# SAFETY ASSESSMENT OF UNIGNITED HYDROGEN DISCHARGE FROM ONBOARD STORAGE IN GARAGES WITH LOW LEVELS OF NATURAL VENTILATION

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## ABSTRACT

This study is driven by the need to understand requirements to safe blow-down of hydrogen onboard storage tanks through a pressure relief device (PRD) inside a garage-like enclosures with low natural ventilation. Current composite tanks for high pressure hydrogen storage have been shown to rupture in 3.5-6.5 min in fire conditions. As a result a large PRD venting area is currently used to release hydrogen from the tank before its catastrophic failure. However, even if unignited, the release of hydrogen from such PRDs has been shown in our previous studies to result in unacceptable overpressures within the garage capable of destroying the structure. Thus, to prevent collapse of the garage in the case of a malfunction of the PRD and an unignited hydrogen release there is a clear need to increase blow-down time by reducing PRD venting area. Calculations of PRD diameter to safely blow-down storage tanks with inventories of 1, 5 and 13 kg hydrogen are considered here for a range of garage volumes and natural ventilation expressed in air changes per hour (ACH). The phenomenological model is used to examine the pressure dynamics within a garage with low natural ventilation down to the known minimum of 0.03 ACH. Thus, with moderate hydrogen flow rate from the PRD and small vents providing ventilation of the enclosure there will be only outflow from the garage without any air intake from outside. The PRD diameter, which ensures that the pressure in the garage does not exceed a value of 20 kPa (accepted in this study as a safe overpressure for civil structures) was calculated for varying garage volumes and natural ventilation (ACH). The results are presented in the form of simple to use engineering nomograms. The conclusion is drawn that PRDs currently available for hydrogen-powered vehicles should be redesigned along with a change of requirements for the fire resistance rating of onboard storage as hydrogen-powered vehicles are intended for garage parking. Regulation, codes and standards in the field should address this issue.

## 1.0 NOMENCLATURE

| | | | |
|---|---|---|---|
| A | vent area ($m^2$) | **Greek** | |
| C | coefficient of discharge | $\gamma$ | ratio of specific heat ratio |
| $\dot{m}$ | mass flow rate (kg/s) | $\rho$ | density ($kg/m^3$) |
| m | mass (kg) | **Subscripts** | |
| M | molecular mass (kg/mol) | atm | Atmospheric |
| n | number of moles | encl | Enclosure |
| P | pressure (Pa) | hr | Hour |
| $P_0$ | ambient pressure (Pa) | nozz | Nozzle |
| Q | volumetric flow rate ($m^3/s$) | s | Second |
| R | universal gas constant = 8.314472 (J/K·mol ) | vent | Vent |
| T | temperature (K) | **Acronyms** | |
| $T_o$ | ambient temp. (K) | ACH | Air Change per Hour |
| t | time (s) | CFD | Computational Fluid Dynamics |
| V | volume ($m^3$) | PRD | Pressure Relief Device |

## 2.0 INTRODUCTION

The use of fuel cell and hydrogen (FCH) technologies is becoming more widespread and they will soon form an essential part of our built environment. The reasons for this growth are numerous and include concerns over scarcity of fossil fuel, energy security, green house gas emissions, quality of life, and climate change. Emerging FCH technologies are vital and there is a need for a safety level at least the same as those in existing fossil fuel applications. This will help ensure public acceptance of the technologies.

The number of hydrogen-powered vehicles in use worldwide is growing, and commercialisation is fast approaching a reality. As we build on demonstration projects and the number of vehicles increases, it becomes important to consider practical scenarios and issues which may arise with day to day use of such vehicles. For example, necessary indoor use e.g. material handling, forklifts etc. or parking of these vehicles i.e. in a garage or car park. By understanding the hazards arising due to placement of hydrogen-fuelled vehicles in confined environments, steps can be taken towards reduction of associated hazards and risks by inherently safer design. In the majority of passenger cars hydrogen is commonly stored as a compressed gas in tanks. Typical storage pressures for vehicle tanks are in the region of 350 bar and this is being increased further to 700 bar. The inventory of hydrogen varies with the size of the vehicle e.g. 1 kg in the case of smaller two seater cars [1] and, according to the US Department of Energy, onboard hydrogen storage in the range of approximately 5–13 kg is required to enable a driving range of greater than 300 miles for the full platform of light-duty automotive vehicles using fuel cell power systems [2].

