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Detailed scenarios of typical accident for selected FCH systems and infrastructures

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Document history

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Template	20/12/2013	Template for Deliverable	UU
V1_AREVA	20/03/2014	Draft version of typical scenarios for hydrogen-energy containers (AREVA)	Audrey Duclos Franck Verbecke
V1_UU	11/04/2014	Table of contents suggested (UU)	Li Zhiyong; Tretsiakova-McNally Svetlana; Molkov Vladimir; Makarov Dmitriy
V1_AREVA_revised	15/05/2014	Revised deliverable of scenarios for stationary (AREVA)	Audrey Duclos Franck Verbecke
V2_UU	22/05/2014	Draft deliverable of scenarios for cars and buses(UU)	Li Zhiyong
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V3	05/06/2014	Finalized deliverable of scenarios for cars and buses(UU)	Li Zhiyong; Tretsiakova-McNally Svetlana
V4	09/12/2014	Finalized version typical scenarios for hydrogen energy containers and stationary storage and piping	Audrey Duclos Adrien Zanoto François Lauman Franck Verbecke
V5	02/04/2015	Final version integrating scenarios for all applications	Audrey Duclos Li Zhiyong Tretsiakova-McNally Svetlana Adrien Zanoto François Lauman Franck Verbecke

V6	14/09/2015	Integration of the new detailed scenarios, scenario matrix and table of potential effects for each application	Franck Verbecke
V7	16/10/2015	Final quality check	Svetlana Tretsiakova-MCNally Audrey Duclos Sebastien Bertau Randy Dey Li Zhiyong

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Vocabulary

- ATEX	**Explosive Atmosphere**
- ELY	Electrolysis
- FC	Fuel Cell
- LC	Level of Confidence
- LEL	Lower Explosive Level
- LFL	Lower Flammable Level
- QHSE	Quality, Heath, Safety and Environment
- SIL	Security Integrity Level
- UVCE	Unconfined Vapour Cloud Explosion
- VCE	Vapour Cloud Explosion

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1. INTRODUCTION

This task aims to identify and detail typical worst case scenarios that can occur on hydrogen applications.

For each FCH installation, feedbacks and lessons learned, hazardous phenomena, detailed scenarios using fault/event tree analysis accounting for positives or negative impact of the tactic conducted by the First Responders is considered.

To assess the consequences of each scenario, typical leak size, storage pressure, hydrogen inventory are selected for each FCH application. Contemporary CFD and/or engineering tools have been used to assess the potential consequences of the hazardous phenomena.

The content of this deliverable will be integrated into educational materials that will be available online through educational activities and will serve to the development of the scenarios used for operational and Virtual Reality trainings.

2. METHODOLOGY

For each FCH application covered by the HyResponse project, the same methodology is applied. In particular, each FCH application is considered in a chapter and each chapter is structured in the same way as described in the following sub-chapters below.

2.1. An example of incident/accident

For each FCH application, at least one example of the reported incidents or accidents is described. These examples are mainly extracted from two tools available online:

- Incident and Accident Database (HIAD HySafe HIAD), the European knowledge base and reporting regime to assist industry and authorities in better understanding the relevance of hydrogen-related incidents and accidents as well as the safety actions taken.
- H2Incidents Hydrogen Incidents Database is a database-driven website intended to facilitate the sharing of lessons learned and other relevant information gained from actual experiences using and working with hydrogen.

2.2. Identification of hazardous phenomena

For each FCH application, the potential hazards that could have an impact on life, property or environment have been summarised in table. As an example Table 1 summarises the potential hazards identified for equipment such as pipes and high-pressure storage tanks.

Table 1: Example of hazardous phenomena for stationary storages

Substance	Equipment of hazards	Potential hazard
Hydrogen	Tanks	Burst of a pressurized tank
Hydrogen	Pipes	UVCE (Unconfined Vapour Cloud Explosion) Jet Fire Flash Fire

2.3. Detailed scenarios using a “bow-tie” diagram

Once a hazardous phenomenon is identified, a “bow-tie” diagram is used to represent the sequence of events that could lead to an accident. As it shown on Figure 1 below, this bow-tie diagram re-groups the representation of a *fault tree* on the left-hand side as well as the representation of a *consequence tree* on the right-hand side.

The same methodology has been used to represent the detailed scenarios that could be encountered by first responders on an accidental scene. It is therefore considered that all the safety barriers inherent to the FCH applications may have failed or that it was a false alarm.

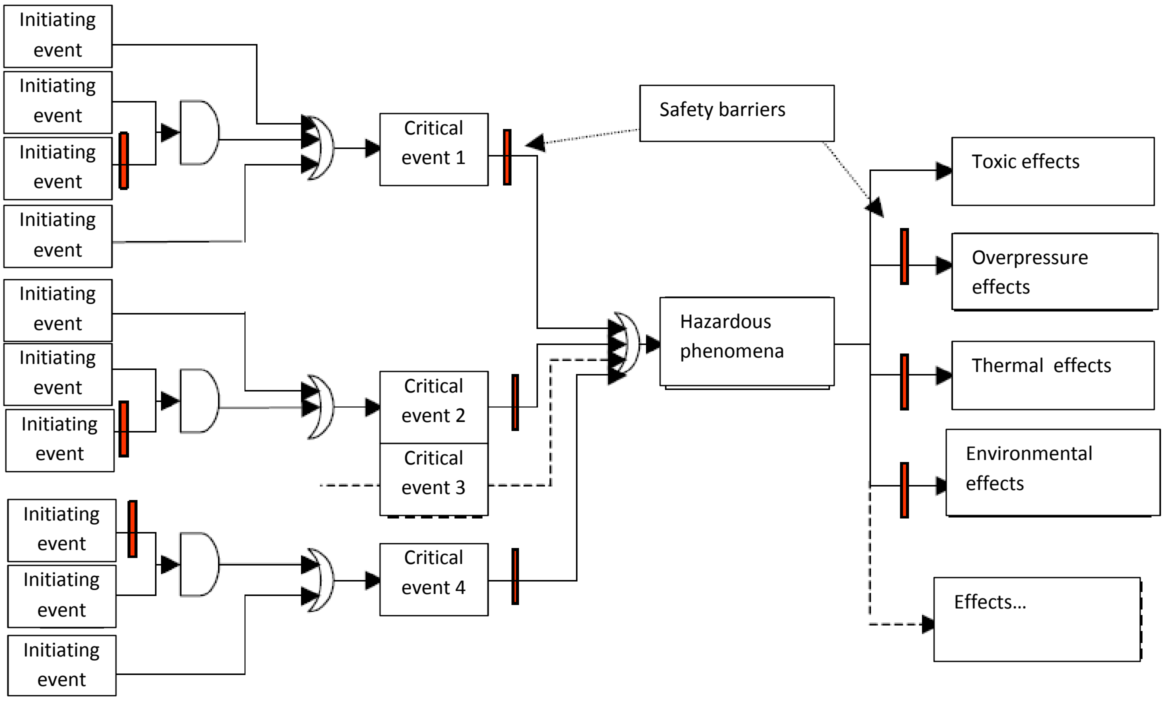

Figure 1: Representation of hazardous phenomena using a “bow-tie” diagram

2.4. Potential consequences

The severity of a hazardous phenomenon is characterized by a potential effect, itself characterized by several threshold distances e.g. explosion overpressure threshold of 20 mbar reached at a distance of 5 m from the FCH application. Depending on the regulation in place locally, each country may use different values of thresholds or even parameters to characterize the potential effects of a hazardous phenomenon.

NOTE: it is not the intent of HyResponse project to provide harmonized harm criteria or thresholds to characterize the potential effects of a hazardous phenomenon. Different tools and different harm criteria have been used in this deliverable. It is of the responsibility of stakeholder to adapt them to reach their reference standard in their own country.

2.4.1. Blowdown time of pressurized tanks

The blow down time can be calculated using engineering tool available within Cyber Laboratory (http://h2fc.eu/cyber-laboratory/44).

2.4.2. Leak from FCH system

The envelopes of the flammability limits from hydrogen jet release can be calculated using engineering tool available within Cyber Laboratory (http://h2fc.eu/cyber-laboratory/44).

2.4.3. Thermal effects

The flame length and separation distances from jet fires can be calculated using engineering tool available within Cyber Laboratory (www.h2fc.eu/cyber-laboratory).

Two examples are provided below to characterize the potential effects of a hydrogen jet fire on a human. As shown in Table 2, the harm criteria for jet fire may be characterized as a function of the temperature degrees of the flame for a given exposure period[1], while, as shown in Table 3, it may also be described as a function of the thermal flux per square meter (kW/m^2) or with a notion of time (kW/m2)$^{4/3}$s.

Table 2: Harm criteria and corresponding separation distances for jet fire[1]

Harm levels	"No harm" limit	"Pain" threshold	"Death" limit
Criteria	70 ^{o}C for any duration	115 ^{o}C for 5 min exposure	309 ^{o}C for 20 s exposure, causing third degree burn
Separation distances	3.5× F_L	3× F_L	2× F_L

Note: F_L stands for Flame Length (m)

Table 3: Example of threshold effect values on humans

	Thresholds of thermal effects	
	kW/m^2	(kW/m^2)$^{4/3}$s
Irreversible effects	3	600
Lethal effects	5	1000
Significant lethal effects	8	1800

2.4.4. Overpressure effects

The overpressure effects from an explosion can be characterized by several thresholds depending on the target i.e. human or structures. The Table 4 and 5 provide an example of threshold effect values for human and constructions, respectively.

- Effects on humans

Table 4: Example of threshold effect values on humans

	Thresholds of overpressure effects	
	mbar	kPa
Irreversible effects by indirect effects (glass breakage)	20	2
Irreversible effects	50	5
Lethal effects	140	14
Significant lethal effects	200	20

- Effects on constructions

Table 5: Example of threshold effect values on structures

	Thresholds of overpressure effects	
	mbar	kPa
Significant destruction of windows	20	2
Light damage of structures	50	5
Important damage of structures	140	14
Domino effects	200	20

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[1] Molkov, V. Fundamentals of Hydrogen Safety Engineering Ⅰ, October, 2012 www.bookboon.com

Prolonged exposition and very important damage of structures, except concrete	300	30

Several tools are provided in Annexe in order to calculate overpressure effects from a pressurized tank burst.

2.5. Scenarios matrix

Based on the detailed scenarios and the bow-tie diagram realized for each FCH application, a scenario matrix has been generated for all FCH applications. This scenario matrix distinguishes four types of incidents:

- No H2 leak, no fire,
- H2 leak,
- FCH application in fire,
- An external fire threatening the FCH application

In addition, the scenario matrix is elaborated by classifying all the scenarios into three levels i.e. “Discovery level”, “Advanced level”, and “Expert level” in order to reflect the increase of the trainee’s skill required for the training exercises that could be played online, on the operational and the virtual reality platforms.

The Table 6 represents the structure of the scenario matrix.

Table 6: Structure of the scenario matrix

FCH application	**Potential danger**	**Discovery level**		**Advanced level**		**Expert level**	
		Scenario identification	**Description**	**Scenario identification**	**Description**	**Scenario identification**	**Description**
XXX	**NO LEAK**						
	LEAK						
	H2 FIRE						
	EXTERNAL THREAT						

3. TYPICAL SCENARIOS FOR FC CAR

3.1. Feedback and lessons learned from an accident

The feedback is extracted from the database h2tools.org/lessons/ and articles.

Hydrogen Fuel Cell Vehicle Traffic Accident (2007)
<http://h2tools.org/lessons/hydrogen-fuel-cell-vehicle-traffic-accident>

Severity	Incident
Leak	No
Ignition	No

DESCRIPTION: On a Friday afternoon in 2007 a traffic accident occurred at the corner of two urban streets. Two vehicles were involved. Each vehicle contained a single driver (no passengers). Vehicle 1 was a Fuel Cell Vehicle. Vehicle 2 was a conventional Toyota Camry. Vehicle 1 was traveling west, approaching an intersection with a green light, and proceeded into the intersection. Vehicle 2 was traveling north on a cross street. The driver of Vehicle 2 incorrectly perceived a green light and proceeded into the intersection. The vehicles collided in the intersection.

RESPONSE: The police were coincidentally in the area and able to respond quickly to the site. The vehicles were moved out of the intersection. Vehicle 1 (fuel cell vehicle) shut down upon impact and was pushed out of the intersection by the police officer. The fire department and EMTs were called to the scene of the accident, and arrived quickly. Both drivers were examined by the fire department and refused medical assistance. Medical release forms were signed by both drivers. INJURIES: The driver of Vehicle 1 sustained minor injuries on the arm as a result of the impact from the collision. The injuries sustained by the driver of Vehicle 1 were minimal; minor scrapes and redness on the forearm in a 1 - 2 inch area. The driver of Vehicle 2 did not sustain any injuries.

EQUIPMENT DAMAGE: Both vehicles sustained "minor to moderate" front-end damage according to the Police report. The driver's side air bag deployed in Vehicle 1. The impact of the collision occurred at the driver-side front quarter panel of Vehicle 1. The frame of the vehicle was damaged too significantly to repair. Digital photos were taken of the damage to the vehicles to document the damage.

RESPONDERS' KNOWLEDGE OF H2: Several emergency personnel teams responded to the vehicle accident. Those entities are listed below with the level of training that they had received about hydrogen and the fuel cell vehicle.

Police Department: Officers from the Police Department that arrived on site had not received hydrogen safety training.
Fire Department: Members of the Fire Department participated in hydrogen safety training, when offered by the project partners, prior to vehicle deployment and the station opening. However, the Fire Department personnel who responded to the incident had not received hydrogen safety training.
EMTs: The EMTs had not received hydrogen safety training.

Fleet Supervisor: The Supervisor that responded to the accident had participated in hydrogen safety training conducted by the fleet agency.

SAFETY PROCEDURES AND DAMAGE EVALUATION: According to the driver of Vehicle 1, the vehicle shut down upon impact. The vehicle was designed to shut down upon impact to isolate the hydrogen fuel and high voltage systems. At the scene of the accident, a visual inspection of the vehicle was performed. Additionally, the vehicle was checked with a sniffer to ensure that there were no hydrogen leaks. The Fire Department and EMTs were last to arrive at the accident site, following the inspection of the vehicles.

The automotive company's preliminary evaluation of the vehicle following the accident proved that the safety systems functioned as designed. The Emergency Shut-Down Procedure activated, and the hydrogen in the storage vessels was isolated. Upon further evaluation, the automotive company determined that the damage to the vehicle was severe despite the appearance of minimal body damage. The impact of the collision occurred at the driver-side front quarter panel of the vehicle. The frame of the vehicle was damaged too significantly to repair. In order for the vehicle to return to operation, the front section of the frame from the damaged vehicle would need to be severed and removed. A frame from another vehicle would then need to be welded to damaged vehicle. The timeline for this process is lengthy, therefore, the vehicle has been retired and the fuel cell stack has been salvaged and reused in another vehicle. The fuel cell supplier conducted an investigation of the fuel cell power plant within the vehicle. The evaluation of the fuel cell proved that the fuel cell system remained intact and unharmed by the impact of the collision.

Lessons Learned:

1. The fuel cell vehicle that was involved in the accident has been retired. The fuel cell power plant from that vehicle has been removed and is being used in another fuel cell vehicle.
2. The fuel cell vehicle accident reinforced the need for training of drivers, supervisors and emergency response personnel. As an action item, this project team will conduct refresher training courses for the drivers and local emergency response personnel. The project leads conducted training classes on hydrogen safety and incident response for local emergency response personnel; including the local fire department and the police prior to vehicle deployment and the station opening. A significant learning by this project team is that emergency response agencies are subject to frequent personnel changes. As such, training should be repeated periodically.

3.2. Hazardous phenomena

The table below identifies the hazardous phenomena related to a FC car:

Table 7: Hazardous phenomena for a FC car

Products	Equipment of hazards	Potential hazard
Flammable materials	Car, batteries, tyres, engine, etc.	Fire
Hydrogen	Tanks	Burst

Hydrogen	TPRD (Temperature activated Pressure Relief Device)	UVCE Jet Fire
Hydrogen	Pipes and other components	UVCE Jet Fire
Electricity	Cable	Electrocution

3.3. Detailed scenarios

The Figure 2 below represents the bow-tie diagram identified for a FC car incident/accident.

