CHEMICAL ENGINEERING TRANSACTIONS
VOL. 90, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Aleš Bernatík, Bruno Fabiano

ISBN 978-88-95608-88-4; **ISSN** 2283-9216

DOI: 10.3303/CET2290039

Preliminary Risk Assessment of Hydrogen Refuelling Stations in a Multifuel Context

Sylvaine Pique[a], Sebastien Quesnel[b], Benno Weinberger[a], Quentin Nouvelot[b], Deborah Houssin[c], Elena Vyazmina[c], David Torrado[d], Ju Lynne Saw[e]

[a] INERIS, Avenue du Parc Alata, 60100 Verneuil-en-Halatte, France
[b] ENGIE Crigen, 4 rue Joséphine Baker, 93240 Stains, France
[c] Air Liquide Innovation Campus Paris, 1 chemin de la Porte des Loges, 78350 Jouy-En-Josas,France
[d] ITM Power, ITM Power Plc, 2 Bessemer Park, Sheffield, S9 1DZ, UK
[e] Health and Safety Executive (HSE), Harpur Hill, Buxton, Derbyshire, SK17 9JN, UK
Sylvaine.PIQUE@ineris.f

The MultHyFuel Project [1], funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), aims to achieve the effective and safe deployment of hydrogen as a net-zero alternative fuel, by developing a common strategy for implementing Hydrogen Refuelling Stations (HRS) in multifuel context. The project contributes to the harmonization of existing regulations code and standards (RCS) for industrial applications by generating practical, theoretical and experimental data related to HRS, embedding regulatory and industrial stakeholders to the project progress.
This paper presents a preliminary risk assessment performed for three different hydrogen refuelling configurations, presented in project Deliverable 3.1 [2], each intended to be integrated into a multifuel station. In terms of the hydrogen refuelling configurations, we discuss the following points:

- detail on typical components of hydrogen refuelling stations, such as compressor, high pressure buffer storage, cooling system and dispenser,
- different modes of supply of hydrogen (high-pressure storage (trailers or bundles), hydrogen production by electrolysis, and stationary liquid hydrogen storage),
- different operating conditions of the dispenser - i.e. flow and pressure - but only delivering compressed gaseous hydrogen.

The objective of this preliminary risk assessment is not limited only to the identification of the major hazards - and the consideration of various prevention and protection measures specific to the hydrogen installation - but also, the mitigation measures to limit the potential of domino effects due to the potential hazards from other fuels within the multifuel refuelling station. In this preliminary risk assessment, Hazards Identification (HAZID) for hydrogen was implemented following the three steps below:

- the description of typical HRSs,
- the characterization of the potential hazards (substance, process...),
- and a previous H_2 facility incident review to formulate lessons learned.

This example preliminary risk assessment illustrates how potential major accident scenarios were identified, and presents proposed prevention or protection measures in order to reduce the occurrence of these scenarios and mitigate the escalation of hazardous events". In addition, some prevention and protection measures were recommended when it was not possible to determine if they were universally implemented in Hydrogen Refuelling Stations. Finally, knowledge gaps for the determination of Hazardous Area Classifications, likelihood of hydrogen leaks and extent of consequences were highlighted, in order to be analysed and investigated experimentally within future steps of the MultHyFuel Project [1].

Paper Received: 30 November 2021; Revised: 14 March 2022; Accepted: 2 May 2022
Please cite this article as: Pique S., Quesnel S., Weinberger B., Nouvelot Q., Houssin D., Vyazmina E., Torrado D., Saw J.-L., 2022, Preliminary risk assessment of hydrogen refuelling stations in a multifuel context, Chemical Engineering Transactions, 90, 229-234 DOI:10.3303/CET2290039

1. Introduction

The MultHyFuel Project [1], funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), aims to achieve the effective and safe deployment of hydrogen as a net-zero alternative fuel, by developing a common strategy for implementing Hydrogen Refuelling Stations (HRS) in multifuel context. The project contributes 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 to the project progress.
In order to achieve these objectives, this project will develop good practice guidelines that can be used as the basis of a common approach to risk assessment for addressing the safe design of HRS in a multifuel context. Different configurations are defined in order to assess the risks in the vicinity of different conventional fuels and for various supply chains options for hydrogen.
Using relevant risk assessment techniques, combined with the data from experimental programs provided by the project, risks will be assessed, considering the additional control/mitigation methods that could be expected to be used in hydrogen dispensers. This project will investigate whether any of these measures should be recommended, and if any of the measures should have priority compared to the others.
One of the first steps of the project is to achieve a preliminary risk assessment on HRS for three different configurations in order to have an appreciation of the main major hazard scenarios implemented in a more conventional multifuel station considering the whole of alternative fuels and energies for light and heavy duty vehicles (LDV, HDV).

