HyApproval

WP4, ST3

Risk assessments & accident simulations as per matrix table

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1. INTRODUCTION

This document aims at presenting the main results of the risk assessment sessions, which gathered WP4 partners, carried out in March and May 2006.

After, reminding briefly the risk assessment methodology that was used (see WP4 ST3, Draft 4.3, V1.0), the main hazardous situations and the proposed safety functions to control them will be presented for each sub-system of a hydrogen refuelling station.

This step will help to draw the list of the accident scenarios to be selected for modelling (see WP4, Draft 4.X, V1.0).

2. RISK ASSESSMENT METHODOLOGY

2.1 Objectives and scope of the risk assessment study

The logical steps to go through in the course of WP4 work are pictured by the graph below.

The figure below shows the different steps used for the risk assessment of a standard hydrogen refuelling station (HRS).

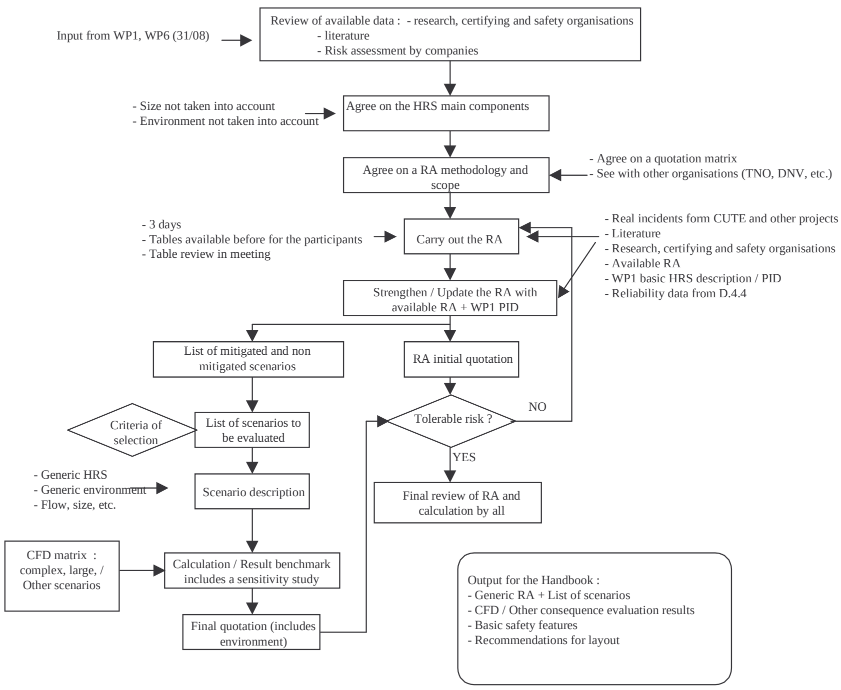

Figure 1: Proposed risk assessment methodology

This work can be divided into four main steps:

- A preliminary work where HyApproval WP4 Partners agree on different parameters to take into account for further work, like the main components of a HRS, the HRS size,
- A risk analysis to identify accidental scenarios and to highlight safety measures. Scenarios are also ranked according to severity and likelyhood.
- Quantification of selected scenarios:
  - The quantified evaluation of non-mitigated scenarios will enable to assess the HRS potential hazards as well as to assess the usefulness of the proposed safety equipment.
  - The quantified evaluation of mitigated scenarios will contribute to demonstrate that residual risks are tolerable.
- And finally the agreement on risk acceptance criteria and acceptable scenarios.

2.2 Functional layout

The HRS was divided into several functional components related to the main equipment of a CGH2 or a LH2 station.

The different sub-systems for a compressed hydrogen refuelling station that were considered for the risk assessment sessions are:

- Reformer inside a closed container,
- Electrolyser inside a closed container,
- Compressor in open air,
- Compressed hydrogen storage in open air,
- Compressed hydrogen dispenser in open air,
- Compressed gas trailer delivery.

The specific elements for a liquid hydrogen refuelling station that were considered for the risk assessment sessions are:

- Liquid hydrogen tanker delivery in open air,
- Liquid hydrogen storage in open air,
- Liquid hydrogen dispenser in open air.

The entire station was partly reviewed.

The assumptions on the hydrogen refuelling stations in the Appendix A “Risk Analysis of Hydrogen Filling Station Assumptions and Study Basis”.

2.3 Tables used for the risk assessment

The following risk assessment table; which use is detailed in the WP4 D4.3, was used.

HYAPPROVAL WP4

Date

Hydrogen System:	**Running mode**
Environment:	**Loop input:**
PID :	**Loop output:**

Ref.	Central event	Causes	Consequences	Leak size	Quantity of combustible gas available	P	S	Remarks	Safety Functions (limit, avoid, control)	Technical barriers	Organisational barriers	P	S	C	Remarks	Scenario to model

Table 1: Extract of the risk assessment table

The risk assessment of a standard HRS was performed during 2 sessions which took place at INERIS offices, the first one on the 29th March 2006 and the second one on the 23rd- 24th May 2006.

The risk assessment sessions gathered the different European actors of the WP4 involved in the hydrogen field, that are:

- Petrochemical representatives – Hydro, Shell,
- Hydrogen station equipment providers – Air Liquide, Air Products, Linde
- Research, certifying & Testing organisations – CEA, DNV, FZK, HSE/HSL, INERIS, TNO.

3. RESULTS OF THE RISK ASSESSMENT

For each sub-system of a HRS, the dangerous phenomena were identified during the risk analysis sessions.
In the following tables, the scenarios with large and medium hydrogen leaks are presented.
The safety functions for the different accident scenarios with the associated safety barriers are listed.

3.1 Sub-system “reformer inside closed container”

The reformer produces hydrogen from natural gas at high temperature. The reforming process requires also stages of desulfurization, CO shift conversion, and purification by pressure swing adsorption (PSA).

The potential dangerous sources in this process are:
- natural gas,
- and hydrogen.

As natural gas and hydrogen are highly flammable gas, the main dangerous phenomena are:
- explosion in case of late ignition
- jet flame in case of early ignition
- burst of a containment where flammable gas is processed.

The reformer is generally installed in a closed container, which can lead to more severe consequences for an explosion than in open air due to the possible gas accumulation.

Gas accumulation or gas ingress can also occur in other confined areas like in the separator or in the PSA.

The following table presents the scenarios identified during the risk assessment.

