A BARRIER ANALYSIS OF A GENERIC HYDROGEN REFUELLING STATION

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ABSTRACT

Any technical installation need appropriate safety barriers installed to prevent or mitigate any adverse effects concerning people, property and environment. In this context, a safety barrier is a series of elements each consisting of a technical system or human action that implement a planned barrier function to prevent, control, or mitigate the propagation of a condition or event into an undesired condition or event. This is also important for new technologies as hydrogen refueling stations being operated at very high pressures up to 900bar. In order to establish the needed barriers a hazard identification of the installation has to be carried out to identify the possible hazardous events. In this study this identification was done using the generic layout of a future large hydrogen refueling station that has been developed by the EU NoE HySafe. This was based on experiences with smaller scale refueling stations that has been in operation for several years, e.g. being used in the former CUTE and ECTOS projects. Using this approach the object of the study is to support activities to further improve the safety performance of future larger refueling stations. This will again help to inform the authorities and the public to achieve a proper public awareness and to support building up a realistic risk and safety perception of the safety on such future refueling stations. In the second step the hazardous events that may take place and the barriers installed to stop hazards and their escalation are analysed also using in-house developed software to model the barriers and to quantify their performance. The paper will present an overview and discuss the state-of-the-art of the barriers established in the generic refueling station.

1.0 INTRODUCTION

During the recent years, there is a growing interest to introduce and develop new energy technologies, as the fossil fuel based technologies are assumed to soon have reached their peak production capacity and are considered to have adverse effects on the climate (green house effect). Other political reasons are also a driving force for this development e.g. for many countries to reach a higher level of self-supply being less dependent on other countries to cover the energy demands.

The application of hydrogen-based technologies is considered to be a promising solution especially for the intermediate storage of electricity produced by wind turbines and solar cells. Both technologies depend on highly fluctuating primary energies as wind and sun-light, respectively. A combination of water electrolysis using the surplus electricity to produce hydrogen and a fuel cell application to produce electricity in situations with lack of primary energy could overcome the problem. It would help to level out the mismatches in energy availability and by that secure the energy supply. Another application is in the transport sector with a vision of hydrogen-driven vehicles. This involves building of a large net of refuelling stations.

Safety is essential in the reshaping of our known infrastructure into new sustainable energy forms. The goal should be to build new more sustainable infrastructures providing at least the same or better societal and individual safety compared to the present situation. The issues concerning the infrastructure are complex and has been subject to many studies worldwide, as e.g. [1-5].

Therefore, new hydrogen technologies as well as all other new technologies need to be assessed with regard to safety. The risk assessment methodologies include many well established tools. In this study a generic refuelling station has been qualitatively assessed using hazard identification, and is then further analyzed using the barrier diagram approach to establish a good and easy to understand communication about the safety aspects of new technologies.

2.0 METHODOLOGY

Hazard identification has been done to identify the safety functions and barriers present in a generic large hydrogen refuelling station. The design of such a possible future large refuelling station is based on the experiences made on a number of smaller stations that have been tested e.g. within the CUTE project. The identified starting events and the resulting consequences are then analysed with focus on the safety functions and safety barriers in the generic design of the station.

The goal is to provide an overview on the main safety functions in such a refuelling station and to discuss these functions in relation to safety management and emergency situations that can develop during the life time of such installations.

2.1 Barrier diagrams

The barrier concept is widely used and discussed in the literature and e.g. being applied in the safety approach of the Norwegian off-shore oil industries [6]. Safety-barrier diagrams [1] have proven to be a useful tool e.g. in Denmark for documenting the safety measures taken to prevent incidents and accidents in process industry. Internationally there is a growing interest in the concept of safety barriers and the use of so-called “bow-tie” diagrams, which are a special case of safety-barrier diagrams [7-10]. Safety-barrier diagrams use the same logic as classical fault trees and event trees, but basic events and logic related to the functioning of safety systems are encapsulated in a single item, which diminishes the number of symbols in the graph, turning fault trees and event trees into diagrams that are much easier to understand by other stakeholders. Especially during the early introduction of hydrogen technology, this technique can support the communication with e.g. authorities and other stakeholders during the permitting process. Another advantage of safety-barrier diagrams is that there is a direct focus on those system elements that need to be subject to safety management in terms of design and installation, operational use, inspection and monitoring, and maintenance. Safety-barrier diagrams support quantitative, qualitative, and deterministic approaches.

