DETERMINATION OF HAZARDOUS ZONES FOR A GENERIC HYDROGEN STATION – A CASE STUDY

Nilsen S.[1], Marangon A.[2], Middha P.[3], Engeboe A.[4], Markert F.[5], Ezponda E. [6], Chaineaux J.[7]

[1]Oil and Energy Research Centre, Norsk Hydro ASA, Porsgrunn, N-3908, Norway,
sandra.nilsen@hydro.com
[2]University of Pisa, DIMNP, 256126 - Pisa, Italy
a.marangon@ing.unipi.it
[3] Gexcon AS, Fantoftveien 38, N-5892 Bergen, Norway, prankul@gexcon.com
[4] Energy and Resources, DNV Research and Innovation, Veritasveien 1, 1322 Høvik, Norway
Angunn.Engebo@dnv.com
[5] Systems Analysis Department, Risø National Laboratory, Technical University of Denmark, Roskilde 4000, Denmark
frank.markert@risoe.dk
[6] Tecnalia Materials and Components Dept./Energy Unit, INASMET, San Sebastián E-20009, SPAIN
eezponda@inasmet.es
[7] Institut National de l'Environnement industriel et des Risques, INERIS, PB2 F-60550, Verneuil en Halatte, France
jacques.chaineaux@ineris.fr

ABSTRACT

A method for determination of hazardous zones for hydrogen installations has been studied. This work has been carried out within the NoE HySafe. The method is based on the Italian Method outlined in Guide 31-30(2004), Guide 31–35(2001), Guide 31-35/A(2001), and Guide 31-35/A; V1(2003). Hazardous zones for a "generic hydrogen refuelling station"(HRS) are assessed, based on this method.

The method is consistent with the EU directive 1999/92/EC "Safety and Health Protection of Workers potentially at risk from explosive atmospheres" which is the basis for determination of hazardous zones in Europe. This regulation is focused on protection of workers, and is relevant for hydrogen installations, such as hydrogen refuelling stations, repair shops and other stationary installations where some type of work operations will be involved. The method is also based on the IEC standard and European norm IEC/EN60079-10 "Electrical apparatus for explosive gas atmospheres. Part 10 Classification of hazardous areas". This is a widely acknowledged international standard/norm and it is accepted/approved by Fire and Safety Authorities in Europe and also internationally.

Results from the HySafe work and other studies relevant for hydrogen and hydrogen installations have been included in the case study. Sensitivity studies have been carried out to examine the effect of varying equipment failure frequencies and leak sizes, as well as environmental condition (ventilation, obstacles, etc.). The discharge and gas dispersion calculations in the Italian Method are based on simple mathematical formulas. However, in this work also CFD (Computational Fluid Dynamics) and other simpler numerical tools have been used to quantitatively estimate the effect of ventilation and of different release locations on the size of the flammable gas cloud. Concentration limits for hydrogen to be used as basis for the extent of the hazardous zones in different situations are discussed.

1.0 INTRODUCTION

A method for determination of hazardous zones for hydrogen installations has been studied. The method is based on guidelines published in Italy to help in the application of the requirements in the ATEX-directives. Hazardous zones for a "generic" Hydrogen Refueling Station (HRS) have been calculated using these guidelines.

The method is in line with the EU directive 1999/92/EC[1] "Safety and Health Protection of Workers potentially at risk from explosive atmospheres" which is the basis for determination of hazardous zones in Europe. The method is also based on the IEC standard and European Norm IEC/EN60079-10 "Electrical apparatus for explosive gas atmospheres. Part 10 Classification of hazardous areas". This is a widely acknowledged international norm, approved by Fire and Safety Authorities in Europe and internationally. The methods presented in the norm are however not extensively validated for hydrogen and may be too optimistic or conservative, depending on the release conditions and surroundings. Some models for calculation of atmospheric dispersion could be used, but they cannot give reliable results for weakly ventilated or semi-confined spaces.

The Italian guidelines including a systematic analytical approach and mathematical formulas have been used for: 1) identification of the release scenarios that will be basis for decision on the type and location of the zones, 2) calculation of discharge and dispersion to determine the zone extent, and 3) determination of the effect of ventilation on the type and extent of the zone. In addition CFD (Computational Fluid Dynamics) tools and the simpler numerical tools Explojet and Phast have been used to quantitatively estimate the effect of ventilation on the size of the flammable gas cloud.

The work has been concentrated on determination of hazardous zones: 1) inside the gas processing building at the HRS and 2) around valves on the high pressure storage vessels. Challenges related to the lack of relevant leak frequencies/leak sizes from this relatively new technology are discussed. Sensitivity studies have been carried out to examine the effect of varying equipment failure frequencies and leak sizes, as well as ventilation capacity and design. Discussion of what hydrogen concentration that should be used as basis for the type and extension of the hazardous zones in different situations are included.

2.0 DEFINITIONS

The definitions are unless otherwise indicated from EN60079-10.

