HYDROGEN Safety Panel

White Paper

Considerations for Ventilation Rates to Mitigate Hydrogen Releases

Purpose

This paper provides an overview of the relationship between hydrogen release scenarios and the ventilation rates recommended by key hydrogen consensus standards/guidance to mitigate hydrogen releases inside buildings and process enclosures. By comparing best practice considerations to currently available ventilation guidance, this paper provides a basis for the Hydrogen Safety Panel to recommend changes to existing standards, highlights the importance of continued research, and potentially forms a basis for development of new standards and guidance.

This paper is based in part on the webinar *AICHE Ventilation Considerations for Hydrogen Safety*, presented by Bob Zalosh, Kelly Thomas, and Will Lowry.[1]

Background and Issue

Many industry standards and guidance documents reference the use of ventilation to mitigate the formation of combustible mixtures of hydrogen within buildings and enclosures. However, current guidance varies and may not protect equipment and personnel in all release scenarios.

National Fire Protection Association (NFPA) 2, *National Hydrogen Code* (2023) [1], specifies the following:

> "Mechanical exhaust or fixed natural ventilation shall be provided at a rate of not less than 1 scf/min/ft^2 (0.0051 m^3/sec/m^2) of floor area over the area of storage or use."[2]

This minimum ventilation rate applies to gaseous or liquid hydrogen "indoor storage and use areas and storage buildings" [3] and was taken from NFPA 55 [2].[4]

Similarly, the Factory Mutual (FM) Global Data Sheet 7-91, *Hydrogen* [3], specifies a minimum ventilation rate of 1 cfm/ft^2 (i.e., same as NFPA 2), combined with "damage limiting construction," for indoor hydrogen equipment rooms. The International Fire Code (IFC) [4] also references that the mechanical ventilation shall be a rate of not less than 1 scf/min/ft^2 (0.0051 m^3/sec/m^2) of floor area over the area of storage.[5]

For a ventilation rate of 1 cfm/ft^2, the vertical air velocity would be 1 ft/min (0.5 cm/s). For horizontal flow, this ventilation rate and a building length-to-height ratio of 10 would give a horizontal air velocity of 10 ft/min (0.05 m/s). To put these values in perspective, the average wind velocity in most locations in the continental United States is roughly 10 mph (880 ft/min, 4.5 m/s), which is approximately 90 times larger than the example horizontal air velocities within an enclosure at a ventilation rate of 1 cfm/ft^2. Hence, releases posing a minor risk outdoors due to rapid dispersion by the wind can be quite hazardous if they occur indoors and are sustained.

[1] https://www.aiche.org/ili/academy/webinars/ventilation-considerations-hydrogen-safety
[2] NFPA 2 (2023), *Hydrogen Technologies Code*, Section 6.18.1.
[3] NFPA 2 (2023), *Hydrogen Technologies Code*, Section 6.18.
[4] NFPA 55, *Compressed Gases and Cryogenic Fluids Code*, Section 6.17.3.2 (2023), Section 6.16.3.2 (2013).
[5] IFC (2021), Chapter 50, 5004.3.1.

Although a prescriptive ventilation rate enables ease of implementation and Authority Having Jurisdiction approval, this method does not consider hydrogen inventory, pressure, accumulation areas, credible leak rate and duration, controls, mitigations, or equipment response time, and therefore the minimum flow rate should not be considered applicable for all installations.

Other standards and regulations specify performance to ensure that ventilation rates provide dilution below a specified concentration of flammable gas. For example:

- The following state that ventilation should be sufficient to dilute leaks to 25% of the lower flammability limit (LFL), which is equivalent to a hydrogen concentration of 1%:
  - U.S. Code of Federal Regulations (29 CFR 1910.106 [5])
  - International Organization for Standardization (ISO) 19880-1, *Gaseous hydrogen – Fueling stations* [6][6]
- Although not specific to hydrogen, the following all have requirements to alarm or maintain a flammable species at below 25% of the LFL:
  - IFC (2021) [4], Chapter 9, Section 916 (916.8 System Activation)
  - International Building Code (IBC) (2021) [7], Chapter 9, Section 916 (916.8 System Activation)
  - International Mechanical Code (IMC) (2021) [8], Chapter 5, Section 502 (502.7.3.3 Air Velocity)
- Chapter 8 of NFPA 69, *Standard on Explosion Prevention Systems* [9], specifies that, for deflagration prevention by combustible concentration reduction, the volume-average fuel concentration shall be maintained at or below 25% of the LFL.[7] Up to 60% of the LFL is allowed if the concentration is continuously monitored and controlled by safety interlocks. This provision explicitly states that it is applicable to "all foreseeable variations in operating conditions and material loadings." The annex of the standard states that this approach "should account for a credible event that could occur during startup, shutdown, or operational upset, such as spillage of the largest single container" and identifies an interlocked supplemental emergency exhaust as a mitigation option.
- ISO 22734, *Hydrogen generators using water electrolysis* [10], requires the use of ventilation to limit concentration to 1% hydrogen "before exiting the enclosure." It also states that, "computational fluid dynamics analysis, tracer gas, or similar methods such as those given in IEC 60079-10-1, *Classification of areas – Explosive gas atmospheres* [11], may be used to determine the 1% volume fraction of hydrogen in air dilution boundary and ventilation requirements."[8]
- International Electrotechnical Commission (IEC) 60079, Part 10-1 [11], Annex B, provides a method to calculate the minimum required ventilation rate based on an expected maximum hydrogen release rate.
- In confined spaces, 29 CFR 1910.146 [5] specifies a hazardous atmosphere as a flammable gas in excess of 10% of its LFL. Accordingly, ventilation for confined space entry must maintain a hydrogen concentration less than 10% of the LFL.

[6] ISO 19880-1 (2020), *Gaseous hydrogen – Fueling Stations*, Section 7.11, Enclosures and buildings containing hydrogen equipment, Section 7.11.3.
7 NFPA 69 (2024), *Standard on Explosion Prevention Systems*, Section 8.3.1.
8 ISO 22734 (2019), *Hydrogen generators using water electrolysis – Industrial, commercial, and residential applications*, Sections 4.1.6.3 and 4.4.1.4.

- NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas* [12], defines "Adequate Ventilation" in 3.3.1 as, "A ventilation rate that affords six air changes per hour, 1 cfm per square foot of floor area (0.3 $m^3/min/m^2$), or other similar criterion that prevents the accumulation of significant quantities of vapor-air concentrations from exceeding 25 percent of the lower flammable limit (LFL)." Paragraph 5.5.2 specifies that certain unclassified locations are considered to have adequate ventilation, including:
  - An outside location
  - A building, room, or space that is substantially open and free of obstruction to the natural passage of air, either vertically or horizontally, could be roofed over with no walls, roofed over and closed on one side, or provided with suitably designed windbreaks
  - An enclosed or partly enclosed space provided with ventilation equivalent to natural ventilation (with adequate safeguards against failure of the ventilation system)

Also different from the standards above, European Industrial Gases Association (EIGA) 15/21, *Gaseous Hydrogen Installations* [13], takes a more generic approach, stating:

> "Ventilation of buildings shall be provided to maintain atmospheres below LEL (lower explosive limit) in the case of minor leaks. Natural ventilation is preferred and should be designed to achieve a certain number of air changes per hour (typically in the range of 6-12 room changes per hour depending on the size of the room."[9]

It is notable that a room with a 10-ft ceiling has an exchange rate of 6 air changes per hour (ACH) when the flow is set to the nominal rate of 1 $scf/min/ft^2$.

The potential danger of using an approach based on the concentration as a volume-average lies with the resolution of averaging over the entire building, room, or enclosure volume. Especially in large installations, there may be significant risk local to the release locations, especially if the same ventilation justification was used to electrically declassify the volume and therefore credible ignition sources are also potentially present.

While all the above standards (and others) reference a maximum allowable concentration in the building or enclosure, they do not always specify how to define a credible release scenario. A potentially hazardous condition can develop if only building, room, or enclosure volume is considered while disregarding leak rate and duration. It is generally accepted that in most instances, ventilation rates are not sufficient to mitigate total loss of containment scenarios; however, the question remains: What size leak should be mitigated by ventilation? As stated in IEC 60079-10-1:2020 [11]:

> "Any assessment of the degree of dilution first requires an assessment of the expected release conditions including the size of the source of the release and the maximum release rate of gas or vapor at the source (see Annex B)."[10]

[9] EIGA 15/21, Section 5.5.2
[10] IEC 60079-10-1:2020, *Explosive atmospheres – Part 10-1: Classification of areas – Explosive gas atmospheres*, Annex C: Ventilation guidance, Section C.3.

Discussion

Determining Appropriate Hydrogen Release Scenarios and Rates

Considerations for evaluating leak potential involve a variety of factors, including phase (gas or liquid), pressure, temperature, inventory available, operational variations, installation environment, fitting/sealing connection type, component count, and more. System maintenance and operations should also be considered, including leak check frequency, methods, and allowable leakage rates. Finally, there needs to be an assessment of what controls are present for detection and mitigation of leaks. All these factors will influence leak rate and duration, which is critical to establishing safe ventilation requirements for the installation.

Given the recent and rapid growth of the hydrogen economy and novel components and systems, historical data on component failure rates is not readily available. Therefore, unlike a well-established industry, credible leak rates for determining ventilation requirements are not well defined in codes, standards, guides, and data sets. It is also important to consider that minimum prescriptive code compliance may not be sufficient for many hydrogen installations.

Some standards applicable to hydrogen systems specify enclosure ventilation rates to accommodate user- or manufacturer-determined hydrogen release rates. For example, ISO 16110-1, *Hydrogen generators using fuel processing technologies – Part 1: Safety* [14], specifies that release rates should be based on leakage testing at 110% of the normal system operating pressure. While this approach validates system integrity, it does not account for or estimate credible leak rates that inevitably occur during operation.

In other codes, credible leak rates are not prescribed and leave it to the manufacturer and/or user to establish without guidance. For example, ISO 22734 (2019), *Hydrogen Generators Using Water Electrolysis* [10], states that ventilation rates shall be based on:

> "the maximum anticipated hydrogen gas leak rate into the enclosure as determined by the manufacturer."[11]

Although ISO 22734 states that sudden and catastrophic failure of vessels or piping systems typically does not need to be considered a leak scenario, no definitive guidance is provided for the manufacturer to establish credible leak rates.

Critical to determining the credible design leak rate is the assumed leak area. Annex B of IEC 60079-10-1 [11] provides valuable guidance on estimating sources of release and release rates, while Annex C provides guidance on ventilation. Detailed information and equations are provided to calculate release rate for assumed hole sizes, and to assess ventilation effectiveness. However, as IEC 60079-10-1 is not specific to hydrogen, generalizations about typical/credible data on hole size are not provided. Also note that because of the flow characteristics and physical properties of hydrogen, flow parameters developed for common hydrocarbons are not directly applicable to hydrogen.

[11] ISO 22734 (2019), *Hydrogen Generators Using Water Electrolysis – Industrial, commercial, and residential applications*, Section 4.4.1.4(e).

NFPA 2 (2023) [1], Annexes E and K, as well as Annex H of NFPA 55 (2023) [2], describe their currently adopted method for establishing leak rates for separation distance and exhaust ventilation rates. Although leak rates used for outdoor separation distances may be logically extended to establish credible leak rates for indoor ventilation, the method for establishing separation distances was based on a fatality risk target of 2×10^{-5} per year, which is consistent with gasoline fueling stations but does not directly relate to the risk of an indoor release. Even so, NFPA 2 (2023), Section K.2.2.2 (Deflagration Prevention by Hydrogen Gas Concentration Reduction) states:

> "the ventilation rate for hydrogen dilution should be based on a hydrogen release rate equal to either the storage pressure and an orifice diameter equal to 3 percent of the diameter (sic)[12] of the largest hydrogen piping or equipment connection, or a risk-based analysis of release rates for the type of hydrogen piping and equipment in the room of building."[13]

Although not directly applicable to gaseous hydrogen, the following standards provide an alternative approach to estimating pressurized system failure rates:

- Canadian Gas Association (CGA) TR-7 (2023), *Methodology to Determine Piping Failure Rates for Nontoxic Cryogenic Industrial Gas Supply Systems with Pipe Size up to 6 inches* [15]
- CGA P-93 (2023), *Guidance for Piping Failure Rates in Nontoxic Cryogenic Gas Supply Systems* [16]

In CGA TR-7, an annualized failure rate is calculated based on the number, type, and size of components and the length and size of pipe in the system. Components are modeled with equivalent lengths and joint types and adjustments are made based on vulnerability due to service conditions and/or location. This methodology requires the user to select a hole size to determine an annual failure rate based on pipe diameter and equipment count. However, a similar approach could be used to select a tolerable failure rate and then calculate the associated leak rate to be mitigated by ventilation for a given system.

While both NFPA 2 and CGA TR-7 prescribe methods that could be used to establish credible leak rates, the methods have not yet been validated against statistically significant data sets from current hydrogen installations.[14] The approaches are based on data for leak frequency and rate taken from a variety of sources in the chemical process, compressed gas, nuclear power, and offshore petroleum industries, which are not specific to hydrogen, and are integrated with no or very limited data specific to hydrogen leakage [17]. The Health and Safety Executive (HSE) Hydrocarbon Release Database[15] is the main source of data for both methods. Although this is an active area of research in the hydrogen industry, leak frequency and rate data has yet to be collected with adequate statistical relevance.