Table 1. Generic barrier types according to the ARAMIS[1] classification

No.	Generic barrier type	Example
1	Permanent – passive – control	Wall of pipe, hose or tank
2	Permanent – passive – barrier	Tank bund, dyke, drainage sump, railing, fence, blast wall, lightning conductor,
3	Temporary – passive Put in place (and removed) by person	Barriers round repair work, blind flange over open pipe, helmet/gloves/safety shoes/goggles, inhibitor in mixture
4	Permanent – active	Active corrosion protection, heating or cooling system, ventilation, system to maintain inert gas in equipment.
5	Activated – hardware on demand – barrier or control	Pressure relief valve, interlock with “hard” logic, sprinkler installation, electro-mechanic pressure, temperature or level control
6	Activated – automated	Programmable automated device, control system or shutdown system

[1] http://aramis.jrc.it

No.	Generic barrier type	Example
7	Activated – manual Human action triggered by active hardware detection(s)	Manual shutdown or adjustment in response to instrument reading or alarm, evacuation, put on breathing apparatus or calling fire brigade on alarm, action triggered by remote camera, drain valve, close/open (correct) valve
8	Activated – warned Human action based on passive warning	Put on personal protection equipment in danger area, refraining from smoking, keeping within white lines, opening labelled pipe, keeping out of prohibited areas
9	Activated – assisted Software presents diagnosis to the operator	Using an expert system
10	Activated – procedural Observation of local conditions not using instruments	(Correctly) follow start up/shutdown/batch process procedure, adjust setting of hardware, warn others to act or evacuate, (un)couple tanker from storage, empty & purge line before opening, drive tanker, lay down water curtain
11	Activated – emergency Ad-hoc observation of deviation + improvisation of response	Response to unexpected emergency, improvised jury-rig during maintenance, fight fire

2.2 Hazard identification

The hazard identification was done for the purpose of identifying hazards with a potential for consequence zones exceeding the station boundary. Also subject of the hazard identification was the main procedures that are needed inside the stations boundary with regard to hydrogen compression, gas cleaning, storage, refuelling, piping and maintenance. The approach was to use the SWIFT (Structured What IF Technique) methodology in the hazard identification. The technique is based on an extensive checklist of What-If questions grouped under the headings Material problems, External effects etc, and for each question discuss and record likely events, consequences, safeguards etc, as seen in Table 2.

Table 2. The scheme used for the structured hazard identification for the generic refueling station.

What If	Event	Consequences/ Release Size	Safeguards / Barriers	Recommendation
Material problems				
External effects				
Operating errors				
Analytical/sampling errors				
Equipment/Instrumental				
Process Upsets				
Utility failures				
Emergency operations				
Environmental release				

The generic layout was analysed and discussed on three meetings and various other communications. By that a list of events and consequences was established. The main events have then been compiled into a barrier diagram.

2.3 The generic refueling station – description and assumptions

The investigation is based on the definition of a generic hydrogen refuelling station that has been established in the Cluster "Risk Assessment" within the European NoE HySafe. The assumed generic layout is based on the available non-confidential information being partially delivered by experts dealing with the establishment of such stations. These experts have also evaluated the generic approach in order to secure conformity with real hydrogen stations. However, the generic station has a hydrogen storage capacity larger than presently existing hydrogen stations. The analysed generic refuelling station as shown in Figure 1 is essentially the station described in the HyQRA benchmark document[2], but with the difference of assuming compressed hydrogen gas delivery using tube trailers instead of a pipeline.

The station is assumed as follows: The delivered hydrogen is compressed using a 2 stage compressor system and stored at 350bar in pressure vessels in several storage racks. The gas is being transferred to the dispensers (3 different) in underground pipelines. On the way to the dispenser the hydrogen is cleaned using a filter to remove different pollutions as oil traces and small particles that might be generated in the system. The dispenser system is utilised by cars and busses. In order to start the refuelling procedure the customer has to use a magnetic card issued for the specific vehicle to be refuelled.