Onboard hydrogen storage tanks are required by regulation to be equipped with pressure relief devices (PRDs) [3]. These are fitted to the fuel tank and function by releasing the fluid in the event of an abnormally high temperature, e.g. in conditions of fire. Current PRDs provide rapid release of the hydrogen, thus minimising the possibility of catastrophic failure of the tank during exposure to fire (composite vessels are made of materials that cannot stand fire long, i.e. plastic liner reinforced by carbon fibre). Type 4 tanks have been shown to rupture within 3.5–6.5 min in fire [4]. Existing PRDs intend to vent the hydrogen before this catastrophic rupture occurs preventing disastrous explosions. High mass flow rates from PRDs are probably "acceptable" outdoors, where the buoyancy of hydrogen is an advantage in aiding dispersion below the lower flammability limit. However, limited information is available on the hazards resulting from a rapid release indoors and is the subject of this study.

It is well-known that the release and dispersion of hydrogen in an enclosure can favour its accumulation and formation of a flammable hydrogen-air mixture. Small hydrogen releases and dispersion into confined spaces have been partially examined, e.g. by work performed within the HySafe [5] and HYPER [6] projects.

From a safety perspective a number of hazards arise following a high mass flow rate release, characteristic for current PRDs, in a confined space containing a vent. The specific phenomenon of interest addressed in this work is the over-pressure development within the enclosure due to an unignited release.

Preliminary work on this topic by the authors [7] focused on a hypothetical scenario, with a constant mass flow rate release. In this preliminary work [7] the phenomenon of "pressure-peaking" following the unignited release of hydrogen through a "typical" PRD (diameter 5.08 mm) in an enclosure with a small vent was discovered and explained. In [7] it was demonstrated, how for a constant release of 0.39 kg/s of hydrogen into a 30.4 $m^3$ garage with a single vent the size of one brick the overpressure within the enclosure resulting from the injection of hydrogen reaches a level of 10-20 kPa, capable of destroying the garage, within only 2 s. The high volumetric flow rate of hydrogen results in these significant overpressures even without combustion. It was demonstrated for the chosen scenario that if the enclosure does not rupture first, the pressure within the garage, reaches a maximum level in excess of 50 kPa for 350 bar storage and 100 kPa for 700 bar. This maximum pressure then drops off and tends towards a steady state value, an order of magnitude lower, and equal to that predicted by the simple steady state estimations [7]. A phenomenological model has been developed, and compared with CFD simulations to predict the pressure dynamics within an enclosure. Figure 1, adapted from [7], illustrates the average overpressure in a 30.4 $m^3$ garage with time, for a constant mass flow release from 350 bar storage, through a 5.08 mm diameter PRD. The garage is assumed to have a single vent equivalent in area to a brick (100 mm X 250 mm). Hydrogen, methane and propane are considered and it is clear from Fig. 1 that unacceptable levels of overpressure above 10-20 kPa are reached within a short timeframe of 1-2 s. It is also illustrated in Fig. 1 that this phenomenon is not evident with other, heavier, fuels.

