

STANDARDS RESEARCH

A Comparison of Hydrogen and Compressed Natural Gas (CNG) Standards

Pressure Terminology and Validation Pressure Test Levels

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Executive Summary

Compressed natural gas (CNG) has been safely used as a motor vehicle fuel for decades. As such, the technical requirements for CNG are well understood, whether for individual part specifications or throughout the broader automotive system.

Hydrogen is a relative newcomer to the motor vehicle fuel industry and is beginning to expand into the aviation field as well. Many of the technical requirements and equipment specifications for hydrogen are similar to those of CNG. However, the two fuels have different chemical properties, and hydrogen is stored and delivered at a higher pressure than CNG.

For an adequate comparison of technical requirements between hydrogen and CNG systems, a common set of terminology must be agreed upon before technical assessments can be made. The test regimens for components and systems, which are based on these commonly understood terms, can then be accurately evaluated against the same criteria.

The purpose of this report is to assess and address variations in pressure terminology for hydrogen and CNG codes and standards. An additional objective is to review pressure test levels for validation testing, based on hydrogen and CNG codes and standards, to identify any differences between regimens for the two fuels.

The existing pressure terminology and definitions from the relevant standards were recorded and assembled into a functionally distributed matrix presentation. Six equipment categories were examined:

1. Dispensing stations
2. Station components
3. Vehicle gaseous fueling interface
4. Vehicle systems
5. Gaseous fuel containers
6. On-board components

Overall, there was general agreement on the baseline pressure terms between hydrogen and CNG standards, with four exceptions:

- For baseline pressure, the ISO standards used hydrogen service level (HSL), while SAE, CSA and NFPA used a combination of nominal working pressure (NWP) and service pressure (SP). CSA/ANSI HGV 4.10:21 [1] used rated pressure (RP) as a baseline.
- The terms maximum operating pressure (MOP), also called maximum filling pressure (MFP), maximum allowable working pressure (MAWP) and maximum developed pressure (MDP) all had the same meaning throughout the documents. Again, CSA/ANSI HGV 4.10:21 only used rated pressure (RP) to define their devices.

- The term minimum component pressure rating, recommended by SAE J2579 [2] and ISO 19880-1:2020 [3], was only specified by name within the hydrogen vehicle interface documents SAE J2600 [4] and ISO 17268:2020 [5].
- The dispenser setpoint differs between hydrogen and CNG. NFPA 2 [6] used 1.38 NWP for hydrogen, while NFPA 52 [7] used 1.25 SP for CNG. The rationale for the higher hydrogen value was to allow for a 10% tolerance over the MOP.

With the exception of the model codes NFPA 2 and NFPA 52, all of the standards had validation test requirements on par with the recommendations of the SAE J2579 and ISO 19880-1:2020 design standards. The model codes deferred to the product standards. These test requirements included the following general elements:

- Verification tests for baseline metrics
- Extreme and ambient temperature gas cycling test
- Leakage test/static pressure gas leak test
- Hydrostatic/pressure proof/ultimate strength/burst test

Both the hydrogen and CNG standards followed this process. While there were some differences in the testing pressures, they are insignificant enough to assume the two fuels follow the same criteria for validating their devices.

Analysis of the data from the relevant standards showed that the pressure test levels were essentially equivalent between hydrogen and CNG, with the exception of the dispenser set point.

All of the standards from the dispensing station and components, as well as the vehicle interface, referred to container pressure, calling it nominal working pressure, service pressure or hydrogen service level. All pressure testing was based off this number.

For on-board component standards, CSA/ANSI HGV 3.1:22 [8] separated the baseline pressures at the pressure reduction stage. Interestingly, CSA/ANSI HGV 4.10:21 [1] eliminated any difference between upstream and downstream by using rated pressure as a baseline for all pressure testing. All testing was based on the rated pressure of the device as designed.

Component and system-level validation test pressure requirements were the same for hydrogen and CNG. The component was to be exercised within its expected design envelope to the pressures anticipated by the system designer. Cycling was to be conducted at the intended usage extreme temperatures, and the pressures were to be cycled according to maximum anticipated design usage.

In summary, the pressure terminology and pressure test levels reviewed in this study represent foundational terminology for the well-established CNG industry. The development of hydrogen system validation test requirements heavily relies on the CNG knowledge base, and user confidence and historical performance provide a good starting point.



"Hydrogen as a motor fuel is a relative newcomer to the ground transportation industry and is beginning to expand into the aviation field as well."

1 Introduction

Compressed natural gas (CNG) has been safely used as a motor vehicle fuel for decades. The technical requirements for CNG used in vehicles are well understood, whether for individual part specifications or throughout the broader automotive systems. They are documented by several Standards Development Organizations (SDOs), such as the Society of Automotive Engineers (SAE), the International Organization for Standardization (ISO) and the Canadian Standards Association (CSA), as well as the American Society of Mechanical Engineers (ASME).