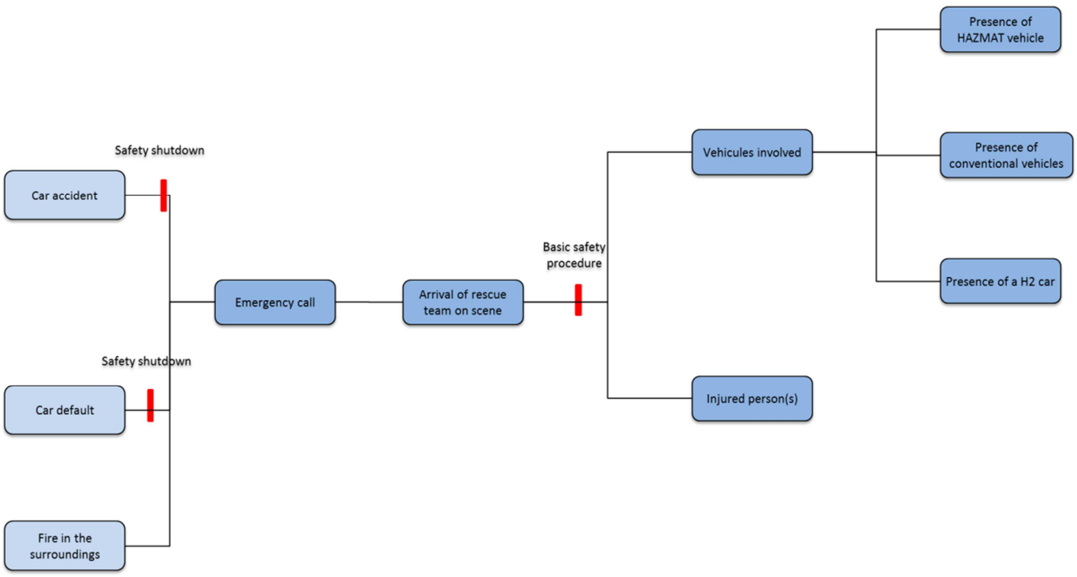

Figure 2: Example of bow-tie diagram for FC car

3.4. Potential consequences

3.4.1. Tank blowdown of a FC car

The Table 8 below gives the blowdown times of hydrogen storage tanks with different capacities and at different pressures, when they are completely full, for 3 different sizes of a hole/leak: 1, 2.3 and 4.2 mm.

Table 8: Blowdown time in function of tank type, pressure and hole size

Tank capacity, L	**Storage pressure (bar)**	**Blowdown time**		
		1 mm	**2.3 mm**	**4.2 mm**
80	350	20 min	**4 min**	**50 s**
171	350	25 min	**9 min**	**80 s**
80	700	> 21 min	**300 s**	**80 s**
150	700	> 40 min	**10 min**	**200 s**

It is important to notice that, during a blowdown process, most of the pressure decays rapidly at the first stage of the process, then, it decays slowly to reach atmospheric pressure as shown on Figure 3 below.

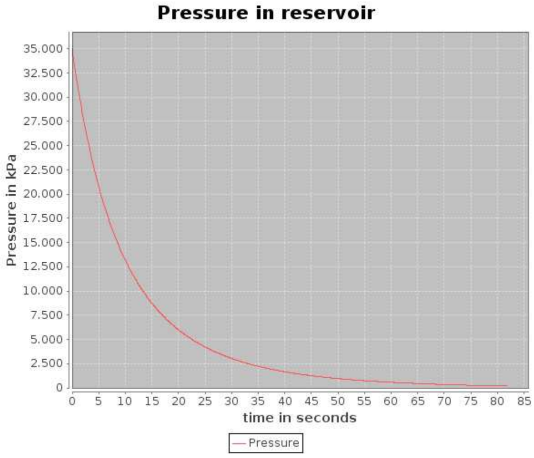

Figure 3: Blowdown process of a 171 L hydrogen tank at initial pressure of 350 bar through a leak of 4.2 mm in diameter

3.4.2. Hydrogen leak from FC car piping system

The distances obtained for different hydrogen concentrations are also given in Table 9 based on the three different sizes of a hole/leak:1, 2.3 and 4.2 mm.

Table 9: Distances to hydrogen concentration for 350 and 700 bar

Pressure (bar)	Release Diameters (mm)	Separation distances to 4 vol. % (m)	Range of flame tip	
			8 vol. % (m) —	16 vol. % (m)
350	1	5.2	2.5	1.1
350	2.3	15	7.2	3.3
350	4.2	6.5	3.1	1.4
700	1	8.4	4	1,.8
700	2.3	19	9	4
700	4.2	35	17	7.8

3.4.3. Hydrogen jet fires from FC car piping system

The Table 10 below gives the thermal and potential overpressures obtained from hydrogen jet fires.

Table 10: Thermal and potential overpressure effects obtained from hydrogen jet fires

Piping leak diameter	Pressure of the tank (bar)	Direct ignition **(JET FIRE)**					Delayed ignition **(UVCE)**			
		Thermal effects (m)			Flame length (m)		Overpressure effects (m)			
		3 kW/m^2	5 kW/m^2	8 kW/m^2	L	r	20 mbar	50 mbar	140 mbar	200 mbar
1 mm	350 bar	3.2	3	2.8	1.6	0.3	9.5	4.8	2	1.5
2.3 mm	350 bar	7	6.5	6	3.8	0.6	22	11	4.7	3.4
4 mm	350 bar	15	14	13	6.8	1.2	38	19	8.2	6
1 mm	700 bar	3.5	3.3	3	1.9	0.3	12	6	2.6	1.9
2.3 mm	700 bar	10	9	8	4.7	0.8	29	14.5	6.1	4.5
4 mm	700 bar	19	17	15	8.3	1.4	50	25	10.7	7.8

3.4.4. Jet fire from a TPRD mounted on 350 and 700 bar hydrogen tanks

The Table 11 gives the separation distances for jet fires for 350 and 700 bar when the TPRD is oriented vertically and the jet oriented towards the floor/ground.

Table 11: Separation distances for jet fires from a TPRD mounted on 350 and 700 bar hydrogen tanks

Release diameters (mm)	Pressure of the tank (bar)	Flame length, m	No harm, m	Pain threshold, m	3rd degree burn, m
4.2 (TPRD opens vertically)	350	6.8	23.8	20.4	13.6
4.2 (TPRD opens vertically)	700	8.3	29	25	16.6
4.2 (TPRD oriented vertically to the floor)	700	< 4	14	12	8

The Figure 4 shows the visible flame and the thermal flux obtained during the activation of a TPRD mounted on a 700 bar hydrogen tank. It was observed that, despite the ignition of hydrogen, the paper flags located at a distance of 4 m from the back of a car were not burnt after the complete blowdown of hydrogen storage tank.

Figure 4: Jet fire exiting from a TPRD mounted on a 700 bar H2 tank

Nonetheless, it can be seen that a hot cloud released at the initial stage of the blowdown reaches longer distance as indicated by thermal image camera in Figure 4 for 700 bar ignited blowdown. As shown in the Figure 5, this hot cloud is clearly demonstrated for the 350 and 700 bar hydrogen storages in the simulation carried out by the University of Ulster.

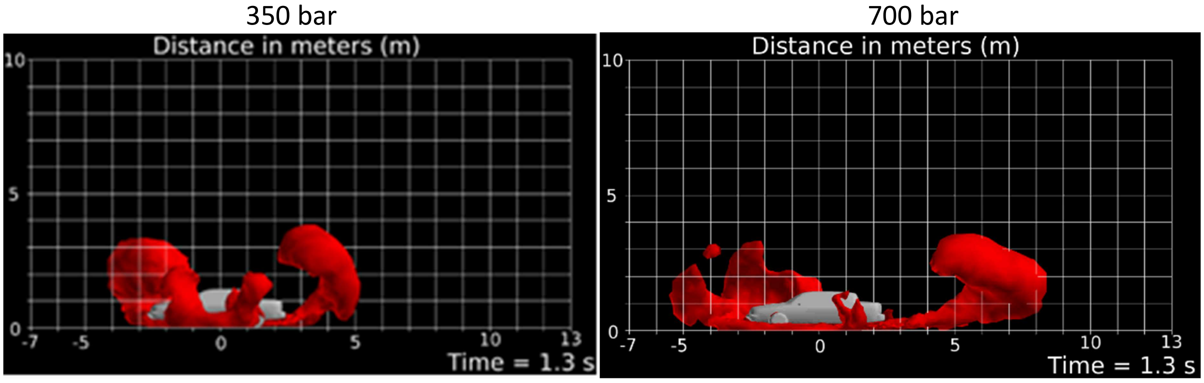

Figure 5: Simulation of ignited hydrogen release from a TPRD mounted on a 350 and 700 bar H2 tank

3.4.5. Tank burst of a FCH car

In case of a TPRD failure, the tank may rupture. The table 12 below gives the potential overpressures distances in case of a tank burst for both 350 and 700 bar and volumes of the tanks of about 80 L and 150 L.

Table 12: Distances of the overpressure effects due to tank burst[2]

Type of storage	Tank capacity	Storage pressure (bar)	Overpressure burst (bar)	Significant lethal effects – Domino effects 200 mbar (m)	Lethal effects 140 mbar (m)	Irreversible effects 50 mbar (m)	Indirect effects : broken glass 20 mbar (m)
Type III	Bottles 74 L	350	595	8	11	25	50
Type III	Bottles 171 L	350	595	12	15	38	77
Type IV	Bottle 80 L	700	770	9	12	28	56
Type IV	Bottles 150 L	700	770	13.5	16	42	84

HySAFER has developed methodologies for blast wave. A graphical representation of the methodology can be found below.

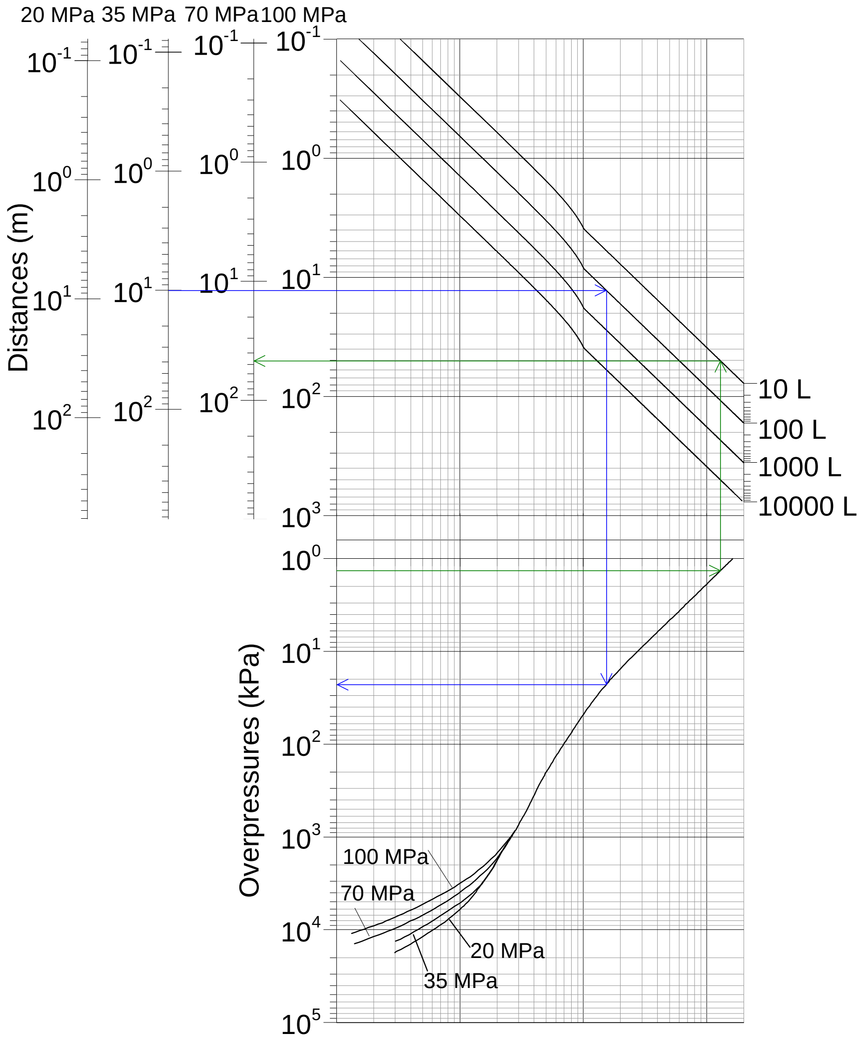

Figure 6 : Overpressure-distance nomogram for stand-alone tank rupture

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[2] Information extracted from "Cadre de bouteilles H4-142 ; logistique 700 bar pour l'hydrogène énergie", January 2013, AIR LIQUIDE written by Verghade

3.5. Scenario matrix for FC car

The table 13 below summarizes the scenarios for a FC car into 4 types of categories i.e. no leak, leak, FCH application in fire, external fire threatening the application and classified according to 3 levels of complexity i.e. discovery level, advanced level and expert level.

Table 13: Scenario matrix for a FC car

FCH application	**Potential danger**	**Discovery level**		**Advanced level**		**Expert level**	
		Scenario identification	**Description**	**Scenario identification**	**Description**	**Scenario identification**	**Description**
FC CAR	**NO LEAK**	FC_Car_D_NL1	Single FC car **accident** - **no H2 leak** - **extrication** - simple environment	FC_Car_A_NL1	Multi vehicle accident - no H2 leak from the FC car - **extrication** - complex environment (motorway, urban environment, tunnel)		
	LEAK	FC_Car_D_L1	FC car default - **H2 leak** - simple environment (small road)	FC_Car_A_L1	FC car default - H2 leak from the FC car - medium complex environment (car mechanics, domestic house, open space parking)	FC_Car_E_L1	FC car default - H2 leak from the FC car - complex environment (motorway, urban environment, tunnel, underground parking)
		FC_Car_D_L2	Single FC car **accident** - **H2 leak** - no **extrication** - simple environment (small road)	FC_Car_A_L2	Single FC vehicle **accident** - **H2 leak** from the FC car - **extrication** - simple environment	FC_Car_E_L2	Multi vehicle **accident** - **H2 leak** from the FC car - **extrication** (FC car and/or conventional car) - complex environment (motorway, urban environment, tunnel)
				FC_Car_A_L3	Multi vehicle **accident** - **H2 leak** from the FC car - **no extrication** - complex environment (motorway, urban environment, tunnel)		
	H2 FIRE	FC_Car_D_F1	FC car default - **FC car in a fire** - simple environment (small road)	FC_Car_A_F1	FC car default - FC car in a **fire** - medium complex environment (car mechanics, domestic house, open space	FC_Car_E_F1	FC car default - FC car in a fire - complex environment (motorway, urban environment, tunnel, underground parking)

					parking)		
		FC_Car_D_F2	Single FC car **accident** - **FC car in fire** - no **extrication** - simple environment (small road)	FC_Car_A_F2	Multi vehicle accident - FC car in fire - no extrication - complex environment (motorway, urban environment, tunnel)	FC_Car_E_E2	Multi vehicle accident - FC vehicle in fire - extrication (FC car and/or conventional car) - complex environment (motorway, urban environment, tunnel)
	EXTERNAL THREAT			FC_Car_A_E1	**Fire in a medium complex environment** (car mechanics, domestic house, open space parking) - FC car in the environment	FC_Car_E_E1	**Fire in a complex environment** (motorway, urban environment, tunnel, underground parking) - FC car in the environment
						FC_Car_E_E2	Multi vehicle accident - conventional car in fire - extrication from the FC vehicle - complex environment (motorway, urban environment, tunnel)
						FC_Car_E_E3	More complex situation with an Hazmat trailer involved

4. TYPICAL SCENARIOS FOR FC BUS

4.1. Feedback and lessons learned

Hydrogen Prototype Bus Slips off Jack Stand (2003)

https://h2tools.org/lessons/hydrogen-prototype-bus-slips-jack-stand

Severity	Incident	
Leak	No	
Ignition	No	

An apprentice mechanic lacerated his right forearm while quickly sliding out from under a hydrogen prototype bus when the bus slipped off a hydraulic jack. The apprentice and another mechanic had raised the bus about 1 foot from the ground to position it on jack stands when the hydraulic jack tipped over. The apprentice went to the site medical facility, where he needed five stitches to close the wound in his forearm.

The mechanics were raising the rear of a hydrogen prototype bus, like the one in the figure below, and placing it on jack stands. After chocking the wheels, they used bottle jacks on each side of the rear axle to raise the bus high enough to place a 20-ton hydraulic jack under the differential. With the bus resting on a pair of small jack stands, they raised the bus by the differential so that the weight of the bus was balanced on the hydraulic jack.

The mechanics then began to place a large jack stand under the driver's side of the bus. The mechanics were under the bus positioning the jack stand when the mechanic noticed that the hydraulic jack was beginning to tip, and he called out to the apprentice that the bus was coming down. The jack tipped to one side, causing the weight of the bus to drop suddenly onto the small jack stand on the passenger side of the bus. As the apprentice slid from under the bus, the weight of the bus landed on the small jack stand under the passenger side, causing it to break and drop the rear tire to the ground. The apprentice cut his right forearm on a jagged metal edge on the storage compartment as he moved out from under the bus.

The construction manager ordered a root cause analysis, which revealed a number of causal factors. The most obvious of these was the small jack stand breaking and dropping the bus to the ground on one side. Even more significantly, the work package failed to provide adequate information on the type of bus and environment in which the mechanics would be working, and no procedure existed for jacking up vehicles. Investigators were unable to conclusively determine the reason the hydraulic jack tipped.

The work package did not describe the bus that would be involved: a hydrogen prototype bus that is heavier than conventional fuel bus models and has an uneven lateral weight distribution. The bus' total weight was 30,000 pounds, two-thirds of which was in the rear. The mechanics had never worked with this type of bus before, and were unprepared for the task. They proceeded to perform the task as they had done in the past with conventional buses.

