DEFINING HAZARDOUS ZONES – ELECTRICAL CLASSIFICATION DISTANCES

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ABSTRACT

This paper presents an analysis of computational fluid dynamic models of compressed hydrogen gas leaks into the air under different conditions to determine the volume of the hydrogen/air mixture and the extents of the lower flammable limit. The necessary hole size was calculated to determine a reasonably expected hydrogen leak rate from a valve or a fitting of 5 and 20 cfm under 400 bars, resulting in a 0.1 and 0.2 mm effective diameter hole respectively. The results were compared to calculated hypothetical volumes from IEC 60079-10 for the same mass flowrate and in most cases the CFD results produced significantly smaller hydrogen/air volumes than the IEC standard. Prescriptive electrical classification distances in existing standards for hydrogen and compressed natural gas were examined but they do not consider storage pressure and there appears to be no scientific basis for the distance determination. A proposed table of electrical classification distances incorporating hydrogen storage volume and pressure was produced based on the hydrogen LFL extents from a 0.2 mm diameter hole and the requirements of existing standards. The PHOENICS CFD software package was used to solve the continuity, momentum and concentration equations with the appropriate boundary conditions, buoyancy model and turbulence models. Numerical results on hydrogen concentration predictions were obtained in the real industrial environment, typical for a hydrogen refueling or energy station.

1.0 INTRODUCTION

Hydrogen codes and standards are being written in many jurisdictions to facilitate the introduction of high pressure hydrogen systems into commercial and residential occupancies. The existing prescriptive electrical area classification distances are contained in industrial hydrogen standards such as NFPA 50A, 55 and 497 and API 505 and electrical codes. Some jurisdictions are using CNG classification distances for hydrogen fueling of vehicles until hydrogen specific standards are developed.

The existing, prescribed clearance distances for CNG distances were not developed using scientific models but more by negotiation in standards committee meetings. Therefore, one cannot ascertain a given leak rate that was used for CNG and compare the resulting, prescribed clearance distance to hydrogen at the same leak rate. Hydrogen clearance distances in industrial standards were likely developed the same way.

Another method to determine the extent of a classified area is to use the formulae in IEC 60079-10 to determine the hypothetical volume of a hydrogen/air mixture caused by a hydrogen leak. This was done for each scenario and the hypothetical volume was compared to the volume calculated by CFD modeling. CFD modeling results were also used to measure the extents of the LFL. This provides a scientific basis for establishing clearance distances based on a known leak rate.

We assumed a leak rate that was substantial enough to cause a noticeable pressure loss from 400 bar storage, but so large that the leak rate would be higher than what might be anticipated from valves and fittings in smaller hydrogen systems where piping connections are welded or use compression fittings and diameters are typically 10 to 19 mm. (Leak rates of this volume from storage would most likely be heard if someone was in the vicinity and storage pressure sensors could detect this leak rate and in conjunction with temperature detectors, provide signals to a Programmable Logic Controller (PLC) that could effect valve closing or emergency venting). From this, the hypothetical ignitable volumes for several scenarios were

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calculated using IEC 60079-10 expressions and these were also compared to the CFD modeling results for ignitable mixture volume and the extents of the mixture from the leak source.

Two H_2 leak rates of 5 and 20 scfm (0.00020 and 0.00079 kg/sec) were used as a starting point and the necessary holes sizes to produce this leak rate were calculated for 400 bar storage pressure.

2.0 SCENARIOS

Hydrogen gas leaks 5 and 20 scfm (2.37 l/sec and 9.47 l/sec) in downward, upward and horizontal orientations in a 0.5 m/sec wind were modeled. A low wind velocity was selected as it would allow the greatest accumulation of hydrogen and this velocity is what is considered by IEC 60079-10 to be the lowest outdoor ground velocity. Additionally, low pressure venting of 10 Nm3/hr from a hydrogen generator was modeled.