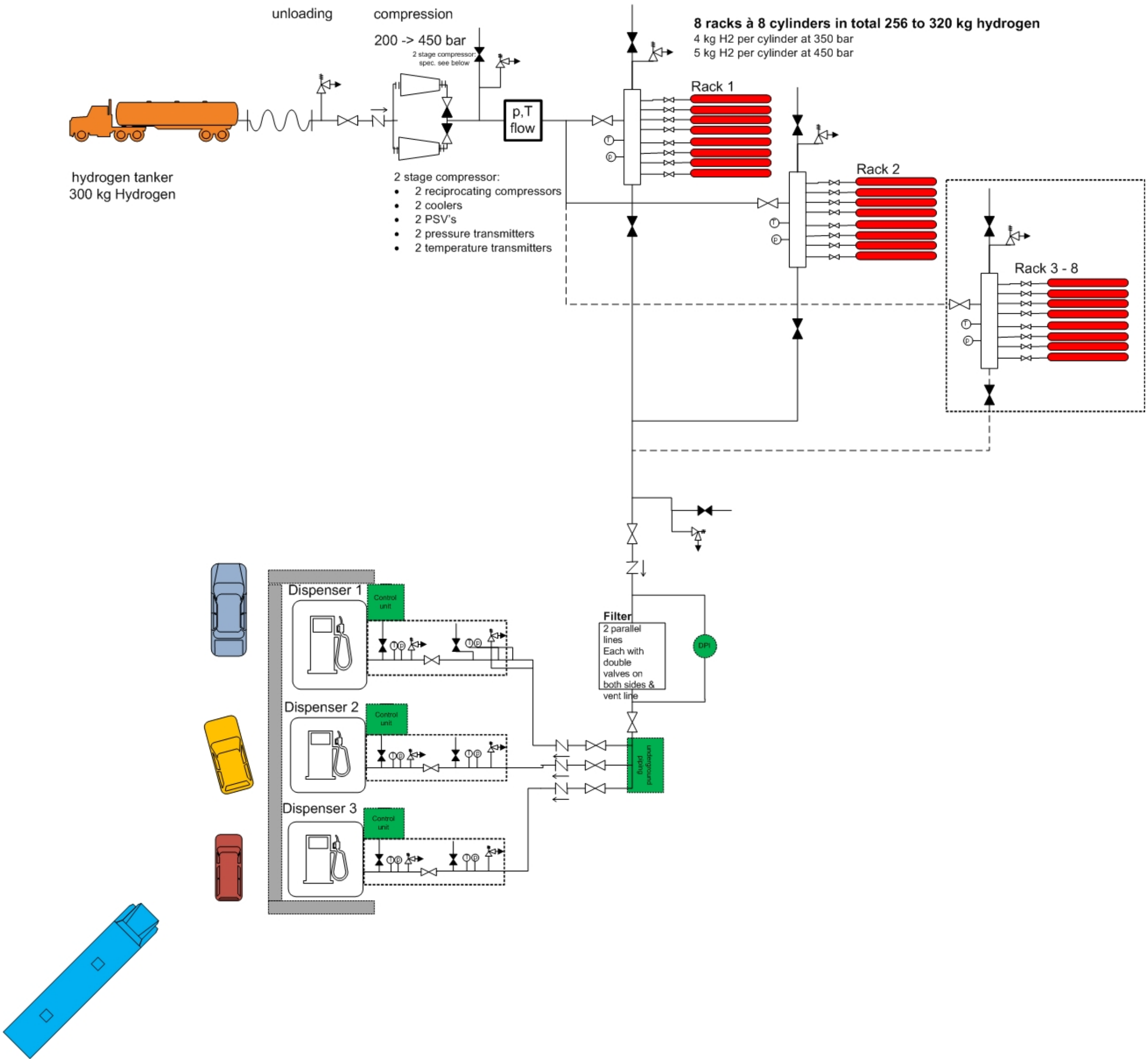

Figure 1. Layout of the generic refuelling station is shown. It is anticipated that the Hydrogen is delivered by trucks and about 300 kg of Hydrogen are at maximum stored on site in pressurized storage racks. It should be noted that in future large stations an even higher mass of hydrogen may be stored. The dispensers enable to refill smaller and larger cars, vans and busses.

[2] Document established within the NoE HySafe project

The station is assumed to be located close to a normal petrol station being manned with sales personnel, who have been given a basic education on the important basic knowledge on the hydrogen part of the station. They are assumed to be able to identify certain failures. These persons may activate the emergency button to prevent accidents, call police and fire department and may be in charge to immediately evacuate the stations area based on predefined instructions. This type of personnel is not allowed to enter the various installations within the Hydrogen station fence. In cases of malfunction and equipment failure, technical experts who are located within a reasonable distance to the station will be called in. The station is remotely monitored by an operator either continuously or in periodic intervals. The station is assumed to automatically go to a safe state, which implies that valves will go to the predefined safe position etc., in case of hazardous deviations from normal operation conditions.