Hydrogen as a motor fuel is a relative newcomer to the ground transportation industry and is beginning to expand into the aviation field as well. With the increase in the number of hydrogen fuel cell vehicles (HFCVs), more hydrogen systems will be required, both for dispensing stations and vehicles themselves.

Many of the technical requirements and equipment specifications are similar for hydrogen and CNG. However, the two fuels have different chemical properties, and hydrogen is stored and delivered to vehicles at a higher pressure than CNG. As such, care must be exercised to help ensure a level of safety and reliability with hydrogen, making it comparable to that of CNG when developing new hydrogen technical requirements.

Common terminology for hydrogen and CNG needs to be used for technical assessments. The test regimens for components and systems for hydrogen can then be accurately evaluated using the same criteria as CNG.

The origins of the hydrogen component and systems technical requirements are rooted in its predecessor, CNG. However, the differences between the two fuels have resulted in some variation in pressure terminology, which may create the following issues:

- Challenges in establishing equivalent testing requirements between standards;
- Potential miscommunication within the industry between station developers, equipment suppliers, component suppliers, vehicle system suppliers and testing agencies;
- A potential safety concern, particularly with the proliferation of high-pressure hydrogen fueling systems.

The purpose of this report is to assess and address variations in pressure terminology across hydrogen and CNG codes and standards. An additional objective is to review pressure test levels for validation testing, based on hydrogen and CNG codes and standards, to identify differences between regimens for the two fuels.

2 Methods

The following questions guided the analysis for this study:

- How similar are the pressure test requirements for hydrogen and CNG?
- In the current product standards, do the pressure test levels for hydrogen and CNG provide enough technical clarity for a common understanding of pressure requirements for the two fuels where there is common usage?
- Is there delineation between the dispensing side and the vehicle side?
- Do the two fuels incorporate the following for pressure testing during validation?
  - Requires a life-cycling test encompassing both temperature and maximum operating pressure extremes (i.e., durability testing for continuous operation);
  - Contains a defined component minimum pressure requirement;
  - Incorporates a proof test;
  - Includes tests for ultimate strength/burst pressure levels.

Hydrogen and CNG documents from multiple SDOs were reviewed for this report, using the following process:

1. Identify all general technical regulations, codes and standards that include or use pressure terminology and are relevant to the Canadian and US market. This includes standards by CSA, SAE, NFPA, UN GTR[1] and ISO.
2. Review and organize relevant pressure terminology definitions.
3. Assess differences in existing terminology and any corresponding rationale for the definitions.
4. Differentiate between the "dispensing side" and "vehicle side" terminology, that is, determine the boundary between the dispensing station and the vehicle, and assess the relevant pressure terms for each side.
5. Compile the various pressure definitions used across codes and standards.
6. Differentiate between CNG and hydrogen terminology. Identify whether the two fuels use the same terminology.
7. Assess pressure test requirements from standards in step 1 above, that is, organize and determine if they are aligned across codes and standards.

The existing pressure terminology and definitions from the relevant standards were recorded and assembled into a functionally distributed matrix presentation (Table 1). Pressure test levels, gas cycle times and hydrostatic cycle times were also recorded in the matrix. This was done in a way that allowed the mapping of definitions and pressure test levels – from the dispensing station, through to the interface and to the on-board components.

Given that one of the objectives was to evaluate standards across the usage spectrum, from dispensing systems to components installed on the vehicle, six functional categories were examined (Figure 1):

1. Dispensing stations
2. Station components
3. Vehicle gaseous fueling interface
4. Vehicle system
5. Gaseous fuel containers
6. On-board components