2.1 Calculation of Hole Diameter to Produce a Specified Leak Rate

For the ideal gas law, the hydrogen compressibility is equal to 1. Without considering the orifice contraction effects and frictional forces, a choked release rate at the initial condition (*t=0*) can be written as:

$$\dot{m}_0 = A\sqrt{r_0 P_0 g \left(\frac{2}{g+1}\right)^{\frac{g+1}{g-1}}},$$

where $\dot{m}_0$, r_0 and P_0 are the hydrogen mass release rate, the density in the tank and the tank pressure. A is the leak orifice area. For hydrogen, $g = 1.41$. For a rounded orifice with small orifice contraction and frictional forces, the mass release rate can be more accurately expressed by introducing the discharge coefficient C_d: (C_d=0.95)

$$\dot{m}_0 = C_d A\sqrt{r_0 P_0 g \left(\frac{2}{g+1}\right)^{\frac{g+1}{g-1}}}.$$

The relation between r_0 and P_0 is

$$P_0 = r_0 RT,$$

where R = 4124 J/(kgK). T is the temperature in tank.

The mass flow rate $\dot{m}_0$ can be converted to the standard volumetric flow rate, Q:

$$Q = \frac{\dot{m}_0}{r_{H_2}} = \frac{C_d A\sqrt{r_0 P_0 g \left(\frac{2}{g+1}\right)^{\frac{g+1}{g-1}}}}{0.0838\,\frac{kg}{m^3}} \quad (\mathrm{m^3/s})$$

The area of the orifice can be expressed by the flow (Q) rate as:

$$A = \frac{r_{H_2} Q}{C_d\sqrt{r_0 P_0 g \left(\frac{2}{g+1}\right)^{\frac{g+1}{g-1}}}} = \frac{0.0838 \cdot Q}{0.95\sqrt{r_0 P_0 g \left(\frac{2}{g+1}\right)^{\frac{g+1}{g-1}}}}.$$

The orifice diameter: $f = \sqrt{\frac{A}{\frac{p}{4}}} = \sqrt{\frac{4 r_{H_2} Q}{C_d p \sqrt{r_0 P_0 g \left(\frac{2}{g+1}\right)^{\frac{g+1}{g-1}}}}}$

2.2 Comparison Between CFD Results and IEC 60079-10 Calculations for H_2 Leak Scenarios

IEC 60079-10 is a standard referred to in the Canadian Electrical Code and NFPA 70 (National Electrical Code in USA) to determine ventilation requirements and hazardous locations. The standard uses a calculation to determine the hypothetical combustible volume caused by a fluid leak under specific conditions, and ventilation rates. Due to hydrogen's high diffusion rate and buoyancy, it is our opinion that the calculations in the standard are possibly too conservative and result in inaccurate combustible volumes for hydrogen. A selection of probable maximum hydrogen vent rates and leak rates from piping connections and equipment, combined with ventilation conditions will be modeled and then compared to the hypothetical combustible volume calculations for the condition referenced in the standard.

Table 1. Results of CFD volumes and extents and IEC60079-10 results.

Scenario	**Description**	**CFD LFL Vol m^3**	**IEC 79-10 K=0.5 Vol m3**	**CFD extent horizontal m**	**CFD extent vertical m**
1	10 Nm3/hr (5.8 cfm) downward @ atmospheric pressure	0.0344 100% LFL 0.131 50% LFL	1.81	0.74 @ 100% LFL 1.25 @ 50% LFL	0.39 @ 100% LFL 0.59 @ 50% LFL
2	5 cfm 400 bar downward leak	0.103 @ 100% 2.1 @ 50%	1.42	0.21 @ 100% LFL 1.62 @ 50% LFL Touch ground	1.2 @ 100% LFL 3 @ 50% LFL (touches ground)
3	20 cfm 400 bar downward leak	0.42 @ 100% 3.7 @ 50% LFL	5.64	0.63 @ 100% LFL 3.3 @ 50% LFL (touch ground)	3 m for both clouds (touches ground)
4	5 cfm 400 bar upward leak	0.23 @ 100% 2.5 @ 50%	1.42	0.28 @ 100% LFL 0.69 @ 50% LFL	1.4 @ 100% LFL 3.9 @ 50% LFL
5	20 cfm 400 bar upward leak	0.52 @ 100% 5.6 @ 50%	5.64	0.37 @ 100% LFL 0.87 @ 50% LFL	2.11 @ 100% LFL 5.5 @ 50% LFL
6	5 cfm 400 bar horizontal leak	0.02 @ 100% 0.22 @ 50%	1.42	0.48 @ 100% LFL 2.0 @ 50% LFL	0.12 @ 100% LFL 0.25 @ 50% LFL
7	20 cfm 400 bar horizontal leak	0.11 @ 100% 1.4 @ 50%	5.64	1.1 @ 100% LFL 4.8 @ 50% LFL	0.20 @ 100% LFL 0.42 @ 50% LFL