The road tanker is delivering up to 300 kg of hydrogen depending on the actual hydrogen level at the station at arrival time of the tanker. For the unloading the driver will connect the tankers flexible hose to the connection point of the station. He will purge the line directly with some hydrogen due to the small volume of air inside the hose[3] that is vented off through the release valve at the station “input” valve (point of connection). After few minutes the release valve is closed. The driver will then open the valve to the compressor line and start the compressor. The unloading procedure starts and will take several hours[4]. The exact time will depend on the compressor efficiency.

Nevertheless, the driver will use a large fraction of the working time to observe the filling and guard the area to e.g. prevent others from entering and prevent unauthorized handling of the equipment. The driver will need some special working facilities in winter time or in case of other tough weather conditions, as e.g. a shelter, the truck cabin, and assistance by the remote control centre may be provided, but the latter will normally not be necessary.

During the unloading the hydrogen is compressed and stored into the hydrogen storage vessels. Due to the considerable time of unloading it is assumed that cars (both petrol and hydrogen cars) may be refuelled during that time. Care has to be taken that Hazardous zones (ex-zones) are respected and to avoid collisions between the customers’ cars and the truck by good design/layout of the refuelling station.

In order to prepare for refuelling, the car is driven to the dispenser and all electronics in the car are automatically switched off when stopping the engine. The dispenser is controlled using logics e.g. controlling the correct positioning of the dispenser connection to the vehicle, correct position/fastening of the refuelling nozzle into the car receptacle, check of the pressure and temperature of the car’s tank. If all controls are OK the refuelling process will start. The refuelling procedure is assumed using the 3 step cascade principle, where the storage vessels are divided into 3 volumes; low, medium and high pressure. The pressure in the vehicles tank is measured and the suitable lowest pressurised banks will fill the car until the pressure on both sides is equalized.

The temperature of the vehicle tank is critical and must be kept below 80^{o}C to secure tank integrity. This is done by the logics included in the monitoring and control system of the dispenser. The refuelling nozzle is connected to the car receptacle and cannot be removed while refuelling. The customer will be notified when the filling is finished by the display or by sound. He will then put the dispenser nozzle/hose in place and drive away.

When the refuelling process is finished, a shut-off valve inside the dispenser will be closed, and also the valve connection to the storage vessels. Therefore, in case of a leak from the refuelling hose after

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[3] the normal procedure is to use inert gas as nitrogen to remove the airs oxygen from the line. Due to the small amount of air within the line it is anticipated that the dilution is sufficient to keep the LEL within the line. The release of the purging line is well above the ground.

[4] An assumption found in [11] page 192 assume a truck load/unload time of 2h for a tanker with a capacity of 180kg. For a 300kg delivery this might be even more time consuming depending on the compressor specifications.

refuelling, only the content of the refuelling hose can be released. If the hose has been damaged, the pressure test at the beginning of the refuelling procedure will detect decaying pressure and refuelling will be inhibited. An error warning will then be given at the display. If the refuelling hose is discovered lying at the ground, there may be a risk that the hose has been damaged e.g. it has been driven over by a customer's car. In that case there are assumed to be procedures in place instructing station personnel to close the respective dispenser temporarily and request inspection and testing before the hose can be used again.

3.0 RESULTS

Following the methodology described above the main events recognized during the hazard identification phase have been converted into barrier diagrams as shown in Figure 2 for the dispenser area and in Figure 3 for the truck unloading, compressor and storage area including the internal pipelines needed to transport the hydrogen on-site. The barriers are also listed in Table 3 ordered by the generic barrier type. It is also listed the probability of failure on demand (PFD) for each barrier function together with a short description. The generic PFD values used here are found in the literature or are based on expert judgements. By that the values are involving a high degree of uncertainty, but the PFD still may be assumed as a reasonable measure on the quality and reliability of a barrier. Ignition sources are modelled to contribute to a delayed ignition only and giving when quantifying the results a uniform ignition probability for the whole station. This is of course a simplification, as it may be that the delayed ignition probability inside the closed area of the refuelling station is reduced compared to the unloading and dispenser area. The former area is better controlled and the requirements e.g. by the Atex directive can directly be incorporated, while the latter areas are more difficult to control with regard to avoid /minimize ignition sources. The most hazardous consequences are assumed to be deflagrations and detonations that might be caused by delayed ignition of the hydrogen gas clouds. Though jet fires initiated by immediate ignition of leaking hydrogen also could contribute to a major accident e.g. by a domino effect if the flame impinges on pipes or storage vessels.