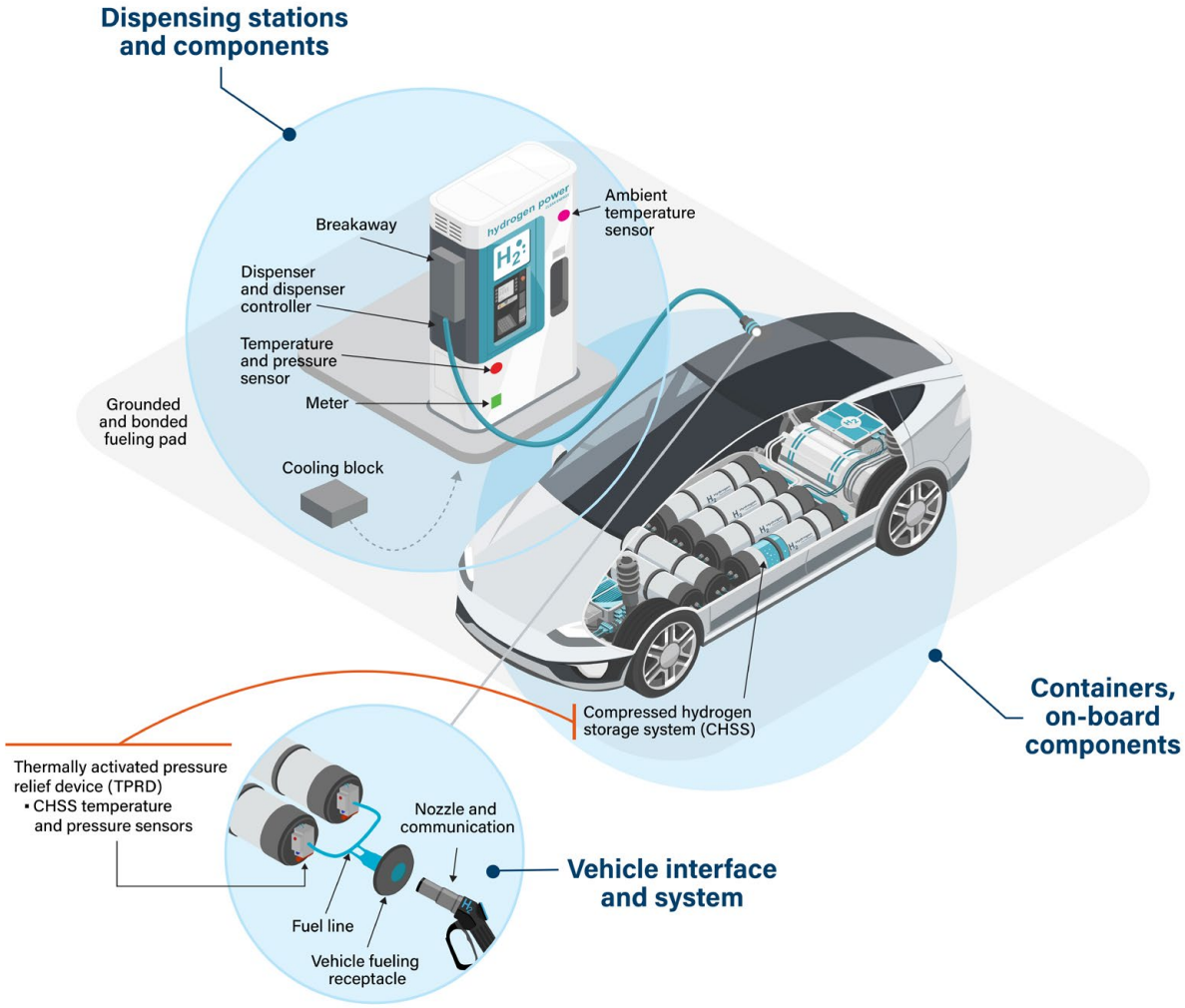
The following pressure terms, definitions and baseline pressure multipliers[2] were identified in each of the documents reviewed:

- Baseline pressure
- Maximum operating pressure
- Maximum allowable working pressure
- Minimum component pressure rating
- Maximum developed pressure
- Dispenser setpoint

1 Global technical regulations (GTRs) are established based on the United Nations Economic Commission for Europe (UNECE).

2 Pressure testing of gaseous systems use test levels in multiples of a baseline or service pressure to simulate worst-case use conditions. Thus, it is common practice to test at pressure levels above normal operating parameters. These elevated pressure test levels are referred to as "baseline pressure multipliers" of normal operating pressure.

Figure 1: Functional categories for hydrogen and CNG standards



Pressure test levels and cycle times from each document were also identified:

- Durability and maintainability (continuous operation)
  - Number of cycles
  - High-low-ambient temperature and minimum/ maximum pressure (container side)
  - High-low-ambient temperature and minimum/ maximum pressure (post-regulator side)
  - Worst case pressure cycle fault (if specified)
  - Gas cycling pressure
- Leakage test
  - High-low temperature and minimum/ maximum pressure (container)
  - High-low-ambient temperature and minimum/ maximum pressure (post regulator)
- Hydrostatic test
- Test multiplier
- Hydrostatic cycling, if specified
- Separation force (breakaways only)
- Proof test baseline multiplier
- Ultimate strength/burst