2.3 Details of CFD modeling for 7 scenarios

Scenario 1: Low pressure venting from hydrogen generator – vertical down

At start-up, to ensure only high purity gas is directed for compression, hydrogen is often vented from a hydrogen generator to atmosphere. Also, sometimes it might be necessary to safely vent hydrogen stored in the pipe, storage tank or hydrogen generator to ambient in case of emergency. The venting process can be controlled at a proper rate, namely, at a small constant release rate.

Scenario A investigated the extension of LFL and 50% of LFL hydrogen cloud during intermittent venting of hydrogen from a Stuart Energy IMET 15 hydrogen generator to the ambient with 0.5 m/s wind. The release direction is downward (vertical). The release is from a 2” orifice at a standard flow rate of 10 m^3/hr.

A domain of 6.5 m × 5 m × 5 m with a grid size of 33×18×31 was used for the numerical simulations. To save CPU time and memory, the incompressible model was used to calculate the hydrogen concentration, velocity and pressure profile in the domain. The release velocity corresponding to 10 m^3/hr and 2” orifice is 1.37 m/s at the orifice, so the Reynolds number is only 585 and the Richardson number is 3.157. The release is fully controlled by the laminar flow, and the buoyancy effects play an important role in the hydrogen dispersion. The released cloud looks like a hydrogen plume floated by the strong buoyancy force rather than a turbulent jet flow.

The convection force of 0.5 m/s wind pushes the floating cloud downstream, causing a horizontal hydrogen cloud extension of 0.44 m for 200% of LFL (8% vol.), 0.74 m for LFL (4% vol.) and 1.25 m for 50% of LFL (2% vol.). The hydrogen cloud extension in the vertical direction is 0.25 m for 200% of LFL (8% vol.), 0.39 m for LFL (4% vol.) and 0.59 m for 50% of LFL (2% vol.). IEC 60079 predicts that the hypothetical volume for the current scenario is 1.81 m^3 with a safety factor k =0.5 and a quality factor f=1. The numerical results show that the volume of the hydrogen cloud is 0.0344 m^3 for LFL (4% vol.) and 0.131 m^3 for 50% of LFL (2% vol.). The CFD modeling can greatly relax the existing codes and standards.

Scenarios 2 through 7: 400 bar hydrogen leaks

If a vessel, a pipe, or a tank, has been damaged to a minor extent, this results in a small opening to the environment leading to relatively small outflow rates compared to the total amount of hydrogen stored. This opening could be an invisible crack or a small pinhole in the vessel wall, or could be a very small rupture of connected piping with a relatively small diameter. Due to the very small ratio between the outflow rate and the total mass of hydrogen stored, the flow can be considered to be steady, meaning that the hydrogen outflow has a constant mass release rate, which is controlled by the difference between the stagnation upstream pressure and the downstream pressure, such as the initial tank pressure and the atmosphere pressure.

In this task, only small releases from little pinholes with a 0.1 mm or 0.2 mm diameter have been investigated for induced hydrogen clouds corresponding to LFL and 50% of LFL. The estimated release flow rates would be 2.5 and 10 l/s (5 and 20 SCFM) for the 0.1 mm (0.004”) and 0.2 mm (0.008”) leak orifices on the 400 bar piping, respectively.

Considering the different release rates and release directions, there are 7 modeling scenarios, which are summarized in Table 2.

Table 2. Summary of the modeling scenarios and the numerical results.