Leak size	Ref.	Scenario
Medium	PR2	Leakage of the NG feed line due to mechanical aggression, corrosion or failure of gaskets/joints leading to an explosion
	PR3	Rupture of the reforming unit tube due to hot spot on tube or excessive water / steam flow inside the tube leading to a jet fire
	PR4	Rupture of a pipe before cooling due to hydrogen embritlement (hydrogen corrosion), excessive temperature or excessive pressure leading to a jet fire
	PR5	Leakage of H2 pipe before cooling due to hydrogen embritlement (hydrogen corrosion), excessive temperature, excessive pressure or failure of gaskets/joints leading to a fire
	PR10	Leakage from the rotary PSA safety valve due to fatigue or failure of gaskets/ joints leading to an explosion or a standing flame
	PR11	Rupture of vent line (low pressure) due to mechanical aggression or overpressure leading to an explosion or a standing flame
	PR12	Leakage from a vent line (low pressure) due to failure of gaskets/joints leading to an explosion or a standing flame
Large	PR1	Rupture of the NG feed line due to mechanical aggression, corrosion or overpressure leading to an explosion
	PR6	Rupture of a H2 pipe after shift and cooling due to hydrogen embritlement (hydrogen corrosion), excessive temperature or excessive pressure leading to an explosion
	PR8	Syngas ingress through phase separation vessel due to low level inside the separator leading to an explosion inside equipment and missiles
	PR9	Burst of the PSA due to overpressure (external fire), excessive pressure at the reformer outlet, hydrogen embritlment (hydrogen corrosion) or mechanical aggression leading to an overpressure, fireball, toxic gas dispersion and missiles
	PR13	Leakage or burst of the H2 line to the compressor leading to a jet fire or explosion inside casing
	PR14	Explosive atmosphere inside equipment due to maintenance error leading to an explosion inside equipment if ignited and missiles
	PR16	Large leak of flammable gas (NG/H2/CO) inside equipment due to wear or human error leading to explosion inside equipment if ignited and missiles

The main causes leading to a loss of containment that were identified are mostly technical causes : excessive temperature or pressure, corrosion, gaskets failures, etc. but they are also related to the design of the installation with the choice of material (hydrogen embritlement) and to human factors (mechanical aggression, maintenance error).

The main safety strategy is to:
- Prevent a leak: avoid mechanical aggression, corrosion, fatigue; control tightness
- limit the leak time and leak flow by detection and shutdown of the input and/or output line
- avoid gas accumulation in the container with a forced and/or emergency ventilation, isolation valves closure
- avoid ignition (ATEX zoning, gas temperature control)
- protect from the consequences (overpressure)

The following table presents the safety functions that are required regarding the identified dangerous phenomena. During the risk assessment, some safety barriers that were identified for each safety function are given as examples.

Dangerous phenomena	Safety functions	Example of safety barriers	Comments
Explosion of CH4 or H2 if late ignition inside container	Avoid mechanical aggression	- Fenced site / closed container - Work permit / trained workers	
	Avoid / Control corrosion	Regular inspection and maintenance	
	Prevent fatigue of vent lines, PSA	Regular inspection and maintenance	
	Control tightness of gaskets / joints	Regular inspection and maintenance	
	Control overpressure	Safety valves	
	Limit leak time (detect and shutdown)	Methane gas detection system with shutdown	
	Limit leak flow	CH4/CO/H2 gas detection system with shutdown	
	Avoid gas accumulation	- Forced ventilation - Actuated emergency ventilation - Opening of ceiling / walls - Closure of isolation valves	
	Avoid ignition	- No source of ignition - ATEX zoning	
	Avoid contact with air and combustible gas inside equipment	- Low pressure control - Inerting equipment before start up	
	Control overpressure effects	Explosion relief panels on container	
Jet fire if early ignition	Control pipe ageing (H2 corrosion)	Regular inspection and maintenance	
	Control gas temperature	Exceeding max operation temperature causes shutdown	
	Limit leak time (detect and shutdown)	Methane gas detection system with shutdown	
	Avoid ignition	- No source of ignition - ATEX zoning	
Toxic gas	Detect toxic gas	CH4 and CO gas detection – system causes shutdown	
Burst of equipment + missiles	Control pressure	Safety valves	
	Control equipment ageing	Regular inspection and maintenance	
	Avoid mechanical aggression	- Fenced site / closed container - Work permit / trained worker	

3.2 Sub-system "electrolyser inside closed container"

Hydrogen can be produced by water electrolysis.
The potential dangerous sources are the lye and the hydrogen.

The main dangerous phenomena involved by these compounds are:
- explosion in case of late ignition
- jet flame in case of early ignition
- burst of a containment where flammable gas is processed (that are the electrolyser itself and the closed container).

The following table presents the scenarios identified during the risk assessment.

Leak size	Ref.	Scenario
Medium	PE3	Lye leak through cells due to overpressure (external fire), failure of gaskets/joints or excessive temperature leading to explosion or jet flame
	PE5	Leakage from lye pipes due to hydrogen embritlement (hydrogen corrosion), overpressure or failure of gaskets/joints leading to explosion or jet flame
	PE6	Lye discharge through vent line due to overpressure in the hydrogen separator or low level in break tank leading to explosion or jet flame
	PE7	Oxygen leak inside the production enclosure leading to fire inside the electrolyser casing
	PE8	Moderate H2 leak in the confined container leading to explosion or jet fire
Large	PE4	Rupture of lye pipe due to hydrogen embritlement (hydrogen corrosion), excessive temperature or excessive pressure leading to explosion or jet flame
	PE9	Large H2 leak in confined container (back flow of H2 from the storage)
	PE10	Discharge from the safety relief valve to an unsafe location leading to explosion or jet fire.

The following table presents the safety functions that are required regarding the identified dangerous phenomena.

Dangerous phenomena	Safety functions	Safety barriers	Comments
Explosion of H2 if late ignition	Control pipe ageing (H2 corrosion)	Regular inspection and maintenance	
	Limit leak time (detect and shutdown)	H2 detection system with shutdown	
	Avoid ignition	- No source of ignition - ATEX zoning	
	Control overpressure	Safety valves	
	Control consequences at the vent line		
Jet flame if early ignition	Control pipe ageing (H2 corrosion)	Regular inspection and maintenance	
	Control gas temperature	Exceeding max operation temperature causes shutdown	
	Limit leak time (detect and shutdown)	H2 detection system with shutdown	
	Avoid ignition	- No source of ignition - ATEX zoning	
	Detect flame	-	

The main safety strategy is to:
- Prevent a leak (avoid mechanical aggression, corrosion, fatigue)
- limit the leak (leak time, leak flow by detection and shutdown of the H2 pipes
- avoid gas accumulation (forced and emergency ventilation, isolation valves closure)
- avoid ignition (ATEX zoning, gas temperature)
- protect from the consequences (overpressure)

3.3 Sub-system "compressor inside closed container"

The hydrogen is pressurized in a compressor from about ten bar to several hundred bar.
The compressor is usually located inside an enclosure or under a weather shed.