Table 1: Example of data comparisons for hydrogen at the dispensing station

	Dispensing Station – Hydrogen	
Standard	**CSA/ANSI HGV 4.1:20 [9]**	**CSA/ANSI HGV 4.9:20 [10]**
Baseline Pressure (BP) Term	Service or Nominal Working Pressure	Service or Nominal Working Pressure
Station Components	Nominal working pressure (NWP) is "the gauge pressure that characterizes the typical operation of a pressure vessel, container, or system. For compressed hydrogen gas containers or stations, service pressure is the container pressure, as specified by the manufacturer, at a uniform gas temperature of 15°C (59°F) and full gas content."	Nominal working pressure (NWP) is "the gauge pressure that characterizes typical operation of a pressure vessel, container or system. Notes: For compressed hydrogen gas containers or stations, the NWP is the container pressure, as specified by the manufacturer, at a uniform gas temperature of 15 °C and full gas content." "Service – see Nominal working pressure."
BP Multiplier	1	1

3 Results

The standards reviewed for this research are listed in Table 2, categorized by type of fuel and by functional category.

3.1 Comparison of Pressure Terminology

3.1.1 Baseline pressure

The terminology in this category was largely uniform among the two fuels. Most hydrogen documents reviewed used nominal working pressure (NWP) and service pressure (SP) interchangeably in relation to baseline pressure (BP) [2,4,6,8-11,17-18,29,32,36,39,42-43,45-49]. The CNG documents used predominantly SP [16,23,26,28,30]. There were two exceptions:

- ISO 19880-1:2020 [3] and ISO 17268:2020 [5] used the term hydrogen service level (HSL).[3]
- CSA/ANSI HGV 4.10:21 [1], a component product specification, used rated pressure (RP), which is defined as "The manufacturer's specified in-service internal pressure assigned to a mechanically attached fitting assembly. This term can also be considered a minimum component pressure rating.

3.1.2 Maximum operating pressure (MOP)

MOP is also known as maximum filling pressure (MFP). This term is used to define the maximum fault-free pressure during normal operating conditions. This term was used consistently across both hydrogen and CNG documents. Where MOP was used, a consistent baseline multiplier of 1.25 was also used.

3.1.3 Maximum allowable working pressure (MAWP)

MAWP is the highest gauge pressure before the onset of fault management. Both the hydrogen and CNG documents define MAWP as "the maximum pressure to which a component is designed to be subjected when handling the specified fluid at the maximum specified temperature." This was largely consistent across all documents, with the hydrogen standards assigning a baseline multiplier of 1.38 and the CNG documents not specifying a multiplier. There were three exceptions:

- CSA/ANSI HGV 4.2:22 [17] uses a multiplier of 1.38 and CSA/ANSI HGV 4.4:21 [18] uses a multiplier of 1.375. There is an opportunity for harmonization across these standards.
- NFPA 2 [6] uses a baseline multiplier of 1.375.
- For the ISO [3,5,26,31,32] and SAE [2,4] hydrogen standards, MAWP is equivalent to the minimum component pressure rating.

3 HSL was introduced by ISO during hydrogen fueling standard development, as the Japanese hydrogen pressure code uses a similar term to NWP, which could result in confusion.

Table 2: Standards reviewed by fuel type and functional category

Functional Component	Hydrogen	CNG
Dispensing stations	▪ CSA/ANSI HGV 4.1:20, *Hydrogen dispensing systems* [9] ▪ CSA/ANSI HGV 4.9, *Hydrogen fueling stations* [10] ▪ ISO 19880-1:2020, *Gaseous hydrogen – Fueling stations – Part 1: General requirements* [3] ▪ GTR 13, *Global technical regulation on hydrogen and fuel cell vehicles* [11] ▪ NFPA 2, *Hydrogen Technologies Code* [6]	▪ CSA/ANSI NGV 4.1, *Natural gas vehicle dispensing systems* [12] ▪ CSA/ANSI NGV 5.1, *Residential fueling appliances* [13] ▪ CSA/ANSI NGV 5.2, *Vehicle fueling appliances* [14] ▪ CSA/ANSI NGV 6.1, *Compressed natural gas fuel storage and delivery systems for road vehicles* [15] ▪ CSA B108.1, *Compressed natural gas refuelling stations installation code* [16] ▪ NFPA 52, *Vehicular natural gas fuel systems code* [7]
Station Components	▪ ISO 19880-1:2020, *Gaseous hydrogen – Fueling stations – Part 1: General requirements* [3] ▪ CSA/ANSI HGV 4.2:22, *Hoses for compressed hydrogen fuel stations, dispensers and vehicle fuel systems* [17] ▪ CSA/ANSI HGV 4.4:21, *Breakaway devices for compressed hydrogen dispensing hoses and systems* [18] ▪ ANSI/CSA HGV 4.8-2012 (R2018), *Station compressors* [19] ▪ CSA/ANSI HGV 4.10:21, *Standard for fittings for use in compressed gaseous hydrogen fueling stations* [1] ▪ CSA/ANSI HPRD 1:21, *Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers* [20]	▪ ANSI/CSA NGV 4.2, *Hoses for natural gas dispensing systems* [21] ▪ CSA/ANSI NGV 4.4, *Breakaway devices for natural gas dispensing hoses and systems* [22] ▪ CSA/ANSI NGV 4.6, *Manually operated valves for natural gas dispensing systems* [23] ▪ CSA/ANSI NGV 4.8:21, *Natural gas vehicle fueling station compressor packages* [24] ▪ CSA/ANSI PRD 1, *Pressure relief devices for natural gas vehicle fuel containers* [25]
Vehicle interface	▪ SAE J2600:2015, *Compressed hydrogen surface vehicle fueling connection devices* [4] ▪ ISO 17268:2020, *Gaseous hydrogen land vehicle refuelling connection devices* [5]	▪ ISO 14469:2017, *Compressed natural gas refuelling connector* [26] ▪ CSA/ANSI NGV 1:22, *Compressed natural gas vehicle fueling connection devices* [27]
Vehicle system	▪ SAE J2579, *Standard for fuel systems in fuel cell and other vehicles* [2] ▪ GTR 13, *Global technical regulation on hydrogen and fuel cell vehicles* [12]	▪ CSA B109.1, *Natural gas for vehicles installation code* [28]
Containers	▪ CSA/ANSI HGV 2:21, *Compressed hydrogen gas vehicle fuel containers* [29]	▪ CSA/ANSI NGV 2:19, *Compressed natural gas vehicle fuel containers* [30]

