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Technical paper

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SAFETY AND OPERATIONAL CONSIDERATIONS FOR COMPOSITE HYDROGEN AND CNG STORAGE CYLINDERS IN VEHICLES

ABSTRACT: The increasing adoption of compressed natural gas (CNG) and hydrogen as alternative automotive fuels has intensified the demand for reliable and safe high–pressure storage technologies. Composite pressure cylinders offer an efficient solution for onboard gaseous fuel storage owing to their high strength–to–weight ratio, corrosion resistance, and favorable fatigue performance. This paper presents a comprehensive analysis of operational conditions, installation requirements, inspection procedures, maintenance practices, and safety considerations associated with Type–3 composite cylinders used for onboard storage of CNG and hydrogen in road vehicles. The study examines the effects of pressure cycling, temperature variations, environmental exposure, mechanical damage, and operational handling on cylinder integrity and service life. Particular attention is given to mounting systems, thermal pressure relief devices, inspection methodologies, and damage assessment criteria. Additionally, the paper examines fueling and defueling procedures, risk mitigation measures, and end–of–life management practices. The analysis highlights the critical factors affecting cylinder reliability and identifies key safety measures necessary for safe long–term operation. The findings contribute to improved operational reliability, risk management, and safety performance of modern alternative–fuel vehicle systems.

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KEYWORDS: Composite pressure cylinders; Hydrogen storage; compressed natural gas (CNG); vehicle safety; inspection and maintenance

BEZBEDNOSNI I EKSPLOATACIONI ASPEKTI PRIMENE KOMPOZITNIH REZERVOARA ZA SKLADIŠTENJE VODONIKA I KPG U VOZILIMA

REZIME: Sve veću primenu komprimovanog prirodnog gasa (KPG) i vodonika kao alternativnih goriva za vozila prati i potreba za pouzdanim i bezbednim tehnologijama za skladištenje ovih gasova pod visokim pritiskom. Kompozitni rezervoari predstavljaju efikasno rešenje za skladištenje gasovitih goriva u vozilima zbog povoljnog odnosa mase i zapremine, adekvatne čvrstoće, otpornosti na koroziju, kao i dobre otpornosti na zamor materijala.
U radu je data analiza uslova eksploatacije, zahteva za ugradnju, postupaka kontrole, održavanja i sistematizovani su osnovni uslovi sa aspekata bezbedne primene kompozitnih rezervoara tipa 3 za skladištenje KPG–a i vodonika u motornim vozilima. Razmatrani su uticaji cikličnih promena pritiska, temperaturnih promena i drugih uslova okoline, kao i mehaničkih oštećenja i načina rukovanja na konstrukciju i radni vek rezervoara. Posebna analiza je izvršena u delu uslova za pričvršćenje rezervoara, ugradnje uređaja i opreme za rasterećenje pritiska, metoda kontrole i kriterijuma za eventualnu procenu oštećenja rezervoara. Takođe su analizirani uslovi za bezbedno punjenje i pražnjenje rezervoara za potrebe servisiranja i održavanja, u cilju smanjenja rizika, i istraživano je postupanje sa rezervoarima na kraju radnog veka. Analizom su identifikovani ključni faktori koji utiču na pouzdanost rezervoara i definisane su osnovne mere i uslovi u cilju njihove bezbedne i dugoročne eksploatacije.

KLJUČNE REČI: Kompozitni rezervoari pod pritiskom, skladištenje vodonika, komprimovani prirodni gas (KPG), bezbednost vozila, kontrola i održavanje

INTRODUCTION

Composite high-pressure cylinders are increasingly used in automotive applications for the storage of compressed natural gas (CNG) and hydrogen. The safe operation of these systems is governed by defined pressure, temperature, and service conditions established by the applicable standards and certification requirements. Accordingly, the cylinders must be operated within their specified design and permissible operating limits throughout their service life. The Type–3 cylinders considered in this research feature a seamless 6061 aluminium alloy liner that is completely enclosed by a carbon–fiber/epoxy composite overwrap, providing the required structural reinforcement and pressure resistance, Figure 1 (Milojević, 2017; Luxfer Gas Cylinders, 2018).