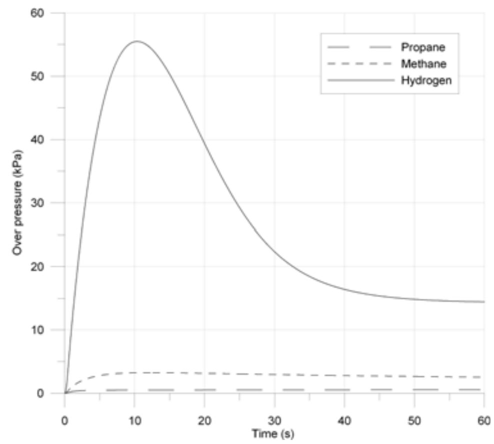



Figure 1. Pressure dynamics in a 30.4 $m^3$ garage, with a single vent, for a constant mass flow release of hydrogen, propane and methane, from 350 bar storage through a 5.08 mm diameter.

Clearly the situation presented in Fig. 1 is undesirable and efforts should be taken to ensure that a release through a PRD in a garage-like enclosure does not result in such destructive overpressures. Increased ventilation or a larger garage will result in a lower overpressure but the onus should not be on e.g. the vehicle owner to park or use the vehicle in a suitable location. Instead the tank and PRD should be designed to be inherently safer.

The work presented here discusses "safe" PRD diameters for enclosures of different volumes with different natural ventilation levels, and builds on [7]. The theory for underexpanded jets and a blow-down model developed at the University of Ulster [8] are utilised to analyse the pressure dynamics within garage-like enclosures.

## 3.0 PROBLEM DESCRIPTON

A range of scenarios are investigated whereby a hydrogen release, from a PRD, is considered in a garage type enclosure with limited ventilation. The hypothetical events involve releases from typical onboard hydrogen storage tanks at pressures of 350 and 700 bar. Inventories of 1, 5 and 13 kg of hydrogen at each storage pressure are considered. The release is assumed to occur in a garage with a vent, the volume of the garage and the size of the vent are varied. Free garage volumes of 18, 25, 30 and 46 $m^3$ were chosen to be representative of small, medium and large residential garages [9]. A range of vent sizes were considered for each volume. The vent sizes were calculated to correspond to Air Change per Hour (ACH) values as described in Section 4. ACH values of 0.18, 0.3, 0.54 and 1 characteristic of residential garages [9, 10], and a value of 0.03 that is extremely conservative (it is the lowest measured value and representative of a worst case scenario [9]) are chosen for calculations. It should be stressed that although the value of 0.03 is low, this value and the others chosen are all based on real world data. Values of 0.54 may seem small but are indeed representative.

## 4.0 METHODOLOGY

A phenomenological model [7] has been used in combination with models for an underexpanded jet and blow-down [8] to examine the pressure dynamics for a range of release scenarios in a garage. For each combination of storage pressure, storage inventory, ACH and garage volume, a "safe" diameter was determined which ensures the pressure in the garage during a release does not exceed 20 kPa. The blow-down time from initial storage pressure down to values of 100 bar, 50 bar, 20 bar, 10 bar, 1 bar and 0.1 bar storage pressure were then determined for each "safe" diameter. It is undesirable for the tank to fail while the pressure inside is still high. If the PRD diameter is reduced the tank will take longer to blow-down, and hence the storage pressure remains higher for longer. Thus the blow-down times through the "safe" diameters could be used to give an indication of "ideal" fire resistance rating of the hydrogen storage tanks.

### 4.1 Phenomenological model of hydrogen pressure-peaking phenomenon in a vented enclosure

In previous work [7] a constant mass flow rate release through a PRD was assumed in calculations. At the steady state, when hydrogen fully occupies the enclosure, $\dot{m}_{vent} = \dot{m}_{nozz}$ i.e. the mass flow into the enclosure $\dot{m}_{nozz}$ (i.e. the mass flow of hydrogen through the PRD) equals the mass flow out $\dot{m}_{vent}$. Simple models such as the orifice equation (1) for a subsonic regime [11] and Bernoulli's equation (2) (assuming zero velocity in the enclosure) can be used to estimate the steady state over-pressure within the enclosure fully filled with hydrogen. The pressure is deemed sufficient in this work to ensure that there is forced convection through the vent, and the effects of natural convection are negligible by comparison. In the below equations A is the area of the vent, C is the vent discharge coefficient, P denotes pressure, ρ is density, in this case the density at the vent is taken as the density of hydrogen in air under atmospheric conditions.

