# IDENTIFICATION OF SAFETY CRITICAL SCENARIOS OF HYDROGEN REFUELING STATIONS IN A MULTIFUEL CONTEXT

**Quesnel, S.[1], Pique, S.[2], Vyazmina E.[3] , Saw J.L.[4]**

**[1] ENGIE CRIGEN, 4 rue Joséphine Baker, 93240, Stains, France, sebastien.quesnel@engie.com**
**[2] Institut National de l'Environnement Industriel et des Risques, Parc Technologique Alata, BP 2, 60550 Verneuil-en-Halatte, France, sylvaine.pique@ineris.fr**
**[3] Air Liquide, 75, quai d'Orsay, 75007, Paris, France, elena.vyazmina@airliquide.com**
**[4] UK Health and Safety Executive (HSE), Harpur Hill, Buxton, SK17 9JN, United Kingdom, Ju-Lynne.Saw@hse.gov.uk**

## ABSTRACT

The MultHyFuel Project, funded by the Clean Hydrogen Partnership, aims to achieve the effective and safe deployment of hydrogen as a carbon-neutral fuel, by developing a common strategy for implementing Hydrogen Refueling Stations (HRS) in a multifuel context. The project hopes to contribute to the harmonisation of existing regulations, codes and standards (RCS) by generating practical, theoretical and experimental data related to HRS.

This paper presents how a set of safety critical scenarios have been identified from the initial preliminary as well as detailed risk analysis of three different hydrogen refueling station configurations. To achieve this, a detailed examination of each potential hazardous phenomenon (DPh) or major accident event at or near the hydrogen dispenser was carried out. Particular attention is paid to the scenarios which could affect third parties external to the refueling station.

The paper presents a methodology subdivided into the following steps:

- determination of the consequence level and likelihood of each hazardous phenomenon,
- the classification of major hazard scenarios for the 3 HRS configurations, specifically those arising on the dispensing forecourt;
- proposal of example preventative, control and/or mitigation barriers that could potentially reduce the probability of occurrence and/ or consequences of safety critical scenarios, and hence reducing risks to a tolerable level or to as low as reasonably practicable.

## 1. INTRODUCTION

The MultHyFuel Project [1], funded by the Clean Hydrogen Partnership (FCHJU) aims to achieve the effective and safe deployment of hydrogen as a net-zero alternative fuel, by developing a common strategy for implementing Hydrogen Refueling Stations (HRS) in multifuel context. The project will contribute to the harmonization of existing regulations, standards and industry codes by generating practical, theoretical and experimental data related to HRS, embedding regulatory and industrial stakeholders in the project progress.

The main goal of MultHyFuel's Work Package 3 is to develop good practice guidelines that can be utilized as a common approach to risk assessment for addressing the safe design of hydrogen refueling stations in a multifuel context. The fuels in scope are hydrogen and conventional fuels such as gasoline, diesel, LPG and CNG. These fuels are to be co-located in the same refueling station.

Using appropriate risk assessment techniques, combined with the data from the experimental programmes provided by Work Package 2 (e.g. expected likelihood and consequence, ignition frequency), risks will be assessed, considering the additional control /mitigation measures that could be implemented in hydrogen refuelling stations. Work Package 3 involves the following tasks:

- Task 3.1 - State of the art study about existing technologies to define configurations of HRS
- Task 3.2 - Benchmark of risk assessment methodologies used on refueling stations
- Task 3.3 - Preliminary risk analysis on previous case study models
- Task 3.4 - Detailed risk assessment on potential safety critical scenarios
- Task 3.5 - Identify and confirm the safety critical scenarios, equipment and safety barriers to be studied in experimental programme in WP2 based on the detailed risk assessment results
- Task 3.6 - Review of the safety critical scenarios with input from the WP2 experimental programme in order to define separation distances and requirements for safety barriers.
- Task 3.7 - Drafting of good practice guidelines for multifuel stations, based on project findings.

This article focuses on tasks 3.4 and 3.5 and describes how a set of safety critical scenarios were identified from the initial preliminary as well as detailed risk analysis of three different hydrogen refueling station configurations. A detailed examination of each potential dangerous phenomenon (DPh) / major accident event on the dispensing forecourt was conducted, to determine how risks to members of the public could be reduced to as low as reasonably practicable.

## 2. CONFIGURATIONS STUDIED AND PRELIMINARY RISK ASSESSMENT

### 2.1 Configurations

Three different exemplar configurations were identified [2]:

- Configuration 1, called "Ready-to-deploy multifuel station" with small capacity, aims to provide hydrogen for vehicles with gaseous hydrogen (GH2) supplied by trailers or bundles,
- Configuration 2, called "Onsite H2" with medium capacity, aims to provide hydrogen for vehicles with an onsite GH2 production by electrolysis,
- Configuration 3, called "High capacity multifuel refueling station", aims to provide a large amount of hydrogen supplied by stationary liquid hydrogen (LH2) storage.