Figure 1 Design of a Type 3 Composite Cylinder (AA6061 aluminium liner with carbon fibre/epoxy overwrap)

In general, the applicable design and safety requirements are specified by the relevant standards and regulations, including ISO 11439 and UN ECE 110R for natural gas applications, as well as Regulation (EU) 2019/2144 and UN Regulation No. 134 for hydrogen–fueled systems (UNECE, 2018; ISO, 2013; European Parliament & Council of the European Union, 2019; UNECE, 2019).

The cylinders are designed for a nominal service pressure of 20 MPa, referenced to an ambient temperature of 15 °C. During refueling, the filling pressure must be controlled so that, after thermal stabilization, the cylinder pressure does not exceed the specified service pressure under the reference temperature conditions. Therefore, the pressure applied during filling should be adjusted according to the actual gas temperature to ensure compliance with the maximum permissible filling pressure. The following approximate relationships can be used for estimating the corresponding pressure conditions (Luxfer Gas Cylinders, 2018):

$$P_{\mathrm{CNG}} = 176 + 1.6 \cdot T_{\mathrm{CNG}} \tag{1}$$

$$P_{H_2} = 189 + 0.73 \cdot T_{H_2} \quad (2)$$

Where are:

P [bar] – the corresponding pressures; and T [°C] – the temperatures of CNG and hydrogen, respectively.

For natural gas applications, the actual cylinder pressure is additionally influenced by the composition of the gas. Regardless of the operating temperature, the filling pressure must remain below the absolute maximum limit of 26 MPa. Furthermore, the cylinders should only be filled using compressors whose maximum discharge pressure does not exceed 1.5 times the specified nominal service pressure.

Hydrogen can also be stored in gaseous form within pressure vessels at substantially higher pressures than those typically used for natural gas. For example, a nominal service pressure of 35 MPa is specified at an ambient temperature of 15 °C. During filling, the pressure should be controlled so that, following thermal stabilization, the cylinder pressure does not exceed the specified service pressure of 35 MPa under the reference temperature conditions (Luxfer Gas Cylinders, 2018).

For hydrogen storage systems, the filling pressure is subject to an absolute upper limit of 43.75 MPa, which must not be exceeded irrespective of the gas temperature. Accordingly, the pressure applied during the refueling process should be determined by taking into account the actual hydrogen temperature, thereby ensuring that the pressure remains within the permissible filling limit. The following approximate calculations can be employed to estimate the appropriate filling pressure under different temperature conditions (Luxfer Gas Cylinders, 2018):

$$P_{H_2} = 331 + 1.26 \cdot T_{H_2} \quad (3)$$

During handling, transportation, and storage, Type–3 cylinders should be depressurized and carefully protected against mechanical damage, particularly to the carbon–fiber overwrap and aluminum liner. Appropriate personal protective equipment should be used, while contact with valves, fittings, and pressure–relief devices should be avoided. Cylinders must be secured against rolling, impacts, and accidental dropping. During storage, they should be protected from excessive heat, moisture, corrosive environments, UV radiation, and surface abrasion, with suitable protective plugs used to prevent contamination of open ports. Appropriate lifting equipment should be employed when necessary.

Type–3 cylinders can withstand normal contaminants encountered in automotive environments; however, exposure to highly corrosive acids, alkalis, or abrasive materials should be avoided. No additional protective coating is recommended, as it could hinder the visual detection of damage to the reinforcing fibers. The existing epoxy surface layer provides adequate protection of the composite overwrap. Particular care should also be taken to prevent the ingress of water into the cylinder, since moisture contamination may adversely affect its service life.

The operating temperature limits for CNG and hydrogen cylinders are defined by the applicable standards and regulations, including ISO 11439, UN ECE 110R, and Regulation (EU) 2019/2144 and UN Regulation No. 134. Under these conditions, the settled gas temperature may range from (−40) − 65 °C for CNG and up to 85 °C for hydrogen. The corresponding allowable temperature range for the cylinder materials extends from (−40) − 82 °C for CNG and up to 85 °C for hydrogen. For CNG cylinders, any local or transient temperature increase above 65 °C must be limited in duration and extent so that the gas temperature inside the cylinder remains below the specified maximum (UNECE, 2018; ISO, 2013; European Parliament & Council of the European Union, 2019; UNECE, 2019).

