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The requirements for the design and construction of a gas cylinders aimed for transportation of a compressed and liquefied gases

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Abstract. In this paper a typical requirements for the design and construction, workmanship and tests of a gas cylinders of water capacity between 150 l and 3000 l are described. This type of gas cylinder presents a refillable seamless steel tube aimed for transportation of compressed and liquefied gases exposed to extreme world-wide ambient temperatures. These tubes can be used alone or in batteries to equip trailers or multiple element gas containers (ISO modules or skids). When it comes about design requirements, the main focus is on the cylindrical shell thickness, which is calculated using the Lamé-von Mises formula. For some applications such as tubes assembled in batteries to equip trailers or skids (ISO modules) or MEGCs for the transportation and distribution of gases, it is important to calculate stresses associated with mounting the tube (bending stresses, torsional stresses, dynamic loadings etc.). Special attention must be paid to design of tube ends, which should be approximately hemispherical. To permit internal visual inspection of the tube, an adequate opening must be provided at the neck ends. The tubes are manufactured from seamless steel tubing, typically hot rolled, extended/extruded or forged. The ends of tube are hot formed using either forging or spinning methods. After manufacturing process, each tube must be inspected in terms of surface imperfections. Next, each tube must be ultrasonically examined for internal and external defects and laminar imperfections and to determine wall thickness. Batch tests for checking the quality of tubes includes mechanical testing, such as tensile and impact testing. Beside the batch tests, all tubes must be subjected to the following tests: a hydraulic proof pressure test or a volumetric expansion test, a hardness test, a visual inspection, a visual check of the stamp markings, a dimensional inspection and an ultrasonic non-destructive testing (NDT). At the end of this paper, the most commonly found manufacturing imperfections are pointed out.

1. Introduction

A gas cylinder is a pressure vessel for storage, containment and transportation of compressed and liquefied gases. Compressed and liquefied gases present dangerous goods, which transportation is regulated by the ADR - Agreement concerning the International Carriage of Dangerous Goods by Road [1]. The ADR states that hazardous materials may, in general, be transported internationally in wheeled vehicles, provided that two sets of conditions described in Annex A and Annex B are met (Annex A regulates the merchandise involved, notably their packaging and labels; Annex B regulates the construction, equipment, and use of vehicles for the transport of hazardous materials). In the scope of Annex A, Part 6 regulates the requirements for construction and testing of packings of dangerous goods and their labelling.



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According to the ADR, gases are classified into Class 2 of dangerous goods which covers pure gases, mixtures of gases, mixtures of one or more gases with one or more other substances and articles containing such substances.. A gas is defined as a substance which:(a) at 50°C has a vapor pressure greater than 300 kPa (3 bar) or (b) is completely gaseous at 20°C at the standard pressure of 101.3 kPa. The substances and articles of Class 2 are subdivided into following groups [1]: (1) compressed gas: a gas which when packaged under pressure for carriage is entirely gaseous at -50°C; this category includes all gases with a critical temperature less than or equal to -50°C; (2) liquefied gas: a gas which when packaged under pressure for carriage is partially liquid at temperatures above -50°C; a distinction is made between high pressure liquefied gas (a gas with a critical temperature above -50°C and equal to or below +65°C) and low pressure liquefied gas (a gas with a critical temperature above +65°C); (3) refrigerated liquefied gas: a gas which when packaged for carriage is made partially liquid because of its low temperature; (4) dissolved gas: a gas which when packaged under pressure for carriage is dissolved in a liquid phase solvent; (5) aerosol dispensers and receptacles, small, containing gas (gas cartridges); (6) other articles containing gas under pressure; (7) non -pressurized gases subject to special requirements (gas samples); (8) chemicals under pressure: liquids, pastes or powders, pressurized with a propellant that meets the definition of a compressed or liquefied gas and mixtures thereof. (9) adsorbed gas: a gas which when packaged for carriage is adsorbed onto a solid porous material resulting in an internal receptacle pressure of less than 101.3 kPa at 20°C and less than 300 kPa at 50°C.