The work package did not specify a safe location for working on this type of bus. The bus was sitting on an asphalt surface, with a slight slope toward the front, and was locked. The mechanics had no way to move it onto a concrete pad, which would have provided greater stability.

The mechanics were relying on skill-of-the-craft to perform this work because there was no procedure on safely jacking heavy vehicles. They did not use cribbing to more evenly distribute the bus' weight, and the hydraulic jack was not equipped with a saddle or cup to prevent slipping. A procedure on jacking up vehicles would have significantly reduced the likelihood of this accident.

Following the critique, the construction manager began developing a procedure on jacking and cribbing mobile equipment. Training will be provided to mechanical personnel when the procedure is complete. In addition, the construction group will develop a system for identifying work requests involving different mobile equipment.

Lessons Learned:

This event illustrates the importance of adequately planning and communicating work. Procedures should cover all types of equipment that will be utilized. Work packages should clearly describe the equipment that will be used and the surrounding environment. Workers should be aware of potential hazards and un-known configurations before they begin work. Job hazard analyses should identify all situations that could pose a hazard to workers.

4.2. Hazardous phenomena

The hazard potentials considered for a FC bus are described below:

Table 14: Hazardous phenomena for FC bus

Products	Equipment of hazards	Potential hazard
Flammable materials	bus, batteries, tyres, engine, etc.	Fire
Hydrogen	Tanks	Burst
Hydrogen	TPRD (Temperature activated Pressure Relief Valves)	UVCE Jet Fire
Hydrogen	Pipes and other components	UVCE Jet Fire
Electricity	Cable	Electrocution

4.3. Detailed scenarios

The Figure 7 below represents the bow-tie diagram identified for a FC bus incident/accident.

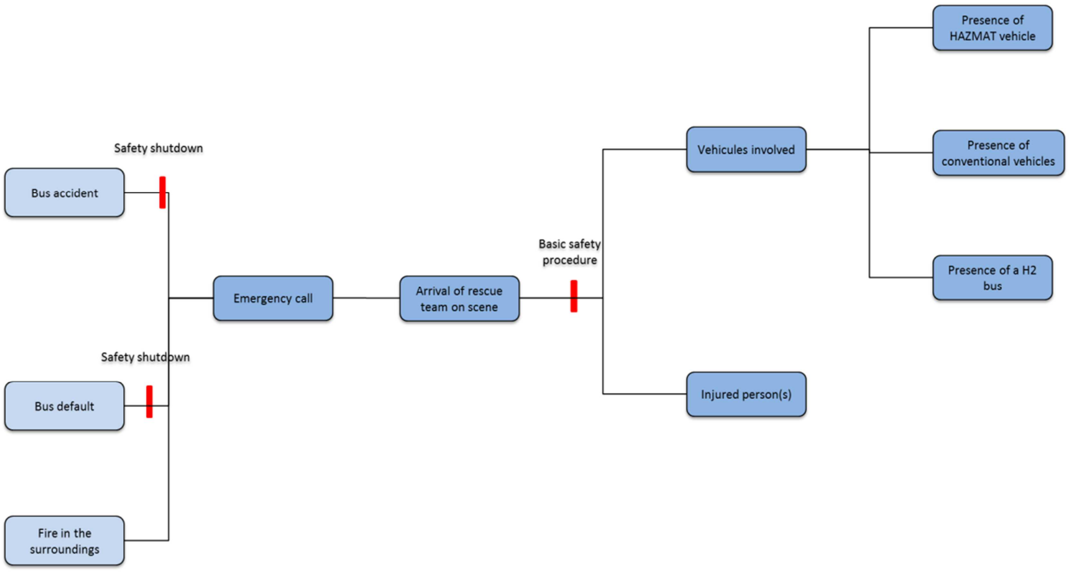
Safety shutdown
Bus accident
Safety shutdown
Bus default
Fire in the surroundings
Emergency call
Arrival of rescue team on scene
Basic safety procedure
Vehicules involved
Injured person(s)
Presence of HAZMAT vehicle
Presence of conventional vehicles
Presence of a H2 bus

Figure 7: Example of bow-tie diagram for FC bus

4.4. Potential consequences

4.4.1. Tank blowdown of a FC bus

The Table 15 below gives the blowdown time of 80 L and about 171 L tanks when they are completely full for 3 different leak sizes: 1, 2.3 and 4.2 mm.

Table 15: Blowdown time as a function of tank type, pressure and leak size

Tank volume, L	**Storage pressure (bar)**	**Blowdown time**		
		1 mm	**2.3 mm**	**4.2 mm**
80	350	20 min	**4 min**	**50 s**
171	350	25 min	**9 min**	**80 s**

4.4.2. Hydrogen leak from FC bus piping system

The distances obtained for different hydrogen concentrations are also given in Table 16 based on the three different leak sizes: 1, 2.3 and 4.2 mm.

Table 16: Distances to hydrogen concentrations from 350 bar pressurized tank

Pressure (bar)	Release Diameters (mm)	Separation distances (m) 4 vol. %	Range of flame tip (m)	
			8 vol. % —	16 vol. %
350	1	5.2	2.5	1.1
350	2.3	15	7.2	3.3
350	4.2	6.5	3.1	1.4

4.4.3. Hydrogen jet fires from FC bus piping system

The Table below gives the thermal and potential overpressures obtained from hydrogen jet fires

Table 17: Thermal and potential overpressure effects obtained from hydrogen jet fires at 350 bar

Piping leak diameter, mm	Pressure of the tank (bar)	Direct ignition **(JET FIRE)**					Delayed ignition **(UVCE)**			
		Thermal effects (m)			Flame length (m)		Overpressure effects (m)			
		3 kW/m^2	5 kW/m^2	8 kW/m^2	L	r	20 mbar	50 mbar	140 mbar	200 mbar
1	350	3.2	3	2.8	1.6	0.3	9.5	4.8	2	1.5
2.3	350	7	6.5	6	3.8	0.6	22	11	4.7	3.4
4	350	15	14	13	6.8	1.2	38	19	8.2	6

4.4.4. Jet fire from a TPRD mounted on 350 bar hydrogen tank

The Table 18 gives the separation distances for jet fires for 350 bar hydrogen storage, when the TPRD is oriented vertically or horizontally. Indeed, there is no harmonization regarding the orientation of the TPRD. Therefore, both directions have to be considered.

Table 18: Separation distances for jet fires from TPRD mounted on 350 bar hydrogen tank

Release diameters (mm)	Pressure of the tank (bar)	Flame length, m	No harm, m	Pain threshold, m	3rd degree burn, m
4.2 (TPRD opens vertically or horizontally)	350	6.8	23.8	20.4	13.6

4.4.5. Tank burst on a FCH bus

In case of a TPRD failure, the tank may rupture. The table 19 below gives the potential overpressures distances in case of tank burst for 350 bar hydrogen storage tank installed on a FC bus.

Table 19: Distances of the overpressure effects due to FC bus tank burst

Type of storage	**Tank capacity**	**Storage pressure (bar)**	**Overpressure burst (bar)**	**Significant lethal effects – Domino effects 200 mbar (m)**	**Lethal effects 140 mbar (m)**	**Irreversible effects 50 mbar (m)**	**Indirect effects : broken glass 20 mbar (m)**
Type III	Bottles 74 L	350	595	8	11	25	50
Type III	Bottles 171 L	350	595	12	15	38	77

4.5. Scenario matrix for FC bus

The Table 20 below presents the scenario matrix compiled for a FC bus.

Table 20: Scenario matrix for a FC bus

FCH application	Potential danger	Discovery level		Advanced level		Expert level	
		Scenario identification	Description	Scenario identification	Description	Scenario identification	Description
FC BUS	**NO LEAK**	FC_Bus_D_NL1	Single FC bus **accident** - no leak - **extrication** - simple environment	FC_Bus_A_NL1	Multi vehicle accident - no H2 leak from the FC bus -**extrication** - complex environment (motorway, urban environment, tunnel)	FC_Bus_E_L1	FC bus default - H2 leak from the FC bus - complex environment (motorway, urban environment, tunnel, underground parking)
	LEAK	FC_Bus_D_L1	FC bus default - **H2 leak** - simple environment (small road)	FC_Bus_A_L1	FC bus default - H2 leak from the FC bus - medium complex environment (car mechanic, bus warehouse, open space parking)	FC_Bus_E_L2	Multi vehicle accident - H2 leak from FC bus - extrication (FC bus and/or conventional car) - complex environment (motorway, urban environment, tunnel)
		FC_Bus_D_L2	Single FC bus **accident** - **H2 leak** - no **extrication** - simple environment	FC_Bus_A_L2	Single FC bus accident - H2 leak from the FC bus - extrication - simple environment		
				FC_Bus_A_L3	Multi vehicle accident - H2 leak from the FC bus - no extrication - complex environment (motorway, urban environment, tunnel)		

	H2 FIRE	FC_Bus_D_F1	FC bus default - FC bus in a **fire** - simple environment (small road)	FC_Bus_A_F1	FC bus default - FC bus in fire - medium complex environment (car mechanic, bus warehouse, open space parking)	FC_Bus_E_F1	FC bus default - FC car in fire - complex environment (motorway, urban environment, tunnel, underground parking)
		FC_Bus_D_F2	Single FC bus **acciden**t - FC bus in **fire** - simple environment (small road)	FC_Bus_A_E2	Multi vehicle accident - FC bus in fire - no extrication - complex environment (motorway, urban environment, tunnel)	FC_Bus_E_F2	Multi vehicle accident - FC bus in fire - extrication (conventional car) - complex environment (motorway, urban environment, tunnel)
	EXTERNAL THREAT			FC_Bus_A_E1	Fire in a medium complex environment (car mechanic , bus warehouse, open space parking) - FC bus in the environment	FC_Bus_E_E1	**Fire** in a complex environment (motorway, urban environment, tunnel, underground parking) - FC bus in the environment
						FC_Bus_E_E3	Multi vehicle accident - conventional car in fire - extrication from the FC bus - complex environment (motorway, urban environment, tunnel)
						FC_Bus_E_E4	More complex situation with an Hazmat trailer involved

5. TYPICAL SCENARIOS FOR HYDROGEN TRAILERS

5.1. Feedback and lessons learned

The analysis of accidents relating to semi-trailers is presented here. The list deliberately does not include events which might have been the result of a road accident. In fact, such an accident analysis might have no direct link with the intended purpose of this document.

Reference	"Tube trailer leak through Over-Pressure-Protection Rupture Disk" http://h2incidents.org/incident.asp?inc=267
Description	Failure of a rupture disc in one of the semi-trailer's tubes and discharge of hydrogen during a filling operation.
Consequence	Intervention by an emergency team. Little or no apparent damage.
Cause	Untimely opening of the rupture disc, probably caused by a poor choice of material.
Ineris[3] comment	**The semi-trailer to be used to supply the site with H_2 does not have a rupture disc.**

Reference	"Hydrogen Delivery Truck Causes Hydrogen Leak at Fill Station Due to Improperly Stored Hydrogen Fill Line at Departure" http://h2incidents.org/incident.asp?inc=239
Description	The driver of a semi-trailer ripped off a poorly stowed hydrogen line and caused a leak in the station. Before driving off, the driver had not stowed the line and had not ensured that the path was free of any obstacle before moving the truck.
Consequence	This incident did not result in a fire or explosion. No one was injured. Following the incident, a protective concrete barrier was constructed all around the storage.
Cause	Human error (failure to comply with the re-fuelling protocol).
Ineris comment	**In the outdoor area, the arrangement of the position for semi-trailers and the HP storage must provide protection against the occurrence of such an incident. Buffers prevent the semi-trailer from knocking into things in the outdoor area.**

Reference	"Hydrogen Tube Trailer Explosion" http://h2incidents.org/incident.asp?inc=135
Description	An unauthorised employee made and fitted a device to connect a tube filled with hydrogen to a multi-gas filling system. A subsequent incomplete purge allowed oxygen to flow into the tube partially filled with hydrogen. An internal explosion then occurred.
Consequence	Several fragments were thrown, including some weighing 20 kg, up to 425 m from the site of the explosion. The fragments did not cause any damage but several employees suffered burns.

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[3] http://www.ineris.fr/en

Cause	Human error (unauthorised modification of pipework)
Ineris comment	**The installation is not a multi-gas plant. Therefore, there is no oxygen equipment. Also, it is not possible to make a connection (no left-handed connection thread for hydrogen).**

5.1.1. Hydrogen tube trailer multiple-vehicle accident with fire

Hydrogen Tube Trailer Multiple-Vehicle Accident with Fire (2003)

<http://h2tools.org/lessons/hydrogen-tube-trailer-multiple-vehicle-accident-fire>

Severity	Incident		
Leak	Yes		
Ignition	Yes		

A hydrogen fire occurred in an early morning accident involving a hydrogen tube trailer and multiple vehicles on a rural highway. The cause of the collision is unknown, however, it appears to be unrelated to hydrogen (i.e., it was likely human driving errors). The hydrogen tubes contained compressed hydrogen gas at a pressure of 15 bar (218 psi). The accident caused a leak in the hydrogen plumbing system and deformed one of the hydrogen tubes, resulting in a 10-centimeter (4-inch) longitudinal crack from which hydrogen began to leak (see Figures 1 and 2). Fire from the conventional vehicles trapped under the hydrogen tube trailer during the accident ignited combustible components on the tube trailer (tires and fuel/oil), and subsequently the leaking hydrogen. Emergency crews arrived and cooled the hydrogen tubes with water to reduce the explosion risk and then put out the fire. No injuries occurred related to the hydrogen fire.

Lessons Learned:

1. A hydrogen tube pressure indication system needs to be developed that is robust enough to withstand an accident, indicates hydrogen pressure regardless of valve position, and would be visible from a safe distance during an accident situation. Hydrogen system pressure is very important in determining incident response actions. Centralizing the system pressure indicators on a highly visible information panel located in a protected area of the tube trailer is a possible solution to increase visibility. Fragile manometers should be replaced with more robust instruments and associated piping/components that can survive accident situations. Finally, pressure indications in all areas of the hydrogen system are desired, but especially the internal hydrogen tube pressure. System pressure components should be designed so that hydrogen pressure in the tubes is measured even when valves are closed and tubes are isolated.
2. Increased structural protection is needed at the back of the hydrogen tube trailer to protect the vulnerable hydrogen systems components in this location (e.g., valves, pressure-indicating devices, manifolds, piping) in case of an accident. More robust components (especially the pressure-

indicating manometers) and better support/tie-down to the tube trailer of the hydrogen pressure components may be beneficial.
3. Hydrogen valves should have a visible means to show that they are in the closed position. A highly visible lock or pin that can only be used when the valves are closed may help guarantee valve closure prior to transport. If the valve positions are visible, an operating procedure could be added that requires a final valve line-up check just prior to hydrogen tube trailer departure.
4. The hydrogen tubes need more fire protection/heat shielding at their location on the tube trailer, especially as related to the key fire load sources (combustible material) at the tire and fuel/oil locations. Local shielding, both at the fire source and at the protected destination, should be considered to provide the best method for reducing flame impingement and thermal loading/impact on the hydrogen tubes and associated components during a fire. Consideration should also be given to hydrogen tubes and components designed for higher pressures and greater fire resistance.

5.1.2. Hydrogen cylinder transport accident resulting in explosion

Hydrogen Cylinder Transport Accident Results in Explosion (2003)
<http://h2tools.org/lessons/hydrogen-cylinder-transport-accident-results-explosion>

Severity	Incident	
Leak	Yes	
Ignition	Yes	

A hydrogen leak and subsequent explosion occurred when tie-downs on a hydrogen transport trailer securing hydrogen cylinder packages failed. The tie-down failure caused the hydrogen cylinder packages to fall off the trailer and eject some cylinders onto the roadway (see Figure above). The cause of the accident is unknown, but it appears to be unrelated to hydrogen (i.e., likely tie-down strap weakness or error in properly securing tie-downs). The cylinders contained compressed hydrogen gas at 200 bar (2900 psi). The accident caused some hydrogen cylinders to leak and the associated cylinder package plumbing systems were breached. A spark or other local heat source (e.g., from a nearby vehicle motor) ignited the leaking hydrogen and caused a deflagration/explosion that damaged a car following the trailer and broke windows in a nearby house. Emergency crews arrived at the accident scene and cooled the hydrogen cylinders with a water stream to reduce their temperature. No injuries resulted from this accident.

Lessons Learned:
1. A hydrogen tube pressure indication system needs to be developed that is robust enough to withstand an accident, indicates hydrogen pressure regardless of valve position, and would be visible from a safe distance during an accident situation. Hydrogen system pressure is very important in determining incident response actions. Centralizing the system pressure indicators on a highly visible information panel located in a protected area of the hydrogen cylinder package is a possible solution to increase visibility.

2. Hydrogen valves should have a visible means to show that they are in the closed position. A highly visible lock or pin that can only be used when the valves are closed may help guarantee valve closure prior to transport. If the valve positions are visible, an operating procedure could be added that requires a final valve line-up check just prior to transport trailer departure.