Hazardous area	Area in which an explosive gas atmosphere is present, or may be expected to be present in quantities such as to require special precautions for the construction, installation or use of apparatus.
Zones	Hazardous areas are classified into zones based upon the frequency of the occurrence and duration of an explosive gas atmosphere, as follows:
Zone 0	An area in which an explosive gas atmosphere is present continuously or for long periods.
Zone 1	An area in which an explosive gas atmosphere is likely to occur in normal operation.
Zone 2	An area in which an explosive gas atmosphere is not likely to occur in normal operation and, if it does occur, is likely to do so only infrequently and will exist for a short period only.
Source of release	Point or location from which a flammable gas, vapour or liquid may be released into the atmosphere in such a way that an explosive gas atmosphere could be formed .
Continuous grade of release	A release which is continuous or is expected to occur for long periods.
Primary grade of release	A release which can be expected to occur periodically or occasionally during normal operation.

[1] ATEX- "User" directive

Secondary grade of release	A release which is not expected to occur in normal operation and if it does occur, is likely to do so only infrequently and for short periods.
Release rate	Quantity of flammable gas or vapour emitted per unit time from the source of release.
Normal operation	Situation when the equipment is operating within its design parameters.
Ventilation	Movement of air and its replacement with fresh air due to the effects of wind, temperature gradients, or artificial means.
Lower explosive limit (LEL)	Concentration of flammable gas or vapour in air, below which the gas atmosphere is not explosive. [2]
Lower flammable limit (LFL) [9]	The lower vapour concentration of fuel in a flammable mixture that will ignite and propagate a flame. This limit is a function of temperature, pressure, diluents, and ignition energy.

2.0 BACKGROUND AND LEGAL FRAMEWORK IN EUROPE

The general safety requirements to evaluation of explosion risk and determination of hazardous zones are outlined in the European directive 1999/92/EC. This document specifies requirements for prevention of and protection against explosions**,** assessment of explosion risks and requirements for classification of places where explosive atmospheres may occur.

The aim of zone classification is to decide the type and extent of so-called hazardous zones where explosive atmospheres might be present continuously, frequently or infrequently at installations processing flammable substances. The decision on the type and extent of the zones depends on the probability of occurrence and extent of explosive atmospheres. The selection of proper equipment (electrical and mechanical) within these zones depends on the type of zone. Working and emergency procedures are also highly influenced by the zones since specific precautions/restrictions have to be taken to reduce the probability of introducing ignition sources when entering the hazardous zones.

This work is a continuation of the work presented earlier in HySafe deliverable D26 [1]. In this report a survey of available methods and guidelines for determination of hazardous zones were presented, both risk based and deterministic methods. The risk-based methods included guidelines proposing risk acceptance criteria, frequency data and giving calculation examples, also for hydrogen. However, the examples given were mainly focused on industrial installations, and there did not seem to be any guidelines for domestic installations. The conclusion from [1] was that the methodology to be used for zone classification should be based on EN60079-10, since it provides general guidelines that are widely acknowledged.

[2] The EN60079-10 states that the terms “explosive” and “flammable” should be considered synonymous. In this document the term “flammable” is used.

3.0 DESCRIPTION OF METHODOLOGIES AND NUMERICAL TOOLS

3.1 Italian guidelines

The Italian method for zone classification is included in two guidelines: 1) Guide CEI 31-35, "Electrical apparatus for explosive atmospheres. Guide for the application of the Norm CEI EN 60079-10 (CEI 31-30)" and 2) Guide CEI 31-35/A, "Electrical apparatus for explosive atmospheres – Guide for the application of the Norm CEI EN 60079-10 (CEI 31-30) Classification of hazardous zones, Examples of application".

These two guides give special features for determination of the type of the zone and for the evaluation of its extent. EN 60079-10 does not have any indications on which failure frequency that should be taken as reference in the process for decision of classification, but the Italian Guide CEI 31-35 has some indications on how to proceed. When the type of the zone has been determined, the Italian methodology include a procedure for verification that the likelihood of the explosive atmosphere in one year and the total duration of the explosive atmosphere in one year (release duration plus time of persistence after the release has been stopped) are below some critical values. This verification introduces a probabilistic risk-based approach (see Table 1).

Table 1 – Reference values for the determination of hazardous areas

Zone	Likelihood of presence of the explosive atmosphere in 365 days (1 year)	Total duration of the release (explosive atmosphere) in 365 days (1 year)
Zone 0	$P > 10^{-1}$	More than 1000 hours
Zone 1	$10^{-1} \geq P > 10^{-3}$	More than 10 hours up to 1000 hours
Zone 2 (2)	$10^{-3} \geq P > 10^{-5}$	More than 0.1 hours up to 10 hours (1)
(1) In the case of total duration of the release (explosive atmosphere) in 365 days (1 year) less than 0.1 hours, the area is generally non hazardous, in particular when the emission are more than one in 365 days. However, to be sure than the area is really non hazardous, it is better case by case to perform a risk assessment analysis. (2) In the case that reliable fault rates are not available, it can be assumed that at least one event is likely to occur in one year.		

The method is a stepwise process that gives both the type and extent of the zone. The process contain indications on 1) the most suitable leakage size dependent on the type of component (pump/compressor, piping connections, valve etc.), 2) flow rates for structural/continuous grade of release as a function of the component's type based on statistical data, 3) flow rates for primary and secondary grade of release calculated by specific reference formulas, and 4) evaluation of the extent of the hazardous zone as a function of the release flow rate, ventilation and flammable substance. Examples of hazardous area classification are given, e.g. for natural gas, including transport and refuelling stations, and one example for hydrogen used as generator's coolant in confined spaces.