Functional Component	Hydrogen	CNG
On-board components	▪ CSA/ANSI HGV 3.1:20, *Fuel system components for compressed hydrogen gas powered vehicles* [8] ▪ ISO 19887, *Gaseous hydrogen – Fuel system components for hydrogen fuelled vehicles* [31] ▪ ISO 12619-2:2014, *Road vehicles – Compressed gaseous hydrogen and hydrogen/natural gas blend fuel system components – Part 2: Performance and general test methods* [32] ▪ CSA/ANSI HGV 4.10:21, *Standard for fittings for use in compressed gaseous hydrogen fueling stations* [1] ▪ CSA/ANSI HPRD 1:21, *Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers* [20]	▪ CSA/ANSI NGV 3.1:22, *Fuel system components for compressed natural gas-powered vehicles* [33] ▪ CSA/ANSI PRD 1:20, *Pressure relief devices for natural gas vehicle (NGV) fuel containers* [25] ▪ ISO 15501-1:2016, *Road vehicles – Compressed natural gas (CNG) fuel systems – Part 1: Safety requirements* [34] ▪ ISO 15501-2:2016, *Road vehicles, Compressed natural gas fuel system components – Part 2: Performance and general test methods* [35]
Other – terminology	▪ ANSI/CSA HGV 4.3-2016, *Test methods for hydrogen fueling parameter evaluation* [36] ▪ ANSI/CSA HGV 4.6-2013 (R2018), *Manually operated valves for use in gaseous hydrogen vehicle fueling stations* [37] ▪ ANSI/CSA HGV 4.7-2013 (R2018), *Automatic valves for use in gaseous hydrogen vehicle fueling stations* [38] ▪ SAE J2760, *Pressure terminology used in fuel cells and other hydrogen vehicle applications* [39] ▪ SAE J2574, *Fuel cell vehicle terminology* [40] ▪ SAE J2578, *Recommended practice for general fuel cell vehicle safety* [41] ▪ SAE J2601, *Fueling protocols for light duty gaseous hydrogen surface vehicles* [42] ▪ ISO 12619-1:2014, *Road vehicles – Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blend fuel system components – Part 1: General requirements and definitions* [43] ▪ ISO 12619-3, *Road vehicles – Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blend fuel system components – Part 3: Pressure regulator* [44] ▪ ISO 12619-4, *Road vehicles – Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blend fuel system components – Part 4: Check valve* [45]	▪ CSA/ANSI NGV 4.3:22, *Temperature compensation for compressed natural gas vehicle fuelling* [52] ▪ ISO 15500-1, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 1: General requirements and definitions* [53] ▪ ISO 15500-2, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 2: Performance and general test methods* [54] ▪ ISO 15500-3, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 3: Check valve* [55] ▪ ISO 15500-4, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 4: Manual valve* [56] ▪ ISO 15500-5, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 5: Manual cylinder valve* [57] ▪ ISO 15500-6, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 6: Automatic valve* [58] ▪ ISO 15500-7, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 7: Gas injector* [59] ▪ ISO 15500-8, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 8: Pressure indicator* [60]