2. Methodology

Firstly, a benchmarking of risk assessment methods and tools for hydrogen applications, allowed selecting the HAZID (Hazard identification) as the approach to achieve a preliminary risk assessment of hydrogen dispensers in a multifuel environment. Simultaneously, a state-of-the-art review of the technologies on fuel stations was conducted in order to define the most representative configurations for the project.
The following steps were followed in order to achieve the preliminary risk assessment:

- definition of methodology to conduct the risk assessment, including the definition of risk matrix and categories for likelihood and consequences,
- characterization of the potential hazards from materials (H_2, gasoline, natural gas, LNG, LPG…) and process related,
- analysis of the lessons learned from past accidents on H_2 and conventional fuel stations available in open-access databases,
- HAZID workshops for critical discussions of the three configurations,
- results of the HAZID (the identified hazards, the potential safety critical scenarios and the recommendations on mitigation measures to improve the safety of hydrogen refuelling stations.

A statistical analysis was conducted with hazards identified from lessons learned to find out:

- which piece of equipment is most frequently mentioned for major hazards or highest risk ranked scenarios,
- what would be the main causes and consequences of accidents in conventional filling stations.

The HAZID method was achieved through working groups and applied on the three configurations presented in the next section.

3. Presentation of configuration studied

The MultHyFuel Project studied three different configurations, see for more details [2] :

- the first configuration, called “Ready-to-deploy multifuel station” aims to provide hydrogen for vehicles with hydrogen supplied - gaseous - by trailers or bundles,
- the second configuration, called “On-site H_2” aims to provide hydrogen for vehicles with an on-site gaseous hydrogen production by electrolysis,
- the last configuration, called “High capacity multifuel refuelling station” aims to provide a large amount of hydrogen supplied by stationary liquid hydrogen storage.

The main equipment on each configuration are summed up in the table hereafter.

Table 1: Main equipment on each configuration

	Hydrogen supply				Process steps				Refuelling	
	Trailers	Bundle	PEM Electrolyser	Stationary liquid storage	Cryopump	Vaporizer	Compressor	Buffer storage	Heat exchanger or Cooling system	Dispenser
Config. 1	X	X					X	X	X	X
Config. 2	X		X				X	X	X	X
Config. 3*				X	X	X	X	X	X	X

* The production, liquefaction and delivery process have not been included in configuration 3. Liquid hydrogen stored in a stationary vessel was considered, refilled by a liquid hydrogen trailer by bunkering

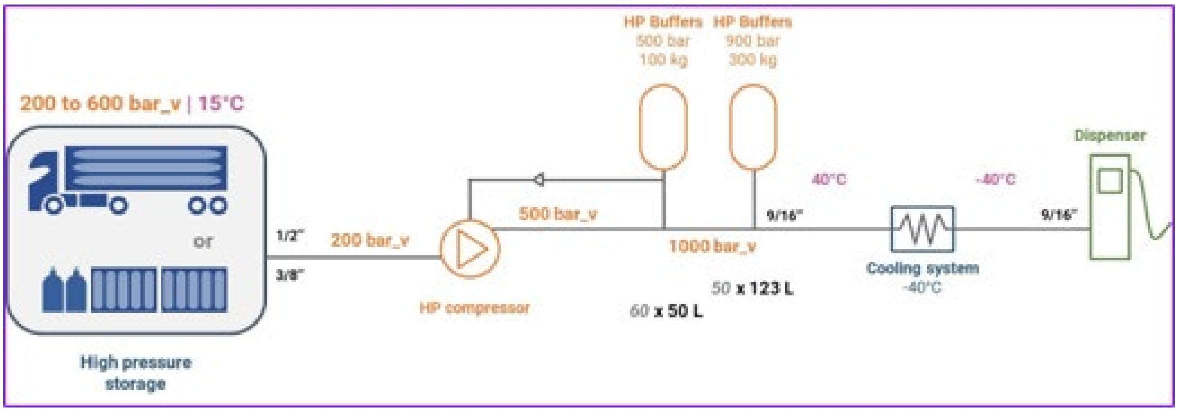

Figure 1: Example of the studied configuration (configuration 1)

5. Potential hazards

The main hazard potentials are linked to:

- the substances:
  hydrogen, oxygen, the other fuels (gasoline, LPG, CNG…) on refuelling stations or the other substances present in the installations, such as catalysts or zeolites for the purification of H_2 after electrolysis, oil in compressors or coolant in the exchanger;
- the process and equipment summarised in Table 1.

