RISK ASSESSMENT OF A GASEOUS HYDROGEN FUELING STATION (GHFS)

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ABSTRACT

Promoted by national and European investment plans promoting the use of hydrogen as energy carrier, the number of Gaseous Hydrogen Fueling Station (or GHFS) has been growing up quite significantly over the past years. Considering the new possible hazards and the related accidents induced by these installations, like seen in 2019 in Norway, this paper presents a risk assessment of a typical GHFS using the same methodology as the one required in France by the authorities for Seveso facilities. The fact that a hydrogen fueling station could be used by a public, not particularly trained to handle hydrogen, underlines the importance of this risk assessment. In this article, typical components related to GHFS (dispenser, high pressure storage, compressor, low pressure storage) are listed, and the hazard potentials linked to these components and the substances involved are identified. Based on these elements and an accidentology, a risk analysis has been conducted in order to identify all accidental situations that could occur. The workflow included a detailed risk assessment, consisting in modeling the thermal and explosion effects of all hazardous phenomena and in assessing the probability of occurrence for these scenarios. Regarding possible mitigation measures the study was based on an international benchmark for codes and standards made for GFHS. These preliminary outcomes of this study may be useful for any designer and/or owner of a GFHS.

1. INTRODUCTION

Over the past few years, the number of Gaseous Hydrogen Fueling Stations (or GHFS) have been greatly increasing all around the world. For instance, at the beginning of year 2021, France is counting 92 hydrogen fueling station and 99 more are in project, in order to supply road vehicles (light or heavy vehicles) with hydrogen [1].

This increasing of GHFS number can be explained by several reasons: a favorable regulatory context [2]; a general will of development of ecology and low-carbon means of mobility; but also by public subsidies and development plans for hydrogen-based vehicles.

Hazards induced by the use of hydrogen fuel as an energy carrier are very different from the ones induced by fossil fuels, and so the French National Institute for Industrial Environment and Risks (Ineris) has decided to carry out a risk assessment of a typical GHFS supplying road vehicles (cars, buses, trucks). Hazards linked to multi-fuel station (hydrogen and diesel or LPG, etc.) are excluded from the scope of this study.

For a definite GHFS implanted in its environment, considering the amount of hydrogen involved in the station, the French regulation requires that a safety report (such as the one required for Seveso establishment) be written. Such a safety report consists in the following steps, described in the “Omega 9” guide [3]:

- Description of the environment, the studied facilities and identification of the hazard potentials;

- Risk analysis;
- Detailed risks study:
    - Modeling of the dangerous phenomena and evaluation of the safety distances;
    - Evaluation of their probability of occurrence;
    - Evaluation of the severity of the dangerous phenomena (determination of the number of persons (other than the facility workers) exposed to its effects);
    - Evaluation of their kinetic of appearance;
- Risk acceptability evaluation using a risk matrix probability / severity imposed by the French regulation [4].

As the risk assessment carried out in this article is supposed to apply to any GHFS, whatever its environment, no evaluation of the severity could be done and, as a consequence, this study does not conclude on the risk acceptability but stop after the evaluation of the probability of occurrence of the dangerous phenomena. This risk assessment is solely aimed at giving some elements about the main risks and also helping project owners to make the safety report of their facilities.

The approach used in the present study, following French regulation, differentiates it to other ones that have been done following their national methodology and regulation, that can considers different thresholds of effect or risk acceptance criteria, as FN curves or risk contours ([5], [6], [7]).

2. COMPONENTS OF A GHFS STUDIED

A GHFS can take different configurations. Figure 1 gives the components of such a station and the configurations retained for this study.