$$\dot{m}_{vent} = CA\left\{\left(\frac{2\gamma}{\gamma-1}\right)P_{atm}\rho_{vent}\left[\left(\frac{P_{atm}}{P_{encl}}\right)^{\frac{2}{\gamma}} - \left(\frac{P_{atm}}{P_{encl}}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{\frac{1}{2}} \quad (1)$$

$$P_{encl} - P_{atm} = \frac{\rho_{vent}\left(\frac{\dot{m}_{nozz}}{\rho_{vent}A}\right)^2}{2} \quad (2)$$

For the case of a release from 350 bar, and the assumption that density in the vent is equal to 0.09 kg/m$^3$, Eqs. (1) and (2) predict an over-pressure in the enclosure of 5.4 and 5.7 kPa respectively for a discharge coefficient C=1 and increase by a factor of three to 17.9 and 15 kPa respectively when C =0.6 for the vent [12], with the ratio of specific heats of $\gamma$=1.4 applicable to two-atomic gases.

However, neither Eq. (1) or (2) accounts for the injection of a lighter gas (hydrogen) into a heavier gas (air) after the start of the release, and the corresponding higher inflow volumetric rate compared to outflow rate in the beginning of the process. Thus, the following system of equations is used to predict the development of the over-pressure within the enclosure with time in the assumption of a perfect stirred reactor (perfect mixing of each released fraction of hydrogen with a mixture already available within the garage)

$$m_{encl}^{t+\Delta t} = m_{encl}^{t} + \left(\dot{m}_{nozz}^{t} - \dot{m}_{vent}^{t}\right)\Delta t, \quad (3)$$

$$n_{encl}^{t+\Delta t} = n_{encl}^{t} + \left(\frac{\dot{m}_{nozz}^{t}}{M_{H_2}} - \frac{\dot{m}_{vent}^{t} n_{encl}^{t}}{m_{encl}^{t}}\right)\Delta t, \quad (4)$$

$$P_{encl(t_{a+1})} = \frac{n_{encl}^{t+\Delta t} RT}{V}, \quad (5)$$

$$\dot{m}_{vent}^{t+\Delta t} = C \cdot \left( \frac{m_{encl}^{t+\Delta t} A}{V} \right) \cdot \left( \frac{2\left(P_{encl}^{t+\Delta t} - P_0\right)V}{m_{encl}^{t+\Delta t}} \right)^{1/2} . \quad (6)$$

### 4.2 Accounting for hydrogen blow-down

The model [8] was used to simulate blow-down of hydrogen from the storage tank. This model takes into account the under-expanded jet theory given in the same work [8] and can be used to calculate decay of pressure and mass flow rate during a release from a storage tank of known volume through an orifice of known diameter. The heat transfer during blow-down was not accounted for; an isothermal approach which assumed a temperature of 288 K was used based on available experimental data for blow-downs at such pressures through orifices of similar size. A validation of this approach is given in [8]. For a given diameter, storage pressure, and hydrogen inventory, the output of the blow-down model (mass flow rate) was used as an input to the phenomenological model to predict overpressure in a garage with a known volume and ACH.

### 4.3 Air Change per Hour

In order to make this work more widely applicable, steps were taken to relate garage volume and vent areas to ACH. However, whilst values of ACH characteristic of residential garages can be found in the literature [9, 10] there was some uncertainty as to how ACH could be translated to vent area for a specific volume. ACH is defined as the volumetric air flow rate per hour, $Q_{hr}$ ($m^3$/hr) per unit volume, V ($m^3$) as

$$\text{ACH} = Q_{hr}/V. \quad (7)$$

Bernoulli's equation can be used to express volumetric flow rate per second $Q_s$ as a function of vent area, A, density of air, ρ, and pressure differential between the volume (e.g. garage) and the atmosphere, ΔP i.e.