Functional Component	Hydrogen	CNG
Other – terminology	▪ ISO 12619-5, *Road vehicles – Compressed gaseous hydrogen (CGH2) and hydrogen/ natural gas blend fuel system components – Part 5: Manual cylinder valve* [46] ▪ ISO 12619-6, *Road vehicles – Compressed gaseous hydrogen (CGH2) and hydrogen/ natural gas blend fuel system components – Part 6: Automatic valve* [47] ▪ ISO 12619-10, *Road vehicles – Compressed gaseous hydrogen (CGH2) and hydrogen/ natural gas blend fuel system components – Part 10: Pressure relief device* (PRD) [48] ▪ ISO 12619-11, *Road vehicles – Compressed gaseous hydrogen (CGH2) and hydrogen/ natural gas blend fuel system components – Part 11: Excess flow valve* [49] ▪ CSA/ANSI FC 1:21/CSA C22.2 No. 62282-3-100:21, *Fuel cell technologies – Part 3-100: Stationary fuel cell power systems – Safety* [50] ▪ ANSI/CSA FC 3-2004 (R2021), *Portable fuel cell power systems* [51]	▪ ISO 15500-9, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 9: Pressure regulator* [61] ▪ ISO 15500-10, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 10: Gas-flow adjuster* [62] ▪ ISO 15500-11, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 11: Gas/air mixer* [63] ▪ ISO 15500-12, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 12: Pressure relief valve* (PRV) [64] ▪ ISO 15500-13, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 13: Pressure relief device* (PRD) [65] ▪ ISO 15500-14, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 14: Excess flow valve* [66] ▪ ISO 15500-15, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 15: Gas-tight housing and ventilation hose* [67] ▪ ISO 15500-16, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 16: Rigid fuel line in stainless steel* [68] ▪ ISO 15500-17, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 17: Flexible fuel line* [69] ▪ ISO 15500-18, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 18: Filter* [70] ▪ ISO 15500-19, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 19: Fittings* [71] ▪ ISO 15500-20, *Road vehicles – Compressed natural gas (CNG) fuel system components – Part 20: Rigid fuel line in material other than stainless steel* [72]

3.1.4 Minimum component pressure rating

Minimum component pressure rating is the maximum pressure to which a component will be exposed up to the initiation of fault management. The only documents that use this term are the ISO [3,5,26,31,32] and SAE [2,4] vehicle interface standards and GTR 13 [11]. The baseline multipliers used in SAE [2,4] and ISO [3,5,26,31,32] interface standards were 1.38 NWP and 1.375 NWP, respectively. GTR 13 [11] used 1.38 NWP.

CSA/ANSI HGV 4.10:21 [1] includes minimum component pressure rating as a basis for the test levels. This is the only document for either hydrogen or CNG that uses this term for all test level references. In some cases, this can provide added confidence by helping ensure a higher degree of reliability to components passing these requirements.

3.1.5 Maximum developed pressure (MDP)

MDP most often appears in the hydrogen design standards [2,3,39]. MDP refers to the highest pressure expected during fault management of the dispenser. It is also referred to as maximum accumulated pressure. For those design standards referencing the term, a multiplier of 1.5 NWP was used.

3.1.6 Dispenser overpressure setpoint or dispenser setpoint

This term represents the pressure level where the dispenser begins to engage the fault management system. The difference in fuel type leads to variability between the terminology used.

Hydrogen model codes NFPA 2 [6] and standards SAE J2579 [2], CSA/ANSI HGV 4.1 [9] and ISO 19880-1 [3] use either 1.375 NWP (SP) or 1.38 NWP (SP). The CNG model code NFPA 52-2019 [7] uses 1.25 SP as the dispenser setpoint.

This difference in setpoints for hydrogen and CNG can be attributed to the hydrogen standards allowing for a 10% margin over the maximum operating pressure, providing an allowance for fault management scenarios. This allowance is also useful for defining a minimum component requirement. The CNG standards do not incorporate this tolerance.

3.2 Comparison of Pressure Test Levels

3.2.1 Durability (continuous operation)

Durability includes requirements for life-cycling tests at both ambient temperature and maximum operating pressure extremes.

Number of cycles

Dispensing cycling requirements are included in CSA/ANSI NGV 5.1-2016 (R2020) [13], CSA/ANSI NGV 5.2:23 [14] and CSA/ANSI NGV 6.1:21 [15]. Most lifetime-use cycling requirements appear in the component or product standards, whereas codes often refer to the specific component standards for testing.

Most product standards require a number of cycles commensurate with the lifetime of the component. These range anywhere from 15,000 fill cycles to over 100,000 cycles for some components.