[12] An inconsistency exists in NFPA 2 (2023) between and K.2.2.2.3.2 and E.9.1. K2.2.2.3.2 states that 3% of the diameter should be used to calculate the hydrogen release rate, while E.9.1 calculates effective leak diameter based on 3% of the flow area of the pipe. It is presumed that K.2.2.2.3.2 is in error.
[13] NFPA 2 (2023), *Hydrogen Technologies Code*, Annex K, Section K2.2.2.3.2.
[14] The approach is described and referenced in Annex H of NFPA 55 (2023).
[15] HSE Hydrocarbon Release Database: www.hse.gov.uk/offshore/statistics.

Below are examples of current industry and research efforts to collect statistical hydrogen leak frequency and rate data:

- LaChance et al. [17] performed analysis to support the development of risk-informed separation distances for hydrogen codes and standards. The authors describe leak rate and frequency data sources and the methods used to compile available sources into a single data set with published uncertainty analysis.
- Wang et al. [18] studied faulty double ferrule fittings removed from fuel cell vehicle fueling systems and found a range of crack widths between 57 and 358 μm. The authors decided that the design basis crack sizes for a larger population of hydrogen fuel systems should be 0.5 mm x 0.5 mm and 0.75 mm x 0.75 mm, and they measured and calculated release rates for these cracks as a function of pipe pressure.
- The National Renewable Energy Laboratory (NREL) developed an apparatus to quantify the mass flow rate of hydrogen gas leaking from medium- and high-pressure components that failed while in service. The effective leakage orifice diameter for a leaking air-operated valve was found to be 0.09 mm, while a soft seat check valve with a weep hole leak was found to have a much smaller, yet less correlated, effective diameter [19].
- NREL, in partnership with Sandia National Laboratories, developed a test apparatus and failure investigation approach to study component reliability in hydrogen dispensers [20]. Although their study did not establish leak rates, the authors found that frequency of leaking components was correlated to pre-cooling temperature with physical degradation occurring in polymers due to low-temperature hydrogen exposure.
- NREL, in partnership with the University of Maryland, is developing a database to track hydrogen-specific component failure rates and failure modes (HyCReD) [21]. The objective of this work is to better understand leak behavior and leak size to improve quantitative risk assessments for hydrogen systems.

Given that hydrogen installations vary significantly, credible scenarios for application-specific hydrogen release are usually identified during a risk analysis exercise such as a hazard and operability study (HAZOP). From these identified leak scenarios, the hydrogen release rate and duration can be assessed. For example, in an electrolyzer enclosure, external leaks from components and fittings are expected, especially where exposed to vibration and thermal gradients and stress. The hydrogen release rate for these scenarios is expected to be initially small, and therefore the ~3% effective diameter leak may be considered a high-end approximation of leak rate for this scenario. The release duration would rely on the presence of controls such as gas detection in the enclosure and/or pressure/flow monitoring accompanied by automatic shutdown. Without these controls, the leak would be continuously supplied and likely grow with time, while with detection and shutdown, the leak duration would be limited to the time needed for the system to detect the leak, respond by changing valve states, and depressurize the contained volume in the piping system through the vent (assuming the control strategy is to vent the contained volume in the piping).

Along with validating the effectiveness of the mitigation and controls, appropriate ventilation configuration and flow rate to mitigate the hazard can be assessed. These potential sources of leaks in components and fittings are also applicable to many other applications for compressed gaseous hydrogen. Notably, momentum and buoyancy forces of the release and the atmosphere into which the hydrogen is dispersing should all be considered when establishing risk.

Certain release scenarios and controls are envisioned in guidance documents such as FM Global Data Sheet 7-91 [3]. For situations where hydrogen piping enters an enclosure, the data sheet calls for an emergency shutoff valve located outside the enclosure, interlocked to hydrogen detectors and set to activate at 25% of the LFL. A restricting flow orifice (RFO) outside the enclosure is also specified to limit the maximum flow rate in case of a leak or breach of the piping or associated equipment. In cases where the enclosure volume is less than the damage-limiting building volume (DLBV) for the maximum flow rate allowed by the RFO, emergency ventilation to maintain the volume-average hydrogen concentration below 50% the LFL at the maximum flow rate is recommended, combined with the damage-limiting concentration. The DLBV is based on the maximum possible flow rate, with a flow rate of 2.2 lb_m/min (1 kg/min) corresponding to an enclosure volume of 710,000 ft^3 (20,100 m^3); it is expected that many enclosures of interest would have volumes below the DLBV, and hence require emergency ventilation. In addition to emergency ventilation maintaining the hydrogen concentration below 50% the LFL, the data sheet specifies an emergency ventilation of 2.5 cfm/ft^2 for cases where hydrogen cylinders are present outside gas cabinets.

Calculations for Example Scenarios

Example scenarios have been considered to illustrate the effectiveness of leak and ventilation rate prescriptive values and calculation methods in currently available codes and guidance documents. The simplified calculation results presented in this section emphasize that if currently available codes and calculation methodologies are directly applied without sufficient engineering judgment, the resulting conclusions may lead to significantly under- or over-engineered systems that have serious impacts on safety. Based on technology advancements and scaling of hydrogen system installations, updates to codes and standards guidance to bound the applicability of prescriptive guidance is needed.

The following set of equations, taken from referenced codes, were used in these calculations:

$$d_{leak} = (0.03)^{1/2} d_{pipe(I.D.)} \quad \text{(Eq. 1)}^{16}$$

$$W_{H2} = C_d Sp \sqrt{\gamma \frac{M}{ZRT} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}} \quad \text{(Eq. 2)}^{17}$$

$$Q_{H2} = \frac{W_{H2}}{\rho_{H2}} \quad \text{(Eq. 3)}^{18}$$

$$y_{H2} = {Q_{H2}}/{(Q_{H2} + Q_V)} \quad \text{(Eq. 4)}$$

$$ACH = \frac{Q_V}{V} \quad \text{(Eq. 5)}$$

where:

d_{leak} is the effective leak diameter

$d_{pipe(ID)}$ is the inside diameter of the characteristic pipe

W_{H2} is the mass release rate of gas (kg/s)

[16] NFPA 2 (2023), Annex E, Section E.9, Determination of Separation Distances for Bulk Gaseous Hydrogen Systems, E.9.1, Introduction.
[17] IEC 60079-10-1:2020, Annex B, Section B.7.2.3.3, Release rate of gas with choked gas velocity (sonic releases) Equation B.5.
[18] IEC 60079-10-1:2020, Annex B, Section B.7.2.3.2, Release rate of gas with non-choked gas velocity (subsonic releases) Equation B.4.