The Italian methodology also has some gaps. The available release frequency data are usually based on large-scale hydrocarbon installations located at a certain distance from a public environment. Gaseous hydrogen refuelling stations can be located in a public environment, the storage pressure is higher, the equipment dimensions and production capacity are smaller, and the technology is immature. So far there are no indications that the hydrogen installations are expected to less frequent releases than the large-scale industrial installations, but the release sizes and release rates, as well as the consequences might be different.

3.2 Use of Explojet for determination of hazardous zones

Explojet is a numerical code based on fluid dynamics of jets and on similarity laws which exist for subsonic and supercritical jets. In case of a gas released into air as a supercritical jet, Explojet considers the jet as stationary (the upstream pressure is assumed constant) and coming out from a circular orifice, in free area (no obstacles impinged).

Explojet describes: 1) the characteristics of the release (mass flow rate, volume flow rate) and of the concentration-, velocity-, and turbulence- fields in the vicinity of the release, 2) the distance x_{LFL} on the jet axis (the distance x where the concentration of the air-gas mixture is equal to LFL and the volume of the explosive atmosphere V_{ATEX}.

Explojet has been experimentally validated for H_2 and CH_4 jets, for hole diameters up to 150 mm and pressures up to 40 bar. INERIS has developed a method for determination of hazardous zones based on [2] and using the Explojet code and the results presented for Explojet are based on this approach.

3.3 FLACS

FLACS is a CFD software used for modeling of gas dispersion, combustion and explosion blast. The focus of the FLACS calculations have been to study dispersion in confined locations (in the gas processing building at the HRS area), and especially the effect of varying ventilation design and capacity.

FLACS is widely used in the offshore industry and is thoroughly verified for hydrocarbon dispersion and explosions. The ability to simulate hydrogen releases and explosions has been validated in the recent years within HySafe and other research programs.

3.4 PHAST

PHAST is a simpler numerical computer tool for modelling of hazardous consequences from releases of flammable or toxic chemicals. PHAST is not extensively validated for hydrogen. PHAST has been used for calculation of discharge and for dispersion for the outdoor release from a valve leak. Assumed wind conditions were F-stability and wind velocity of 1 m/s. The recommended wind velocity in Italian methodology is 0.5 m/s, but the PHAST guidelines recommend using a minimum limit of 1 m/s to get reasonable results.

4.0 DESCRIPTION OF A GENERIC GASEOUS HYDROGEN REFUELING STATION

The main sections of a HRS consist of 1) Hydrogen on-site generation or delivery, 2) Drying/purification system, 3) Compression, 4) High pressure storage and gas distribution, and 5) Hydrogen dispenser, including station/vehicle interface. The considered layout of the generic HRS assumes that gas is delivered in a pipeline to the station, at an inlet pressure of 15 barg. Purification/drying of the gas is assumed to take place in the station area. The main principles can be considered to be representative of today’s demonstration projects, even if there might be slightly different solutions and processes. Future stations will probably have a larger capacity (hydrogen generation/delivery or storage capacity).

A layout drawing of the generic hydrogen station is shown in figure 1 - plan view (on the right) and 3D view (on the left). The 8 storage vessels are assumed to be located in two racks, one above the other. A simplified process drawing of the generic HRS is shown in figure 2.