The potential risks are induced by the hydrogen at high pressure combined with the containment of the compressor.

The following table presents the scenarios identified during the risk assessment.

Leak size	Ref.	Scenario
Medium	K4	Leakage from the compression chamber due to overpressure, lack of cooling or gasket damage leading to a standing flame or an explosion inside casing
	K8	H2 leakage from the compressor output line due to mechanical aggression, hydrogen embritlement (hydrogen corrosion), failure of gaskets/joints or overpressure leading to an explosion or a jet flame
	K10	Discharge of H2 through a PRD due to a PRD not reseated properly leading to explosion or a momentum jet flame
Large	K1	Burst of buffer at the compressor outlet due to mechanical aggression, hydrogen embritlement (hydrogen corrosion), overpressure, explosive mixture inside the buffer (low pressure at the compressor input or air ingress due to isolation of upstream equipment), explosive mixture form the electrolyser or external fire leading to an explosion or a jet flame
	K3	Burst of the compression chamber due to cooling fluid ingress or entrance of a non compressible fluid, hydrogen embritlement (hydrogen corrosion), explosive mixture inside compression chamber (low pressure at compressor intake) or outlet valve remains closed leading to internal damage but no loss of containment + missiles
	K5	Rupture of a compressor input line due to mechanical aggression, hydrogen embritlement (hydrogen corrosion), overpressure or fatigue of pipes caused by vibration leading to a jet fire or explosion inside casing
	K7	Rupture of the compressor output line due to mechanical aggression, hydrogen embritlement (hydrogen corrosion), fatigue of pipes caused by vibration or overpressure / closure of the downstream valve leading to a jet flame or an explosion with a double feed
	K10	Discharge of H2 through a PRD due to overpressure leading to explosion or a momentum jet flame

The following table presents the safety functions that are required regarding the identified dangerous phenomena.

Dangerous phenomena	Safety functions	Example of safety barriers	Comments
Explosion of H2 if late ignition inside container	Avoid mechanical aggression	- Fenced site / closed container - Support trays and mechanical barriers for instrument connection line and connected equipment	Buffer on low pressure sources (15 bar, 2m3 in Iceland downstream electrolyser) – Buffer sometimes used to collect boil off phase from LH2 (5m3 in München)
	Control ageing (H2 corrosion)	- Design - Periodic control	
	Control vibration level of the compressor	- Design (resonance & frequency control, pipe support) - Maintenance	
	Detect explosive mixture at electrolyser output	- Online gas analyser - Periodic testing / calibration	Explosive mixture at electrolyser service pressure – potential for highly explosive mixture
	Detect small leakage	Regular inspection to detect small leakage	Difficult to monitor pressure drop for large volume because of temperature fluctuations – Low pressure switch reliability ? – Various checks more or less deep : daily (visual), monthly or annually (technical checks) – Preventive maintenance plan
	Prevent pressure build up downstream the compressor	PRV vent in a safe location	
	Limit leak time (detect and shutdown)	H2 gas detection system with shutdown if in confined ventilated space	
	Limit pressure on the line for leakage on connected equipment	Pressure reducer as close as possible to the high pressure source	Beware explosive atmosphere in detection cabinet (detection, ventilation)
	Avoid H2 accumulation	- Ventilation - Safety valve at the outlet of the buffer storage (released by a fuse)	Locate either outside (large buffer storage) or in a properly ventilated area
	Avoid ignition	- No source of ignition - ATEX zoning	
	Avoid burst in case of internal ATEX	- Low pressure switch at compressor inlet - Periodic testing	Max overpressure inside buffer below 10 bar in case of an explosion

	Control overpressure increase in the stages of the compressor	Safety valve at each stage	
	Control overpressure effects	Pressure relief device and pressure switch on compressor beyond pressure threshold (high and low pressure)	
Jet fire if early ignition	Control combustible materials	- Avoid combustible material use in design - Housekeeping + site layout	
	Avoid flame impingement	- Design - Number and location of connections - Lay out / location of pressurised capacities	
	Detect flame	- Flame detection - Melting fuses	Flame detection barely used anymore due to numerous faults unless in confined environment
	Control fire consequences (radiation, expansion)	- Design - Location of vent outlet (open air, no congestion)	

The usual main safety functions on the compressor would be:

- to prevent an excessive hydrogen pressure from feeding the compressor,
- to prevent hydrogen leak with design, detection and maintenance,
- to limit the number of connections in the input and output lines of the compressor,
- to limit a hydrogen leak at the outlet of the compressor (high pressure) with a flow reducer or an isolating valve,
- to protect the compressor from overpressure with safety valves, pressure relief devices and a vent in a safe location.

3.4 Sub-system "buffer storage in open air"

High pressure hydrogen (about several hundred bar) is transported via pipelines to a buffer storage before being delivered at the dispenser. This buffer storage is usually in open air and consists in several bundles of H2 bottles.

The main dangerous phenomena when storing high pressure hydrogen are:

- explosion in case of late ignition
- jet flame in case of early ignition

The following table presents the scenarios identified during the risk assessment.

Leak size	**Ref.**	**Scenario**
Large	S1	Rupture of the H2 buffer storage input line leading to a jet fire or an explosion (see compressor output scenarios)
	S2	Rupture of the H2 buffer storage output line due to mechanical aggression (digger), hydrogen embritlement (hydrogen corrosion), external fire or overpressure (excessive temperature) leading to a jet fire or an explosion
	S4	Rupture of the H2 bundle manifold or of the manifold feed line due to mechanical aggression (drop of a heavy equipment, displacement of cylinders), hydrogen embritlement (hydrogen corrosion) or external fire leading to a jet fire or an explosion
	S6	Release of hydrogen through the PRV line due to external fire or overpressure / excessive pressure input leading to a jet fire or an explosion
	S7	Release of hydrogen through the vent line due to voluntary action / human error (maintenance) or voluntary emergency release (fire) leading to a jet fire or an explosion
	S8	Burst of hydrogen tank due to an external fire, jet flame / impingement on storage, overpressure (input line), loss of mechanical properties (ageing, mechanical aggression, material defect), or chemical aggression leading to pressure wave + missiles + fireball

The scenario of a burst of a hydrogen tank (S8) is considered as a catastrophic scenario. Still, no sufficient data is available to say if one bottle at a time would burst and how the domino effect would be on the other bottles.

The following table presents the safety functions that are required regarding the identified dangerous phenomena.

