AN OVERVIEW OF NGV CYLINDER SAFETY STANDARDS, PRODUCTION AND IN-SERVICE REQUIREMENTS.

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EXECUTIVE SUMMARY

Today there are around four million vehicles on the road using compressed natural gas for fuel, and that number is increasing every year. To ensure that safe and efficient high-pressure gas cylinders are used in these vehicles it is important that we have appropriate cylinder safety standards. A number of national and international standards have been issued that specify design and testing requirements for NGV cylinders, as well as provide guidelines on inspection, use and maintenance.

Cylinders for the on-board storage of fuel are required to be lightweight and at the same time maintain the levels of safety expected for other pressure vessels. In the NGV Cylinder design standards such as ISO 11439, ECE R110 and NGV2 2000 these criteria are achieved by:

a) Specifying service conditions,
b) Assessing the cyclic pressure fatigue life and establishing allowable defect sizes,
c) Compliance with a set of design qualification tests,
d) Requiring non-destructive testing and inspection of all production cylinders,
e) Requiring destructive tests on cylinders and cylinder material taken from each batch of cylinders produced,
f) Requiring manufacturers to have a comprehensive quality system,
g) Requiring periodic re-inspection in accordance with the manufacturer’s instructions,
h) Requiring manufacturers to specify as part of their design, the safe service life of their cylinders.

Cylinder designs that meet the requirements of these standards:
a) Will have a fatigue life that exceeds the specified service life,
b) When pressure cycled to failure, will leak but not rupture,
c) When subject to hydrostatic burst tests, will have stress ratio factors that exceed the values specified for the cylinder type and the materials used.

This paper provides:

A summary of the major NGV cylinder standards: ISO 11439, NGV2 2000, ECE R110
A definition and outline of the four cylinder types,
Information on the major design criteria and an outline of the major approval tests,
Batch testing and In-service inspection requirements of the major standards.

1. INTRODUCTION

Compressed natural gas has been used as a vehicle fuel since the early 1940's and today the number of vehicles on the road is approximately four million. Initially the high-pressure cylinders used to store the natural gas were manufactured and tested in accordance with the industrial cylinder standards, but this resulted in cylinders that were far heavier than they needed to be.

Also, with the development of high strength steel and aluminium alloys and the increasing acceptance of composite cylinder technology, authorities identified the need for standards to adopt the new materials so that lightweight, strong and safe cylinders could be approved for use.

2. NGV CYLINDER DESIGN STANDARDS DEVELOPMENT

Up until the late 1970's countries adopted industrial gas cylinder standards to approve NGV cylinders for vehicle fuel storage. However it became apparent that these standards were not the best in terms of either safety or ensuring the optimum performance of the product. At that time new Italian regulations for lighter-weight high-strength steel cylinders were introduced and these proved to be very successful. Many hundreds of thousands of NGV Cylinders made to these Italian specifications have since been used in service around the world.

In North America, the large-scale conversion of vehicles to natural gas fuel commenced in the 1980's. In 1982, hoop wrapped cylinders made from aluminium liners and a glass fibre composite began to be used in NGV service. Steel cylinder manufacturers followed this trend to lighter-weight designs in 1985, producing steel hoop-wrapped cylinders with glass fibre reinforcement. These products were approved by exemption from the DOT, as no dedicated NGV cylinder standard was available.

NZS 5454. New Zealand published the first cylinder standard specifically for NGV service in 1989. Although this was mainly concerned with steel cylinders, it did allow for approval of hoop wrapped composite cylinders for the first time.

CSA B51-1995. In 1991 Canada issued the CSA B51-1991 Appendix G standard "Requirements for CNG Refuelling Station Pressure Piping Systems and Containers for CNG". This adopted a number of principles from NZS 5454, but also specifically allowed the use of fully wrapped composite cylinders for the first time in NGV service.

