METHOD FOR CHARACTERIZING ACCEPTANCE CRITERIA DUE TO MECHANICAL IMPACTS ON COMPOSITE CYLINDERS

Doc 221/19

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Prepared by WG-2 Gas Cylinders and Pressure Vessels

Disclaimer

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1 Introduction

Cylinders of composite construction are sensitive to mechanical impact damage, especially when carbon fibre is used. Damage due to mechanical impact(s) require further investigations to quantify damage severity.

The design standards for fully wrapped composite cylinders EN 12245, ISO 11119-2, -3 and -4, and ISO 11515[1] set the minimum requirements for the materials, design, construction, prototype testing and routine manufacturing inspections of composite gas cylinders for compressed and liquefied gases, [1,2.3.4,5].

In particular, these standards require mechanical impact tests such as a drop test and/or blunt impact test for the approval of composite cylinders.

Consequently, the impact traces left on the cylinders resulting from these tests are acceptable.

However, when a cylinder is subjected to more critical impacts, the visual damage of these impacts is unknown.

EN ISO 11623, *Gas cylinders – Composite construction – Periodic inspection and testing,* sets the reference to define damage severity classes to give acceptance/ rejection criteria for composite cylinders, both for the periodic and for the pre-fill inspection procedures [6].

Traces of mechanical impacts observed on the external surface of a cylinder or tube vary, depending on cylinder type, design, size. The requirements of EN ISO 11623 [6] to be applied to qualify/quantify mechanical impact damage severity are in some cases not clear enough and need to be clarified.

Appendix 1 gives an example of a photograph where the decision to discard a cylinder is not clear for the inspector.

2 Scope and purpose

2.1 Scope

This publication gives a method to establish the acceptance criteria for impact damage on Type 3 and Type 4 cylinders and tubes.

This publication specifies the tests to be performed for producing pictures of acceptable and non-acceptable defects.

2.2 Purpose

To provide a method for visual inspection of refillable, transportable fully wrapped composite cylinders with acceptable and non-acceptable examples of impact defects.

3 Definitions

3.1 Publications terminology

3.1.1 Shall

Indicates that the procedure is mandatory. It is used wherever the criterion for conformance to specific recommendations allows no deviation.

[1] References are shown by bracketed numbers and are listed in order of appearance in the reference section.

3.1.2 Should

Indicates that a procedure is recommended.

3.1.3 May and need not

Indicate that the procedure is optional.

3.1.4 Will

Is used only to indicate the future, not a degree of requirement.

3.1.5 Can

Indicates a possibility or ability.

3.2 Technical definitions

3.2.1 Cylinder

Transportable pressure receptacle of water capacity not exceeding 150 litres.

3.2.2 Tube

Transportable pressure receptacle of seamless or composite construction having a water capacity exceeding 150 litres and of not more than 3000 litres.

3.2.3 Type 3 cylinder

Cylinder that is fully wrapped with a load sharing liner.

3.2.4 Type 4 cylinder

Cylinder that is fully wrapped with non-load sharing liner.

4 Symbols

The following symbols are used in this publication

- p_b : Burst pressure of finished cylinder or tube, in bar
- p_h : Test pressure, in bar
- p_{max} : Maximum developed pressure at 65°C, in bar
- p_w : Working pressure, in bar
- n_{cycle} : Number of fatigue cycles of finished cylinder or tube at test pressure p_h
- $p_{burst\ mini}$: Minimum burst pressure of cylinder required by design standards (or specifications)
- $n_{cycle\ mini}$: Minimum number of fatigue cycles of cylinder required by design standards (or specifications)
- R_i = internal radius of the cylinder/tube (in metres)

5 Recommendations

5.1 General

All design standards for composite cylinders and tubes specify impact or drop test conditions and requirements for minimal performance. In addition to the tests required by these standards, for each type of cylinders, the manufacturer shall provide pictures which represent acceptable and non-acceptable defects.

5.2 Recommendations for composite cylinder manufacturers

The following are recommended for Type 3 and Type 4 cylinders:

5.2.1 Recommendation 1

The cylinder manufacturer shall provide in the approval report:

- description and pictures of the new composite cylinder including its accessories ready for service
- results / parameter of cycling and/or burst test after impact test specified by the design standards
- pictures showing external and internal states of the cylinders resulting from the impact conditions required by the construction standards [2].

By definition this first set of pictures corresponding to Recommendation 1 represents conditions where cylinders are acceptable for service at inspection (Level 1) and are used for reference.