The cylinders are suitable for CNG, compressed hydrogen, and hydrogen–gas mixtures. The composition of CNG shall meet the requirements specified in ISO 11439 and UN ECE 110R, while Compressed hydrogen shall comply with the fuel quality requirements specified in ISO 14687:2025 (UNECE, 2018; ISO, 2013, 2025).

The service life of the cylinders is limited to approximately 15–20 years from the date of final inspection, depending on the applicable national requirements and specified annual filling cycles. The expiration date is indicated on the cylinder label. Once the specified service life or maximum number of filling cycles is reached, the cylinder must be permanently withdrawn from service. For CNG cylinders, the allowable number of fillings is limited to 1000 cycles per year of service life, while hydrogen cylinders are limited to 5000 filling cycles (Luxfer Gas Cylinders, 2018).

For hydrogen cylinders, the applicable regulations may permit a lower maximum number of filling cycles when an appropriate monitoring and control system is implemented. In such cases, the specified cycle limit is marked on the cylinder label, Figure 2, and the cylinder must be withdrawn from service once this limit has been reached.

Periodic external visual inspections of the composite overwrap are required after installation or reinstallation to identify possible defects. The inspection frequency and procedures shall comply with the applicable national standards and regulations; for CNG cylinders, UN ECE 110R specifies an interval of at least 48 months after the vehicle is placed into service. Shorter intervals may apply depending on the cylinder type and applicable type–

approval requirements. Inspections should be performed according to ISO 19078:2013 or national standards (UNECE, 2018; ISO, 2013).



Figure 2 Examples of CNG and Hydrogen Cylinder Labels

Routine hydraulic pressure testing is generally not required. Where such testing is mandated by national regulations, only appropriately treated water should be used, with chloride removal and suitable corrosion inhibitors, while exposure time should be minimized to protect the AA6061 aluminum liner from corrosion.

Cylinders that have been subjected to a vehicle collision shall undergo a re–inspection conducted by an agency authorized by the manufacturer and, where applicable, by the relevant regulatory authority. If the inspection confirms that the cylinder has not sustained any impact–related damage, it may be returned to service. However, if any damage resulting from the collision is identified, the cylinder shall be returned to the manufacturer for further assessment and evaluation.

Cylinders exposed to fire shall be immediately removed from service and shall not be returned to service unless their safety and structural integrity have been verified through an appropriate inspection and assessment. A cylinder may have been adversely affected by fire or excessive heat without exhibiting any visible signs of damage. Therefore, the prescribed inspection and assessment procedures shall be followed to ensure that the cylinder remains safe for further service.

CYLINDER AND EQUIPMENT INSTALLATION REQUIREMENTS

The cylinders shall be installed in accordance with the applicable installation requirements for the specific model. The installer is responsible for ensuring adequate protection of cylinder valves, pressure relief devices (PRD), and connections, in compliance with the applicable national standards and regulations.

All components must be suitable for a working pressure of at least the nominal service pressure of the cylinder, i.e., 20 or 35 MPa, depending on the cylinder type. Components used in accordance with UN ECE 110R and the relevant requirements for hydrogen vehicles must be approved for a working pressure corresponding to at least the maximum filling pressure of 26 or 43.75 MPa, respectively (Luxfer Gas Cylinders, 2018).

For fire safety, each cylinder must be equipped with an appropriate PRD compatible with the cylinder type and approved in accordance with the relevant standards.

Valves and End Plugs with O–Ring Seals

All valves and end plugs shall be provided with an O–ring sealing seat and shall have at least 7 engaged threads for 20 MPa cylinders and 11 engaged threads for 35 MPa cylinders. The components shall be tightened to the specified torque. Tapered threads shall not be used (Luxfer Gas Cylinders, 2018).

Before installation, the valve or end plug, mating threads, and sealing surfaces shall be inspected for damage and cleaned with a suitable detergent or solvent using a nylon brush. The surfaces shall then be dried with a clean cloth and kept free of dirt and debris. The specified O–ring shall be selected according to Table 1 and installed carefully without damage. Other O–rings shall not be used without prior qualification.