An analysis of these elements highlights the following potential hazards on hydrogen equipment:

Table 2: Potential hazards by equipment

	Hydrogen supply				Process steps				Refuelling	
	Trailers	Bundle	PEM Electrolyser	Stationary liquid storage	Cryopump	Vaporizer	Compressor	Buffer storage	Heat exchanger or cooling system	Dispenser
Explosive Atmosphere (ATEX) formation inside equipment			X	X	X	X	X	X	X	X
Loss of containment	X	X	X	X	X	X	X	X	X	X
Release at vent line or TPRD	X	X	X	X	X	X	X	X		X
Equipment burst	X	X	X	X	X	X	X	X		X

6. Lessons learned on hydrogen refuelling station and related equipment

6.1 Hydrogen refuelling stations

Data on hazardous scenarios have been collected from different sources [3] [4] , enabling a statistical review of the lessons learned for the HRS. The purpose of the statistical analysis was to know which equipment is the most frequently involved in accidents and what would be the main causes and consequences.
Hence, thanks to the analysis, we observed that pipework and valves, dispensers and filling hoses, compressors, and tube trailers are the types of equipment that are the most commonly involved in hydrogen accidents. Electrolysers can also generate specific scenarios such as internal explosion according to the few lessons on this equipment [4].
These accidents are most frequently caused by equipment or component failures related to human error (e.g. design flaw or manufacturing error, lack of process control, or maintenance error). Finally, hydrogen accidents do not always involve ignition, but if these leaks get ignited, explosions or fires can occur.
Finally, some recommendations on safety measures are provided by the EHSP report [5]. For example, it is recommended to have periodic training of personnel, leak detection, adequate Explosive Atmosphere (ATEX) zoning and to keep the equipment and systems up to date and clean with appropriate inspection and maintenance.

6.2 Conventional refuelling stations

Data collected from [3] enabled to set up a statistical analysis on the lessons learned for gasoline, diesel and LPG refuelling stations. Additional potential critical scenarios for LNG and CNG refuelling were identified from HAZOP studies held by MultHyFuel partners on such stations.
We observed that irrespective of the fuel types in a conventional fuel station, the storage would be the piece of equipment that would be involved in most of the accidents especially due to the filling operations. Nevertheless, these conventional fuel storages such as gasoline are usually underground thus it limits the impact or domino effects between the fuel storages.
In addition, equipment failure would be the cause of accidents that is mentioned the most frequently for all the mentioned fuels in a conventional filling station. Other causes such as external aggressions and operating errors would also be the sources of an accident. Besides these, maintenance and supply operations also appear as common causes of the analysed accidents, and hence it is recommended that operators pay a careful attention to them. Finally, some recommendations on safety barriers are given in ARIA's report regarding accidentology on filling stations from 1958 to 2007 [3]. For example, it is recommended to install leak detection systems and appropriate means of containment in case of discharge.

7. Results of HAZID

HAZIDs were conducted for each of the three configurations. The results are presented in the following sections by describing potential causes, dangerous phenomena and identifying safety barriers.

7.1 Causes

The main root causes identified from the HAZIDs are summarized below:

- equipment and/or instrumentation failure (erosion, corrosion, metal embrittlement due to hydrogen, welding failure, cycle fatigue, vibrations),
- human error due to maintenance (check not done, parts missing, inadequate sealing, non-compliance of screwing procedures...),
- domino effects due to overpressure (projection, for example) or fire due to other fuels,
- blockage of discharge lines, downstream valve or vent,
- impact like crash, dropped objects,
- back flow between equipment with different pressures,
- presence of air in equipment during transient phases (start/stop) that can lead to Explosive Atmosphere (ATEX) scenarios,
- natural hazards,
- malicious acts.

7.2 Dangerous Phenomena

The main Dangerous Phenomena (DPh) were identified and listed by equipment hereafter for each configuration.

Table 3: Dangerous phenomena identified for each hydrogen refuelling station configuration

Dangerous phenomena	Configuration #1	Configuration #2	Configuration #3
Jet fire	X	X	X
Flash fire	X	X	X
Vapour Cloud Explosion (VCE)	X	X	X
Unconfined Vapour Cloud Explosion (UVCE)	X	X	X
Burst (e.g. physical explosion inside the equipment or overpressure or thermal aggression)	X	X	X
Asphyxiation (no ignition)	X	X	X
Cryogenic risks			X
Liquid H_2 pool fire			X
Whipping of hose	X	X	X
Unexpected fire due to over oxygenation		X	

7.3 Recommendations

Many recommendations were identified during the HAZIDs and the main topics are detailed below with some examples of prevention and protection barriers.