C_d is the discharge coefficient (dimensionless), assumed to be 0.75 for an irregular hole

S is the cross section of the opening (hole), through which the fluid is released (m^2)

p is the internal pressure (Pa)

γ is the ratio of specific heats (dimensionless), taken as 1.4 for hydrogen

M is the molar mass of gas (kg/kmol), taken as 2.016 for hydrogen

Z is the compressibility factor (dimensionless) as a function of temperature (assumed to be 20 °C [293.15 K]) and pressure [22]

R is the universal gas constant (8314.5 J/kmol K)

T is the temperature, assumed to be 20 °C

Q_{H2} is the volumetric flow rate of flammable gas from the source (m^3/s)

ρ_{H2} is the gas density at ambient conditions (kg/m^3), taken as 0.08375 kg/m^3

y_{H2} is the hydrogen concentration assuming steady state well-mixed

Q_V is volumetric ventilation flow rate based on the 1 $scf/min/ft^2$ (0.0051 $m^3/sec/m^2$) minimum required ventilation rate

ACH is the air changes per hour within the enclosure or building

V is the volume of the enclosure or building

These equations assume a continuous steady release, an instantaneous well-mixed enclosure (ignoring concentration gradients), and bulk average concentrations. Note that while 3% of the internal area of the pipe was used in this demonstrative calculation methodology, 1% was applied to update separation distances in NFPA 2 (2020 and 2023) as explained in Section E.7, Updates to the Gaseous Hydrogen Separation Tables. The use of these equations is not an endorsement but rather a means to highlight the inconsistency and drawbacks in the current methodologies.

In Figure 1 through Figure 5, the following system pressures, pipe internal diameters, and enclosure / building dimensions were considered:

- System pressure: 150, 450, 2,400, 7,500, and 15,000 psig
- Pipe ID: 0.30, 0.96, 2.90, and 9.56 in. (corresponding to 1/4, 1, 3, and 10-in. schedule 80 pipe)
- Enclosure/building dimensions and corresponding ventilation rate assuming 1 $scf/min/ft^2$:
  - 3x 3 x 3 ft representing a small enclosure, 20 ACH
  - 20 x 8 x 8.6 ft representing a shipping container, 7 ACH
  - 50 x 50 x 40 ft representing a high bay, 1.5 ACH
  - 400 x 100 x 30 ft representing a large building, 2 ACH

Figure 1 through Figure 4 plot the steady-state hydrogen concentration (vol%) as a function of system pressure and nominal pipe size for each enclosure size.

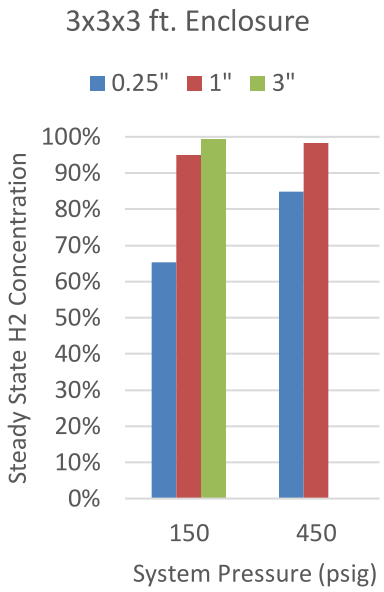


Figure 1. Bulk average steady-state concentration as a function of system pressure and nominal pipe size assuming a 1-scf/min/ft^2 exhaust ventilation rate in a 3 x 3 x 3 ft enclosure (ACH 20) and effective leak diameter of 3% of the flow area of the pipe.

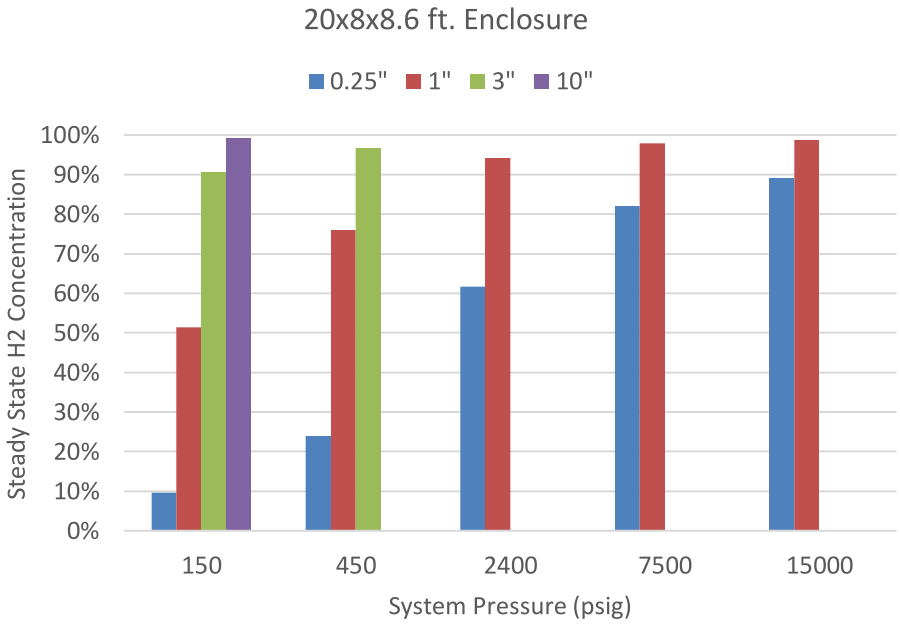


Figure 2. Bulk average steady-state concentration as a function of system pressure and nominal pipe size assuming a 1-scf/min/ft^2 exhaust ventilation rate in a 20 x 8 x 8.6 ft enclosure (ACH 7) and effective leak diameter of 3% of the flow area of the pipe.