For the hydrogen dispensers, two types of dispensers were studied in order to take into account the different geometry and models used in typical HRSs. The two geometries are shown in Figure 1.

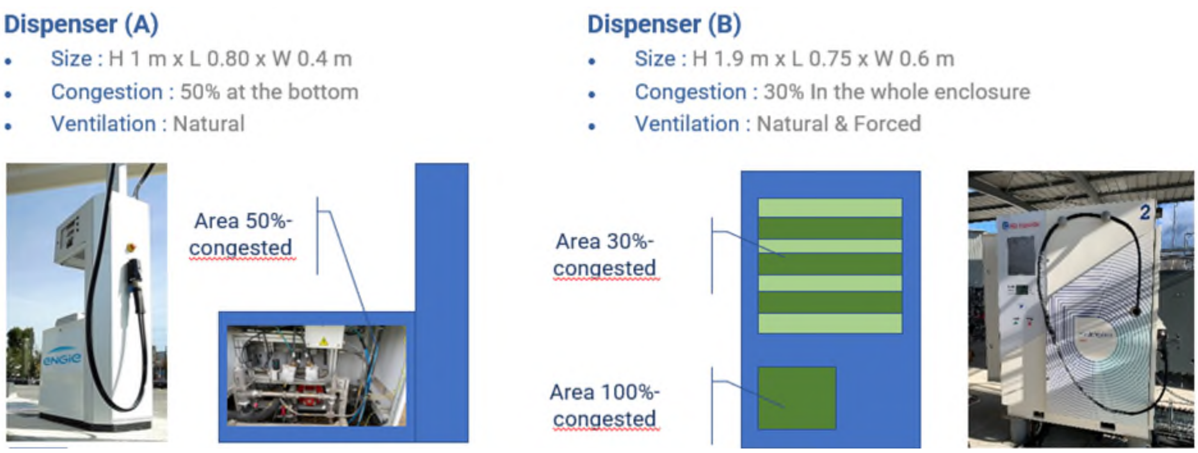



Figure 1. Geometries of the hydrogen dispensers studied

## 2.2 PRA main results

The main results of the preliminary risk assessment on the aforementioned three configurations studied as part of Task 3.3[3] are summarized here with a focus on hydrogen dispenser scenarios.

During the HAZID sessions, the following DPh/ major accident events were identified: Jet fire, Flash fire, Vapour Cloud Explosion (VCE), Unconfined Vapour Cloud Explosion (UVCE), Burst (e.g. physical explosion due to overpressure), and whipping of hose. The HAZIDs led to the identification of 258 DPh that were then studied in MultHyFuel Task 3.4 'Detailed risk assessment'. Among the 258 DPh, 29 are related to the hydrogen dispenser.

In addition, a list of preliminary recommendations of safety barriers for the prevention and mitigation of these DPh was compiled as part of the HAZID. These recommendations served as input into several tasks within the project and will be checked for completeness and practicability in the final stages of the project. The following are some key recommendations:

- technical safety barriers (flame and H2 detection with emergency shutdown ESD) should be installed due to the fast kinetics of the DPh,
- isolation systems (e.g. break-away couplings, shut-off valves) should be installed to reduce the $H_2$ inventory released in case of loss of containment,
- a smart review of the layout of equipment should be carried out to avoid/minimize domino effects,
- a systematic materials selection process should be implemented to guarantee hydrogen compatible systems,
- the definition of a maintenance and periodic control plan should be conducted for H2 equipment.

# 3. LIKELIHOODS

## 3.1 Methodology

There are several methods for estimating the likelihood of occurrence of dangerous phenomena/ major hazard events. The approach chosen will need to be driven by proportionality, the availability of data and the resolution of the modelling of the system being studied. Estimating the likelihood of occurrence of dangerous phenomena can be carried out qualitatively, semi-quantitatively (using probability classes/ranges), or quantitatively (using values). After a brainstorming exercise amongst partners, a semi-quantitative approach was chosen, and the likelihood of the dangerous phenomena was estimated in the form of classes (probability ranges).

Table 1. Presentation of likelihood ranges/ intervals.

| Probability interval | E | D | C | B | A |
|---|---|---|---|---|---|
| Frequency (per year) | $E < 10^{-5}$ | $10^{-5} < D < 10^{-4}$ | $10^{-4} < C < 10^{-3}$ | $10^{-3} < B < 10^{-2}$ | $10^{-2} < A$ |

The approach chosen comprises evaluating the probability of occurrence from the central feared event CFE/ top hazardous event. It is a simplified and quick approach to classify the different DPh/ major accident events.

Raw data for central feared event/ top event frequencies are predominantly extracted from databases specific to hydrogen, such as SANDIA database [4] or obtained from international databases such as BEVI [5] Norskeolje&gass PLOFAM "Process leak for offshore installations frequency assessment model" [6] and Offshore & Onshore Reliability Data [7]. With the exception of the data from SANDIA, the rest of the frequency data were derived from oil and gas or chemical process data for the most part.

