HyCOMP

WP6 - Design requirements and testing procedures

HyCOMP dissemination workshop

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Organization in Work Packages

WP1 – Air Liquide
Executive Committee
/ Project management

Material scale

Cylinder scale

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

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

Reminder of the main WP objectives

- Define design requirements ensuring that risk limits are met for specified lifetime for type III and type IV cylinders and each application
- Define improved procedure for design type testing – taking into account cylinder type, application specificity if necessary
- Define procedure for batch testing for manufacturing quality assurance
- Define methods & procedures for inspection in service
- Define appropriate pass/fail criteria for the above tests & inspection procedures

Organization of the WP

Task 6.1
Existing Requirements for Cylinders and Identification of Gaps and Improvements

Task 6.2
Design Requirements Definition

Task 6.3
Testing Procedures for Type Approval

Task 6.4
Batch Testing Procedures for Manufacturing Quality Assurance

Task 6.5
Methods and Procedures for Inspections in Service

Task 6.6
Validation of Type Test Procedures on new design cylinders & new manufacturing quality

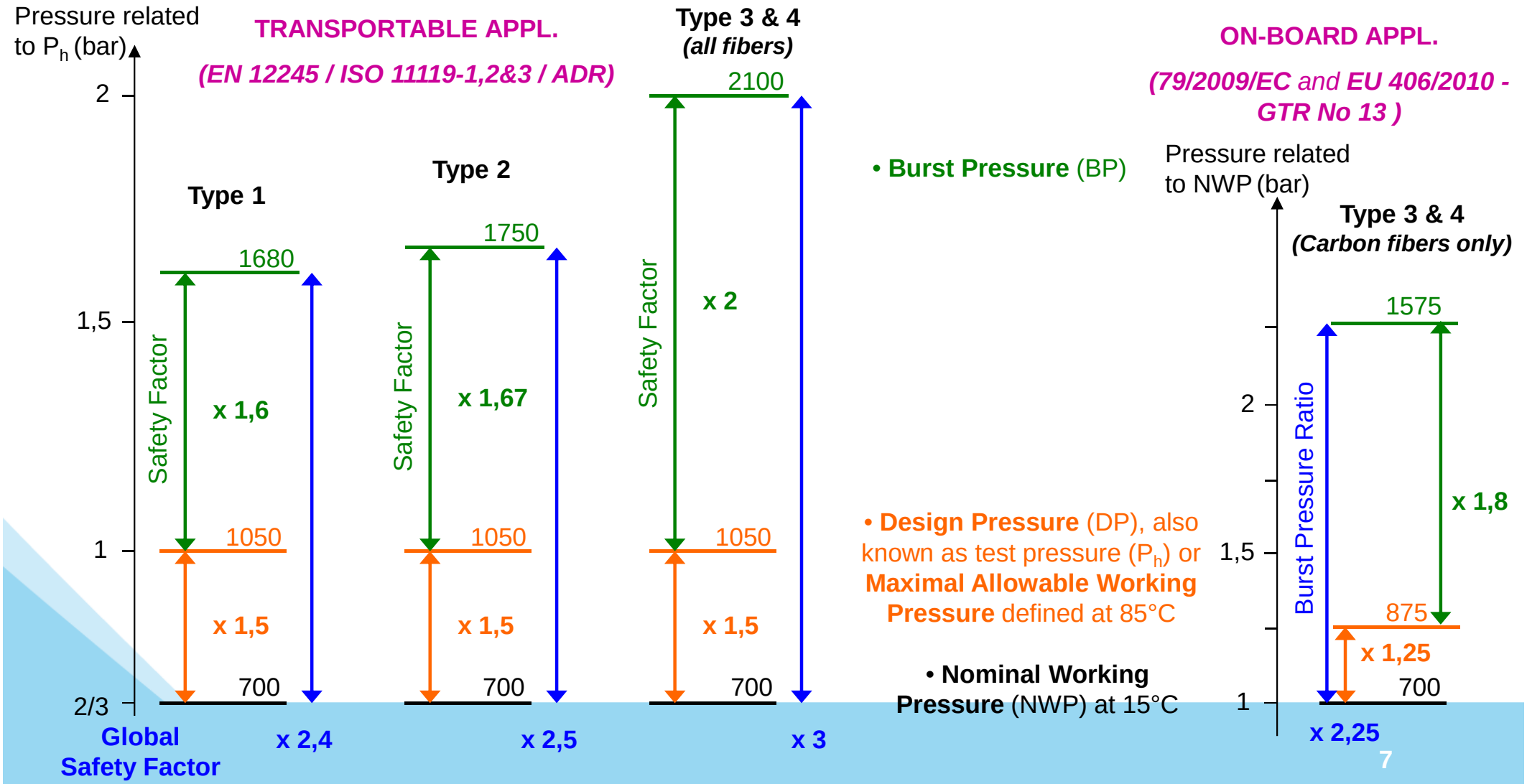
WP7

List of existing standards and regulations

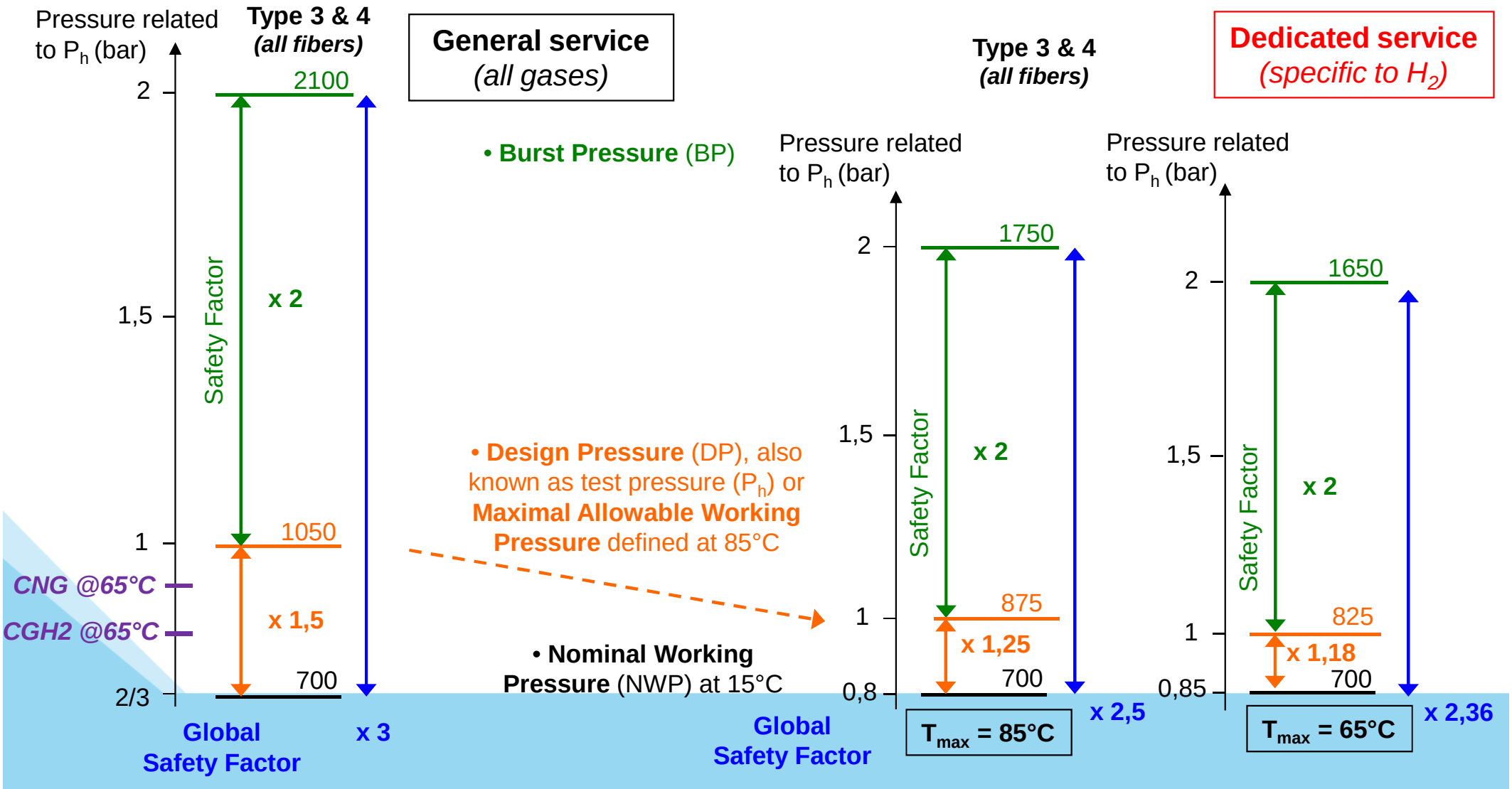
- Transportable:
  - **ISO/FDIS 11119** Gas cylinders - Refillable composite gas cylinders and tubes - Design, construction and testing - Edition 2
    - Part 2: “Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with load-sharing metal liners”
    - Part 3: “Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with non-load-sharing metallic or non-metallic liners”
  - **EN 12245**:2012 Transportable gas cylinders – Fully wrapped composite cylinders
  - European Agreement concerning the International Carriage of Dangerous Goods by Road
- On-board:
  - **ISO/TS 15869** Gaseous hydrogen and hydrogen blends – Land vehicle fuel tanks. Edition 1
  - **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
  - **Global Technical Regulation No. 13**, EC/TRANS/180/Add.13, Global technical regulation on hydrogen and fuel cell vehicles, United Nations, July 2013
- Stationary:
  - **ISO/CD 15399** Gaseous Hydrogen – Cylinders and tubes for stationary storage Edition 1

