in the composite wrapping. The effect of the temperature on damage process of the composites is relatively small when the maximum ambient temperature is 30 °C below the glass transition temperature, Tg.

A quasi-asymptotic behavior of intrinsic safety factor (iSF) value with respect to the lifetime was observed. Indeed, the lifetime increases at a log-linear rate as the applied load level decreases. The iSF value only rises on a small time scale (less than 15 years) and remains stable afterwards even when an extremely long lifetime is considered (more than 1E5 years). Based on theoretical and experimental studies on flat panels made of specific materials (carbon fibre), the safety factor covering intrinsic material properties can be down to 1.4 for sustained loading, given an unlimited lifetime: a probability of failure of 10^{-6} is considered. A value of 1.6 is found for a probability of failure of 10^{-9}. The value of 1.4 must be seen as the minimum theoretical value covering intrinsic material properties (variability of carbon fibre properties). The limitations of the iSF analysis are described in the report. It is also recognized that for composite cylinders, others geometrical factors must be taken into account to cover other aspects, such as structural integrity.

Findings for acoustic emission (AE) evaluation

There is no standardization for AE systems from different manufactures. In general, the parameters (such as energy) used for setting-up AE acquisition are not identical between different systems. For non-destructive evaluation of composite pressure vessels (CPV), to perform full-field monitoring on composite cylinders, numbers of AE probes (or sensors) distributed over the cylinder surface have to be applied to facilitate quasi full-field monitoring on composite cylinders.

Important: Testing was done at material scale and all results reported must be considered for composite material purposes although some references are given for CPV.

3.2.2 WP3 - Summary of findings
Refer to Final WP3 Report - D3.4

The aim of this Work Package was to develop a better understanding of the effects of cyclical and hybrid loads on the cylinder structure in order to justify allowable service life. The results are used to determine test protocols and methodologies to ensure that the cylinder will not fail in specified service conditions, with the required level of assurance.

Type 3 and type 4 cylinders have specific structural requirements and limitations. These include different failure modes specific to the type and style of liner used, as well as the influence of manufacturing and environmental conditions on the failure behaviour.

Furthermore two NDT methods, AE and Optical Fibre (OF) strain measurements, were used to evaluate their usability and the state of damage of composite cylinders.

Conclusions of test results (type 3; steel liner)

1. A modification of autofrettage control parameters (p, t, V, T etc.) influence the internal state of stress (load sharing) and the resulting mean value and scatter of residual strength.

2. Gaseous cycling: The temperature cycles parallel to pressure cycles and the much longer total test time (about 45min vs. 6sec per cycle) increases the scatter!

3. At constant high temperature the metal liner expands. Thus part of load sharing of composite is temporally higher than at RT! Those effects can be observed as permanent changes, too.

4. The order of cycle loads and sustained load has a very high influence on residual strength i.e. degradation!

5. A sustained load influences the residual cycle strength – especially with respect to increase of scatter.

6. High temperature during a sustained load leaded to higher burst pressure while LC-strength has been reduced.

7. That means: Burst test shows safety against (one-time) overload dominated by composite – but has no relevance for service strength of metal liner!

Conclusions of test results (type 4; plastic liner)

1. Cycling has a very small effect on the composite wrapping compared to metal liners! Therefore cycling to failure is not efficient, sometimes impossible.

2. A sustained load influences the residual cycle strength: higher slow burst strength with constant or reduced scatter!

3. Gaseous cycle loads result in a lower degradation compared to high or ambient temperature cycling!

3.2.3 WP4 - Summary of findings
Refer to Final WP4 Report - D4.4

The Work Package 4 "Manufacturing quality assurance" has been split in three tasks.
The first task aimed to identify the manufacturing parameters that could influence cylinder performance. The parameters that have been identified as the most affecting the cylinder performance are:

- MF1: Winding geometry,
- MF2: Improper resin mix
- MF3: Improper curing
- MF4: Carbon fibre mechanical characteristics.