High-low-ambient temperature and minimum/maximum pressure (container)

All of the documents within the station components, vehicle interface, vehicle system, container and on-board component categories contain cycling requirements based on the NWP or SP of the system, which is the container side of the interface, or those components exposed to container pressure. At ambient temperatures, testing is conducted at 1.25 NWP, at a minimum. At the high and low test temperatures, the pressure levels are at minimum 1.25 NWP and 0.8 NWP, respectively.

High-low-ambient temperature and minimum/maximum pressure (post-regulator side)

Only the on-board component standards contain post-regulator type requirements [8,31,33]. At ambient temperatures, cycling tests are done at maximum operating pressure. This differs from the container definition in that these components do not experience container pressure, but rather a reduced operating pressure environment. At temperature extremes, the pressure levels are 1.25 NWP (maximum) and 0.8 NWP (minimum).

Worst-case pressure cycle fault (if specified)

Currently, HGV 4.4 [18] is the only station component standard identifying such a requirement. In this case, the



"Most product standards require a number of cycles commensurate with the lifetime of the component. These range anywhere from 15,000 fill cycles to over 100,000 cycles for some components."

pressure fault is to be 1.1 MAWP (1.1 x 1.38 NWP) = 1.5 NWP. This pressure level coincides with the system maximum developed pressure and is related to the proof pressure test (see "Proof test/ultimate strength/burst").

Gas cycling pressures

Cycling pressure requirements appear in the vehicle system standards [2,11,28] and the container standards [29,30].

The vehicle interface standards cycle the components at MOP (1.25 NWP) and at MDP (1.5 NWP), depending on the temperature [4,5,26,27]. The container documents require gas cycling to be run for several cycles at 1.25 NWP (SP) [29,30]. CSA/ANSI NGV 4.4:21 contains the option of either hydraulic or gas cycling to 102,000 cycles [18].

3.2.2 Leakage

High-low-ambient temperature and minimum/maximum pressure (container side)

All components and systems are subjected to leak tests at both temperature and pressure extremes. Where specified, they are routinely run at 1.5 NWP (SP) at ambient temperature, with a level of 1.5 NWP (SP) for high temperature cycling and 1 NWP (SP) for low temperatures [17,20,22,29].

The exception to this is HGV 4.10 [1], where the baseline pressure is approximately MAWP. Here, all leakage testing is done at 1.5 rated pressure (MAWP), or 1.5 x 1.38 NWP = 2.07 NWP.

High-low temperature and minimum/maximum pressure (post-regulator side)

For those components on the post-regulator side of the system, pressures are defined as "the maximum pressure to which a component is designed to be subjected when handling the specified fluid at the maximum specified temperature." This is not the same pressure as was defined for the container side of the systems. Pressure for the container side of the systems is represented by the container rating.

Maximum pressure levels for post-regulator systems are determined by the system design engineers, and components are procured to those pressure specifications, which may be lower than the container side. For those documents having post-regulator requirements [8,31,33], they are conducted at 1.5 MOP at ambient and maximum temperature, and 1 MOP at minimum temperature. HGV 4.10 is unique in that it requires tests to be conducted at 1.5 rated pressure (MAWP) [1].

3.2.3 Hydrostatic strength tests

Baseline multipliers range from a low of three times SP for natural gas pressure relief devices (PRD 1) [25] and hydrogen pressure relief devices (HPRD 1) [20], to a high of four times rated pressure (MAWP) for HGV 4.10 [1]. Nominally, values range between 2.5 NWP to 4 NWP. The vehicle interface standards currently call for testing to 3.75 NWP [4,5,26].

On-board component standards differentiate between pre- and post-regulator systems by defining a requirement of 2.5 NWP for upstream (pre-regulator) and 2.5 MOP for downstream (post-regulator) components [8,31].

It should be noted that HGV 4.10 [1] also requires 1.00E+6 cycles at room temperature at 1.33 rated pressure (MAWP) – far more than other components. This helps ensure a high degree of reliability to components passing these requirements. For a container-side application, this would be 1.33 x 1.38 NWP = 1.8 NWP.

3.2.4 Proof test/ultimate strength/burst

Proof testing is required in ISO 19880-1 [3] and the GTR 13 [11] hydrogen documents and is given as 1.5 NWP (HSL). For context, this is generally considered as the onset of protective measures by the system. SAE J2579 [2] requires a test pressure of 1.8 NWP for either the vessel only, or of the entire system at the discretion of the system manufacturer. For HGV 2 [30], that proof pressure level is 1.5 NWP.

In general, the interface documents SAE J2600 [4] and ISO 17268 [5] do not specify a proof pressure requirement. Pressure testing is done at 1.5 NWP (HSL) during leakage testing followed by hydrostatic testing to 3 NWP (HSL).

