

**Development of H₂ Safety Expert Groups and due diligence tools for
public awareness and trust in hydrogen technologies and
applications**



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State of play H₂ issues

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List of Abbreviations

AIRP	Air Products PLC
ASME	American Society of Mechanical Engineers
ATEX	EXplosive ATmosphere
CAPEX	Capital Expenditure
CCHP	Combined Cooling Heating and Power
CFD	Computational Fluid Dynamics
CHP	Combined Heating and Power
CM	Sociedad Española de Carburos Metálicos S.A. (Air Products Group)
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CSA	Canadian Standard Association
CTECH	Ciaotech S.R.L.
DDT	Deflagration to Detonation Transition
EIGA IGC	European Industrial Gases Association - Industrial Gases Council
EU	European Union
FAST/EHA	European Hydrogen Association- Federazione delle Associazioni Scientifiche e Tecniche
FC	Fuel Cell
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FCV	Fuel Cell Vehicle
GH ₂	Gaseous Hydrogen
H ₂	Hydrogen
HAZOP	HAZard and OPerability
HIAD	Hydrogen Incident and Accident Database

HP	High Pressure
HPGH ₂	High Pressure Gaseous Hydrogen
HRS	Hydrogen Refueling Station
HSE	Health Safety and Environment
HT-PEM	High Temperature Polymer Electrolyte Membrane
HTS	High Temperature shift converter
HyCO	Hydrogen plant where carbon monoxide is captured
IRR	Internal Rate of Return
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
JARI	Japan Automobile Research Institute
K	Kelvin degree
LEL	Lower Explosive Limit
LFL	Lower Flammability Limit
LH ₂	Liquid Hydrogen
LNG	Liquid Natural Gas
LP	Low Pressure
LPG	Liquefied Petroleum Gas
LT-PEM	Low Temperature Polymer Electrolyte Membrane
MATGAS	MATGAS 2000 AIE
MCFC	Molten Carbonate Fuel Cell
MCPHY	McPhy Energy S.A.
N ₂	Nitrogen
NFPA	National Fire Protection Association
NG	Natural Gas
NRV	Non Return Valve
O ₂	Oxygen

OPEX	Operational Expenditure
PED	Pressure Equipment Directive
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PFD	Process Flow Diagram
POLIMI	Politecnico di Milano
PRD	Pressure Release Device
PRV	Pressure Release Valve
PSA	Pressure Swing Adsorption
PSM	Process Safety Management
RCS	Regulations, Codes and Standards
SAE	Society of Automotive Engineers
SCC	Stress Corrosion Cracking
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel cell
SOL	Sol S.P.A.
SPPI	Solvay Specialty Polimer Italy S.P.A.
TPED	Transportable Pressure Equipment Directive
TU/e	Technische Universiteit Eindhoven
TRD	Temperature Release Device
UPS	Uninterruptible Power Supply
US	United States (of America)
UV	Ultraviolet
WP	Work Package

Executive summary

This document corresponds to the deliverable D3.1 of H2TRUST project, which is the outcome of the activities carried out in Work Package 3 (WP3).

The objectives of WP3 are:

- Conduct comprehensive and detailed data gathering exercises aimed at of hazard and risk assessment in the FCH industry in each of the main application areas (H₂ Production, Storage and Distribution, Mobility and Vehicles, Non-vehicles and Residential Power Generation)
- Collect information from the regulatory and safety stakeholders, consumers and incident response bodies associated with FCH industries
- Collate and package the information structured and accessible format for the risk analysis and recommendations phase
- Seek input from previous, on-going and upcoming FCH JU demonstrations and pre-normative and training projects and from similar international activities

The document is divided in five chapters, one for each of the main application areas or task. Each chapter gives general information on technology applied in the specific field of application and reports the main results coming from data gathering activity carried out in Work Package 3.

There are some differences between the tasks but in general there are information coming from interviews and/or questionnaires, with opinions on hydrogen technologies and their potentials, limitations and public perceptions, and information coming from documents reviews, with more technical data associated to technologies and related risks. An important part of each chapter is dedicated to the case studies, where real examples of applications of hydrogen technologies are reported, with an analysis mainly focused on the safety aspects. There are positive cases, or best practice, illustrating applications where no accidents occurred and negative cases, or worse practice, where an accident occurred and the causes are analyzed to better understand the risk associated to the use of hydrogen.

In each of the above mentioned chapters there are information on related technologies, main risks and countermeasures, public perception, limiting factors seen for technology market introduction and so on. Some observations and consideration are anyway quite common for

all the application areas. Trying to summarize the main outcomes of this work we can say that in general the safety issues related to hydrogen utilization are considered important, or even fundamental, but they are not seen as the limiting factors for the diffusion of the technology. From our analysis we have noticed that it is not easy to find cases of worse practice where a serious accident occurred because hydrogen was used in a process or application. Often an accident similar to what described could have happened also in case of use of methane or another compressed gas. Very often the level of risk associated to hydrogen is considered similar to that of other fuels like gasoline or natural gas.

We have to say anyway that most of the cases analyzed are applications in well controlled areas and involving well trained people. A different situation could be present in case of spread of technology to a large and domestic public, where not trained people could make risky mistakes in handling hydrogen.

From this last statement derives the important point of an appropriate formation and training in case of diffusion of new and risky technologies. Formation through seminars, courses, school lessons, is considered important not only to train people to reduce the risk of hydrogen mishandling but also to improve the acceptance of hydrogen introduction in everyday life. People in general seem ready to use new technologies but hydrogen sometime is still connected to fire and explosion, often without a rational explanation. Explaining and showing differences and similarities with other fuels can increase the level of hydrogen acceptance.

To improve the awareness of hydrogen technologies and their potential, in addition to dissemination of information also a higher number of demonstration projects would be needed, projects focused on applications and also specifically on safety, like fire or crash tests.

In general the stakeholders, especially the industries, do not see the safety aspects related to hydrogen as a limiting factor for market introduction. In case of spread of the technology a critical point could be the leakage of hydrogen in closed environments, like in a home garage for a fuel cell vehicle.

The industry is facing mainly other problems like the still high cost of the technology, the lack of infrastructure, like and hydrogen grid, and especially a lack of a common and simple legislation. Very often now the safety rules for new type of installations are not clear or it is not clear who is the responsible for giving the permissions. There are also different rules inside the EU countries and this is an additional obstacle. It is also important that the safety

codes are well defined and balanced, without introducing an excess of safety measures, to avoid a not needed increase of costs and also to avoid a not justified alarm in the public perception.

Deliverable No. 3.1

Introduction

The main objectives of H₂TRUST project is the analysis and review of hydrogen technologies in the main applications areas with a specific attention on risk and safety aspects, disseminate the results and make recommendations for further safety efforts by FCH community. The Work Package 3 “Data Gathering and Mirror Groups” (WP3) is the part of project activities mainly dedicated to the collection of information and data for each application areas.