In 1994 after failures of composite-wrapped cylinders in NGV service in the US Canada revised their requirements based on the NGV2 1992 standard. The new document was reissued as the CSA B51-95 standard

NGV2 – 2000. In 1992, the US developed their ANSI/AGA NGV2 "American National Standard for Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers". This is a voluntary standard that was initiated by the industry when there were concerns about the lack of regulation for NGV cylinders. It was initially based on the DOT industrial standards for steel and aluminium and the DOT FRP standards for composite designs. In addition to defining the NGV cylinder service conditions and defining appropriate performance tests, the NGV2 standard was the first that defined testing specifically for Type 4 cylinders with plastic liners.

NGV2 was revised in 1998 and again in 2000. This documents is used where companies want to demonstrate that their cylinders are suitable for use over the life of the Natural Gas Vehicle and it has also been adopted as a regulation in various states including California. A number of the principles of NGV2 were used in the drafting of ISO 11439, and in turn, the draft of ISO 11439 was used in harmonizing the NGV2 2000 issue.

Japan's Ministry of Economy, Trade and Industry (METI) enacted regulations in March 1998 that have similar in requirements to NGV2-1998.

Canada now also accepts NGV cylinders produced to NGV2 2000.

ISO 11439. In 1987 ISO set up a working group to start development of a design safety standard for NGV cylinders but it would take until 2000 to be formally issued as ISO 11439 “Gas cylinders - High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles”

ISO 11439 took the US NGV2 standard as it’s starting point, but it was modified by consensus to accept the views of the industry in Europe and Asia. It provides a series of tests for type approval and batch approval of NGV cylinders, as well as guidance on cylinder design, service conditions and exterior environmental protection. A summary of the important tests and requirements is presented in the Section 4.

The finished document was first issued in September 2000 and this version has not been fully adopted by any country as yet, although the UN adopted a working draft of 11439 into the ECE R110 regulation. However since it’s development 11439 has been influential on a number of other standards around the world, as well as the new draft ISO standard for High-pressure Hydrogen Tanks for use on vehicles, ISO 15869.

ECE R110. This regulation was issued in 2000 by the United Nations to define “Uniform Provisions concerning the Approval of “Specific Components of Motor vehicles using Compressed Natural Gas (CNG) in their Propulsion System”. As the title suggests, this document considers all of the components in the fuelling system of Natural Gas Vehicles, including the CNG cylinders.

There are a number of differences between R110 and the final version of ISO 11439. The differences are not very significant, but a comparison between the two documents was issued by ISO as ISO TC58/SC3 document N1036. Ultimately there will be convergence between ISO 11439 and ECE R110, as was the original intention.

The original version of the ECE R110 was issued in December 2000 with a revised version issued on March 2001. This document is used to regulate NGV cylinders in the European Union, Brazil, Argentina and other countries. As yet the USA has not adopted this UN Regulation.

FMVSS 304. In the USA cylinders used for fuel on NGV have to comply with the FMVSS 304 regulation of the National Highway Traffic Safety Administration (DOT-NHTSA). FMVSS has few prescriptive guidelines and relatively few performance tests, requiring only burst, cycle, bonfire, and permeation tests.

NHTSA regularly withdraws NGV cylinders from the field and ensures compliance with the regulation. Instances of non-compliance with the regulation can be seen at http://www.nhtsa.dot.gov/cars/problems/comply/equfmvs2.dbm

Over the past ten years there has been a growing consensus as to what constitutes a safe and reliable NGV cylinder and the national and international standards organizations have been working to harmonize the documents to ensure a high level of efficiency and a high degree of product safety. Complete harmonization has not been achieved however and there are still some differences between the three major NGV cylinder standards to be resolved.

3. NGV CYLINDER TYPES

In general there is a common categorization of NGV cylinders used across the major NGV safety standards.

Type 1 Cylinders – All Metal.