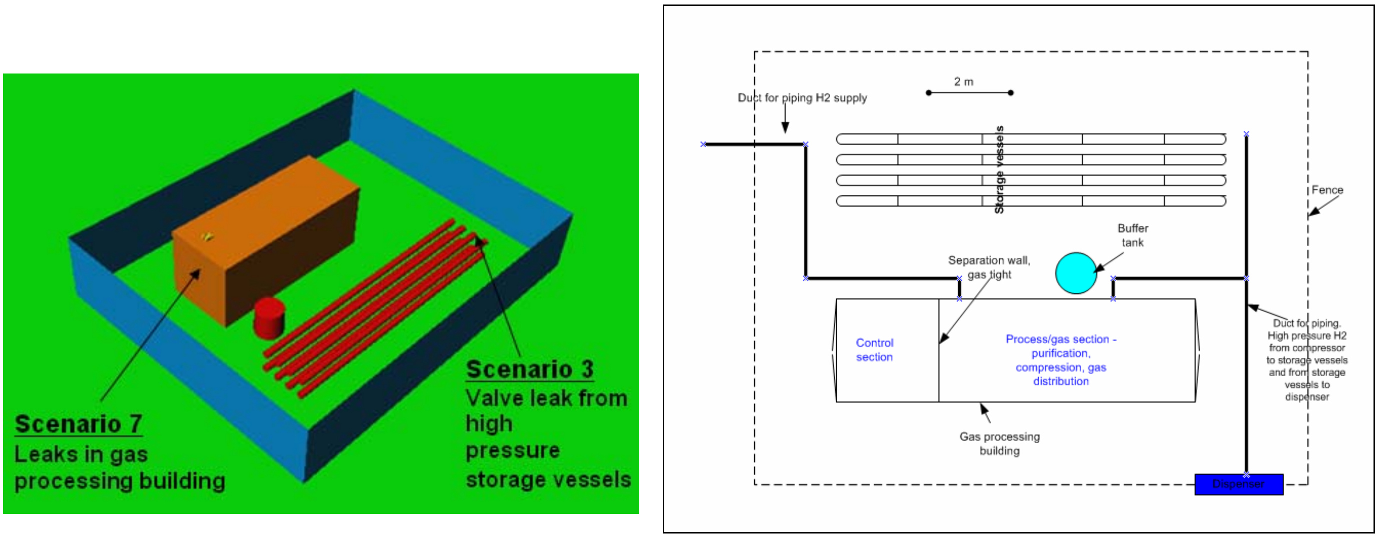

Figure 1 Layout drawing for the generic hydrogen refuelling station

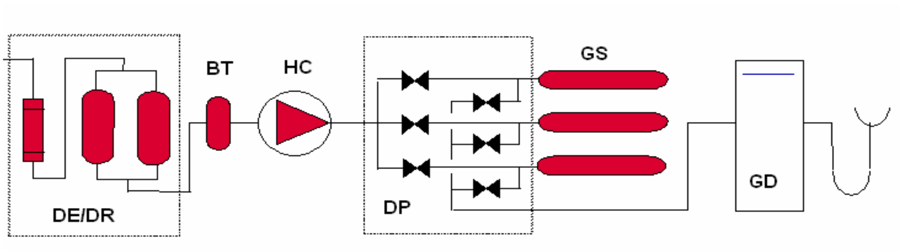

Figure 2.Simplified process diagram of the generic HRS: DE/DR-Deoxidiser/dryer, HC-High pressure compressor, BT-Buffer tank, DP-Distribution valve panel, GS-Gas storage, GD-Gas dispenser

Quantitative assumptions used as the basis for the calculations are provided below. These assumptions are representative of several of the CUTE and Highfleet CUTE stations [3]: 1) Hydrogen delivery or generation capacity of 60 Nm^3/hour, 2) Pressure upstream compressor is 15 barg, maximum pressure downstream compressor and in high pressure storage vessels is 460 bar, 3) Eight storage vessels are arranged in three pressure banks, 4) Maximum amount of gas stored in high pressure vessels: 200 kg, 5) Typical piping and valve dimensions: 10-15 mm upstream compressor, 6-8 mm downstream compressor, and 6) Amount of hydrogen inside process equipment in the gas processing building (including drying/purification and compression): 300 g.

5.0 DEFINITION OF SCENARIOS FOR ZONE CLASSIFICATION

5.1 Selection of release scenarios for zone classification

For a hydrogen refuelling station as well as for any gas processing system hazardous zones have to be considered for every potential release source, such as compressors, valves, flanges, hoses, pumps etc. Continuous, primary and secondary releases have to be considered, when relevant. According to EN60079-10 catastrophic rupture is not to be considered, and all-welded pipelines are not considered as release sources. Compressor leak releases are relevant scenarios, but since the statistical data listed in the Italian guidelines and also in other data sources are not representative for the type of compressors used at hydrogen refuelling stations, secondary grade of release from compressors were not assessed in detail. The following release sources were therefore identified: 1) Valve leak inside dispenser enclosure, 2) Opening of safety valve release through vent line, 3) Leak from outdoor valves at storage vessel, 4) Leak from refuelling nozzle, 5) Leak from valve at buffer tank, 6) Leak from automatic shutoff valve outside gas processing building and 7) Releases (continuous and secondary grade) inside the gas processing building.

Only scenarios 3 and 7 are presented, representing secondary grade of release in an unconfined and confined location. The location of these scenarios is also illustrated in figure 1.

5.2 Leak frequencies and leak sizes

Presently relevant statistics on leak size and frequency are not available for the type of hydrogen station discussed in this example. Available guidance in the Italian guidelines is for natural gas systems with typical equipment dimensions of piping and valves < 150 mm, and a leak area of 0.25 mm^2 (leak diameter 0. 56 mm) for valves is proposed for a secondary grade of release. This may not be relevant for the generic HRS since typical equipment dimensions (piping and valves) for this type of installations are 6 – 25 mm, and the pressure is also significantly higher than for natural gas stations (450 bar versus 200 bar). The natural gas data probably are based on industrial installations with larger equipment dimensions and lower process pressure than for the current HRS technology. The assumptions about hole size, process pressure and duration of the release are very important for the type and extent of hazardous zones. A hole size area of 0.25 mm^2 for the generic HRS may be unrealistic and may lead to very large hazardous zones and/or zone 1 instead of zone 2, which could be a challenge for a HRS in dense urban settings where the available areas for siting are limited.

Some other data sources showing leak frequencies and corresponding leak sizes can be found in [4], [5] and [6]. In [5] and [6] it is suggested that "in general the release which occurs at a frequency of Level I (1.0E-2/release source-yr) should be used to establish the Zone 2 outer boundary; however, if the exposure[3] is high, a frequency of Level II (1.0E-3/release source-yr) should be used". For valves a release size diameter of 0.1 mm, corresponding to a failure frequency of 10^{-2} per valve yr. is proposed. It must be noticed that this is a cumulative approach so if there are many valves or other secondary grade release sources in an area, all of these sources must be added considering the zone 2. To examine the effect of reduced, and maybe more realistic release sizes for secondary grade of release it was decided to consider 3 release sizes for valves, with hole diameters of 0.1, 0.2 and 0.56 mm. The release rates for the three hole diameters were calculated to 0.2, 0.7 and 5.7 g/s of hydrogen assuming a source pressure of 460 bar.