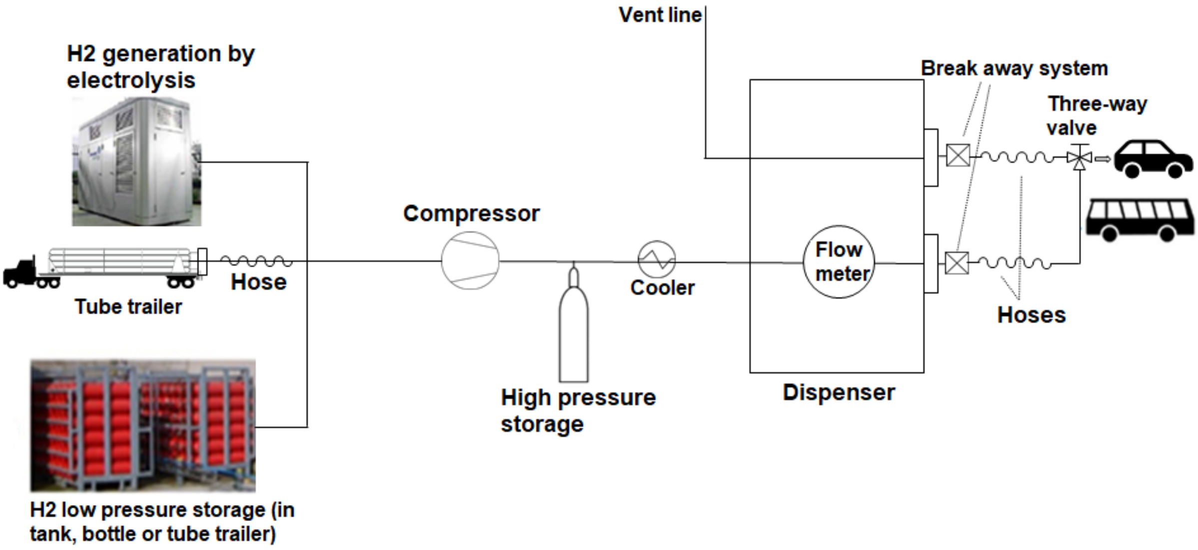

Figure 1. System studied

As it can be seen on the figure, the hydrogen can be produced directly by the GHFS, by electrolyzing water, or can be delivered on site using tube trailers or racks of bottles. In this study, the hydrogen is in the gaseous state from end to end. Cryogenic hydrogen was out of scope of this study. Other studies with this specific fluid can be found in the literacy (for instance [8]).

Based on several previous safety studies carried out by Ineris and based on visits made by the institute on some existing GHFS, the following hypotheses have been considered:

- Gaseous hydrogen storage could be stationary or mobile. Transfer from the tube trailer to the storage is made by pressure balancing.
- The storage in the tube-trailer is made by bottles with a unit volume of 2090 L at 200 bar or by bottles with a unit volume of 335 L at 500 bar. The unloading hose has a 3 mm inner diameter. We consider that a tube trailer is delivering hydrogen to the GHFS once a week and that the delivery lasts about 10 minutes.
- The electrolyser and the compressors are sheltered in standard 20-feet maritime container (outer dimensions: L=6.06 m, l= 2.44 m and h= 2.59 m). The electrolyser has a maximum operating pressure of 15 bar. Water/hydrogen separator has a volume not exceeding 25 L.
- High pressure (HP) and low pressure (LP) storage are aboveground and unsheltered.
- Compressors considered are 2 non-ionic compressors, with a maximum volume of 10 L and the operating pressure is at most equal to 450 or 1000 bar, depending on the expected delivery pressure for the vehicles.
- The LP storage is made at 50 bar and its unit volume is not greater than 45 m^3. The HP storage could be made at 440 or 950 bar (depending on the expected delivery pressure for the vehicles) with a unit volume no greater than 80 L.
- Pipes can be underground or aboveground. Their inner diameter is taken equal to 12.7 mm between the electrolyser and the compressor and 10 mm everywhere else.
- The maximal mass flow rate at the dispenser is fixed to be 60 g/s for light vehicles and 120 g/s for buses (requirement from the French Arrêté of the 22nd October 2018). The inner diameter of loading hose is 3 mm. For this study, we consider a daily attendance of 5 vehicles, with a loading time of 10 minutes for light vehicles and 7 for the others.
- Light vehicles have 80 L hydrogen tanks at 700 bar or 87 L tanks at 350 bar. Buses have 225 L hydrogen tanks at 350 bar. For this study, we consider that the tanks of a vehicle are independent from each other.

3. IDENTIFICATION OF THE HAZARD POTENTIALS

3.1 Hazard potentials involved by the substances

Hazardous substances to consider in GHFS are likely to be hydrogen, nitrogen and/or argon or helium (inert gases). When hydrogen is electrolyzed on site, the electrolyte and the oxygen (as co-product of the electrolyze) have also to be considered.