Ultimate strength testing (also called Burst Pressure in SAE J2579 [2]) is addressed in ISO 19880-1 [3] with a multiplier of > 3.3 HSL, and SAE J2579 [2] with a multiplier of greater than 1.8 NWP. If a target burst pressure is specified, then the burst pressure of the containment vessel shall exceed the target burst pressure.

4 Discussion

4.1 Terminology

For pressure terminology, based on the data detailed in Section 3.1, there is general agreement on the baseline pressure terms between hydrogen and CNG standards, with four exceptions.

- The ISO standards use hydrogen service level (HSL) as a baseline pressure term, while SAE, CSA and NFPA use a combination of nominal working pressure (NWP) and service pressure (SP). HGV 4.10 uses rated pressure as a baseline.
- The terms maximum operating pressure (MOP), also called maximum filling pressure (MFP), maximum allowable working pressure (MAWP) and maximum developed pressure (MDP) all have the same meaning throughout the documents. Again, HGV 4.10 only uses rated pressure (RP) to define their devices.
- The term minimum component pressure rating, recommended by the design codes [2,3], is only specified by name within the hydrogen vehicle interface documents [4,5].
- The dispenser setpoint differs between hydrogen and natural gas. The model codes use 1.38 NWP for hydrogen [6], and 1.25 SP for CNG [7]. The rationale for the higher hydrogen value is to allow for a 10% tolerance over the MOP.

4.2 Pressure Test Levels

Based on the data collected, the following observations and conclusions can be made by responding to the questions posed in Section 2 regarding pressure test levels.

- How do the reviewed documents align with the validation test requirements or recommendations of ISO, SAE and the UN GTR 13?
- How similar are the pressure test requirements between the hydrogen and CNG standards?
- In the current product standards, do the pressure test levels of hydrogen and CNG provide enough technical clarity for a common understanding of pressure requirements between the fuels where there is common equipment usage?
- Is there delineation between the dispensing side and the vehicle side?
- How do the component- and system-level validation test pressure requirements differ between hydrogen and CNG?

With the exception of the model codes [6,7], all of the standards have validation test requirements on par with the recommendations of ISO [3] and SAE [2] design standards. The model codes defer to the

product standards. These test requirements include the following general elements:

- Verification tests for baseline metrics
- Extreme and ambient temperature gas cycling test
- Leakage test/static pressure gas leak test
- Hydrostatic/pressure proof/ultimate strength/ burst test

Both the hydrogen and CNG standards follow this process. While there are some differences in the testing pressures, they are insignificant enough to assume that the two fuels follow the same criteria for validating their devices.

Based on analysis of data from relevant standards, the pressure test levels are essentially equivalent between the hydrogen and CNG (with the exception of the dispenser setpoint).

All of the standards from the dispensing station and components, as well as the vehicle interface standards, refer to container pressure, calling it NWP, SP or HSL. All pressure testing is based off this number.

For on-board component standards, CSA/ANSI HGV 3.1:22 [8] separates the baseline pressures at the pressure reduction stage into the following:

- Nominal working pressure (NWP): The settled pressure at a uniform gas temperature of 15 °C (59°F). NWP pertains only to components that are upstream of the first stage of pressure reduction.
- Maximum operating pressure (MOP): The maximum pressure that a component is expected to experience in actual service. MOP pertains only to components that are downstream of the first stage of pressure reduction.

Interestingly, CSA/ANSI HGV 4.10:21 [1] eliminates any difference between upstream and downstream by using rated pressure (RP), which is essentially the MAWP of the component, as a baseline for all of their pressure testing. All testing is based on the RP of the device as designed.

Component and system-level validation test pressure requirements are the same for hydrogen and CNG. The component is exercised within its expected design envelope to the pressures anticipated by the system designer. Cycling is conducted at the intended usage extreme temperatures, and the pressures are cycled according to maximum anticipated design usage.

5 Conclusions

The pressure terminology and pressure test levels reviewed in this study represent foundational terminology for the well-established transportation related CNG industry. These test and validation requirements for CNG are in use worldwide.

If hydrogen is to be broadly accepted as a safe and reliable transportation fuel, it requires an equally comprehensive level of understanding and clarity.

The development of hydrogen system validation test requirements heavily relies on the CNG knowledge base, with user confidence and historical performance providing a good starting point. The continued growth of the hydrogen ecosystem has led to the need to review the current state of terminology and pressure test levels, such that a consistent set of pressure testing criteria for systems and components can be achieved.

The test and certifications requirements contained in the standards represent a minimum set of testing, and there may be different interpretations of testing depending on the end use.

However, there currently is general agreement on the equivalent pressure terminology between hydrogen and CNG. There is also agreement that certain basic testing at pressure and temperature extremes will be required to certify systems and components.

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