The WP3 activities are organized and divided in the following five tasks, each one dedicated to a specific field of application:

- *Task 3.1. Collect H₂ Production Safety Data:* addressed to safety issues and measures in the process of steam methane reforming (and CO₂ sequestration) and other fossil based processes (partial oxidation, plasma reforming, coal) for hydrogen production, as well as water based techniques of electrolysis, thermolysis, photocatalytic water splitting, sulfur-iodine cycle and biohydrogen.
- *Task 3.2 Collect Safety Data on Storage and Distribution:* focused on safety issues and measures in storage modes of (i) high pressure gas cylinders (up to 800 bar), (ii) liquid hydrogen in cryogenic tanks (at 21 K), (iii) absorbed hydrogen in materials with a large specific surface area (at T < 100 K), (iv) absorbed hydrogen on interstitial sites in a host metal (at ambient pressure and temperature), (v) chemically bonded in covalent and ionic compounds (at ambient pressure), and oxidation of reactive metals (e.g. Li, Na, Mg, Al, Zn) with water. Special emphasis on prevention of pressure built-up in the cylinder by external factors (Thermal protection and relief devices) has been considered.
- *Task 3.3 Collect Safety Data relating to Mobility and Vehicles:* focused on safety issues around the area of private, commercial and heavy transport powered by FCH and gather the corresponding safety issues and measures. The study includes cars, buses, forklift trucks, motorbikes and bicycles, aircraft, boats and submarines with a focus on the vehicles with most potential for early and widespread use such as fleet buses and passenger vehicles.
- *Task 3.4 Collect Safety Data relating to non-vehicles and residential power generation:* FCH applications for non-vehicle application especially on decentralized power-generation and remote back-up power systems, as a stationary storage mechanism for renewable energy and as part of smart grid systems has been taken into account.

- *Task 3.5 Collect Safety Information on Regulators, 1st Responders, Consumers:* focused on establishing the state of the art as far as regulation, environmental protection, certification, incident handling and consumer perceptions.

The approach and the methodology applied in WP3 for collecting data is based on indications that came out from the activities of Work Package 2 “Develop Analytical Framework”, and that are reported in deliverable D2.4 entitled “Mirror groups organisation chart and data gathering procedures”.

First of all for each of the main application areas mentioned above (corresponding to the different tasks), one mirror group was created. Each mirror group is formed by H2TRUST partners and relevant stakeholders and is specifically dedicated to the analysis of technologies and related safety aspects of one application area. The leader of the mirror group is one of the H2TRUST partners, selected taking into account their expertise:

Area	Leader	With the support of:
H ₂ Production	Carbueros Metálicos (CM)	Technische University of Eindhoven (TU/e)
Storage and Distribution	McPhy Energy (MCPHY)	Politecnico di Milano (POLIMI)
Mobility and Vehicles	Solvay Specialty Polymers Italy (SPPI)	Politecnico di Milano (POLIMI)
Non-vehicles and residential power generation	SOL	Politecnico di Milano (POLIMI)
Regulators, 1 st Responders, Consumers	European Hydrogen Association- Federazione delle Associazioni Scientifiche e Tecniche (FAST/EHA)	-

The mirror groups mainly supported the collection of safety data in WP3 but started also putting the basis for mapping, assessment and recommendations to be done in WP4.

In WP2 was defined not only the organization in mirror groups but also the tools to be used for collecting data. These tools were organised in six typologies:

1. **Questionnaires, surveys, checklists**, i.e. collection of information from all hydrogen sector stakeholders
2. **Interviews** with selected actors who are very relevant for the hydrogen and fuel cells sectors.
3. **Document review**, i.e. literature study (papers, technical magazines, other, etc..),
4. **Observation**, i.e. gathering and tracking of hydrogen related information (e.g. activities, events, news).
5. **Focus groups**, i.e. gathering of information from members, gauging of public perception.
6. **Case studies**, i.e. analysis of single individual groups.

Although different data gathering procedures have been defined, the questionnaire was considered the main tool to collect data and information from the relevant stakeholders in order to analyze in depth the influence of the actors on the hydrogen safety, their attitude and interest towards the project activities. The questionnaire has been carried on using a web-tool created by SOL partner to facilitate the data collection. The questions were prepared in WP2 and reported in deliverable D2.4. They have been elaborated in three sections:

1. Main questions for all stakeholders, to get as much information as possible about the market, barriers, safety perception and solutions related to the Hydrogen industry.
2. Specific questions on safety and hydrogen technologies, according to the stakeholders' groups and subgroups.
3. Supplementary questions: questions beyond the scope of the safety assessment, in particular regarding: suggested actors and stakeholders for the data collection campaign, lack of funding, communication and knowledge issues, transfer of scientific results.

The questionnaires were sent to the relevant stakeholders included in the list prepared in deliverable D2.4 and enlarged in WP3, which included almost 300 contacts.

The activity did not proceed as planned since the answers received were less than expected and with incomplete data, making difficult their exhaustive analysis. The stakeholders showed a low level of responsiveness, less than expected during the definition of the survey.

Several stakeholders were contacted by telephone in order to find out the reasons behind the lack of participation and to encourage the response. The main problem seemed related to the quality or type of questions; the questionnaire was too general and open and answering all the questions required a too high effort. By this point of view, the suggestion for future development of this kind of activity of data collection is to prepare a multiple-choice questionnaire and to minimize as much as possible the use of the open questions, so that the relevant stakeholders can find easy to answer all the questions.

The questionnaire was instead too demanding in term of time required for its completion and probably was not considered worthwhile by most stakeholders. However, encouraged also by telephone and further email contacts, some of them finally completed the questionnaire, at least partially. Some others preferred to limit their contribution to informal comments during telephone or personal interviews, as evidenced in the chapters of this report.

The interviews gave a more positive response from the people contacted in comparison with the written questionnaire. It is easy in general to discuss face to face or by telephone on the topics selected for the survey because the questions can be better explained and because the discussion can also adjusted on topics that result more interesting for the interviewed person. The outcomes of interviews are reported either specifically or as collective comment in the several chapters of the report, depending on the possibility to appear explicitly of different stakeholders and/or companies involved.

An important part of data collection was represented by the document reviews. As already said it has been difficult to gather an amount of information through the survey to make a good analysis of the safety status for different hydrogen technologies and the literature and document review revealed to be an important alternative for that scope. Papers, project reports, websites and other sources have been studied to find different type of information, like hydrogen properties, hazards associated to hydrogen, possible accidents for several areas of applications, risk analysis, countermeasures for risk reduction and so on.

The literature search has been also a good instrument to find and select some case studies that have been more carefully analyzed. A case study represents a practical experience of

hydrogen production, storage, transportation or final use, where specific safety-related issues have been faced and discussed. For each main application area about 4-5 case studies are presented and analyzed. The scope of this tool of data gathering was to show examples of best practice or worse practice in the framework of fuel cell and hydrogen technologies. Best practices are mainly example of installations and/or operations where hydrogen is safely handled without serious incidents. For example data of operation of a fleet of hydrogen buses are reported, showing hours or driven kilometers without accidents. Worse practices, on the other side, are cases where an accident occurred and the analysis tries to evidence what was the main cause in order to avoid similar mistakes in the future.