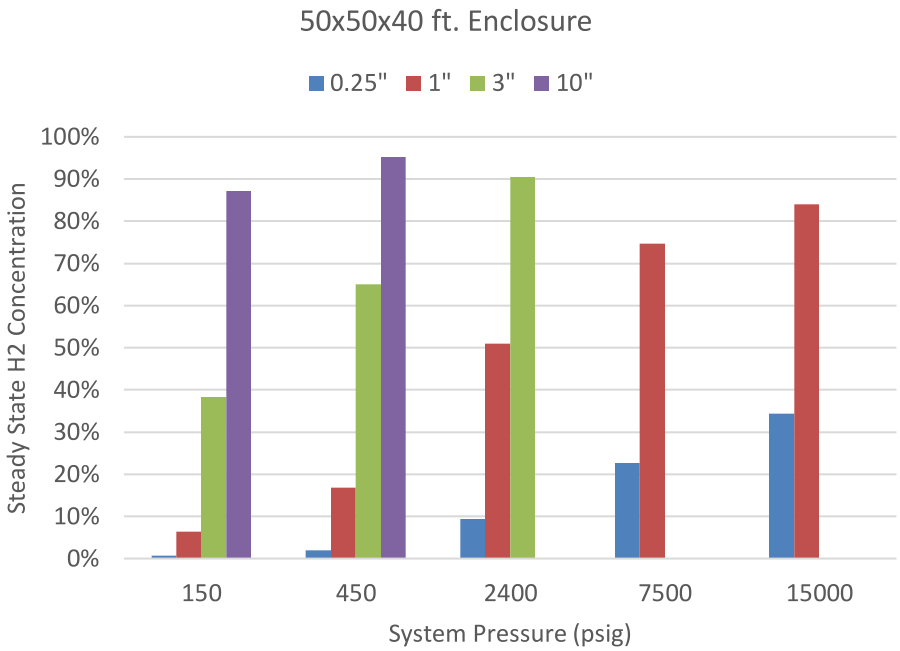


Figure 3. Bulk average steady-state concentration as a function of system pressure and nominal pipe size assuming a 1-scf/min/ft^2 exhaust ventilation rate in a 50 x50 x 40 ft enclosure (ACH 1.5) and effective leak diameter of 3% of the flow area of the pipe.

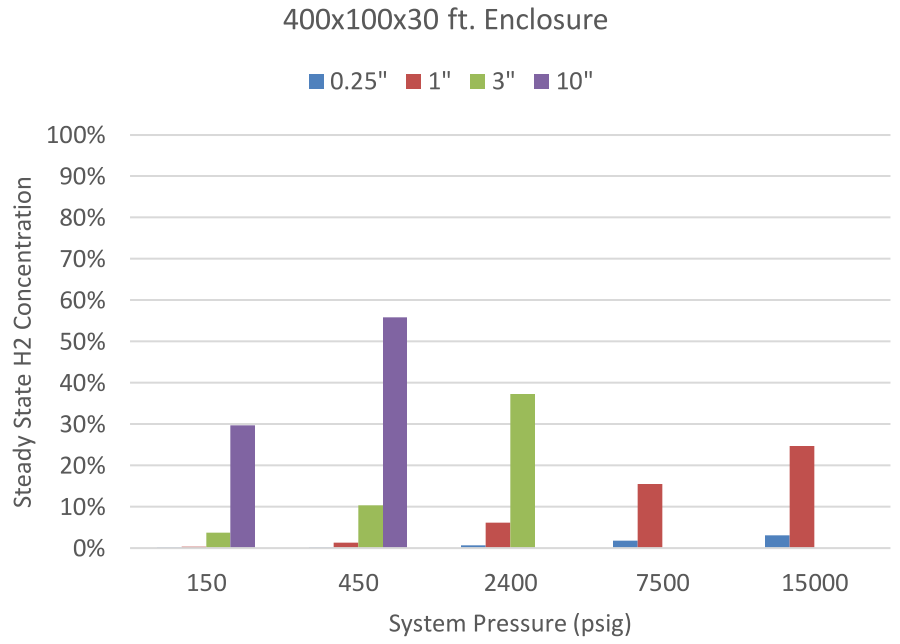


Figure 4. Bulk average steady-state concentration as a function of system pressure and nominal pipe size assuming a 1-scf/min/ft^2 exhaust ventilation rate in a 400 x 100 x 30 ft enclosure (ACH 2) and effective leak diameter of 3% of the flow area of the pipe.

Based on a ventilation rate of 1 scf/min/ft^2 and a leak rate of 3% of the flow area corresponding to the largest internal pipe downstream of the highest-pressure source in the system, most scenarios, even at low pressure and small pipe sizes, do not meet the 25% of LFL (1 vol% hydrogen) bulk-average concentration limit given in many standards until very large volumes are considered. Notably, when large pipe sizes are used, especially at high pressure, the volumetric flow rates from the assumed credible leak are extremely high compared to the same conditions using small pipes. Similarly, when tall enclosures (such as a high bay) are used, minimum prescribed ventilation rates may be too low to mitigate the risk. It is important to reiterate that large volumes do not consider spatial resolution around potentially large leaks, and although bulk averaging results may show sufficient dilution, local risks around credible leaks remain significant.

These inconsistencies in the regulatory guidance cause significant confusion and necessitate that the stakeholder use safety judgement, even for the implementation of prescriptive code compliance. For example, in an extreme case, for a 70-MPa dispenser (containing up to 15,000 psig hydrogen) with dimensions 4 x 3 x 10 ft, bulk average concentrations of hydrogen exceed 99 vol% for even the smallest pipe size considered (1/4-in.) with an effective leak diameter based on 3% of the flow area. However, current standards for hydrogen dispensing systems do not require mechanical ventilation and instead specify that dispenser enclosures have an opening near the top totaling greater than 20 cm^2 [23].[19] This guidance differs significantly from other applicable standards for hydrogen systems (e.g., minimum 1 scf/min/ft^2, 25% of the LFL bulk average concentration, ACH 6-12, etc.). Based on this analysis, it is recommended that codes and standards guidance be clarified to increase consistency across hydrogen reference standards and bound the applicability of existing prescriptive code compliance. The applicability and limitations of the 1 scf/min/ft^2 ventilation guidance should be resolved.

Design Considerations for Effective Exhaust Ventilation

Exhaust ventilation systems are typically described as either natural/passive or forced/active. Passive ventilation relies on natural forces (e.g., diffusion, wind), while forced ventilation drives air flow through mechanical means. Due to its simplicity, natural ventilation is commonly preferred, while forced ventilation is used when natural ventilation is inadequate to mitigate risk. Either means for ventilation can be used to successfully dilute hydrogen leaks. However, flammable mixtures are still expected in the direct vicinity of leaks, and a time delay occurs to dilute flammable gas volumes by ventilation. Also noteworthy is that heating, ventilation, and cooling (HVAC) systems are not a substitute for exhaust ventilation.

For any leak, the size and concentration of the flammable gas cloud will increase until reaching a steady state based on the size of the leak and ventilation flow rate. The hazard will continue until the source has been isolated and the remaining gas in the piping decays out of the leak or is removed from the system via a vent valve to relieve pressure. Only after this delay will exhaust ventilation effectively reduce the flammable concentration in the air to zero. Figure 5 illustrates the bulk average concentration as a function of time for a 2,400-psig system leak in a 0.75-in. schedule 80 pipe evacuating into a 20 x 8 x 8.6 ft shipping container with a 7-ACH ventilation rate. The leak rate of 0.02 kg/s (520 SCFM) was calculated from an effective diameter orifice size based on 1% of the flow area of the pipe. Detector trip limits were assumed to be 1 vol% hydrogen with a delay for the response to full shutdown being 10 and 30 seconds, respectively.

[19] HGV 4.1, Section 5.2.4.