1- Design Requirements (Safety Factor)

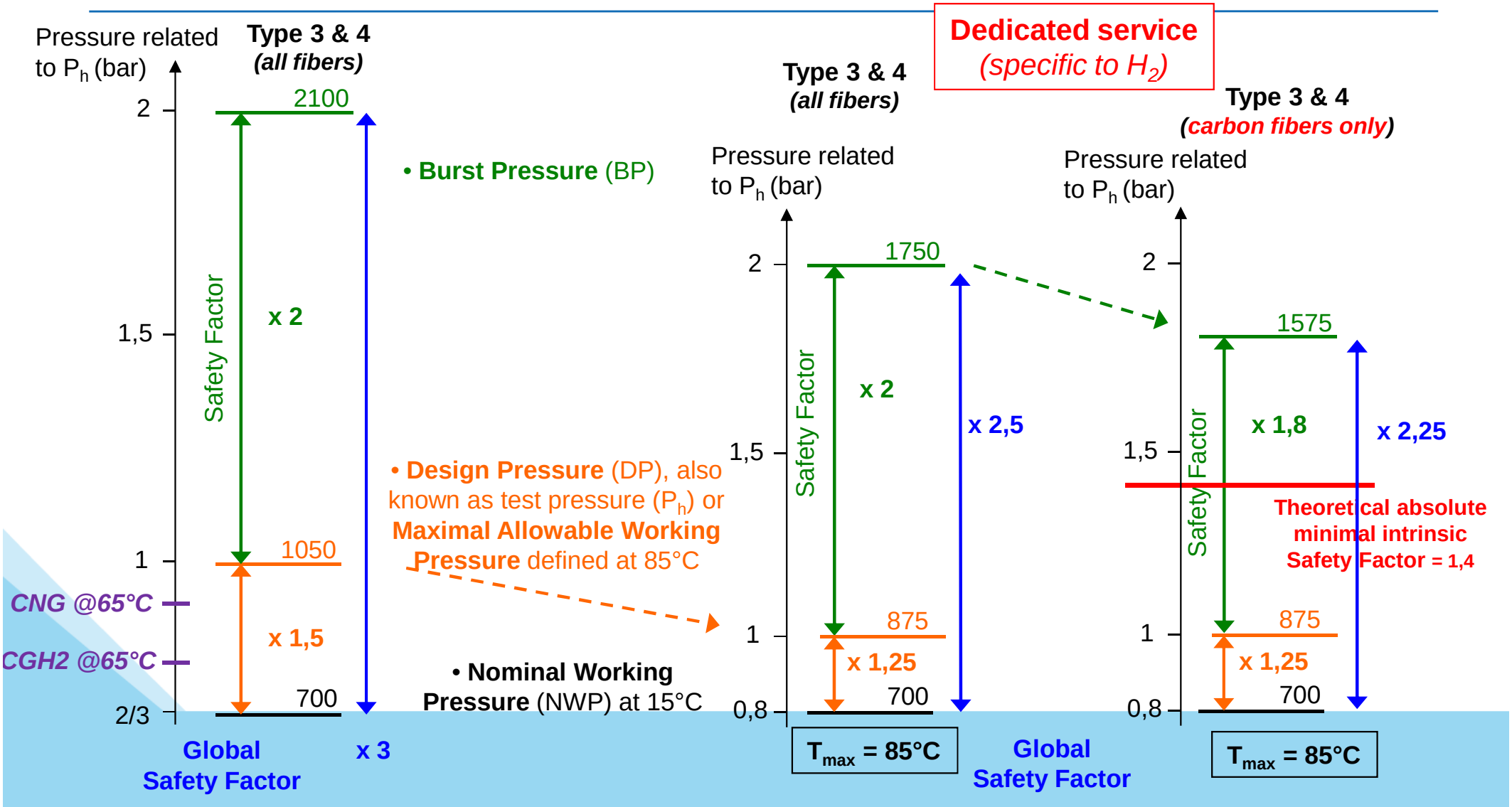
Analysis of existing design requirements