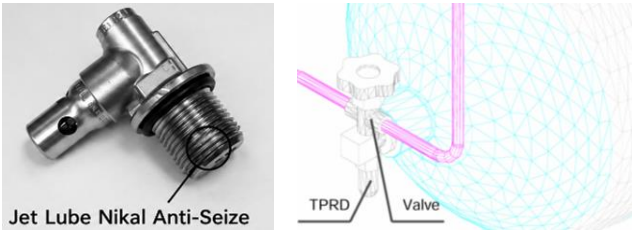
Table 1 Example: O–Ring Specifications and Tightening Torques for 1.125″ and 2.0″ Threads

Thread designation	O–ring dimensions [mm] (inside diameter x cross–section diameter)	Torque [Nm] 20 / 35 MPa cylinder series
1.125 – 12 UNF	28.17 x 3.53	217 (± 14) / 240 (± 10)
2.0 – 12 UN	50.39 x 3.53	305 (± 15) / 320 (± 10)

The valve or end plug shall be manually screwed into the cylinder port and tightened to the specified torque using appropriate tools. The required tightening torques shall comply with the values given in Table 1. After tightening, a

suitable torque–indicating compound shall be applied to the external joint between the end plug and cylinder neck to confirm completion of the installation (Luxfer Gas Cylinders, 2018).

For hydrogen service, the use of O–ring lubricant or anti–seize compound should be minimized to avoid potential gas contamination. If required, a thin film of suitable O–ring lubricant may be applied to the O–ring. A small amount of copper–free anti–seize compound may be applied to the first threads, as shown in Figure 3.a, while avoiding contact with the O–ring.



(a) (b)

Figure 3 (a) Application of Anti–Seize Compound to the Valve Thread; (b) Typical Valve and TPRD Assembly

Pressure Relief Devices

Thermally activated pressure relief devices (TPRDs) shall be incorporated into the cylinder piping system to provide controlled pressure relief in the event that the cylinder is subjected to fire or excessive heat, Fig.3.b. The required number and configuration of TPRDs shall be specified in the applicable installation drawing. The TPRD discharge outlets shall remain unobstructed and shall not be blocked, sealed, or covered by adjacent components or attachments.

For longer cylinders, a middle–plug TPRD may be installed at the center of the cylinder and connected to the valve or end plug by a dedicated TPRD pipe, Figure 4.

The TPRD pipe remains under cylinder pressure even when the valve is manually and/or electrically closed. Installation and servicing shall therefore be performed only by personnel trained in compression fitting installation.

The TPRD and pipe shall be positioned and installed in accordance with the applicable installation drawing and the manufacturer's instructions. The pipe shall be cleaned immediately before installation. The TPRD shall be secured using a saddle clamp with a rubber strip between the clamp and cylinder surface. The clamp shall be correctly positioned, tensioned, and locked in accordance with the manufacturer's instructions, Figure 4.



Figure 4 TPRD Pipe, Middle Plug and Saddle Bracket on Bus–Mounted Cylinders

A minimum clearance of 5 mm shall be maintained between the TPRD pipe and the cylinder surface. Where necessary, a soft elastomeric support may be installed between the pipe and cylinder, Figure 4 (Luxfer Gas Cylinders, 2018).

Cylinder Installation and Mounting

The cylinder, cylinder assembly, or cylinder rack, including the associated safety devices and complying with UN ECE 110R or Regulation (EU) 2019/2144 and UN Regulation No. 134, shall be securely installed and restrained to withstand the specified accelerations and decelerations given in Table 2, without failure or loosening of the mounting system. Compliance shall be demonstrated by appropriate testing or calculation, using a mass representative of the fully equipped and filled cylinder, cylinder assembly, or cylinder rack (UNECE, n.d.; UNECE, 2019; ISO, 2025).

As example, neck mount brackets are designed to securely fasten CNG or hydrogen storage cylinders to automotive vehicles in a horizontal position, Figure 5. Where neck mounting is specified, the cylinder model number includes the designation “N” at the end. The Figure 5 also shows the installation position of the cylinder on the factory–mounted roof rack of the bus (Milojević, 2017; Milojević et al., 2025).