For scenario 7**,** considering the 0.56 mm hole, it was assumed that 20 g of the 300 g hydrogen available was released at a rate of 5 g/s whereas for the remaining amount of hydrogen (280 g) the release rate was 1.4 g/s – equal to the generation/delivery rate. This was done to take into account that only a small volume of the hydrogen in the gas processing building is contained at 460 bar. It is, however, very important to stress that this condition depends on the assumption that there is a non-return valve just downstream the compressor, outside the gas processing building so that the gas inside the high pressure gas vessels and connecting pipeline between the compressor and storage vessels cannot flow back into the building. If not, the amount of gas inside the high pressure vessels (200 kg) will flow back into the gas processing building where the consequences in case of ignition will be catastrophic. That is why it is paramount to prevent backflow of high pressure hydrogen gas into the process building. As an effective risk reducing measure, placement of redundant non-return valves, one at the gas storage manifold and another outside the process building, is thus recommended. For the 0.1 mm and 0.2 mm release it was assumed that the initial release rate would continue until the 300 g of hydrogen had been released. The 0.56 mm hole release is also considered to be representative for

[3] $Exp=P_{occ}*N_{range}$, Exp=exposure, P_{occ}=probability the worker is on site within the hazardous area, N_{range}=time weighted average number of release sources which can affect the individual during their time within the hazardous area

compressor releases since it is assumed that the control system automatically will shut down the compressor in case of a release exceeding the normal production capacity.

In the CFD simulations for simplicity the release was assumed to be located in the middle of the gas processing building, directed downwards.

Different ventilation capacities were considered: Natural ventilation (corresponding to air velocity 0.5 m/s according to the Italian methodology), 10, 150, 300 and 800 ACH (air changes per hour). Two different ventilation *designs* were considered for the CFD-simulations: 1) Louvre at one of the short sides as air inlet and a fan that sucks out the gas/air in the ceiling, and 2) Fan location in the middle of the roof, and 2 louvres at the lower part of the long walls, l x h = 6 x 0.5 m. Ventilation design 1 is illustrated in figure 3.

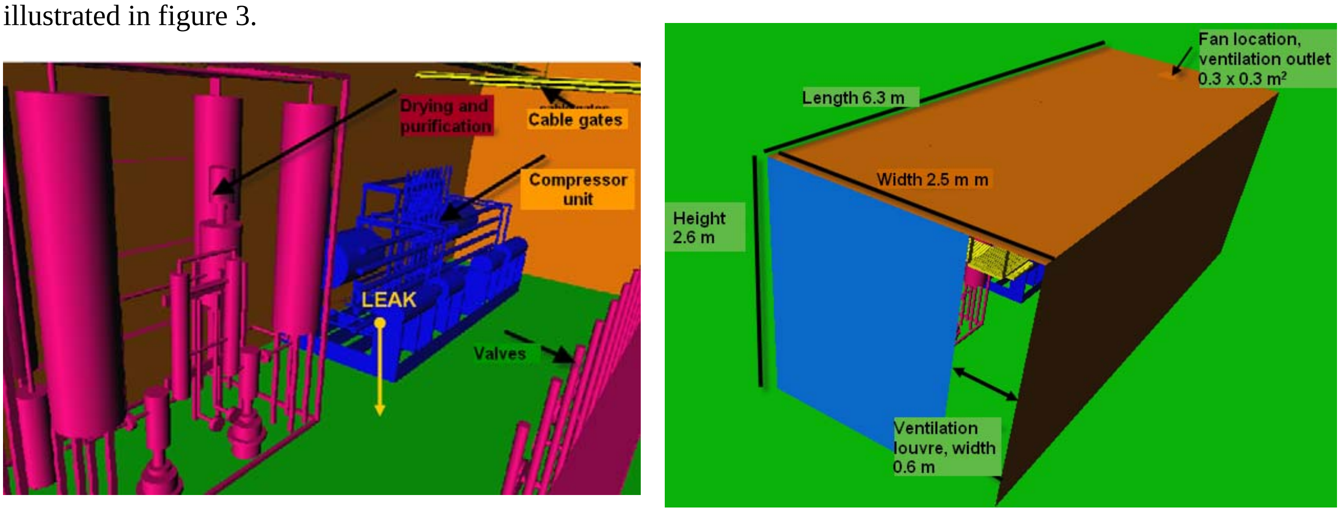

Figure 3 Illustration of release position and ventilation design nr 1 for scenario 7

6.0 RESULTS AND DISCUSSION

6.1 Scenario 3 - Hazardous zone around valves on the high pressure storage vessels

The results using the various calculation tools are given in tables 2 and 3 presenting the radius of the hazardous zone. The release is considered as a secondary grade so this will be zone 2. Table 2 is based on ½ LFL deciding the extent of the zone, and table 3 is based on LFL.