3. Hydrogen cylinders grouped together and secured for transport as packaged assemblies should be designed for potential accident conditions. The package tie-down system should be designed with adequate safety margins to assure that hydrogen cylinder packages remain secured to the transport trailer under adverse conditions. However, the package design should assume that the package might fall from a moving transport vehicle and impact the ground, but the hydrogen cylinders should still be contained within the package. A program to test hydrogen cylinder packages under hypothetical accident conditions would be useful for developing designs that could be certified to survive potential accident conditions.

5.1.3. Accident between two trucks on the road

Accident between two trucks on the road E34 at the level of Vrasene (2013)

The accident happened on Thursday, April 25th, 2013 at about 1 pm on the road E34 at the level of Vrasene and in the direction of Knokke. A truck, charged with gas cylinders, was overtaking another truck, when it collided with the central reservation before catching fire. The driver of the truck was killed instantly.

The truck would have tried to avoid an obstacle fallen on the road (most probably a spare tire of another truck). It so left the road, collided with the central reservation and tipped over on the way the other way around. At first, the tractor caught fire. Then a leak on one of the bottles containing hydrogen (14 on 22 bottles) ignited. The fire started to propagate.

A security perimeter was set up by fire fighters / authorities. The road, as well as the parallel roads, was cut in both ways of traffic. A diversion was organized.

Fire brigades quickly mastered the fire of the tractor and continued to splash bottles to cool them. Fire brigades also verified the state of gas cylinders. Bottles having a leak burned under control of fire brigades, the others / those having no leak were cooled. The follow-up of the fire of bottles was made via thermography / a thermal camera. It was estimated that the fire burned at a temperature superior to 2 000°C.

On Friday morning, several bottles had burned, four were still closed and two others remained wedge under the truck. Fire brigades continued to splash with water bottles to cool them, before being able to analyse the situation more in detail. On Saturday, the fire was totally under control by fire brigades and any danger involving bottles is considered past (all the bottles which can be considered as safe) the operations of clearing were able to begin. On Sunday, the crisis unit met and decided to open again a part of the road in the traffic in both ways. The traffic was disrupted during approximately one week because of renovation work.

5.2. Hazardous phenomena

The hazard potentials considered for a hydrogen trailer are described in the Table 21. It is important to note that, in Europe, hydrogen trailers are not equipped with TPRD.

Table 21: Hazardous phenomena for hydrogen trailers

Products	Equipment of hazards	Potential hazard
Flammable materials	Car, batteries, tyres, engine, etc.	Fire
Hydrogen	Tanks	Burst
Hydrogen	Pipes and other components	UVCE Jet Fire

5.3. Detailed scenarios

The Figure 8 below represents the bow-tie diagram identified for a hydrogen trailer incident/accident.

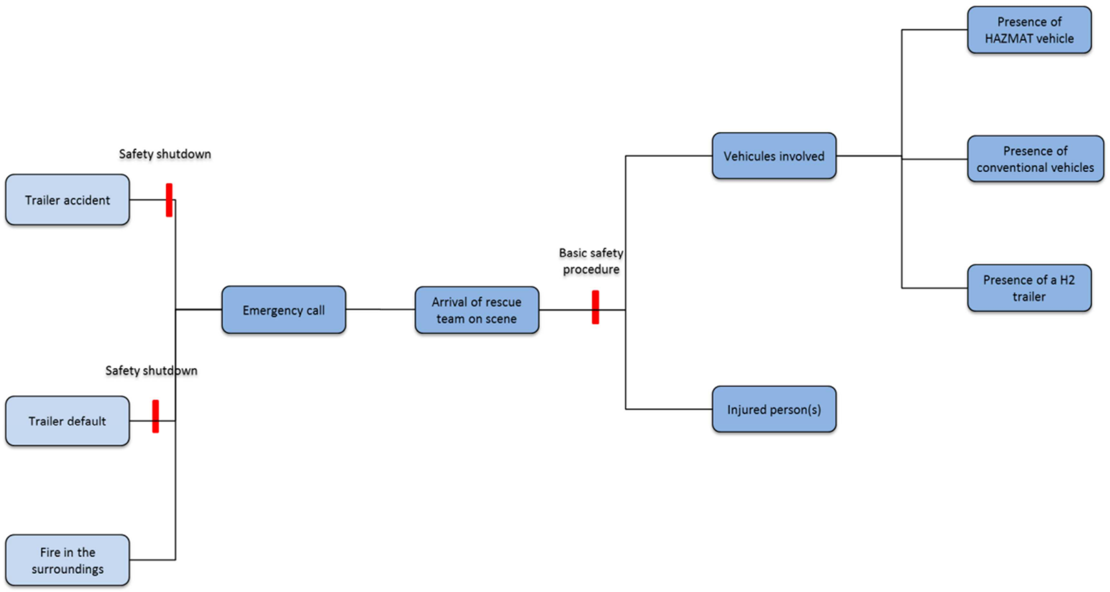

Figure 8: Example of bow-tie diagram for H2 trailer

5.4. Potential consequences

5.4.1. Blowdown

The Table 22 below gives the blowdown time for several hydrogen tanks installed on a trailer for 3 different leak sizes i.e. 0.1, 0.25 and 4 mm.

Table 22: Blowdown time in function of tank type, pressure and hole size

Type of tank	**Storage pressure (bar)**	**Blowdown time**				
		0.1 mm	**0.25 mm**	**1 mm**	**2.3 mm**	**4 mm**
Rack V9 B50	200	48 h	461 min	-	-	**2 min**
Rack V18 B50	200	96 h	921 min	-	-	**4 min**
Tube (2 m^3)	200	213 h	34.08 h	-	-	**8 min**

5.4.2. Hydrogen leak from hydrogen trailer piping system

The distances obtained for different hydrogen concentration are also given based on the three different leak sizes i.e. 1, 2.3 and 4.2 mm.

Table 23: Distances to hydrogen concentrations from 200 bar pressurized tank

Pressure (bar)	Release Diameters (mm)	Separation distances, m 4 vol. %	Range of flame tip, m	
			8 vol. % —	16 vol. %
200	1	5.1	2.5	1.1
200	2.3	11.8	5.7	2.6
200	4	20	10	4.5
200	8	41	19.8	9.1

5.4.3. Jet fire and UVCE from a hydrogen trailer

The Table 24 gives the separation distances for jet fires and unconfined vapor cloud explosion (UVCE) for 200 bar pressure storages and several leak diameters.

Table 24: Thermal and potential overpressure effects obtained from hydrogen jet fires at 200 bar

Type of tanks	Piping leak diameter, mm	Pressure of the tank (bar)	Direct ignition **(JET FIRE)**					Delayed ignition **(UVCE)**			
			Thermal effects			Flame length (m)		Overpressure effects			
			3 kW/m^2	5 kW/m^2	8 kW/m^2	L	r	200 mbar	140 mbar	50 mbar	20 mbar
Rack V9 B50, Rack V18 B50, Trailer	0.1	200	0.2	0.2	0.2	0.2	0.03	0.5	-	-	-
	0.2	200	0.5	0.4	0.4	0.4	0.06	1	0.5	-	-
	4	200	11	9	8	7	1.2	20	10	6	5
	Full rupture of flexible piping	200	7.2	7.2	7.2			13.1	8.2		

5.4.4. Tank burst of a hydrogen trailer

The table below gives the potential overpressures distances reach in case of 200 bar storage burst installed on a hydrogen trailer.

Table 25: Distances of the overpressure effects due to hydrogen storage burst on a trailer

Type of storage	Tank capacity	Storage pressure (bar)	Overpressure burst (bar)	Significant lethal effects – Domino effects 200 mbar	Lethal effects 140 mbar	Irreversible effects 50 mbar	Indirect effects : broken glass 20 mbar
Type I	B50 (50 l), Rack V9 B50, Rack V18 B50	200	380	7	9	22	44
Type I	Trailer (2 m^3)	200	430	22	29	67	134

5.5. Scenario matrix for hydrogen trailers

The Table 26 below presents the scenario matrix compiled for a hydrogen trailer.

Table 26: Scenario matrix for a hydrogen trailer

FCH application	**Potential danger**	**Discovery level**		**Advanced level**		**Expert level**	
		Scenario identification	**Description**	**Scenario identification**	**Description**	**Scenario identification**	**Description**
H2 TRAILER (bundles cylinders or long cigars)	**NO LEAK**	H2_Trailer_D_NL1	Single hydrogen trailer **accident** - no leak from the H2 trailer - **extrication** - simple environment	H2_Trailer_A_NL1	Multi vehicle **accident** - no H2 leak from the H2 trailer - **extrication** - complex environment (motorway, urban environment, tunnel)		
	LEAK	H2_Trailer_D_L1	H2 trailer default - **H2 leak** - simple environment (small road)	H2_Trailer_A_L1	H2 trailer default - **H2 leak** from the H2 trailer - medium complex environment (trailer warehouse, parking, etc.)	H2_Trailer_E_L1	H2 trailer default - **H2 leak** from the H2 trailer - complex environment (motorway, urban environment, tunnel, industrial environment)
		H2_Trailer_D_L2	Single H2 trailer **accident - storage on the trailer** - **H2 leak** - **extrication** - simple environment	H2_Trailer_A_L2	Multi vehicle **accident - storage on the trailer** - **H2 leak** from the H2 trailer - **extrication** - complex environment (motorway, urban environment, tunnel, industrial environment)	H2_Trailer_E_L2	Multi vehicle **accident** - storage on the trailer - **H2 leak** from H2 trailer - **extrication** (H2 trailer and/or conventional car) - complex environment (motorway, urban environment, tunnel, industrial environment)

		H2_Trailer_D_L3	Single H2 trailer **accident - dismantled storage (MIKADO)** - **H2 leak** - **extrication** - simple environment	H2_Trailer_A_L3	Multi vehicle **accident** - dismantled storage (MIKADO) - **H2 leak** from the H2 trailer - **extrication** - complex environment (motorway, urban environment, tunnel, industrial environment, etc.)	H2_Trailer_E_L3	Multi vehicle **accident** - dismantled storage (MIKADO) - **H2 leak** from H2 trailer - **extrication** (H2 trailer and/or conventional car) - complex environment (motorway, urban environment, tunnel, industrial environment)
	H2 FIRE	H2_Trailer_D_F1	H2 trailer default - H2 trailer in **fire** - simple environment (small road)	H2_Trailer_A_F1	H2 trailer default - H2 trailer in a **fire** - medium complex environment (trailer warehouse, parking)	H2_Trailer_E_F1	H2 trailer default - H2 trailer in a **fire** - complex environment (motorway, urban environment, tunnel, industrial environment)
		H2_Trailer_D_F2	H2 trailer **accident -** H2 trailer in **fire** - storage on the trailer - simple environment (small road)	H2_Trailer_A_F2	Multi vehicle **accident - H2 trailer in fire -** medium complex environment (trailer warehouse, parking, etc.)	H2_Trailer_E_F2	Multi vehicle accident - H2 trailer in a fire - storage on the trailer -- complex environment (motorway, urban environment, tunnel)
		H2_Trailer_D_F3	Single H2 trailer accident - dismantled storage (MIKADO) - H2 jet fire - extrication - simple	H2_Trailer_A_F3	Multi vehicle accident - dismantled storage (MIKADO) - H2 jet fire from the H2 trailer - extrication - complex environment (motorway, urban environment, tunnel, industrial environment)	H2_Trailer_E_F3	More complex situation with an Hazmat trailer involved

			environment				
						H2_Trailer_E_F4	Multi vehicle accident - dismantled storage (MIKADO) - H2 jet fire from H2 trailer - extrication (H2 trailer and/or conventional car) - complex environment (motorway, urban environment, tunnel?, industrial environment)
						H2_Trailer_E_F5	More complex situation with an Hazmat trailer involved
	EXTERNAL THREAT			H2_Trailer_A_E1	Fire in a medium complex environment (trailer warehouse, parking, ?) - H2 trailer in the environment	H2_Trailer_E_E1	Fire in a complex environment (motorway, urban environment, tunnel, industrial environment) - H2 trailer in the environment
						H2_Trailer_E_E2	Multi vehicle accident - fire close to the trailer - complex environment (motorway, urban environment, tunnel)

6. TYPICAL SCENARIOS FOR FC FORKLIFT

6.1. Feedback and lessons learned

Reference	“Fuel Cell Evaporator Pad Fire” http://www.h2incidents.org/incident.asp?inc=296
Description	Ignition of the battery's evaporator (intended to evacuate the water produced). The fuel cell continued to operate normally during the incident and none of the six hydrogen sensors on the truck measured an abnormal concentration.
Consequence	Damage to the battery but not to the forklift truck.
Cause	The causes of the presence of a combustible mixture in the evaporator were not identified.
Manufacturer's comment	**Fuel cells currently supplied do not have an evaporator. The water produced by the battery is drained each time the truck is filled with H_2 (which explains the presence of the collection tank)**

Reference	“Ball of Fire from Hydrogen Fuel Cell Forklift Flashes and Quickly Extinguishes” http://www.h2incidents.org/incident.asp?inc=297
Description	The operator saw a "ball of fire" emerge in the form of a flash from the side of the forklift. Upon disassembly, the fuel cell showed signs of heating and electrical arcs and a drill bit was discovered on the battery plates, which must have been the cause of the electrical incident. No maintenance had been carried out requiring the use of a drill. No leakage fault detected in the hydrogen circuit.
Consequence	Damage to the battery but not to the forklift truck.
Cause	Presence of a drill bit on the battery plates.
Manufacturer's comment	**There are no drilling operations required on fuel cells.**

Reference	“Fire on the unit” source American manufacturer
Description	In a welding shop, sprayed sparks caused the fuel cell unit to catch fire.
Consequence	Slight damage to the battery: the battery fan, the air filter, the low pressure H_2 circuit and the cooling circuit were affected.
Cause	Sparks produced by welding caused the Gendrive to catch fire.
Manufacturer's comment	**Screens have been added in front of ventilation grilles to prevent sparks from entering again and the time spent by forklifts in this area has been reduced to 500 hours** **The customer is aware that it is using the system outside normal operating conditions** **This incident has occurred six times. with, in four cases, a localised fire in the air filter.**

Reference	“Fire on the unit” source American manufacturer
Description	An external ignition source started a fire in the Gendrive.
Consequence	The fire damaged the fuel cell, the air circulation pump and the filter.
Cause	A spark from outside probably came into contact with an electrical contact generating an electrical arc which caused the recirculation pump to catch fire.
Manufacturer's comment	**A screen has been added, so that sparks can no longer enter via the opening where the forklift's power cables exit from the fuel cell unit.**

Reference	“Fire on the unit” source American manufacturer
Description	A very brief fire in the cylinder valve occurred in the low pressure circuit.
Consequence	The fire damaged the low pressure hydrogen circuit, the cylinder valve, the electrical and communication cables.
Cause	One of the probable causes is a leak in the low pressure circuit.
Manufacturer's comment	**Only the quantity of hydrogen present in the low pressure pipe burned. The brief rise in temperature was not sufficient to activate the thermal fuse.**

6.2. Hazardous phenomena

The table below identifies the hazardous phenomena related to a FC forklift:

Table 27: Hazardous phenomena for a FC forklift

Products	Equipment of hazards	Potential hazard
Flammable materials	Forklift, batteries, tyres, engine, etc.	Fire
Hydrogen	Tanks	Burst
Hydrogen	TPRD (Temperature activated Pressure Relief Device)	UVCE Jet Fire
Hydrogen	Pipes and other components	UVCE Jet Fire
Electricity	Cable	Electrocution

6.3. Detailed scenarios

The Figure 9 below represents the bow-tie diagram identified for a FC forklift incident/accident.

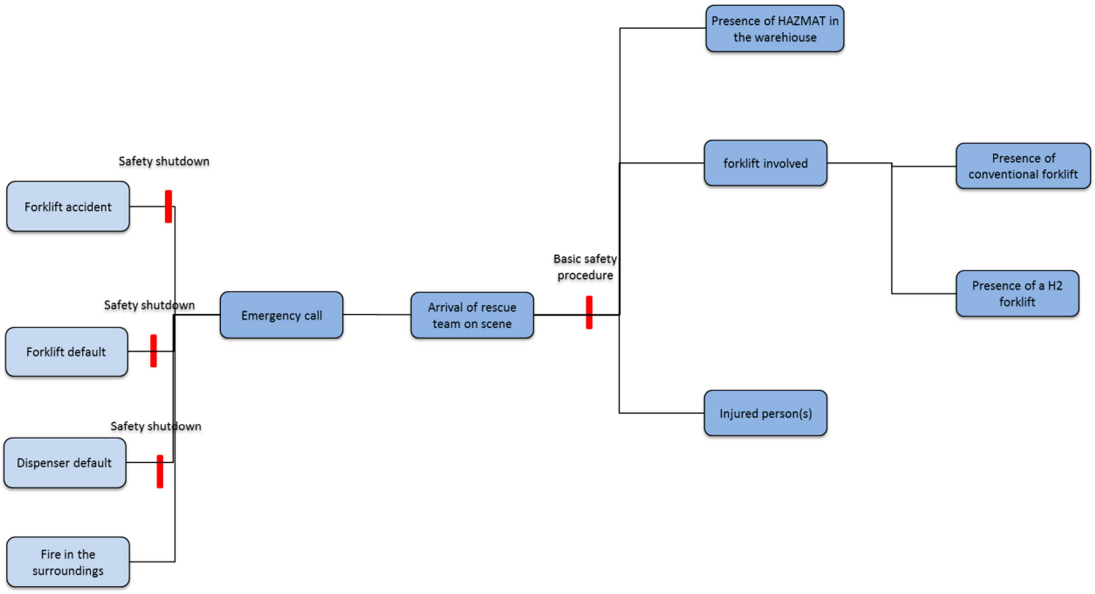
Presence of HAZMAT in the warehiouse
Safety shutdown
forklift involved
Presence of conventional forklift
Forklift accident
Basic safety procedure
Presence of a H2 forklift
Safety shutdown
Emergency call
Arrival of rescue team on scene
Forklift default
Injured person(s)
Safety shutdown
Dispenser default
Fire in the surroundings

Figure 9: Example of bow-tie diagram for a FC forklift

6.4. Potential consequences

6.4.1. Tank blowdown of a FC forklift

The Table 28 below gives the blowdown time of 80 and 171 L when the tanks are completely full for 3 different sizes of hole/leak: 1, 2.3 and 4.2 mm.