Dangerous phenomena	Safety functions	Examples of safety barriers	Comments
Explosion of H2 if late ignition	Avoid mechanical aggression	- Fenced site - Work permit / Trained employees	
	Control ageing (H2 corrosion)	- Design - Periodic control	
	Control storage / use of non flammable materials	- Design - Site maintenance	
	Avoid leakage	- Regular inspection - Maintenance	
	Detect / Control leak	Safety valve at the buffer storage output (released by a fuse)	
	Avoid H2 accumulation	Design	
	Control access to storage manifold	- Frame around cylinders enclosures the manifold - Valve mounted on supported frame	
	Limit overpressure / excessive pressure input	See compressor	
	Limit overpressure / excessive pressure output	See dispenser	
	Detect / Limit the flow / quantity of H2 that can leak at the H2 bundle manifold or at the manifold feed line		Isolation with cascade valves / valve fail safe?
	Control venting	Design: release hydrogen in a safe location	
	Avoid ignition	- No source of ignition - ATEX zoning	
Jet fire if early ignition	Control combustible materials	- Avoid combustible material use in design - Housekeeping + site layout	
	Avoid flame impingement	- Design - Number and location of connections - Lay out / location of pressurised capacities	
	Control fire consequences (radiation, expansion)	- Design - Location of vent outlet (open air, no congestion)	
	Limit manifold material to those that can withstand an ignited leak	Design	

The usual main safety functions on the buffer storage would be:

- to prevent an excessive hydrogen pressure at the inlet and outlet of the buffer storage,
- to prevent hydrogen leak with design (number of connection, layout, access to storage manifold) and maintenance,

- to limit a hydrogen leak at the outlet of the buffer storage with an isolating valve as close as possible to the outlet of the storage,
- to protect the buffer storage from overpressure (in case of a fire) with a safety valve on each bottle released by a thermal fuse and a vent in a safe location

As the buffer storage would be in open air, hydrogen detection would not be adequate and thus would not be recommended.

3.5 Sub-system “dispenser in open air”

The dispenser is usually based on a cascade filling from the high pressure storage.
The dispenser consists in the refuelling unit and the dispensing hose. The dispenser is usually covered by a weather shed.

The main risk due to the high pressure hydrogen is leakage of hydrogen that could lead to:
- explosion in case of late ignition
- jet flame in case of early ignition

The following table presents the scenarios identified during the risk assessment.

Leak size	Ref.	Scenario
Medium	D3	Leakage inside the dispenser enclosure due to mechanical aggression / collision with a vehicle leading to an explosion or a jet flame
	D5	Leakage on the dispensing line due to mechanical aggression (puncture), wear of the filling hose with the ground, run over the filling hose by a vehicle, hose failure (delamination, chemical aggression, …), maintenance replacement schedule not followed or vandalism leading to an explosion or a jet flame
	D7	Leakage at the nozzle during stand-by due to isolation valve seal deterioration and self-obturating valve in nozzle deterioration leading to an explosion or a standing flame
	D8	Leakage at the nozzle during the connection leading to an explosion or a standing flame
Large	D1	Rupture of the main line between buffer and dispenser due to overpressure, hydrogen embritlement (hydrogen corrosion) or mechanical aggression / collision with a vehicle / digger leading to an explosion or a jet flame
	D4	Rupture of the dispensing line (flexible hose) due to mechanical aggression / start of vehicle during refuelling, fatigue, vandalism or wrong type of hose or wrong type of material leading to an explosion or a jet flame
	D9	Back-flow of hydrogen from the vehicle storage tank due to check valve failure leading to an explosion or a jet flame
	D10	Opening of a safety relief valve / venting of hydrogen due to failure of the pressure safety valve leading to an explosion or a jet flame
	D13	Opening of tank pressure relief device due to overheating or excessive filling speed leading to an explosion or a jet flame
	D12	Burst of vehicle tank due to overfilling (350 bar vehicle at the 700 bar station), excessive filling speed, fatigue of the tank or overfilling of the tank leading to overpressure + missiles +fireball (catastrophic)

The following table presents the safety functions that are required regarding the identified dangerous phenomena.

Dangerous phenomena	Safety functions	Safety barriers	Comments
Explosion of H2 if late ignition	Avoid mechanical aggression on the line between storage and dispenser, on the dispenser, on the dispensing line and nozzle	- Underground line (ditch or buried) - Crash barriers - Dispenser located above ground level (vehicle barrier) - Work permit / Warning signs - Break-away on the dispensing line - Flexible hose kept above ground - Preventive maintenance and change on the dispensing line and nozzle - Periodic visual checks on the dispensing line and nozzle	
	Control ageing (H2 corrosion)	- Design - Periodic control	
	Avoid misuse of hose and nozzle	- Manufacturer design and recommendations - Dedicated nozzle design depending on refuelling pressure	
	Control filling speed	Process control	What is the type of communication between car and dispenser?
	Control pressure inside hose before connection	Pressure check at the nozzle before refuelling	
	Avoid back-flow of H2 from the vehicle storage tank		What is done onboard vehicle to control / prevent back-flow ?

	Limit quantity of released hydrogen (detect and shutdown)	- Dispenser isolated from buffer storage during stand-by - Automatic isolation in case of mechanical shock on the dispenser - Emergency shutdown button (dispenser in use) - Isolation valve on storage - Excess flow valve (EFV) on the dispensing line - Pressure check at the nozzle before refuelling operation	- No automatic shutdown between dispenser and buffer storage - Give details about the EFV: closing time, residual leakage ? - If necessary, keep the customer away from the nozzle during refuelling
	Detect isolation valve leakage		-
	Avoid junction leakage	- Design standards - Preventive maintenance - Periodic leak tests	
	Avoid H2 accumulation	- Design - Ventilation openings on the dispenser - Appropriate roof design to avoid H2 accumulation - Limit congestion nearby the dispenser	Minimum natural air change rate ?
	Avoid ignition	- No source of ignition - ATEX zoning	Weak structure to vent / control explosion ?
	Control overpressure in the line between buffer and dispenser	- PRD on storage - Thermal fuse on storage - Standards (withstand the maximum compression pressures)	
	Control venting consequences	- Select safe vent outlet location - Good engineering practices	Size / Locate the vent for the more severe scenario
Jet fire if early ignition	Control combustible materials	- Avoid combustible material use in design - Housekeeping + site layout	
	Control fire consequences (radiation, expansion)	- Design - Location of vent outlet (open air, no congestion)	

The usual main safety functions on the dispenser unit would be:
- to prevent the dispenser from mechanical aggression with design (dispenser above ground, crash barriers) and maintenance,
- to limit a hydrogen leak with an automatic isolation at dispenser,
- to avoid hydrogen accumulation with natural ventilation inside the dispenser and design of the weather shed

The main safety functions on the dispensing line would be:
- to prevent hydrogen leak with design (dispensing line above ground, dedicated hose, etc.), operating procedures and maintenance,
- to limit a hydrogen leak on the dispensing line with an excess flow valve and a break-away on the line,
- to control the venting with a safe outlet location

As the dispenser area is in open air, hydrogen detection would not be adequate and thus would not be recommended.