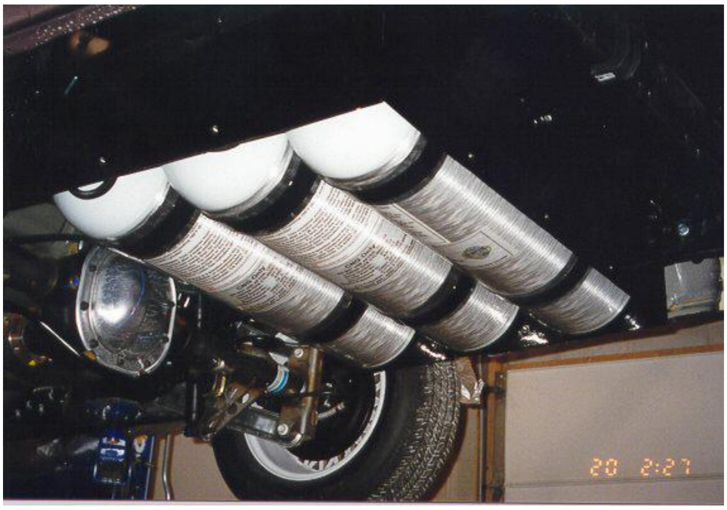
Since the 1940's seamless steel cylinders have been by far the most widely used for storage of CNG on vehicles. The introduction of Italian high-strength lightweight cylinders in the late 1970's was a very significant step forward in the development of the industry and since then this type of product has been adopted all over the world.

Some standards also allow welded steel cylinders, but require a higher safety factor. Aluminium cylinders have also been used for on-board storage of CNG and can provide a lighter weight alternative.

Suppliers of Steel CNG containers include White Martins (Cilbras), Inflex and Faber. Luxfer offers a small range of 7000 series aluminium CNG cylinders.

Type 2 CNG Cylinders – Hoop Wrapped Composite.

Type 2 fuel containers have a metal liner and a composite reinforcement on the straight side only; a hoop overwrap. Products on the market steel or aluminium liners and a glass, aramid, or carbon fibre reinforcement. Type 2 cylinders are designed to have a liner with sufficient thickness and strength to contain the service pressure, even without the composite overwrap. They provide a compromise between the low cost of Type 1 cylinders and the lightest weight Type 3 and 4 cylinders.



Suppliers of Type 2 containers include Faber, Mannesmann, and Luxfer.

Type 3 CNG Cylinders – Fully Wrapped Composite with Metal Liners.

Type 3 CNG cylinders have a seamless metal liner over wound on all surfaces by a composite reinforcement that provides between 75 and 90% of the strength to the vessel. The liner provides the rest of the strength, plus acts as a rigid membrane to hold the gas and provide extra impact resistance to the product.

There are over 2 million fully wrapped composite cylinders in use in portable applications such as breathing apparatus; medical oxygen storage and aircraft slide inflation.

Type 3 cylinders are used in a wide range of applications where weight reduction is important, for example in transit buses and delivery trucks. Type 3 cylinders have also been used on various OEM vehicles such as the Volvo and Volkswagen CNG cars. Suppliers of Type 3 containers include Luxfer, Dynetek, and Structural Composites, Inc.

Type 4 CNG Cylinders – Fully Wrapped Composite with Non-Metallic Liners.

Type 4 fuel containers have a plastic liner and a full overwrap of carbon fibre or mixed fibre construction. The liners of Type 4 tanks provide no structural strength to the product and act only as a permeation barrier. Although these liners are not gas tight, the rate of permeation has been found acceptable for use with CNG.

As a rule Type 4 CNG cylinders are fitted with impact protection on the domes, as the plastic liner does not provide a rigid backing to the composite overwrap.

Again, Type 4 cylinders are used where weight is important such as on buses, trucks and OEM vehicles such as the Honda Civic. Suppliers of Type 4 containers include Quantum, Ullit, Lincoln Composites, and Ragasco.

A Comparison of the CNG Cylinders Types.