	Flowrate (SCFM)	Re # 10^5 **	2% vol. Hydrogen cloud volume (m^3)		Horizontal cloud extension (m)			Vertical cloud extension (m)		
			IEC	CFD	8 % vol.	4% vol.	2% vol.	8 % vol.	4% vol.	2% vol.
1	6.3 (down)	585	1.81	0.034	0.44	0.74	1.25	0.25	0.39	0.59
2	20 (down)	5.11	5.64	3.74	0.14	0.63*	3.31*	0.6	3*	3*
3	5 (down)	2.55	1.42	2.12	0.09	0.21	1.62*	0.28	1.18	3*
4	20 (up)	5.11	5.64	5.66	0.16	0.37	0.87	0.69	2.11	5.55
5	5 (up)	2.55	1.42	2.53	0.12	0.28	0.69	0.47	1.44	3.95
6	20 (horiz.)	5.11	5.64	1.40	0.37	1.14	4.81	0.09	0.2	0.42
7	5 (horiz.)	2.55	1.42	0.22	0.12	0.48	2.02	0.05	0.12	0.25

Notes: * These clouds touch the ground, which is 3 m below the leak orifice.
** Except for Scenario 1 that has Re # equal to 585.

The Reynolds number at the leak orifice corresponding to the 20 SCFM and 5 SCFM release is 5.11×10^5 and 2.55×10^5, respectively, indicating a strong turbulent flow near the orifice. The critical hydrogen density at the leak orifice is about $18.28\,\frac{kg}{m^3}$, which is 14 times larger than the ambient air density at 1 standard atmosphere due to the high release pressure (about 210 bars), resulting in a negligible buoyancy effect in the vicinity of the leak orifice.

Symmetric computational domains and structured grids were used for the simulations of the above six scenarios to save the computational resources: a symmetric domain of 12 m × 2.5 m × 15 m divided by a grid of 51×23×39 cells was used for Scenarios 1 and 2, a domain of 12 m × 2.5 m × 7.5 m divided by 51×23×39 cells for Scenarios 4 and 6, and a domain of 8 m × 2.5 m × 7.5 m divided by 31×23×43 cells for Scenarios 5 and 6. The numerical results obtained with the compressible model using the ideal gas law show that the hydrogen clouds reach a steady state 10 seconds after the onset of the upward and downward releases. But for the horizontal releases, it takes about 15 seconds to reach the steady state.

The compressed hydrogen expands after releasing from the orifice, causing 50% of LFL hydrogen clouds with the numerical cloud volumes of 3.735 m^3, 2.12 m^3, 5.66 m^3, 2.53 m^3, 1.3099 m^3 and 0.22 m^3 for Scenarios 1 to 6, respectively. The IEC 60079-10 predicts that the hypothetical hydrogen cloud volumes are 5.64 m^3 and 1.42 m^3 for 20 SCFM and 5 SCFM, respectively. The existing standards and codes can be significantly relaxed for the horizontal releases corresponding to 5 SCFM and 20 SCFM using the above numerical results.

Proposed Hydrogen Systems Electrical Classification Distances

The following table has been created based on the results of the CFD modeling. The 440 bar pressure was chosen as this is the pressure required to cascade fill 350 bar on-board containers. The H_2 LFL cloud extent caused by a 400 bar leak from a 0.2 mm diameter hole in a 1.5 mm wall thickness pipe as worst potential leak under normal operating conditions was used to determine sizes of hazardous locations. This resulted in a 20 cfm H_2 flowrate. The extents for pressures over 400 bar were increased by 50% assuming a doubling of the pressure to 800 bar and the property that the extent increases by 41% with a doubling of the pressure (using the following correlation: concentration envelope extension is proportional to square root of pressure).

The table accounts for both quantities of hydrogen stored and the maximum allowable pressure of the system. Standards for natural gas fueling stations and hydrogen were also reviewed and compared to the CFD results. As no premise for existing electrical classifications is known in any existing standard such as the size of hole used to establish the extent of an LFL cloud resulting from a gas leak, the CFD LFL extents were used as a basis for establishing the extents and these distances were increased for increased storage volume. Reference sources include:

- International Code Council, International Fuel Gas Code, International Fire Code
- CSA B108 Natural Gas Fuelling Stations Installation Code 1999 and 2004 draft
- NFPA 52 CNG Vehicular Fuel Systems Code 2002
- NFPA 50A Standard for Gaseous Hydrogen Systems at Consumer Sites 1999
- NFPA 55 Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders and Tanks 2003
- 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 2004
- International Code Council International Fire Code 2006 modified Table 2209.3.1 proposed by Ad Hoc Hydrogen Committee
- VdTUV Code of Practice 510 Version 08.99 Guide for the design, construction, testing, commissioning and operation of natural gas refueling stations
- European Integrated Hydrogen Project (EIHP2) Gaseous Hydrogen Vehicle Refuelling Stations Rev 3

Table 3. Proposed Hydrogen Systems Electrical Classification Distances.