3.6 Sub-system "CH2 tanker delivery in open air"

Instead of being produced on site, high pressure hydrogen can also be delivered by trailers to fill the buffer storage.

The main risks when handling high pressure hydrogen are:
- leak of hydrogen that could lead to explosion in case of late ignition or a jet flame in case of early ignition
- burst of the trailer that could lead to overpressure wave, missiles and fireball.

The following table presents the scenarios identified during the risk assessment.

Leak size	Ref.	Scenario
Medium	T3	Leakage of hydrogen from the trailer hose / connection line during refilling due to displacement of the trailer, mechanical aggression, voluntary action or bad coupling leading to an explosion or a jet flame
	T 8	Leakage of hydrogen from the trailer due to mechanical aggression, failure of a valve or of an equipment on the trailer leading to an explosion or a jet flame
Large	T 1	Disconnection of the trailer dispensing line during use due to displacement of the trailer, mechanical aggression, voluntary action or bad coupling leading to hydrogen spill and explosion / jet flame (considered as catastrophic)
	T 2	Hose failure during refilling due to fatigue, not appropriate hose for hydrogen service or mechanical wear leading to an explosion or a jet flame (considered as catastrophic)
	T 6	Burst of the trailer due to pressurisation from buffer storage through the compressor or bypassing the compressor, external fire or external fire fed by hydrogen leading to an overpressure + missiles + fireball (considered as catastrophic)
	T 4	Leakage after the discharge when decoupling from trailer side (hydrogen source not isolated) due to isolation valve lest open or a leaking isolation valve leading to an explosion or a jet flame
	T 5	Leakage after the discharge when decoupling from station side (hydrogen source not isolated) due to manual valve left open leading to an explosion or a jet flame
	T 7	Release of hydrogen through the vent to the open air due to purge of the hose line, the opening of the high pressure relief valve (protecting downstream for overpressure), thermal fuses or voluntary action leading to an explosion or a jet flame

The following table presents the safety functions that are required regarding the identified dangerous phenomena.

Dangerous phenomena	Safety functions	Safety barriers	Comments
Explosion of H2 if late ignition	Detect bad coupling or leakage between the tanker and the CH2 storage	- Procedure is to depressurise the hose and then disconnect. If left open, the driver will notice it during hose purging. - If the isolation valve is leaking, it is possible to isolate each tank. They are normally isolated before going on the road.	Vacuum could make the connection tight, “only” pressurisation allows to detect leak.
	Prevent back-flow from the tank	- Remotely actuated isolation valve - Check valve on the tank side	Check valve would not be systematic
	Prevent hose from being disconnected	- More difficult to disconnect when pressurised - Hose line should normally be isolated before decoupling - Trained personnel only	
	Prevent excessive fatigue	- Hose maintenance - Replacement within lifetime	Industrial experience on them. Accidental data?
	Prevent using wrong hose	- Design to prevent use of inappropriate hose - Hose specification - Trained personnel	
	Protect hose from abrasion	- Appropriate length (not too long) and dedicated stand-by place - Connection and handling procedure (avoid excessive bending) - Periodic visual inspections	
	Limit the quantity of discharged hydrogen	- Manual isolation valve or possibly remotely actuated valve - Trailer valve is possibly connected to the site air for equipment - Emergency shutdown would also close the trailer isolation valve	- Would be better to have an automated isolation to be coherent with the pressure storage ? - Hydrogen detectors not appropriate in open air

	Prevent trailer from moving	- Interlocked brakes - Possibly shorter wire than discharging hose. If discharging hose is pulled, this short wire would activate valves to isolate the refuelling station & the trailer	Prevent leakage if the driver moves away with the trailer while it is still connected.
	Limit hydrogen leakage on truck side	Manually actuated line to safely depressurise the trailer through the vent	
	Control leak consequences / Limit congestion in the vicinity of the trailer	- Isolation distance between discharge point and properties - Design (dedicated parking area)	
	Prevent mechanical aggression	- Fenced site - Work permit / Trained employees - No discharge point near power lines, trees … isolation distance	EIGA and EU document reference?
	Control pressure build-up in the trailer	- Thermally actuated device could be fitted on the trailer to empty the trailer before it loses its resistance - PRV on the trailer and station interface - Last option could be the possibility to manually actuate trailer depressurisation in case of fire	Burst pressure 3 times operating pressure. Final pressure depends on the buffer volume compared with the trailer volume. Trailer usually not protected in Europe against overpressure. Trailer could be vented.
	Avoid combustible material other than the trailer itself	Sitting / site housekeeping	
	Avoid ignition	- No source of ignition - ATEX zoning	
Jet fire if early ignition	Control combustible materials	- Sitting / site housekeeping	
	Prevent fire from propagating / impinging another trailer or another pressurised equipment	- Fire extinguisher onboard the trailer - Firewalls	
	Prevent impingement	Design	

The usual main safety functions on the transfer operation from the trailer to the buffer storage are:

- to prevent hydrogen leak during the transfer operation from mechanical aggression, from the trailer movement, from bad coupling
- to limit a hydrogen leak on the trailer side with an isolation valve and a remotely actuated isolation valve on the trailer, on the storage side with an emergency isolation valve
- to control pressure build-up in the trailer with pressure relief valves on the trailer and the station interface
- to protect the trailer or pressurised equipment from fire propagation with firewalls or fire extinguishers onboard the trailer and a manually actuated line to safely depressurise the trailer through a vent

A special care should be given to the operating procedures to avoid bad coupling or decoupling of the transfer hose.

As the unloading operation would be in open air, hydrogen detection would not be adequate and thus would not be recommended.

3.7 Sub-system “LH2 road delivery in open air”

In a liquid H2 refuelling station, hydrogen is always delivered by road tankers.

The major risks when delivering liquid hydrogen are:
- leak of hydrogen at connection points that could lead to an explosion,
- leak of hydrogen following the burst of a pressurised pipe due to hydrogen vaporisation,
- leak and fire of the road tanker,
- catastrophic burst of the trailer that could lead to overpressure wave, missiles and fireball. This event is unlikely to occur.

Moreover, pressurised hydrogen can be released at the vent outlet of the trailer. Subsequent explosive volumes may form.

