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H_2FC

Integrating European Infrastructure to support science and development of Hydrogen- and Fuel Cell Technologies towards European Strategy for Sustainable, Competitive and Secure Energy

Deliverable 9.1

D9.1 Harmonised Methodology for Testing of Pressure Relief Devices

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Document History

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26.10.2013	1.0	First draft of literature survey/Svetlana Tretsiakova-McNally (**UU**)
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29.11.13	1.1	Footnote and starting page by Olaf Jedicke

Table of Contents

1 Outline

The H2FC European infrastructure project started in 2011. The aim of the project is to identify and solve industry knowledge gaps by collaboration between three hydrogen communities (Fuel Cells, Safety and Storage). Deliverable 9.1 (JRA 3.1, Work Package 9 (WP9)) concerns: Methods, Protocol and Benchmarking, with the aim of identifying gaps in the knowledge of standards, testing protocols and manufacturer literature, relating to safety.

Task JRA3.1.1 within WP9 aims to develop a methodology for the testing of Pressure Relief Devices (PRDs). UU had provided a literature survey of current PRD systems for on-board hydrogen storage and carried out CFD simulations with the view to suggest suitable PRD design. HSL had contributed to this deliverable by conducting a literature review of the available hydrogen PRD and TPRD standards. The literature review aimed to identify gaps in the testing procedures and standards of PRDs and TPRDs and their potential impact on safety.

2 PRD systems for on-board hydrogen storage - literature survey

2.1 Introduction

Hydrogen as a fuel has a low energy density per unit volume. To overcome this limitation hydrogen storage containers store this gas at very high pressures. On current development vehicles hydrogen had been typically stored at a nominal working pressure (NWP) of 350 or 700 bar. On-board storage tanks accepted for hydrogen-fuelled vehicles are made from either fibre-reinforced composite material with a polymeric liner (Type 4) or with an aluminium liner (Type 3) [1]. In the event of a collision and/or in a fire of hydrogen-powered vehicle the storage tank becomes a considerable hazard due to the risk of explosion or catastrophic vessel failure at high temperatures that could be followed by a severe blast wave. This can be explained by the fact that composite materials cannot withstand the fire for a long time (currently it varies from 3.5 to 6.5 minutes) before undergoing a catastrophic failure. The European Commission Regulation (EU) No 406/2010 from 26 Apr 2010 implementing the regulation (EC) No 70/2009 of the European Parliament and the Council on type approval of hydrogen-powered motor vehicle requires the use of pressure relief devices (PRDs) for on-board hydrogen storage. A pressure relief device (PRD) is a safety device that protects against a failure of a pressure containment system by releasing some or the entire tank contents in the event of high temperatures, high pressures or a combination of both [2].

PRDs are designed according to codes and standards. PRDs should be manufactured, installed, operated, maintained, inspected, and repaired according to laws and rules of local jurisdictions [3]. Most PRDs are designed to open when pressure or temperature reaches a certain limit. For a full container in a hydrogen-powered vehicle the release (blowdown) can last up to 6.5 minutes. A temperature activated PRD (TPRD) is a device that activates by temperature to release pressure and to prevent a fuel tank from bursting due to fire effects and that will activate regardless of fuel tank pressure [4]. TPRDs are used more often as opposed to pressure activated PRDs. The latter ones are generally inadequate owing to the insulating properties of composite materials and lead to a partially filled container. When the heat is applied to a partially filled container, the equilibrium temperature can become very high before maximum allowable working pressure (MAWP) is exceeded [2].

Fuel tanks shall be protected from fire effects using non-reclosing TPRDs. Non-reclosing pressure-activated PRDs can only be used in parallel with thermally activated pressure relief devices. A TPRD shall not under any circumstances require the operation of the pressure-activated pressure relief device in order to function properly. The fire protection of fuel tanks may also be supplemented by the use of thermal insulation [4].

In the event of fire, TPRDs provide a controlled release of the gas from the compressed hydrogen storage containers before they are weakened at high temperatures and cause a hazardous rupture. TPRDs are designed to vent the entire contents of the container rapidly. They do not re-seal or allow re-pressurization of the container. Storage containers and TPRDs that have been subjected to a fire are expected to be removed from service and destroyed [5].

A typical compressed hydrogen storage system consists of a pressurized container, three primary closure devices and their fittings (Figure 1). The closure devices include: a TPRD, a check valve that prevents reverse flow to the fill line, and an automatic shut-off valve that can close to prevent flow from the container to the fuel cell or to the internal combustion engine. Any shut-off valve and TPRD shall be mounted directly on or within each container. At least one component with a check valve function shall be mounted directly on or within each container [5].

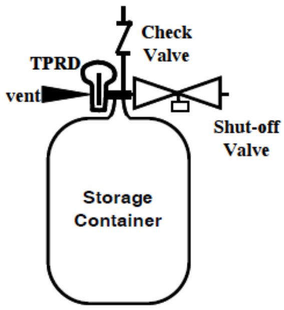

Figure 1. Typical compressed hydrogen storage system [5].

In the absence of a PRD an overpressure can arise in several ways. It can be associated with: an instrument or a valve failure; improper use of a valve; an operator error; a phase change or reaction of system contents; heating of storage contents, for instance by a fire [2].

There are two types of PRD failures. Type 1 occurs when a PRD fails to vent properly. Type 2 is a premature activation of a PRD. The devices can be blocked by dirt, stones or ice and thus fail to act when necessary. Also they can become corroded or otherwise damaged such that they relieve pressure when they should not be. Therefore an appropriate maintenance and inspection of PRDs is an important issue [2].

To prevent a catastrophic failure of a storage tank hydrogen is usually released through PRDs with high mass flow rates (i.e. with large venting areas). However, at a typical storage pressure of 700 bar a PRD with relatively large outlet diameter of about 5 mm can result in a jet flame length of 10-15 meters. Moreover, a high mass flow release of hydrogen can destroy a civil structure (such as a garage) in 1-2 seconds without leaving any chance for self-evacuation or for any rescue operation. Therefore, the only engineering solution for a PRD is to decrease the flow rate of hydrogen released. This will increase the blowdown time and thus the fire resistance of a storage vessel should be increased from current few minutes to at least tens of minutes [1]. An efficient PRD, when triggered, should produce a jet fire of the shortest possible length, if hydrogen leak is ignited, or a flammable envelope of minimum size, if release is not ignited [6]. The PRDs with improved design will essentially decrease the flame length from current 10-15 m to about 1 m.

2.2 Types of PRD systems

There is a variety of types and sizes of PRDs available owing to their diverse range of applications. The contents of the storage tanks may include compressed gases, corrosive liquids, two-phase fluids, and some of them such as liquid hydrogen can change phase upon venting. Thus, it is impossible to find a universal PRD that will fit all of these applications. There are two main categories of PRDs for pressurised storage vessels: reclosing and non-reclosing.

A reclosing PRD is designed to close after its operation [3] and can be reused after their activation. Although this type of PRD can be attractive in applications where overpressures may occur occasionally, it is not suitable for storage tanks in hydrogen-powered vehicles due to the following reasons: it is only activated by pressure (not by temperature); it restricts the flow rate and does not allow a full release of storage content. The most common device is a spring-loaded PRD shown on Figure 2. A sealing occurs between the disk and the seating surface. The adjusting screw allows the spring tension to be varied, which adjusts the downward force on the disk and thus the relieving pressure. If outflow pressure in reclosing PRD increases upon activation, the disk can reseat and then reopen again, resulting in decreased venting rates and chatter that can damage the valve [2].

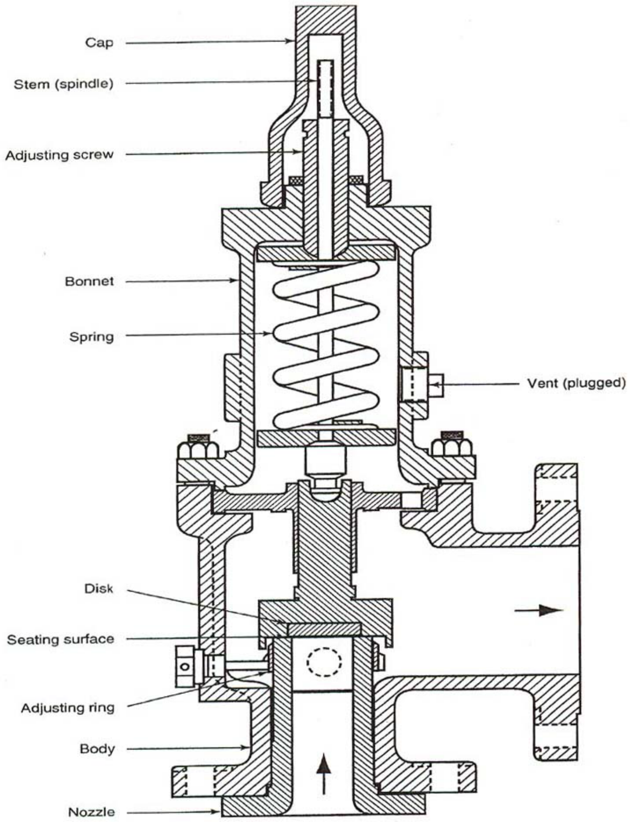

Figure 2. A scheme for a spring-loaded PRD (arrows indicate the direction of gas inflow and outflow) [3].

For many reclosing PRDs, flow area increases with upstream pressure. As system pressure increases, the valve opens at its set pressure point. This is normally the maximum allowable working pressure (MAWP). Further increase in pressure (to the maximum relieving pressure level) causes the valve to open fully and system pressure begins to drop. Once the pressure is relieved valve closes. Some relief valves have lifting mechanisms, which allow the valve to open manually. Although, lifting devices are prohibited from use in compressed natural gas (CNG) vehicles. The other types of reclosing PRDs include pilot operated, balanced bellows, power- and temperature-activated [3].

A non-reclosing PRD remains open after its operation. Non-reclosing PRDs can be classified into the following groups: rapture/burst disks; buckling pin devices; breaking pin devices; shear pin devices and fusible plugs. They are used where activation requires a fully opened PRD and a complete venting of a vessel. The key aspect of non-reclosing PRDs is that they must be replaced after the operation. Only pin-type PRDs are pressure relief valves, which respond to an excessive pressure (higher than MAWP) either by breaking, or buckling, or by shearing failure of a metal pin. This pin keeps the valve closed until the point of failure [2].

2.2.1 Rupture/burst disks

Rupture or burst disks are non-reclosing PRDs that are activated by high pressure leading to a disk rupture. They are classified by the Compressed Gas Association (CGA) as type CG-1 PRDs (Figure 3). Their behaviour is nearly independent of temperature. Type CG-1 device has a flat disk, typically made of metal, designed to a specification, which will allow it to burst at a pre-determined pressure to permit the release of hydrogen. The rupture disk relieves overpressure in cylinders that may result from a fire or from over-filling the cylinder. The burst pressure of rupture disks should not exceed the minimum pressure (required by the Department of Transport (DOT)), which is generally 5/3 of the cylinder service pressure. Some exceptions to this rule are: the burst pressure must not exceed 4500 psig for DOT-3E or CTC-3E specification cylinders; the burst pressure must not be less than 105% of the cylinder test pressure or greater than 80% of the minimum burst pressure for DOT-39 cylinders. The pressure rating is usually stamped onto the face of the device [7].