To remain conservative, the ignition likelihood was assumed to be equal to 1, in consideration of the low ignition energy required to ignite (immediately or delayed) a flammable cloud of hydrogen. The 2023 MultHyFuel WP2 experimental programme as well as the consideration of safety barriers, could help refine the evaluation of likelihoods.

### 3.2 Comparative assessment

The assessment of likelihood was conducted for the 3 configurations described earlier and the full details are available in Deliverable 3.4 and its Appendix [8] as well as Deliverable 3.5 [9]. The following section is related to the forecourt and focuses on the critical scenarios on the dispenser hose.

Input data for the dispenser hose

For the likelihood assessment of events related to the dispenser hose, it is necessary to consider the duration of delivery per day of the dispenser during which the risk exists. To estimate this, the calculation was done with the time to fill a light and heavy vehicle and the number of vehicles for each configuration. We considered one dispenser for each type of vehicle per configuration. These input data are detailed in Table 2 and Figure 2, as determined with input from MultHyFuel project partners.

Table 2. Input data for likelihood assessment of dispenser (time to maximum fill).

| Vehicles | Trucks | Cars |
|---|---|---|
| Time for filling | 20 mins | 3mins |

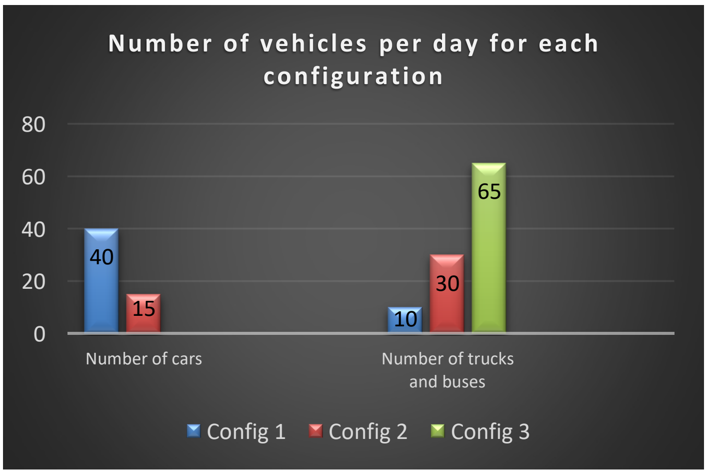



Figure 2. Number of filling operations per day

Likelihood assessment for dispenser hose

The likelihood for scenarios on a dispenser hose is estimated using several database sources, at a number of pressures, and for each configuration. The results of the likelihood assessment are shown in the Table 3. A collective decision was made by the project partners to utilise the data from Sandia National Laboratories in the risk analyses.

Table 3. Result of likelihood assessment for loss of containment from the dispenser hose.

| Config. | Central Feared Event (CFE)/ Top Event | Pressure | Time maximum filling (h/day) | DATABASE | | | DPh/ major accident event |
|---|---|---|---|---|---|---|---|
| | | | | **BEVI** | **Sandia** | **Norskeolje&gass PLOFAM** | |
| **1** | Loss of $H_2$ containment (medium leak 10%) on hose | 350 bar | 3.33 | A | D | E | (U)VCE<br>Flashfire<br>Jet fire |
| **2** | | | 5 | A | D | E | |
| **3** | | | 21.7 | A | C | D | |
| **1** | | 700 bar | 3.33 | A | D | E | |
| **2** | | | 5 | A | D | D | |
| **3** | | | 21.7 | A | C | D | |
| **1** | | 1000 bar | 3.33 | A | D | D | |
| **2** | | | 5 | A | D | D | |
| **3** | | | 21.7 | A | C | D | |
| **1** | Full bore rupture (1'' = 2.54 mm) on hose | 350 bar | 3.33 | B | D | E | |
| **2** | | | 5 | B | D | E | |
| **3** | | | 21.7 | A | C | D | |
| **1** | | 700 bar | 3.33 | B | D | E | |
| **2** | | | 5 | A | D | D | |
| **3** | | | 21.7 | B | C | D | |
| **1** | | 1000 bar | 3.33 | B | D | D | |
| **2** | | | 5 | B | D | D | |
| **3** | | | 21.7 | A | C | D | |

### 3.4 Recommendations for further work

The work within MultHyFuel Deliverables 3.4 [8] and 3.5 [9] around likelihood and summarised in the previous section revealed some gaps in knowledge, in terms of:

- Validation of the occurrence of leakage using experimental data or lessons learned from new installations operated,
- Estimation of the likelihoods to take into account the mitigation and protective barriers,
- Consideration of the ignition likelihood in the event of loss of containment

## 4. CONSEQUENCES

### 4.1 Methodology

Following the basic risk assessment, the next step is to define the source terms for the loss of containment scenarios that need to be considered. This section provides an overview and recommendations on the methodology and assumptions that followed by the detailed risk assessment

The harm criteria thresholds for severity assessment are from French regulations and shown in Table 4.