It can be found in the literature that, in general, a gas cylinder is also designated by the term pressure receptacle. "Pressure receptacle" means a collective term that includes cylinders, tubes, pressure drums, closed cryogenic receptacles, metal hydride storage systems, bundles of cylinders and salvage pressure receptacles. Each of these terms covered by "pressure receptacle" has its own definition:

- "cylinder" means a transportable pressure receptacle of a water capacity not exceeding 150 litres, Figure 1a;
- "tube" (regarding dangerous goods Class 2) means a transportable pressure receptacle of seamless or composite construction having a water capacity exceeding 150 litres and of not more than 3 000 litres;
- "bundle of cylinders" means an assembly of cylinders that are fastened together and which are interconnected by a manifold and carried as a unit, where the total water capacity doesn't exceed 3 000 litres, Figure 1b;
- "pressure drum" means a welded transportable pressure receptacle of a water capacity exceeding 150 litres and of not more than 1000 litres (e.g. cylindrical receptacles equipped with rolling hoops, spheres on skids), Figure 1c.

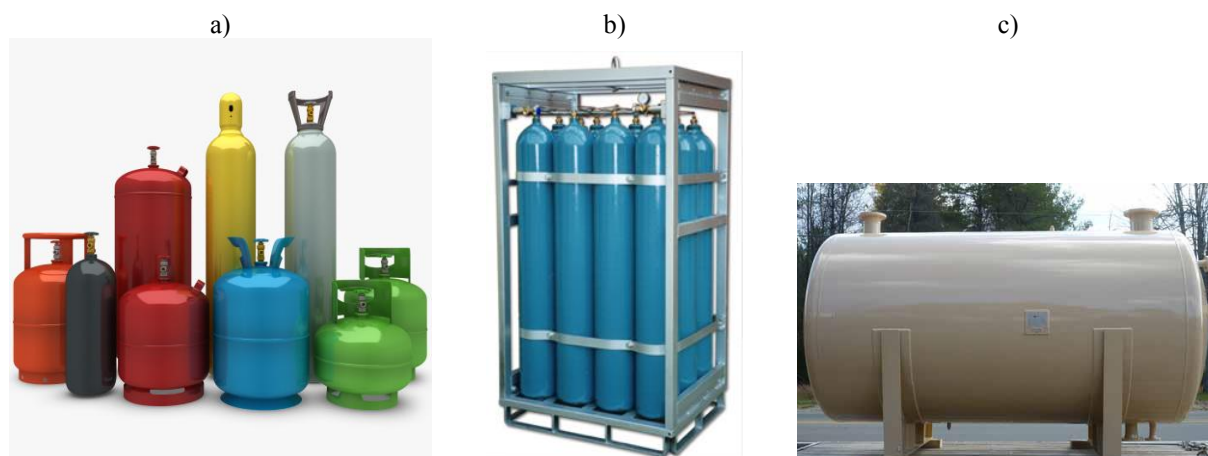


Figure 1. Pressure receptacles: a) cylinders, b) bundle of cylinders, c) pressure drum

According to these definitions, a gas cylinder of water capacity between 150 l and 3000 l presents a refillable seamless steel tube aimed for transportation of compressed and liquefied gases exposed to extreme world-wide ambient temperatures (normally between -50°C and $+65^{\circ}\text{C}$). They generally have a larger diameter and length than high pressure cylinders, and usually have a tapped neck at both ends. Due to their length, they are mounted horizontally on mobile structures. These tubes can be used alone or in batteries to equip trailers or multiple element gas containers. "Multiple-element gas container" (MEGC) means a unit containing elements which are linked to each other by a manifold and mounted on a frame, Figure 2. The following elements are considered to be elements of a multiple-element gas container: cylinders, tubes, pressure drums or bundles of cylinders as well as tanks for the carriage of gases having a capacity of more than 450 litres [1].



Figure 2. MEGC containing tubes linked to each other

2. Requirements for design, construction and testing of a gas cylinders

Published codes and standards have a guiding role in the design and manufacture of pressure equipment. Opposite to many other types of engineering equipment, codes and standards for pressure equipment provide comprehensive coverage of all aspects, from design and manufacture, through to work inspection, testing, and in/use inspection. Pressure receptacles and their closures are designed, manufactured, tested and equipped in such a way as to withstand all loads, including fatigue, to which they are subjected during normal conditions of carriage and use.