$$Q_s = CA\sqrt{2\Delta P / \rho} \quad (8)$$

In Equation 8 the value of ΔP, i.e. the pressure differential assumed between the interior and exterior of the enclosure will obviously have an influence on the vent area calculated for a given ACH, the larger the "standard" ΔP, the smaller the corresponding vent area for a given volume and given ACH. A value of 50 Pa was chosen for ΔP in the majority of this work. This was chosen as "n50" is a standard measurement to determine the air leakage rate in a residential buildings, which is calculated based on a pressure difference of 50 Pa [13]. However, a pressure difference of 5 Pa was also used for comparison in the case of 5 kg of hydrogen at 350 bar. This was included to demonstrate the sensitivity of the calculations to the method chosen for calculating ACH. In Eq. 8, the discharge coefficient C was taken as the commonly recommended C=0.6 [12].

## 5.0 RESULTS

Scenarios for garages of free volumes of 18, 25, 30 and 46 $m^3$ were considered [9], and for each volume a vent size corresponding to an ACH of 0.03, 0.18, 0.3, 0.54 and 1 [9, 10] were calculated as described in Section 4.3. It should be stressed that these ACH values are based on real world measurements. The corresponding vent sizes are given in Table 1, note this is based on the assumption of a single "accumulated" vent. In the following sections ACH is calculated based on ΔP = 50 Pa unless otherwise stated.

A "safe" diameter was calculated for each inventory of hydrogen (1, 5 and 13 kg) for each volume and ACH value considered. The safe diameter is taken as that PRD diameter which results in an overpressure no greater than 20 kPa (and no less than 15 kPa) for a chosen volume and ACH. This overpressure is calculated by first calculating the mass flow rate decay from a tank for a specific inventory and diameter (the “safe” diameter in this case), the mass flow rate decay data is used as an input to the phenomenological model to predict overpressure in the garage based on the garage volume and vent area, where vent area is calculated from ACH. Figure 2 gives the pressure dynamics for a release of 5 kg of hydrogen at an initial storage pressure of 350 bar, in a garage of volume 30 $m^3$ with an ACH of 0.18. The figure shows the pressure dynamics for a currently typical PRD diameter of 5 mm compared with the dynamics for the “safe” diameter, found to be 0.55 mm in this case. From Fig. 2 it is demonstrated that for this specific case the PRD diameter should be reduced by an order of magnitude compared with a “typical” PRD diameter. If the storage pressure is increased, the ACH is reduced, the volume of the garage is reduced or the inventory of hydrogen is increased then this diameter would need to be decreased still further.

Table 1. Vent area for each volume and ACH considered

| **Free volume of garage ($m^3$)** | **ACH** | **Vent size ($m^2$) n50** | **Vent size ($m^2$) ΔP = 5Pa** |
|---|---|---|---|
| 18 | 0.03 | 2.74E-05 | 8.66025E-05 |
| | 0.18 | 0.000164317 | 0.000519615 |
| | 0.3 | 0.000273861 | 0.000866025 |
| | 0.54 | 0.00049295 | 0.001558846 |
| | 1 | 0.000912871 | 0.002886751 |
| 25 | 0.03 | 3.8E-05 | 0.000120281 |
| | 0.18 | 0.000228218 | 0.000721688 |
| | 0.3 | 0.000380363 | 0.001202813 |
| | 0.54 | 0.000684653 | 0.002165064 |
| | 1 | 0.001267876 | 0.004009377 |
| 30 | 0.03 | 4.56E-05 | 0.000144338 |
| | 0.18 | 0.000273861 | 0.000866025 |
| | 0.3 | 0.000456435 | 0.001443376 |
| | 0.54 | 0.000821584 | 0.002598076 |
| | 1 | 0.001521452 | 0.004811252 |
| 46 | 0.03 | 7E-05 | 0.000221318 |
| | 0.18 | 0.000419921 | 0.001327906 |
| | 0.3 | 0.000699868 | 0.002213176 |
| | 0.54 | 0.001259762 | 0.003983717 |
| | 1 | 0.002332892 | 0.007377 |