Cylinder type	*Cost, $/L*	*Weight, kg/L*
Steel Type 1	6 – 10	0.9 - 1.2
Aluminium Type 1	8 –10	0.9 - 1.0
Metal, hoop wrapped Type 2	10 – 15	0.8 – 0.6
Fully wound composite, aluminium liner Type 3	20 –25	0.3 - 0.4
Fully wound composite, plastic liner Type 4	20 –25	0.3 - 0.4

4. NGV CYLINDER DESIGN APPROVAL TESTS

The main CNG cylinder standards have a very comprehensive series of safety related performance criteria covering features such as burst pressure and cycle life, ability to resist damage and the effect of extreme environments. In this paper it is not possible to summarize all of the performance criteria in the main NGV Cylinder Safety Standards, but some of the more important criteria are as follows.

Service Pressure – The standards use a settled service pressure of either 200 bar (2900 psi) or 245 bar (3600 psi). They allow for overfilling to take account of the increased temperature generated during fast filling and therefore use the overfilled condition as the upper limit in the pressure cycle tests. A maximum pressure of 260 bar is permitted in ISO 11439 regardless of ambient temperature

Service Conditions – The cylinders are generally designed to be filled to service pressure 1000 times per year of service life, up to a maximum of 20 years (ISO 11439). They are expected to operate effectively in temperatures from –40 °C to 65 °C with occasional temperature rises up to 82 °C.

Burst Pressure – The cylinder burst pressure is generally related to the cylinder Type. The minimum burst safety factor varies according to the standard, but ISO 11439 can be summarized as follows:

Cylinder Type	Fibre Reinforcement	Minimum Burst Ratio	Minimum Stress Ratio
Type 1 - seamless steel and aluminium CNG cylinders		2.25	N/A
Type 2 - hoop wrapped CNG cylinders	Glass fibre	2.50	2.75
	Aramid fibre	2.35	2.35
	Carbon fibre	2.35	2.35
Type 3 - fully wrapped CNG cylinders with metal liner	Glass fibre	3.50	3.65
	Aramid fibre	3.00	3.10
	Carbon fibre	2.35	2.35
Type 4 (fully wrapped) CNG Cylinders with plastic liner	Glass fibre	3.65	3.65
	Aramid fibre	3.10	3.10
	Carbon fibre	2.35	2.35

The stress ratio is defined as the stress in the fibre at the specified minimum burst pressure divided by the stress in the fibre at working pressure. The burst ratio is defined as the actual burst pressure of the cylinder divided by the working pressure:

The justification for the higher burst factors for composite cylinders with Glass Fibre and Kevlar is that they are more susceptible to environmental factors, such as stress rupture and chemical attack.

Cycle Performance – The cycle life of the product is very important because NGV cylinders are likely to be filled frequently on high mileage vehicles, like buses and taxis.

The main requirement in ISO 11439 and ECE R110 is for cylinders to be pressure cycled to maximum filling pressure at ambient temperature until failure.

The cylinders must not fail before reaching the specified service life in years multiplied by 1 000 cycles. Cylinders exceeding 1 000 cycles multiplied by the specified service life in years must fail by leakage and not by rupture. So a 15 year cylinder must demonstrate at least 15 000 cycles to maximum developed pressure and fail by leakage only after this figure has passed. The test is suspended after 45 000 cycles.

Composite Flaw Tolerance – Unlike conventional cylinders, NGV cylinders are intended to be fixed to a vehicle for the life of the product. It was the intention of the ISO standards committee that the cylinders not be removed from the vehicle for periodic hydraulic test, as is common for portable and industrial cylinders. As the cylinders will not be inspected internally the regulators decided to adopt the principle of the maximum allowable defect.

The manufacturer defines the maximum defect that can be permitted in the wall of the metal cylinder or liner. A flaw of this size is machined into the cylinder wall and has to be detectable by Non-Destructive Examination.

The cylinder is then cycle tested to the normal requirements of the cycle test; for example, 1 000 cycles per year of design life without failure. The intention of this test is to establish that any defect in the cylinder wall that could reduce service life will be detected by NDE, so further internal examination is not required.

Damage Resistance – Another fundamental factor in considering the safety of a NGV cylinder is its ability to resist damage. One of the most severe tests in all of the standards is the drop test and this is intended to show that if the cylinder suffers a severe impact, either before installation or in service, it will still contain the gas safely and if it fails, it will fail by leakage rather than bursting.