Not all the case studies come from literature and some of them derive from a direct analysis of real example done contacting the involved entity or company. The case studies are reported either anonymously or explicitly according to the source and to the frequent limitation to the disclosing of proprietary or private information.

The leader of each mirror group organized the information gathered during WP3 in a single document, forming one chapter of the final report. All chapters are presented in this deliverable.

This document (D3.1) comprises 5 chapters, one for each of the areas outlined above:

- Chapter 1: State of Play Safety and H₂ Production.
- Chapter 2: State of Play Safety and Storage and Distribution
- Chapter 3: State of Play Safety and Mobility and Vehicles
- Chapter 4: State of Play Safety and Non-vehicles and residential power generation
- Chapter 5: State of Play Safety and Regulators, 1st Responders, Consumers

Deliverable No. 3.1

Chapter 1

H₂ Production

1.1 Introduction

According to the tools defined in the deliverable D2.4 to be used for collecting data, the mirror group focused on identifying the H₂ Production safety matters organized the collected data in two main groups:

- Data from stakeholders, through the Questionnaires and Interviews.
- Data gathered from Document Review, Observation and Case Studies.

The first group of data was obtained from the survey and several interviews, regarding expectations, needs and issues related to the safety of hydrogen production processes.

The questionnaire was divided in three sections:

1. Main questions.
2. Specific questions.
3. Supplementary questions.

The first and third sections were common to all mirror groups; the specific questions were adapted to the five main application areas of safety matters:

1. Hydrogen production.
2. Storage and Distribution.
3. Mobility and vehicles.
4. Non-vehicles and residential power generation.
5. Regulations, codes and standards.

The respondents to the questionnaire had the possibility to choose one or more groups, according to their interests, using the online tool developed for this purpose. The interviews were focused on production safety matters. The interviews were performed face to face, taking the questionnaire as a guideline. Therefore **the opinions of the interviewees have been analyzed together with the answers to the questionnaire.**

The survey was conducted to the relevant stakeholders identified in the deliverable D2.4. In the course of the H2TRUST project, additional stakeholders were incorporated to the initial list. However **respondent's profile was mainly from the research sector, although also some industry stakeholders participated.**

It was intended to treat the questionnaires with anonymity and confidentiality. But in the end it was given the stakeholders the opportunity to disclose their anonymity and be cited as

contributors to the H2TRUST project. The list of entities that accepted to be cited and completed the questionnaire is enclosed at the end of the deliverable.

The second group of data, gathered from Document Review, Observation and Case Studies, was mainly collected from the online databases Hydrogen Incident and Accident Database (HIAD) [1] and www.h2incidents.org [2], also from partner internal resources, covering previous and ongoing FCH JU and similar international demonstrations, and industrial hydrogen production activities.

It was intended to address safety issues and measures primarily in two hydrogen production processes:

- steam reforming of natural gas, and
- alkaline electrolysis of water.

Both are mature hydrogen production technologies. In the context of the so-called hydrogen economy, the first one tends to be considered a transitional technology for his use of a fossil feedstock, whereas the second one can be a source of sustainable hydrogen for the future. In essence, both will have an important impact on public awareness and trust in hydrogen technologies and applications in the coming decades. To this end, a comprehensive data gathering exercise has been performed aimed at the hazard and risk assessment in the hydrogen production area.

This section is conceived as a continuation of the corresponding chapters in the deliverable D2.2 *Reference benchmark for H₂ production–storage–distribution technologies*, where the main hydrogen production technologies were described by means of a conceptual plant configuration, stream operating conditions and a qualitative size evaluation of the main plant components, in order to highlight the inherent technology hazards.

1.2 Questionnaires and Interviews

For each question, answers were grouped in terms of similarity of ideas. A statement resumes the concept, and a selection of the original answers is cited in blue color.

Main questions

1.1. In what sector, or sectors, are you mainly interested in relation to the hydrogen technologies and fuel cells safety matters (H₂ Production, Storage and Distribution, Mobility and Vehicles, Non-vehicles and residential power generation, Regulations, Codes and Standards (RCS)).

Most of the stakeholders were interested in more than one specific group of safety matters. This can be an indication that hydrogen production is not an objective itself but it has to be considered in a broader context including the end use.

With one exception, the respondents only interested in hydrogen production were all researchers.

1.2. Could you provide an estimate of the hydrogen/fuel cells market related to your specific sector in Europe and globally (market share)?

The few answers received to this question were not concordant, which can be an indication that the knowledge about the FC sector is still poor.

Here is a picture of the answers:

The market share of the fuel cells in Europe (mainly Germany) is estimated to be the 25% of the global market (50% Asia, 25% North America the other countries).

In terms of number of units more than 20,000 fuel cells have been shipped globally for stationary applications by all vendors.

Market estimated in 10,000 demonstration units before 2020.

There are many unjustified expectations and some misunderstandings about the possibilities that "H₂ based" vehicles could solve some of the current environmental problems. The dimension of the market, if will ever exists, will be relatively small

since the energy efficiency numbers of the "well to wheel" pathway would not be sustainable with the exception of few specific situations.

Technology is not mature.

Safety is about 10% of the FCH market share.

1.3. Could you provide an estimate of the hydrogen/fuel cells market related to your specific sector in Europe and globally (competitors)?

Maybe the question was not correctly formulated. The entities not commercially active in fuel cell devices did not relate his specific sector to the fuel cells.

The most complete answer is attached below:

The main competitors I know in fuel cell market are: SofcPower (Italy), Electro Power Systems (Italy), FuelCell Energy, Bloom Energy, Hydrogenics, Ballard Power Systems, ITM Power, Giner, Sunfire, Hydrogenics, Versa Power Systems, Kerafol. Their market share depends on the specific application of each technology they produce.

1.4. How do you think the H₂ safety is perceived among your suppliers?

Three groups of answers were received:

- Hydrogen is safe following appropriate measures, in any case it isn't the most dangerous chemical.

Our suppliers are professionals in the field of H₂ gas and equipments, they know that the use of H₂ is safe if the correct equipments and procedure are utilized.

Suppliers consider oxygen and methane more dangerous than hydrogen. They consider hydrogen moderately dangerous.

Hydrogen safety is a relevant aspect but not a critical issue.

It is an internalized issue in their day-to-day business.

My suppliers consider that use of H₂ is a safe activity.

H₂ safety is under control.

- Suppliers follow safety standards.

Not relevant for the suppliers not directly involved with the H₂ component. For the ones involved in the H₂ process, they follow ATEX directive.

They follow safety standards.

Safety is perceived with a high degree of responsibility because our suppliers sell components, equipment, industrial gases, etc., that we use in our research facilities that require strict safety standards.

- Somehow over-sizing the safety issue?

Safety is the first priority they have to consider if they want to be our suppliers.