5.2.2 Recommendation 2

The cylinder manufacturer shall:

- Perform impact tests more severe than those defined in Recommendation 1, for example, at double impact energy density or more if necessary to reduce mechanical performance of the cylinders [3]. A formula has been developed to determine the threshold energy value of an impact, for which, the residual performances becomes non-acceptable (see section 5.3);
- Provide burst and cycling performance in these conditions. Performance reduction factors shall be provided by the manufacturer vs. Requirement 1; and
- Provide pictures showing external and internal states of the cylinders (Level 2) under these impact conditions.

This set of pictures corresponding to Recommendation 2 represent conditions where cylinders could need to be rejected during inspection at time of filling or periodic inspection. Decisions shall depend on damage severity versus their application.

5.2.3 Acceptance conditions

The following information has been taken from Recommendation 1 and 2,

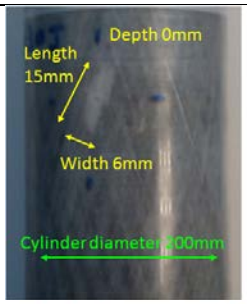
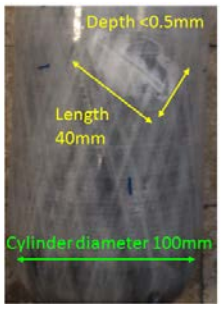
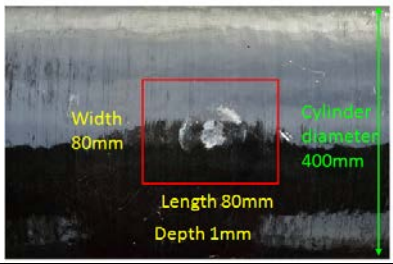
- Acceptance requirements can be specified for pre-fill inspection. An example is given in Table 1. Four cases are defined depending on the performance reduction and the cylinder failure mode; and
- Acceptance requirements can be specified for periodic inspection. An example is given in Table 2. In addition to pre-fill inspection (external inspection only), rejection criteria are defined based on the internal liner condition.

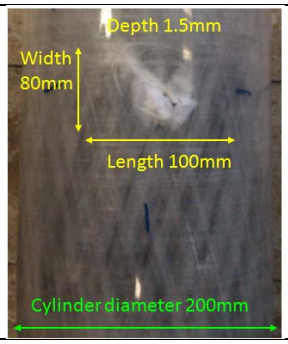
[2] The same observation device (e.g. endoscope) as the one used for periodic inspection shall be used.

[3] The same impact technique as the one specified in the design standard for the approval shall be used.

A summary of the current tests required by the construction standards and new damage test requirements of this publication are shown in Appendix 2.

Table 1 Requirements including an example of pictures for inspection at time of filling

Case	Performance results	Example of corresponding pictures *	Acceptance/ rejection at time of filling
Case 1	Cylinder burst value and cycle performance not reduced below design standards (or specifications) requirement	 	Cylinder accepted
Case 2	Cylinder burst value is not reduced to be less than the design standards (or specifications) requirement but cycling life reduced to less than the design standards (or specifications) requirement (i.e. $n_{cycle} < n_{cycle\ mini}$). Failure is a leak.	 	Depending on application service, cylinder: - can continue to be used until next periodic inspection -shall be rejected
Case 3	Cylinder burst value is not reduced to be less than the design standards (or specifications) requirement but cycling life reduced to less than the design standards (or specifications) requirement. Failure is a burst.		Cylinder rejected

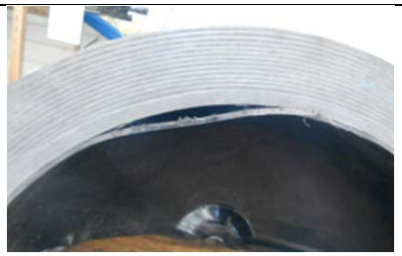
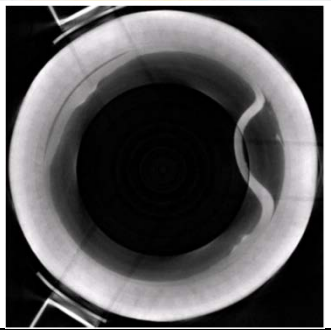
Case 4	Cylinder burst reduced below design standards (or specifications) requirement (i.e. $p_b < p_{burst\ mini}$)		Cylinder rejected

*For example, only, pictures should be supplied by the manufacturer for each cylinder type approval.

Table 2 Requirements including an example of pictures for inspection at time of periodic inspection

Case	Observations	Example of corresponding pictures **	Acceptance/ rejection at time of periodic inspection
Cases 1, 2, 3 and 4	Scenarios and pictures of Table 1 apply.		Cylinder accepted or rejected, as explained in Table 1
Case 5 [4]	Visible deformation or crack or other damage on liner's internal surface.	**Example 1: mechanical deformation for Type 3**   **Example 2: blistering / liner collapse for Type 4**	Cylinder accepted, or cylinder rejected, (to be indicated by the manufacturer in front of each example they provide).