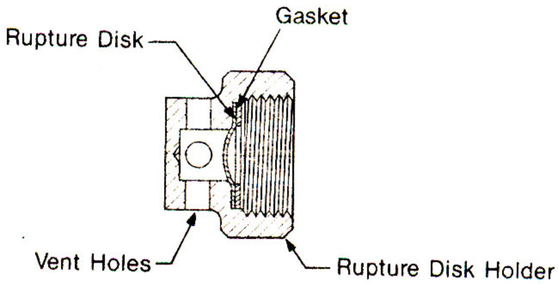

Figure 3. A rupture disk PRD [2]

2.2.2 Fusible plug and combination PRDs

Fusible metal PRDs contain an eutectic metal alloy with a low melting point. When its melting temperature is reached the metal weakens and deforms, enabling pressure relief. There are two common actuation temperatures for fusible metal PRDs: 74 °C (165 °F), which is CGA type CG-2, and 100 °C (212 °F), which is CGA type CG-3. PRDs at the lower temperature are appropriate only for pressures below 34 barg (500 psig). Although the activation of a fusible metal PRD primarily depends upon temperature, pressure and time, they cannot be relied upon to relieve at excess pressure at normal temperatures.

A sample of fusible plug PRD is shown on Figure 4. This device has the eutectic alloy in direct contact with the compressed gas. This simple type of PRD is not used in compressed gas storage systems because both hydrogen and CNG may damage the alloy.

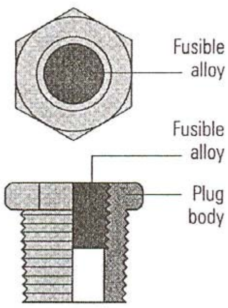

Figure 4. A typical fusible plug PRD [3]

Some PRDs are combinations of fusible metals and rupture disks (Figure 5). These are CGA type CG-4 or CG-5 devices depending on the temperature ratings. The activation of this type of PRD requires simultaneous high temperature and high pressure. The rupture disk is in contact with the fuse metal and thus, regardless of pressure, cannot release the contents when the fuse metal remains in place.

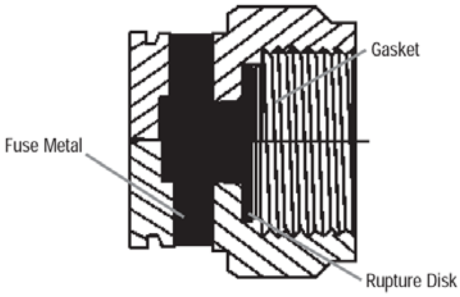

Figure 5. A typical combination PRD [7]

Type CG-4 is a combination of a rupture disk and a fusible alloy rated at 74 °C. The CG-4 device consists of a rupture disk backed by a fusible plug on the atmospheric side of the disk. The burst pressure of the disk must not exceed the minimum of DOT required test pressure of the cylinder (except as noted under Type CG-1); the fusible metal must yield between 69-77 °C (74 °C nominal). This combination type PRD provides protection against cylinder rupture caused by fire or high temperatures. In the case of fire the fusible metal melts and cylinder overpressure caused by the heated hydrogen is relieved by the bursting of the rupture disk. Both the pressure and temperature requirements of the device must be met before the device can function. This device will not protect a cylinder from over-pressurisation if the fusible alloy is not heated to its yield temperature. The fusible alloy will prevent the disk from rupture if it remains in place. The fusible metal prevents premature rupture disk failure from momentary over-pressurisation and also protects the disk from corrosion which could cause its premature activation. The face of these devices is marked with the burst pressure rating of the disk and the yield temperature of the fusible alloy [7].

Type CG-5 device is the same as the CG-4 PRD with the exception that it uses a fusible metal with a higher melting point. The CG-5 device uses a fusible alloy with a melting temperature ranging from 98 to 104 °C (100 °C nominal). Unfortunately, the temperature and pressure variations could cause premature leakage due to a fusible metal creep and fatigue of the burst disk. In addition, these combination PRDs were unable to protect partially filled fuel tanks from fire effects.

The CGA lists the pressure relief devices to be used on specific products in the Pamphlet S-1.1 "Pressure-Relief Device Standards Part 1: Cylinders for Compressed Gases". DOT regulations require compliance with this document. According to Safetygram-15 [7] hydrogen cylinders less than 1.65 m (65") long must be equipped with rupture disk/fusible alloy of type CG-4 or type CG-5 devices. The cylinders greater than 1.65 m (65") in length and 0.24 m (9 5/8") in diameter must be equipped with CG-4, CG-5, or CG-1 types rupture disk devices. Cylinders over 1.65 m (65") in length and 0.56 m (22") in diameter must use type CG-1 rupture disk devices.

Fusible plug PRDs have a considerable mass flow and respond rather slowly to heat. A faster response time was obtained for Mirada's (www.miradaresearch.com) PRDs shown on Figure 6. Here the small trigger made from a bismuth/lead eutectic alloy protrudes into the heated gas atmosphere. Upon reaching its triggering temperature (124 °C), the trigger melts and allows a ball bearing to move upward. This allows the bayonet to move to the left under the force of the loaded spring, and to pierce the safety disk. Storage tank content is released through the hollow bayonet [2].

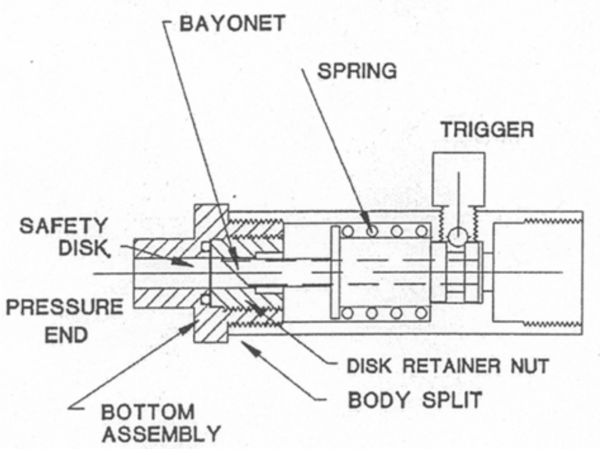

Figure 6. A bayonet PRD used in CNG buses [8]

The 8100 series PRDs were designed by the Circle Seal Controls (www.circle-seal.com) for application in hydrogen and CNG vehicles. Similar to the PRDs manufactured by Mirada, this design avoids problems associated with metal creep and metal plasticity of eutectic alloys when exposed to high pressure hydrogen or CNG. The 8100 series PRD uses an eutectic alloy (nickel-plated brass) to hold in place a poppet and a seal. Upon heating, the alloy deforms and allows the seal to open. It relieves the gas at 104 ^{o}C.

PRDs for hydrogen vehicles are also manufactured by other companies. For instance, Rotarex Automotive (www.rotarex.com) supplies brass safety plugs and glass bulb PRDs. Although these are listed for use in CNG buses, they are similar to devices used in hydrogen vehicle containers. They are rated for 200 bar CNG and 300 bar hydrogen tanks. The Rotarex brass safety plug PRD contains a fusible metal element that deforms at 110 ^{o}C and a poppet. When metal begins to melt, the poppet moves upward leading to the opening of two O-rings, and eventually a gas vents radially.

The Rotarex glass bulb PRD is similar to the technology used for automatic fire sprinklers. The glass bulb is hollow and contains liquid. It avoids concerns and restrictions associated with the use and possible release of heavy metals in fusible alloys plugs. Upon heating the bulb breaks down (at 110 ^{o}C) and frees the poppet to move to the left. This opens the O-ring seal and vents the gas through the radial ports [1, 2].

Typical examples of safety devices for hydrogen storage are:
- Cylinder pressure relief devices [7]
- Safety valve for high pressure-hydrogen tank [9]
- Safety valve of high pressure hydrogen storage tank [10]
- Safety valve for high pressure storage of hydrogen and other flammable materials (UU) [1].

Prof Vladimir Molkov (UU) had invented a technology for a gas storage vessel that comprises of an internal tank partially surrounded by an external tank (with higher fire resistance) and equipped with a PRD. The internal tank (which is made from a light-weight material) is designed to store gas at a higher pressure compared to the external tank. The external tank has means to control possible leaks of hydrogen from the internal tank. The PRD has a variable aperture size, which is small at the start of the release and increases in the end of the blowdown. This feature prevents both high flame length and the occurrence of overpressure within an enclosure [1].

The competitive advantages of this invention are:
1. A reduction in the flame length from the safety valve during its operation keeping the hydrogen blowdown time at the same level. It is expected that with the use of this technology the flame length will be reduced to less than 1 m for pressure of 700 bar in the storage tank. This is an essential mitigation of fire hazards and associated risks for hydrogen and fuel cell technologies.

2. An inherent protection of vents for hydrogen dispersion from adverse atmospheric effects (such as corrosion, dirt, external damage, etc.), and from blocking by a rupture disk(s) debris and particles of fusible metal components. This feature increases significantly valve's operational reliability.
3. There are no products with such performance characteristics currently on the market. Existent devices will either produce unacceptably long flames, when large nozzle diameter is used, or in contrary case of smaller nozzle diameter will have unacceptably long blowdown time.
4. A reliability of existent devices in case of use of multiple small size orifices is very low due to known reasons, including blocking of small vents by atmospheric dirt, particles of fusible metal and/or rupture disk debris after its activation, as well as susceptibility to occasional external damage or fire damage. Capillary effect of fusible metal behaviour in narrow channels can deactivate the valve too.
5. This invention could build on strengths of existent PRDs, e.g. use of fusible metal and rupture disk, and add innovative features providing safer and more reliable blowdown of high pressure hydrogen from the storage tank in predetermined time with lesser hazards, i.e. shorter safety distances determined by flame length or flammable envelope, and associated risks [1].

2.3 Procedures for PRD testing within compressed hydrogen storage systems

In a global industry, automakers are faced with a wide variety of different regulations, codes and standards (RCS) in different countries, often aimed at achieving the same purpose, but differing for historical reasons. Codes and standards are developed by industry. They specify requirements for operation so that the components and systems made by different suppliers will work together. They also specify requirements for safe design, operation, and test standards for certifying performance. Regulations are developed by governments and specify legally enforced safety requirements to the use of technology [11]. For instance, reference [12] includes a list of 44 entries. Table 1 shows only selected RCS of most interest to PRDs in hydrogen-fuelled vehicles.

Table 1. Selected RCS applicable to PRDs in hydrogen-fuelled vehicles.