Hydrogen is a colorless, odorless and non-toxic gas. Due to the small size of its molecule, hydrogen can easily leak. A fugitive leakage is difficult to detect with human sensitivity. However, a high-pressure leakage is audible in a quiet environment. Hydrogen is not corrosive but can embrittle some materials. Under ambient conditions of temperature and pressure (ATP), the density of hydrogen is lower than air (respectively 0.08 and 1.23 kg/m^3) and so hydrogen will have a light gas behavior once its dispersion phase is no more dominated by leakage inertia.

Hydrogen have a wide flammability range and a low minimum ignition energy which make it a very easily flammable gas [9]. If the flammable cloud encounters an ignition source, the expected dangerous phenomena are the same than for other flammable gases: jet fire with thermal effects, explosion of the flammable cloud with blast effects (UVCE - Unconfined Vapour Cloud Explosion) and flash fire with thermal effects. Hydrogen jet fire create a low radiating and quasi invisible flame. Due to its high laminar flame velocity, hydrogen is highly reactive in case of an explosion.

Density (at 101 325 Pa and 15°C)	0.08 kg/m^3
Flammability range (at 101 325 Pa and 15°C)	4 – 75 % v/v
Stochiometric concentration	29.5 % v/v
Ignition temperature	580°C
Minimum ignition energy in air	17 µJ
Adiabatic Flame Temperature in air	2 200°C
Laminar Flame Velocity	3 m/s

Table 1. Hydrogen properties

Nitrogen, argon, helium may be used to inert the installation. These gases only present a risk of anoxia for people at a short range of the leak and when used in a confined environment.

Potassium or sodium hydroxide can be used as electrolyte in alkaline electrolysers. As these hydroxides are corrosive, using them in container (confined environment) is not hazardless. However, except during maintenance operations, this hazard appears to be limited. For PEM (Proton Exchange Membrane) or SOEC (Solid Oxide Electrolyser Cell) electrolysers, electrolytes are solid (polymers or ceramics) and do not present particular hazards.

Oxygen is an odourless and colourless gas. It is a combustion agent; it does not burn but generate combustion and may exacerbate flammable properties of other materials. For example, when hydrogen is released in a pure oxygen environment (and not in air), its upper flammability limit increased from 75 to 95% v/v, its MIE from 17µJ to 1µJ and its flame temperature from 2 200 to 3 200°C. Moreover, oxygen reacts with most of metals and organics materials.

3.2 Hazard potentials involved by equipment

Among the main components of a GHFS, one can cite: hydrogen bottles for storage, buffer tanks, compressors, pipes, dispenser and possibly electrolysers. A loss of containment may occur on each equipment and can lead to a jet fire, an (U)VCE or a flash fire of hydrogen. These events can occur inside or outside the container, depending on the leak location. Every storage capacity can burst in case of mechanical or thermal assault. Explosions can also occur into buffer tanks or electrolysers separators if a flammable mixture is formed inside them and in case of overfilling.

4. ACCIDENTOLOGY

Reference [10] compares incidents and accidents that occurred on GHFS installed in Japan (between 2005 and 2014) and in the USA (between 2004 and 2014). 21 events have been identified in Japan and 22 in USA. These events can be classed in six categories:

- Leakage I: leakages due to the damage and fracture of main bodies of apparatuses and pipes (including welded parts): 3 cases in Japan and 4 in USA. It is mainly because of mechanical fatigue due to a design error;
- Leakage II: leakages from flanges, valves, and seals (including deteriorated nonmetallic seals): 14 cases in Japan and 6 in USA. Thread connections are main causes;
- Leakage III: leakages due to other factors, e.g., human error and external impact: 2 cases in Japan and 3 in USA. Human error is the main cause;
- Explosion and fire: 1 case in Japan;

- Burst and fracture: 1 case in Japan and 5 in USA
- Others: 4 cases in USA.