Other technical and non-technical barriers by procedures, emergency actions etc. are identified, but are not shown in the barrier diagrams. These are:

- The skills of the driver and plant personnel
- The inspections done by the truck driver prior to unloading
- A number of additional safety devises as e.g. alarms and detection at various locations not discussed here in detail
- The remote monitoring and secure power supply and data connections.
- Station in connection with petrol station -> staff will inspect the station, but likely not allowed to enter process enclosures
- Staff will have a basic education to distinguish various hazards and what actions to be taken and how to behave in an emergency situation incl. evacuation of staff and customers
- In case of hazards detection the staff report to remote operator
- Manuel activation of emergency button setts the station to fail safe position
- Unauthorized people are not allowed to do any other physical actions on equipment
- Responsible operator situated at remote location with (not always continuously) monitoring of deviations from normal operation
- Responsible operator will be notified and decide on start up if it can be restarted from remote centre
- Depending on the alarm type maintenance personnel (experts on the refuelling station type) will manually restart on station location
- Fire brigades will be educated on H2 hazards

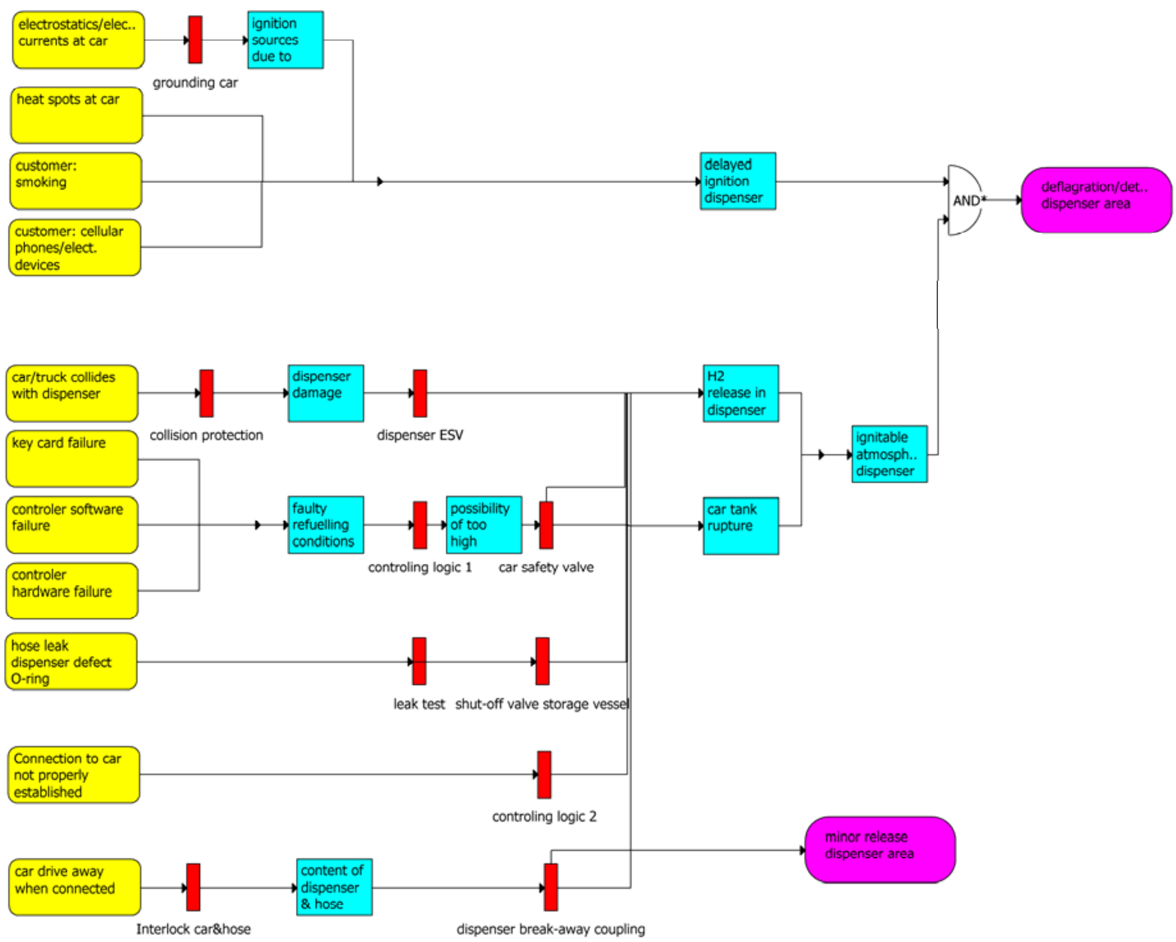

Figure 2. Barrier diagram for the dispenser area of the generic refuelling station.

- Fire brigades/police may be responsible for further actions, as wider evacuation of area around refuelling station, cordon-off the area, fire fighting, etc.
- Fire brigades may not be allowed to enter the station area, but only the experts due to explosion risk

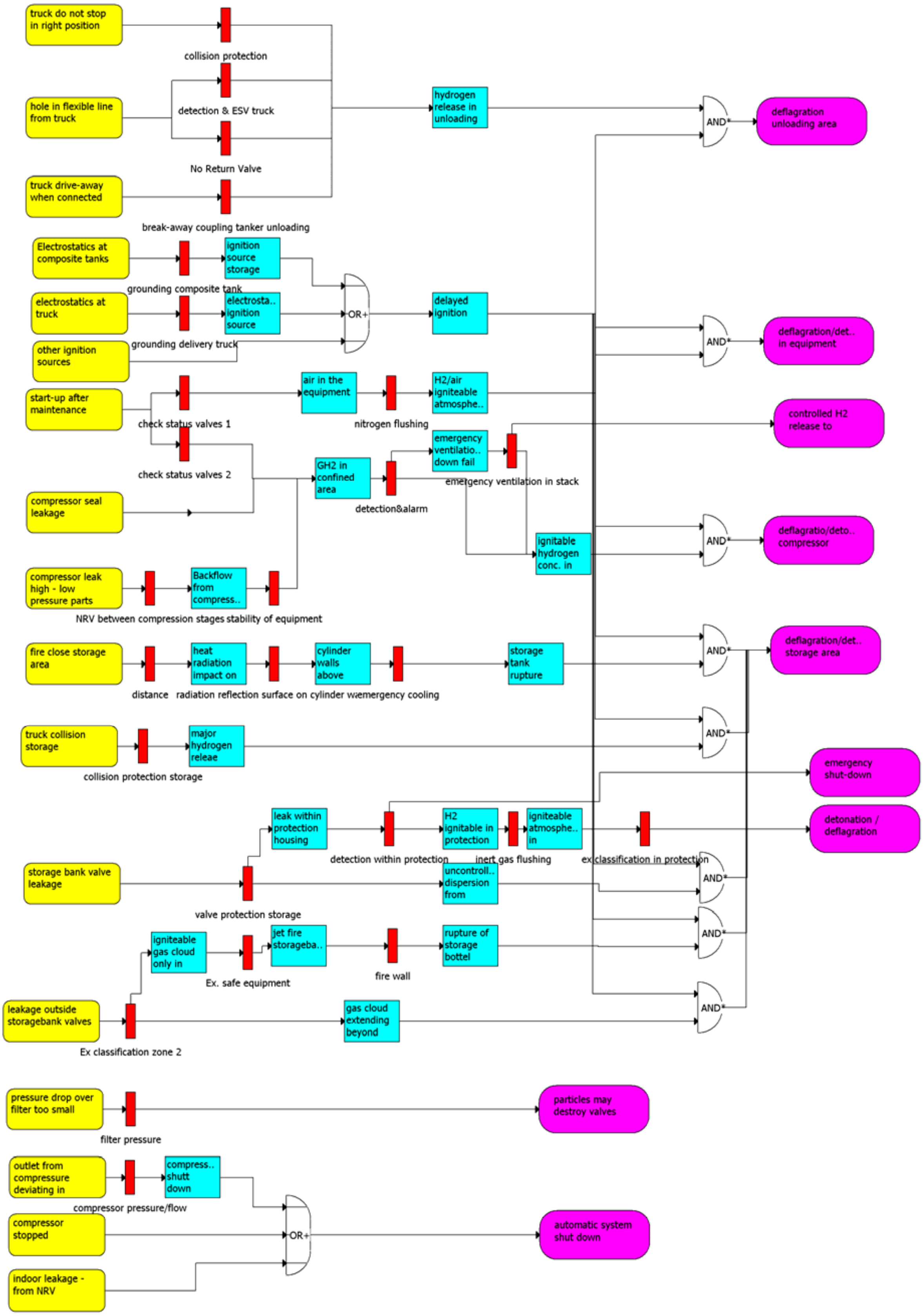

Figure 3. Barrier diagram for the truck unloading, compressor, and storage area (incl. piping) of the generic refuelling station.