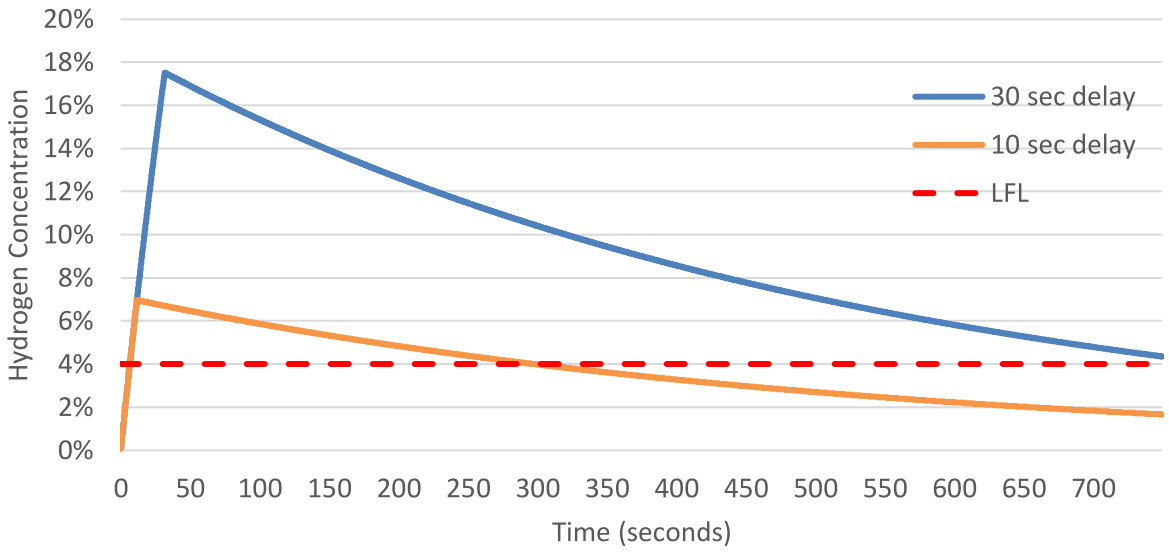


Figure 5. Bulk average concentration as a function of time for a 0.02-kg/s leak in 2,400-psig 0.75-in. schedule 80 pipe evacuating into a 20 x 8 x 8.6 ft shipping container with a 7-ACH ventilation rate. Full shutdown was simulated at 10 and 30 seconds after 1% hydrogen was exceeded. The 1% threshold was reached in approximately 1.7 seconds after the start of the leak.

As illustrated in the transient scenarios in Figure 5, exhaust ventilation should not be considered the first or only line of defense to prevent hydrogen fires and explosions. Rather, best practices to minimize leak size and leak duration applied during design, installation, and maintenance play an essential role in conjunction with exhaust ventilation effectiveness. Importantly, the bulk average concentrations shown in Figure 1 through Figure 5 are not representative of the concentration of the released gas cloud and flammability hazards near the release.

Due to the buoyancy of hydrogen, buildings and enclosures should have good low- and high-level natural ventilation to the open air. The outlet opening should be located at the highest point in the exterior walls or roof. Ventilation design should consider all potential restricted spaces caused by equipment and construction (e.g., inverted pockets in ceilings) where escaped hydrogen gas can accumulate.

Forced exhaust ventilation may be used continuously and/or in response to emergencies such as significant leaks. If forced ventilation systems are relied on to mitigate gas accumulation hazards, controls, procedures, and operational practices should ensure that the ventilation system is always operational when hydrogen is present. If the ventilation system is lost, hydrogen equipment and systems should be shut down into a fail-safe state. Some designs increase ventilation rates when leak monitoring senses a hydrogen release. Although increasing the ventilation rate (and therefore increasing the air exchanges) will decrease the overall time needed to dilute the leak, the impact of increased ventilation is not immediate and also relies on the response time of the detection system [24].

Exhaust ventilation systems should be separate from HVAC systems used to heat or cool a building, since the exhaust air from the ventilation system should not be recirculated. Where combined ventilation/HVAC and/or recirculation systems are used and allowed per code, the possibility of hydrogen contamination should be considered and adequate precautions taken.

Since exhaust ventilation systems must stay on during a fault, electrical classification and non-sparking fans are typically required. The potential for flammable concentrations to ignite within the ventilation ducting should be considered carefully as the confinement created by the ducting will accelerate the flame and increase the consequence of the event. Although the ventilation system should be designed to be ignition-resistant, the prevention of flammable concentrations within the ductwork should first be controlled by limiting release rate/quantity and ventilation rate to dilute hydrogen to below flammable limits.

Ventilation inlets and outlets should be located away from potential hazards. Not only the rate, but also the placement and size of the inlet(s) and outlet(s), will dictate ventilation effectiveness in sweeping the entire volume of the enclosure or building. The forced ventilation system should be designed to prevent dead zones and accumulation areas. Installed equipment and/or barrier walls may restrict the flow of ventilation air while simultaneously increasing the consequence of an explosion through flame acceleration and reflected pressure waves.

Although no-momentum releases will plume upward in an enclosure and may be mitigated by natural ventilation or forced ventilation through exhaust openings at the high point of the structure, momentum-driven releases mix substantially within the surrounding air and will likely require forced ventilation higher than the minimum 1 scf/min/ft^2 specified in many references. Ventilation and dilution effectiveness may be assessed using experimentation, calculations, and/or computational fluid dynamics (CFD). For enclosures and indoor installations, CFD is particularly useful for spatial resolution to establish ventilation effectiveness for different leak scenarios and locations. It can also be used to dictate appropriate placement of fixed detectors for gas monitoring. Sensor placement is a key component of overall safety since fixed detectors are only effective when the leaking hydrogen encounters the detector. Without detection and associated mitigation, the continuing leak may overcome the ventilation's capability to dilute below the LFL. Emerging technology such as acoustic detectors may enable wide area monitoring and improved response time. All ventilation systems require regular maintenance and testing, including calibration of detection equipment.