Next, an experimental test plan has been defined and carried out in the second task, to evaluate the influence of the above parameters on the performance of the cylinder. A test plan has been developed with the aim to evaluate the cylinder performance in the short term and in the long term.

The third task of the work package aimed to evaluate the NDE (non-destructive examination(NDE)) methods for production monitoring. AE test has been performed during the first pressurization of the cylinders, searching for an NDE capable of evaluating the long term cylinder performance with a single test at the beginning of the cylinder life (i.e. at the manufacturing stage).

Finally, an evaluation of the results has been made to understand if the requirements of existing RCS for materials, production test, batch test and mandatory process control are adequate, excessive or inadequate to guarantee the product performance.

Test results

Manufacturing Variation - Winding geometry (MF1)
A variation of winding parameters, simulated with an offset modification of one bandwidth, shows a negligible effect in the case of type 3 cylinder and a significant effect on type 4 cylinders. In the case of type 3 cylinders, the absence of significant effects can be explained because of the relevant contribution of steel liner on the shoulder and base ends. In case of type 4 cylinder the effect is more relevant in terms of a much higher scattering of burst test results.
Present RCS generally prescribe that the winding parameters must be defined and for this reason can be considered adequate.

Manufacturing Variation - Improper resin mix (MF2)
A variation of resin mixture composition, simulated by an increase of 20% of hardener, shows no significant change in cylinder performance in either type 3 or type 4 cylinders.
Present RCS that prescribe the process control of the resin mixture can be considered adequate.

Manufacturing Variation - Improper curing (MF3)
A variation of composite curing, simulated by leaving the wound cylinder in curing at room temperature, shows an important effect in the case of type 3 and type 4 cylinders. In the case of type 3 cylinders, it affects mainly the scattering of burst test but also the cycling test performance has been affected with an increment of scattering in the test results. Type 4 cylinders have been affected mainly in terms of scattering of burst test after preconditioning. This suggests the need of introducing a control of this characteristic by additional tests (such as a Barcol test on each cylinder) to verify the proper curing of the resin mix.

Present RCS prescribe tests in production, during batch certification and also address curing parameters to be defined and controlled as process control. Due to the importance of the effect of improper curing, additional requirements to check the curing can be recommended.

Manufacturing Variation - Carbon fibre mechanical characteristics (MF4)
A variation of fibre mechanical characteristics, simulated by replacement of T700 fibre with T300 having lower mechanical characteristics, as expected shows a very important effect in both cases of type 3 cylinder and type 4 cylinders. In the case of type 3 cylinders, it affects mainly the burst test value but also the cyclic test performance has been influenced. Type 4 cylinders have been affected in terms of burst test result in the case of new cylinders and also in case of preconditioned cylinders.

The burst test prescribed by present RCS would detect such variation, being the resistance of the cylinder proportional to the mechanical characteristics of the fibres.

Acoustic Emission (AE)
In HyComp the capability of AE method was verified on type 3 and type 4 cylinders with artificially introduced defects described above. The influence of the four manufacturing deviations for both cylinder types was detected.

3.2.4 WP5 –Summary of findings

Refer to Final WP5 Report - D5.3

The objective of the work package 5 was to characterize the service life of the carbon fibre composite cylinders in the different applications to be considered

- Cylinders for automotive use (permanently mounted in a vehicle)
- Transportable cylinders.
  - Smaller portable single cylinder/small portable bundles
  - Larger cylinders/bundles of cylinders permanently mounted in frames/containers
- Stationary storage cylinders for hydrogen refuelling stations

The first part of the WP consists of an analysis of the **Cylinder Accidentology** of the carbon fibre composite cylinders. A review of bibliography, industrial databases and demonstration project results has been made to gather information about events and incidents involving the use of composite cylinders for storage of flammable gases (e.g. hydrogen or natural gas). These events have been classified by assessing the causes, effects, evaluation of damages and mitigation measures.

The 2nd goal was to summarize and to report on the **Operational Loads** as specified/expected by European Automotive makers (based on latest revisions of specifications from selected automotive makers, refueling station makers and bulk providers of compressed hydrogen).