Design requirements (1st recommendation)



Design requirements (2nd recommendation)



Design requirements

- Recommendation 2:
  - *Proposal:*
    - Safety Factor (SF) must be related to the Design Pressure.
    - The **minimum SF** must not be lower than **a fixed value in between 1.4 and 2**, e.g. SF = 1.8
  - *Rationale of the 1.4 value* :
    - Must be seen as the **minimum theoretical value (intrinsic Safety Factor)** covering intrinsic material properties (variability of carbon fibre properties) in ambient conditions
    - A specimen can be loaded up to 71% of its ultimate tensile strength (= SF of 1.4), without any rupture during 20 years, given a probability of failure of 10^{-6}.
      - An asymptote is observed for a value of 1.6, corresponding to a lifetime of 100 000 years (a probability of failure of 10^{-9})

      Note: In the absence of rationale for other fibres, it must be **considered for carbon fibres only**.
    - Limitations:
      - Value demonstrated on plate specimens, with specific materials:
        - Resin T_g = 115°C (DSC), Carbon fiber : E = 230 GPa, ε = 2,1%, UTS = 4,9 GPa

          → Influence of other materials on this value? Extension to cylinders?
      - Influence of temperature: tests at elevated temperature should be considered (as it is in present standards)

Design requirements

- Recommendation 2:
  - *Proposal:*
    - The **minimum SF** must not be lower than **a fixed value in between 1.4 and 2**, e.g. SF = 1.8, depending on the application
    - Additionally, to get the type approval, **cylinders must successfully pass all the other tests as defined in standards** for different applications
  - *Consequence*:
    - Necessity to reinforce the cylinder if it fails to a test → increase of SF.
    - SF_{final} is the maximum value required to pass all tests

Becomes the new SF for this design

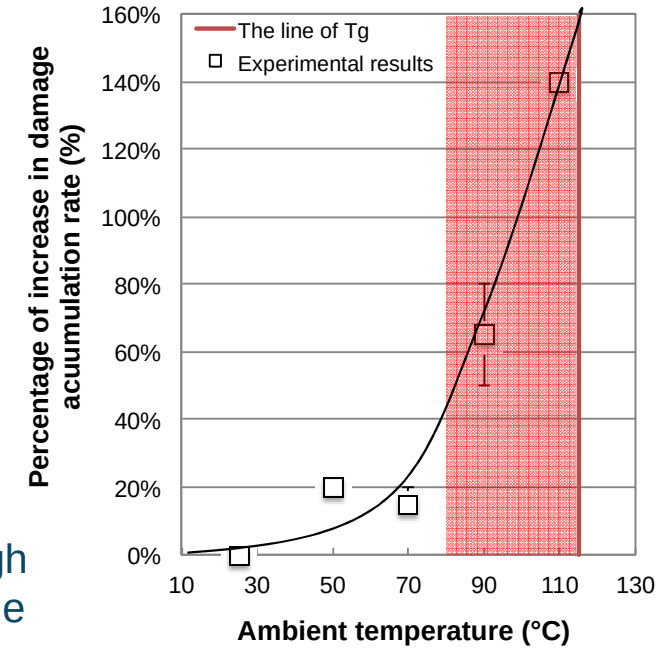
Design requirements

- Recommendation 3:
  - *Proposal:*
    - Add specifications on T_g

      Example: T_g must be higher than T_{max} + 30°C.

      Remark: If T_g has to be measured, the type of test to determine T_g must be specified, as the value is highly dependent of the method.

  - *Rationale:*
    - High influence of temperature (*see WP2*): **Observation on plate panels**
    - Need to ensure that difference between T_{max} and T_g is enough (up to 30°C to cover all epoxy resin materials) so that damage does not accumulate too quickly when temperature is getting close to T_{max}



Tests on specimens

2- Testing Procedures for Type Approval

Testing for type approval

- Recommendation 4:
  - *Proposal:*
    - Make a statistical assessment of the key propertie
  - *Rationale:*
    - An important scatter has been observed on a same design *(see WP3/WP4 presentations)*
    - Dispersion must be characterized (3 tests might not be enough)