Table 2 Required Accelerations and Decelerations for Gas Cylinders

Motor Vehicle Categories	M1 and N1	M2 and N2	M3 and N3
Vehicle Acceleration:			
– In the Direction of Travel	20·g	10·g	6.6·g
– Perpendicular to the Direction of Travel	8·g	5·g	5·g

Motor Vehicle Categories: M1 with ≤ 9 passengers or N1 (for goods) ≤ 3.5 t;
M2 with > 9 passengers and ≤ 5 t or N2 (for goods) > 3.5 t and ≤ 12 t;
M3 with > 9 passengers and > 5 t or N3 (for goods) > 12 t

The brackets shall only be used within the conditions specified in this Statement of Service. Installation shall comply with the applicable requirements of ISO 11439 and UN ECE 110R for CNG cylinders, or Regulation (EU) 2019/2144 and UN Regulation No. 134 for hydrogen cylinders (UNECE, n.d.; ISO, 2013; UNECE, 2019; ISO, 2025).

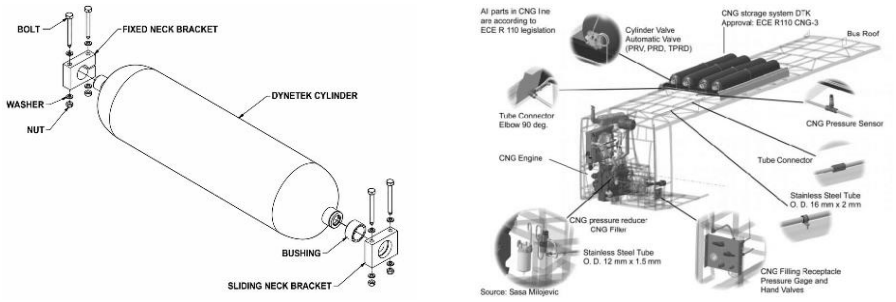


Figure 5 Cylinder Neck Mount Assembly and Installation of the Cylinder Rack on the Roof of a City Bus

Cylinders are installed using two neck–mounting brackets that secure the extended cylinder necks. One end of the cylinder is rigidly restrained, while the opposite end is allowed to slide within the bracket to accommodate dimensional changes caused by variations in temperature and internal pressure, Figure 5. When properly installed, the fixed neck–mounting bracket prevents longitudinal movement of the cylinder neck within the bracket up to a maximum longitudinal load of 17 kN. This load corresponds to the following weights for a fully filled cylinder, Table 3 (Luxfer Gas Cylinders, 2018):

Table 3 Permissible Total Cylinder Weight According to ECE R110, (EC) No. 79/2009, and (EC) No. 406/2010

Acceleration	20·g	10·g	6.6·g
Maximum Permissible Weight of a Filled Cylinder [kg]	86	173	262

Max. Permissible Weight of a Filled Cylinder = 17 kN / (9.81 m/s² x acceleration)

A neck mount bracket set consists of a fixed bracket, a sliding bracket, and a pre–installed high–molecular–weight polyethylene bushing. The fixed bracket is installed on the cylinder neck with the cylinder serial number and bracket marking facing outward and upward, while the sliding bracket is installed on the opposite neck in the same orientation. The cylinder is then placed on the vehicle rack and rotated to position the fixed (valve) end as required. The neck position in the sliding bracket shall be adjusted to provide sufficient clearance for cylinder expansion caused by pressure and temperature variations Figure 5.

The M12 sliding and fixed bracket bolts shall be selected according to the working loads, with minimum property classes of 70 for stainless steel and 8.8 for steel bolts. The bolts shall be tightened to the specified torque, but not less than 70 Nm, and secured against loosening using an appropriate locking method. After tightening the fixed bracket, the cylinder position shall be checked and readjusted if necessary (Luxfer Gas Cylinders, 2018).

Cylinder Protection and Shielding Requirements

The cylinder shall be installed with suitable protection and shielding to prevent damage under vehicle operating conditions. The shielding shall protect the cylinder from road debris, contact with cargo, excessive heat, harmful vehicle fluids, and prolonged UV exposure.

The shielding shall be installed without direct contact with the cylinder and without creating areas where debris or liquids can accumulate. It shall also prevent contact between the cylinder and vehicle components such as the frame, body panels, brake lines, and exhaust system, thereby reducing the risk of abrasion and surface damage. Open–mesh shielding is generally preferred because it minimizes the accumulation of water and other liquids while allowing visual inspection of the cylinder.