Table 4. Effects thresholds for H2 scenarios severity assessment.

| | Radiative heat fluxes | Overpressures | Whipping |
|---|---|---|---|
| Significant Lethal Effects (5%) | 8 kW.m$^{-2}$ | 200 mbar | - |
| First Lethal Effects (1%) | 5 kW.m$^{-2}$ or 100% LFL | 140 mbar | 100% hose length |
| Irreversible Effects | 3 kW.m$^{-2}$ or 110% LFL | 50 mbar | 110% hose length |
| Indirect Effects (glass break) | - | 20 mbar | - |

*LFL: Lower Flammability Limit*

The following methodology is used for the detailed calculations of hazardous phenomena defined by the risk assessment GH2 [8]

- **Release** is modelled as steady in time, at the maximum flowrate (round orifice) with a size: 0.2 mm for small leaks, 10% of external diameter for medium leak, and external diameter for full bore rupture; the diameter of calibrated orifice (where existing) and flowrate characterized by the excess flow valve (where existing) are taken into account.
- **Free field gaseous release flammable mass** is calculated based on the flowrate and the following concentration thresholds (4%-$H_2$ (LFL), 8%-$H_2$ (NFPA-2) and 10%-$H_2$)
- **UVCE** calculations are based on the TNO Multi-Energy Model using the flammable mass (calculation within the envelope of 10%-$H_2$). The associated thresholds are in Table 4. The TNO Multi-Energy (ME) index is assumed to be 4 for hose release (limited flowrate and no congestion), please see Reference [10].
- **Flash fire** calculations are based on the thresholds for the irreversible effect (cloud length corresponding to 110% of the LFL at the jet centreline) and lethal effects (100% of the LFL)
- **Jet fire** calculations are based on the associated thresholds from Table 4, whereas the releases are orientated horizontally
- **Burst** calculations are based on the associated thresholds from Table 4, fragments and missiles are not considered.
- **Whipping hose** calculations are based on the associated thresholds from Table 4.
- **VCE – Build-up – $H_2$ concentration inside the dispenser** is based on the assumption of natural ventilation with 2-openings (one on the top and one on the bottom of the vertical wall with the following sizes (each) Height = 10% dispenser height and Length = dispenser width; for the size the effective ventilation area is considered (i.e. no grid, obstruction, protection... in front of the opening); the calculations are performed for the steady state to estimate the maximum concentration inside the dispenser.
- **VCE – Dispenser** is based on the assumption that the $GH_2$ concentration is homogeneous in the whole dispenser volume (conservative approach for $H_2$ mass assessment); if the calculated concentration is higher than 30% in the dispenser, then 30% is taken into account for a deflagration consequences calculation (30%-$H_2$, stoichiometry or the worst case); Ventilation openings are considered as explosion venting panels; Overpressure thresholds are taken from Table 4; however, for dispenser structure (low strength), it is assumed that the enclosure is not destroyed if the overpressure does not exceed 100 mbar. If 100 mbar internal overpressure is reached, then the dispenser is considered to be destroyed and the overpressure decay is a function of the distance from the dispenser.

In the case of burst and dispenser destruction, missiles and fragments are not considered. Cryogenic risks and asphyxiation are not considered for the forecourt either.

### 4.2 Risk assessment of representative accidental scenarios

Two main categories of events are identified on the forecourt: hazardous events inside and outside the dispenser. In general, irrespective of the station configuration, (i.e. Configurations 1-3), the scenarios are very similar. The Dispensers presented in Figure 1 are used for the risk assessment. Forecourt consequence assessment was carried out for 75 scenarios in total, including 43 scenarios for Configurations 1 and 2 and 32 scenarios for Configuration 3.

These scenarios include dispensers A and B with natural ventilation, maximum pressures of 350/ /700/1000 bar, and maximum flowrates of 60/120/300 $g.s^{-1}$.

The following accidental events inside the dispenser are considered:

- Dispenser A (the smallest volume): irrespective of leak rates and assumed pressures, natural ventilation is considered insufficient to prevent the accumulation of a flammable cloud, thus producing flammable conditions; in case of ignition. The dispenser box is assumed to be completely destroyed, potentially impacting any neighbouring equipment
- Dispenser B: for small leaks (e.g. ≤ 0.2 mm diameter) the associated potential explosion will be confined within the dispenser.