Table 28: Blowdown time in function of tank type, pressure and hole size

Tank volume, L	**Storage pressure (bar)**	**Blowdown time**		
		1 mm	**2.3 mm**	**4.2 mm**
80	350	20 min	**4 min**	**50 s**
171	350	25 min	**9 min**	**80 s**

6.4.2. Hydrogen leak from FC forklift piping system

The distances obtained for different hydrogen concentration are also given in based on the three different sizes of hole/leak:1; 2.3 and 4.2 mm.

Table 29: Distances to hydrogen concentrations for 350 and 700 bar

Pressure (bar)	Release Diameters (mm)	Separation distances, m 4 vol. %	Range of flame tip, m	
			8 vol. %	16 vol. %
350	1	5.2	2.5	1.1
350	2.3	15	7.2	3.3
350	4.2	6.5	3.1	1.4

6.4.3. Hydrogen jet fires from FC forklift piping system

The Table 30 below gives the thermal and potential overpressures obtained from hydrogen jet fires.

Table 30: Thermal and potential overpressure effects obtained from hydrogen jet fires

Piping leak diameter, mm	Pressure of the tank (bar)	Direct ignition **(JET FIRE)**					Delayed ignition **(UVCE)**			
		Thermal effects (m)			Flame length (m)		Overpressure effects (m)			
		3 kW/m^2	5 kW/m^2	8 kW/m^2	L	r	20 mbar	50 mbar	140 mbar	200 mbar
1	350	3.2	3	2.8	1.6	0.3	9.5	4.8	2	1.5
2.3	350	7	6.5	6	3.8	0.6	22	11	4.7	3.4
4	350	15	14	13	6.8	1.2	38	19	8.2	6

6.4.4. Jet fire from TPRD mounted on a 350 bar hydrogen tank

The Table 31 gives the separation distances for jet fires for 350 and 700 bar when the TPRD is oriented vertically and oriented towards the floor.

Table 31: Separation distances for jet fires from aTPRD mounted on 350 bar hydrogen tanks

Release diameters (mm)	Pressure of the tank (bar)	Flame length, m	No harm, m	Pain threshold, m	3rd degree burn, m
4.2 (TPRD opens, directed vertically)	350 bar	6.8	23.8	20.4	13.6

6.4.5. Tank burst of a FC forklift

In case of failure of the TPRD, the tank may rupture. The table below gives the potential overpressures distances reach in case of 350 bar tank burst and volumes about of 74 L and 171 L.

Table 32: Distances of the overpressure effects due to tank burst

Type of storage	**Volume, L**	**Storage pressure (bar)**	**Overpressure burst (bar)**	**Significant lethal effects – Domino effects 200 mbar (m)**	**Lethal effects 140 mbar (m)**	**Irreversible effects 50 mbar (m)**	**Indirect effects : broken glass 20 mbar (m)**
Type III, bottles	74	350	595	8	11	25	50
Type III, bottles	171	350	595	12	15	38	77

6.5. Scenario matrix for FC forklift

The Table 33 below presents the scenario matrix compiled for a hydrogen trailer.

Table 33: Scenario matrix for a hydrogen trailer forklift

FCH application	**Potential danger**	**Discovery level**		**Advanced level**		**Expert level**	
		Scenario identification	**Description**	**Scenario identification**	**Description**	**Scenario identification**	**Description**
FC FORKLIFT AND INSIDE REFUELLING	**NO LEAK**	FC_Forklift_D_NL1	Single forklift **accident** - **no H2 leak** - **extrication** - simple environment (outside warehouse)	FC_Forklift_A_NL1	Single forklift **accident** - **no H2 leak** - **extrication** - medium complex environment (inside warehouse)	FC_Forklift_E_NL1	Single forklift **accident** - **no H2 leak** - **extrication** - complex environment (inside warehouse close to the refuelling station)
	LEAK	FC_Forklift_D_L1	Forklift default/accident - **H2 leak** - simple environment (outside warehouse)	FC_Forklift_A_L1	Forklift default/accident - H2 leak - medium complex environment (inside warehouse)	FC_Forklift_E_L1	Forklift default/accident - H2 leak - complex environment (inside warehouse close to the refuelling station)
	H2 FIRE	FC_Forklift_D_F1	Forklift default - **forklift in a fire** - simple environment (outside warehouse)	FC_Forklift_A_F1	Forklift **accident** - **forklift in a fire** - medium complex environment (inside warehouse)	FC_Forklift_E_F1	Multi vehicle **accident** - **Forklift in a fire** - complex environment (inside warehouse close to the refuelling station)
	EXTERNAL THREAT					FC_Forklift_E_E1	**Fire in the warehouse** - Forklift in the environment

7. TYPICAL SCENARIOS FOR REFUELLING STATION

7.1. Feedback and lessons learned

The feedback is extracted from the database h2tools.org/lessons/ and articles.

Hydrogen Delivery Truck Causes Hydrogen Leak at Fill Station Due to Improperly Stored Hydrogen Fill Line at Departure (2008)
<http://h2tools.org/lessons/hydrogen-delivery-truck-causes-hydrogen-leak-fill-station-due-improperly-stored-hydrogen>

Severity	Incident
Leak	Yes
Ignition	No

A hydrogen leak occurred at a plant's hydrogen fill station when a vendor's hydrogen fill truck trailer pulled away after filling and caught an improperly stored hydrogen fill line. The driver of the hydrogen truck trailer did not properly stow the hydrogen fill line after filling and failed to verify that the hydrogen fill line was clear of the trailer prior to departure. As the driver pulled away from the fill station, the hydrogen fill line caught on the trailer and subsequently pulled on the hydrogen fill station's ground storage tubes distribution manifold. The force of this pull bent the plant's hydrogen distribution manifold and hydrogen began leaking from a threaded connection and from the hydrogen fill line. The truck trailer driver reported hearing a "pop and hissing sound", stopped the truck movement, and then promptly left the truck to report the incident at approximately 6:45 PM. The local fire department was contacted and the building was evacuated. The fire department arrived by 8:00 PM, along with the hydrogen vendor's service technician, to isolate the hydrogen leak. The hydrogen leak at the plant's hydrogen ground storage system was stopped by closing the individual valves on each hydrogen storage tube, thereby isolating the distribution manifold. At 10:00 PM, the all clear was given. Hydrogen operations were restored to the plant the next day by removing the damaged hydrogen ground storage unit and replacing it with a hydrogen tube trailer with concrete barriers installed to provide protection. The hydrogen leak from this event caused no hydrogen fire/explosion or personnel injuries.

Lessons Learned:
1. Train personnel on delivery procedures and emphasize the safety aspects of hydrogen connections and disconnections, and verification of clearance for trailer movement prior to departure.
2. Provide site-specific delivery procedures and possibly include a checklist as a reminder of key safety items prior to departure.

The feedback is extracted from the database h2tools.org/lessons/ and articles.

Hydrogen Cylinder Leak at Fuelling Station (2012)
<http://h2tools.org/lessons/hydrogen-cylinder-leak-fueling-station>

Severity	Incident

Leak	Yes
Ignition	No

An alarm sounded at a recently inaugurated hydrogen fuelling station in a major metropolitan area. One out of a total of 120 high-pressure hydrogen cylinders, located on the roof of the fuelling station, failed in service. Gaseous hydrogen was leaking from a screw fitting of the cylinder, but the hydrogen was not ignited. Three hydrogen gas sensors detected the leakage and triggered an alarm that resulted in an immediate emergency shutdown, isolating the leaking high-pressure cylinder bank from the other three banks and notifying the local fire department. No personnel were allowed to enter the roof area, approximately 7-9 meters above ground level.

The police isolated the area around the fuelling station within a radius of 200 meters. The maximum content of the leaking cylinder bank was determined to be ~ 70 kg of hydrogen at 800 bar. The leak rate at the high-pressure storage bank was ~5 kg/hr.

After 2.5 hours, the hydrogen supplier's technician manually opened a bypass line to let the hydrogen escape through a vent line. This action was taken from the ground-floor control room well outside an area that might have exposed personnel to additional hazards.

About four hours later, the leaking high-pressure bank was essentially empty, with a pressure of around 1 bar. The cylinder with the failed teflon-sealed screw fitting was sealed with a plug with the intention of never using it again. There was no threat to employees or the public from this incident.

Lessons Learned:

1. The hydrogen supplier installed a fire-resistant material board adjacent to the high-pressure hydrogen storage banks to prevent any potential jet flames from affecting adjacent high-pressure cylinders for several minutes. The 0.25 mm sandwich board of fiberglass-reinforced, lightweight concrete is easy to maintain and does not rot under outside conditions. This safety measure was implemented just three days after the incident occurred, although it had been planned for a long time.
2. The hydrogen supplier installed a semi-automated sprinkler system to cool the high-pressure hydrogen storage banks to prevent any potential escaping hydrogen gas that might ignite in jet flames from affecting other hydrogen cylinders. In addition, the dry piping system above the high-pressure hydrogen storage banks can be flooded with water by the fire department in case of fire or leakages in the high-pressure banks.
3. The alarm system was refined to send automated messages to relevant personnel informing them of gas/fire alarms.
4. The remote control room where service personnel are monitoring the fuelling station is now equipped with an additional audio system to draw faster attention to alarms.
5. All plans and emergency procedures have been reviewed, adjusted and edited to document changes and fully capture the lessons learned.
6. Other learnings: Training for worst-case scenarios is recommended in order to be prepared for those situations.

Pressure Relief Device Fails at Fueling Station / Leak of hydrogen in a hydrogen refuelling station at Emeryville, California (2012)

< http://h2tools.org/lessons/pressure-relief-device-fails-fueling-station>

Severity	Incident
Leak	Yes
Ignition	Yes

Ignition Source: Either static electricity or spark from escaping particle

The town of Emeryville put in operation in august 2011 a refuelling station for its buses and cars using hydrogen. This station has storage with a capacity of 2,800 kg of hydrogen and was composed of an electrolyser coupled with photovoltaic panels, liquid storage, two compressors (one at 700 bars for the cars and the other at 350 bars for the buses) and buffer capacities.

Around 7:30 AM, a pressure relief device (PRD) valve failed on a high-pressure storage tube at a hydrogen fuelling station, causing the release of approximately 300 kilograms of hydrogen gas. The gas ignited at the exit of the vent pipe and burned for 2-1/2 hours until technicians were permitted by the local fire department to enter the station and stop the flow of gas. During this incident the fire department evacuated nearby businesses and an elementary school, closed adjacent streets, and ordered a high school to shelter in place.

There were no injuries and very little property damage. The corrugated roof on an adjacent canopy over a fuelling dispenser was slightly singed by the escaping hydrogen flame, causing less than $300 in damage.

The station's operating systems worked as they were designed to function in an emergency. All equipment and fuel supplies were completely isolated, and all storage vessels were well within acceptable and safe pressure and temperature limits prior to and throughout the incident.

After a thorough analysis of the incident was conducted, corrective actions were taken to replace PRD valves, heighten vent stacks, modify response procedures and improve communication protocols with first responders. A considerable amount of time was taken to review the station design, evaluate emergency action plans and procedures, meet with the public, train first responders, and conduct follow-up drills with employees and first responders. The station reopened nine months after the incident and has been fully operational since that time.

Lessons Learned:

Three root-causes were noted during the investigation: (1) the use of incompatible materials in the manufacturing of the PRD valve, (2) improper assembly resulting in over-torquing of the inner assembly, and (3) over-hardening of the inner assembly materials by the valve manufacturer. These problems could have been avoided by adequate quality assurance/quality control procedures during the design and safety reviews.

The canopy was added to the station as an afterthought, sometime following the HazOps review. The prestart-up safety review by all parties and the local authority having jurisdiction did not recognize the setback distance of the canopy. Had an engineering management of change, follow-up HazOp or other form of risk assessment been conducted, it is likely that the vent stacks adjacent to the canopy would have been raised in order to avoid any damage in the event of a fire.

Prior to reopening the station, physical changes were made using the correct PRD valves and higher vent stacks, and new and modified procedures were instituted to improve the timely communication of station status during emergency events. Additional training of personnel focused on improving the response time and effective communication between employees, first responders, and the hydrogen equipment supplier.

COMPRESSOR

Reference	"Combustion inside a high pressure liquid hydrogen test tank" ARIA 26618
Description	Combustion inside a high pressure liquid hydrogen test tank on a space equipment test site. Detectors identified the problem and the test was stopped.
Consequence	No consequence
Cause	Suspicion that the gaseous hydrogen network had become polluted following an intake of air upstream of the compressor.
Ineris[4] comment	**This accident had nothing to do with gaseous hydrogen. The only interest here is due to a pressure measurement at the intake to the compressor.**

Reference	"Leak on Compressor at Fueling Station" http://h2incidents.org/incident.asp?inc=249
Description	The shaft bearings on a compressor started to fail after two hours of operation. This caused increased clearance in the bearings and therefore greater movement of the compressor shaft. Ultimately, a hydrogen leak occurred.
Consequence	Compressor shut down due to low inlet pressure and the installation sent into emergency shutdown.
Cause	Failure of one of the compressor bearings
Ineris comment	**The compressor technology at fault here is not stated. However, it should be stated that the preferred technology to be used id the diaphragm compressor. This diaphragm separates the H_2 circuit from the oil circuit , which itself is compressed by a piston. There is never any contact between the piston and the gas.**

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[4] http://www.ineris.fr/en

Reference	"Discharge Valve Installation Error" http://h2incidents.org/incident.asp?inc=147
Description	An explosion occurred in a hydrogen compressor, following a maintenance operation. The compressor was fitted with interchangeable intake and output valves. An inquiry showed that the discharge valve had been installed at the intake and that had burst the compressor and discharged hydrogen into the atmosphere.
Consequence	Damage to the building
Cause	Human error (incorrect connection of the compressor)
Ineris comment	**The compressor used is fitted with non-return valves at the intake and exit.**

Reference	"Hydrogen Make Up Compressor Piping Hole" http://h2incidents.org/incident.asp?inc=50
Description	The screw and nut on a temperature sensor installed on some stainless steel pipework was resting on other HP hydrogen pipework. Vibration from the compressor caused repeated friction on the pipework from this screw and nut and ultimately led to a hydrogen leak. The area concerned was hard to see and only the noise allowed the leak to be detected.
Consequence	-
Cause	Compressor vibration causing a hole in the pipework.
Ineris comment	**Clearance is sufficient between the various components in the compressor installation to prevent such an incident occurring.**

Reference	"Hydrogen Boosting Compressor Fails" http://h2incidents.org/incident.asp?inc=195
Description	Failure of a hydrogen compressor caused by a hole in a diaphragm. This hole was detected due to a rise in pressure measured between the layers of the diaphragm (in normal operation, such a rise in pressure is not anticipated).
Consequence	-
Cause	Loss of seal in the diaphragm.
Ineris comment	**The installation uses the same type of compressor and the same pressure measurement is made between the layers of the diaphragm.**

DISPENSER

Reference	"Hydrogen Fueling Dispenser Nozzle Drive Away" http://h2incidents.org/incident.asp?inc=246
Description	A vehicle left a filling point without disconnecting the hose and the "rupture device" fitted to protect against such human error did not work. This led to the hose rupturing between the vehicle and the dispenser and a release of hydrogen.
Consequence	Localised damage
Cause	Failure to comply with the refuelling protocol and over-sized rupture

	device.
Ineris comment	**The hose is protected by a breakaway rupture device which is tested before entry into service and then checked regularly.**

7.2. Hazardous phenomena

The hazard potentials considered for a refuelling station are described below:

Table 34: Hazardous phenomena for hydrogen refuelling station

Products	Equipment of hazards	Potential hazard
Flammable materials	vehicles, batteries, containers, tyres, engine, etc.	Fire
Hydrogen	Tanks	Burst
Hydrogen	Pressure relief valve	UVCE Jet Fire
Hydrogen	Pipes and other components	UVCE Jet Fire
Electricity	Cable	Electrocution

7.3. Detailed scenarios

The Figure 10 below presents the typical scenarios related to a refuelling station.