See the following for further information on ventilation considerations and design:

- ASHRAE 62.1, *Ventilation for Acceptable Indoor Air Quality* [25]
- BS 5925, *Code of Practice for Ventilation Principles and Designing for Natural Ventilation* [26]
- API RP500, *Recommended Practice for Classification of Locations for Electrical Installations at Petroleum Facilities Classified as Class I, Division 1 and Division* 2 [27]
- API RP505, *Recommended Practice for Classification of Locations for Electrical Installations at Petroleum Facilities Classified as Class I, Zone 0, Zone 1, and Zone 2* [28]
- ISO TR 15916, *Basic Considerations for the Safety of Hydrogen Systems: Ventilation Specifications* [29]
- IEC 60079, *Explosive atmospheres*, *Part 10-1: Classification of areas – Explosive gas atmospheres* [11], Annex C: Ventilation guidance

Results from Experimental and Numerical Ventilation Studies

Several studies have sought to understand the effects of ventilation on the formation of flammable mixtures of hydrogen in enclosures and buildings of varying sizes [24, 30-40]. Studies have considered the effectiveness of both natural and forced ventilation. In many cases, an experimental study was

performed to evaluate or anchor numerical models, indicating the importance of both analytical and experimental methods to validating proposed ventilation designs. While a comprehensive review of all hydrogen ventilation studies is beyond the scope of this paper, four recent examples are presented that illustrate different release/ventilation scenarios:

- Grune et al. [30] evaluated the effect of forced ventilation direction with respect to the source for a large leak resulting from a high-pressure failed component.
- Saikali et al. [31] carried out experimental validation of an analytical model that considered small leaks inside of a 1-m^3 enclosure representative of a typical fuel cell container.
- Ehrhart et al. [32] considered the safety of hydrogen light-duty automotive maintenance facilities and the effects of ventilation on safety for different release scenarios.
- Bernard-Michel and Houssin-Agbomson [33] studied the correlation between helium and hydrogen releases to assess the suitability of helium as a substitute for experimental ventilation studies.

Example 1, Ventilation for localized hydrogen releases and accumulations: Grune et al. [30] conducted an experimental test program to examine how ventilation direction affects the dispersal/dilution of local hydrogen releases. They measured and compared the effects of co-flow, counter-flow, and cross-flow ventilation on jet release dilution, as illustrated in Figure 6 (Figure 3C in the original publication). The tests were conducted in a large (220-m^3) test chamber with two parallel flanged openings where the test could be configured for the various flow geometries. The hydrogen jet release rates were between 1 and 5 g/s through either a 1- or 4-mm-diameter orifice. Ventilation velocities varied from 0 to 5 m/s using a propeller fan. Hydrogen concentrations were measured using nine sensors that were placed along sample points horizontal and perpendicular to the jet release axis. The results clearly demonstrated the enhanced effectiveness of cross-flow ventilation compared to the other two configurations. Distances to the LFL concentration were reduced by 65% to 80% with cross-flow ventilation at 5 m/s, compared to much lower reductions of 35% to 65% with co-flow and counter-flow ventilation. Note that the ventilation rates examined in this paper were much higher than those in codes discussed above, ranging from ~19 to 62.5 ACH for flow velocities between 1.5 and 5 m/s.

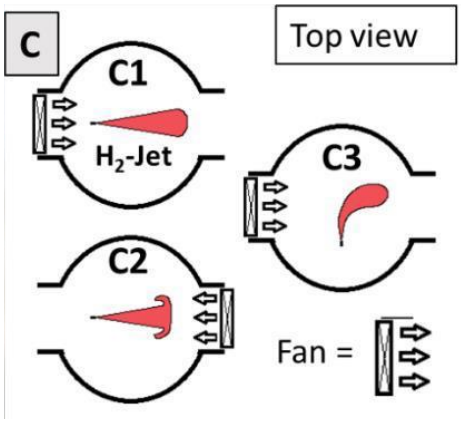


Figure 6. Jet co-flow (C1), counter-flow (C2), and cross-flow (C3) ventilation tests.

Example 2, Moderate release with passive ventilation: Saikali et al. [31] studied a common hydrogen release scenario with a small-to-moderate release rate in a passively vented enclosure. The enclosure had a high opening for escape of the buoyant hydrogen-air ceiling layer and another opening much lower for air inflow. Figure 7 (Figure 1 in [31]) shows a laboratory test version of this configuration, which was developed to address the question of passive ventilation effectiveness for small releases. The hydrogen release rate into the 1-m^3 enclosure in this experiment was 0.014 g/s, two-orders-of-magnitude lower than the jet release experiments conducted by Grune et al. [30]. The ventilation openings were located such that there was a slight cross ventilation flow, which can be seen in the minor distortion of the incoming hydrogen flow in Figure 8 (Figure 17 in [31]).

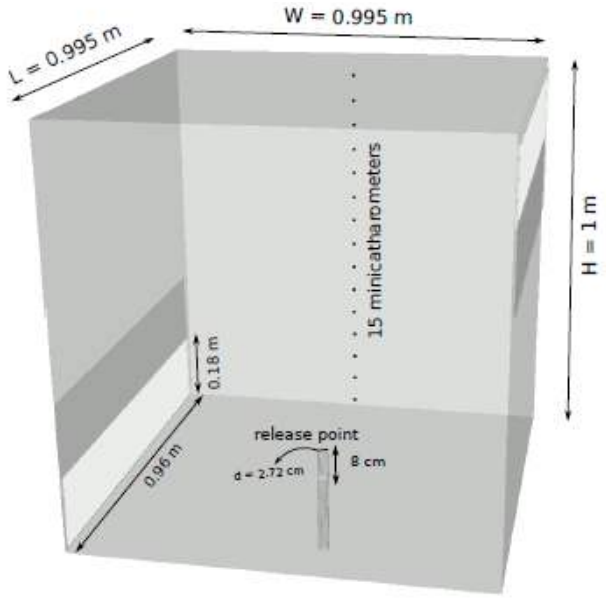


Figure 7. Hydrogen release experiment in a passively vented enclosure.

Figure 8 presents the time-averaged numerical results showing hydrogen concentration for the passively vented enclosure. Hydrogen concentrations greater than 4% were only found in the plume directly above the release location. Concentrations in the ceiling layer were nearly uniform, roughly equal to 1.5% for the conditions tested. The authors reported that the CFD simulations of the experiment produced good agreement with experimental data, provided that the CFD mesh was adequately resolved to reproduce the finer flow structure at the intersection of the plume and ceiling layer. This is noteworthy, as unvalidated CFD results can be inaccurate if mesh independence studies are not performed.

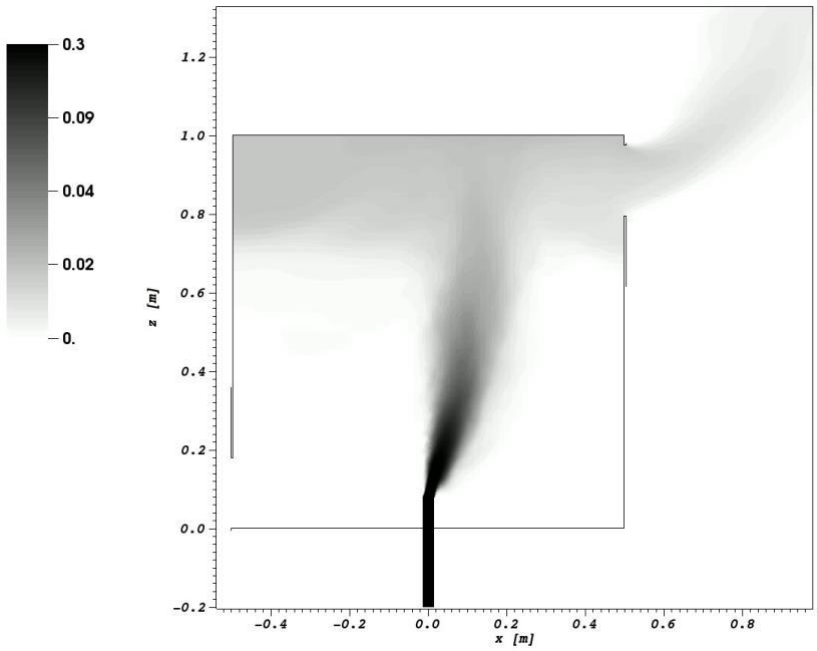


Figure 8. Hydrogen concentration distribution for release in passively vented enclosure.