The following table presents the scenarios identified during the risk assessment.

Leak size	Ref.	Scenario
Medium	TL2	Leakage of hydrogen from the tanker connection line due to mechanical aggression, voluntary disconnection, improper connection, temperature effects, damaged connector (wear of discharge nozzle), foreign substance in connector during refilling leading to an explosive atmosphere in open air
	TL4	Pressure build-up in the storage tank during refilling / Storage tank PRV opening due to valve on hydrogen gas phase closed leading to an emergency release at the storage vent
	TL5	Venting of hydrogen from the storage tank during refilling due to tank isolation valves remained open during the “decoupling” procedure, pressure build-up during refilling leading to an explosive atmosphere at the storage tank vent (explosion or permanent flame)
	TL8	Venting of hydrogen form the tanker due to external fire, loss of vacuum, pressure relief device (PRD) abnormal opening or heat exchanger runaway leading to an explosive atmosphere at the trailer vent (explosion or permanent flame)
Large	TL3	Hydrogen release after refilling when decoupling the hose due to remaining LH2 or H2 gas in the hose (tank valve remains open) leading to a hydrogen release and subsequent explosion or fire
	TL6	Hydrogen leak from the tanker due to leaking isolation valve leading to a hydrogen spill and subsequent explosion or pool fire

	TL 1	Disconnection of the tanker dispensing line during refilling due to mechanical aggression, voluntary disconnection, improper connection or displacement of the tanker during refilling leading to a large hydrogen spill and subsequent explosion or pool fire (considered as catastrophic)
	TL7	Burst of the tanker storage due to external fire caused by ignited leakage or other combustible material (the tanker itself or something else) leading to an overpressure + missiles + fireball (considered as catastrophic)

The scenario of a burst of a hydrogen tank is considered as a catastrophic scenario but very unlikely to occur.

The following table presents the safety functions that are required regarding the identified hazardous phenomena.

Hazardous phenomena	Safety functions	Safety barriers	Comments
Explosion of H2	Avoid hydrogen gas accumulation in case of release	Unloading operations in open air	
	Prevent decoupling and leakage of the tanker dispensing line during refilling	- Refilling line screwed at both ends. When pressurised, it cannot be disconnected manually - Choice of materials - Trained personnel only with permanent supervision - Trailer parked and operated in a dedicated and safe area (tanker parked away from power lines, trees, …)	Never heard of a disconnection in accidental history
	Detect bad coupling or leakage between the tanker and the LH2 storage	- Filling line is possibly vacuumed. If line is not tight, the vacuum will not be reached. - Other applied method is filling the hose with inert gas. Line is then pressurised with H2 gas at few bar. If the connection is not good, it will leak during pressurisation - Trained personnel only with permanent supervision	Vacuum could make the connection tight, “only” pressurisation allows to detect leak.

	Prevent back-flow from the storage tank	- Remotely actuated isolation valve - Sometimes a check valve on the storage tank side	Check valve would not be systematic
	Limit the quantity of released hydrogen	- Isolation valve on the tanker actuated by an emergency button - Sometimes, the emergency shutdown on truck also operates the isolation valve on the storage tank - Trained operator in the vicinity of the emergency stop	LH2 induced ice could eventually hinder the safety valve. It should therefore be located appropriately.
	Prevent tanker from moving during refilling	- Brakes are actuated (interlocking) during discharge. Truck cannot move.	
	Prevent leakage from the road tanker	- Connector inspection before each delivery - Spare parts available in the truck - Double isolation valves: manual and automated one	Manual isolating valve closed during the decoupling procedure
	Control leak consequences	Isolation distance between discharge point and properties	
	Prevent LH2 or gaseous hydrogen to remain in the hose	Decoupling procedure.	Wait for a certain time before purging the line with gas. Tanker outlet valve is closed then the tank inlet valves are closed. Any liquid in the transfer hose is boiled off in the top of tank haulage. Then the hose is warmed with H2 gas and purged with inert gas procedure
	Prevent mechanical aggression	- Fenced site / closed container - Work permit / Trained employees - No discharge point near power lines, trees … isolation distance - Dedicated delivery area	EIGA and EU document reference?

	Prevent pressure build-up in the storage tank during refilling	- PRV on inner tank and associated vent - Pressure sensors on the inner storage tank	A valve fitted on a line that connects the feed line and the tank haulage is opened. H2 gas condenses and the pressure remains constant during storage refilling inside the tank. In “normal” operation, a valve connected to a vent is kept open to prevent pressure build-up in the inner tank during refilling.
	Avoid combustible material other than the trailer itself	Sitting / site housekeeping	
	Protect against pressure build-up inside the trailer	- Pressure sensor that shuts down exchanger feed with LH2 - PRD on the trailer and associated vent	
	Avoid ignition	- No source of ignition - ATEX zoning	
Pool fire	Control combustible materials	- Sitting / site housekeeping	
	Control fire	- Fire extinguisher onboard the trailer - Diked area	- Transfer hose of 3 or 5 meters - Truck in the vicinity to the fixed tank

The usual main safety functions during the transfer operation from the trailer to the buffer storage are:

- To delivery liquid hydrogen in open air,
- to prevent hydrogen leak at connection point during the transfer operation due to mechanical aggression, trailer displacement, bad coupling
- to manually interrupt any hydrogen leak on the trailer side with isolation valves
- to control pressure build-up in the trailer and in the storage tank with pressure relief valves and associated venting lines
- to protect the trailer or the storage tank from fire propagation with fire extinguishers and dikes.

A special care should be given to the operating procedures to avoid bad coupling or decoupling of the transfer hose. Trained personnel is a key element for controlling risks.

As the unloading operation would be in open air, hydrogen detection would not be adequate and thus would not be recommended.

3.8 Sub-system “LH2 storage in open air”

Liquid hydrogen is stored at –253°C at a pressure of about 10 bar, above ground or below ground storage.

The major risks when delivering liquid hydrogen are:
- leak of hydrogen following the burst of a pressurised pipe due to hydrogen vaporisation,
- leak and fire of the storage tank,
- pressure build-up in the storage tank,
- catastrophic burst of the storage tank that could lead to overpressure wave, missiles and fireball. This event is unlikely to occur.

The following table presents the scenarios identified during the risk assessment.