Component		**Zone 1** **from source**	**Zone 2** **from source**	**Comments**
Any volume of gaseous storage or Hydride storage up to 25 bar		zero	0.3 m from valves	Valves are the only source of leak if vent pipes are discharged at a safe location
> 25 bar to <440 bar pressure	Up to 250 l water capacity	zero	0.5 m	A leak will be short lived and pressure will reduce quickly
	> 250 l to 2000 l	zero	1.2 m horizontal and 2.2 m up	Downwind H2 LFL is 4% at 1.14 m
	Over 2000 l < 8000 l	zero	1.2 m down and horizontal 2.2 m up	Distance equals CFD model
	8000 l and over	zero	2 m horizontal and 3 m up	Greater volume has more sites that could leak simultaneously
>440 bar pressure	250 l water	.5 m	1 m	Double the pressure will increase distance 50%
	> 250 l to 2000 l	1 m	2 m horizontal and 3.5 m up	Mass flow rate will be greater with higher pressure. 1 m zone 1 added due to volume and longer leak duration
	Over 2000 l but < 8000 l	1 m	2 m horizontal and 3.5 m up	This accounts for the difference between vertical and horizontal LFL envelope. 1 m zone 1 added due to volume and longer leak duration
	8000 l and over	1 m	4 m	Greater volume has more sites that could leak simultaneously
Fast fill Dispenser	Up to 440 bar	As listed or Zone 1 inside if not	1.2 m horizontal and 2.2 m up	Some leakage may occur. CSA is drafting a standard for H2 dispensers
Fast Fill Dispenser	>440 bar	Zone 1 inside	1.8 m	More mass flow with higher pressure
Dispenser nozzle	Up to 440 bar	zero	1.5 m	Moving parts that wear may cause allow leakage
Dispenser nozzle	>440 bar	0.5 m	2.5 m	Higher mass flow may occur
Slow fill vehicle fueling dispenser – any pressure		As per listing inside	1 m	Any substantial leak will be detected and cause filling to stop; also there is only a small amount of gas in the hose.
Compressor Enclosed - and listed	All pressures	Hazloc zone as per listing	Hazloc zone as per listing	CSA America is drafting a standard. The installation requirements should be included
Compressor not enclosed or listed	Up to 440 bar	1 m	1.2 m down and horizontal 2.2 m up	Distance equals CFD model
Compressor not enclosed or listed	>440 bar	1 m	2.0 m down and horizontal 3.5 m up	Distance increased by 50% for higher pressure due to greater H2 mass flow and momentum
Piping valves and fittings	Up to 440 bar	zero	zero	CSA B108 and NFPA 52 have zero distance requirement

Piping valves and fittings	>440 bar	0.5 m Zero if welded	1 m Zero if welded	With greater pressure, there is more leakage possible.
Hydrogen generators, fuel cells	Any pressure	Clearance distance according to the listing requirements		Hydrogen generator and fuel cell manufacturers shall state installation requirements ISO 22734, UL 2274, CSA FC1

Notes:

Leaks from hydrogen systems can occur at fittings that in their normal operation move while under pressure such as valves hoses, compressors, etc. Pipe joints are not considered to be leak sources (CSA B108 and NFPA 52). Where relief valves are piped to a safe location, the area classification is zero in the valve area.

No building or machine air intakes can be in the Zone 2 area.

Distance can be reduced to 1.5 m if H_2 systems are separated by a 2 hour fire barrier.

The distances are based on the CFD modeling to determine the LFL envelope of a 400 bar 20 cfm H2 leak from a 0.2 mm diameter hole in 1.5 mm wall tubing (see scenario 4 and 5).