RCS	Title	Country	Year	Reference
SAE J2578	Recommended practice for general fuel cell vehicle safety	U.S.	2002	[13]
SAE J2579	Technical information report for fuel systems in fuel cell and other hydrogen vehicles	U.S.	2008	[14]
ISO 11439	Gas cylinders – high pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles	International	2000	[15]
ISO 15869	Gaseous hydrogen and hydrogen blends-land vehicle fuel containers	International	2009	[4]
CGA S-1.1	Pressure relief device standards -part I - cylinders for compressed gases	U.S.	2007	[16]
CSA HGV2	Standard for compressed hydrogen gas vehicle fuel containers (draft)	U.S., Canada	2007	[17]
ANSI HPRD1	Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers	U.S., Canada	2013	[18]
CSA NGV2	Standard for natural gas vehicle containers	Australia, Japan, Mexico, U.S.	2007	[19]
FMVSS 304	Compressed natural gas fuel container integrity	U.S.	2003	[20]
NFPA 52	Vehicle fuel systems code	U.S.	2006	[21]

Regulation No 79/2009	Type-approval of hydrogen-powered motor vehicles	EU	2009	[22]
Regulation No 406/2010	Implementing EC Regulation 79/2009	EU	2010	[23]
UN GTR ECE/TRANS/WP.29 /2013/41	Draft global technical regulation (GTR) on hydrogen fuelled vehicle	UN	2013	[5]

Despite the large number of RCS for PRDs, they are usually similar both in the US and in Europe, and where differences occur they are generally not significant [2]. Many of the codes and standards for compressed gas vehicle containers and PRDs, such as FMVSS 304, are performance-based. This admits novel designs and reflects recent trends in Fire Protection Engineering.

The following sections provide the review of RCS that aims to analyse the available hydrogen PRD and TPRD standards identifying gaps in the testing procedures and standards and their potential impact on safety.

2.3.1 Automotive hydrogen specifications

The specifications governing automotive hydrogen pressure relief devices are split into several areas, such as tank assembly, fire protection, and fuel specifications. A large proportion of knowledge surrounding the use of compressed gas as a fuel in the automotive sector considers the use of LPG compressed gas vessels. Whilst the method of tank storage is clearly similar for LPG and hydrogen, there are significant differences between the storage vessel materials. Hydrogen causes the embrittlement of many materials which can lead to deformation and leakage from the vessel. Hydrogen is also stored at much higher pressures than LPG with a typical OEM pressure of 350 to 700 barg, compared to 17 barg for LPG. Due to the increased pressure and materials compatibility problems that the use of hydrogen poses, alternative hydrogen specific standards are required.

2.3.1.1 ANSI HPRD 1 – 2013 Thermally activated pressure relief devices for compressed hydrogen fuel containers. (Published March 2013)

ANSI HPRD 1 sets out the materials, type and applications requirements for hydrogen PRD and TPRDs. Previously standards relating to PRDs and TPRDs specified the materials to be used and operating requirements for a hydrogen system. ANSI HPRD 1 brought together standards and test procedures for TPRDs and PRDs with fire impingement testing into one standard. The standard establishes the qualifying requirements for PRDs for use on fuel containers (CSA B51 part 2 Boiler Pressure Vessels and Pressure Piping Codes or SAE J2579 Hydrogen Vehicles). PRDs which qualify for ANSI HPRD-1 are designed to comply with SAE J2719 (fuel systems and other hydrogen vehicle systems) and ISO 14687 (hydrogen fuel quality) specifications. A specific design for a PRD is not given in this standard; however, if the PRD meets all design and testing requirements it will be accepted.

2.3.1.2 SAE J2579 – 2013 Standards for fuel systems in fuel cell and other hydrogen vehicles

SAE J2579 specifies a standard for the whole automotive hydrogen system. The standard covers the design, operation and maintenance of the hydrogen vehicle. The standard also covers performance based requirements for hydrogen storage and handling system prototypes. SAE J2579 refers to ANSI HPRD 1 2013 for PRD materials and operation testing. The specification includes localised and extended fire testing to ensure that TPRDs activate when a vessel is subjected to localised fire impingement.

2.3.1.3 Draft ISO 12619 - Road vehicles compressed gaseous hydrogen (CGH2) and methane blends fuel components

ISO 12619 (Draft) states the requirements for hydrogen pressure vessels. Part 1 stipulates the general requirements and definitions; part 2 sets out the performance and general test methods such as the bonfire test. Part 3 sets out the requirements for pressure regulating devices. Pressure relief valves are specified as re-closable pressure devices which may directly attach to pressure regulators.

2.3.1.4 ISO DIS 15869 draft – 2009 Gaseous hydrogen and hydrogen blends land vehicle fuel tanks

ISO 15869 specifies materials, operation and application specific requirements for lightweight refillable, on board hydrogen storage tanks. The standard describes all tank materials that have proved suitable for the application and service conditions. TPRDs are required under the specification.

2.3.1.5 SAE J2719 Information report on the development of hydrogen quality guidelines for fuel cell vehicles

SAE J2719 sets out the requirements for hydrogen fuel purity, with regards to commercial proton exchange membranes in fuel cells (PEMFC) vehicles.

2.3.1.6 ISO 14687 Hydrogen fuel product specification

ISO 14687 specifies the requirements for fuel purity in hydrogen systems. ISO 14687 ensures hydrogen purity for all hydrogen applications such as stationary power generation units.

2.3.1.7 EC 79/2009 European union regulation – Type approval of hydrogen powered motor vehicles and amending directive 2007/46/ EC

The European Union passed regulations specifying the type of hydrogen powered land based systems permissible in the EU. The regulation states the system requirements for the vehicle itself and the installation of such systems. The regulations ensure the safe design of hydrogen systems with particular reference to the hydrogen dispersion route to the surroundings of PRDs within a vehicle. EC 79/2009 gives guidance and regulations on materials and operation testing to be undertaken on all materials and devices exposed to hydrogen.

2.3.1.8 ISO 23273/2013 fuel cell road vehicles – safety specifications – protection against hydrogen hazards for vehicles fuelled with compressed hydrogen

ISO 23273 sets out regulatory and safety requirements of hydrogen powered vehicles with respect to persons and the environment. The standard specifies the use of TPRD on hydrogen containing vessels for fire protection. The standard also gives guidance on design considerations for the safe discharge of hydrogen from a pressurised vessel. Refuelling design requirements are also covered.

2.3.2 PRD specific hydrogen standards

2.3.2.1 ANSI HPRD 1 – 2013 Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers

The requirements set out in ANSI HPRD 1 contain materials, operations and applications specific to fire testing of TPRDs. The standard splits the requirements into design qualification testing, inspection and acceptance testing and production batch testing.

ANSI HPRD 1 includes testing methods for PRDs. The standard clearly states areas of the PRDs which require special attention and inspection prior to and post testing. Materials testing specified within ANSI HPRD 1 ensures that the PRDs used can withstand exposure to hydrogen and continuous use outdoors in a road environment. Testing protocols include exposure of the PRDs to atmospheric and UV sources to give an indication of in-service life time.

ANSI HPRD 1 also provides guidance and test methodology for operations testing of PRD. Operation testing ensures that the PRDs are able to withstand the continuously changing conditions of the vessel, such as environmental temperature and increasing and decreasing pressure when refuelling. The PRDs should be able to withstand vibration from an impact with an uneven road surface without leaking. The PRDs are also checked to ensure they activate at their set pressure and relieve at a suitable flow rate.

2.3.2.2 SAE J2579 – March 2009 Standards for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

SAE J2579 sets out the requirements for hydrogen automotive vehicles. The design of the storage system is discussed in detail with many TPRD and PRD related specifications. The standard stipulates the type and placement of PRDs, with reference to localised fire impingement testing. The standard refers to ANSI HPRD 1 for further guidance on materials requirements and testing for TPRDs and PRDs. SAE J2579 also stipulates the checks that a hydrogen vehicle must undergo to ensure on-going safety.

SAE J2579 provides guidance and regulation to the type of PRD used, with specific recommendations on their placement. Particular reference is made to the mounting and orientation of the hydrogen vessel with regards to localised fire activation of the TPRDs. If the orientation of the vessel is known, the siting of a TPRD should not be such that an increased risk of accidental activation occurs. The TPRD itself must be non-re-closable and all venting lines should be designed to prevent blockages of the TPRD.

Fire safety tests are set out with particular focus on localised flame impingements. There was concern among the hydrogen safety community that type 3 and 4 composite vessels have a decreased rate of heat conduction to the TPRDs and would therefore increase the likelihood of vessel rupture. SAE J2579 specifies localised and extended fire testing for all hydrogen vessels with TPRDs fitted. Testing of TPRDs in the localised fire tests considers the worst case scenario where the TPRD is located at the opposite end of the tank to the fire impingement giving the largest heat conduction distance possible.

2.3.2.3 DIS ISO / TS 15869 – 2009 Gaseous hydrogen and hydrogen blends – land vehicle fuel tanks

ISO 15869 focusses on the role of PRDs and TPRDs in land vehicle tanks in the event of fire. The standard specifies the type of TPRDs to be used, referencing the ANSI/IAD PRD -1 1998 specification for advice on TPRD selection. The specification requires the whole vessel to be emptied in one continuous TRPD action. Fire protection testing is required in the form of the standard bonfire test.

2.3.2.4 ISO 12619-3 – 2012 Road vehicles compressed gaseous hydrogen (CGH2) and hydrogen / methane blends fuel components

ISO 12619-3 specifies the type requirements for pressure relief valves. PRDs are mentioned in this standard as an ancillary part to the pressure regulator system. The testing required to register ISO 12619-3 includes pressure impulse testing and leakage testing.

2.3.2.5 EC 79/2009 European Union Regulation – 2009 Hydrogen automotive systems components design and installation

European regulation EC 79/2009 specifies tests required for hydrogen components other than vessels designed to use gaseous hydrogen. The standard focuses on ensuring that the system does not leak gaseous hydrogen to the vehicles' surroundings and that all articles handling hydrogen are suitable for the application. Hydrogen embrittlement is a concern to the hydrogen community. Defects can occur in metal structures causing possible deformation, therefore increasing the risk of leakage. Corrosion protection is also tested on all hydrogen handling components to ensure that the material's integrity is maintained throughout service. Fire safety is also covered in the standard with the standard bonfire test being used to ensure that PRDs activate and prevent tank rupture.

2.3.2.6 EC 406/2010 European Regulation

European regulations on the use of hydrogen vehicles within the European Union were created in 2010. An internal target of 2020 was given for the European Union to have the infrastructure and regulation needed for mass hydrogen vehicle use. The regulations specify design areas such as PRD mounting and type. The regulation specifies that the hydrogen vessels' design should ensure that accidental activation of the PRDs does not occur. The regulation also states that the venting hydrogen gas must not pass through any potential ignition sources inside the vehicle such as electrical installations.Test methods

2.3.3 Test methods used for PRDs without tank assemblies

Test methods for hydrogen PRDs and TPRDs themselves originated from LPG and pressure vessel standards. Manufactures typically provide conditions testing such as leakage and pressure testing of PRDs. ANSI HPRD 1 brought together the necessary conditions testing for PRDs and TPRDs into a standalone standard. ANSI HPRD 1 is now referenced in hydrogen vehicle specifications such as SAE J2579 as the full testing protocol for hydrogen PRDs. ANSI HPRD 1 (ANSI American National Standards Institute, 2013) shows a number of conditions tests and specifies the areas of interest on the PRDs prior and post testing.