No additional coating shall be applied to the composite cylinder if it could adversely affect the composite material or interfere with visual inspection. The shielding and mounting arrangement shall also ensure that the cylinder identification markings remain clearly visible, including the cylinder label and barcode, the dome sticker and barcode, and the serial–number marking on the cylinder neck, Figure 6.

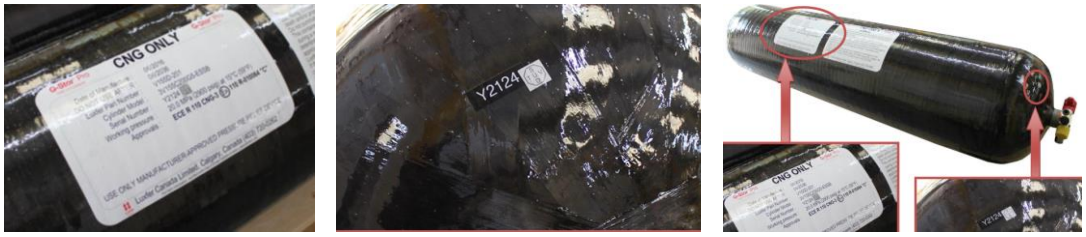


Figure 6 Cylinder Serial Number Locations

A permanent electrical connection between the cylinder, including its attached components, and the vehicle shall be provided to prevent the accumulation of static electrical charge and minimise the risk of sparking that could ignite escaping gas.

CYLINDER AND MOUNTING SYSTEM INSPECTION AND MAINTENANCE

When filling, defueling, inspecting, or servicing cylinders and associated components containing pressurized hydrogen or natural gas, appropriate safety precautions shall be followed. Only trained and authorised personnel shall fill, defuel, inspect, or service cylinders and components containing pressurized hydrogen or natural gas, following the manufacturer's procedures and using appropriate protective equipment.

All potential ignition sources, including open flames and heat sources, shall be eliminated. Electrical connections shall be disconnected where necessary, and the system shall be properly grounded to prevent sparking. The system and its components shall always be assumed to be pressurized. Fittings and ports shall therefore be opened slowly, and work shall be stopped immediately if gas leakage occurs or excessive torque is required.

Particular care shall be taken when a potentially flammable gas mixture may be present. Hydrogen is flammable in air at concentrations of approx. 4–74%, while natural gas is flammable at approx. 5–15%. Systems containing potentially flammable mixtures shall not be operated, stored, or transported and shall be properly purged before further work. Electrical connections shall not be made to systems containing a potentially flammable mixture (Luxfer Gas Cylinders, 2018; Loman et al. 2026).

Preparation of Cylinders and Components for Inspection and Maintenance

Depending on the maintenance activity, the cylinder and associated components may require defueling and/or purging before work begins. For visual inspection and leak testing, where no mechanical work is performed, the cylinder assembly shall be properly grounded. If maintenance is performed without breaking connection seals, such as re–torqueing fittings or end plugs, the assembly shall be grounded and defueled to prevent the ingress of air or debris. If connection seals must be broken, such as when replacing a valve or fitting, the cylinder or component shall be grounded, defueled, and purged before work begins.

The cylinder and associated components should be cleaned before visual inspection using clear or soapy water. Abrasive detergents and aggressive cleaning agents, such as acetone, solvents, or gasoline, shall not be used because they may damage the cylinder surface. A pressure washer may be used with a maximum spray pressure of 10 MPa and a minimum distance of 50 cm. The water jet shall not be directed at cylinder labels, solenoid valves, electrical connectors, or safety devices such as TPRDs (Luxfer Gas Cylinders, 2018).

Inspection of Cylinders and Components

Inspection is an essential safety measure for detecting damage to the cylinder or mounting system and identifying any adverse environmental effects during operation. Inspections shall be performed using appropriate tools, such as measuring instruments for determining defect dimensions, a flashlight, an adjustable mirror, and a cleaning cloth. Two types of inspections are specified: General Inspection and Certification Inspection, as summarized in Table 4.

The General Inspection is not mandatory but is recommended every 3 months to verify that the fuel storage system remains in good condition. It covers the mounting system and cylinder(s).