For the events where the implicated component is precise, the events mainly happened at the dispenser (15 cases), the hydrogen compressor (7 cases) and the gaseous hydrogen storage (6 cases). One case has been detected at the electrolyser. Concerning leaks causes, the article mentions an inadequate seal (10 cases), an inadequate torque (9 cases), a design error (9 cases), a human error (8 cases), a manufacturing error (3 cases), an insufficient maintenance (1 case), an earthquake (1 case), a malfunction (1 case) and an external impact (1 case).

In addition, Ineris looked at the american database h2tools.org in order to supply more learnings from the accidentology. For the storage, releases of hydrogen (inflamed or not) could be due to a leaking connection (ref. “hydrogen cylinder leak at fueling station” on the website) or to the inadvertent opening of a pressure relief device valve (“pressure relief device fails at fueling station”). Regarding the compressor, loss of containment has been caused by a crankshaft bearing failure (“leak on compressor at fueling station”) or by a bad connection of the equipment (“discharge valve installation error”). Also, there is a case where the compressor vibrations have caused the rubbing of a sensor on a hydrogen pipe in turn involving a leak (“hydrogen make up compressor piping hole”). Then, at the dispenser, there are some cases where the cause is not clearly identified (“fueling hose fails”) or due to the non-respect of a filling procedure (“hydrogen fueling dispenser nozzle drive away”).

Among all events, one has had a large impact, at least on a mediatic point of view. It happened in Oslo suburb in 2019 (“fueling station high pressure storage leak” on h2tools.org). On the 19th of June 2019, hydrogen leaked from a plug and encountered a not-yet identified ignition source. An explosion and a fire occurred, making no human casualties and no critical damage on other components of the GHFS. An inadequate torque of HP tank plugs caused a small leak of hydrogen which grew and create a flammable cloud and then met an ignition source.

5. RISK ANALYSIS OF THE FACILITY

The main goal of this risk analysis is to identify, with utmost exhaustivity, every accidental scenario that could take place on hydrogen fueling station equipment (storage, electrolyser, pipes, compressor, dispenser…) for every operating mode (vehicle filling, maintenance, hydrogen production or delivery…). Considering that a part of the facilities is directly manipulated by customers, all scenarios may impact someone filling his car at the dispenser. The risk analysis conducted by Ineris was a Preliminary Hazard Analysis (PHA), and allowed to identify Critical Events (CE) and Dangerous Phenomena (DP) listed in Table 2. Among the possible causes for these CE, we can mention mechanical and/or thermal assault, of natural (earthquake, flood, forest fire ...) or anthropic origins (collision with a vehicle, unwanted movement of a vehicle, domino effects from an adjacent site or vehicle ...), and human errors during design (equipment not adapted or badly positioned ...) or during control / maintenance of the facilities (corrosion, wear of fittings or valves, non-compliance of periodic replacement of hoses…). Scenarios due to specificities of technologies of electrolysers have not be considered in this study.

Critical Events (CE)	**Dangerous Phenomena (DP)**
STORAGE	
Rise of temperature and/or pressure	Burst of storage
Loss of containment on the storage tank/bottle	Hydrogen leak Jet fire, UVCE, flash fire
If delivered by truck: Loss of containment on the hose (at the delivery post)	
ELECTROLYSER	
Loss of containment on the electrolyser	Hydrogen leak Jet fire, UVCE, flash fire

Critical Events (CE)	Dangerous Phenomena (DP)
Formation of an explosive mixture in hydrogen and/or oxygen separators	Burst of the separator
PIPES	
Loss of containment on pipes (leak or full-bore rupture)	Hydrogen leak Jet fire, UVCE, flash fire
Pressure safety valve opening	Hydrogen reject Jet fire, UVCE, flash fire
COMPRESSOR	
Loss of containment on the compressor	Hydrogen leak Jet fire, UVCE, flash fire
Formation of an explosive mixture in the compressor	Burst of the compressor
SHELTER (buildings, container) containing a part of the hydrogen facilities	
Formation of an explosive mixture	Burst of the shelter
DISPENSER	
Loss of containment on the filling hose	Hydrogen leak Jet fire, UVCE, flash fire
Vehicle Fire	Burst of vehicle tank
Filling with “too hot” hydrogen	

Table 2. Risk analysis synthesis

6. MODELING OF THE EFFECTS OF THE HAZARDOUS PHENOMENA

By means of simulations, Ineris assessed the intensity of the different hazardous phenomena identified by the risk analysis. For blast and thermal effect, the safety distances are determined in the French regulation considering different effects on humans and structures and using thresholds that are specified by a ministerial decree [11]. The threshold values are given in Table 3.