Test methods used for hydrogen specific PRDs and TPRDs can be split into two different types; materials and conditions test methods. The tests all ensure that the PRDs are suitable for use in a hydrogen containing system and will not give rise to potential safety risks such as explosions.

2.3.3.1 Materials test methods

Test methods to show the material's compatibility with hydrogen are common throughout standards literature. Signs of hydrogen embrittlement are evident in the material's structure when viewed under a microscope. Small deformation cracks occur and the material's resistance to deformation is altered. Hydrogen compatibility specifications are present in all standards as a check of component suitability. However, European regulation and specification EN 406/2010 and EC 79/2009 give a specific hydrogen compatibility testing regime.

ANSI HPRD 1 gives a comprehensive overview of PRD material requirements. The standard considers the use of non-metal components in service or contact with hydrogen to be acceptable. The standard also states that PRD or TPRD manufacturers should state the suitability of their products with consideration to hydrogen contact deformation. ANSI HPRD 1 refers to ISO/PDTR 15916 and ANASI/A1AA G-095 – 2004 for guidance on the effects of hydrogen embrittlement.

2.3.3.2 Conditions based test methods

Conditions test methods ensure that the conditions encountered by PRDs and TPRDs in service do not trigger the premature activation of the device. Condition testing also gives an indication of the product's lifetime when exposed to corrosion or radiation. ANSI HPRD 1 gives a comprehensive list of conditions testing such as pressure cycling and thermal cycling. European regulations EC 406/2010 and EC 79/2009 include temperature range testing for all hydrogen handling components such as PRDs.

2.3.4 Test methods used to test PRD in a tank assembly

Tank assembly specifications such as ISO DIS 15869 include detailed testing regimes for the pressurised vessel and accessories such as pressure regulators. Materials testing is common throughout hydrogen vessel and automotive systems specifications. ISO 11114-4 is commonly referenced as a standard test for compatibility of materials with hydrogen.

PRDs and TPRDs preform a vital safety role for pressurised tank assemblies. The TPRDs chosen for automotive hydrogen service can depend on the vessels type. Specifications for LPG and compressed gas systems traditionally used the standard bonfire technique to check the effectiveness of TPRDs. Standards and regulations such as EC 406/2010, SAE J2579, ISO / TS 15869 all require bonfire testing of pressurised vessels to be carried out with all PRDs and TPRDs present.

Concerns were raised by the hydrogen community regarding localised fire impingement effects on type 4 tanks with TPRDs fitted. SAE J2579 introduced a localised fire test for all hydrogen containing pressure vessels. An extended fire test was also introduced to ensure that TPRDs will activate. The tests are run in a worst case scenario situation with the TPRDs located at the maximum distance possible from the localised fire impingement point.

2.3.5 Evaluation and comparison of hydrogen specifications regarding PRDs

Specifications regarding PRDs and TPRDs were spread between hydrogen tank and fuel systems specifications before the introduction of ANSI HPRD 1 in March 2013. The ANSI HPRD 1 standard uniquely sets out all required tests within the standard. Links are also made within the ANSI standard to existing hydrogen systems specifications.

All standards and regulations address the issue of material's compatibility with hydrogen. Standards such as ANSI HPRD 1, SAE J2579, ISO DIS TS 15869 and European regulations EC 406/2010 and EC 79/2009 all reference standard hydrogen compatibility tests such as ISO 11114-4. ANSI HPRD 1 also mentions ISO/PDTR 15916 and ANASI/A1AA G-095 – 2004 for guidance on hydrogen embrittlement.

ANSI HPRD 1 sets out a comprehensive scheme of conditions testing such as exposure to automotive fluids and UV. The tests ensure that accidental activation or degradation of the PRDs and TPRDs does not occur in service. Testing regimes for conditions testing was not covered for the PRDs themselves in other hydrogen standards such as European regulations EN 406/2010 and EC 79/2009. Standards such as SAE J2579 provide conditions tests for tank assemblies with the PRDs and valves removed. However leakage tests are an exception. The test is performed on PRDs individually in ANSI HPRD 1 and as part of a tank assembly in SAE J2579.

Safety devices such as TPRDs and PRDs were tested as part of a tank assembly in specifications SAE J2579, ISO / TS 15869 and European specifications EC 406/2010 and EC 79/2009, using the standard bonfire test. ANSI HPRD 1 checks the performance of the TPRDs themselves using a range of tests, including bench top activation, flow capacity and high pressure activation.

Following concerns raised by the hydrogen community, an extended bonfire and localised bonfire test was introduced to SAE J2579. These extended tests have not been introduced into revisions of the current European regulations.

ANSI HPRD 1 and SAE J2579 are unique in indicating that inspection of the TPRDs and PRDs would be periodically required for in-service hydrogen vehicles.

2.3.6 Comparative assessment of hydrogen PRD and LPG PRD standards

Specifications regarding the use of PRDs were created for pressurised boiler systems. The introduction of LPG compressed gas vessels into automotive systems required new PRD specifications to be applied. The new specifications accounted for the contact of the PRD with LPG and the increased pressure of gas storage. LPG specifications were themselves used as a basis for hydrogen specifications.

LPG specifications such as PR-EN-14129, PR-EN 14071 and BS EN ISO 4126-1 show similarities with ANSI HPRD 1. The specifications require PRDs to be tested for pressure activation, flow characteristics and bursting disc pressure tests.

Hydrogen and LPG PRD standards are similar with respect to the material's suitability for use with compressed gas. PR-EN-14129 gives a full specification of suitable materials for use with LPG. Hydrogen standards however are more stringent on material compatibility. ANSI HPRD 1 specifies batch testing of PRDs for hydrogen compatibility by the manufacturer after a change to the design has taken place.

LPG compressed vessel specifications include a fire safety standard bonfire test. The bonfire test was transferred to hydrogen standards to show that TPRDs and PRDs would activate in the event of fire impingement. The standard bonfire test was then modified and extended for hydrogen. This was due to use of high strength composite materials for hydrogen storage.

The use of LPG standards as a basis for hydrogen standards is evident. Test methods such as the bonfire test were developed for LPG vessels and were further developed for hydrogen use. Material's compatibility testing was a requirement of LPG PRDs specifications and became a larger concern for hydrogen standards due to embrittlement.

The harmonization of these regulations worldwide can offer savings in technical resources, which can be applied elsewhere, e.g. to produce better, cleaner and safer vehicles. It also offers the possibility of reducing production complexity, resulting in lower costs and prices and a wider choice of vehicles available to all consumers. International vehicle standards have been under development primarily at the Society of Automotive Engineers (SAE) and the International Organization for Standardization (ISO). Worldwide harmonization of vehicle regulations takes place in the United Nations, where the World Forum for Harmonization of Vehicle Regulations, (WP29) and its groups of government and industry experts develop new Global Technical Regulations (GTR) [5]. This document has been approved recently and therefore the testing procedures described below are referred to the most recent proposal [5].

For the purposes of containers designed to use compressed (gaseous) hydrogen, a PRD shall be a non-reclosing, thermally activated device that prevents a container from bursting due to fire effects. A PRD shall be directly installed into the opening of a container or at least one container in a container assembly, or into an opening in a valve assembled into the container, in such a manner that it shall discharge the hydrogen into an atmospheric outlet that vents to the outside of the vehicle [5].

It shall not be possible to isolate the PRD from the container protected by the pressure relief device, due to the normal operation or failure of another component. The internal dimensions of the vent shall not impede the function of the PRD. The vent of the PRD shall be protected against blockage, e.g. by dirt, ice, and ingress of water, so far as is reasonably practicable. The outlet of the PRD shall be orientated such that if the vent becomes detached from the pressure relief device, the resulting gas flow does not impinge directly on other containers or container assemblies unless they are protected [5].

The hydrogen gas discharge from PRD shall not be directed:
(a) towards exposed electrical terminals, exposed electrical switches or other ignition sources;
(b) into or towards the vehicle passenger or luggage compartments;
(c) into or towards any vehicle wheel housing;
(d) towards any class 0 component;
(e) forward from the vehicle, or horizontally from the back or sides of the vehicle.

2.3.7 TPRD qualification performance tests

According to the GTR the entire hydrogen storage system does not have to be re-qualified if primary closure components are exchanged for equivalent closure components having comparable function, fittings, materials, strength and dimensions, and qualified for performance using the same qualification tests as the original components. However, a change in TPRD hardware, its position of installation or venting lines requires re-qualification with fire testing according to verification test for service terminating performance in fire [5]. Design qualification testing shall be performed on finished PRDs which are representative of normal production. Manufacturers shall maintain records that confirm that TPRDs meet the qualification requirements listed below:

- Pressure cycling test
- Accelerated life test
- Temperature cycling test
- Salt corrosion resistance test
- Vehicle environment test
- Stress corrosion cracking test
- Drop and vibration test
- Leak test
- Bench top activation test
- Flow rate test

Testing is performed with hydrogen gas having gas quality compliant with [24, 25]. All tests are performed at ambient temperature 20 (±5) °C unless otherwise specified.

2.3.7.1 Pressure cycling test.

Five TPRD units undergo 11,000 internal pressure cycles with hydrogen gas. The first five pressure cycles are between 2 (±1) MPa and 150% of NWP (±1 MPa); the remaining cycles are between 2 (±1) MPa and 125% of NWP (±1MPa). The first 1500 pressure cycles are conducted at a TPRD temperature of 85 °C or higher. The remaining cycles are conducted at a TPRD temperature of 55 (±5) °C. The maximum pressure cycling rate is 10 cycles per minute. Following this test, the pressure relief device shall comply with the requirements of the Leak test, Flow rate test and the Bench top activation test.

2.3.7.2 Accelerated life test.

Eight TPRD units undergo testing; three at the manufacturer's specified activation temperature (T_{act}) and five at an accelerated life temperature (T_{life}). T_{life} = 9.1 x T_{act} 0.503.

The TPRD is placed in an oven or liquid bath with the temperature held constant (±1 °C). The hydrogen gas pressure on the TPRD inlet is 125% of NWP (±1 MPa). The pressure supply may be located outside the controlled temperature oven or bath. Each device is pressurized individually or through a manifold system. If a manifold system is used, each pressure connection includes a check valve to prevent pressure depletion of the system when one specimen fails. The three TPRDs tested at T_{act} shall activate in less than ten hours. The five TPRDs tested at T_{life} shall not activate in less than 500 hours.

2.3.7.3 Temperature cycling test.
a) An unpressurized TPRD is placed in a liquid bath maintained at -40 °C or lower for at least 2 hours. The TPRD is transferred to a liquid bath maintained at 85 °C or higher within 5 minutes, and maintained at that temperature for at least 2 hours. The TPRD is transferred to a liquid bath maintained at -40 °C or lower within 5 minutes;
b) Step (a) is repeated until 15 thermal cycles have been achieved;
c) With the TPRD conditioned for a minimum of 2 hours in the -40 °C or lower liquid bath, the internal pressure of the TPRD is cycled with hydrogen gas between 2 MPa (+1/-0 MPa) and 80% of NWP (+2/-0 MPa) for 100 cycles while the liquid bath is maintained at -40 °C or lower;
d) Following the thermal and pressure cycling, the pressure relief device shall comply with the requirements of the Leak test, except that the Leak test shall be conducted at -40 °C (+5/-0 °C). After the Leak test, the TPRD shall comply with the requirements of the Bench top activation test and then the Flow rate test.