For the gas cylinders of water capacity between 150 l - 3000 l, all relevant requirements regarding design and construction are given in appropriate technical standards: ISO 11120:2016 and ADR (especially Packing Instruction P200 from ADR, where an information about substances intended for carriage in the pressure receptacle are given).

2.1. Materials requirements

The material used for the manufacture of tubes is steel containing no less than 95% of carbon, fully killed with aluminium and/or silicon. Tubes are manufactured from carbon steel, carbon manganese steel, chromium-molybdenum steel, nickel-chromium-molybdenum steel, chromium-molybdenum-vanadium steel, or a similar alloy steel. Chemical composition tolerances of each steel are given in [2]. The manufacturer of the finished tube provides a detailed specification with tolerances for the supplied tubing including: chemical composition, dimensions and surface quality. Especially attention must be taken about grades of steel used for tube manufacture regarding compatibility with the intended gas service, e.g. corrosive gases and embrittling gases. Each tube is subjected to heat treatment and for each stage of treatment, i.e. quenching and tempering, the heat treatment procedure includes a record of the temperature, the temperature holding time, and the cooling medium. Finally, the mechanical properties of the finished tube or the test ring obey to verification and the results should be in compliance with the design drawing.

2.2. Design requirements

Most pressure receptacles are cylindrical in form and are designed using cylindrical shell theory. There are various practical requirements such as the need for cylinder and closure, holes for inlet/outlet pipes and attachments. Further design criteria must then be applied to take account of the probability of weld flaws and similar defects [3].

When it comes about the design of the tube of water capacity between 150 l - 3000 l, the guaranteed minimum thickness of the cylindrical shell should not be less than the thickness calculated using the Lamé-von Mises formula:

$$a = \frac{D}{2} \left(1 - \sqrt{\frac{10FR_{eg} - \sqrt{3}p_h}{10FR_{eg}}} \right) \quad (1)$$

where:

a - calculated minimum thickness, in millimetres, of the cylindrical shell;

D - nominal outside diameter of the tube, in millimetres;

F - design stress factor;

p_h - hydraulic test pressure, in bar, above atmospheric pressure;

R_{eg} - minimum guaranteed value of yield strength, in megapascals;

R_{mg} - minimum guaranteed value of the tensile strength, in megapascals.

Design stress factor F is the ratio of the equivalent wall stress at test pressure, p_h , to guaranteed minimum yield strength, R_{eg} . The value of F is the lesser of $0.65 / (R_{eg}/R_{mg})$ or 0.85 , and ratio R_{eg}/R_{mg} should not exceed 0.90 .

Between other parameters, minimum thickness of tube wall depends on the test pressure p_h - that is required pressure applied during a pressure test. Test pressure depends on the type of compressed or liquefied gas intended to be filled and must comply with ADR packing instruction P200 for specific gas. Packing instruction is highly important part of ADR containing all instruction regarding test pressure, filling ratios and filling requirements, periodic inspection requirements for cylinders, tubes, pressure drums and bundles of cylinders. One insert from the ADR packing instruction P200 which is intended for liquefied gases is shown in Figure 3.

P200 PACKING INSTRUCTION (cont'd) P200											
Table 2: LIQUEFIED GASES AND DISSOLVED GASES											
UN No.	Name and description	Classification code	LC ₄₀ ml/m ³	Cylinders	Tubes	Pressure drums	Bundles of cylinders	Test period, years ^a	Test pressure, bar	Filling ratio	Special packing provisions
1001	ACETYLENE, DISSOLVED	4F		X			X	10	60		c, p
1005	AMMONIA, ANHYDROUS	2TC	4000	X	X	X	X	5	29	0.54	b, ra
1008	BORON TRIFLUORIDE	2TC	387	X	X	X	X	5	225 300	0.715 0.86	a
1009	BROMOTRIFLUORO-METHANE (REFRIGERANT GAS R 13B1)	2A		X	X	X	X	10	42 120 250	1.13 1.44 1.60	ra ra ra