Leak size	Ref.	Scenario
Medium	LS1	Inner tank leakage leading to the pressurisation of outer vessel, the burst of the rupture disk on the outer vessel causing its loss of vacuum. Hydrogen would be released through the ruptured disk of the outer vessel and through the vent of the inner vessel (loss of vacuum causes overpressurisation of the inner tank)
	LS1/LS2	Loss of vacuum, pressurisation of inner tank and subsequent release through the inner tank PRV
	LS2	Loss of vacuum due to corrosion of outer shell. Pressure build-up in inner tank, subsequent vent of hydrogen
	LS3	Storage in vault: hydrogen leak in vault either in the pipes compartment or in the tank compartment. Explosive mixture. In case of explosion, more severe damage are expected (domino effect: pipes rupture)
Large	LS1/LS2/LS3	External fire (fed by hydrogen) leading to a BLEVE (considered as catastrophic) or to a collapse of the tank
	LS5	Explosive mixture inside inner tank due to LH2 / solid O2 (impurities) mixture leading to the storage destruction and large spill of hydrogen (considered as catastrophic)
	LS4	Inner tank pressurisation due to heat exchanger runaway or failure of boil off management system / blockage of boil off valve (icing) leading to the shear of the inner tank and large release of hydrogen
	LS6	Rupture of LH2 line due to mechanical aggression, overpressurisation (liquid trapped between two valves) or non compatible materials leading to hydrogen spill and explosive mixture (explosion or pool fire)
	LS7	Voluntary release of hydrogen through the inner tank vent during tank commissioning causing a large hydrogen plume at the vent outlet

The main differences between an above ground storage and a storage in vault are:
- explosive mixtures can form in the confinement of the vault and cause more severe damage if ignited,
- storage in vault can be affected by a hydrogen pool fire
- in the contrary, the storage in vault are less vulnerable to mechanical aggressions.

The following table presents the safety functions proposed to control the above scenarios.

Hazardous phenomena	Safety functions	Safety barriers	Comments
Explosion of H2	Prevent mechanical aggression	- Designated closed area - Barrier to prevent impact from refuelling trailer	- Double wall with outer wall 9 mm thick - BMW performed physical aggression tests on vehicle tanks. None of the mechanical aggressions caused immediate loss of the tank content - Vehicles excluded from this area but the tube trailer - Storage in vault are less vulnerable to mechanical aggressions
	Control corrosion	- PTFE sleeve around external vessel - Cathodic protection	
	Prevent pool fire from thermally aggressing the storage in vault	- Compartimented vault with fire-proof wall	Vault can be divided in two separated parts (one with the tank and the other one with manifold). Fire is not a likely option in the tank side because there is no leak point. Fire is more likely on the manifold side. Compartment prevent fire from propagating to the tank side.

	Prevent pressure build-up in the inner tank	- Relief valve and possibly rupture disk designed for loss of vacuum or run away of LH2 heat exchanger - Periodic control and periodic change of rupture disk and PRV - Outer jacket is always replaced after an accident. Vacuum is checked as part of the first fill procedure - Visual checks (ice on outer jacket)	- No pressurised test for cryogenic vessel: therefore, two PRV in parallel to test one while the other only one is in service - Vacuum integrity not tested after commissioning - Service time not determined - Pressure sensor and pressure transmitter could operate a valve to decrease pressure
	Prevent pressure build-up in the vacuum space	- Vacuum tight plate at the top of the tank / H2 released directly into the air - Site survey and site requirements before tank siting - Visual checks (ice on outer jacket)	
	Prevent hydrogen build-up in the vault	- Ventilated space - Weak panel in case of explosion	
	Prevent icing at vent outlet / Prevent ice blockage	- Vent outlet designed to prevent rain ingress - Sign on fences to prevent use of water (in case of fire, …)	Ice on outer vent pipe is possible but will not affect the flow of hydrogen through the vent
	Avoid combustible material	No combustible material in the vicinity of the storage	Avoid water on vents to prevent ice blockage
	Prevent oxygen from accumulating inside the tank	- Fill hose purged with inert gas before filling - Some gas suppliers purge the storage tank on a periodic basis. This is however not common..	Solid O2 particles come from impurities in LH2, they sink and accumulate over time at the bottom of the tank.
	Detect and stop hydrogen leak	- System is isolated when not in use - When in use, trained people are on site - Easy and safe access to emergency shutdown	
	Prevent overpressurisation of pipes	Every pipe that can be isolated with LH2 inside is protected with a relief valve	
	Avoid ignition	- ATEX zoning : no source of ignition - Inerting?	Storage in vault may be protected from explosion with emergency inerting.
Pool fire	Control combustible materials	- Sitting / site housekeeping	

	Prevent hydrogen from feeding fire	- Fail-safe valve with melting fuse to isolate the storage - Limit flange connections nearby the tank - In vault, isolation valves are also fire proof	- Avoid water on vents to prevent ice blockage - In vault: Isolation valve cannot be buried
	Prevent storage collapse	- Liquid hydrogen leak diverted to a remote dike - In vault: vault is compartimented with fire-proof walls to avoid propagation of fire from the manifold side to the storage side	Tank legs fireproof with 2 hours rated material (not applied in Europe because all pipes from stainless steel) Vault: Fire is not a likely option in the tank side because there is no leak point. Fire is more likely on the manifold side. Compartment prevent fire from propagating to the tank side.

The main safety functions when storing liquid hydrogen are:
- to prevent pressure build-up in the inner tank and in the vacuum space with a relief valve associated with a rupture disk on the vessel, vacuum tight plate on the top of the tank and checks of the vacuum
- to prevent, in case of loss of confinement, liquid H2 accumulation underneath the storage
- to prevent ice from blocking the vent
- and to locate the vent at safe height
- to isolate the storage with actuated isolation valves in case of emergency
- to protect the outer vessel from mechanical aggression and overpressure

3.9 Sub-system "LH2 dispenser in open air"

Hydrogen can be transferred by pressure difference or by a transfer pump.

The major risks when refuelling a car with liquid hydrogen are:
- leak of hydrogen at the nozzle of the dispensing line that could lead to an explosion,
- shear of the hose line that could lead a large hydrogen spill and to an explosion,
- burst of hose line if left isolated with liquid hydrogen inside,
- cold burns for the personal in charge of the refuelling.

The following table presents the scenarios identified during the risk assessment.

Leak size	**Ref.**	**Scenario**
Medium	DL1	Leakage at the nozzle during refuelling due to untightness leading to cold gas escaping, and further explosion or a flame
	DL 4-5	Leakage of liquid hydrogen at nozzle during plugging or unplugging due to untightness leading to LH2 escaping and further explosion or a flame
	DL 9	Leakage inside the dispenser cabinet due gaskets' untightness leading to an explosion inside the dispenser and its burst
Large	DL 8	Shear of the hose line (loss of vacuum + H2 leak) due to severe mechanical impact leading to large LH2 spill and further explosion or flame

The following table presents the safety functions that are required regarding the identified hazardous phenomena.