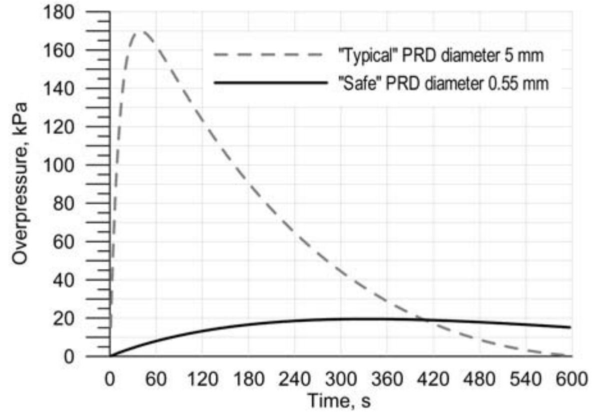
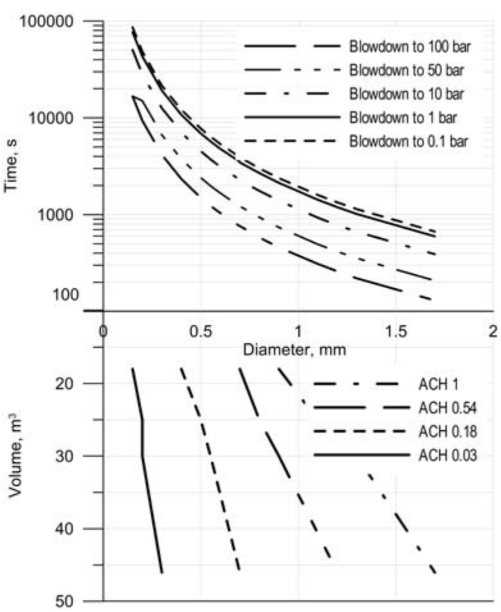



Figure 2. Pressure dynamics in a 30 $m^3$ garage, ACH = 0.18, 5 kg of hydrogen at 350 bar, diameters of 5 mm and 0.55 mm.

In each case the calculated "safe" diameter is significantly smaller than values typical of current PRDs. The smaller diameter means that the hydrogen takes longer to blow-down from the tank and thus the tanks should have an improved fire resistance. The time taken for the tank to blow-down through a safe diameter to pressures of 100 bar, 50 bar, 10 bar, 1 bar and 0.1 bar were calculated for guidance. Figures 3 and 4 below are nomograms for the examples of 5 kg of hydrogen at initial pressures of 350 bar and 700 bar respectively. The "safe" diameter can be estimated from the lower half of the graph by reading horizontally across from the chosen volume until intersecting with the chosen ACH value, then read vertically up from this point of intersection to the x axis. The point of intersection with the x axis is the "safe" diameter for the chosen ACH, volume, inventory of hydrogen and storage pressure. Reading vertically up from the x axis to the point of intersection with the pressure curves can be used as a means to estimate blow down time to that pressure for the "safe" diameter.



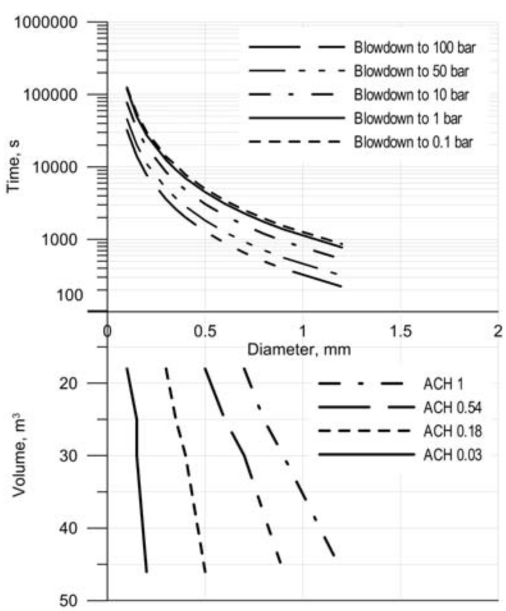




Figure 3. Nomogram for 5 kg hydrogen at 350 bar. Figure 4. Nomogram for 5 kg hydrogen at 700 bar.