	Blast effects	**Thermal effects**	
	mbar	**kW/m^2**	**$(kW/m^2)^{4/3}.s$**
Indirect effect threshold (by broken window)	20	-	-
Irreversible effects threshold (IET)	50	3	600
First lethal effects threshold (FLET)	140	5	1000
Significant lethal effects threshold (SLET)	200	8	1800

Table 3. French regulatory thresholds of effect evaluated in a risk assessment

The work was carried out using the descriptive elements of section 2 of this article and the following modelling tools:

- For the evaluation of the consequences of an ignition of a flammable mixture formed within a component (electrolyser separator, container), Ineris used its internal tool EFFEX [12] in order to predict the maximum blast of the explosion, and then its other internal tool PROJEX [13] to study the blast decay with the distance from the equipment ;
- For the evaluation of the blast effects of a capacity burst (storage, vehicle tank), Ineris once again used the PROJEX tool;
- For the evaluation of the effects of an UVCE or a flash fire of hydrogen, Ineris used an internal modelling tool called EXOJET. This tool predicts the concentration decay in the release using

classical similarity laws and, for example, allowed us to determine the lower flammability distance. For the effects of a flash fire, the distances of effects are then determined using the French ministerial circular of the 10th of May 2010 [4]. Blast effects are calculated by using the Multi-Energy method, considering a violence index from experimentations abacus.

- For the evaluation of the effects of a jet fire of hydrogen, Ineris used the Johnson model of the PHAST software (v6.53).

Table 4 gives some of the results for the three main effects (IET, FLET, SLET). When several hazardous phenomena give the same effect (for example: jet fire and flash fire for thermal effects), the result given in the table corresponds to the maximal value obtained for this particular effect considering all phenomena.

Moreover, the runaway of the eventual people exposed is not considered in this evaluation and the leak of hydrogen has been simulated considering a steady and maximum working pressure for the component. These two hypotheses enable to make a careful evaluation of the consequences of such scenarios.

Scenario	Effects	Safety distance [m]		
		SLET	**FLET**	**IET**
STORAGE				
Burst of storage capacity:				
LP - 50 m^3, 45 bar	Blast	58	75	170
HP - 80 L, 440 bar	Blast	9	12	27
HP - 80 L, 950 bar	Blast	12	15	35
Burst of tube-trailer:				
Trailer 1 - 2090 L, 200 bar	Blast	23	29	67
Trailer 2 - 335 L, 500 bar	Blast	15	20	45
Rupture of delivery hose:				
Hose 1 - ∅3 mm, 200 bar	Thermal	11	11	12
	Blast	NR	NR	7
Hose 2 - ∅3 mm, 500 bar	Thermal	17	17	19
	Blast	NR	6	15
ELECTROLYSER				
Burst of the separator:				
Separator	Blast	4	5	12
Rupture of pipe:				
∅12,7 mm, 15 bar	Thermal	13	13	15
	Blast	NR	NR	11
PIPES				
Rupture of pipe:				
Before compressor (∅10 mm, 200 bar)	Thermal	37	37	41
	Blast	23	26	39
Before compressor (∅10 mm, 450 bar)	Thermal	54	54	60
	Blast	36	41	64
After compressor (∅10 mm, 450 bar)	Thermal	54	54	60
	Blast	36	41	64
After compressor (∅10 mm, 1000 bar)	Thermal	77	77	84
	Blast	55	62	99
SHELTER / CONTAINER				
Burst of capacity:				
Electrolyser container	Blast	6	8	18
Compressor container	Blast	12	16	36
DISPENSER				
Rupture of filling hose:				