Figure 3. An insert from ADR Packing instruction P200

For some applications such as tubes assembled in batteries to equip trailers or skids (ISO modules) or MEGCs for the transportation and distribution of gases, it is important to take into account the

stresses associated with mounting the tube (e.g. bending stresses, torsional stresses, dynamic loadings etc.). In addition, during hydraulic pressure testing, tubes could be supported or lifted by their necks. Therefore, it can be necessary to consider potential bending stresses of tube. The tube end also should satisfied requirements regarding the wall thickness (it is not less than the calculated minimum wall thickness, a) and dimension of the opening at the neck ends to permit visual inspection of the tube.

2.3. Construction and workmanship

The tubes are manufactured from seamless steel tubing, typically hot rolled, extended/extruded or forged. The ends of tubes are formed by means of forging or spinning methods. It is essential to perform the visual internal and external inspection of the formed tube because surfaces of the finished tube should be free from imperfections which could adversely affect the safe working of the tube. A various examples of imperfections and guidance on their evaluation are given in [2].

2.3.1. Surface imperfections. Several types of imperfection, either material or mechanical, may occur during the manufacturing of a seamless steel tube. These imperfections can be produced due to the basic material used, manufacturing process, heat treatments, manipulations, necking, machining or marking operations and other circumstances during manufacture. A few examples of surface imperfections are shown in Figure 4.