[4] Pictures for Case 5 were taken using different techniques (visual after cut-through, endoscope, tomography). Some of these techniques are not feasible in a normal operational mode. It is therefore proposed that corresponding pictures of typical defects or/ and that representative samples be provided for reference/training.

**For example, only, Pictures should be supplied by the manufacturer for each cylinder type approval.

5.3 Determination of the threshold value

An estimation of the energy threshold, $E_{incident}$, is given by the following formula, see [7]:

$$E_{incident} = (P_b * R_i) \cdot 3.10^{-5} / 0.65 \cdot (\text{units} = \text{S.I.})$$

This formula has been developed mainly for Type 4 cylinders but is applicable to Type 3 cylinders.

An impact test above the threshold energy is likely to significantly reduce the cylinder burst pressure while an impact test below the threshold energy would probably not significantly reduce the burst pressure.

Using this approach, it is expected to help to minimize the number of impact tests.

Figure 1 explains how to use the formula to determine the threshold energy.

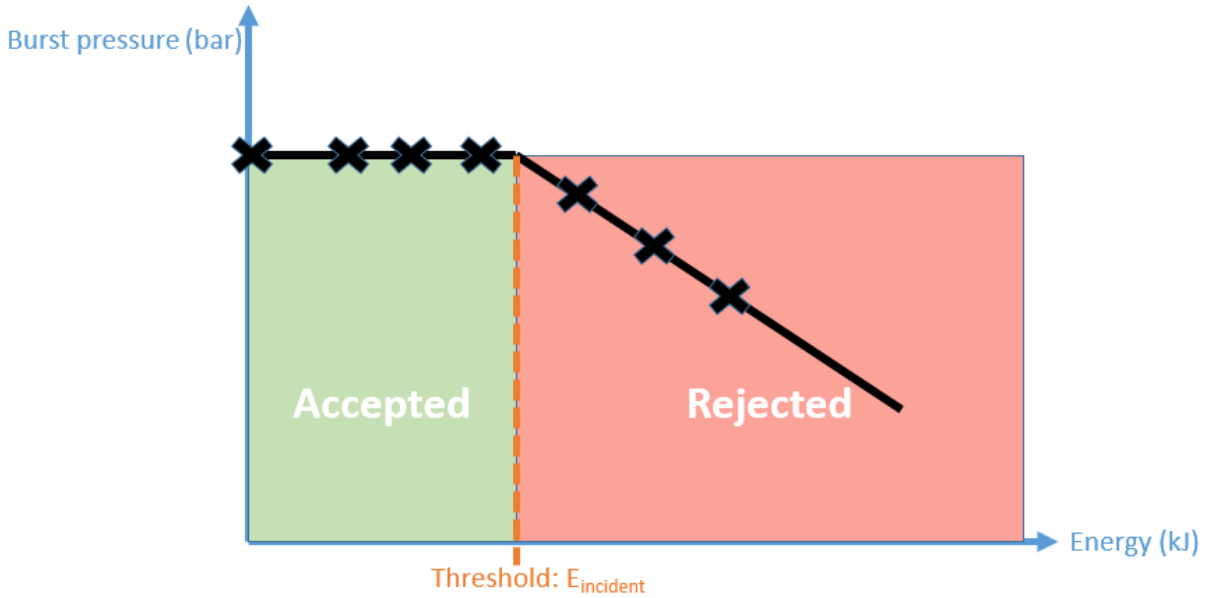


Figure 1- Burst pressure versus mechanical impact energy

6 References

Unless otherwise stated the latest edition shall apply.

[1] EN 12245, *Transportable gas cylinders. Fully wrapped composite cylinders* www.cen.eu

[2] EN ISO 11515, *Gas cylinders – Refillable composite reinforced tubes of water capacity between 450 l and 3000 l – Design, construction and testing* www.cen.eu

[3] EN ISO 11119-2, *Gas cylinders – Refillable composite gas cylinders and tubes – Design, construction and testing – Part 2: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with load-sharing metal liners* www.cen.eu

[4] EN ISO 11119-3, *Gas cylinders – Refillable composite gas cylinders and tubes – Design, construction and testing – Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with non-load-sharing metallic or non-metallic liners* www.cen.eu

[5] EN ISO 11119-4, *Gas cylinders – Refillable composite gas cylinders and tubes – Design, construction and testing – Part 4: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 150 l with load-sharing welded liners* www.cen.eu