Scenario	**Effects**	**Safety distance [m]**		
		SLET	**FLET**	**IET**
Hose 1 - ∅3 mm - 350 bar max flow = 120 g/s	Thermal	14	14	16
	Blast	NR	NR	12
Hose 2 - ∅3 mm - 700 bar max flow = 60 g/s	Thermal	10	10	11
	Blast	NR	NR	8
Burst of a tank in a vehicle in fire:				
80 L, 700 bar	Blast	9	12	28
87 L, 350 bar	Blast	8	10	23
Burst of a tank in a vehicle by overpressure:				
80 L, 700 bar	Blast	13	17	39
87 L, 350 bar	Blast	11	14	32

Table 4. Distance of effect for the dangerous phenomena

(IET = irreversible effects threshold, FLET = first lethal effects threshold, SLET = significant lethal effects threshold, NR = Not Reached)

7. EVALUATION OF THE PROBABILITY OF OCCURRENCE OF THE IDENTIFIED DANGEROUS PHENOMENA

Scale	E	D	C	B	A
Meaning	"Event not impossible but never encounter worldwide"	"Event very unlikely": similar event already encountered in the past but was tackled by means of corrective actions hence reducing significantly its likelihood	"Unlikely event": similar event already encountered in the past with the corrective actions not having a significant impact on the likelihood	"Likely event"	"Current event"
Quantitative	10^{-5}	10^{-4}	10^{-3}	10^{-2}	

Table 5. Classes of probability of occurrence of dangerous phenomena

In a French regulatory risk assessment, the probability of occurrence of dangerous phenomena is evaluated with a semi quantitative method, using probability classes such as defined in the Annex 1 of [4]. These classes are given in Table 5. This semi quantitative estimation consists in three steps:

- Step 1: Choice of a probability estimation method. The probability could be estimated from the CE (a leak, for example) or from the cause of the CE (wrong fitting, clamping defect…);
- Step 2: Data collection for the estimation of the probability. Expert view, publications or dedicated data bases could be used for this step;
- Step 3: Summary of data and determination of a probability class for the dangerous phenomena from the data and considering the possible influence of safety measures.

In this study, Ineris evaluated the probability of occurrence from CE (step 1). Since the accidentology involving GHS is relatively poor, which should not necessarily be interpreted as an absence of incident and/or accident but rather a current lack of detailed data, Ineris decided to use generic data sources from the RIVM [14] and the OREDA [15] (step 2), even if these data are not specific to hydrogen nor to GHFS. Table 6 shows the input data collected.

Critical event (CE)	**Frequency**
STORAGE	
Burst of a capacity	5×10^{-7} / year / capacity
COMPRESSION	
Break of a compressor	1×10^{-4} / year / compressor
Compression fault	2.3×10^{-5} / hour
PIPES	
Rupture	1×10^{-6} / year if $\varnothing < 75$ mm
Leak	5×10^{-6} / year if $\varnothing < 75$ mm
HOSE	
Rupture	4×10^{-6} / hour
Leak	4×10^{-5} / hour
VEHICLE'S TANK	
Default of cooling or flow regulation during filling	2.3×10^{-5} / hour

Table 6. Critical events frequencies

Table 7 shows how the probability classes were determined using data from Table 6 (step 3) for the different CE. Some CE can be caused by dominos effects. In this case, Ineris considered that occurrence probability is increased by a 10^{-5}/year factor. This is a lump-sum value based on industrials facilities feedback

Critical event	**Evaluation of the probability of occurrence**	**Probability Class**
STORAGE		
Burst of a capacity	5×10^{-7} / year	E
Rupture of delivery hose	≈ 10 h of working/year (1 truck/week and filling time ≈ 10 min) F_1 = hose rupture frequency = $10 \times 4 \times 10^{-6} = 10 \times 4 \times 10^{-5}$ / year F_2 = dominoes effect frequency = 10^{-5} / year $F = F_1 + F_2 = 5 \times 10^{-5}$ / year	D
SHELTER / CONTAINER		
Explosion of the electrolyser container	F_1 = Pipe rupture frequency ($\varnothing$ 12,7 mm, L = 10 m) = $10 \times 10^{-6} = 10^{-5}$ / year F_2 = dominoes effect frequency = 10^{-5} / year $F = F_1 + F_2 = 2 \times 10^{-5}$ / year (Electrolyser leaks are not considered)	D (Leaks not considered)
DISPENSER		
Burst of tank in a vehicle in fire	F = dominoes effect frequency = 10^{-5} / year	D
Burst of vehicle tank due to « too hot » hydrogen or to overpressure	≈ 300 h of working/year (5 vehicles/day and filling time ≈ 10 min) F_1 = Cooling default frequency = $300 \times 2.3 \times 10^{-5} = 7 \times 10^{-3}$ / year F_2 = Flow regulation default frequency = $300 \times 2.3 \times 10^{-5} = 7 \times 10^{-3}$ / year F_3 = Compression default frequency = $300 \times 10^{-5} = 3 \times 10^{-3}$ / year F_4 = dominoes effect frequency = 10^{-5} / year $F = F_1 + F_2 + F_3 + F_4 = 1.7 \times 10^{-2}$ / year	A