Suppliers perceive it in a primitive way, due to lack of education/training and insufficient investment in hydrogen safety research. Mistakenly hydrogen safety is treated by many not as technological issue but as psychological.

1.5. *How do you think the H₂ safety is perceived among your customer?*

The majority of answers can be summarized as follows:

- Customers understand that hydrogen is safe following adequate measures. The understanding comes after the pertinent explanations from the supplier and/or on the assumption that the supplier has taken measures to handle hydrogen installations safely.

Our main customer sees hydrogen as a utility, without further safety considerations.

My customers understand that H₂ can be managed in a safe way.

They rely on our professionalism.

Customer feels confident. They are engineer and safety aspects are well understood and shared with them.

(Better end-user than customer) No relevant fears; only reasonable questions in the confidence that someone is taking care.

With doubts, but after explanation positive.

Other opinions were:

- The perception of lack of safety resulting in over-sizing the safety measures

It's a worry for the customer: they will ask us, the local authorities and the notifying body. If all agree, no problem; if there is a discrepancy (usually related to not

understanding the H₂ process), the consequence will be that the distances to the H₂ source will be increased.

- The attempts to convince that it is safe are not truly successful.

Customers are still afraid of hydrogen, as there is no program to demonstrate safety by experiments and videos. Instead attempts to push 'safety' by repetition of words 'it is safe' continue.

- Safety is perceived with enormous interest, it's a high priority, very relevant issue.

1.6. *How do you think the H₂ safety is perceived among your own workers?*

The main finding from the answers was:

- Workers are trained on the particularities of hydrogen handling, they are professionals who follow the recommendations to prevent incidents. Training is repeated periodically in order not becoming confident with repetitive tasks.

The workers in our facilities are aware of the risks of handling H₂, they are trained for a safe use of H₂ and related equipments, thus they handle them in a professional way. Some workers that have been working with H₂ for a long time tend to underestimate the risk of handling H₂ and to ignore some safety rules, so it is necessary to frequently renew the safety training to maintain the sufficient level of professionalism in the use of H₂ among workers.

Safety is the most important matter. Workers are trained to take the appropriate safety measures when handling hydrogen. The training is refreshed periodically, in order not becoming confident with repetitive tasks.

They are aware of the safety procedures and these are followed.

All researchers involved adhere to guidelines set by NFPA (50A, 55), EIGA IGC 15/06/E, PED and specific risk assessment and HAZOP studies based on application.

Our workers are scientists that know well the importance of safety.

Safety of gases is important. The way to treat them varies from one gas to another; H₂ needs different, specific treatment, compared with N₂ or NG.

Great respect and awareness.

As a very relevant issue. They always take care of this, specially when high pressure hydrogen is used.

It is not more dangerous or safe (than other chemicals). It is different and should be dealt with professionally.

Hydrogen is moderately dangerous.

H₂ safety under control.

- To avoid problems related to the technology rejection, it is recommended to explain the project to the workers unions.

No relevant problems have been observed, but a previous approach with the workers unions seems always advisable (we did so).

1.7. How do you think the H₂ safety is perceived among your subcontracted workers, which work in this issue?

The answers to this question were not substantially different from 1.4, 1.5 or 1.6. A majority has the same perception for suppliers, customers, own workers or subcontractors:

- Hydrogen is safe following the appropriate measures and subcontractors are trained periodically in handling it safely.

If they are informed on the safety practices to follow in H₂ facilities and know that the plants are completely safe if all the procedure is respected, they can work perceiving H₂ safety as any other common industrial safety issue.

In terms of safety measures, they receive the same treatment as the own workers. Besides, they are periodically audited on their performance. They perceive safety as the most important matter.

High priority: We pass on them our safety policy.

Subcontractors are equivalent to the own workers in terms of safety measures, despite they are not involved in all production steps.

- Initial perception of either fear or underestimation of its danger, betraying the lack of experience in hydrogen handling, but after a while there is no difference from the own workers.

Short term subcontracted workers have low perception of the hazards related to hydrogen; long term they have a similar perception as the own workers.

Disoriented but confident. Normally they do not really know the object, so they just trust us.

- The potential technology rejection by the workers unions can be avoided with subcontractors.

A subcontractor never rises problems.

1.8. How do you think the H₂ safety is perceived among your neighbour, where are installed your hydrogen facilities?

The answers were polarized in several groups, depending on the neighbour knowledge of the hydrogen activities being carried in the vicinity.

- The neighbour don't know about the hydrogen activities.

People is not aware that hydrogen is already used in an industrial environment. The industrial users understand our explanations. Domestic neighbourhood don't know about what is happening there.

They don't know what it's all about behind the fence.

I don't think that our neighbours know that we use hydrogen. In any case, as my institute is a research facility they will think that the amount of hydrogen used is rather low.

- The neighbour understands the process (after being informed), and feel confident that proper safety measures are taken. However, isolated negative attitudes from only one neighbour can result in serious problems.

Presently our H₂ production plants are located in refinery environments and hence in situations in which there is a clear awareness of the H₂ safety issues.

This is a delicate issue. Neighbourhood appreciates being informed and, if so, there is a general trust on the good practices from our side. However, isolated negative attitudes from only one neighbour can result in serious problems.

The H₂ facilities where I work are inside a public university and are used for research purposes. The neighbours are people that have full knowledge of the risks of handling hydrogen and compressed gases and know that the facilities we use fulfill all the safety requirements. Therefore, they do not have problems to stay many

hours at a day near the facilities and perceive the risk of working near H₂ facilities as completely acceptable.

With some concern although they know that correct preventive actions are taken.

Disoriented but confident. The problem is that there are still too few installation and people do not know the technology.

Our labs are on campus with proper monitoring service

- The neighbour is not afraid about hydrogen because it is not toxic

As hydrogen is not toxic, there is a small concern on safety, compared to other facilities holding toxic products.

- The neighbour is afraid about hydrogen, due to the lack or wrong information.

Zeppelin incidents (Hindenburg) are in the mind of older generations, maybe not in younger ones.

Hydrogen safety is perceived as a critical issue.

Specific questions on hydrogen production

2.1. What sub-category best identifies your interests? i) Steam methane reforming and CO₂ sequestration; ii) Fossil based processes like partial oxidation, plasma reforming, coal; iii) Water based techniques (electrolysis, thermolysis etc.).

There were double of respondents interested in Steam Methane Reforming and CO₂ sequestration compared to the ones interested in water based techniques. This can be due to the small sample of respondents more than a real market tendency interest. To highlight however that only two stakeholders were interested in fossil based processes and his interest wasn't the only interest but shared with SMR or water based techniques.

2.2. What are the decision making criteria within your organisation when introducing new processes, products or services related to hydrogen production?

First decision making criteria is shared equally between safety and economics, then some other reason is mentioned.

- Safety.

The process is only considered if it can be done in a safe manner; then other factors are taken into account as economics.

Safety first, then productivity.

Evaluate if there is a market for onsite H₂ production and then if the equipment can be built in a safe way.

The approval of local authorities is required.