In this test the cylinders are typically dropped in each of three positions.
One drop horizontal, plus one drop vertically on each end from at least 1,8 m, followed by one drop at a 45° angle, from a height such that the centre of gravity is at least 1,8 m.

Following the drop impacts, the cylinders are then pressure cycled to maximum developed pressure, initially for 3 000 cycles, then followed by an additional 12 000 cycles. The cylinder must not leak or rupture within the first 3 000 cycles, but may fail by leakage during the next 12 000 cycles.

Bonfire Test – The bonfire test verifies that the combination of cylinder, valve and pressure relief device will safely vent in the event that the system is exposed to a fire or extreme temperatures.

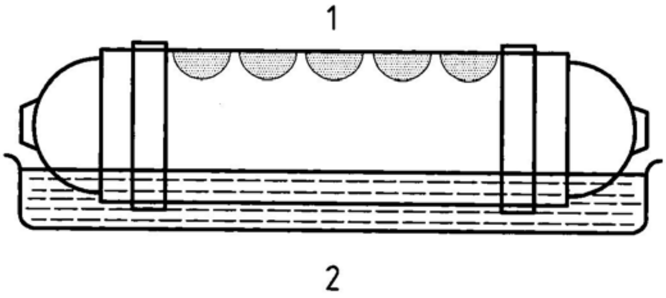
Temperature or pressure, or a combination of temperature and pressure may activate the pressure relief device but the cylinder and fittings must be safe in a fire whether it is at full pressure, or partially charged.

Penetration Test – This test demonstrates that the charged cylinder will not fragment if a high-energy impact causes penetration of the structure. The cylinder is pressurized with gas and impacted by an armour-piercing bullet of 7.62 mm or larger. The cylinder must remain intact after the test.

Environment Test – This test is intended to prove the ability of NGV cylinders to operate in a variety of extreme environments that vehicles may be exposed to. This complex and expensive test requires that cylinders be preconditioned by exposure to various fluids and then subjected to a sequence of pressure and temperature cycles.

First the cylinders are impacted at areas on the surface, by either a metal pendulum or gravel (small stones). The cylinder is then preconditioned by exposure to the following fluids at the impacted areas (1) while sitting in a bath of simulated acid rain/road salt-water solution (2):

Sodium hydroxide: 25 % aqueous solution
Methanol/gasoline: 30/70 % concentrations
Ammonium nitrate: 28 % aqueous solution
Windscreen washer fluid



Then the cylinders are pressure cycled between 20 bar and 260 bar for up to 1 000 times per year of design life, at ambient temperature, high temperature (82 °C) and low temperature conditions (-35 °C).

After all these exposures and cycles the cylinder is burst, and has to demonstrate a burst pressure of no less than 1,8 times the service pressure.

5. PRODUCTION TESTS AND IN-SERVICE INSPECTION

Batch Tests

The ECE R110 and ISO 11439 safety standards require the following tests to be carried out on each batch (lot) of cylinders:

a) One hydraulic burst test,
b) A check of the critical dimensions against the design,
c) A tensile test on the cylinder or liner,
d) For steel cylinders, three impact tests,
e) When a protective coating is a part of the design, a coating batch test is required.

Also, a pressure cycling test is carried out on finished cylinders at a test frequency defined in the specification.

Tests on every cylinder

ECE R110 and ISO 11439 require that each cylinder is examined and tested as follows:

a) By NDE to verify that the maximum defect size does not exceed the size specified for the design;
b) Measured to verify that the critical dimensions and mass of the completed cylinders are within design tolerances;
c) Inspected to verify compliance with the specified surface finish with special attention to deep drawn surfaces and folds or laps in the neck or shoulder areas;
d) The markings and label have to be verified;
e) Hardness tests of heat treated cylinders are required and

f) A hydraulic test of finished cylinders is required either by volumetric expansion or proof testing

In Service Inspection

As CNG cylinders are intended to be permanently fixed in a vehicle, all the major CNG standards recommend that the cylinders are not removed for a periodic inspection and hydraulic testing. Cylinders are designed and tested to be safe for their design life in conjunction with a periodic visual inspection and there is the likelihood of the cylinder being damaged if it is removed from the vehicle.