2.3.7.4 Salt corrosion resistance test.
Two TPRD units are tested. Any non-permanent outlet caps are removed. Each TPRD unit is installed in a test fixture in accordance with the manufacturer's recommended procedure so that external exposure is consistent with a realistic installation. Each unit is exposed for 500 hours to a salt spray (fog) test as specified in ASTM B117 (Standard Practice for Operating Salt Spray (Fog) Apparatus) except that in the test of one unit, the pH of the salt solution shall be adjusted to 4.0±0.2 by the addition of sulphuric acid and nitric acid in a 2:1 ratio, and in the test of the other unit, the pH of the salt solution shall be adjusted to 10.0±0.2 by the addition of sodium hydroxide. The temperature within the fog chamber is maintained at 30-35 °C. Following these tests, each pressure relief device shall comply with the requirements of the Leak test, Flow rate and Bench top activation test.

2.3.7.5 Vehicle environment test.
Resistance to degradation by external exposure to automotive fluids is determined by the following test:
a) The inlet and outlet connections of the TPRD are connected or capped in accordance with the manufacturers installation instructions. The external surfaces of the TPRD are exposed for 24 hours at 20 (±5) °C to each of the following fluids:
(i) Sulphuric acid – 19% solution by volume in water;
(ii) Sodium hydroxide – 25% solution by weight in water;
(iii) Ammonium nitrate – 28% by weight in water; and
(iv) Windshield washer fluid – 50% by volume methyl alcohol and water.
The fluids are replenished as needed to ensure complete exposure for the duration of the test. A distinct test is performed with each of the fluids. One component may be used for exposure to all of the fluids in sequence.
b) After exposure to each fluid, the component is wiped off and rinsed with water;
c) The component shall not show signs of physical degradation that could impair the function of the component, specifically: cracking, softening, or swelling. Cosmetic changes such as pitting or staining are not failures. At the conclusion of all exposures, the unit(s) shall comply with the requirements of the Leak test, Flow rate test and Bench top activation test.

2.3.7.6 Stress corrosion cracking test.

For TPRDs containing components made of a copper-based alloy (e.g. brass), one TPRD unit is tested. All copper alloy components exposed to the atmosphere shall be degreased and then continuously exposed for 10 days to a moist ammonia-air mixture maintained in a glass chamber having a glass cover. Aqueous ammonia having a specific gravity of 0.94 is maintained at the bottom of the glass chamber below the sample at a concentration of at least 20 ml per litre of chamber volume. The sample is positioned 35 (±5) mm above the aqueous ammonia solution and supported in an inert tray. The moist ammonia-air mixture is maintained at atmospheric pressure at 35 (±5) °C. Copper-based alloy components shall not exhibit cracking or delaminating due to this test.

2.3.7.7 Drop and vibration test.

a) Six TPRD units are dropped from a height of 2 m at ambient temperature (20±5^{o}C) onto a smooth concrete surface. Each sample is allowed to bounce on the concrete surface after the initial impact. One unit is dropped in six orientations (opposing directions of 3 orthogonal axes: vertical, lateral and longitudinal). If each of the six dropped samples does not show visible exterior damage that indicates that the part is unsuitable for use, it shall proceed to step (b);

b) Each of the six TPRD units dropped in step (a) and one additional unit not subjected to a drop are mounted in a test fixture in accordance with manufacturer's installation instructions and vibrated 30 minutes along each of the three orthogonal axes (vertical, lateral and longitudinal) at the most severe resonant frequency for each axis. The most severe resonant frequencies are determined using an acceleration of 1.5 g and sweeping through a sinusoidal frequency range of 10 to 500 Hz within 10 minutes. The resonance frequency is identified by a pronounced increase in vibration amplitude. If the resonance frequency is not found in this range, the test shall be conducted at 40 Hz. Following this test, each sample shall not show visible exterior damage that indicates that the part is unsuitable for use. It shall subsequently comply with the requirements of the Leak test, Flow rate test and Bench top activation test.

2.3.7.8 Leak test.

A TPRD that has not undergone previous testing is tested at ambient, high and low temperatures without being subjected to other design qualification tests. The unit is held for 1 hour at each temperature and test pressure before testing. The three temperature test conditions are:

a) Ambient temperature: condition the unit at 20 (±5) °C; test at 5% of NWP (+0/-2 MPa) and 150% of NWP (+2/-0 MPa);

b) High temperature: condition the unit at 85 °C or higher; test at 5% of NWP (+0/-2 MPa) and 150% of NWP (+2/-0 MPa);

c) Low temperature: condition the unit at -40°C or lower; test at 5% of NWP (+0/-2 MPa) and 100% of NWP (+2/-0 MPa).

Additional units undergo leak testing as specified in other tests with uninterrupted exposure at the temperature specified in those tests. At all specified test temperatures, the unit is conditioned for 1 minute by immersion in a temperature controlled fluid (or equivalent method). If no bubbles are observed for the specified time period, the sample passes the test. If bubbles are detected, the leak rate is measured by an appropriate method. The total hydrogen leak rate shall be less than 10 Nml/hr.

2.3.7.9 Bench top activation test.

Two new TPRD units are tested without being subjected to other design qualification tests in order to establish a baseline time for activation. Additional pre-tested units undergo bench top activation testing as specified in other tests.

a) The test setup consists of either an oven or chimney which is capable of controlling air temperature and flow to achieve 600 (±10) °C in the air surrounding the TPRD. The TPRD unit is not exposed directly to flame. The TPRD unit is mounted in a fixture according to the manufacturer's installation instructions; the test configuration is to be documented;

b) A thermocouple is placed in the oven or chimney to monitor the temperature. The temperature remains within the acceptable range for two minutes prior to running the test;

c) The pressurized TPRD unit is inserted into the oven or chimney, and the time for the device to activate is recorded. Prior to insertion into the oven or chimney, one new (not pre-tested) TPRD unit is pressurized to no more than 25% of NWP (the pre-tested); TPRD units are pressurized to no more than 25% of NWP; and one new (not pre-tested) TPRD unit is pressurized to 100% of NWP;
d) TPRD units previously subjected to other tests shall activate within a period no more than 2 minutes longer than the baseline activation time of the new TPRD unit that was pressurized to up to 25% of NWP;
e) The difference in the activation time of the two TPRD units that had not undergone previous testing shall be no more than 2 minutes.

2.3.7.10 Flow rate test.
a) Eight TPRD units are tested for flow capacity. The eight units consist of three new TPRD units and one TRPD unit from each of the following previous tests;
b) Each TPRD unit is activated according to Bench top activation test. After activation and without cleaning, removal of parts, or reconditioning, each TPRD unit is subjected to flow test using hydrogen, air or an inert gas;
c) Flow rate testing is conducted with a gas inlet pressure of 2 (±0.5) MPa. The outlet is at ambient pressure. The inlet temperature and pressure are recorded;
d) Flow rate is measured with accuracy within ±2%. The lowest measured value of the eight pressure relief devices shall not be less than 90% of the highest flow value.

2.3.8 Service terminating performance in fire

Hydrogen releases can be ignited, either from nearby fire or from shock compression or particulate impacts. Hydrogen flames are difficult to see in the day light, thus this could be hazardous, especially when vehicle is not resting with four wheels on the ground [2]. A fire is the only scenario where activation of PRD is compulsory. The biggest concern is the fire caused by a localized heating leading to a failure in TPRD activation. For the first time, the GTR addresses the issues of the localized fire that were absent from previous RCS.

The GTR specifies the procedures for both localized and engulfing fire tests with compressed hydrogen as a test gas. Containers tested with hydrogen gas shall be accepted by all Contracting Parties. However, Contracting Parties under the 1998 Agreement may choose to use compressed air as an alternative test gas for certification of a container for use only within their countries or regions. A hydrogen storage system is pressurized to 100% of NWP and exposed to fire. A TPRD shall release the contained gas in a controlled manner without a rupture [5].

A test article is a compressed hydrogen storage system (i.e. a hydrogen storage tank fitted with TPRDs, a shut-off valve and a check valve) with additional relevant features, including the venting system (such as the vent line and vent line covering) and any shielding affixed directly to the container (such as thermal wraps of the container(s) and/or coverings/barriers over the TPRD(s)). The container assembly is positioned horizontally approximately 100 mm above the fire source.

Either one of the following two methods are used to identify the position of the system over the initial (localized) fire source:
Method 1: Qualification for a generic (non-specific) vehicle installation
If a vehicle installation configuration is not specified (and the qualification of the system is not limited to a specific vehicle installation configuration) then the localized fire exposure area is the area on the test article furthest from the TPRD(s). The test article, as specified above, only includes thermal shielding or other mitigation devices affixed directly to the container that are used in all vehicle applications. Venting system(s) (such as the vent line and vent line covering) and/or coverings/barriers over the TPRD(s) are included in the container assembly if they are anticipated for use in any application. If a system is tested without representative components, retesting of that system is required if a vehicle application specifies the use of these type of components [5].

Method 2: Qualification for a specific vehicle installation
If a specific vehicle installation configuration is specified and the qualification of the system is limited to that specific vehicle installation configuration, then the test setup may also include other vehicle components in addition to the hydrogen storage system. These vehicle components (such as shielding or barriers, which are permanently attached to the vehicle's structure by means of welding or bolts and not affixed to the storage system) shall be included in the test setup in the vehicle-installed configuration relative to the hydrogen storage system. This localized fire test is conducted on the worst case localized fire exposure areas based on the four fire orientations: fires originating from the direction of the passenger compartment, cargo/luggage compartment, wheel wells or ground-pooled gasoline [5].

2.3.8.1 Localized portion of the fire test.
(a) The localized fire exposure area is located on the test article furthest from the TPRD(s). If Method 2 is selected and more vulnerable areas are identified for a specific vehicle installation configuration, the more vulnerable area that is furthest from the TPRD(s) is positioned directly over the initial fire source;
(b) The fire source consists of LPG burners configured to produce a uniform minimum temperature on the test article measured with a minimum 5 thermocouples covering the length of the test article up to 1.65 m maximum (at least 2 thermocouples within the localized fire area, and at least 3 thermocouples equally spaced and no more than 0.5 m apart in the remaining area) located 25±10 mm from the outside surface of the test article along its longitudinal axis. At the option of the manufacturer or testing facility, additional thermocouples may be located at TPRD sensing points or any other locations for optional diagnostic purposes;
(c) Wind shields are applied to ensure uniform heating;
(d) The fire source initiates within a 250±50 mm longitudinal expanse positioned under the localized exposure area of the test article. The width of the fire source encompasses the entire diameter of the storage system. If Method 2 is selected, the length and width shall be reduced, if necessary, to account for vehicle-specific features;
(e) The temperature of the thermocouples in the localized fire area has increased continuously to at least 300 °C within 1 minute of ignition, to at least 600 °C within 3 minutes of ignition, and a temperature of at least 600 °C is maintained for the next 7 minutes. The temperature in the localized fire area shall not exceed 900 °C during this period. Compliance to the thermal requirements begins 1 minute after entering the period with minimum and maximum limits and is based on a 1-minute rolling average of each thermocouple in the region of interest. (Note: The temperature outside the region of the initial fire source is not specified during these initial 10 minutes from the time of ignition) [5].