- Economical criteria.

Needs of the business, IRR, OPEX, maturity of technology.

Cost / benefit.

Efficiency, capital costs, production costs, safety, market opportunities.

It depends on the research funds available.

- Others.

Lower energy consumption.

Ease of implementation, environmental impact.

Innovation.

Collegiate of professionals if available.

2.3. What order of importance does your company give to the following hazards?

Unimportant = 1; Very Important = 5; Do not know = 0

Hazards related to hydrogen	% of 1	% of 2	% of 3	% of 4	% of 5	% of 0
<i>Ignition when mixed with oxygen</i>		5		5	90	
<i>Propensity to leak and flow</i>		5	10.5	10.5	74	
<i>Ability to embrittle certain materials</i>	10	16	32	10	32	
<i>Invisible flame</i>		16	16	31	37	
<i>Very cold in liquid form (-253°C)</i>	37	10.5	10.5		26	16
<i>Highly pressurised (70 Mpa)</i>	21	5.3	5.3	10.5	52.6	5.3
<i>Asphyxiant</i>	21	26.3	5.2	16	26.3	5.2
<i>Hazards linked to H₂ colourless/ odourless nature</i>	16	10.5	26	10.5	32	5

The hazard of hydrogen to ignite is by far the most important one, followed by its propensity to leak, and the risk associated to store it at high pressures. The risk related to the HP is mentioned by some stakeholders interested not only in hydrogen production but also in mobility. It is remarkable the low consideration of the risks associated with handling liquid hydrogen.

2.4. What risks, hazards related to hydrogen mostly affect your organisation and clients and what are the consequences you face?

Risks that mostly affect organizations are leaks (36%), ignition (25%), explosions (18%), high pressure (7%), ability to embrittle (3.5%), invisible flame (3.5%), asphyxiant (3.5%), colorless/odorless (3.5%), being very cold in liquid form (0%).

To highlight the high level of respondents stating the risk of explosion, a hazard that wasn't purposely named in the above question 2.3. This also means that explosions are always in mind, despite [until today no such events have happened](#), as one stakeholder said. In the same line it also concerns the potential [interruption of the activity and associated loss of revenue after Local Authority notice](#), if there is an incident.

The consequences, i.e. the instruments to address hazards relate almost exclusively to leakages:

The main safety matter is the release of hydrogen in a place where it is not supposed to be. When you expect a leak in an area, you put safety systems there. A leak in this area won't be a problem till there is an accumulation.

Engineered design to prevent the leak to happen. Detection systems in places where it might still leak.

The consequence is the need for premises equipped with venting systems and gas leak detectors and the need for training courses for the operators involved with hydrogen operation. The maintenance of safety systems and the training of the personnel can produce lags in the research activities.

Suitable sensing in the event of leakage, ventilation, lighting, and correct handling of pressurized vessels.

Equipment for hydrogen production has to be specially designed, and its location together with the need to vent the installation doesn't have to cause safety issues to the neighbourhood.

2.5. What are the main barriers to the introduction of new H₂ production plants, in particular considering H₂ safety?

- Most of the respondents mentioned the lack of dedicated RCS as the main barrier:
The lack of regulations or, alternatively, the application of regulations not designed for this purpose to get the new systems approved.

Lack of codes or standards for the H₂ installations in urban areas or inhabited premises. In the absence of standards, the first answer of the authorities is that it is not possible to implement the project. In the end and up to now, industrial RCS have been applied. But to apply industrial regulations for public sites doesn't cover all situations, e.g. noise limitations.

Industrially wise, regulations and good engineering practices are applied. SMRs haven't been installed in a public site yet; as starting point preventing the access from public to the installation will have to be considered.

- Important the lack of a H₂ pipeline network to connect H₂ production centers with customers, whose availability would increase of the road traffic safety.

The main barrier is the missing of regulation for H₂ pipelines in Italy (but also in other countries), so it is a problem to introduce new centralized hydrogen production plants because it is impossible to directly connect hydrogen facilities with users.

There is no hydrogen pipeline in Spain to connect supplier and consumers, as in the US. That would reduce traffic risks.

- Cost, together with some safety concerns, are also seen as main barriers.

Cost and industry defined safety distances adding location restrictions, i.e. the high defined safety distances requiring more space to install a hydrogen production than for other chemicals, creates a concern to potential customers.

Due to the business with high competency in H₂ production and utilization, H₂ safety is not perceived as a barrier; it is most important the operation knowledge and CAPEX barrier.

Possibilities of H₂ accumulation.

High pressure H₂ production.

2.6. Are there any solutions to overcome these barriers?

- Dedicated RCS need to be developed and approved.

To set specific regulations for public H₂ infrastructure.

If safety standards are implemented H₂ is quite safe.

- Increase communication with authorities.

Better understanding from the authorities, to make easier suggesting engineering solutions.

Persuasion actions with the public authorities. Analysis of pilot projects.

Political solutions: the formulation of integrated national and EU energy plans which take into account the hydrogen production and distribution.

- Development and implementation of engineered solutions.

Yes, but at a cost, e.g. safety distances can be reduced increasing cost.

To prevent H₂ accumulations, consider a natural aeration and not a forced one.

R&D of new H₂ production technology.

2.7. What are the main H₂ production safety issues faced by your organisation?

- The top two are hydrogen leaks and the risk to ignite.

Fortunately, no safety problems have occurred until today. Main hazards involve possibility of H₂ leaks and ignition when mixed with O₂.

The risk that leaks generate fires.

None, once addressed the risks related to the ignition, leaks, invisible flame, asphyxiant and colourless/odorless nature of the hydrogen.

- Another safety issue relates specifically to SMR installations and production byproducts.

CO byproduct toxicity, SMR damage, cracking, transport.

- Finally some stakeholders consider that there are no safety issues or even that the safety concern is too much magnified.

At the moment none.

From this question onwards it seems that safety issue is too much magnified. There is no need to create concerns and then to fix them.

2.8. What solutions and measures were adopted by your organisation and how are they effective?

- Most of the measures relate to safety devices.

A devoted building for hydrogen storage was built and an UPS unit was installed to ensure the continuity of power supply to all the equipments, including the ones involved in H₂ safety measurements; both measures were very effective.

Comply with internal safety and national standards. Mitigation of gas leaks – Gas detection, Pressure monitoring, Flame detection, Linear Heat [rise] detection.

Recombination process to limit the probability of occurrence of H₂ and O₂ mixtures well below the flammability limits.

Design of systems with less interconnections as possible. Installation of H₂ detection systems in potential leaking points. The safety system is designed to disconnect the operation when a leak is detected.

Suitable sensing in the event of leakage, ventilation, lighting, and correct handling of pressurized vessels. Effectiveness is checked and maintenance operations are performed regularly.

Pressurised pipes are inspected periodically. The new staff working with H₂ is instructed. H₂ sensors were installed in certain places. The pressure in the gas cylinders is monitored and compared to the registered amount of H₂ spent. We have experimental rigs provided with safety valves connected to a flare.