[6] EN ISO 11623, *Gas cylinders – Composite construction – Periodic inspection and testing* www.cen.eu

[7] International Conference on Hydrogen Safety 2017, ID 136 *–Residual performance of composite pressure vessels submitted to mechanical impacts* www.hysafe.org

Appendix 1 – Example from EN ISO 11623, where the decision for cylinder discard is not clear

Cylinders of composite construction are sensitive to mechanical impact damage. Damage due to mechanical impact requires further investigations to quantify damage severity. For example, Figure 1 shows a small external trace of impact (27mm length) on a Type 3 cylinder, with a negligible damage depth. Nevertheless, further examination shows significant deformation of the liner; as shown in Figure 2. In this case the criterion given in EN ISO 11623 [6] is not obvious and probably too optimistic (Figure 3).

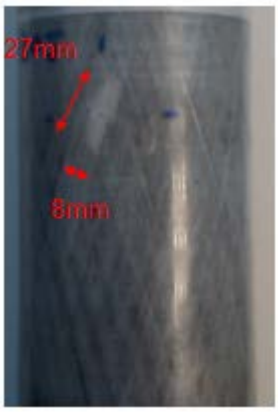
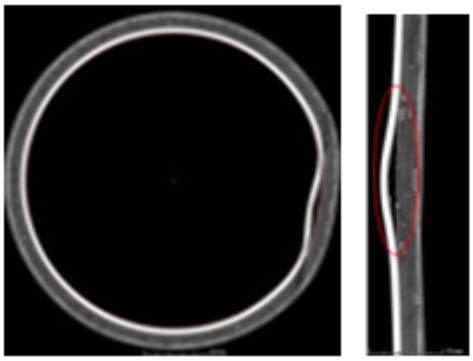


Figure 1: External damage created by a mechanical impact on a 2L Type III cylinder.



(a)

(b)

Figure 2: Liner damage created by a mechanical impact on a 2L Type III cylinder (same case as Figure1), observed by (a) tomographic and (b) endoscopic methods.

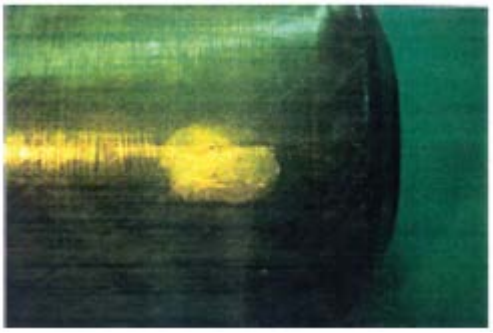


Figure 3: Level 3 impact damage from EN ISO 11623, with depth of damage over 15% of thickness.

EN ISO 11623 [6] sets the reference to define damage severity classes to give acceptance / rejection criteria for composite cylinders, both for the periodic and for the pre-fill inspection procedures. Inspection

criteria are described to verify the integrity of gas cylinders for further service, with respect to visible damage on their surface.

These criteria are general and applies to all:

- cylinder manufacturers;
- composite cylinder types i.e. Types 2 or 3 or 4;
- composite cylinder designs, for example from 0.5 to 450L water capacity, materials (liner type if any, fibres, resin, coating if any…), thickness of composite layer, surface preparation (glass fibres, exterior coating…), service pressure; and
- usage conditions, such as industrial, medical, single cylinders or mounted in a bundle of cylinders.

These criteria are not correlated to any cylinder performance reduction. They are therefore considered subjective.

Appendix 2 - Current tests required by the standards for design and new damage test recommendations

Cylinders / Tubes definition	Test definition at approval in construction standards		New additional recommendations for inspection guideline (for qualification of impact damages)	
	Test conditions	Test requirements	Test conditions	Test requirements
Cylinders up to and including 80 litres water capacity	Drop tests (Two cylinders dropped five times from 1.2m height)	1 Cycling test at test pressure 1 burst test for types III and IV	1. At approval test conditions; and 2. At impact energies larger than that defined for approval.	1 cycling test (such as that defined for approval) + 1 burst test + photos of external and internal surface of cylinder
Cylinders over 80 litres water capacity	Drop tests (4 drops x 1.8m height)	1 Cycling test at 2/3 times test pressure for types III and IV	1. At approval test conditions; and 2. At impact energies larger than that defined for approval.	
Composite tubes of water capacity between 450 L and 3 000 L	Blunt test, see EN ISO 11515 [2] (dia. 70-80mm impactor, max. 1200J)	1 Cycling test at maximum developed pressure	1. At approval test conditions; and 2. At impact energies larger than that defined for approval.	