There are no published International standards for In-Service Inspection of CNG Cylinders as yet. One document in process is ISO FDIS 1708 Gas cylinders – "Inspection of the cylinder installation, and the requalification of high-pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles". This has been released as a draft ISO document for public comment.

NGV2 2000 states that the inspections follow the procedures in Compressed Gas Association (CGA) pamphlet C-6.4 – "Methods for External Visual Inspection of Natural Gas Vehicle Fuel Containers and their Installations" and the container manufacturer's recommendations. This can be purchased from their web site http://www.cganet.com/

ISO 11439 and ECE R110 require that In-Service Periodic requalification be performed in accordance with the relevant regulations of the country where the cylinders are used. This is a significant problem in that most countries still have not adopted specific guidelines for CNG cylinders and require that cylinders be removed from a vehicle for hydraulic test after three or five years. This obviously is against the intention of the CNG cylinder design standards and work is underway within Europe to update the national requirements for periodic inspection of CNG cylinders.

ISO 11439 also requires that the cylinder manufacturer provide recommendations for periodic requalification by visual inspection or testing. It specifies that each cylinder should be visually inspected for external damage and deterioration at least every 36 months, and at the time of any re-installation. "The visual inspection should be performed by a competent agency approved or recognized by the regulatory authority, in accordance with the manufacturer's specifications". Typically these would specify that a qualified inspector must note cuts, cracks, gouges, abrasions, discoloration, broken fibres, loose brackets, damaged gaskets or isolators, heat damage or other problems, and recommend proper action to assure safety.

Cylinders that have been involved in a vehicle collision should be re-inspected by an authorized inspection agency. Cylinders that have not experienced any impact damage from the collision may be returned to service, otherwise the cylinder should be returned to the manufacturer for evaluation.

Cylinders that have been subject to the action of fire should be re-inspected by an authorized inspection agency, or condemned and removed from service.

There has been a lot of interest in the possibility of conducting Non-Destructive Examination of CNG cylinders while still on the vehicle. While techniques for evaluating all-metal cylinders and the liners are well proven, there are no commercially available techniques for NDE of Type 3 or 4 composite cylinders.

6. OVERVIEW OF CNG CYLINDER STANDARDS

Over the past ten years there has been a growing consensus as to what constitutes a safe and reliable CNG cylinder. Rather than just adopting Industrial gas cylinder standards, regulators have accepted the principle that CNG cylinder standards can have specific tests and requirements this has led to the development of ranges of lightweight product that is safe for the design life of the vehicle.

The major international standards now available are ISO 11439 and ECE R110. ISO 11439 is a comprehensive standard, which has been used to influence a number of international standards and is undergoing review at this time within ISO.

ECE R110 is the UN regulation for CNG vehicle components including storage cylinders and the cylinder section was based on an early version of ISO 11439. ECE R110 is being applied in Europe, Brazil, Argentina and other countries, but the US has yet to adopt it into their regulations.

NGV2 is a cylinder standard issued in the US by ANSI and recognized by the CNG industry in the USA and Canada. The 2000 issue of NGV2 also adopted a similar approach to ISO 11439 and there are efforts to harmonize all three of the above documents.

The ISO standard for Inspection and requalification of high-pressure CNG cylinders is still being drafted.

The US Compressed Gas Association has produced a booklet C-6.4 – "Methods for External Visual Inspection of Natural Gas Vehicle Fuel that is referenced in NGV2 2000.

ISO 11439, ECE R110 and NGV2 require the cylinder manufacturer to provide recommendations on installation, use and periodic requalification for their CNG cylinders.

Harmonization of the various standards will help to control costs by limiting the number of qualification tests that must be performed by cylinder manufacturers, as well as help to ensure the use of safe CNG cylinders around the world.

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