Laboratories are equipped with an extraction system.

H₂ detectors connected to the H₂ sources that close the relevant valves and shutdown the relevant equipments whenever a leak is detected.

For possible leakage and ignition issues we utilise H₂ detectors whose signals determine automatic Emergency Shut Down procedures of the production plants. The procedures are very effective.

- But not less important, the measures related to personnel.

The BSP mechanism: Basic Safety Process to skill individuals and groups to be alert and to detect situations of risk or risky behaviors; it focus efforts on prevention activities to reduce incidents.

Careful implementation of relevant standards and guidelines as well as personnel training to adhere to these standards.

2.9. What are your needs in relation of the H2 production safety?

A variety of needs was detailed:

We have the need for **continuous maintenance of equipment and safety detectors** and the need for **training the personnel** working with hydrogen and related equipments.

Prescribed safety zones for ATEX areas: for a particular system it is needed to have predefined how big the ATEX area is to avoid flammable atmosphere. Now this is a point of discussion between customer and supplier, because there aren't standards setting it. In the US the NFPA standards define more what it should be done. In Europe each entity has to perform a Risk Assessment of what to do under each circumstance. Besides ATEX areas have no correlation with safety distances.

HAZOP study and control system on the plants, besides people with experience.

Specific RCS.

Harmonization of regulations among countries.

2.10. How the aforementioned measures are perceived by your academic collaborators, customers and suppliers?

- Almost all respondents think that the measures are well perceived.

Collaborators and suppliers accept the measures without problems.

They rely on our professionalism.

The competence of people is perceived as good index.

APCI (Air Products) has a great safety record, and that can be perceived.

Academics and technicians understand the low complexity of the problem.

- Although when the measures mean a cost for the customer, then it's not so easy.

Necessary measure to comply with requirements but not necessarily understood by customers – cost impact to comply. Cost increase difficult to justify (firewalls, more distance booked).

2.11. How the H₂ production safety and your measures are perceived by workers / employees / collaborators in your organisation?

Unanimous answer stating that the safety measures are perceived as necessary to prevent incidents and that people accept or even feel comfortable with them.

Work safely is an accepted rule in my organization, and all the safety measures are accepted without any problem.

They are perceived as necessary in order to avoid potential problems.

ATEX measures perceived as a necessary part of the installation - accepted method of protection.

They feel quite comfortable.

2.12. How do you think H₂ production safety is perceived by EU citizens and citizens in your region?

- Perception of fear.

In my region (North of Italy), a large fraction of the population overestimate the risks connected with every energy installation, including hydrogen, because very little education is made by public media on risks and safety of energy installations. I think EU citizens are on average better informed on industrial safety issues and can more easily consider acceptable the risks connected with hydrogen production.

With doubts.

Citizens have a perception of risk in H₂ production.

Citizens often think that H₂ is explosive.

People either don't think about it or the opposite: they have an irrational fear that H₂ is a bomb.

Common people are deep influenced by non-technical and fear the H₂.

- No opinion, as the use of hydrogen is unknown.

Concerning the citizens in Greece, H₂ production safety is not a very common concept since the use of H₂ is not very widespread.

No interest, but also no adverse impact – will depend on personal exposure and if it impacts on their normal daily activities.

There is a general lack of knowledge on this issue. People considers H₂ dangerous but without instructed criteria.

The H₂ productions and safety issues are relatively unknown.

- Perception that it is an issue limited to industrial areas.

I think that they perceive that it is a relevant issue but that it is only restricted to industrial environments.

- Finally a few portion of respondents has a positive perception.

Generally quite safe due to long industrial experience.

They agree with it.

Relevant but not a critical issue.

2.13. Are you aware of promising technologies that might reduce safety issues in your sector?

The few percentage of respondents who are aware of new technologies don't detail them with one exception, whose promising technology don't relates to H₂ production but to storage.

Not aware of any new technology, other than the ones already in use.

The use of hydrogen storage technologies, such as metal hydrides that ensure low reactivity without compromising the energy density of the storage, can reduce safety issue in H₂ storage.

2.14. Are you aware of promising practices that reduce or might reduce safety issues in your sector?

Similar answers like before: not really any new practice and the very few respondents that say “Yes” don’t give any detail about them, with one exception, whose promising practice doesn’t relate to H₂ production but to vehicle fueling.

Regular seminars, exhibitions and shows about hydrogen technologies.

Safety practices are quite well established. No “promising” practices are envisioned.

No, SMR is an established mature process with no new safety innovations – but ISO Draft standards on H₂ vehicle fuelling.

Not aware. But if we don't apply the current practices, the process will become unsafe.

Supplementary questions

7.1. What aspects do you think should be improved regarding H₂ safety (incl. regional, national and EU aspects)?

- The implementation of common RCS across all Europe is a “common” answer.

Regulatory aspects should be improved. An International (EU level) common regulatory framework that creates favourable conditions for the widespread application of H₂ technologies in Europe must be developed.

- In public applications, it has to be proved that the environmental benefits of the technology prevail over the perception of danger.

In public applications, it has to be proved if danger perception would prevail on the environmental aspects; a good dissemination of the positive aspects of these technologies coupled with a correct information on safety should avoid barriers generated by prejudices. The impact of safety issues on public opinion is sometimes underestimated by experts.

- Increase the number of demonstration projects for instructing people, as well as easy access to specific information on safety.

It is imperative to continue working on the development and implementation of RCS as well as in demonstration projects to instruct people.

More specific information with easy access should be provided.

7.2. What recommendations on hydrogen safety do you have for the EU institutions (incl. regional and national aspects)?

Stakeholders hardly answered the last part of the questionnaire. One of them cited the H2SusBuild project, which outlined safety recommendations as part of the project results; however this information is not public.

To highlight that while some answers recommend education and information activities, there is also the opposite opinion that it is better *to not make too much noise* talking about hydrogen safety. Some of the recommendations are cited below.

Education and information activities for citizens and public administrations on real risks and advantages of H₂ applications should be issued in EU countries to increase the acceptability of H₂. Promotion of safety practices in the H₂ related industries and continuous dissemination of best practices in the industry should be done to maintain a high level of professionalism in the H₂ production sector.

A first step is an adequate training of operators and personnel safety, in order to avoid dangerous situations related with bad practices. In general, hazards due to hydrogen are overestimated with respect to other fuels; all the fuels are dangerous and have to be handled consequently, it's a matter of information.

More regular seminars, exhibitions and shows about hydrogen technologies.

Efforts in R+D should be done if we want to really use H₂ as an energy vector.

7.3. Do you have any H₂ related actors and stakeholders that you wish to suggest for the present interview?

In addition to suggesting some well known entities working in this sector, it has been recommended to collect *the opinion of fire-fighting bodies or civil protection responsible (who) can provide interesting points of view.*

7.4. Do you think is there any lack of funding in relation to the development of hydrogen and fuel cell technologies, and H₂ safety. Please, justify.