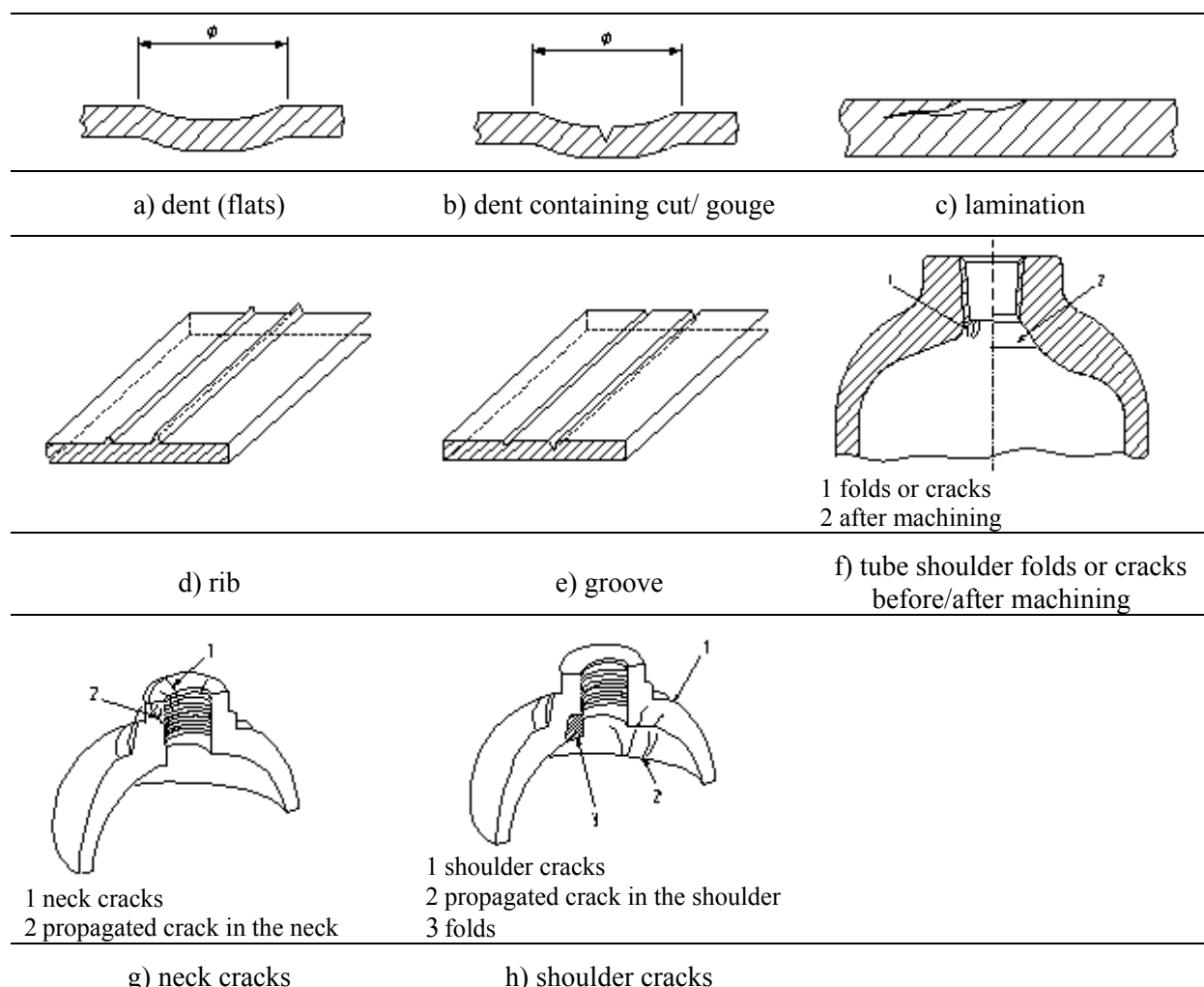


Figure 4. An examples of surface imperfections [2]

2.3.2. Ultrasonic examination. After completion of the final heat treatment and any operation resulting in loss of wall thickness (e.g. grinding or machining), each tube is subjected to ultrasonically examination for internal and external defects and laminar imperfections and to determination of wall thickness.

2.3.3. Dimensional tolerances. Following dimensional tolerances are checked:

- Out-of-roundness (the difference between the maximum and minimum outside diameters at the same cross-section, should not exceed 2 % of the mean value of these diameters measured at least at the quarter and mid-length locations on the tube);
- Outside diameter (the mean outside diameter should not deviate by more than ± 1 % from the nominal outside diameter);
- Straightness (the maximum deviation of the cylindrical part of the shell from a straight line parallel to the tube axis should not exceed 0.003 times the full body length);
- Eccentricity (the values of the minimum and maximum thicknesses should not differ by more than 12.5 % from the mean value of these two thicknesses);
- Length (the tolerance on the design overall length of the tube only, excluding fittings, should not exceed the lesser of ± 1.5 % or ± 50 mm);
- Water capacity (the tolerance on the design water capacity should be within the range of ± 10 %)
- Mass (the tolerance on design mass of any individual tube should not exceed ± 10 %. If tubes are intended to constitute a battery, the tolerance on the shipment average tube mass should be within the range of -10 % to $+5$ % of the unit design mass).

2.4. Batch testing

From each production batch (a batch is a quantity of up to 30 tubes of the same nominal diameter, thickness and design made successively from the same steel cast and processed in the same heat treatment equipment), test pieces should be selected for mechanical testing from a ring of material of minimum length 200 mm taken from supplied tubing which is representative of the final condition of the tube(s), including any heat treatment. At the completion of tube manufacture, following tests are carried out:

- mechanical tests (one tensile test and one impact test)
- all tests and inspections predicted to be done on every tube.

2.4.1. Tensile test. The tensile test is carried out in accordance with ISO 6892-1 on a cylindrical proportional test piece taken longitudinally (along the axis of the ring) in the ring wall and machined. The gauge length of the test piece is $L_0 = 5.65\sqrt{S_0}$, where S_0 is an original cross-sectional area of tensile test piece, in square millimeters, according to ISO 6892-1. The results of the tensile test should be at least equal to the minimum guaranteed values of the properties, and in all cases:

- R_{ma} should be less than 1100 MPa,
- the elongation after fracture, A , should be not less than 14 %,
- the ratio R_{ea} / R_{ma} should be not more than 0.95,

where: R_{ea} is an actual value of the yield strength, in megapascals, as determined by the tensile test; R_{ma} is an actual value of tensile strength, in megapascals, as determined by the tensile test.