Table 4: Examples of recommendations listed during the HAZID sessions

Topics	**Examples of recommendations**
Design of the refuelling station	- Design of canopy roof to limit degree of confinement - Prefer storage with open structure on the top, or placed underground
Management of refuelling station	- Avoid unloading during thunderstorms / inclement weather conditions
Detection systems to implement	- H_2 flame and gas detection with associated emergency protocols (e.g. alarms, shutdown…)
Importance of isolation device	- Shut-off valves to isolate equipment in case of burst or dysfunction
Choice of materials	- H_2 compatible materials (e.g. for fittings, pipings, seals…) - Asphalt is prohibited to avoid air (O_2) condensation increasing combustible reactivity in case of ignition of LH_2
Location of equipment to limit domino effect	- Safe location of outlet of vent lines - Location of venting of TPRD to avoid impact on other installations
Consideration of natural hazards specific to each site	- Consider the specificities of the natural hazards (i.e. snow, rain, wind/tornado, seismic area, seaside environment) of the site
Periodic control	- Commissioning and periodic control for the integrity of H_2 equipment on the whole HRS (i.e hoses, liquid tank or tube trailer, dispenser, piping, buffer storage)
Addition of prevention and/or mitigation barriers	- Flowrate restriction orifices, break-aways, quick couplings, pressure safety valves, bursting discs, explosion panels, concentration sensors, pressure and temperature sensors, flow meter
Key parameters to monitor and control	- Temperature and pressure of the type-III and IV cylinders should be considered in the transfer protocol from compressor/buffer to fuel cell vehicle - Vibration alarm on compressor with emergency shutdown
Management of ignition sources	- Comply with Hazardous Area Classification - Explosive Atmosphere (ATEX)-certified devices

8. Conclusion

The MultHyFuel Project aims to achieve the effective and safe deployment of hydrogen as a net-zero alternative fuel, by developing a common strategy for implementing Hydrogen Refuelling Stations (HRS) in a multifuel environment. In this framework, a HAZID study has been conducted for three HRS configurations supplied by gaseous or liquid hydrogen.

This analysis benefited from a review of lessons learned from different accidents records for HRS and conventional filling stations. As a result, major hazard scenarios as well as a list of preventative, control or protective barriers against these scenarios were identified for HRS intended to be integrated with conventional and alternative energies filling stations.

8.1 Highlights of the risk analysis

During the HAZID sessions of configurations #1, #2 and #3, the following Dangerous Phenomena (DPh) were identified: jet fire, Flash fire, Vapour Cloud Explosion (VCE), Unconfined Vapour Cloud Explosion (UVCE), Burst (e.g. physical explosion due to overpressure), Asphyxiation (no ignition) and Other DPh (i.e. whipping of hose, cryogenic risks, unexpected fires due to oxygen enrichment…).
The HAZIDs have led to the formulation of a list of 258 DPh to be studied in a dedicated and upcoming Task of the MultHyFuel Project entitled 'detailed risk assessment'. In addition, a list of preliminary recommendations of safety barriers for the prevention and mitigation of these DPh have been identified. These recommendations are set to be input into several tasks of the project and will be checked on for completeness and practicability in the final stages of the project. The following points of the recommendations are highlighted:

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

8.2 Next steps

The 258 DPh identified during the preliminary risk assessment need to be studied in detail in the next tasks within the MultHyFuel project in order to:

- evaluate the severity by consequence modelling and estimate the likelihood - when possible - of these scenarios (MultHyFuel "Detailed risk assessment" Task),
- identify which scenarios and related safety barriers are critical (MultHyFuel "Identification of critical scenarios" Task) and require experimental tests (MultHyFuel "Experimentation" Work Package),
- study the potential domino effects on the dispensers.

Based on these upcoming assessments and experimental programs, the MultHyFuel Project will develop good practice guidelines that will be easily understandable and can be used as a common approach to risk assessment for addressing the safe design of HRS in order to support the deployment - in suburban and urban areas, for light and heavy-duty vehicles - of numerous multifuel stations offering conventional and alternative energies to gradually move towards a net-zero mobility.

Acknowledgments

This work has been achieved in the framework of a project which has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under Grant Agreement ID: 101006794. We thank all partners of the MultHyFuel project (https://multhyfuel.eu/) for their contribution to this work, namely: Air Liquide, ENGIE, HSE, Hydrogen Europe, INERIS, ITM, KIWA, Shell, SNAM, and ZSW.

References

ARIA (Analyse, Recherche et Information sur les Accidents), database on accidents : https://www.aria.developpement-durable.gouv.fr/

EHSP, Statistics, lessons learnt and recommendations from the analysis of HIAD 2.0 database, 2020

Houssin D., E. Vyazmina, S. Quesnel, Q. Nouvelot, J. L. Saw, S. Pique, N. Hart, S. Montel, M. Robino, M. Jenne, State of the Art on hydrogen technologies and infrastructures regarding a multi-fuel station environment, Deliverable 3.1, FCH JU funded project MultHyFuel, 2021.

Gentilhomme O., B. Weinberger, L. Joubert. Etude de sécurité d'une station de distribution d'hydrogène gazeux. 22. Congrès de Maîtrise des Risques et Sûreté de Fonctionnement (Lambda-Mu 22), Oct 2020,. pp.45-50. ineris-03319945

Multhyfuel project : https://multhyfuel.eu/