Table 5. Consequences of the ignition of a 30% H2-air mixture inside dispensers A & B.

| | Dispenser A | Dispenser B |
|---|---|---|
| **Volume** | 0.32 $m^3$ | 0.855 $m^3$ |
| **Initial $H_2$ concentration** | 30%* | 30%* |
| ***Internal effects*** | | |
| Overpressure | 284 mbar | 195 mbar |
| Consequence on structure* | Destruction | Destruction |
| ***External effects*** – Overpressure decay with the distance | | |
| 200 mbar | 1 m | 1 m |
| 140 mbar | 1 m | 2 m |
| 50 mbar | 3 m | 4 m |
| 20 mbar | 6 m | 8 m |

** For lower $H_2$ concentrations, internal overpressure is lower than 100 mbar; thus, consequences are limited to inside the dispenser, which is not destroyed*

It is assumed that the gas concentration monitoring/ measurement inside the dispenser is used for the activation of an appropriate safety protocol, which can stop the release and limit the amount of the accumulated hydrogen, leading to reduced explosion effects if ignited.

The scenarios linked to the hose are the accidental events outside the dispenser. The hose length varies from 2.5 to 3.5 m. Whipping of the hose due to pressure and momentum effects in the case of full-bore rupture was found to induce no domino effects and the maximum effect distances (Irreversible Effects for instance) are lower than 10 m for HDV dispensers and even lower for LDV dispensers.

Other hazardous events considered for the full-bore rupture of the hose are:

- a jet fire with very high hazard distance, reaching more than 80 m for 700 bar, but the duration of the jet fire is limited by the automatic shut-off of the valve; and in reality, the release flow will be also limited by a restriction orifice;

- a delayed ignition following the release has maximum effects at 15 m from the dispenser, the flowrate will be limited by the restriction orifice, and the likelihood of ignition could be reduced by the quick shut-off valve.

## 5. MAIN RESULTS

### 5.1 Critical scenarios

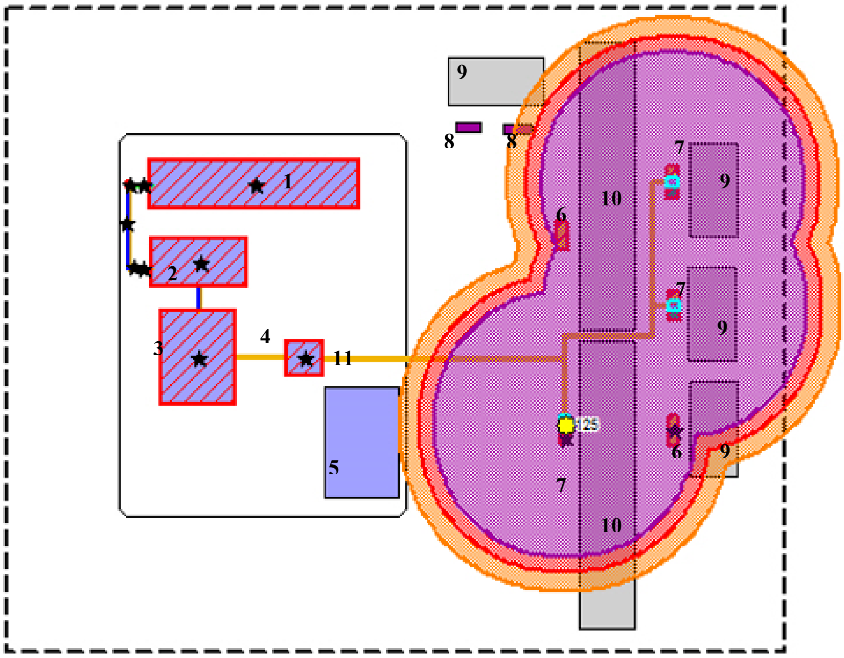
The goal of this work was the identification and classification of the safety critical scenarios from a much larger set that were identified in the preliminary risk analysis. A benchmark exercise identified the different implementation of the Seveso Directive in Europe, in terms of risk tolerability criteria. The benchmark exercise, which involved a literature review and interviews with regulators, focused on the following countries: United Kingdom, France, Netherlands and Belgium. It was decided by the MultHyFuel consortium that the French risk tolerability criteria were to be used in the exemplar.

**Determination of the level of severity**

Following the identification of major hazard scenarios during the preliminary risk analysis and the modeling of each of the of the major dangerous phenomena in the detailed risk assessment, the goal was to determine the severity, i.e. the degree of harm to humans who may potentially be within the hazard range. In a first step, the layouts (Figure 3) and the vulnerable elements (Table 6) for the different configuration of refuelling station were identified. The hazard extents are superimposed onto a schematic diagram of the forecourt to help illustrate the potential number of people impacted by each DPh's threshold of lethal/irreversible effect.