Table 3. Barriers and barrier types identified in this study. The Probability for failure on demand (PFD) are frequencies based on expert judgment and generic literature findings as described in [12-14]. They are only to be regarded as an estimate to indicate and roughly compare the reliability of the different barriers listed here.

Barrier Type/Name	**PFD**	**Barrier Type/ Description**
Type 2:		**Permanent Passive Barrier**
NRV between compression stages Generic Barrier: no return valve	0.00001	NRV at compressor to prevent backflow
grounding delivery truck	0.00001	prevent electrostatic potentials
collision protection Generic Barrier: concrete border	0.000001	Structural element to protect equipment from being damaged by vehicles (dependent on the vehicle, if a large vehicle is arriving/colliding it might destroy equipment, so the actual PFD might be higher)
stability of equipment	0.01	While backflow parts of the compressor equipment designed for a lower pressure may be facing a too high pressure, e.g. compressor walls, flanges to truck hose connection etc. Barriers PFD is influenced by the design of the equipment.
grounding composite tank	0.1	Grounding of composite tank is difficult and may not be possible. A metal net in composite wall to improve grounding could be installed
distance	0.01	distance to external fire e.g. gasoline tanker for mixed stations: dependent on size , duration and distance from H2 refuelling station
radiation reflection surface on cylinder walls	0.1	The cylinder walls are painted giving a good reflexion of the heat radiation exposing the pressure vessels by an external fire. The insulation and heat capacity will protect (delay) the temperature increase that may weaken the walls. The PSD is available permanently, but depends on maintenance -> cleaning of surface. Further the heat radiation intensity depend on the position and size of the external fire and its duration -> therefore the PSD is assumed insufficient 1 time every 10 fires
collision protection storage	0.00001	Collision protection e.g. designed for brittle composite tanks. Lay out of storage and refuelling station is planned so that a truck will not pass storage banks (protection would not be sufficient). Consider elevated storage or storage below ground. Check for safety distancing.
valve protection storage	0.00001	Storage bank valves (except one per bank) located inside container. This will decrease the probability for leaks and increase the probability for effective gas detection, but might increase the consequences in case of ignition due to confinement.
Ex classification zone 2	0.00001	Explosion classification of the equipment due to the Atex directive, zone 2

fire wall	0.1	
ex classification in protection	0.1	Equipment inside enclosure is explosion classified to minimise the risk of explosion. It is therefore assumed that the ignition probability is reduced to 0.1
collision protection	0.00001	Collision protection around the dispensers in form of a 20cm concrete boundary colour marked with stripes. Depends on size and velocity of vehicles
Type 3:		**Temporary Passive Barrier**
grounding car	0.0001	Car is grounded during refuelling
Type 4		**Permanent Active Barrier**
break-away coupling tanker unloading	0.001	Coupling that closes the hose if an attached vehicle is driving away without first disconnecting properly from dispenser environmental project 112 (1989) give 3 point (chosen as worst case here) or 6 point in cases for equipment especially designed for safety and high reliability
Type 5:		**Activated Barrier - Hardware on demand**
No Return Valve	0.01	
Ex. safe equipment	0.01	
car safety valve	0.001	Safety valve on car storage
Interlock car & hose	0.0001	Recommendation: the interlock between vehicle and dispenser will disable the vehicle while being connected to the dispenser nozzle
dispenser break-away coupling	0.01	Break away coupling in cases the hose breaks
Type 6:		**Activated Barrier – Automated**
detection & alarm Generic Barrier: hydrogen sensors	0.005	Detection is causing an alarm triggering the emergency ventilation Common Element: main power supply
emergency ventilation in stack	0.02	
detection within protection Generic Barrier: hydrogen sensors	0.01	Gas detector is placed within the protection housing which reliable can detect any leaks Common Element: main power supply
inert gas flushing	0.01	Common Element: main power supply
controlling logic 1 Generic Barrier: dispenser control logic	0.001	Dispenser controlling device is controlling the refuelling operation using computer logics. Essential is the identification of the car's storage type to deliver the right pressure and refuelling sequence (avoid too high temperatures and pressures)
dispenser ESV	0.001	ESV at dispenser closes immediately on mechanical impact of the dispenser
leak test	0.01	Hose leaks due to a defective O-ring, the flow rate is reduced by on restriction orifice
shut-off valve storage vessel	0.01	Between fillings the valve on the storage vessel is closed. Before the valve is opened a leak test after connection is done.
controlling logic 2 Generic Barrier: dispenser control logic	0.0001	
Type 7:		**Activated Barrier - Manual (Human action triggered by active hardware detection)**
nitrogen flushing	0.1	In repair situations when the equipment is opened and