2.3.8.2 Engulfing portion of the fire test.
Within the next 2-minute interval, the temperature along the entire surface of the test article shall be increased to at least 800 °C and the fire source is extended to produce a uniform temperature along the entire length up to 1.65 m and the entire width of the test article (engulfing fire). The minimum temperature is held at 800°C, and the maximum temperature shall not exceed 1100 °C. Compliance to thermal requirements begins 1 minute after entering the period with constant minimum and maximum limits and is based on a 1-minute rolling average of each thermocouple. The test article is held at temperature (engulfing fire condition) until the system vents through the TPRD and the pressure falls to less than 1 MPa. The venting shall be continuous (without interruption), and the storage system shall not rupture. An additional release through leakage (not including release through the TPRD) that results in a flame with length greater than 0.5 m beyond the perimeter of the applied flame shall not occur [5].

2.3.8.3 Documenting results of the fire test.
The arrangement of the fire is recorded in sufficient detail to ensure the rate of heat input to the test article is reproducible. The results include the elapsed time from ignition of the fire to the start of

venting through the TPRD(s), and the maximum pressure and time of evacuation until a pressure of less than 1 MPa is reached. Thermocouple temperatures and container pressure are recorded at intervals of every 10 sec or less during the test. Any failure to maintain specified minimum temperature requirements based on the 1-minute rolling averages invalidates the test result. Any failure to maintain specified maximum temperature requirements based on the 1-minute rolling averages invalidates the test result only if the test article failed during the test [5].

2.3.8.4 Engulfing fire test.

The container may be subjected to engulfing fire without any shielding components. The test unit is the compressed hydrogen storage system. The storage system is filled with compressed hydrogen gas at 100 % of NWP. The container is positioned horizontally with the container bottom approximately 100 mm above the fire source. Metallic shielding is used to prevent direct flame impingement on container valves, fittings, and/or pressure relief devices. The metallic shielding is not in direct contact with the specified fire protection system (pressure relief devices or container valve).

A uniform fire source of 1.65 m length provides direct flame impingement on the container surface across its entire diameter. The test shall continue until the container fully vents (until the container pressure falls below 0.7 MPa (100 psi)). Any failure or inconsistency of the fire source during a test shall invalidate the result. Flame temperatures shall be monitored by at least three thermocouples suspended in the flame approximately 25 mm below the bottom of the container. Thermocouples may be attached to steel cubes up to 25 mm on a side. Thermocouple temperature and the container pressure shall be recorded every 30 seconds during the test. Within five minutes after the fire is ignited, an average flame temperature of not less than 590°C (as determined by the average of the two thermocouples recording the highest temperatures over a 60 second interval) is attained and maintained for the duration of the test.

If the container is less than 1.65 m in length, the centre of the container shall be positioned over the centre of the fire source. If the container is greater than 1.65m in length, then if the container is fitted with a pressure relief device at one end, the fire source shall commence at the opposite end of the container. If the container is greater than 1.65 m in length and is fitted with pressure relief devices at both ends, or at more than one location along the length of the container, the centre of the fire source shall be centred midway between the pressure relief devices that are separated by the greatest horizontal distance. The container shall vent through a pressure relief device without bursting [5].

2.3.9 Gap analysis of hydrogen specifications

2.3.9.1 Rate of release of hydrogen

The required release rate of compressed hydrogen from an open TPRD is not specified in either the ANSI HPRD 1 or hydrogen vessel specifications. The specifications for tanks state that the TPRD must open and vent continuously until the tank pressure reads below 1 barg. The rate of the release from a PRD or TPRD can be readily calculated. The rate is governed by the exit diameter, bursting disc orifice and tank pressure.

The rate of hydrogen release poses a potential safety risk, if the hydrogen is released rapidly there would be very little time for dispersion into the air and a large flammable gas cloud may form.

2.3.9.2 In situ service inspection

ANSI HPRD 1 and SAE J2579 state that a regular inspection of the TPRD should be made to ensure continuous fire protection. The specifications do not include a time regime for visual inspection of the PRDs or an inspection procedure. TPRD replacement schedules are not included in the specifications. TPRDs used within road vehicle assemblies may experience sharp knocks and / or vibrations. ANSI HPRD 1 requires that TPRDs are tested for vibration and impact resistance as part of design requirements. Hydrogen vehicles are expected to have a lifetime of over 100,000 miles and the effect of continuous vibration and sharp knocks from the road conditions may lead to degradation of the PRD.

2.3.10 PRD manufacturers of hydrogen products

Hydrogen specific PRDs and TPRDs have limited availability on the open market, with only five manufacturers found. Three products were marketed as TPRDs for automotive hydrogen systems and two as PRD devices. The specifications to which the manufacturers have classified their products varies widely. One product out of five specified that their TPRD had been tested in accordance with ANSI HPRD 1 and ISO 1550. One PRD product had been tested in accordance with materials tests laid out in the European regulations Regulation (EC) No. 79/2009 and (EC) No 406/2010.

All TPRDs and PRDs indicate that they are suitable for use with hydrogen and specify a working pressure, temperature or burst temperature where appropriate. All TPRD products also specify a flow rate for the product. Product types and conditions are shown in Appendix A

3 CFD-based PRD design

This section of the document is associated with the CFD-based design of PRDs suitable for testing. Such research was recently undertaken at the University of Ulster and had been published in the International Journal of Hydrogen Energy by D. Makarov and V. Molkov [26].

As mentioned previosly many applications using hydrogen as an energy carrier require hydrogen to be stored, in gaseous form, at pressures up to 100 MPa. Due to the presence of such high pressures the required separation distances can be quite large. Therefore, to reduce the costs of the required systems and infrastructure, there is a need to develop innovative engineering systems that can allow these distances to be safely reduced, when considering both unignited hydrogen releases and jet fires. For example, a correctly designed and installed PRD should produce a jet fire with the shortest possible flame length or, in case of unignited release, a flammable cloud with the smallest dimensions. In order to achieve this aim, plane nozzle flow is considered to be a realistic scenario to investigate leaks from high-pressure equipment cracks, fittings, connections etc.

There is a lack of experimental data when considering hydrogen jets emanating from plane nozzles. The behaviour of highly under-expanded unignited hydrogen plane nozzle jets is not currently predictable and there is an absence of experimental data. Without such data the proper design of appropriate PRDs cannot be undertaken, which will allow deterministic reduction of separation distances. The model introduced below aims to numerically predict the behaviour and structure of highly under-expanded hydrogen plane jets emanating from round and plane nozzles, considering different aspect ratios (ARs). This will allow the concentration decay to be understood and predicted to where the hydrogen concentration in air drops to below the lower flammability limit (LFL) of 4% by volume.

3.1 Model description

When considering the scenario(s) under investigation a number of key issues and modelling difficulties, which must be dealt with, become readily apparent. In the near field due to the small aperture of the nozzle and high pressures there will be an under-expanded jet shock structure formed. This highly unsteady scenario would necessitate a small time step to solve with simulations. Conversely, away from the nozzle a large flammable envelope, or jet flame, and slow velocities would require substantial computing resources and calculations to be undertaken over long real times. Therefore due to this disparity of spatial and velocity scales and in order to reduce the computational effort the problem was modelled in two stages. Firstly the compressible flow in the near-to-nozzle field was simulated and then these results were used as boundary conditions for the far-from-nozzle field simulations, where the incompressible flow approach could be utilized.

The mathematical model utilized included three-dimensional Favre-averaged mass, momentum, energy and hydrogen conservation equations. Flow turbulence was modelled using the standard k-ε turbulence model, as described by Launder and Spalding [27]. As this model was developed to predict axisymmetric and plane, turbulent non-premixed flame length the effect of lift-off on the jet flame length was neglected. Therefore the Eddy Break-Up (EBU) combustion model, as described by Magnussen and Hjertager [28], could be employed for combustion modelling. The hydrogen source term (i.e. mass burning rate per unit volume) was modelled using:

$$S_{H_2} = -C\bar{\rho}\bar{\varepsilon} = \min_k \left\{ \tilde{Y}_{H_2}, \frac{\tilde{Y}_{O_2}}{s} \right\} \quad (1)$$

Where:

- $C = 4.0$ is the empirical coefficient,
- $\tilde{Y}_{H_2}$ = mass fraction of hydrogen,
- $\tilde{Y}_{O_2}$ = mass fraction of oxygen, and
- $s = 8.0$, is the stoichiometric coefficient for the hydrogen-oxygen reaction.

This approach was considered to be appropriate as, following Mogi et al. [29], the lift-off distance of hydrogen flames is not more than 0.08 m which is an order of magnitude less than the overall length of experimental jet fires, 1.0 – 2.6 m.

The experimental details described in [30] were then used to test this modelling approach. During the simulations three nozzles, all with the same cross sectional area, were modelled:

1. Round nozzle with diameter 1.0 mm
2. Plane nozzle with dimensions 2.0 x 0.4 mm (length to width aspect ratio (AR) = 5.0)
3. Plane nozzle with dimensions 3.2 x 0.25 mm (AR = 12.8)

The calculation domains for all three nozzles were similarly designed, as far as possible. However, in the two plane nozzle cases the calculation domains utilized symmetry in the vertical plane, meaning simulations were undertaken for half of the plane nozzle jet. Shown below is an overview of the computational domain for the round nozzle jet case (Figure 7).

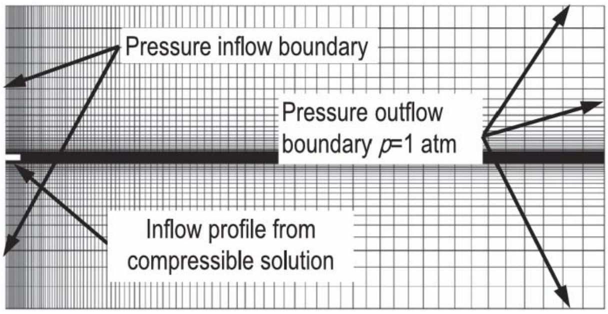

Figure 7. Overview of the computational domain for the round nozzle jet case

As previously outlined the computational domain was split into two stages. The calculation domain for the near-to-nozzle region had dimensions length (L) x diameter (D) = 0.1625 x 0.104 m. This first domain was discretized into 412,736 hexahedral control volumes (CVs). The second domain, describing the far-from-nozzle region, was discretized into 356,868 hexahedral CVs. Shown below in Figure 8 is the location of the interface between these two regions.