Example 3, Ventilation impacts in light-duty maintenance facilities: Ehrhart et al. [32] computationally determined the flammable mass available in two different release scenarios from a light-duty vehicle tank with 2.5 kg of onboard fuel. Releases were modeled in two large repair garage facilities: a 10-bay garage with over 60,000 ft^3 (1,715 m^3) total volume and a 12-bay garage with over 100,000 ft^3 (3,072 m^3) total volume. Three scenarios were considered: (a) no building ventilation, (b) building ventilation per minimum code requirements such as 1 ft^2 per minute per square foot floor area, and (c) a local box fan near the vehicle. The authors found that code-compliant ventilation in the entire facility had no significant impact on the amount of instantaneous flammable hydrogen in the facility unless the leak point was near a ventilation inlet. The results suggested that a portable fan may provide a suitable way to increase safety without structural changes to the garage or ventilation system. It is noteworthy that in these simulations, the amount of released fuel was very small compared to the building size and therefore the fuel dispersed without accumulating as a flammable volume at the ceiling. For larger or longer duration releases and/or smaller building sizes, the result would be expected to deviate. Regardless, this study highlights the effectiveness of local dispersion at mitigating risk and illustrates that code-compliant building ventilation based on floor area may be overly conservative or ineffective in some scenarios.

Example 4, Comparison of helium and hydrogen releases: Bernard-Michel and Houssin-Agbomson [33] experimentally studied a similar configuration to Saikali et al., but with both hydrogen and helium gaseous releases. Results indicated that “helium cannot be directly used as a substitute for hydrogen to predict the distribution of gas concentration.” However, the authors also acknowledge that “helium still remains a good substitute to hydrogen for conservative predictions” and “for a plume release, helium gives a good prediction which only worsens when the flow turns into a jet at the nozzle's exit.” The authors concluded that helium can be used to validate computation models predicting helium dispersion,

which can then be predictive for hydrogen releases; however, helium and hydrogen release and dispersion behavior are dissimilar and therefore cannot be directly correlated.

Conclusions

As shown in this paper, exhaust ventilation for safe mitigation of hydrogen release scenarios is a complex topic with many considerations. The following are key takeaways from the discussion above:

Potential Problems with the Exhaust Ventilation Rates Specified in Industry Standards and Guidance Documents

- Ventilation rates prescribed based on floor area do not consider inventory of hydrogen, pressure, accumulation areas, credible leak rate and duration, reflective or confining geometries, controls, or mitigations. It is critical to consider these factors when establishing suitable ventilation rates for enclosures and indoor installations.
- Ventilation rates required for rooms and buildings based on floor area are not appropriate for small enclosures or cabinets.
- Volume-averaged flammable concentrations do not consider spatial resolution around the leak source. For larger enclosures or buildings, the instantaneous mixing assumption may not be appropriate, and local accumulations of higher concentrations of hydrogen can present a significant hazard.
- Defining credible release scenarios is essential to determining appropriate ventilation rates.

Determining Appropriate Hydrogen Release Scenarios and Rates

- Factors that influence leak rate and duration include service conditions, connection type, inventory of hydrogen, system maintenance and operation, and detection and mitigation methods.
- Leak rates used to calculate outdoor separation distances might not be directly applicable to indoor applications.
- Statistically significant data on hydrogen component failure rates is not readily available and therefore minimum prescriptive code compliance for leak mitigation may not be sufficient in many cases.
- Studies are underway to attempt to quantify and build data sets for credible leak rates of hydrogen components in present-day installations.
- Credible, application-specific scenarios for hydrogen release can be qualitatively identified during risk assessments.
- Only after credible leak scenarios, rates, and durations have been established can the ventilation approach, rate, and effectiveness be developed and reviewed.

Calculations for Example Scenarios

- Current prescriptive guidance for exhaust ventilation and release rates is not suitable for all present-day applications.
- Bounds on the applicability of current prescriptive guidance should be added to codes, standards, and guidance documents.

Design Considerations for Effective Exhaust Ventilation

- Ventilation effectiveness is not just dictated by rate, but also by many other factors including the release scenario, ventilation system design, and building/enclosure design/construction.
- Ventilation can be natural, forced, or a combination thereof.
- Rapid detection for fail-safe isolation is key to the effectiveness of ventilation systems.
- Passive reduction of potential leak flow rates (e.g., by using an orifice in the hydrogen supply line) can significantly reduce ventilation required and/or will increase its effectiveness.
- Ventilation should be assessed through calculations, experimentation, and/or modeling.
- HVAC ventilation is not a substitute for exhaust ventilation.

Results from Experimental and Numerical Ventilation Studies

- Experimental evaluations of active ventilation indicate that cross-flow ventilation is more effective than co- or counter-flow ventilation.
- Experimental evaluations of passive ventilation indicate that cross-flow ventilation with a low entrance flow and a high exit flow in the container is effective for small leak rates. For larger leak rates, active ventilation may be required to mitigate the hazard.
- Local air flow velocity near a leak can be more effective than large-scale building ventilation, assuming that the total hydrogen released does not accumulate in the structure.
- Depending on the release scenario, helium may not be an adequate substitute for hydrogen when conducting experiments on ventilation effectiveness. Bernard-Michel Houssin-Agbomson [33] found that experiments using helium overpredicted concentrations reached with hydrogen under the same conditions.
- Mathematical and CFD modeling as well as experimental testing can be used to establish ventilation effectiveness for assumed release locations, rates, and leak durations.
- Further research and full-scale application studies are ongoing that will inform future risk analysis, codes, standards, and best practice guidance.

Recommendations

The following actions should be prioritized:

- Develop easy-to-use modeling tools for the dispersion of hydrogen with clear definition of the validated range of model inputs.
- Compile and develop credible data on leak rates for hydrogen components.
- Update codes and standards to bound the applicability of currently available prescriptive leak and ventilation rates.
- Update codes and standards to define worst-case credible leak rates and the associated required ventilation rate.
- Develop guidance documents to support ventilation assessments.

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