Table 2 – Extent of zone 2 based on ½ LFL, calculated with different calculation tools

Zone 2 radius (m), based on ½ LFL	Leak diameter 0.56 mm			Leak diameter 0.2 mm			Leak diameter 0.1 mm		
	Italian met	Explojet	Phast	Italian met	Explojet	Phast	Italian met	Explojet	Phast
	5	8.6	5.1	2.1	3.1	2.2	1.5	1.5	1.2

Table 3 – Extent of zone 2 based on LFL, calculated with different calculation tools

Zone 2 radius (m), based on LFL	Leak diameter 0.56 mm			Leak diameter 0.2 mm			Leak diameter 0.1 mm		
	Italian met	Explojet	Phast	Italian met	Explojet	Phast	Italian met	Explojet	Phast
	3.3	4.1	3.6	1.4	1.5	1.5	1.0	0.75	0.9

Comparing the different tools shows that Phast and the Italian methodology produce very similar results. The Explojet code gives somewhat larger hazardous zones, but the results are still of the same order. The difference between using ½ LFL and LFL as basis for the extent of the hazardous zone is significant (0.5 – 0.7 reduction dependent on calculation code). Considering the largest leak size and using ½ LFL as the basis for the hazardous zone classification might lead to very large HRS land requirements. This might be difficult to obtain in the largely crowded cities where space is limited.

6.2 Scenario 7 – Hazardous zone inside the gas processing building

The results for scenario 7 are summarized in table 4 and 5 based on LFL and ½ LFL as basis for determination, respectively. The FLACS calculations are carried out for ventilation design 2.

Table 4 Results for scenario 7 – leaks in gas the processing building, based on ½ LFL concentration

Venti-lation capacity	Leak diameter 0.56 mm			Leak diameter 0.2 mm			Leak diameter 0.1 mm		
	Italian met	Explojet	FLACS	Italian met	Explojet	FLACS	Italian met	Explojet	FLACS
Natural	Zone 2	Zone 2	No calc	Zone 2	No calc	No calc	Zone 2	No calc	No calc
10ACH	Zone 2	Zone 2	Zone 2	Zone 2	No calc	No calc	Zone 2	No calc	No calc
150ACH	No zone	Zone 2	Zone 2	No zone	No calc	No calc	No zone	No calc	No calc
300ACH	No zone	Zone 2	No calc	No zone	No calc	No calc	No zone	No calc	No calc
800ACH	No zone	Zone 2	No calc	No zone	No calc	No calc	No zone	No calc	No calc

Table 5 Results for scenario 7 – leaks in gas processing building, based on LFL concentration

Venti-lation capacity	Leak diameter 0.56 mm			Leak diameter 0.2 mm			Leak diameter 0.1 mm		
	Italian met	Explojet	FLACS	Italian met	Explojet	FLACS	Italian met	Explojet	FLACS
Natural	Zone 2	Zone 2	No calc	Zone 2	Zone 2	No calc	No zone	Zone 2	No calc
10ACH	Zone 2	Zone 2	Zone 2 V_{fl} = 350 l	Zone 2	Zone 2	No zone V_{fl} = 1.4 l	No zone	Zone 2	No zone V_{fl} = 1.4 l
150ACH	No zone	Zone 2	Zone 2 V_{fl} = 100 l	No zone	No zone	No zone	No zone	No zone	No zone
300ACH	No zone	No zone	No calc	No zone	No zone	No zone	No zone	No zone	No zone
800ACH	No zone	No zone	No calc	No zone	No zone	No zone	No zone	No zone	No zone

Using ½ LFL as basis for the determination of the zone classification the Italian methodology indicates that a ventilation capacity of 150 ACH is sufficient to avoid ex classification, and thus, achieve a non-hazardous area for the 0.56 mm leak. The Explojet calculations result in zone 2 for all ventilation capacities when using ½ LFL. The difference might be that a safety factor of f=4 related to the degree of congestion was basis for the Explojet calculations whereas f=2 was assumed using the Italian methodology.

When LFL is considered as the basis for the zone classification the results using the Italian methodology are similar as for ½ LFL for the 0.56 mm leak. Here the Explojet calculations show that the ventilation capacity of 300 ACH is sufficient to avoid ex classification. The FLACS calculations indicates that a higher ventilation capacity than 150 ACH would be necessary to achieve a non-hazardous area based both on the ½ LFL and LFL concentration, and this indicates that the assumption of f=2 in the Italian methodology might be too optimistic.

The FLACS calculations also indicate that the momentum of the release is an important parameter. The FLACS results in table 4 and 5 are based on sonic velocity of the leak. However, simulations with a reduced momentum indicated that the ventilation rate had a much more significant effect for the 0.56 mm leak. In fact, the flammable cloud was negligible for a ventilation of 150 ACH, while it was significant considering 10 ACH.

Regarding the leak size of 0.2 mm and LFL as basis the ventilation capacities of 10 ACH will not be sufficient to achieve a non-hazardous area inside the building, but 150 ACH will be large enough according to the Explojet calculations and Italian guidelines. The FLACS calculations indicate that a ventilation capacity of 10 ACH will give a negligible volume of the gas cloud, thus, a non-hazardous area. Considering the 0.1 mm leak and LFL as the basis for the results also the Italian methodology predicts no hazardous zone necessary even for the case situation with natural ventilation inside the building.