Testing for type approval

- Recommendation 5:
  - *Proposal:*
    - Tests at elevated temperature should be performed **at 5°C above T_{max}** defined for the application
  - *Rationale:*
    - Temperature has an important effect on damage accumulation rate *(see WP2 presentation, recommendation n°3)*: **Observation on plate panels**
    - When $T \approx T_g$ - 20°C, drastic acceleration of damage accumulation is observed
    - Test temperature conditions must be properly chosen to ensure that cylinders will withstand elevated temperature in service (up to T_{max})
  - *Consequence:*
    - Change test temperature to T_{max} + 5°C for:
      - Sustained test at elevated temperature
      - Extreme conditions cycling test

	Sustained test at elevated T	**Cycling test at extreme conditions**	**T_{max} in service**
Transportable (ISO 11119-2&3)	60 to 70°C	65°C	65°C
On-board (EU406/2010)	85°C	85°C	85°C

Testing for type approval

- Recommendation 6:
  - *Proposal:*
    - Perform tests at the new Design Pressure (= maximum developed pressure at T_{max}) for ambient and elevated temperature
  - *Consequence:*
    - Change test pressure to the maximum developed pressure, instead of P_h = 1,5*NWP
  - *Rationale:*
    - Cylinders will never be pressurized beyond the maximum developed pressure
    - Need to demonstrate that cylinder will withstand the most severe loads (not more)

3- Batch Testing Procedures for Manufacturing Quality Assurance

Batch testing procedures for Manufacturing Quality Assurance

- Recommendation 7:
  - *Proposal:*
    - Add tests in standard to verify the good curing of the resin

      Example: Perform a Barcol hardness test on each cylinder after curing

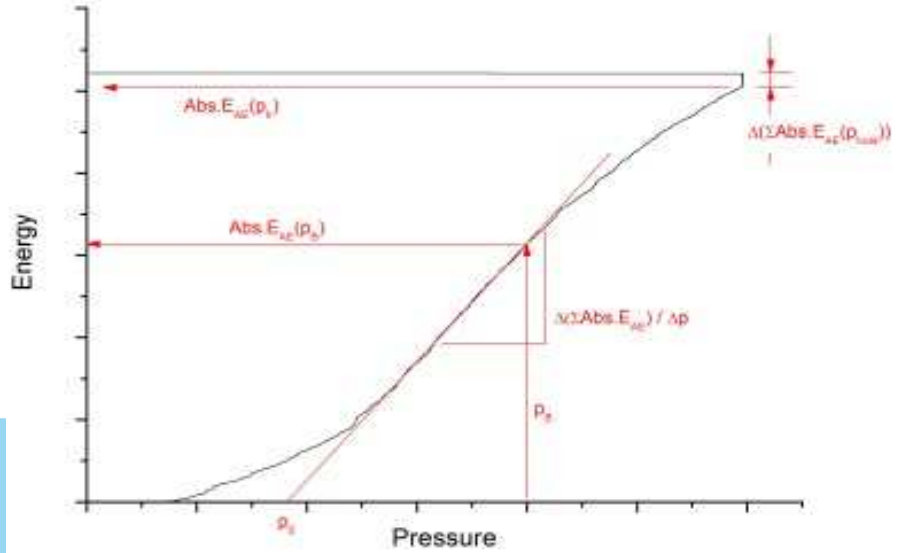
      Barcol test: Often used for composite materials to determine how much resin has cured. Inexpensive and quick.

  - *Rationale:*
    - Important effect of an improper curing of the cylinder performance (see WP4)
      - Reduced cycling performance on Type 3 cylinders
      - Increase of burst pressure scatter on Type 4 cylinders
    - Curing quality is of high importance to ensure good performance of the composite wrapping.

Batch testing procedures for Manufacturing Quality Assurance

- Recommendation 8:
  - *Proposal:*
    - Control each manufactured cylinders to detect any deviation from a reference batch, for example by using Acoustic Emission
      - More research and test is needed for the demonstration of the technique, as a unique production control method

  - *Rationale:*
    - Potential of AE to detect artificially introduced manufacturing defects (see WP4)
    - Analysis of several AE parameters compared to a reference batch supposed to behave as expected
    - Control must be performed during the very first pressurization of the cylinder (autofrettage for T3 cylinders and hydraulic proof test for T4 cylinders).
      → No additional effort for the manufacturer to control each piece of its production.