The mounting inspection shall verify that all brackets are undamaged and securely attached to the vehicle, with all bolts present and properly tightened. For belly–mounted systems, protection pads shall be present, in good condition, and each cylinder shall be securely restrained. Loose mounting components shall be re–secured in accordance with the applicable installation procedure. Damage to the mounting system may indicate vehicle accident involvement and requires a Certification Inspection. Missing or damaged components shall be replaced with approved parts.

Table 4 Inspection Categories Summary

Inspection Type	Description	Inspection Frequency
General Inspection	Performed by the driver, maintenance personnel, or other qualified service technician, this inspection is primarily visual and is intended to verify that the cylinder, mounting system, and piping are in good condition, properly secured, and free from visible damage.	Recommended every 3 months
Certification Inspection	Performed by trained personnel certified in accordance with applicable local regulations and requirements. This inspection provides a more detailed examination of the cylinder, mounting system, and piping.	Typically performed at commissioning and every 3–4 years, subject to local authority requirements.

The cylinders shall be inspected for signs of damage in accordance with the applicable inspection criteria, Table 5. Any indication of damage shall be assessed and appropriate corrective action determined. Minor cutting or abrasion limited to the outer pure epoxy resin layer is not considered critical and does not require further damage assessment.

Table 5 Cylinder Damage Types, Signs, and Potential Causes

Cylinder Damage Type	Signs of Damage	Potential Causes
Impact Damage	Dents, scratches, cracked or peeling laminate, or crazing (hairline cracks in the laminate)	Impact from a blunt object or dropping the cylinder
Cutting Damage	Cuts, scratches, gouges, or peeling laminate	Contact with a sharp or pointed object
Abrasion Damage	Scuffs, dull or whitish areas, or flat spots	Friction between the laminate and an object in contact with the cylinder
Fire or Excessive Heat Damage	Charred or discolored laminate, soft spots, blistering, or swelling	Exposure to direct flame, contact with an excessive heat source, or proximity to a high–temperature source
Weathering Damage	Cloudy appearance, discoloration, or soft spots	Exposure to UV radiation or water ingress through cracks in the laminate
Chemical Damage	Discoloration, soft spots, blistering, or swelling	Exposure to brake fluid or other corrosive fluids

The Certification Inspection is a detailed examination of the cylinder and mounting system performed by personnel certified in accordance with local regulations. The inspection frequency is determined by the relevant authorities and is typically every 4 years for CNG cylinders under UN ECE 110R and every 3 years for other cylinders. Following a vehicle accident, a Certification Inspection should be considered even if no visible damage is apparent (UNECE, n.d.; Milojević et al. 2025).

Before filling, the hazards associated with hydrogen and natural gas, including fire, explosion, and asphyxiation, shall be considered. Filling shall be performed in a well–ventilated area free of ignition sources, with appropriate leak testing, evacuation, and purging procedures to prevent the formation of flammable gas mixtures. Proper system design and operating procedures are essential for safe handling (Turek et al. 2024; Aldhafeeri et al. 2020).

Defueling shall be performed by controlled venting to approx. 0.2 MPa, preventing air ingress and safely discharging the gas through an appropriate venting or flare system. The procedure shall be performed outdoors in a controlled safety zone, with the system grounded, ignition sources eliminated, and appropriate protective equipment used (Luxfer Gas Cylinders, 2018).

CONCLUSIONS

The analysis confirms that the safe and reliable operation of Type–3 composite cylinders for CNG and hydrogen storage depends on proper control of operating conditions, installation, inspection, maintenance, and handling procedures. Particular attention should be given to pressure and temperature limits, secure mounting, protection against mechanical and environmental damage, and correct installation of pressure–relief devices.

Regular visual and certification inspections are essential for the early detection of damage and for maintaining cylinder integrity throughout its service life. Safe filling and defueling procedures, together with appropriate grounding, ventilation, purging, and control of ignition sources, are critical for reducing fire, explosion, and asphyxiation risks.

Overall, the implementation of appropriate technical and safety procedures, in accordance with applicable standards, regulations, and manufacturer requirements, provides the basis for extending operational reliability, minimizing risks, and ensuring the safe long–term use of composite CNG and hydrogen storage systems in vehicles.

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