Critical event	Evaluation of the probability of occurrence	Probability Class
Rupture of filling hose	If flow rate is limited to 60 g/s: ≈ 300 h of working/year (5 vehicles/day and filling time ≈ 10 min) F_1 = Hose rupture frequency = $300 \times 4 \times 10^{-6} = 1.2 \times 10^{-3}$ / year F_2 = dominoes effect frequency = 10^{-5} / year $F = F_1 + F_2 = 1.2 \times 10^{-3}$ / year	B
	If flow rate is limited to 120 g/s: ≈ 200 h of working a year (5 vehicles/day and filling time ≈ 7 min) F_1 = Hose rupture frequency = $200 \times 4 \times 10^{-6} = 8 \times 10^{-4}$ / year F_2 = dominoes effect frequency = 10^{-5} / year $F = F_1 + F_2 = 8.1 \times 10^{-4}$ / year	C

Table 7. Critical events probability classes

Some comments can be done:

- As the evaluation was made using generics data sources, the values given in Table 7 do not take into account the influence of technical safety barriers and/or rules of good practices that would be specific to GHFS. The influence of such barriers is studied in Chapter 8.
- The probability classes for a hazardous phenomenon was considered to be the same as for the CE. Indeed, hydrogen being a highly flammable gas, Ineris consider conservatively that its ignition probability is equal to 1 [16].

8. IDENTIFICATION OF SAFETY MEASURES AND THEIR POTENTIAL IMPACT ON THE PROBABILITY OF OCCURRENCE OF THE DANGEROUS PHENOMENA

Identification of relevant safety measures was done based on earlier works from Ineris [17] and on the reading of current regulations and standards ([18], [19], [20], [21], [22], [23], [24]) and of the Canadian hydrogen installation code [25].

A technical safety measure can be valued in a risk assessment only if it meets 3 criteria [26]:

- It is independent from the CE provoking the event that will then lead to its solicitation;
- It is efficient to fulfill the safety function it was chosen for;
- Its response time is appropriate given the kinetic of the hazardous phenomenon it must control.

If these three conditions are met, a trust level (TL) can be attributed to the measure, in order to qualify its level of risk reduction. The probability can be decreased of 1 class for each TL (1 step for a TL1, 2 for TL2…). One should remember that the performance of a safety measure can deteriorate with time. Therefore, maintaining performance must be ensured by maintenance and appropriate inspection, and by carrying out periodic operating tests. Considering the global nature of this study, the TL of each measure was not deeply evaluated (efficiency response time…) but a conservative value has been proposed.

Table 7 shows the work done for the dispenser part only. This table lists good practices rules and safety measures, which may be used for such equipment, and gives a preliminary evaluation of the TL for most measures. By means of this preliminary work, it is possible to determine the work that could be done to decrease the probability of occurrence of dangerous phenomena to a desired class and to determine the nature and the number of safety measures needed to reach this goal.