From Figs. 3 and 4 it can be seen that the “safe” diameter is significantly smaller than “typical” PRD diameters currently used. It can also be seen that for lower ACH values the blow-down time through a “safe” diameter is several hours. This is currently an unrealistic requirement for fire resistance rating and thus more innovative approaches should also be taken for PRD and tank design.
Figures 5, 6 and 7 represent nomograms for calculating the “safe” diameter for 1 kg, 5 kg and 13 kg of hydrogen at both 350 bar and 700 bar, the upper half of each graph allows the blow-down time to an overpressure of 1 bar within the tank to be calculated for each storage pressure. It is clear from Fig. 5 that storage tanks with inventories of 1kg do not present the same hazards as larger inventories. Thus smaller vehicles, with 1 kg tanks using “typical” PRD diameters should not cause significant problems in larger garages. As expected, it can be seen from Figs. 5-7 that “safe” diameter decreases and hence blow-down time increases, with increasing hydrogen inventories and increasing storage pressure.

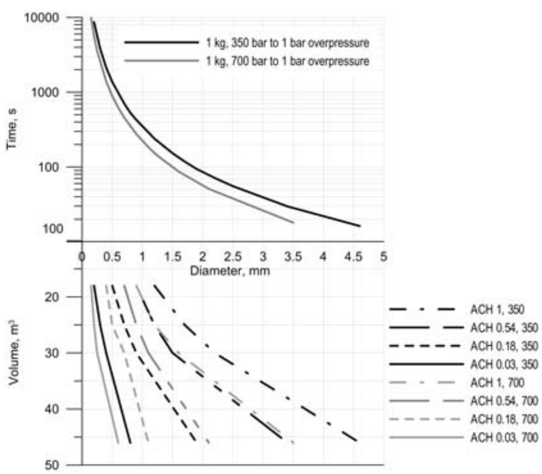



Figure 5. Nomogram for 1kg, 350 and 700 bar.

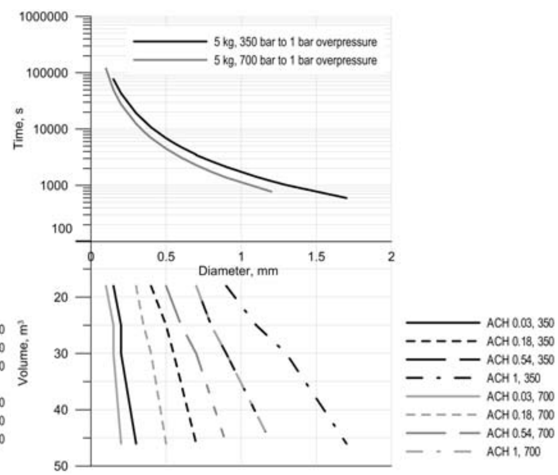



Figure 6. Nomogram for 5 kg, 350 and 700 bar.

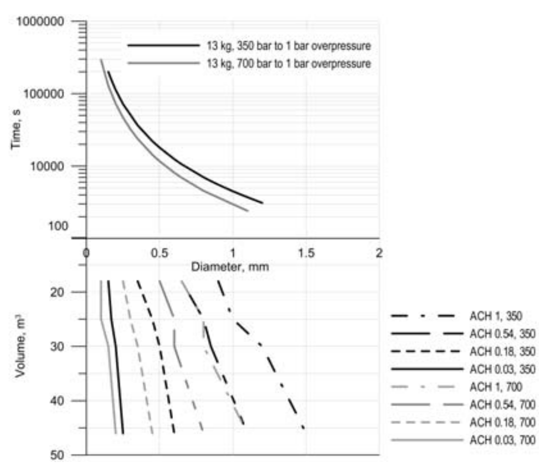



Figure 7. Nomogram for 13 kg, 350 and 700 bar.