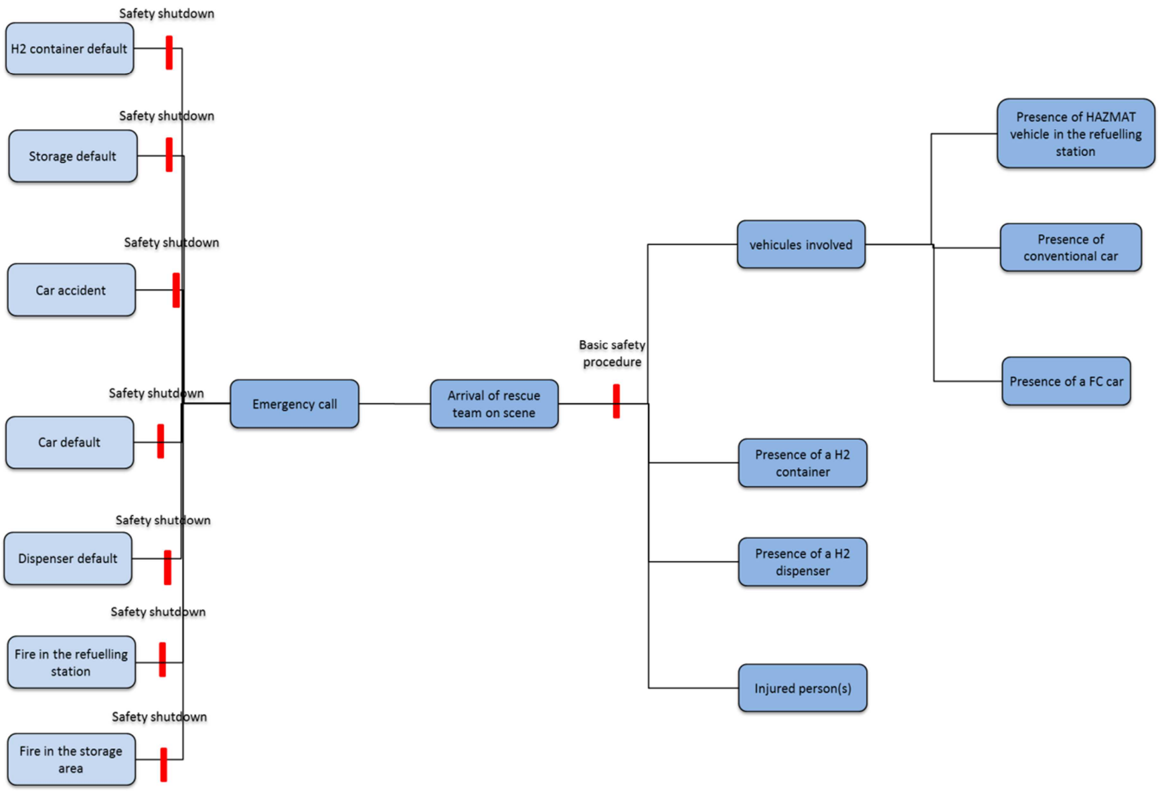

Figure 10: Example of bow-tie diagram for a hydrogen refuelling station

7.4. Potential consequences

A refuelling station is mainly composed of the following sub-systems:

- Storage and piping system
- Compressor
- Dispenser

7.4.1. Potential consequences on the storage and piping system

7.4.1.1. Tank blowdown

The Table 35 below presents the blowdown time calculation obtained for typical storages that can be encountered at a refuelling station.

Table 35: Blowdown time in function of tank type, pressure and hole size

Type of tank	**Storage pressure (bar)**	**Blowdown time for a leak size**						
		0.1 mm	**0.25 mm**	**1 mm**	**2.3 mm**	**4 mm**	**5.3 mm**	**9.1 mm**
B50 (50 l)	200	320 min	52 min	-	-	**12 s**	-	-
Rack V9 B50	200	48 h	461 min	-	-	**2 min**	-	-
Rack V18 B50	200	96 h	921 min	-	-	**4 min**	-	-
Trailer (2 m^3)	200	213 h	34.08 h	-	-	**8 min**	-	-
Bottles 74 L	595	10 h	2 h	6 min	-	**23 s**	-	-
Buffer 1 m3	450	144 h	23 h	-	-	-	3 min	**1min**
Buffer 2 m3	450	288 h	46 h	-	-	-	6 min	**2 min**
Rack H4 B142	525	86 h	14 h	52 min	**10 min**	-	-	-
Bottle 80	700	13 h	127 min	8 min	**1.5 min**	-	-	-
Rack H4 B142	700	93 h	15 h	56 min	**11 min**	-	-	-
Buffer (cigar) 1 m3	1000					> 30 min		
Buffer 2 m3	1000					80 min		

7.4.1.2. Hydrogen leak from piping system

The distances obtained for different hydrogen concentration are given in Table 36 for three different sizes of hole/leak i.e. 1, 2.3 and 4mm for tank pressures of 200, 350, 700 and 1000 bar.

Table 36: Distances to hydrogen concentration for 200 bar, 350 bar, 700 bar and 1000 bar

Pressure (bar)	Release Diameters (mm)	Separation distances, m 4 vol. %	Range of flame tip, m	
			8 vol. % —	16 vol. %
200	1	5.1	2.5	1.1
200	2.3	11.8	5.7	2.6
200	4	20	10	4.5
200	8	41	19.8	9.1
350	1	5.2	2.5	1.1
350	2.3	15	7.2	3.3
350	4.2	6.5	3.1	1.4
350	8	52	25	11.5

700	1	8.4	4	1.8
700	2.3	19	9	4
700	4.2	35	17	7.8
700	8	67	32	15
1000	1	9.4	4.5	2.1
1000	2.3	21.6	10.4	4.8
1000	4	25	18	8.3
1000	8	75	36	16

7.4.1.3. Hydrogen jet fires from piping system

The Table 37 below gives the thermal and potential overpressures obtained from hydrogen jet fires.

Table 37: Thermal and potential overpressure effects obtained from hydrogen jet fires

Piping leak diameter, mm	Pressure of the tank (bar)	Direct ignition (JET FIRE)					Delayed ignition (UVCE)			
		Thermal effects (m)			Flame length (m)		Overpressure effects (m)			
		3 kW/m2	5 kW/m2	8 kW/m2	L	r	20 mbar	50 mbar	140 mbar	200 mbar
1	200	3.1	2.9	2.7	1.3	0.22	-	-	-	-
2.3	200	5.6	5.4	5.2	3	0.5	17	8.5	3.8	2.7
4	200	11	10.5	10	5.5	0.9	30	15	6.5	4.8
8	200	24	22	20	11.3	9	60	30	12.9	9.4
1	350	3.2	3	2.8	1.6	0.3	9.5	4.8	2	1.5
2.3	350	7	6.5	6	3.8	0.6	22	11	4.7	3.4
4	350	15	14	13	6.8	1.2	38	19	8.2	6
8	350	30	28	26	13.5	2.3	78	39	16	12
1	700	3.5	3.3	3	1.9	0.3	12	6	2.6	1.9
2.3	700	10	9	8	4.7	0.8	29	14.5	6.1	4.5
4	700	19	17	15	8.3	1.4	50	25	10.7	7.8
8	700	36	34	32	16.5	2.8	100	50	21.4	15.6
1	1000	4.3	4.1	3.9	2.1	0.4	13.8	6.9	2.9	2.3
2.3	1000	10	9	8	5	0.85	32	16	6.7	4.9
4	1000	19	17	15	8.8	1.5	56	28	11.9	8.6
8	1000	40	38	36	18.2	3	112	56	24	17.5

7.4.1.4. Tank burst

The table 38 below gives the potential overpressures distances in case of tank burst.

Table 38: Distances of the overpressure effects due to tank burst

Type of storage	Tank volume	Storage pressure (bar)	Overpressure burst (bar)	Significant lethal effects – Domino effects 200 mbar (m)	Lethal effects 140 mbar (m)	Irreversible effects 50 mbar (m)	Indirect effects : broken glass 20 mbar (m)
Type I	B50 (50 l), Rack V9 B50, Rack V18 B50	200	380	7	9	22	44
Type I	Trailer (2 m^3)	200	430	22	29	67	134
Type I	Buffer (cigar) 1 m^3	450	675	23	29	72	145
Type I	Buffer 2 m^3	450	675	26	36	85	170
Type IV	Rack H4 B142	525	578	9	13	31	62
Type IV	Bottle 80	700	770	9	12	28	56
Type IV	Rack H4 B142	700	770	13	16	40	79
Type I	Buffer (cigar) 1 m3	1000	2000	34	40	105	211
Type I	Buffer 2 m3	1000	2000	42	50	133	266

7.4.2. Hydrogen accumulation followed by an explosion in a containerized compressor

It is considered in this case that the compressor is integrated in a 10 feet or a 20 feet container, for which the characteristics are showed in the Table below. The free volume of a container is considered to be around 70% of the total volume.

Table 39: Different volumes considered for H2-energy systems (FC, electrolyser, H2-energy storage system)

Different container	Dimension L x l x H (m)	Volume, m^3	Free volume
Explosion container 10 feet	3 x 2.4 x 2.4	17	12
Explosion container 20 feet	6 x 2.4 x 2.4	34	24

In the event of a pipe rupture, the volumetric Richardson number[5] is calculated. If the Richardson number is lower than 1, consequently, the hypothesis of the homogeneous mixture formation in the enclosure is made.

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[5] Volumetric Richardson number, parameter giving the ability of a jet to promote mixing within the volume can be determined: $Ri_v = g\frac{(\rho_a - \rho_0)}{\rho_0}\frac{V^{1/3}}{{u_j}^2}$

Where ρ_a is the ambient air density, ρ_0 is the gas density, V the volume of gas available in the enclosure and u_j is the jet velocity. With a value of the volumetric Richardson number really inferior to 1, it can be deduced that the mixture formed into the enclosure is a uniform mixture.

A calculation of non-stationary concentration is carried out, by making a balance of the quantity of hydrogen injected and this one of substance evacuated by the container surfaces permanently opened. The maximum concentration is calculated. If it is higher than the stoichiometric concentration, it means that during the hydrogen release in the container, the stoichiometric volumetric fraction is reached. Thus, this value is chosen, knowing that the explosion will be most violent for this one.

The barriers implemented to avoid this scenario, are not taken into account and considering to be failing.

The combustion of an ATEX of a stoichiometric hydrogen-air mixture in the process compartment of the hydrogen-energy containers is considered, after a pipe rupture.

Since the mechanical resistance of the container is not well known, it has been chosen arbitrarily to consider the explosion of an explosive volume occupying the free volume of the container. The stoichiometry is reached during the leak and an index 10 (from the multi-energy method) is thus selected to characterize the violence of the explosion. This approach is conservative taken into account of the lack of information regarding the pressure rupture of the container and the pressure opening of the doors.

The table 40 below gives the distances of overpressure effects in the case of an explosion inside the container.

Table 40: Distances of the overpressure effects due to the explosion of hydrogen-energy containers

Hazardous phenomena	**Significant lethal effects – Domino effects 200 mbar (m)**	**Lethal effects 140 mbar (m)**	**Irreversible effects 50 mbar (m)**	**Indirect effects : broken glass 20 mbar (m)**
Explosion of container 10 feet L x l x H (m): 3 x 2.4 x 2.4	14	17	40	80
Explosion container 20 feet L x l x H (m): 6 x 2.4 x 2.4	17	21	51	102

7.5. Scenario matrix for refuelling station

The Table below presents the scenarios matrix related to a refuelling station.

Table 41: Scenarios matrix for a refuelling station

FCH application	**Potential danger**	**Discovery level**		**Advanced level**		**Expert level**	
		Scenario identification	**Description**	**Scenario identification**	**Description**	**Scenario identification**	**Description**
H2 REFUELLING STATION (without storage)	**NO LEAK**	H2_Refuelling_D_NL1	Dispenser/FC car false alarm - Refuelling station in a remote environment	H2_Refuelling_A_NL1	Dispenser/FC car false alarm - Refuelling station in a medium complex environment (outside urban or industrial environment)	H2_Refuelling_E_NL1	Dispenser/FC car alarm - Refuelling station complex environment (inside urban or industrial environments)
	LEAK	H2_Refuelling_D_L1	Dispenser/FC car default - **H2 leak** - simple environment (remote environment)	H2_Refuelling_A_L1	Dispenser/FC car default - H2 leak - medium complex environment (outside urban or industrial environment)	H2_Refuelling_E_L1	Dispenser/FC car default - H2 leak - complex environment (inside urban or industrial environments)
	H2 FIRE	H2_Refuelling_D_F1	Dispenser default - **H2 jet fire** - simple environment (remote environment)	H2_Refuelling_A_F1	Dispenser default - H2 jet fire - medium complex environment (outside urban or industrial environment)	H2_Refuelling_E_F1	Dispenser - H2 jet fire - complex environment (inside urban or industrial environments)
	EXTERNAL THREAT	H2_Refuelling_D_E1	**Fire in a refuelling station (remote environment)**	H2_Refuelling_A_E1	**Fire in a refuelling station (outside urban or industrial environment)** - FC car in the environment	H2_Refuelling_E_E1	**Fire in a refuelling station** (inside urban or industrial environments) - FC car in the environment

8. TYPICAL SCENARIOS FOR HYDROGEN STATIONARY STORAGES AND DISTRIBUTION

8.1. Feedback and lessons learned

The feedback is extracted from the database h2tools.org/lessons/ and articles.

8.1.1. Hydrogen storage

Reference	"Hydrogen Cylinder Leak at Fueling Station" http://h2incidents.org/incident.asp?inc=312
Description	Leak in one of the HP hydrogen storages situated on the roof of a recently opened filling installation, right in a town centre. The leak did not ignite.
Consequence	Sensors detected the leak which resulted in the installation being shut down and the leaking storage being isolated.
Cause	Leaking connection
Ineris[6] comment	**The semi-trailer and HP storage are situated outdoors and at ground level (easier to inspect). A leak tightness test is carried out every day. With each visit to site (i.e. approximately one hour a week), the operator carries out a visual check on the draw-off hose. It can shut down the installation and issue an alert, if necessary. There is hydrogen and flame detection in the outdoor area.**

Reference	"Pressure Relief Device Fails at Fueling Station" http://h2incidents.org/incident.asp?inc=311
Description	Failure of a relief valve in one of the HP storage tubes which resulted in the discharge of 300 kg of hydrogen into the atmosphere. At the exit from the vent, the discharge ignited and burned for more than two hours.
Consequence	Evacuation of offices and schools in the vicinity of the incident. No casualties. Rather minor damage estimated at $300. Corrective action was taken, e.g. the replacement of the relief valve, the raising of the vents and coordination with the emergency services.
Cause	Untimely opening of a relief valve
Ineris comment	**Poor choice of material and/or fitting of the relief valve.**

Reference	Rupture CO_2 Cylinder Causes Hydrogen Fire http://h2incidents.org/incident.asp?inc=201
Description	A CO_2 cylinder stored in a shelter suffered a catastrophic failure and became a missile. The cylinder destroyed its shelter and then crashed into a storage containing six cylinders of hydrogen. One of them was propelled out of the storage. The loss of this cylinder severely damaged the rest of the storage and caused a leak which ignited.
Consequence	Limited damage to the CO_2 cylinder and the six hydrogen cylinders and associated connectors.

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[6] http://www.ineris.fr/en

Cause	Domino effect (failure of the CO_2 cylinder caused by over-filling)
Ineris comment	**Nitrogen cylinder may be present in the area.**

8.1.2. Piping

Reference	"Manufacture of plastic products" ARIA 21965
Description	Violent and untimely movements of hose connected to a cooling device in the unit knocked over an operative and damaged several small pipes, resulting in the discharge into the atmosphere of hydrogen and butylene.
Consequence	Unit shut down for seven hours. Operative suffered serious leg injuries.
Cause	Domino effect (the movement of the hose damaged the pipework), also derogation from pre-defined procedures with no specific study of the risks.
Ineris comment	**When the operator handles the forklift refuelling hose, the hose is not under pressure. Refuelling is controlled remotely. If it is torn out, then the breakaway operates and this is tested before first use and is checked regularly.** **The draw-off hose from the semi-trailer is equipped with an anti-whipping cable.**

Reference	"Petroleum refining" ARIA 33966
Description	In a refinery, a leak ignited in a heavy fuels sulphur removal unit and, seven minutes later, under the action of the thermal flow, a 3" hydrogen pipe ruptured. The released hydrogen fuelled the fire.
Consequence	Ni human consequence, no impact on the environment. The damage to installations was considerable: it was estimated at €5 million for the structures and €7.6 million for the reconstruction costs and refurbishment work.
Cause	Domino effect (the initial ignited leak was due to a rupture in a tap-off).
Ineris comment	**The outdoor area complies with the "industrial" hydrogen installation rules (order dated 12 February 1998).**

Reference	"Manufacture of basic pharmaceutical products ARIA 7518
Description	In a factory manufacturing pharmaceuticals, an explosion occurred during the first use of a hydrogenation reactor during a leak tightness test on a seal conducted in a hydrogen atmosphere at very high pressure. The cause of the accident was one of the seals tested, followed by the spontaneous ignition of 30 l of an air/H_2 mixture. Pre-testing done using nitrogen was insufficient.
Consequence	Five employees admitted to hospital suffering from burns and hearing discomfort associated with the over-pressure. Damage to equipment was limited to the immediate area around the reactor.
Cause	Ruptured seal

Ineris comment	**There are no flanges in the pipework and no connections apart from those required for the safety equipment. Inerting with nitrogen before introducing hydrogen into the line.**

8.2. Hazardous phenomena

The hazardous potential for this stationary storages and piping systems, are identified in Table 42 below:

Table 42: Hazardous phenomena for stationary storages

Products	Equipment of hazards	Potential hazard
Hydrogen	Tanks	Burst
Hydrogen	Pipes	UVCE Jet Fire

8.3. Detailed scenarios for hydrogen stationary storage

8.3.1. Typical storages

As a reminder, in the following table 43, the different type and size of typical stationary storages, i.e. bottles and tanks, are presented, their pressure, volume (in water litre and of hydrogen contained) and mass of hydrogen contained.