		likely to be filled with air flushing with the inert gas nitrogen is required to prevent inside explosions during start up! It is assumed an active barrier that is initiated by a workers manual activation Common Element: start-up procedures Common Element: emergency shut-down
detection & ESV truck	0.1	Emergency shut-down valve at truck, ARAMIS provides (page36 in user guide) a LC 1 response time 10 to 50 s (Conservative assumption: seems to be very long time for hydrogen installations) and 100% efficiency 0.01<PSD<0.1 Environmental report 112 (1989) give 1e-4 when the valve is driven automatically and automatic ventilation
Type 8		**Activated Barrier - Warned (Human Action based on passive warning)**
filter pressure	0.1	a broken filter (by particles etc. passing the filter and destroying valves
compressor pressure/flow	0.1	
Type 10:		**Activated Barrier - Procedural (Observation of local conditions not using instruments)**
check status valves 1 Generic Barrier: control valves	0.01	The status /position of valves are checked before start-up to prevent the wrong flow of gases, i.e. hydrogen and directed outside the equipment and air is not introduced into the equipment. Faulty valve status can either result in an explosion inside the equipment (air intrusion into equipment) or outside the equipment (release of hydrogen) Common Element: remote control e.g. by the internet Common Element: start-up procedures
check status valves 2 Generic Barrier: control valves	0.01	Common Element: start-up procedures Common Element: remote control e.g. by the internet
Type 11:		**Activated Barrier - Emergency (Ad-hoc observation of deviation and improvised response)**
emergency cooling (in case of fire)	0.3	heat radiation is prolonged and too strong so that the storage vessel is getting too hot

4.0 CONCLUSIONS

Hazard identification has been done on a future generic large hydrogen refuelling station and the results are further analyzed by means of barrier diagrams. In the present study only major events and consequences are regarded. Therefore, the study cannot be taken as a comprehensive analysis of the reliability of such a station, but only as a study to give a representative overview on the safety functions that are available and built in a modern design of such stations. It is further important to know that the refuelling station is generic and larger (i.e. storing and handling larger quantities of hydrogen) than the present available refuelling stations that have been or are in operation, as e.g. those in the EU CUTE project. Therefore, the present study had to take a number of assumptions. Also the layout of the refuelling station is based on public information only, but technical experts ensured that the present layout is still representative.

A large number of different barriers are identified and classified using the ARAMIS [14] approach. It is seen that many events have several barriers to minimize the overall potential of hazardous failures. The main issues are found regarding the control of ignition sources and the incidents that can lead to accidental leaks in the public parts of the refuelling station and the coordination between the control centre, the technical experts in a remote location, the personnel at the hydrogen/petrol station and the emergency service. This coordination is complex and training and maintenance of competence of personnel have to be carried out continuously over the lifetime of refuelling stations. Especially, the start-up procedures after an unplanned stop have to be carefully defined and be followed, as e.g. a remote start-up requires detailed knowledge on why the automatic shut down was initiated, not to oversee hazardous deviations that may cause an accident during restart!

5.0 ACKNOWLEDGEMENTS

The authors like to thank our HySafe colleagues that supported the described work with their knowledge and fruitful discussions. Further, we like to thank Mr. Nijs Jan Duijm who made his software to draw the diagrams available for our work and for the very helpful discussions. The work was performed within the frame work of the NoE HySafe (SES6-CT-2004-502630) and last not least the partial financial support from the European Commission is gratefully acknowledged.

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