Cylinder Accidentology

Ensuring the safety of hydrogen vessel storage is of prime importance. Hence, manufacturers must guarantee a good mechanical strength for its cylinders. This is accomplished by compliance with industry standards (ISO 11439, ISO 15869, NGV2, et al).

By analyzing causes of previous accidents, a lot of lessons can be learned from cylinders accidents in service (exposure conditions, causes, consequences, etc…). Two databases

(HAID/JRC and H2Incidents/PNNL) relative to hydrogen incidents are available to share information No incident relative to hydrogen has occurred

Learning from metallic cylinder failure modes was helpful even though the project is devoted to damage accumulation processes in composite cylinders. However, some pieces of metallic materials are present in composite cylinder; therefore it was required to have a look at it.

Composite cylinder usage for hydrogen storage is quite recent, but it is increasing for stationary and automotive applications. CNG has been used since many years as fuel for vehicles. Up to now, a relatively low number of 54 CNG cylinders have failed (compared to millions of CNG vehicles in-service).

Tracking of cylinder failures resulted in a classification of the most frequent failure causes.

- Vehicle fires
- Environmental damage
- Metallic liner issues manufacturing
- Plastic liner issues (type 4 cylinders)
- External mechanical damage
- Over pressurization

Fire is the main cause of cylinder failure. In most cases, a pressure relief device (PRD) was not present or approved or it failed to operate due to the PRD being isolated from the fire source.

Under normal conditions of use (no fire, no impact, and no contact with corrosive compounds); no accident has been reported yet. This demonstrates that composite cylinders designed according to current standards present a high level of safety.

The tracking of cylinder failures has resulted in improving the cylinder safety standards.

<u>**Operational loads**</u>

Operational loads including fill cycles for composite cylinders in hydrogen applications, varies between the main **groups of applications (onboard, stationary and transport purposes).**

- **Smaller portable cylinders or bundles of cylinders (WP: 200 to 700 bar, water capacity: 20 to 100 liters):**

One delivery equals one pressure cycle, but the frequency is assumed to be low (1/month to 1/year). Refueling can be as fast as for automotive application cylinders (3 min). Moderate depressurization rate (4-24 hours) can be expected. Pressure is expected to be constant at high level (100% service pressure) most of the lifetime.

- **Transportable – Larger Cylinders/bundles permanently mounted in frames (WP: 200 to 700 bar, water capacity: 50 to 10,000 liters):**

One fill equals one pressure cycle (one fill per day over 20 years equals 7.300 cycles). For short transport distances 1-2 deliveries might happen, representing up to 15.000 pressure cycles over 20 year. Moderate refueling time (hours) can be expected. In combination with onsite storage system and if gas is dumped to larger low pressure volume, depressurization rate can very fast. Pressure is expected to be higher than 100% service pressure for ½ of the service life and at low pressure during the return to the production site or waiting for next loading.

- **Stationary – Hydrogen Refueling Stations:**

Each vehicle to be filled represents one pressure cycle. 20 refuelling per day over 20 years equal 146.000 cycles – (low estimate for the future). 100 vehicles every day over 30 years equals about 1.000.000 cycles. These fill cycles are shallow and quite different from those for transportable and automotive applications. Depending on the station design, the high pressure tanks are only used for vehicle top fill, resulting in smaller pressure decreases and increase per pressure cycle. Moderate refueling time (by on site compressor) are expected. Quick depressurization within pressure amplitude range the cylinders will operate. Cylinders in a hydrogen refueling station will stay most of the lifetime at high pressure.