There is lack of funding, lack of awareness about available funding and difficulty to find funding or access to the funds. But the answers are not unanimous. See two apposite ones:

Yes, there is a lack of funding. From what I know, from the point of view of the academic research in my university, there aren't research projects with dedicated PhD scholarships on fuel cell development and hydrogen safety.

No, there are many public funded projects, and many companies working in this topic.

It is remarkable to mention that the research money now is more scarce than in recent years and this is not good for the hydrogen technologies:

In the last years there have been plenty of research money. In my opinion FC and H₂ are a longer-term research and research money should be there for this longer period of time.

About the focus of the funds, it should move from H₂ production to H₂ applications:

Yes. More efforts focused on the use of hydrogen than on hydrogen production from renewable energy.

7.5. Do you think the hydrogen stakeholders are not efficiently connected to technology transfer centres and hydrogen clusters/platforms? Please, justify.

Answers were clearly in favour of “Yes” (not efficiently connected).

I have seen examples of hydrogen-related companies that were not fully aware of the existing technologies.

No. They could ask Universities to try to solve specific issues they have (not occurring in Portugal).

Yes, I do. Greater coordination is needed and develop communication networks among experts.

Generally speaking I think not. Much greater efforts are required for the general dissemination and promotion and publicize the activities of the centres and platforms.

With one exception:

I think they are connected when necessary.

1.3 Document Review, Observation and Case Studies

1.3.1 H₂ Production technologies background

About 96% of the worldwide hydrogen production uses fossil fuels. Among the possible feedstocks for hydrogen production, approximately 48% uses steam reforming of natural gas, 30% partial oxidation of hydrocarbons and 18% coal gasification. The remaining 4% uses electricity through the electrolysis.

Steam reforming of natural gas, with efficiencies of 70-80%, is one of the most effective and the cheapest hydrogen production process. Large steam reforming units have production capacities of up to 100,000 m³ H₂/h per unit. In the context of fuel cell technology, the interest in decentralized production and small production units is growing. These plants range from small units of less than 500 m³ H₂/h to medium size plants in the range of 1,000-5,000 m³ H₂/h.

In this chapter, safety data has been collected either from large scale or small steam reforming plants.

On the other hand, the massive utilization of fossil fuels represents serious environmental threats such as natural resource exhaustion, pollutant gas emission, waste generation and climate change. As a result of public awareness of this reality, an agreement has been reached in the sense that a novel, clean, sustainable and renewable resource based energy system is needed [3]. In this context, the development of renewable energies, especially the ones dedicated to electric generation has been spectacular in recent years. The existing worldwide renewable power capacity reached about 1,230GW in 2009, 7% more than in 2008, and about a quarter of the global power-generating capacity, estimated at 4,800GW. In 2009, these energies supplied 18% of the global electricity production [4].

An electric system based on renewable energies creates new challenges concerning storing and utilization of the surplus energy, system operation, distributed generation management, energy supply reliability and future integration with an automotive sector based on the electric vehicle. Hydrogen technologies can help to cope with these challenges and to contribute to the new energy system development. In this respect, the hydrogen economy considers a future scenario in which hydrogen is produced through low cost environmentally clean processes by means of renewable energy sources [5].

Water electrolysis hydrogen production systems supplied by renewable energies are now attracting an increasing interest, since they are considered the only ones that may obtain large amounts of sustainable hydrogen with neither emission of pollutant gases nor consumption of fossil or nuclear resources [6].

That's why the second group of safety data analyzed in this chapter is from water electrolysis, in particular alkaline water electrolysis, one of the simplest methods for hydrogen production. Thanks to the modularity of the electrolysis technology, hydrogen production plants based on alkaline electrolyzers are available from low to high hydrogen outputs (e.g. >10.000 Nm³/h for large installations coupled with hydroelectric plants). Alkaline electrolyzers usually operate with efficiencies in the range of 40 ÷ 80 % [7].

1.3.2 Steam Methane Reforming – Best practices of general safety

Hazardous Materials

In hydrogen and HyCO plants, not only hydrogen can release or create an emergency event, but also a quite long list of other chemicals:

1. **Ammonia** (NH₃) – Colorless gas or liquid with a strong pungent odor. It may cause severe eye, skin and respiratory irritation and react violently with acids, oxidizers like chlorine, and other chemicals and materials. Two forms of ammonia can be found in a hydrogen plant, anhydrous (without water) or aqueous (about 55% water). The gas will burn but is difficult to ignite. **Affected areas should be flushed with water. Respiratory protection is required when working on any equipment in ammonia service.**
2. **Amines** – Identified by the function group NH₂, are commonly viewed as derivatives of ammonia. Glycols are any group of alcohols with a hydroxyl group (-OH) attached, such as ethylene glycol (anti-freeze).
3. **Argon** (Ar) – Non toxic gas, but asphyxiant. It is typically stored under pressure in cylinders. Asphyxia is indicated by dizziness, loss of balance, speech irregularities and other symptoms. As a liquid, argon is a cryogenic (very low temperature) material and may cause severe burns. Liquid or gaseous argon may be stored at various points of use in the plant.

4. **Carbon Dioxide (CO₂)** – Colorless and odorless gas heavier than air. It is mildly toxic and acts as an asphyxiant. It is not flammable and **persons should not enter any area where the concentration exceeds 5,000ppm or where there are visible clouds of gas without appropriate respiratory protection.**
5. **Carbon Monoxide (CO)** – Colorless, odourless and highly toxic gas. As a gas it enters the blood stream and blocks the absorption of oxygen. Small concentrations can be extremely hazardous and/or fatal. **Appropriate respiratory protection is required for concentrations above 25ppm. Wearing a personal CO detection/monitoring device is required where CO is produced or handled.** CO₂ and CO are found in high & low temperature shift reactors, PSA units and plant piping.
6. **Caustics** – It refer to a broad category of chemicals, which include bleach, soda ash and caustic soda. Mild concentrations of vapor can burn the eyes and mucous membranes, and liquid forms can cause severe skin irritation, burns and blindness. Ingestion can be fatal. Caustics also react violently with acids.
7. **Chlorine** – Yellowish-green liquid or gas with a penetrating odor, that acts as an irritant by means of ingestion, contact or inhalation. Chlorine presents a significant biological, chemical and physical hazard. Chlorine may be found in the cooling tower and cooling water treatment areas of the plant.
8. **Diesel fuel** – Used to operate internal combustion engines. The fuel is flammable but not explosive. Breathing vapors, ingestion, and contact with skin and eyes have to be avoided. Combustion by-products include carbon and sulfur oxides, which are known asphyxiants.
9. **Hydrogen (H₂)** – Colorless, odorless and non toxic gas. It is extremely flammable and often ignites without an apparent ignition source. A mixture of 4 to 75% hydrogen in air will burn if ignited. Hydrogen burns with a nearly invisible flame making it difficult to detect. **Flame retardant clothing such as NOMEX™ is required to be worn in hot plants such as hydrogen and HyCO plants.** Hydrogen is found in the primary reformer, compressors, PSA units and piping at varying pressures.
10. **Hydrogen Sulfide (H₂S)** – Highly toxic gas that can be identified by the “rotten egg” odor. It is sometimes stored as compressed gas, in which form it is flammable and explosive. It is also considered an asphyxiant. High concentrations of this gas can paralyze the olfactory nerve and may be difficult to detect by smell. Hydrogen sulfide is

found in compressors, pre-reformers, conversion reactors and plant piping; and in some locations blow in from off site.