Table 43: Pressures, Volumes and Masses of different stationary storages

Tank type and composition	**Tank capacity**	**Storage pressure (bar)**	**Volume in water (L)**	**Volume of hydrogen contained**	**Mass of hydrogen (kg)**
Type I (Steel)	B20	200	20	3.3	0.3
	B50	200	50	8.4	0.75
	Rack V9 B50	200	450	75.2	6.76
	Rack V18 B50	200	900	150.4	13.5
Trailer (2 m3)	Trailer	200	2 000	350	29
Type I (Steel)	Tank (7 m^3)	35	7 000	236	19.7
Type I (Steel)	Tank (14 m^3)	35	14 000	473	39.4
Type I (Steel)	Tank (28 m^3)	35	28 000	946	78.8
Composite type III	Bottles 74 L	595	74	20	1.8
Type IV	Rack H4 B142	525	568	207.5	18.7
	Bottle 80	700	80	35.8	3.2
	Rack H4 B142	700	568	254.1	22.8
	B142	700	142	63.5	5.7

For more precision for tanks, the characteristic dimensions are given as function of the tank volume.

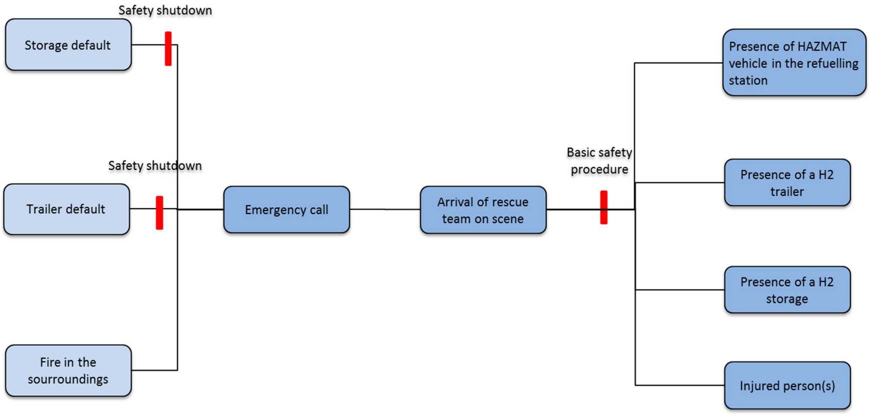
Table 44: Characteristic dimensions of tanks

Volume of tank, m^3	**Characteristic size, m**	
	Length	**Diameter**
7	3	1.7

14	6	1.8
28	9	2
56	18 11	2 2.5

8.3.2. Detailed scenarios

The Figure 11 presents a typical bow-tie diagram for a storage and distribution platform.



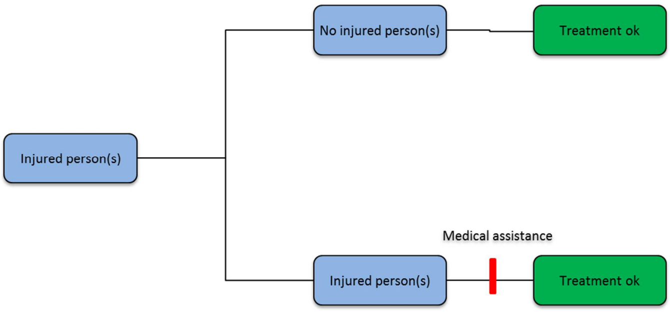


Figure 11: Example of bow-tie diagram for hydrogen storage and distribution platform

8.4. Potential consequences

8.4.1. Blowdown

The blowdown time is given as a function of tank volume, storage pressure and for different sizes of hole/leak.

Table 45: Blowdown time in function of tank type, pressure and hole size

Type of tank	Storage pressure (bar)	Blowdown time						
		0.1 mm	0.25 mm	1 mm	2.3 mm	4 mm	5.3 mm	9.1 mm
B20 (20 l)	200	128 min	21 min	-	-	**5 s**	-	-
B50 (50 l)	200	320 min	52 min	-	-	**12 s**	-	-
Rack V9 B50	200	48 h	461 min	-	-	**2 min**	-	-
Rack V18 B50	200	96 h	921 min	-	-	**4 min**	-	-
Trailer (2 m^3)	200	213 h	34.08 h	-	-	**8 min**	-	-
Tank (7 m^3)	35	-	-	-	-	-	-	**6 min**
Tank (14 m^3)	35	-	-	-	-	-	-	**13 min**
Tank (28 m^3)	35	-	-	-	-	-	-	**25 min**
Bottles 74 L	595	10 h	2 h	6 min	-	**23 s**	-	-
Buffer 1 m3	450	144 h	23 h	-	-	-	3 min	**1min**
Buffer 2 m3	450	288 h	46 h	-	-	-	6 min	**2 min**
Rack H4 B142	525	86 h	14 h	52 min	**10 min**	-	-	-
Bottle 80	700	13 h	127 min	8 min	**1.5 min**	-	-	-
Rack H4 B142	700	93 h	15 h	56 min	**11 min**	-	-	-

8.5.1.1. Hydrogen leak from piping system

The distances obtained for different hydrogen concentrations are given in Table 46 for three different sizes of hole/leak: 1, 2.3 and 4mm, for tank pressures of 35, 200, 350, 700 and 1000 bar.

Table 46: Distances to hydrogen concentration for 35 bar, 200 bar, 350 bar, 700 bar and 1000 bar

Pressure (bar)	Release Diameters (mm)	Separation distances, m 4 vol. %	Range of flame tip, m	
			8 vol. % —	16 vol. %
35	1	2.3	1.1	0.5
35	2.3	5.2	2.5	1.2
35	4	9.1	4.4	2
35	8	18.2	8.8	4
200	1	5.1	2.5	1.1
200	2.3	11.8	5.7	2.6
200	4	20	10	4.5
200	8	41	19.8	9.1
350	1	5.2	2.5	1.1
350	2.3	15	7.2	3.3
350	4.2	6.5	3.1	1.4
350	8	52	25	11.5
700	1	8.4	4	1.8
700	2.3	19	9	4

700	4.2	35	17	7.8
700	8	67	32	15
1000	1	9.4	4.5	2.1
1000	2.3	21.6	10.4	4.8
1000	4	25	18	8.3
1000	8	75	36	16

8.5.1.2. Hydrogen jet fires from piping system

The Table 47 below gives the thermal and potential overpressures obtained from hydrogen jet fires.

Table 47: Thermal and potential overpressure effects obtained from hydrogen jet fires

Piping leak diameter, mm	Pressurein the tank (bar)	Direct ignition (JET FIRE)					Delayed ignition (UVCE)			
		Thermal effects (m)			Flame length (m)		Overpressure effects (m)			
		3 kW/m^2	5 kW/m^2	8 kW/m^2	L	r	20 mbar	50 mbar	140 mbar	200 mbar
0.1	35	0.06	0.06	0.06	0.06	0.01	-	-	-	-
1	35	0.8	0.8	0.7	0.7	0.1	-	-	-	-
5	35			3.9	3.9	0.7	-	-	-	-
10 mm	35	14	12	10	8	1.3	40	20	8.5	6.1
1	200	3.1	2.9	2.7	1.3	0.22	-	-	-	-
2.3	200	5.6	5.4	5.2	3	0.5	17	8.5	3.8	2.7
4	200	11	10.5	10	5.5	0.9	30	15	6.5	4.8
8	200	24	22	20	11.3	9	60	30	12.9	9.4
1	350	3.2	3	2.8	1.6	0.3	9.5	4.8	2	1.5
2.3	350	7	6.5	6	3.8	0.6	22	11	4.7	3.4
4	350	15	14	13	6.8	1.2	38	19	8.2	6
8	350	30	28	26	13.5	2.3	78	39	16	12
1	700	3.5	3.3	3	1.9	0.3	12	6	2.6	1.9
2.3	700	10	9	8	4.7	0.8	29	14.5	6.1	4.5
4	700	19	17	15	8.3	1.4	50	25	10.7	7.8
8	700	36	34	32	16.5	2.8	100	50	21.4	15.6
1	1000	4.3	4.1	3.9	2.1	0.4	13.8	6.9	2.9	2.3
2.3	1000	10	9	8	5	0.85	32	16	6.7	4.9
4	1000	19	17	15	8.8	1.5	56	28	11.9	8.6
8	1000	40	38	36	18.2	3	112	56	24	17.5

Table 48: Distances of thermal and overpressure effects due to a pipe rupture outside the container[7]

Type of tanks	Piping leak diameter, mm	Pressure of the tank (bar)	Direct ignition **(JET FIRE)**					Delayed ignition **(UVCE)**			
			Thermal effects (m)			Flame length (m)		Overpressure effects (m)			
			3 kW/m^2	5 kW/m^2	8 kW/m^2	L	r	20 mbar	50 mbar	140 mbar	200 mbar
Tank (7 m^3)	0.1	35	0.06	0.06	0.06	0.06	0.01	-	-	-	-
Tank (14 m^3),	1	35	0.8	0.8	0.7	0.7	0.1	-	-	-	-
Tank (28 m^3),	5	35			3.9	3.9	0.7	-	-	-	-
Tank (56 m^3),	10	35	14	12	10	8	1.3	40	20	8.5	6.1
Trailer, Rack V9 B50,. Rack V18 B50	0.1	200	0.2	0.2	0.2	0.2	0.03	0.5	-	-	-
Trailer	0.2	200	0.5	0.4	0.4	0.4	0.06	1	0.5	-	-
	4	200	11	9	8	7	1.2	20	10	6	5
	Full rupture of flexible of trailer	200	7.2	7.2	7.2			13.1	8.2		
Buffer 1 m^3.	0.1	450	0.2	0.2	0.2			0.8	0.4		
Buffer 2 m^3	4	450	16	14	12	11	1.8	30	15	9	7
Rack H4 B142	0.1	525	0.4	0.3	0.3	0.4	0.06	1	0.5	-	-
	0.21	525	0.7	0.6	0.6	0.8	0.13	2	1	-	-
	2.3	525	9	7.9	7	7	1.2	18	9	6	5
	4	525	17	15	13	12	2	32	16	9	8
	5.2	525	22	19	17	15	2.5	42	21	12	10
Rack H4 B142	0.1	700	0.2	0.2	0.2	0.5	0.08	1	0.5	-	-
	0.2	700	0.8	0.4	0.4	0.8	0.13	2	1	-	-
	2.3	700	10	9	8	8	1.3	22	11	6	5
	4	700	19	17	15	14	2.3	38	19	11	9

8.4.2. Potential impact related to storage burst

The bursting is assumed to occur after the impact of a hydrogen jet fire on a material used for tank walls. This scenario gives the most important parameter such as bursting pressure. The bursting pressure is estimated using the methodology from INERIS-OMEGA 15[8] on the tanks bursts. The bursting pressure is calculated by multiplying by 3 the calculation pressure, taken equal to the maximal operation pressure i.e. the storage pressure. Then a factor of ½ is applied in order to take into account the weakening of the structure caused by thermal attack.

This method is valuable only for metal tanks. For Type IV storages (composed of carbon), the bursting pressure is taken equal to the storage pressure.

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[7] Information extracted from “Propriétés de l’hydrogène”, AIR LIQUIDE written by Simon Jallais

[8] HEUDIER, L., Les éclatements de capacités, phénoménologie et modélisation des effets - Ω 15, INERIS Report, 2013

The results of the distances at the different thresholds of overpressure effects are collated in the following table 49.

Table 49: Distances of the overpressure effects due to tank burst[9]

Type of storage	Tank capacity	Storage pressure (bar)	Overpressure burst (bar)	Significant lethal effects – Domino effects 200 mbar (m)	Lethal effects 140 mbar (m)	Irreversible effects 50 mbar (m)	Indirect effects : broken glass 20 mbar (m)
Type I	B20 (20 l)	200	380	5	6	16	32
Type I	B50 (50 l), Rack V9 B50, Rack V18 B50	200	380	7	9	22	44
Type I	Tank (7 m^3)	35	53	18	22	55	110
Type I	Tank (14 m^3)	35	53	22	28	69	139
Type I	Tank (28 m^3)	35	53	28	35	87	175
Type I	Tank (56 m^3)	35	53	35	44	110	220
Type I	Trailer (2 m^3)	200	430	22	29	67	134
Type I	Buffer (cigar) 1 m^3	450	675	23	29	72	145
Type I	Buffer 2 m^3	450	675	26	36	85	170
Type IV	Rack H4 B142	525	578	9	13	31	62
Type IV	Bottle 80	700	770	9	12	28	56
Type IV	Rack H4 B142	700	770	13	16	40	79
Type I	Buffer (cigar) 1 m3	1000	2000	34	40	105	211
Type I	Buffer 2 m3	1000	2000	42	50	133	266

8.5. Scenario matrix for hydrogen stationary storages and distribution

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[9] Information extracted from “Cadre de bouteilles H4-142 ; logistique 700 bar pour l’hydrogène énergie”, January 2013, AIR LIQUIDE written by Verghade

FCH application	**Potential danger**	**Discovery level**		**Advanced level**		**Expert level**	
		Scenario identification	**Description**	**Scenario identification**	**Description**	**Scenario identification**	**Description**
H2 STORAGE	**NO LEAK**	H2_Storage_D_NL1	H2 storage false alarm - simple environment (remote environment)	H2_Storage_A_NL1	H2 storage false alarm - medium complex environment (outside urban or industrial environment)	H2_Storage_E_NL1	H2 storage false alarm - complex environment (inside urban or industrial environments)
	LEAK	H2_Storage_D_L1	H2 storage default - **H2 leak** - simple environment (remote environment)	H2_Storage_A_L1	H2 storage default - H2 leak - medium complex environment (outside urban or industrial environment)	H2_Storage_E_L1	H2 storage default - H2 leak - complex environment (inside urban or industrial environments)
	FIRE	H2_Storage_D_F1	H2 storage default - H2 jet fire - simple environment (remote environment)	H2_Storage_A_F1	H2 storage default - H2 jet fire - medium complex environment (outside urban or industrial environment)	H2_Storage_E_F1	H2 storage - H2 jet fire - complex environment (inside urban or industrial environments)
	EXTERNAL THREAT	H2_Storage_D_E1	**Fire in a simple environment (remote environment)** - Storage in the environment	H2_Storage_A_E1	**Fire in a medium complex environment (outside urban or industrial environment)** - Storage in the environment	H2_Storage_E_E1	Fire in a complex environment (inside urban or industrial environments) - Storage in the environment

9. TYPICAL SCENARIOS FOR FC STATIONARY APPLICATIONS

9.1. Feedback and lessons learned

No information on H2tools was found regarding stationary applications.

9.2. Identification of hazardous phenomena

9.2.1. Hydrogen production

Hydrogen combustion presents one of the main risk during the exploitation of hydrogen system regarding the safety of persons and goods. This risk is generalized through the whole range of facilities (system, storage and pipes). The causes leading to the formation of a flammable mixture, which will be detailed in the following paragraphs, are:

- Leaks of gaseous hydrogen on pipes connecting the electrolyser and an external tank/system of storage
- Leaks and accumulation of hydrogen inside the electrolyser
- Internal gas leaks within the electrolyser stack:
  - Circulation of water gas charged from the hydrogen loop towards the oxygen loop and creating a H_2/O_2 mixture in the gas separator.
  - Hydrogen diffusion towards the oxygen compartment creating a H_2/O_2 flammable mixture.

The scenarios of major accidents are those leading to:

- Hydrogen accumulation and ignition in the electrolyser (in an enclosure or container),
- Hydrogen ignition at the level of the gas separator of the electrolyser
- UVCE hydrogen ignition at the level of storage and pipes
- Storage burst

The hazardous potential considered for this application are shown in Table 50.