Component	**Critical event**	**Starting probability class (see Table 7)**	**Proposed safety measures**	**Proposed good practices**	**Final probability class**
Dispenser	Rupture of the filling hose	If flow rate limited to 60 g/s: **B**	- Flow limiter (safety measure already considered for evaluation of intensity) - To put at least one manual emergency stop button (ESB) at the dispenser and a second (recommended) to stop the filling remotely. Actions: to stop the filling immediately (shut valves) and start depressurization of the hoses (shut the compressors) - To put an isolation valve before the dispenser - If a main pipe split to feed several dispensers, to put an isolation valve on each branch. Regulation and flow valves must be independent; the second one is used for the normal filling stop and the safety one (**TL0**) - Check valve on the dispenser to avoid a return of hydrogen from the vehicle when the filling is stopped (**TL0**) - Hydrogen detecting system in the dispensing area action an automatic shutdown of the hydrogen feed (**TL1 only if the dispenser is in a semi-confined area, TL0 otherwise**) - Presence of safe break device (SBD) at the base of every filing hose with automatic filling shutdown (**TL1**) - Sealing test of the filling hose before every filling (**TL1 for leak only**) - Pressure switch low (PSL) at the dispenser with facility shutdown (**TL1**)	- To plan the change of filling hose on a periodic manner - To conceive the dispenser such as the hydrogen quantity freed when disconnecting the hose not being higher than the amount contented in the hose and the dispenser intern pipes at ATP - To conceive the dispensing pistol such as it can't be untied from the vehicle before being depressurized - To install in the dispensing area a vent system for semi-confined system or to put the dispensing area unsheltered. If there is a shelter, it must be conceived to prevent hydrogen accumulation - To position the filling hose such as it doesn't touch the ground when not used - To position the filling hose such as vehicles can't roll over it - To use filling hose shorter than 5 m - To protect the filling hose against abrasion and crease formation - To put permanent lights in the transfer and dispensing areas for facilities opened at night - To protect dispensers against vehicles assaults - To install dispensers on a base at least 150 mm over the ground -To install a filling hose with an electrical continuity or only use dissipative material (floor, coating…) into the dispensing area to avoid electrostatic charges accumulation on peoples	**D** if presence of 2 measures (SBD+PSL)
		If flow rate limited to 120 g/s: **C**			**E** if presence of 2 measures (SBD+PSL)
	Leak on the filling hose	If flow rate limited to 60 g/s: **A**			**B** if sealing test (PSL is judged ineffective for leaks)
		If flow rate limited to 120 g/s: **B**			**C** if sealing test (PSL is judged ineffective for leaks)

Component	**Critical event**	**Starting probability class (see Table 7)**	**Proposed safety measures**	**Proposed good practices**	**Final probability class**
				-To put a robust and flat floor in the dispensing area (a low slop is authorised to evacuate water) - To install only the terminal and the filling hose in the dispensing area - To deny the access of the installation, without supervision. If it is not possible, use a security system such as access card, key or code to make the dispenser system work. To put a remote monitoring device and send a report to guard staff if the ESB is activated.	
Vehicle tank	Burst of vehicle tank due to « too hot » hydrogen or to overpressure	**A**	-To supervise the cooling system by commanding the facility shut down (closing of exit of storage or of the compressor at low flowrate) **(TL1 but could be applied only on 700 bar stations and so for light vehicles)** -To follow the temperature after the cooling system by a transmitter or an alarm commanding the compressor and storage shut down **(TL1)** -To install at every dispenser a pressure transmitter which stop the gas alimentation if pressure increase beyond a defined threshold. Pressure control failures must be detected and lead to emergency shut down **(TL1 if different actuator. If not, TL0)**		**D** if presence of 3 measures (pressure control + temperature control + pressure relief device valve) **E** if presence of 4 measures (pressure control + temperature control + pressure relief device valve + another temperature or cooling system control)
	Burst of tank in a vehicle in fire	**D**	- To install mobile means of firefighting system at the dispensing area		**D**

Table 8. Safety measures study for the H_2 dispenser

9. CONCLUSION

This article presents the risk assessment of a gaseous hydrogen fueling station (GHFS). Using a generic case study, Ineris inventoried the potential hazards that could occur on the different parts of a GHFS and identified the main accidentology for this kind of facilities. A risk analysis was carried on in order to define accidental reference scenarios. The workflow included then a detailed risk assessment, consisting in modeling the hazardous phenomena and in evaluating their probability of occurrence. The study also reviewed different mitigation measures from codes and standards likely to be relevant for GHFS and, for some of them, assessed their impact on the occurrence probability of these phenomena. These preliminary outcomes of this study may be useful for any designer and/or owner of a GHFS who have to perform a safety report.

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