Table 6. Vulnerable elements for the 3 configurations

| | Outside fueling station | Inside fueling station | | | | |
|---|---|---|---|---|---|---|
| | | Option 1 | | Option 2 | | |
| | | Light vehicles (lV) | Heavy vehicles (HV) | Light vehicles (lV) | Heavy vehicles (HV) | |
| Configuration 1 | 600 people per hectare | 1 × 4 people (lV1) + 1 × 1 person (lV2) | 1 bus (50 people) (HV1) | 1 × 4 people (lV1) + 1 × 1 person (lV2) | 1 bus (2 people) (HV1) | H2 dispensers |
| | | 1 × 4 people (lV3) + 1 × 1 person (lV4) | 1 truck (1 person) (HV2) | 1 × 4 people (lV3) + 1 × 1 person (lV4) | 1 truck (2 people) (HV2) | Others fuels dispensers |
| Configuration 2 | Suburban: 50 people per hectare | 1 × 4 people (lV1) + 1 × 1 person (lV3) | 1 bus (50 people) (HV1)<br>1 truck (1 person) (HV3) | 1 × 4 people (lV1) + 1 × 1 person (lV3) | 1 bus (2 people) (HV1)<br>1 truck (2 person) (HV3) | H2 dispensers |
| | | 1 × 4 people (lV2) + 1 × 1 person (lV4) | 1 truck (1 person) (HV2) | 1 × 4 people (lV2) + 1 × 1 person (lV4) | 1 truck (1 person) (HV2) | Others fuels dispensers |
| Configuration 3 | -Rural: very sparsely populated, 20 people per hectare<br>- Highway located 35 m from the liquid hydrogen storage area | | 1 bus (50 people) (HV5)<br>1 truck (1 person) (HV6) | | 1 bus (2 people) (HV5)<br>1 truck (2 people) (HV6) | H2 dispensers |
| | | | 1 bus (50 people) (HV2)<br>3 trucks (3 x 1 person) (HV1, HV3, HV4) | | 1 bus (2 people) (HV2)<br>3 trucks (3 x 2 people) (HV1, HV3, HV4) | Others fuels dispensers |




| 1 | **Gaseous hydrogen storage area** | 7 | **Multifuel dispensers** |
|---|---|---|---|
| 2 | Compression skid | 8 | Electric charging point |
| 3 | MP & HP buffers | 9 | Distribution area for cars |
| 4 | Chiller | 10 | Distribution area for buses and heavy-duty vehicles |
| 5 | Control & technical room | 11 | Pipes $H_2$ |
| 6 | Conventional fuel dispensers | | |

Figure 3. Example of maps realized for the scenario 6.3e - H2 dispenser/ hose - Loss of H2 containment (large leak) on pipe/valve/hose - Full bore rupture (1") on hose (350 & 700 bar) - Jet fire

The scale for assessing the severity of the potential human consequences arising from an accident, external to the installations, are shown in Table 7 below.

Table 7. Scale for assessing the severity to humans from an accident outside the facilities (French Order of 20/09/2005)

| Severity level of consequence | Area defined by the thresholds of significant lethal effects (in French “Seuil des effets léthaux significatifs” SELS) | Area bounded by lethal effects thresholds (in French “Seuil des effets léthaux” SEL) | Area defined by the thresholds of irreversible effects (in French “Seuil des effets irréversibles” SEI) |
|---|---|---|---|
| **V. Disastrous** | More than 10 people exposed | More than 100 people exposed | More than 1000 people exposed |
| **IV. Catastrophic** | Less than 10 people exposed | Between 10 and 100 people exposed | Between 100 and 1000 people exposed |
| **III. Major** | At most 1 person exposed | Between 1 and 10 people exposed | Between 10 and 100 people exposed |
| **II. Serious** | No person exposed | At most 1 person exposed | Less than 10 people exposed |
| **I. Moderate** | No lethality zone outside the establishment | | Less than 1 person exposed |

If the three criteria of the severity scale (significant lethal effects, first lethal effects and irreversible effects for human health) do not lead to the same severity class, the most serious class is adopted. Table 8 presents an example of severity classification for one of the scenarios analysed.

Table 8. Example of severity evaluation for the scenario 6.3e - H2 dispenser/ hose - Loss of H2 containment (large leak) on pipe/valve/hose - Full bore rupture (1") on hose (350 & 700 bar) - Jet fire) for the different options.

| Option | Number of people impacted by SELS | Severity for SELS | Number of people impacted by SEL | Severity for SEL | Number of people impacted by SEI | Severity for SEI | Severity class |
|---|---|---|---|---|---|---|---|
| **Only people outside the site** | < 1 | Major | 2 | Major | 3 | Serious | **Major** |
| **People outside and inside the site (option 1)** | 61 | Disastrous | 62 | Catastrophic | 64 | Important | **Disastrous** |
| **People outside and inside the site (option 2)** | 14 | Disastrous | 15 | Catastrophic | 17 | Important | **Disastrous** |

**Classification of major hazard scenarios for the 3 configurations**

Each event arising from the hazardous phenomena/ major hazard scenario identified in the HAZID is plotted on the "risk matrix representing the potential accidents in terms of the probability-severity pair of cons.