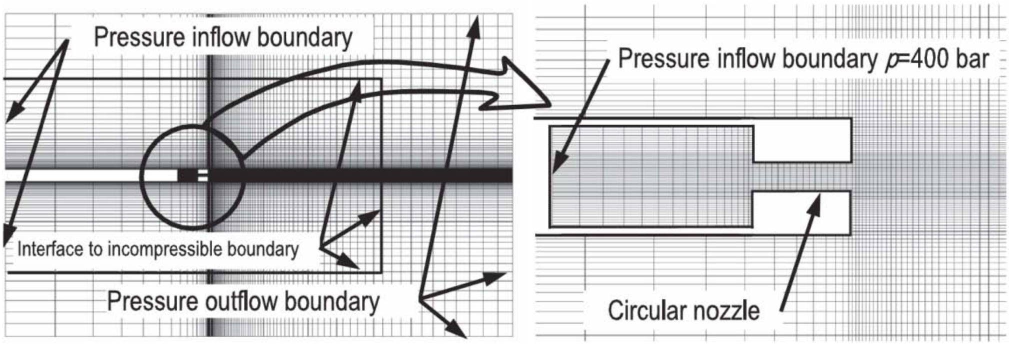

Figure 8**.** Interface between the near-to-nozzle region and the far-from-nozzle region

The details of the two plane nozzle cases can be summarised as follows. For the nozzle with AR = 5.0 the near-to-nozzle region had dimensions L x D = 0.26 x 0.16 m, it was discretized by a hybrid mesh consisting of 530,546 CVs and the nozzle itself was discretized using 6 CVs across its width and 14 CVs across its half-length. When considering the third nozzle with AR = 12.8 the same dimensions were used for the near-to-nozzle region, however in this case the nozzle was discretized using 6 CVs across its width and, in contrast, 32 CVs across its half-length. Following this change the mesh consisted of 504,040 CVs. For both the plane nozzle cases the far-from-nozzle region had the same dimensions, L x D = 3.1 x 4.0 m, and was discretized into 868,546 hexahedral CVs.

Finally, the model and modelling techniques implemented required a number of modifications prior to the undertaking of simulations. In order to compensate for the overestimation of the spread rate of axisymmetric jets encountered when using the standard k-ε turbulence model, as detailed by Pope [31], the MUSCL third order approximation scheme, outlined by Houf et al. [32], was used in conjunction with the model. Additionally, at the inflow boundary of the incompressible region domain an interpolation of the simulation results was required. In order to keep the potential error that this requirement could introduce to a minimum, key flow parameters at the interface were matched to each other.

Using the summarised model and these calculation domains, in the near-to-nozzle region simulations were started using explicit (transient) time marching and then switched to steady-state at a later time when the shock structure was established. In the far-from-nozzle region simulations were run as steady-state. The simulations themselves were carried out using ANSYS Fluent (release 13.0). The density-based explicit solver was applied to solve the compressible part of the problem, and the pressure-based implicit solver was used for the incompressible simulations.

3.2 Hydrogen flammable envelope and axial concentration decay

Shown below in Figures 9-11 are the hydrogen concentrations for the three investigated experiments, displaying the range 4-100% H_2 by vol. These figures show a cross section of the far-from-nozzle field in the direction parallel to the principal axis, as well as a number of selected cross sections perpendicular to the axis. The major axis of both plane nozzles, Figure 10 and 11, is horizontally orientated.

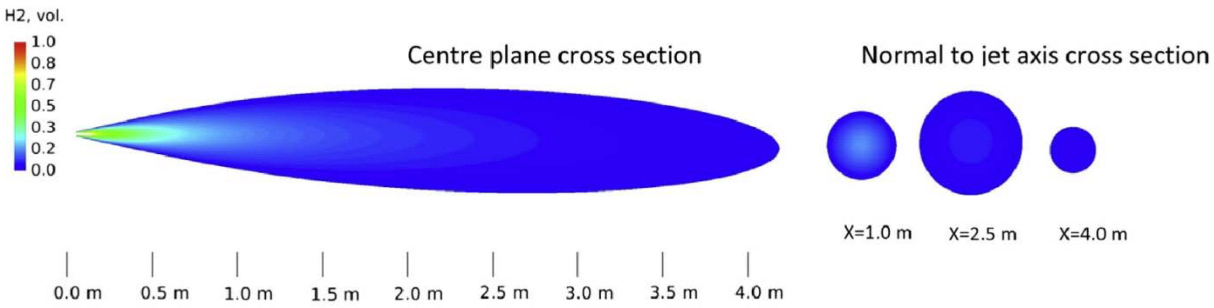

Figure 9. Hydrogen volume fraction distribution along the minor axis: round nozzle

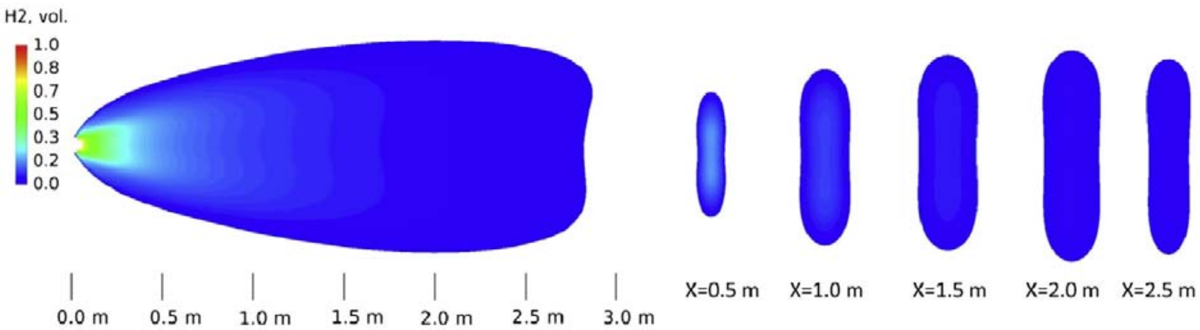

Figure 10. Hydrogen volume fraction distribution along the minor axis: plane nozzle, AR = 5.0

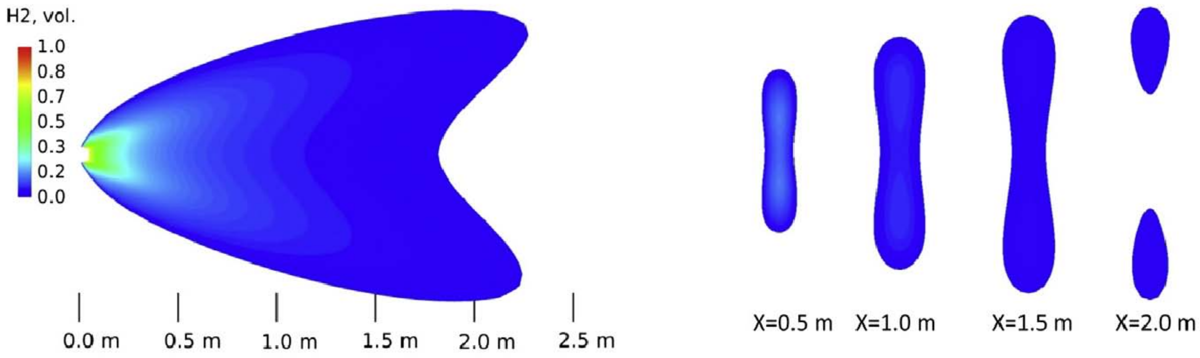

Figure 11. Hydrogen volume fraction distribution along the minor axis: plane nozzle, AR = 12.8

As shown above, in Figures 9-11, hydrogen enters the far-from-nozzle field through the interface boundary on the left hand side of each figure. When comparing these figures, it is clear that the longest flammable envelope was produced during the simulation of the axisymmetric jet emanating from the round nozzle. The maximum distance to the LFL was 4.2 m downstream, up to at least this limit the jet is in the momentum-dominated region and the jet itself retains its round shape.

The shape of the jets emanating from the two plane nozzles are flattened by comparison. As shown in Figures 10 and 11 for these two plane nozzles, the simulations produced higher spread rates in the vertical direction. These more flattened jets have a larger 'mixing layer' area compared to the axisymmetric jet. This results in more intensive mixing with the ambient air and subsequently a shorter flammable envelope. The distance to the LFL for the plane nozzle with AR = 5.0 was 2.8 m downstream and for the plane nozzle with AR = 12.8 was 2.3 m. Therefore despite having almost identical mass flow rates the distance to LFL for the plane nozzles when compared to the axisymmetric nozzle was 1.5 and 1.8 times shorter, respectively.

Shown below in Figure 12 are the simulation results for the three investigated nozzles plotted on the same graph as the similarity law for axial concentration decay in axisymmetric jets [33], which has been recently validated by Molkov et al. for under-expanded jets [30] for comparison:

$$y_{H_2} = 5.4 \cdot (D/x) \cdot (\rho_N/\rho_S)^{0.5} \tag{2}$$

Where:

- $D =$ plane nozzle width,
- $\rho_N =$ hydrogen density at the nozzle exit, and
- $\rho_N =$ density of ambient air.

Also shown on Figure 12 is a red horizontal line corresponding to 4% by volume (LFL) of hydrogen. The dashed line represents the similarity law for concentration decay in infinite 2D jets [33]:

$$y_{H_2} = 2.13 \cdot (D/x) \cdot (\rho_N/\rho_S)^{0.5} \tag{3}$$

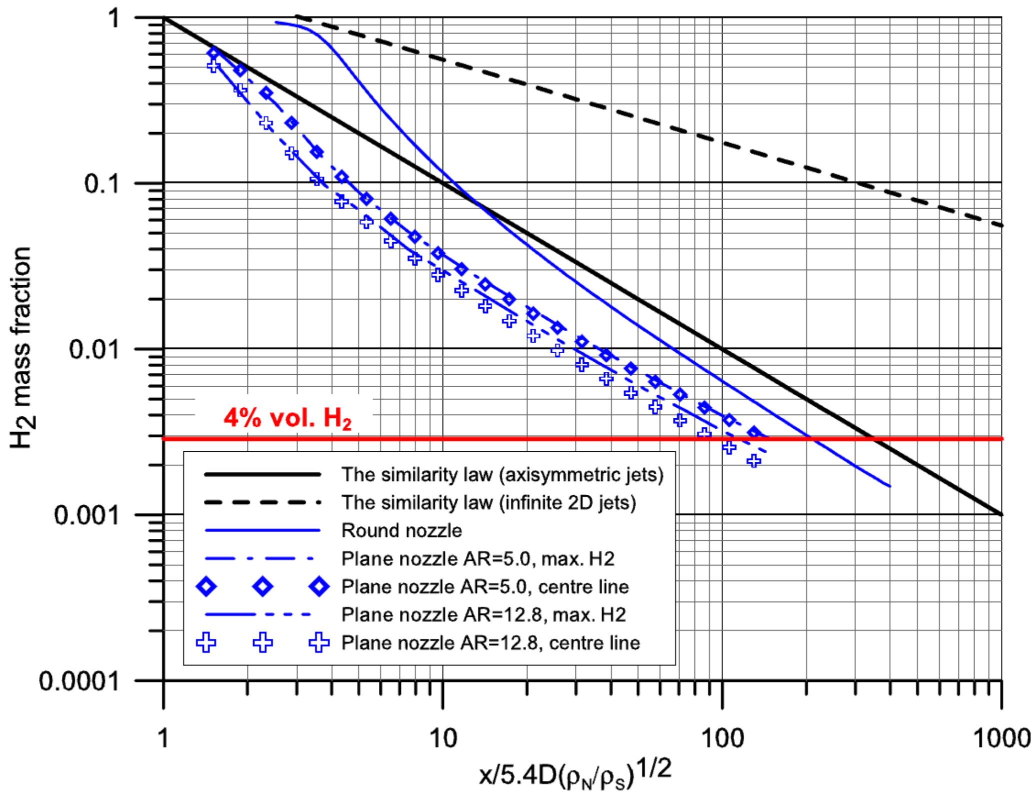

Figure 12. Simulated hydrogen mass fraction decay compared to similarity law for under-expanded jets [30,33]

In order to produce this graph the data is presented as a function of a non-dimensional coordinate $\bar{x}$.

$$\bar{x} = x/5.4 \cdot D \cdot (\rho_N/\rho_S)^{0.5} \tag{4}$$

Therefore the similarity law for the asymmetric jet can be written as:

$$y_{H_2} = 1/\bar{x} \quad (5)$$

Similarly, the 2D similarity correlation takes the following form:

$$y_{H_2} = 2.13/(5.4)^{0.5}(\rho_N/\rho_S)^{0.25}(1/\bar{x})^{0.5} \quad (6)$$

It should be noted that hydrogen densities obtained in CFD simulations at the nozzle exit are affected by frictional losses along the nozzle walls. Therefore, the use of analytically calculated densities in (2) and (3) may lead to a maximum difference of ±4% compared to densities obtained from the CFD simulations undertaken.