- **Automotive applications:**

For a fuel cell passenger car, one fill per day over 20 years can be assumed worst case, equals 7.300 cycles.
If the car is in a local fleet-service operation 24h a day, we can assume that the vehicle will be filled once in each shift (3 times a day), which will equal to 21.900 partial fills. Refueling from 3% to 125% of service pressure within 3 min can be expected. The fill gas temperature will be as low as -40°C at the start, with end of fill temperature in the cylinder up-to 85°C. Depressurization (at all environmental temperature conditions) worst case can be as short as 1 h. For average highway/city cycles, the time can vary from several hours up to days

Testing and certifying a composite cylinder for multipurpose applications, to which worst case throughout all applications has to be taken into consideration, will in most cases contribute to a cost increase of most cylinders.

3.2.5 WP6 –Summary of findings

Refer to Final WP6 Report - D6.4

The objective of the first task in WP6 was to identify the existing requirements for composite cylinders for all applications (transportable, on-board and stationary). This included a comparison of on-board storage requirements of not only ISO standard and the EU 406/2010 regulation, but also the SAE work and to a certain extent on the Global Technical Regulation No. 13, EC/TRANS/180/Add.13 on hydrogen and fuel cell vehicles, of the UN-ECE. Based on this comparison, gaps and/or opportunities for improvement for some of the specific tests were pointed out.

The other task was to summarize the results of WP2-WP5 and to make recommendations to cover design requirements, testing procedures for type approval, manufacturing quality assurance and in-service inspection. Based on the review of the results of WP2-5, a list of recommendations was proposed in this report with the corresponding explanations coming from experimental results.

A possibility to reduce over-dimensioning is to **use the maximum developed pressure** as the design pressure of transportable cylinders with dedicated gas service (as e. g. exclusive hydrogen). This is justified by a relatively low expansion of hydrogen at elevated temperature.

For transportable applications, there **could be a possibility to reduce minimum safety factor from 2**, if justified by further testing. Additionally, to get the type approval, cylinders must successfully pass all the other tests as defined in the standards for the different applications. Lifetime of the cylinder may influence the value used.

To ensure the proper choice of the resin (relative to T_g), it has been proposed to **perform certain tests at elevated temperature** at a temperature not less than T_{max} defined for the application. To ensure cylinder quality related to this parameter, **it is proposed to add specifications on glass transition temperature** of the composite to verify the suitability of the resin. Also, there is a need to **control the resin mixture and the curing process.**

Furthermore, as scatter can be important for the same design, one proposition is to make a statistical assessment of the key performance properties in combination with strength tests to failure of the composite, respectively cylinder.

For in-service inspection of CPV, the AE method seems promising for composite materials (possibility to discriminate types of damage and to quantify each of them), but further research is needed.

3.2.6 WP7 Report - Summary of findings

All deliverables of WP7 have been completed.

Automotive Advisory Group (AAG): With CRF, the only automotive OEM on HyCOMP, leaving the group early in the project, the formation of the Automotive Advisory Group (AAG) was a difficult proposition. First, a description of the role of the AAG was prepared which included among others things, to provide guidance regarding the description of the typical service loads seen by gas cylinders in vehicles and various OEMs like Daimler, Opel, Volkswagen and BMW were consulted. Daimler and Opel finally accepted the invitation and participated in an AAG meeting which was held in M20. The objective was to get the adhesion of the automotive industry in the scientific approach performed in HyCOMP. As it turned out, the extent to which they were willing to actively contribute and liaise with relevant activities at their companies was quite low. One reason was also the decision by GM to terminate the fuel cell vehicle development GM in Europe respectively at Opel at the end of 2012.

As a result, this matter of the AAG was brought forward to the PO by the Coordinator. In agreement with the PO, the AAG task has been “suspended” and the information exchange was planned to take place during a dissemination workshop at the end of the project. Again, relevant people at Daimler, Opel, Volkswagen. Honda and BMW were approached for their participation at the meeting organized on March 5th, 2014 at AFNOR in Paris.

3.2.6.1 Preliminary and Final reports – D7.1 and D7.4

The preliminary WP7 report, D7.1 was completed in M34 with results from WP2-4 only that were available at the time.