Hazardous phenomena	Safety functions	Safety barriers	Comments
Explosion of H2	Prevent crash / mechanical impact on dispenser or dispensing line	Refuelling takes place in a secured area	It is possible to isolate the car tank in case of a leakage despite nozzle is connected?
	Avoid misuse of hose and nozzle	- Manufacturer design and recommendations - Dedicated nozzle design depending on refuelling pressure	
	Prevent leak from the nozzle	- Leak tightness tests after connection (H2 pressure drop control) - Double isolation of the liquid flow - Operated by trained personnel - Regular check of coupling leak tightness - Design that not allows the nozzle clamp to be opened during refuelling - Periodic visual checks on the nozzle	Particular behaviour of cold gaseous hydrogen (higher density)
	Prevent refuelling if car is not ready	Automatic check up procedure (handbrake, windows closed, ..) before refuelling starts	
	Control leak if nozzle torn away	- Permanent communication between the dispenser and the vehicle: refuelling stops if the signal “car ready for refuelling” is gone - Close main valve upstream on abnormal situation detection	
	Control cold finger leakage	Leakage feeds the boil off line	
	Limit quantity of hydrogen in nozzle when coupling and decoupling	- Hose line kept under moderate (<2 bar) gaseous hydrogen pressure when coupling or decoupling (H2 is flushed before decoupling) - Hose line isolated form liquid sources when coupling or decoupling	If flushing did not operate, the only liquid hydrogen that can be released is the one trapped between ball valves.

	Control hydrogen boil off and overpressure in dispensing line	- Pressure relief device on liquid line - Hydrogen vented	
	Control loss of vacuum of dispensing line	- Pressure sensor and automatic shutdown - Periodic visual checks on the dispensing line	
	Prevent overpressure in vacuum of dispensing line	PRD on vacuum line (vacuum relief device) vented to open air	
	Limit quantity of released hydrogen (detect and shutdown)	- Shear detected by loss of vacuum of the dispensing line - Automatic shutdown of the dispensing line - Dispenser isolated from storage during stand-by - Emergency shutdown button (dispenser in use)	
	Avoid H2 accumulation	- Design - Ventilation openings on the dispenser - Appropriate roof design to avoid H2 accumulation - Limit congestion nearby the dispenser - Refuelling takes place in open air	
	Avoid back-flow of H2 from the vehicle storage tank		What is done onboard vehicle to control / prevent back-flow ?
	Avoid ignition	- No source of ignition - ATEX zoning	Weak structure to vent / control explosion ?
	Control venting consequences	- Select safe vent outlet location - Good engineering practices	Size / Locate the vent for the more severe scenario
H2 flame	Control combustible materials	- Sitting / site housekeeping	-

The usual main safety functions on the dispenser unit would be:

- to prevent the dispenser from mechanical aggression with design (dispenser above ground, crash barriers) and maintenance,
- to limit a hydrogen leak with an automatic isolation at dispenser,
- to avoid hydrogen accumulation with natural ventilation inside the dispenser and design of the weather shed.

The main safety functions on the dispensing line would be:

- to prevent hydrogen leak with design (dispensing line above ground, dedicated hose, etc.), operating procedures and maintenance,
- to always flush the dispensing line when not in use,
- to protect the liquid hydrogen line and its vacuum jacket from overpressure,
- to always isolate the dispensing line when not in use,
- to interrupt the flow of liquid hydrogen in case of line shear,
- to detect loss of vacuum and interrupt the refuelling,
- to control the venting with a safe outlet location.

The dispenser is usually in open air to favour hydrogen dilution.

3.10 Sub-system "entire station"

Some unwanted external events are likely to impact globally the refuelling station, such events include:

- extreme meteorological and natural conditions: flooding, earthquake, hail, snow/ice, sandstorm, tornadoes, etc.
- malevolent acts (robberies, sabotage, etc.),
- loss of utilities with power supply fluctuations.

When relevant, the following safety barriers are suggested for each of the event:

External events	Safety barriers	Comments
Flooding	- Anchored storage or light equipment - Operating procedure to stop and secure the station - siting	Trailer would not be anchored but is likely to float
Earthquake	Designed in accordance with local requirements	
Lightning	Designed in accordance with local requirements	
Landslide	Siting	
Malevolence	- Fences around site - Minimise quantities on site - Put in safe status when unattended - Closed circuit TV (CCTV) and safe lighting - Hide equipment from sight (containers, underground, walls, …) - Personnel access control	
Small aeroplanes	Siting	

Domino effect should be considered in the layout of the refuelling station (isolation distance between equipment). Minimum isolation distance should be the result of the modelling task. At least, the dispensing area should be physically separated from the other parts of the refuelling station.

In case of loss of utilities (electricity, air, natural gas, …), the refuelling station shall be stopped in a safe mode. It cannot restart automatically.

The design and layout of the station is a key factor as well as locations of manual emergency shutdown buttons.

4. CONCLUSION

The risk assessment was carried out for the main equipment for both CGH2 and LH2 refuelling station.

This report aims at summarising the main findings from the 4 days of risk assessment sessions that took place in the framework of the Hyapproval WP4.

It presents the potential accident scenarios and the associated safety functions to prevent and mitigate accidental scenarios.

The main unwanted central events that were identified are:

- A large leakage of gaseous or liquid hydrogen fed by the main storage,
- An accumulation of an explosive atmosphere inside process containers,
- The burst of compressed equipment,
- Any leak that takes place at the refuelling location (nozzle or hose leak).

The usual safety strategy to be followed for a hydrogen refuelling station consists in:

- preventing hydrogen leakage by mechanical aggression, corrosion, fatigue, etc.
    - with physical barriers implementation
    - choice of materials and maintenance
    - leak detection systems
    - operational procedures
- controlling/limiting the leak flow
    - by excess flow valves
    - by automatic shutdown of the hydrogen flow with isolation valves.
- Preventing hydrogen accumulation by
    - operating in open air
    - ventilating confined spaces
- controlling ignition source by ATEX zoning and choice of appropriate equipment
- protecting from overpressure with pressure relief devices and a safe outlet venting location
- limiting explosion consequences
    - by protecting closed containers against overpressure
    - by limiting congestion due to layout
- protecting hydrogen storage from thermal aggression
- limiting internal domino effects by design and layout.

From a general perspective, training of the personnel and procedures are required for both normal operations and emergency situations. In any case, emergency stop are provided at safe locations.

5. APPENDICES

Number	Title
A	Risk assessment tables

APPENDICE A –

RISK ASSESSMENT TABLES FOR A STANDARD HRS WITH CGH2 AND LH2