6.2.2 Importance of risk reducing measures – rapid shutdown and prevention of backflow

It must be underlined that the results reported for the largest leak size are based on the presumption of several risk reducing measures: Is has been assumed that there is reliable non-return valves directly downstream the compressor so that backflow from the high pressure storage vessels cannot occur. These valves should be located on the outside of the gas processing building since, if not, the leaks from the non-return valve itself have to be considered as one of the scenarios for zone classification, and then a significantly larger amount of gas will be released from high pressure giving a larger leak, zone 2 for all of the ventilation capacities and also a very hazardous situation. This is illustrated in figure 5 where it was assumed that a larger volume of hydrogen gas at 460 bar could be released.

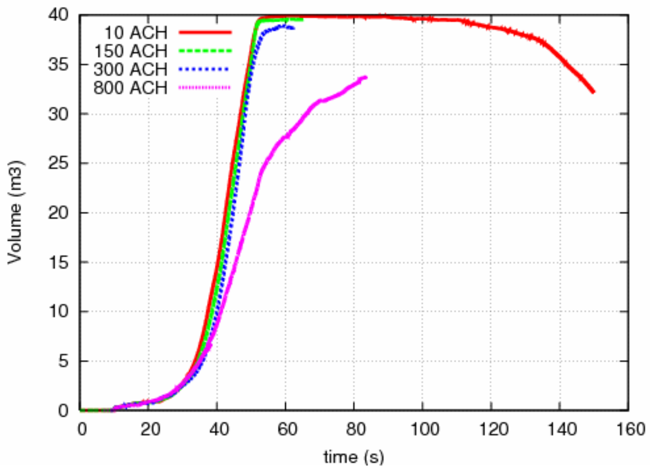

Figure 4 Results from FLACS calculations. Transient development of gas cloud volume with concentration larger than LFL. Effect of increasing ventilation capacity for ventilation design 1. Release of about 5 g/s duration 100 s.

In this case it was assumed that automatic Emergency Shut Down (stop of supply/production and isolation towards high pressure storage vessels) would be initiated automatically by gas detection. Even then the complete building volume is filled with a gas concentration higher than LFL within 50s, see figure 4. Only a ventilation capacity of 800 ACH is able to delay this development, but also for 800 ACH the building will be filled up with flammable gas within a short time period. Without rapid detection and shutdown of the release this would be a very hazardous situation.

6.2.3 Effect of ventilation design

The effect of the different ventilation designs could only be examined using the FLACS code since the other tools are not able to carry out detailed calculations of the complex flow in a confined and congested area. The difference between ventilation design 1 and 2 indicated that ventilation design 2 were better than design 1. This illustrates that to examine the ventilation design using CFD calculations or gas dispersion tests can be important to achieve an efficient ventilation system.

6.2.4 Discussion of gas concentrations as basis for determination of hazardous zones for hydrogen

Many methodologies for zone classification use ½ LFL as the basis in order to take into account the uncertainty related to local and non-ideal conditions that might lead to flammable gas concentrations at longer distances than leaks in open unconfined areas. In [2] and in the Italian guidelines a set of rules providing simple calculations for the hazardous zone classification that have to be adopted for all flammable atmospheres are suggested. One of the important properties to be used in this classification is the LFL concentration for the respective gas mixture. In order to make a conservative determination of the hazardous volume in an open environment, EN60079-10 is using ¼ LFL for continuous and primary grade of releases, and ½ LFL for secondary grade of release. This is also incorporated in the Italian guidelines. Also for the calculations of the extent of the flammable cloud the lower flammability limit is used, and the extent is evaluated by calculating the distance of cloud dilution to below LFL or ½ LFL. In small scale experiments it has been established that hydrogen's LFL is 4 vol% for an upward propagating flame, while for a horizontal propagating flame LFL = 7.2 vol% and for downward propagating flames LFL= 8.5-9.5 vol%. Thus, hydrogen's lower flammability limit is highly dependent on the release geometry, which makes it different from other fuels. Swain et al [7] investigated horizontal hydrogen releases at jet velocities of Mach 0.1 and Mach 0.2. Concentration measurements and CFD calculations at specific locations showed good agreement. They determined maximum ignitable distances by performing hydrogen concentration measurements and CFD calculations to establish the concentration contours. The found distances to a sustained jet flame were considerably shorter than the predicted and measured ones using an LFL of 4 vol%. The experimentally determined ignition distance was found at 144.8 cm while the distance to LFL 4 vol% was predicted to 195.6 cm (35 % longer) for the Mach 0.1 release, while the differences for the Mach 0.2 release were even larger (87 % longer) with experimentally found 119.4 cm and predicted 223.5 cm. It was found that in the region between 4 vol% and about 8 vol% the ignition of the gas cloud was quickly quenched and not developing into a sustained flame. The flame created by 0.85 Sm^3/min of 9 vol% hydrogen concentration mixture flowing out of a 10.8 cm diameter pipe would not ignite a sheet of paper after 1 min exposure.