Table 9. Matrix presenting the potential events in terms of the probability-severity of harm to people

| Severity of the consequences on the people exposed to the risk | Likelihood (increasing direction from E to A) | | | | |
|---|---|---|---|---|---|
| | E | D | C | B | A |
| **V. Disastrous** | NO partiel (new site) / MMR rank 2 (existing site) | NO rank 1 | NO rank 2 | NO rank 3 | NO rank 4 |
| **IV. Catastrophic** | MMR rank 1 | MMR rank 2 | NO rank 1 | NO rank 2 | NO rank 3 |
| **III. Major** | MMR rank 1 | MMR rank 1 | MMR rank 2 | NO rank 1 | NO rank 2 |
| **II. Serious** | | | MMR rank 1 | MMR rank 2 | NO rank 1 |
| **I. Moderate** | | | | | MMR rank 1 |

The risk matrix defines three risk zones:

- a high-risk zone, represented as "NO" (where action must be taken to reduce risks irrespective of costs);
- an intermediate risk zone, represented as "MMR" (***M**esures de **R**éduction des **R**isques* or risk reduction measures) rank1 or rank2, within which risks need to be continually reduced to as low as reasonably practicable, proportionate to the level of risks whilst also considering economic viability;
- a lower-risk zone, where compliance to RCS and established good practice is still expected.

The risk assessment for the forecourt scenarios led to the following distribution of the scenarios in the categories shown in the previous risk matrix as in Table 10:

Table 10. Distribution of events in the different risk categories for the three configurations

| Number of events | High-risk zone | Intermediate risk zone | Lower-risk zone |
|---|---|---|---|
| Configuration1 | 13 | 28 | 2 |
| Configuration 2 | 13 | 27 | 3 |
| Configuration 3 | 24 | 26 | 4 |

Most of the events were found to sit in the Intermediate Risk zone where risks need to be continually reduced to as low as reasonably practicable via the adoption of relevant risk reduction measures.

**Conclusions**

The equipment that registers the highest number of critical hazardous events is the dispenser, but the storage, compression, and liquid equipment in the backyard (processing and bulk storage of hydrogen not part of this analysis), also present a significant number of scenarios as well. The main safety critical major hazard events are unconfined/confined vapour cloud explosion (UVCE/VCE) and jet/flash fire.

This study shows that the dispenser is a safety-critical piece of equipment in a refueling station. The central feared/ top event is a loss of containment which can lead to explosions in the open air (UVCE) or in a confined environment (VCE inside the dispenser) or to jet fires or flashfires. The results also highlight that the large number of leaks are related to high numbers of fittings in the different dispensers, potential failure of equipment due to hydrogen embrittlement, human error during maintenance, bad connection with hose or nozzle, impact such as crash, vehicle driveaway or domino effects due to the other fuels.

## 5.2 Safety barriers

The potential effects on people are expected to be immediate, given the proximity of the people on the refueling station dispensing area. This study shows the impact of having vehicle passengers on the number of critical scenarios (i.e. difference between Options 1 and 2). A key critical measure is to minimize the number of people near the dispensers during any refueling operation.

There are many other safety barriers or risk reduction measures that could be adopted to prevent or reduce the likelihood of loss of containment from the dispenser such as that can have impact on likelihood, examples include but are not limited to:

| | |
|---|---|
| Technical measures | Breakaway device<br>Pressure safety valve<br>Dedicated connection/ coupling breaks to reduce and prevent leakage in the event of an accidental driveaway scenario<br>Crash protection around the island<br>Design of the nozzle (prohibition of refueling if the connection is not well established) |
| Safety Instrumented Systems | Gas detection in the dispenser with shutdown of the installation and activation of ventilation<br>Redundancy of pressure sensors with isolation system in case of high pressure<br>Two temperature sensors (before the breakaway) with automatic shutdown of refueling if the temperature is too high or too low (refueling protocol) |
| Operational measures | Inspection, maintenance, and procedure of controls for dispenser and hose<br>Clear step-by-step instructions for users to fill their cars (e.g. signage, *etc*.) |

## 5.3 Knowledge gaps identified

The risk analysis highlighted further areas to be explored:

- Breakaway reliability and the implementation of restricted orifice or excess flow valve;
- Safe design of multifuel dispenser (critical element in design, fire and gas detection);
- The domino effects between the different dispensers;
- The design of the nozzle (how to avoid humidity at the end and the fall of nozzle);
- The design of the island to avoid crash involving the dispenser due to vehicles impact; and
- The organizational measures to be implemented to avoid passengers near the dispenser

It is worth noting that the various European approaches as well as the risk matrix used to classify the scenarios that may cause harm to people located external to the site. The risk matrix could be adapted to take into consideration people inside the refuelling station.

One last recommendation to make in terms of improving the classification of these scenarios, is to refine the consequence modelling and likelihood estimations, by taking into account the impact of the various safety barriers in the risk assessment.

## 6. CONCLUSIONS

A detailed risk assessment for the forecourt major hazard scenarios shows that:

- The most foreseeable leaks are the small ones with likelihood in the range of $10^{-6}$/year,
- More specifically for the forecourt, the most foreseeable hazardous events occur on the hose with likelihoods in the range of $10^{-4}$/year.