2.4.2. Impact testing. The test is carried out on three test pieces taken longitudinally from the sample ring wall. The impact test is conducted at a temperature of -20°C , because a successful impact test carried out at -20°C provides absence of risk of in-service brittle failure of a tube down to lower service temperatures (e.g. -50°C) for tube types used for transport of gases. The values of impact test results should meet the following requirements:

- individual values $\geq 40 \text{ J/cm}^2$;
- mean value $\geq 50 \text{ J/cm}^2$.

2.5. Tests on every tube

After completed heat treatment, all tubes are subjected to the following tests:

- a hydraulic proof pressure test or a volumetric expansion test;
- a hardness test;
- a visual inspection;
- a visual check of the stamp markings;
- a dimensional inspection;
- ultrasonic non-destructive testing (NDT).

2.5.1. Hydraulic test. A hydraulic test is carried out using water. After testing, the interior of the tube shall be dried to avoid oxidation and/or corrosion. This hydraulic test can be performed as a proof pressure test or a volumetric expansion test:

- Proof pressure test is carried out in a way that the hydraulic pressure in the tube should be increased at a controlled rate until the test pressure, p_h , is reached with a measuring tolerance of +3% or +10 bar, whichever is the lower. The tube test pressure is held for a sufficiently long period (at least 2 min) to ascertain that there is no tendency for the pressure to decrease or for permanent visible deformation and that the tube does not leak.
- Volumetric expansion test is carried out in a same way as a proof pressure test. After the total volumetric expansion is measured, the pressure should then be released and the volumetric expansion re-measured. The tube will be rejected if it shows permanent expansion (i.e. volumetric expansion after the pressure has been released) in excess of 10% of the total volumetric expansion measured at the test pressure, p_h .

2.5.2. Hardness testing. The purpose of this test is to check the homogeneity of a tube and the level of its mechanical properties after heat treatment. A Brinell hardness test is carried out on each tube in accordance with ISO 6506-1, ISO 6506-2 and ISO 6506-3, preferably with a ball having a diameter of 10 mm and at a load of 29420 N, except when circumstances do not permit.

2.5.3. Visual inspection. The inner and outer surface of each finished tube is inspected visually for cleanliness and imperfections. This is intended to check, in particular for the inner surface, that no foreign matter or grease is present, no liquid or moisture is present inside the tube, and no shoulder cracks are present.

2.5.4. Dimensional inspection. Following dimensional inspection are done on each tube:

- inspection of wall thickness to check conformity with the requirements of ultrasonic examination,
- checks of the outside diameter and length,
- the water capacity and mass,
- neck threads and openings, when they are present, should be checked using gauges corresponding to the specified dimensions, or by some alternative method.

2.5.5 Ultrasonic non-destructive test. Each tube undergoes ultrasonic examination (UE) for imperfections and thickness verification. The wall thickness at any point should not be less than the guaranteed minimum thickness.

2.6. Marking

Refillable UN pressure receptacles should be marked clearly and legibly with permanently affixed marks (e.g. stamped, engraved, or etched) [1].

The marks should be on the shoulder, top end or neck of the pressure receptacle or on a permanently affixed component of the pressure receptacle (e.g. welded collar or corrosion resistant

plate welded on the outer jacket of a closed cryogenic receptacle). The marks are placed in three groups:

- manufacturing marks,
- operational marks,
- certification marks,

as it is shown in Figure 5.