As described in Section 4.3, the relationship between vent area and ACH is dependent on the value taken for the pressure difference between the interior and exterior of the enclosure ($\Delta P$). Figure 8 below takes the example of 5 kg of hydrogen at 350 bar, “safe’ diameters and corresponding blow-down time to an overpressure of 1 bar in the tank are compared for the cases of (I) vent area based on

$\Delta P$ = 50 Pa and (II) $\Delta P$ = 5 Pa. It can be seen that how ACH is defined has a significant impact on calculation of "safe" diameter. This would indicate that a clear consensus should be reached for similar applications. It is unclear in e.g. [9] which value of $\Delta P$ should be taken to calculate ACH.

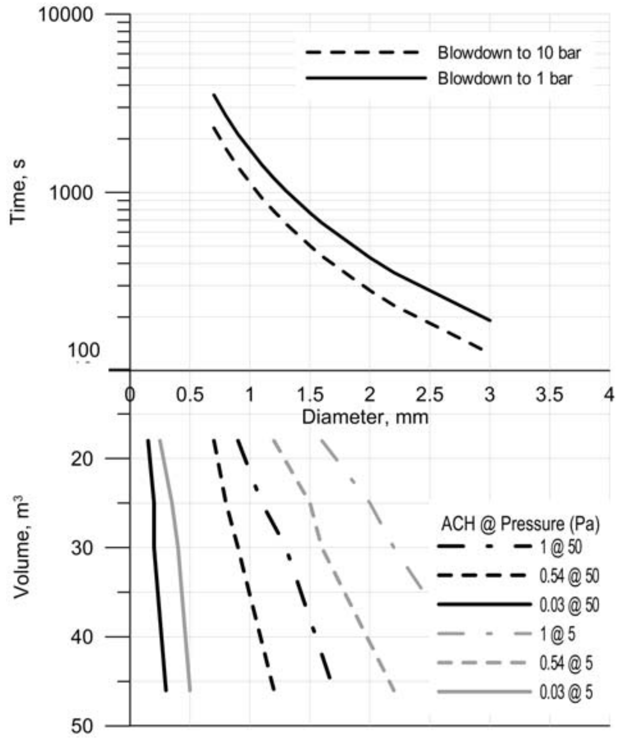



Figure 8. Nomogram for 5 kg of hydrogen at 350 bar, blowdown time to 1 bar overpressure in the storage tank, ACH calculated using $\Delta P$ = 50 Pa and $\Delta P$ = 5 Pa.

## 6.0 CONCLUSIONS

A study has been performed to investigate the relationship between PRD diameter, ACH, and volume for releases in enclosures with a single vent from onboard storage tanks of 1, 5 and 13 kg at 350 and 700 bar.

The phenomenon of pressure-peaking during release of hydrogen in a vented enclosure has been discussed [7] and 'safe" diameters were determined for a range of scenarios. The "safe" diameter was determined as that PRD diameter which would not result in an overpressure exceeding 20 kPa in a garage in the event of a leak.

The phenomenon of pressure-peaking which is unique for a release of hydrogen within a ventilated enclosure, should be accounted for when performing hydrogen safety engineering for indoor use of hydrogen and fuel cell systems and must be reflected in RCS.

Currently approached to fire resistance of onboard storage and parameters of PRDs have a number of deficiencies as follows from this study. On one hand, it is clear that current arrangements, lacking fire resistance of onboard storage, generate unacceptable performance of systems in enclosures if the PRD is activated even with an unignited release. On the other hand, simplified "redesign" of the PRD to protect the garage structure from collapse puts hardly realizable requirements to fire resistance of up to several hours. Further research is needed to develop safety strategies and engineering solutions to tackle the problem of fire resistance of onboard storage tanks and requirements to PRD performance.

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