3.0 CONCLUSIONS

The proposed electrical classifications in Table 3 were produced as a first step in a science based system that is also subject to opinion from regulators and thus may ultimately become a blend of science and committee negotiation. More modeling and physical testing is required to verify what the distances should be and to also convince authorities who enforce the resultant regulations that the science is sound. One issue to be determined is: what volume leak will be assumed?

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EXAMPLES OF CFD MODELING RESULTS AND COMPARISON WITH IEC 60079-10 BASED CALCULATIONS

Scenario 1. Venting from hydrogen generator – Vertical downward

Continuous flow rate: 10 m^3/hr (347 ft^3/hr), low pressure

Vent stack height: 1 m (3.3 ft) above the top of the generator

Vent stack orifice: 50 mm (2 in) diameter pipe

Horizontal wind velocity: 0.5 m/s (1.6 ft/s)

Re=585, Ri=3.157

Extents of concentration envelopes:

Concentration	Horizontal (m)	Vertical (m)
200% LFL (8% vol.)	0.44	0.25
LFL (4% vol.)	0.74	0.39
50% LFL(2% vol.)	1.25	0.59

Hydrogen cloud volume:

0.0344 m^3 for LFL (4% vol.) and 0.131 m^3 for 50% of LFL (2% vol.).

Hydrogen volume according to IEC 60079-10: 1.81 m^3 for k=0.5, f=1.

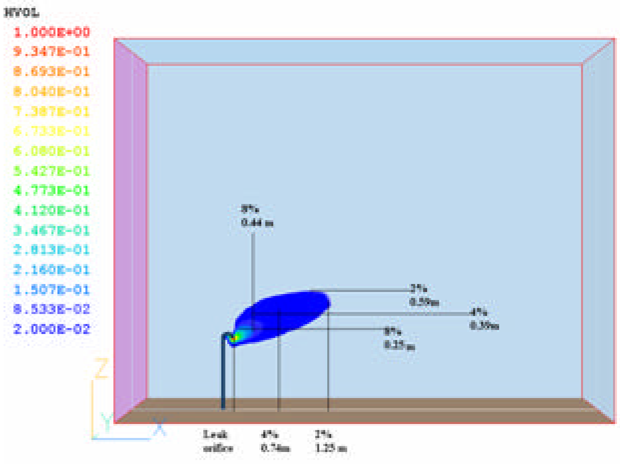

Figure 1. Low pressure venting from hydrogen generator @ 10 m^3/hr (347 ft^3/hr), downward direction

400 bar leaks from hydrogen piping – vertical and horizontal outdoors

Flow rate: 2.5 and 10 l/s (5 and 20 CFM)

Pressure in the piping: 40 MPa (400 bars)

Pipe wall thickness: 1.5 mm for 10 mm pipe, (pressure rated for 40 MPa (400 bar))

Horizontal pipe located 3 m above ground level

Horizontal wind velocity: 0.5 m/s (1.6 ft/sec)

Calculated orifice diameters: (a) 0.10 mm (0.004 in)

(b) 0.20 mm (0.008 in)

$Re=2.5\times10^5$ for 5 CFM and $Re=5\times10^5$ for 20 CFM.

Due to paper space limitations only 20 CFM leaks are shown in this paper.

Scenario 3: 20 CFM downward flow

Extents of concentration envelopes:

Concentration	Horizontal (m)	Vertical (m)
200% LFL (8% vol.)	0.6	0.14
LFL (4% vol.)	3* (Touch the ground)	0.63* (Touch the ground)
50% LFL(2% vol.)	3*(Touch the ground)	3.31*(Touch the ground)

Hydrogen cloud volume:

$0.412m^3$ for LFL (4% vol.) and $3.735m^3$ for 50% of LFL (2% vol.).

Hydrogen volume according to IEC 60079-10: $5.64m^3$ for k=0.5, f=1.