4- Methods & Procedures for Inspection In-Service

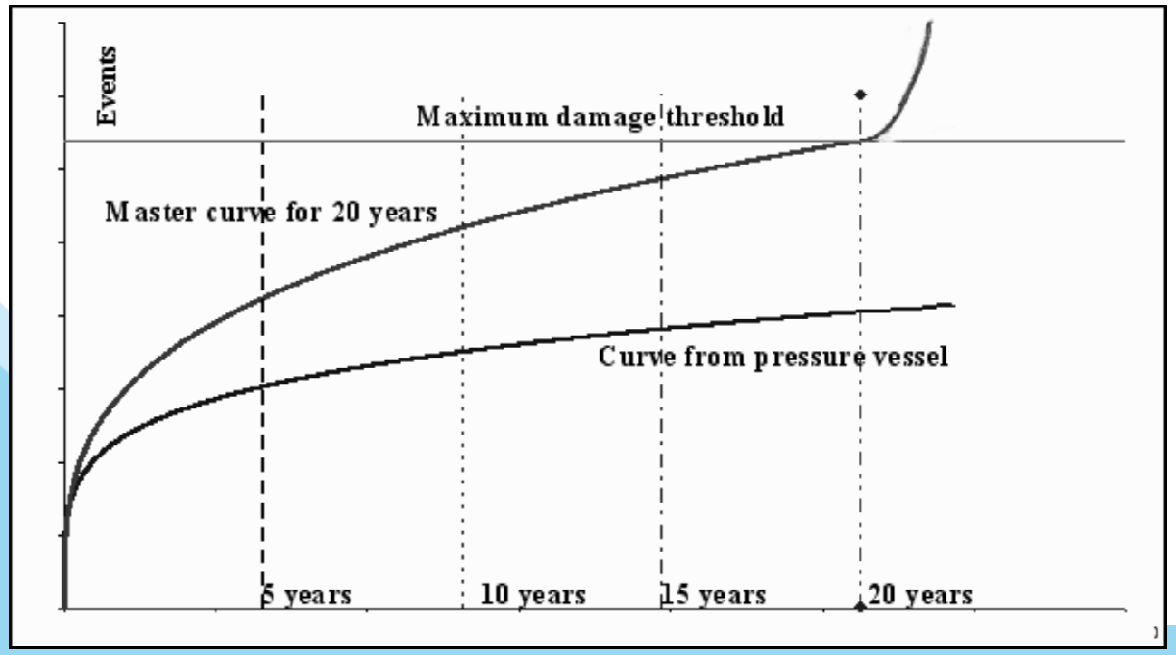
Methods and procedure for inspection in service

- Recommendation 9:
  - *Proposal:*
    - **Continue to develop Non-Destructive Techniques** to carry out periodic inspection of composites pressure vessels.
    - Acoustic Emission (AE) seems to be a promising technique for in-service inspection of composite pressure vessels. Nevertheless **further research is needed**.
  - *Rationale:*
    - Actual procedure: visual inspection (external and internal) and a hydraulic proof test
      - External visual inspection criteria needs to be adapted for composite cylinders (linked to a impact study)
      - Hydraulic proof test does not give any information of state of damage in composite wrapping due to the difference of failure modes compared to metallic cylinders.

Methods and procedure for inspection in service

- Recommendation 9:
  - *Rationale:*
    - Acoustic Emission was used in different ways during the project:
      - By BAM: for the control of each manufactured cylinders during first pressurization
      - By Armines: on specimens to quantify damage accumulation under different loads
      - By WUT: on cylinders to quantify damage level after preconditioning

Based on the « master curve approach »



- Difficulties faced:
  - How to get a master curve under accelerated conditions?
  - How to correlate test in accelerated conditions to real life?
  - Which parameters to follow? Is number of hits sufficient? Need a combination of several parameters?
  - Need harmonization between the different AE equipments

CONCLUSIONS

WP conclusions

- Synthesis of recommendations:
  1. Reduce the Design Pressure to the **Maximum Developed Pressure** at the maximum temperature
  2. Reduce Safety Factor to a **fixed value in between 1,4 and 2** (to be decided), e.g. 1,8
  3. Add specifications on T_g
  4. Make statistical assessment
  5. Perform tests at the new Design Pressure
  6. Tests at elevated temperature should be performed at **5°C above T_{max}** defined for the application
  7. Add test to verify the good curing of the resin (e.g. Barcol test)
  8. Control each manufactured cylinders to detect any deviation from a reference batch, for example by using Acoustic Emission
  9. Continue to **develop Non-Destructive Techniques** to carry out periodic inspection of composites pressure vessels.

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THANK YOU FOR YOUR ATTENTION.

ANY QUESTION?