This report is the final report D7.4, which was completed in M39. It outlines the work that HyCOMP set out to do, the test program and results (WP2-4) and the collection and characterization of operational and accidental load for composite cylinders (WP5), the design and testing recommendations (WP6), the Industry report on recommendations for design and testing (D7.2, M39), the RCS recommendations (D7.3, M39) and the dissemination of these results (D7.5, M39).

To have a more detailed description of the HyCOMP project outcomes, refer to:
Final deliverable reports D2.4, D3.4, D4.4, D5.3 and D6.4
WP7 deliverable reports D7.1, D7.2, D7.3 and D7.5.
Annex A: List of questions prepared by WP7 is attached. These questions were answered by the WP2-6 in their final reports.

3.2.6.2 Report on recommendation for design and testing

Refer to report - D7.2

This deliverable proposes recommendations intended for Industry which is separated into two parts, composite cylinder manufacturers and end-users (gas supplier), based on results of WP2-6. For manufacturers of composite cylinders, the control of some key manufacturing process parameters such as choice of the epoxy resin (specification on Tg - glass transition temperature) and its curing process are important for the reliability of the cylinder.

For end-users, 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.

3.2.6.3 Summary report on recommendations to support RCS initiatives

Refer to report – D7.3

Throughout the project, there was strong interaction between WP7 and WP2-6, in going over drafts and final reports in an effort to identify any RCS recommendations that may come from the result of their work in HyCOMP. In the beginning, the interaction with WP6 facilitated the preparation of the RCS list of active and published standards as well as a RCS gaps report which were presented to the group as they were preparing their test program. The RCS gaps report (D6.1) including the RCS lists was updated several times throughout the project.

The D7.3 (M39) report lists the recommendations which are to move forward as project RCS recommendations as soon as possible. Another category of RCS recommendations in the report includes a list of items that are quite interesting but will need further development in the future. The D7.3 report also provides a path forward on how the project findings can be integrated into ongoing or new RCS activities such as the proposed revision of ISO 11119-3 and EN 12245 standards.The RCS recommendations came from a joint effort by all HyCOMP members.

Although some pathways have been discussed in the report, it will not be the work of HyCOMP to implement these RCS recommendations.

3.2.6.4 Dissemination Workshop

Refer to Report – D7.5

The objective of the workshop was to present HyCOMP experimental results and outcomes, mainly recommendations, to experts in the field of CPV for the storage of hydrogen (manufacturers, end users, test laboratories, OEMs, etc). The choice of the event was largely discussed between partners and finally came down to organizing the workshop jointly with meetings of ISO working groups of TC58/SC3/WG 24 (Factors of safety for composite cylinders) and WG35 (Refillable permanently mounted composite tubes for transportation. To get a maximum of participants, HyCOMP workshop was organized one day before the ISO WG meetings, on March 5th, in the AFNOR facilities in Paris. Experts from ISO TC58 (Gas cylinders) and TC197 (Hydrogen technologies) were invited. Finally around 40 people attended this workshop, among which 22 people external of HyCOMP consortium. Attendees expressed their feedback on the work carried out in HyCOMP and the recommendations coming from the project. Globally, project outcomes were well received.

Furthermore, throughout the duration of the project, several publications, posters and/or presentations have been made in Europe and elsewhere as dissemination activities. All of these dissemination communications are listed in the PUDF document (Plan for Use and Dissemination of knowledge).

4. Suggestions for continuation of the work started by the project

Although the main tasks of the HyCOMP project and the final deliverable reports WP2-7 reports were completed including interesting industry and RCS recommendations which were well accepted by hydrogen stakeholders and RCS experts alike during the dissemination workshop, there were indeed other new challenges that the project consortium identified which were not addressed in this project. Therefore, the HyCOMP consortium has recommended the continuation of the research effort for CPV, to address these challenges.

The use of various **inspection methodologies** during manufacturing and in service inspection such as AE, Optical Fibre and Barcol hardness test methods.

- In particular, AE methodology seems to be a promising technique to have a reliable inspection method of CPV to assess level of damage, remaining lifetime and/or fitness for service, but it needs further development.