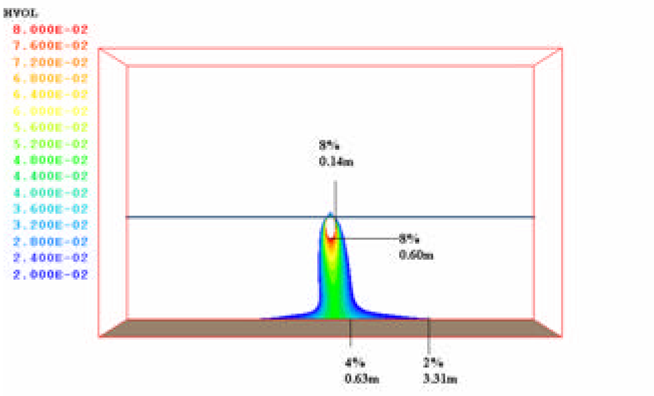

Figure 2. Small leaks from hydrogen piping 20 CFM, downward direction

Scenario 5: 20 CFM upward flow

Extents of concentration envelopes:

Concentration	Horizontal (m)	Vertical (m)
200% LFL (8% vol.)	0.16	0.69
LFL (4% vol.)	0.37	2.11
50% LFL (2% vol.)	0.87	5.55

Hydrogen cloud volume:

0.524m^3 for LFL (4% vol.) and 5.66m^3 for 50% of LFL (2% vol.).

Hydrogen volume according to IEC 60079-10: 5.64m^3 for k=0.5, f=1.

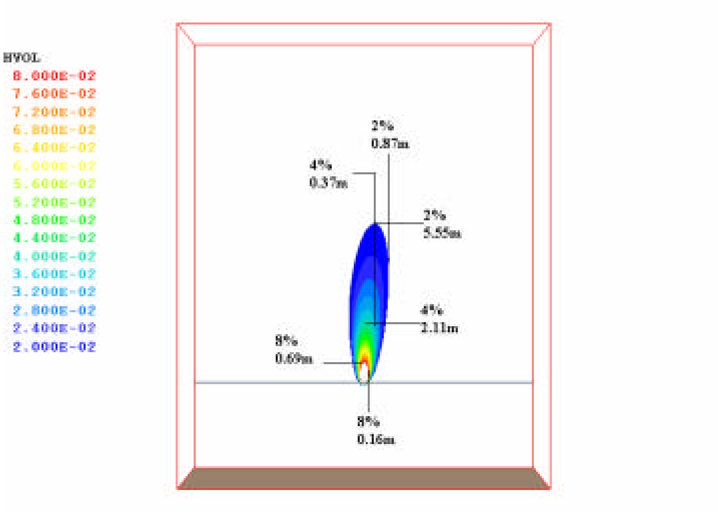

Figure 3. Small leaks from 40 Mpa hydrogen piping 20 CFM, upward direction

Scenario 7: 20 CFM horizontal flow

Extents of concentration envelopes:

Concentration	Horizontal (m)	Vertical (m)
200% LFL (8% vol.)	0.37	0.09
LFL (4% vol.)	1.14	0.2
50% LFL(2% vol.)	4.81	0.42

Hydrogen cloud volume:

0.106m^3 for LFL (4% vol.) and 1.399m^3 for 50% of LFL (2% vol.).

Hydrogen volume according to IEC 60079-10: 5.64m^3 for k=0.5, f=1.

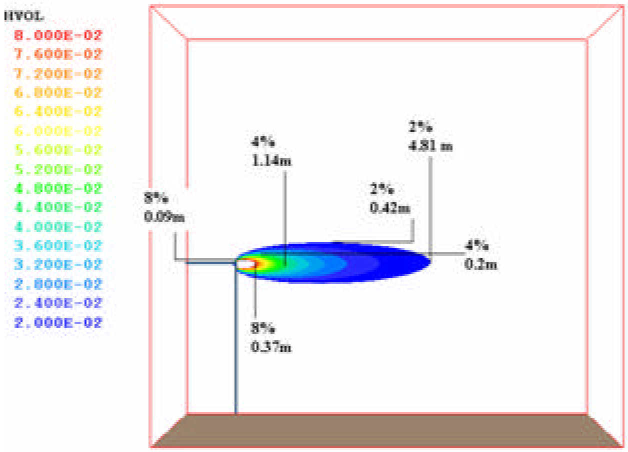

Figure 3. Small leaks from 40 Mpa hydrogen piping 20 CFM, upward direction