Nevertheless, the commonly listed LFL value for hydrogen is the lowest (4 vol%), and this is normally applied for risk assessment purposes. In order to illustrate the practical implications of distances to LFL or ½ LFL [8] is cited: Houf and Schefer compared predicted centreline concentration decays for unignited free vertical hydrogen jets (about 18 and 208 bar, respectively) with natural gas. The distance to LFL for the lower pressure release was found to be about 4 m for hydrogen and about 1 m for methane. For the high pressure release distances of about 13.5 m and about 4 m were found, respectively. In both release scenarios and for both gases it may be seen that the decay after reaching the LFL concentration is much slower. Therefore, the distance to ½ LFL is about twice as long and to ¼ LFL about four times as long, e.g. for the low pressure hydrogen release these distances are about 8.5 m (½ LFL) and 17 m (¼ LFL).

8.0 CONCLUDING REMARKS AND RECCOMENDATIONS FOR FURTHER WORK

The method for zone classification based on Italian guidelines has been tested in a case study assessing hazardous zones at a gaseous hydrogen refuelling station, including assessment of hazardous zones inside the gas processing building and around outdoor valves. The method is recommended as a systematic analytical approach for decision of the type and extent of hazardous zones, including the effect of ventilation and gives also some indications on relevant leak sizes for different types of equipment. Verification of the zones is based on a risk based approach. However, lack of relevant data on leak frequency and leak size for this type of installations and also conservative assumptions regarding calculations of the gas dispersion may lead to overly conservative requirement to the type and extent of the zones. Use of CFD tools and other simpler tools which are able to take into account a more realistic prediction of the gas dispersion in confined and obstructed areas might give more realistic results and give more reliable results using the method.

As long as relevant frequency/leak size data for hydrogen refuelling stations do not exist, a leak size of 0.25 mm^2 is considered to represent the most appropriate, however conservative, leak size for the leak scenarios that were considered in this study.

Based on the Italian guidelines zone 2 with a radius of 5 or 3.5 m was calculated depending on using ½ LFL or LFL, respectively, as the basis for the extent of the zone around the outdoor valves. When the leak diameter is reduced to 0.2 and 0.1 mm, the zone radius would be reduced to 50 and 30 %, respectively.

Assuming the 0.25 mm^2 leak, zone 2 is recommended for a ventilation capacity of 10 ACH and 150 ACH, while for ventilation higher than 300 ACH the gas processing building can be considered as a non-hazardous area. The recommendation related to non-hazardous area for high ventilation is, however, based on the presumption of risk reducing measures: Reliable non-return valves are recommended to be located directly downstream the compressor and the storage vessels manifold so that backflow from the high pressure storage vessels into the process building cannot occur. These valves have to be located on the outside of the gas processing building. Reducing the leak size would lead to reduced ventilation capacity to achieve non-hazardous area.

CFD simulations show that the ventilation *design*, not only the capacity can be very important to achieve an efficient ventilation system. It is therefore recommended to examine the ventilation design using CFD calculations or gas dispersion tests.

Based on literature findings, it is suggested to discuss the proper LFL criterion (LFL, ½ LFL or ¼ LFL) to be used for hydrogen's zone classification and zone extent between regulators and scientists. Based on present findings it seems that using ½ or ¼ LFL as basis for determination of the hazardous zone for hydrogen jets in open areas is an overly conservative approach.

Further research is necessary to improve and verify the method and should be focused on:

- Collection of relevant leak frequency and leak size data for hydrogen refuelling stations
- The method for determination of the volume and size of the hazardous zone in the Italian guidelines should also be considered for various leak configurations, since the shape of the gas jet close to the leak orifice for these high pressures is very elongated and far from spherical
- Parallel use of validated CFD tools for verification of Italian guidelines-based findings
- Experimental studies to assess the flammability of hydrogen releases under various and real scale conditions including various geometries and surface effects. Further experimental investigations to confirm the present findings are encouraged

Acknowledgement: The authors would like to thank the European Commission for partial funding of this work through the NoE HySafe project, Contract: SES6-CT-2004-50 26 30. The authors would also like to acknowledge the advice and comments of Dr. A. Tchouvelev of the HySafe Advisory Council.

REFERENCES

1. NoE HySafe D26. Risk Analysis Methodology and Acceptance criteria (WP12).
2. European Commission DG Employment and Social Affairs. Health, Safety and Hygiene at Work. Non-binding Guide of Good Practice for implementing of the European Parliament and Council Directive 1999/92/EC. Final Version April 2003.
3. CUTE project http://www.fuel-cell-bus-club.com/index.php?module=pagesetter&func=viewpub&tid=1&pid=2.
4. EIGA document (IC Doc 75/01/E/rev Determination of safety distances, http://www.eiga.org/.
5. IP(Institute of Petroleum, London), Model Code of safe practice. Part 15 Area classification code for installations handling flammable fluids" 3rd Edition July 2005, ISBN 0 85293 418 1.
6. IP, A risk based approach to hazardous area classification, Nov. 1998, ISBN 0 85293 238 3.
7. Swain, M.R.; Filoso, P.A.; Swain, M.N. International Journal of Hydrogen Energy 32 (2007) 287-295.
8. Houf, W; Schefer, R.; International Journal of Hydrogen Energy 32 (2007) 136-151.
9. Basic considerations for the safety of hydrogen systems, ISO/TR 15916, ISO 2004