The results from the simulations showed that the onset of the incompressible flow regime (assumed at M ≤ 0.33) occurred at x ≈ 0.25 m for the round nozzle jet, at x ≈ 0.12 m for the plane nozzle jet with AR = 5.0 and at x ≈ 0.10 m for the plane nozzle jet with AR = 12.8. These results refer to $\bar{x}$ ≈ 12.6, 6.0 and 5.0 respectively (Figure 12).

From the Figure 12 when comparing the plotted results from (2) and (3) the concentration decay due to the entrainment of air in the infinitely long 2D jet (shown by the dashed black line) is less intensive than the axisymmetric jet (solid black line). However when comparing the results obtained from the simulations the opposite trend was encountered. The hydrogen concentration decay from the finite aspect ratio plane jet nozzle simulations was significantly faster than from both the round nozzle jet simulation and the similarity law for axisymmetric jets. This behaviour may be explained following a consideration of the differences in the jet profiles of the plane nozzles and round nozzle. When considering the plane nozzles a wider flattened hydrogen distribution profile develops during the switch-of-axis phenomenon. This provides a larger mixing area per unit mass flow rate, when compared to the jet from the round nozzle with the equivalent area and therefore may explain the faster rate of concentration decay in the plane nozzle cases.

The results shown on Figure 12 also demonstrates that hydrogen concentration decay in the round nozzle jet is faster than the decay rate predicted by the similarity law for axisymmetric jets. A grid convergence study was undertaken to exclude the possibility of numerical error as a potential reason for this result. Following this study centreline concentration decay rates, obtained for the round nozzle jet, using both the courser and finer grids were found to be identical. Finally, following Ouellette et al. [34], the influence of changing the value of the k-ε turbulence constant $C_{\varepsilon 1}$ was also investigated. The value of $C_{\varepsilon 1}$ was increased from 1.44 to 1.52. This led to a larger hydrogen concentration, for the higher value of $C_{\varepsilon 1}$. However the centreline hydrogen concentration distribution from both constants ran parallel to each other and the concentration decay rates were identical.

3.3 Concluding remarks

During this investigation simulations were carried out on non-reacting under-expanded hydrogen jets emanating from three different nozzles. Each nozzle had the same cross-sectional area. This work investigated the subsequent differences in the structure of the jets produced. CFD simulations were performed using a two-stage procedure, where the compressible solver was applied to the near-to-nozzle region and then the incompressible solver was applied to the far-from-nozzle region. Following this, the developed modelling technique was applied to the experiments reported by Mogi et al. [29].

The results from the simulations undertaken revealed that the longest flammable envelope was produced by the round nozzle jet, reaching around 4.1 m downstream. In contrast the plane nozzle jets produced much shorter flammable envelopes, the plane nozzle with AR = 5.0 reached 2.8 m downstream and the plane nozzle with AR = 12.8 reached 2.3 m downstream. For AR=12.8

flammable envelop shortened 1.8 times compared to circular nozzle where AR=1. When compared to the similarity law for under-expanded axisymmetric jets, the simulated hydrogen concentrations in the far-field were lower. However simulated concentration decay rate was faster. Additionally, the hydrogen concentration decay rate, when considering the plane jets, was closer to the similarity law for axisymmetric jets than for an infinite 2D jets. The results can be applied to design a PRD suitable for on-board hydrogen storage.

4 Conclusions and recommendations

PRD and TPRD tests for hydrogen systems are derived directly from LPG vessel and PRD specifications. LPG specifications were extended and modified for the use of hydrogen. The introduction of ANSI HPRD 1 brought together materials and conditions testing of PRDs. Before the introduction of ANSI HPRD 1, the standards relating to PRDs and TPRDs were spread across many standards and referred to LPG PRD standards. ANSI HPRD 1 includes tests that were not previously specified in hydrogen standards such as vibration and drop testing of the PRDs themselves.

SAE J2579 addressed concerns from the hydrogen community regarding the activation of TPRDs on type 3 and 4 composite vessels. The use of composite materials will rise with the use of increased hydrogen pressures of up to 700 barg. Localised and extended bonfire tests were introduced to show the ability of a TPRD to prevent composite tank rupture.

ANSI HPRD 1 is heavily referenced in SAE J2579 for PRD advice and specifications. The design qualifications tests required by ANSI HPRD 1 can all be carried out by manufacturers or test houses to register a product for the standard. Both ANSI HPRD 1 and SAE J2579 indicate that regular inspections of the PRD devices will be required for in-service vehicles.

The gap analysis of the standards found two areas of potential concern: the rate of release of hydrogen from a TPRD and the in service inspections of PRDs and TPRDs.

- Concern 1: Hydrogen vessels are pressurised from 350 to 700 barg with hydrogen. In the event of a release from the TPRD it is possible that a gas cloud could form and be ignited especially in high risk areas such as tunnels and underground parking lots. Standards literature does not recommend a safe release rate for a TPRD release.
- Concern 2: In service inspections and replacement of TPRDs and PRDs. Road and environmental conditions will degrade TPRDs and PRDs. Both ANSI HPRD 1 and SAE J2579 indicate the need for in-service checks of TPRDs and PRDs to ensure on-going safety. However the timing for the inspections and replacement of PRDs and TPRDs is not covered by the current literature. With an average vehicle's lifetime being 100,000 miles, the TPRDs and PRDs will require maintenance.

Hydrogen PRDs in the open market have a varying amount of testing information available. Only one TPRD currently on the open market specifies it has been tested to the new ANSI HPRD 1 standard. All TPRDs include information on working pressures and burst temperatures in their literature.

ANSI HPRD 1 has provided a clear testing regime for PRDs and TPRDs including materials and conditions testing which was previously scattered throughout several hydrogen standards. The introduction of ANSI HPRD and SAE J2579 has filled many specification gaps which were identified by the hydrogen community. Two gaps have been identified in the current specifications: the rate of hydrogen release from PRDs and the in service inspection and replacement of PRDs schedules.

Recommendations on harmonized methodology for testing PRD

It is recommended that the hydrogen standards community continue to work on vehicle standards to incorporate inspections of TPRDs and PRDs. Clear and concise timetables and instructions are required for TPRD and PRD inspection and replacement regimes. HSE also recommends that the hydrogen community propose a research topic to investigate the possible safety effects arising from an ignited TPRD release. UU suggest to use PRD design with plane nozzle, with AR=12.8. In addition UU would like to suggest carrying out bonfire tests on tanks fitted and not fitted with PRDs. These recommendations are to be implemented and analysed further by the partners.

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TPRD and PRD manufacturers

Appendix A

Circle Seal controls 8100 IC

Table 2. 8100 series Pressure Relief Device (Circle-seal.com, n.d.)

TPRD properties	
Type approval	Non stated
Pressure rating	Operating 0-5,000 psig (0-345 barg)
Compatible gas	Hydrogen , Natural gas, Air, Carbon Monoxide, Helium, Hydrogen
Flow	90 SCFM of air at 100 psid Cv=1.1
Thermal relief temperature	Nominal at 104 °C
Type	Thermal temperature activated PRD
Material	Nickel- plated brass (standard) or 316 stainless steel , Buna N O-ring, PTFE backup ring
Leakage	Internal : zero until actuation External: zero
Other features	Does not rely upon the thermal eutectic material

Emcara Gas Development Inc.

Table 3. COBRA single trigger PRD (Emcara, n.d.)

TPRD properties	
Type approval	PRD 1 and ISO1550. Hydrogen or customer specific versions, if different, can be certified in 1-2 months to these standards or others.
Pressure rating	3600 psi nominal for CNG , 350 Barg (5000 psi) for hydrogen
Compatible gas	CNG, Hydrogen (approval pending)
Activation temperature	110 °C
Activation Time	30 seconds
Flow rate	85 – 350 SCFM
Type	Temperature activated PRD

Minimum exposure length	15 cm
Body size	37 mm * 51mm * 51mm
Tank Thread (End boss version)	1 1/8” (larger versions possible)
Other features	Patented “long trigger” technology allows a single device to protect a tank that would otherwise require multiple PRDs. The high flow rate, long trigger and fast activation can protect large type 3 and type 4 tanks with a single device

Graveco

Table 4. Type 833 Hydrogen TPRD Gaveco (Stockholm, n.d.)

PRD properties	
Type approval	EHIP draft regulation
Pressure rating	440 Barg MAX
Compatible gas	Hydrogen
Activation temperature	110°C
Activation Time	Not available
Flow rate	Available on literature as graph
Type	TPRD
Minimum exposure length	Not available
Body size	70 mm
Tank Thread (End boss version)	Parallel thread
Other features	Can be equipped with a temperature sensor States EHIP draft regulation in literature

PRD Hy-lok

Table 5. Properties of Hy-lok Hydrogen PRV (Hy-lok, n.d.)

PRD properties	
Type Approval	Non stated
Pressure rating	5075 psig (35Mpa)

Temperature range	-40°C to 85°C
Type	Inline Pressure relief Valve (PRV)
Other features	Back Stopped Poppet EPDM Seat Design Indicator Ring: for easily identifying the cracking pressure

Witt- Gasetechnik SV 811L

Table 7. Witt-Gasetechnik GMBH & CO KG, SV 811L Pressure relief valve

PRD properties	
Type approval	Regulation (EC) No. 79/2009 (EC) No 406/2010
Pressure rating	4.5 – 45.0 Barg
Compatible gas	Hydrogen
Temperature range	-40 °C / 85 °C
Type	Spring loaded direct acting pressure relief valve for hydrogen powered motor vehicles
Material	Housing and turned parts made of stainless steel 1.4404 Pressure spring made of stainless steel 1.4310 Valve seal EPDM
Adapter	For connection to ventilation pipe at the outlet 900 Barg
Burst pressure of housing	Heavy duty version (model SV811) 1600 Barg
Other features	N/A