Table 50: Hazardous phenomena for electrolysers

Products	Equipment of hazards	Potential hazard
Hydrogen	Container	Container explosion Jet fire
Hydrogen	Storage	Burst
Hydrogen	Gas separators (electrolyser systems)	Burst
Hydrogen	Pipes	UVCE VCE Jet Fire
Electricity	Cable	Electrocution

9.2.2. Hydrogen fuel cell applications

The causes leading to the formation of a flammable mixture, which will be detailed in the following paragraphs, are:

- Leaks of gaseous hydrogen on pipes between the fuel cell system and an external storage.
- Leaks and accumulation of hydrogen inside the fuel cell.
- Internal gas leaks within the Fuel Cell stack by Hydrogen diffusion towards the oxygen compartment creating a H2/O2 flammable mixture.

The scenarios of major accidents s are those leading to:

- Hydrogen accumulation and ignition in the fuel cell (in an enclosure or container),
- UVCE hydrogen ignition at the level of storage and pipes

The hazardous potential considered for this application are shown in Table 51

Table 51: Hazardous phenomena for FC systems

Products	Equipment of hazards	Potential of Hazard
Hydrogen	Container	Container explosion Jet fire
Hydrogen	Pipes	UVCE VCE Jet Fire
Electricity	Cable	Electrocution

9.2.3. Hydrogen-based energy storage systems

Hydrogen-based energy storage systems are composed of a FC and electrolyser systems. They consequently combine the hazardous phenomena of both stationary FC and electrolyser systems. The causes leading to the formation of a flammable mixture, which will be detailed in the following paragraphs, are:

- Burst of hydrogen storage tank.
- Leaks of gaseous hydrogen on pipes between the storage tank and the hydrogen-energy system (Fuel Cell, electrolyser, hydrogen energy storage system)

The scenarios of major accidents are those leading to:

- Hydrogen accumulation and ignition in the hydrogen-energy container,
- UVCE hydrogen ignition at the level of storage and pipes
- Storage burst

The hazardous potential considered for this application are shown in Table 52.

Table 52: Hazardous phenomena for hydrogen-energy storage systems

Products	Equipment of hazards	Potential of Hazard
Hydrogen	Container	Container explosion Jet fire
Hydrogen	Pipes	UVCE VCE Jet Fire
Hydrogen	Gas separators (electrolyser)	Burst
Electricity	Cable	Electrocution

9.3. Detailed scenarios of hazardous phenomena

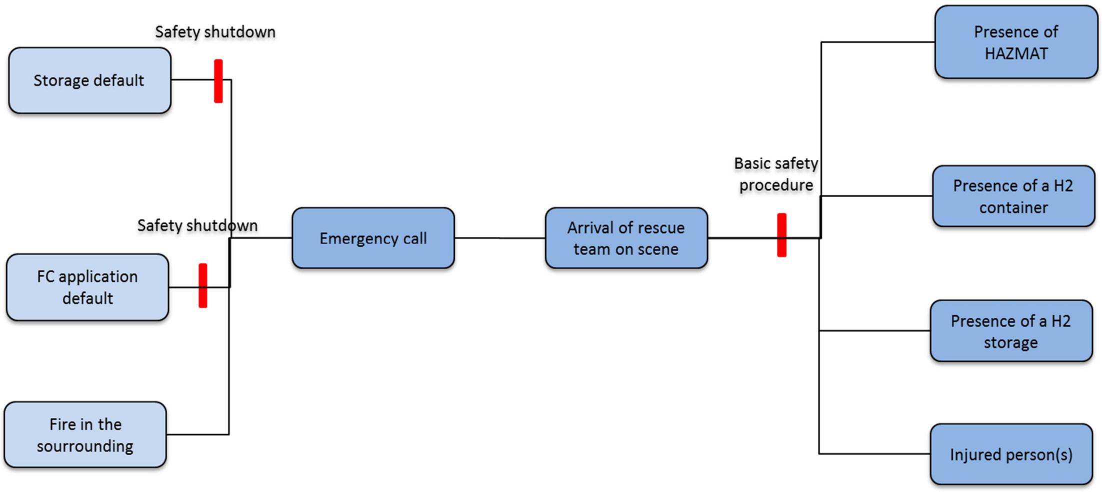

Figure 12: Example of bow-tie diagram for FC stationary applications

9.4. Potential consequences

9.4.1. Pipe rupture inside the container: Jet fire

The case of the rupture of a pipe and an immediate ignition leading to a jet fire is considered and values of distances are shown in Table 51.

Table 53: Distances to the thermal effects (l: longitudinal length and r: radial length)

Pipe diameter, mm	Pressure, bar	Thermal effects			Flame length, m		Separation distance to avoid ignition, m	Domino effects, m
		3 kW/m²	5 kW/m²	8 kW/m²	l	r		
8	9	4	3	2.5	3.5	0.6	4	2.5
12	9	6	5	4	5	0.9	5.8	4
8	35	8	6	5	5.5	0.9	6.1	5
12	35	12	9	7	8.5	1.4	9.3	7

9.4.2. Hydrogen accumulation followed by container explosion

The Table 54 below presents the characteristics dimension and volumes for 10, 20 and 40 feet containers. The free volume of a container is considered to be around 70% of the total volume.

Table 54: Different volumes considered for H2-energy systems (FC, electrolyser, H_2-energy storage system)

Different container	Dimension L x l x H (m)	Volume, m^3	Free volume
Explosion container 10 feet	3 x 2.4 x 2.4	17	12
Explosion container 20 feet	6 x 2.4 x 2.4	34	24
Explosion container 40 feet	12 x 2.4 x 2.4	68	48

The same methodology described in the paragraph in 7.4.2 is applied to calculate the distances of overpressure effects in the case of an explosion inside the container.

Table 55: Distances of the overpressure effects due to the explosion of hydrogen-energy containers

Hazardous phenomena	Significant lethal effects – Domino effects 200 mbar (m)	Lethal effects 140 mbar (m)	Irreversible effects 50 mbar (m)	Indirect effects : broken glass 20 mbar (m)
Explosion of container 10 feet L x l x H (m): 3 x 2.4 x 2.4	14	17	40	80
Explosion container 20 feet L x l x H (m): 6 x 2.4 x 2.4	17	21	51	102
Explosion container 40 feet L x l x H (m): 12 x 2.4 x 2.4	22	27	64	128

9.4.3. Formation and ignition of a hydrogen-oxygen mixture in the gas separator (for electrolyser systems)

The scenario considered here is the bursting of a separator by ignition of an H_2/O_2 mixture. The figure below shows that there is two possible ways[10] to get a flammable mixture within the separator:

- by a failure of the solenoid valve (way (a) on the figure below)
- by a membrane rupture of the stack membrane (way (b) on the figure below)

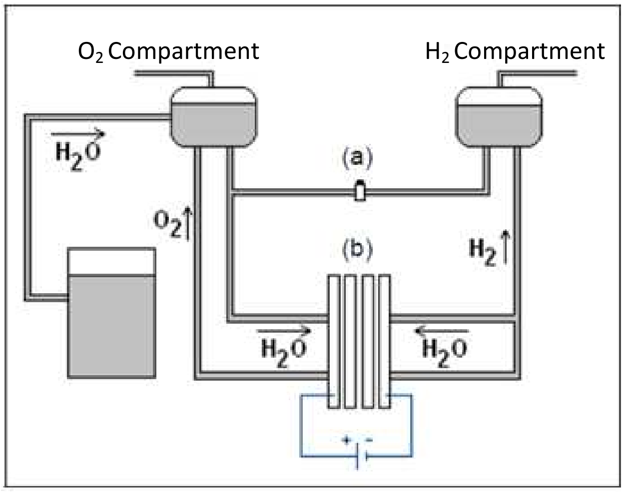

Figure 13: Schematic diagram of the electrolysis system

To calculate the potential overpressure distances obtained consequently to the burst of a gas separator, the methodology described below is applied.

It should be noted that the model below does not take into account the presence of the process compartment and the container around the separator. When the bursting occurs the process will absorb a part of the energy released by the explosion. Consequently, the distances obtained with this method are considered as conservative distances.

It is considered in this case that the operation pressure of the separator is 40 barg and that its a volume is equal to 45 L.

It is good practice to take as hypothesis that the bursting pressure of a closed volume is equal to 2.5 times the operation pressure, i.e. 100 bars.

The energy associated with the brutal reduction in pressure of gas is given by:

$$E = \frac{p_0.V}{\gamma - 1}\left[1 - \left(\frac{p_a}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

With:

- E : Energy of the pressure reduction (J)

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[10] The present analysis is resulting from the document "Analyse des risques relative à des systèmes d'électrolyseurs PEM haute pression" of INERIS

- p_0 : Internal pressure during the rupture (100*10^5 Pa)
- p_a : Atmospheric pressure (101,325 Pa)
- V : Volume of the gas involved (0.045 m^3)
- γ : Ratio of the specific heat of hydrogen/oxygen mixture (1.4)

Thus, it can be estimated that *E*=0.64 MJ. Approximately 80% of this energy (0.51 MJ) can be affected to the blast effects, which represents a TNT equivalent of approximately 110 g.

The overpressure distances are gathered in the table 56 below.

Table 56: Distances of the overpressure effects due to the burst of gas separator

Hazardous phenomena	**Significant lethal effects – Domino effects 200 mbar**	**Lethal effects 140 mbar**	**Irreversible effects 50 mbar**	**Indirect effects : broken glass 20 mbar**
Burst of a gas separator (V = 45L)	4 m	5 m	13 m	26 m

Once again, noting that this model does not take into account the presence of the process compartment around the separator. Before bursting, the compartment will absorb a part of the energy released by the explosion.

9.5. Scenario matrix for stationary FCH systems

The Table 55 summarises the scenarios matrix obtained for typical stationary FCH systems.

Table 57: Scenario matrix for typical stationary FCH systems

FCH application	**Potential danger**	**Discovery level**		**Advanced level**		**Expert level**	
		Scenario identification	**Description**	**Scenario identification**	**Description**	**Scenario identification**	**Description**
FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM	**NO LEAK**	FC_System_D_NL1	FC system false alarm - simple environment (remote environment)	FC_System_A_NL1	FC system false alarm - medium complex environment (outside urban or industrial environment)	FC_System_E_NL1	FC system false alarm - complex environment (inside urban or industrial environments)
	LEAK	FC_System_D_L1	FC system default - **H2 leak** - simple environment (remote environment)	FC_System_A_L1	FC system default - H2 leak - medium complex environment (outside urban or industrial environment)	FC_System_E_L1	FC system default - H2 leak - complex environment (inside urban or industrial environments)
	H2 FIRE	FC_System_D_F1	FC system default - **H2 jet fire** - simple environment (remote environment)	FC_System_A_F1	FC system default - H2 jet fire - medium complex environment (outside urban or industrial environment)	FC_System_E_F1	FC system - H2 jet fire - complex environment (inside urban or industrial environments)

	EXTERNAL THREAT	FC_System_D_E1	**Fire in a simple environment (remote environment)** - FC system in the environment	FC_System_E_E1	**Fire in a medium complex environment (outside urban or industrial environment)** - FC system in the environment	FC_System_E_E1	Fire in a complex environment (inside urban or industrial environments) - FC system in the environment

10. Conclusion

This deliverable aims to develop and detail accident scenarios (i.e. case studies) as well as to evaluate their associated consequences. Each scenario relates to a particular transport or stationary FCH system selected in the deliverable D2.1. It takes into account hazards, relevant safety requirements and preventative measures for each FCH application discussed in D2.1.

The detailed scenarios presented in the current deliverable are considered as the worst case scenarios for each FCH application. They take into account the effect of First Responders' intervention (both recommended and incorrect actions) for selected applications.

The same methodology was applied to every FCH installation in order to develop the scenario matrix. The methodology includes: feedback and lessons learnt from the incidents/accidents already recorded, identification of potential hazards, evaluation of consequences (bow-tie diagrams), safety measures and concepts, accident progression, effects on humans and structures. Overall, the matrix contains over 100 detailed scenarios of different level of difficulty: beginner, advanced and expert. The scenarios will be considered during the development of operational response strategies and tactic.

Also, these scenarios will be used in the educational training content of HyResponse training programme. Some of them will be used to design training exercises that will be implemented on both the operational and virtual reality platforms.

ANNEXES

Table of annexes

CyberLaboratory

Cyber Laboratory (CL) was developed within the frame of H2FC European Infrastructure project.
It is a comprehensive and properly validated set of numerical and modelling tools in the field of hydrogen and fuel cell technologies.
HySAFER centre @ UU, is the leader and main developer/provider of engineering tools to the Cyber Laboratory.
CL tools available in open access to all European stakeholders
Software suite will be maintained and made available after the end of the H2FC project (after October 2015).
Link: www.h2fc.eu/cyber-laboratory
Currently available engineering tools on safety:

- Hydrogen jet parameters
- Free jet model
- Adiabatic blowdown of storage tank
- Isothermal blowdown of storage tank
- Flame length and separation distance for jet fires
- Unignited jets – axial distance to different H2 concentrations
- Pressure peaking phenomenon (constant mass flow rate)
- Pressure peaking phenomenon (tank blowdown)
- Calculation of required reservoir volume

Methods to calculate overpressure effects from tank burst

Tank burst

Metal tank

2.5 times the operating pressure

Type IV tanks

Burst pressure = 1,1 x operating pressure

It is good practice to take as hypothesis that the bursting pressure of a closed volume is equal to 2.5 times the operation pressure, i.e. 100 bars.

The energy associated with the brutal reduction in pressure of gas is given by:

$$E = \frac{p_0 . V}{\gamma - 1}\left[1 - \left(\frac{p_a}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

With:

- E : Energy of the pressure reduction (J)
- p_0: Internal pressure during the rupture (Pa)
- p_a: Atmospheric pressure (101,325 Pa)
- V : Volume of the gas involved (m^3)
- γ : Ratio of the specific heat of hydrogen/oxygen mixture (1.4)

Once the energy estimated, it is considered that 80% of this energy can be affected to the blast effects, which represents a TNT equivalent. Based on this TNT equivalent, overpressure effects can be estimated at several distances.

HySAFER has developed methodologies for blast wave. A graphical representation of the methodology can be found below.

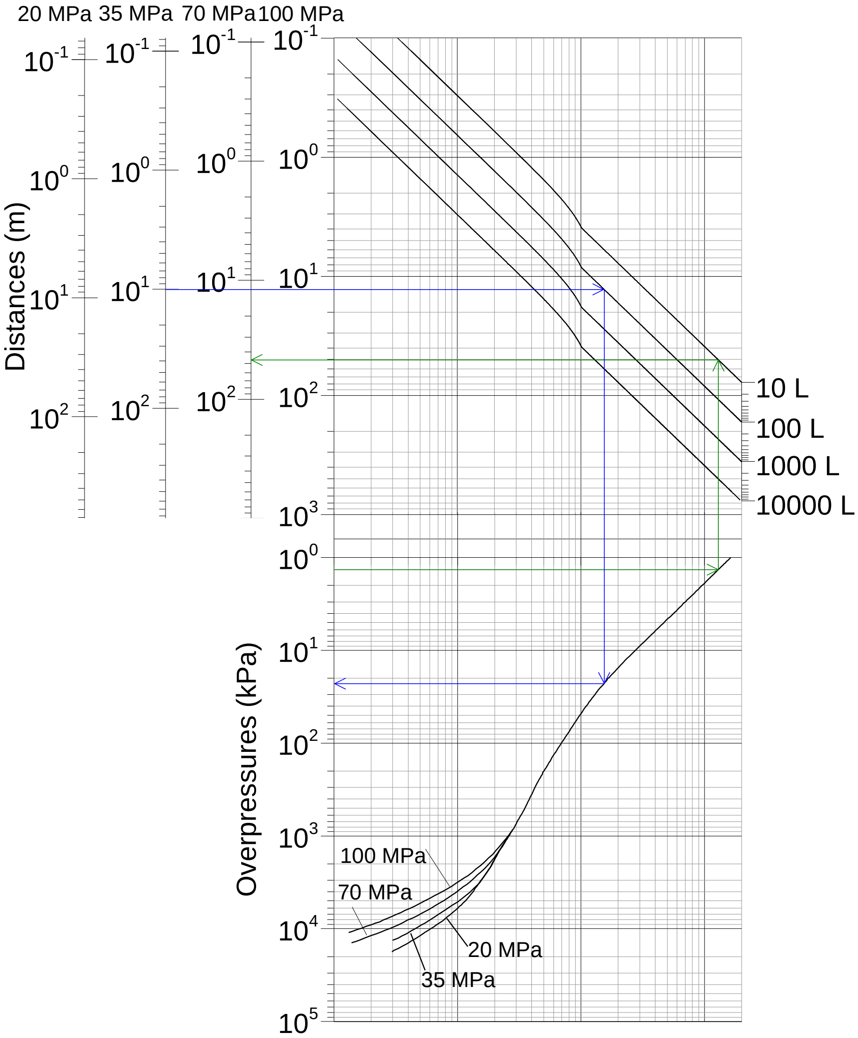

Figure 14 : Overpressure-distance nomogram for stand-alone tank rupture