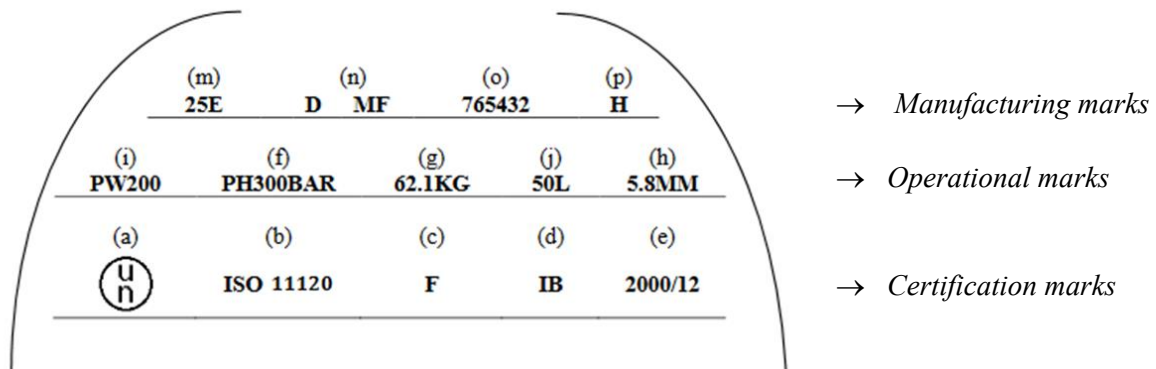


Figure 5. An example of tube marks

2.6.1. *Certification marks.* Following certification marks are applied:

- a) The United Nations packaging symbol;
- b) The technical standard (e.g. ISO 11120) used for design, manufacture and testing;
- c) The character (e.g. F) identifying the country of approval as indicated by the distinguishing sign used on vehicles in international road traffic;
- d) The identity mark or stamp of the inspection body (e.g. IB) that is registered with the competent authority of the country authorizing the marking;
- e) The date of the initial inspection, the year (four digits) followed by the month (two digits) separated by a slash (i.e. "/").

2.6.2. *Operational marks.* Following operational marks are applied:

- f) The test pressure in bar, preceded by the letters "PH" and followed by the letters "BAR";
- g) The mass of the empty pressure receptacle including all permanently attached integral parts (e.g. neck ring, foot ring, etc.) in kilograms, followed by the letters "KG";
- h) The minimum guaranteed wall thickness of the pressure receptacle in millimetres followed by the letters "MM";
- i) In the case of pressure receptacles for compressed gases, UN No. 1001 acetylene, dissolved, and UN No. 3374 acetylene, solvent free, the working pressure in bar, preceded by the letters "PW". In the case of closed cryogenic receptacles, the maximum allowable working pressure preceded by the letters "MAWP";
- j) In the case of pressure receptacles for liquefied gases and refrigerated liquefied gases, the water capacity in litres expressed to three significant figures rounded down to the last digit, followed by the letter "L".

2.6.3. *Manufacturing marks.* Following manufacturing marks are applied:

- m) Identification of the cylinder thread (e.g. 25E);
- n) The manufacturer's mark registered by the competent authority. When the country of manufacture is not the same as the country of approval, then the manufacturer's mark shall be preceded by the character(s) identifying the country of manufacture as indicated by the distinguishing sign used on vehicles in international road traffic. The country mark and the manufacturer's mark shall be separated by a space or slash;

- o) The serial number assigned by the manufacture;
- p) In the case of steel pressure receptacles and composite pressure receptacles with steel liner intended for the carriage of gases with a risk of hydrogen embrittlement, the letter "H" showing compatibility of the steel.

3. Conclusion

An actual standards and codes have a guiding role in the design, manufacturing and inspection of pressure receptacles. In contrast to other types of engineering equipment, standards and codes for pressure receptacles provide extensive coverage of all stages, such as design, construction and testing. When it comes about a refillable seamless steel tubes of water capacity between 150 l and 3000 l, this type of gas cylinders obey requirements of EN ISO 11120:2015 and Agreement Concerning the International Carriage of Dangerous Goods by Road. According to these standards, gas cylinders and their closures must be so designed, manufactured, tested and equipped in such a way as to withstand all loads, including fatigue, to which they are subjected during normal conditions of carriage and use. The minimum wall thickness should not be less than that specified in the design and construction technical standards. The test pressure of gas cylinders should be in accordance with packing instruction P200 (ADR), depending on the type of compressed or liquefied gas intended to be filled.

References

- [1] ***ADR - Agreement Concerning the International Carriage of Dangerous Goods by Road, 2017, Economic Commission for Europe Inland Transport Committee, ECE/TRANS/257.
- [2] ***EN ISO 11120:2015 Gas cylinders - Refillable seamless steel tubes of water capacity between 150 l and 3000 l - Design, construction and testing.
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