The equipment that registers the highest number of safety critical scenarios is the dispenser. The central feared event/ top event is loss of containment (10% diameter of pipe and the full-bore rupture of the hose). These hydrogen leaks can lead to vapour cloud explosions in the open air (UVCE) or in a confined environment (VCE inside the dispenser) or to jet fires or flashfires.

It highlights that the large number of leaks are related to the high numbers of fittings in the different dispensers, potential failure of equipment due to hydrogen embrittlement, human error during maintenance, bad connection with hose or nozzle, impact such as crash, vehicle driveaway or domino effects due to the other fuels, *etc*. Simplification of systems within the dispenser, including reducing the number of connections as well as the use of alternative fitting types should also be investigated.

A key critical measure is to minimize the number of people in the vicinity of the dispensers during any refueling operation. There are many other safety measures that could be adopted on the dispenser to prevent or reduce the likelihood of loss of containment from the dispenser such as: breakaway coupling, crash protection around the dispenser island, gas detection with emergency shutdown, as well as inspection and maintenance of equipment.

The main knowledge gaps identified for further research and exploration:

- Confirmation with experimental data the occurrence and consequence of leakage;
- Breakaway coupling reliability
- Implementation of restriction orifice or excess flow valve;
- Safe design of multifuel dispenser (inherently safe design, reduction of connections, use of alternative fittings/ valves, incorporation of safety critical elements such as fire and gas detection), *etc*.;
- The domino effects between different dispensers;
- The design of the nozzle (how to avoid humidity at the end and the fall of nozzle);
- The design of the island to avoid a crash involving the dispenser due to vehicle impact; and
- The organizational measures to be implemented to avoid presence of people near the dispenser

In order to improve the classification of these scenarios, it will be necessary to refine the risk assessment of the scenarios and events by considering safety barriers for severity and likelihood evaluation. The following experiments as part of MultHyFuel's WP2 will help to refine:

- Hydrogen leakage on dispenser with and without ignition (inside/outside the dispenser);
- Mechanical tests on dispenser components (pressure cycling, vibration, fatigue); and
- Domino effects between the hydrogen dispenser and the conventional dispensers.

## 7. ACKNOWLEDGEMENTS

This work has been achieved in the framework of a project which has received funding from the Clean Hydrogen Partnership (previously 'Fuel Cells and Hydrogen 2 Joint Undertaking') under Grant Agreement ID: 101006794. We would like to thank all partners of the MultHyFuel project (https://multhyfuel.eu/) for their contribution to this work: Air Liquide, ENGIE, UK HSE, Hydrogen Europe, INERIS, ITM, KIWA, Shell, SNAM, and ZSW. The work undertaken by HSE in support of this project was carried out under contract. The contents of this paper, including any opinions and/or conclusions expressed or recommendations made, do not supersede current HSE policy or guidance.

## 8. REFERENCES


1. MultHyfuel project. Safety and Permitting for Hydrogen at Multifuel Retail. Retrieved March 13, 2023 from https://multhyfuel.eu/. 2021.
2. Houssin D., Vyazmina E., Quesnel S., Nouvelot Q., J. L. Saw J. L., Pique S., Hart N., Montel S., Robino M., Jenne M., State of the Art on hydrogen technologies and infrastructures regarding a multi-fuel station environment, Deliverable 3.1, FCH JU funded project MultHyFuel, 2021.
3. Pique S., Quesnel S., Weinberger B., Nouvelot Q., Houssin D., Vyazmina E., Torrado D., Saw J.-L., Preliminary risk assessment of hydrogen refueling stations in a multifuel context, Chemical Engineering Transactions, 90, 229-234, 2022.
4. LaChance J., Houf W., Middleton B., Fluer L. Analyses to support development of risk-informed separation distances for hydrogen codes and standards, SAND2009-874. Sandia National Laboratories, 2009.
5. RIVM, 2009, Reference Manual Bevi Risk Assessments (Handleiding Risicoberekeningen Bevi), version 3.2, dated 1 July 2009.
6. Lloyd’s Register Consulting, Process Leak for Offshore Installations Frequency Assessment model – PLOFAM (2). Report No. 1007566/R1 Rev: Final, December 2018.
7. SINTEF, “OREDA, offshore reliability data”, Edition 5, 2009
8. Houssin D., Vyazmina E., Quesnel S., Pique S., Detailed risk assessment on potential safety-critical scenarios, Deliverable 3.4, FCH JU funded project MultHyFuel, 2021.
9. Pique S., Houssin D., Vyazmina E., Quesnel S., Identification of critical scenarios, Deliverable 3.5, FCH JU funded project MultHyFuel, 2021.
10. S. Jallais, E. Vyazmina, D. Miller, J. K. Thomas, “Hydrogen Jet Vapor Cloud Explosion: A Model for Predicting Blast Size and Application to Risk Assessment”, Process Safety Progress, Vol 37, No 3 (2018) 397-410, 2018. DOI:10.1002/prs.11965.