Further testing and research is called for **better understanding of safety factor** and towards its reduction, particularly in transportable applications.

- To quantify factors covering aspects such as change of scale from material to cylinders, manufacturing variability, temperature impacts etc. to better define which parameters cover the safety factor.

Further work to take into account observed scatter of performance in pass/fail criteria for cylinders used in transportable, on board and stationary applications.

- Make a **statistical assessment** of the key properties. There is a need to look further into Probabilistic assessment approaches.

Opportunity: An opportunity exists to perform further PNR work which will lead to a better understanding of the behavior of composite materials and CPVs and result in further recommendations for industry and RCS, thereby advancing the state of the art for hydrogen storage in different applications.

The Transport Committee of the NEW IG, the Industry Grouping of the FCH JU, was made aware of the further PNR needs for CPV as mentioned above. As a result, one of the topics in the next call is planned for *Hydrogen Storage Components Optimization for Mass Production*. The call is planned for release in July 2014, and covers on-board hydrogen storage system for fuel cell powered vehicles of which CPV is a key component.

5. Symbols and Acronyms

Symbols

P_{max}	maximum developed pressure at 65 °C for transportable, 85 °C for on-board
T_{max}	maximum temperature (65 °C for transportable, 85 °C for on-board)
T_g	glass transition temperature (for epoxy resin)

Acronyms

AAG	Automotive Advisory Group
AE	acoustic emission
CNG	compressed natural gas
CPV	composite pressure vessel
FCH	Fuel Cell and Hydrogen
FCH JU	Fuel Cell and Hydrogen Joint Undertaking
iSF	intrinsic safety factor
JTI	Joint Technology Initiative
NDT	non-destructive testing
OF	optical fibre
PRD	pressure relief device
RCS	regulations, codes and standards

6. Annex A – List of questions

Questions to be addressed by WP2-6
Prepared by T7.1.
Note: These questions were answered by the WP2-6 in their final reports.

WP2
Q 2.1: What is the influence of damage accumulation to the carbon fibre composite on the cylinder's strength and mechanical integrity?
Q 2.2: What are the characteristics (Physical characteristics) determining resistance to degradation of the composite material?
Q 2.3: Which load parameters and service conditions determine the rate of degradation of the composite material? According to what relationships?

WP3
Q 3.1: How can changes in the wrapping cause premature liner failure?
Q 3.2: Do gaseous loads have the same effect on the composite as hydraulic loads on the composite structure?
Q 3.3: What is the impact of pressure cycle amplitude (R= Pmin/Pmax, for given Pmax) on damage rate from pressure cycling in a cylinder?
Q 3.4: How can damage accumulation be measured in a pressure vessel?

WP4
Q 4.1: What control is most needed on production to ensure that manufactured cylinders will behave as observed under type approval?
Q 4.2: What are methods that can be used for thus control on production?

WP5
Q 5.1: For each type of application what are the gas pressure related loads and service temperatures for which the vessel needs to be designed?

WP6
Q 6.1: Design validation - What is the most appropriate test protocol (effectiveness, safety, efficiency, reproducibility) for demonstrating fitness for the anticipated service?
Q 6.2: What is the right stress ratio to reliably ensure absence of burst, assuming adequate material and manufacturing?
Q 6.3: Static loads
What test method should be applied for demonstrating ability to withstand elevated loads for whole lifetime duration?
What are the right test conditions – applied pressure, temperature, duration – to reliably ensure resistance to static loads?
How many samples should be tested? (depending on production volume and type)
Q 6.4: Cyclic loads
What are the right test conditions - applied pressure and number of cycles - to reliably ensure cycle life?
How many samples should be tested? (depending on production volume and type)
Q 6.5: Control of manufactured products
What is the most appropriate test protocol for checking that manufactured cylinders will behave as observed under type approval? According to what sampling rules? With what pass/fail criteria? (CF WP4)
Q6.6: Periodic inspection testing in service
What is the most appropriate test protocol for inspection in service? With what pass/fail criteria? At what frequency? Is subjected to normal conditions