11. Methane (CH₄) – A major component of natural gas, colorless and odorless. It is extremely flammable and needs only a spark to ignite in air mixtures. Methane is also an asphyxiant. **Personnel should not enter any area in which the concentration levels exceed 25%. Flame retardant clothing such as NOMEX™ is required to be worn.** Methane is found in compressors, as a feedstock and/or fuel source in the primary reformer, and in plant piping.

12. Monoethanolamine (MEA) and Monodiethanolamine (MDEA) – Corrosive liquids that cause burns to the eyes and skin. They are harmful if swallowed. MEA and MDEA are found in the stripper area and used for CO₂ removal.

13. Nitrogen (N₂) – Colorless, odorless inert gas or liquid that acts as an asphyxiant. Liquid nitrogen is a cryogenic material and can cause severe burns to skin. Nitrogen (gas) is used for purging and cleaning vessels and piping on the plant site.

If nitrogen is stored on site as a liquid and vaporized prior to use, cryogenic burns are possible in and around the storage tank and vaporizer. Gaseous or liquid nitrogen may be stored at various locations within the plant.

14. Oxygen (O₂) – It supports combustion but does not burn itself. **Areas where the concentration of oxygen exceeds 23.5% must never be entered.** Oxygen is highly hazardous since it dramatically increases the flammability of other materials, including those not normally flammable. **Oxygen enriched clothing should be exposed to fresh air for at least 30 minutes or removed, and all sources of ignition should be avoided.** As a liquid, oxygen is a cryogenic material and can cause severe burns to skin. It can be found at various points within the plant as well.

15. Sodium Hydroxide (NaOH) and Sodium Hypochlorite and Bromine (Br) – They are dangerous poisons, that are also corrosive. Sodium Hydroxide is found in labs, and Sodium Hypochlorite and Bromine are found in cooling tower and cooling water areas. They are harmful or fatal if swallowed and will cause burns to areas of contact.

16. Syngas – Mixture of hydrogen and carbon monoxide, that exhibits properties of both gases. Syngas should be treated with the same precautions as hydrogen and carbon monoxide. Syngas will be found in hot areas of the front end of the plant.

17. Steam – Essentially inert although containing a significant threat for burns. High pressure steam, i.e. 100barg, is a physical threat that is difficult to see and can cut through skin and bone with little effort. Steam leaks can often be detected by high noise in the vicinity, and water dripping or accumulating in puddles under the leak. Steam is found in primary reformer and plant piping at temperatures from 38°C to 534°C and a range of pressures.

18. Sulfuric Acid – Poisonous liquid that reacts violently with water and is extremely corrosive. Harmful or fatal if swallowed or inhaled and will cause burns to eyes and skin. Sulfuric acid is a significant biological hazard, used for cooling water treatment.

Protection systems

1. Monitoring Systems

Hydrogen and HyCO facilities will have safety monitoring systems in place to protect workers by either detecting or removing potential hazards.

These systems may include:

- Ultraviolet (UV) flame detectors to sense the presence of UV radiation from unseen flames.
- Flare systems that expel flammable gases to the flare header, to be burned off or “flared”
- Lower Explosive Limit (LEL) detection system monitors for combustible gases
- CO monitors (including personal CO monitors)
- In some cases H₂S monitors.

2. Noise Protection

High noise levels are common in the plants and proper use and wearing of noise protection devices such as earplugs and earmuffs will be required.

3. Warning signs

Hydrogen plants operate under extremes of temperature and pressure from the compressors to primary reformers to the PSA units. These extremes present many hazards and proper

procedures should always be followed when in or around these areas. Caution should be used and all posted warning signs followed, and areas with these signs do not entered, e.g.:



Figure 1.1. Warning signs in hazardous areas in a hydrogen plant.

- Under the primary reformer furnace and transfer main area
- Primary reformer furnace, upper decks, and penthouse area
- Areas adjacent to the flare stack or ground flare
- Steam Drum (boiler) main deck
- Areas protected by barrier chains, sound walls, or safety/caution tape
- Switchgear rooms, Power Distribution Centers (PDC) or substations; and UPS battery rooms
- Continuous Emissions Monitoring System (CEMS), Water Treatment buildings, Oil Water Separator or Cooling Tower.

Auto-Start Hazard

Another hazard involves auto-start equipment. Hydrogen plants often have dual pumps, fans and compressors. This equipment may start automatically with no prior warning; extreme caution is required in the plant when working near any machinery.

Hydrogen invisible fire Incident

Details of Incident

An industrial heater used to heat a naphtha-hydrogen mixture developed a small leak in one of its finned tubes. The leak resulted in a 60cm long torch flame, which was eventually noticed by an employee, during operations. Upon discovering the fire, the hydrotreater was shut down by cutting off the flow of naphtha and the flow of fuel to the burners in the heater. The hydrogen flow was maintained in order to cool and sweep the reactor during the shutdown operation.

The torch flame appeared to diminish significantly while only the hydrogen was flowing. However, molten metal dripping from the heater indicated that a much more severe fire was still in progress. The fire was eventually controlled by reducing the hydrogen flow and injecting steam into the heater. Inspection of the damaged heater revealed that the fire had completely melted 3.7m long sections of 32 finned tubes.

Lessons Learned

This incident illustrates how a hydrogen fire which appears to be 'quite small' can actually be only the visible portion of a much larger fire. Observation alone is not a reliable technique for detecting pure hydrogen fires and/or assessing their severity.

1.3.3 Steam Methane Reforming – Best practices to prevent cracking

Introduction

When a stress process condition (temperature, pressure) is applied to a metal and there is a cracking mechanism present, cracking may occur.

The cracks can initially form inside the pipe and therefore tend to be unnoticed. The cracks form many, tight branches and are often referred to as “spider cracking”. Eventually these branches will combine to form a crack. Cracking can lead to a sudden unexpected material failure.



Figure 1.2. Crack formed on a plant tube.

Two main mechanisms can result in cracking in hydrogen plants:

- Thermal Fatigue Cracking, and
- Stress Corrosion Cracking.

1. Thermal Fatigue Cracking

It can occur when exposing a metal to extreme temperatures on two sides of a mixing point of fluids.

It can be caused by piping changing its temperature over time, due to fluid temperatures inside the pipe changing. Basically the repeated expansion and contraction induce cyclic stresses in the metal and cause them to fail.

It can also be caused by fluids joining in a pipe that have a large temperature difference between them ($>50 \Delta T$). When two fluids with different temperatures mix in a pipe, this temperature delta puts large stresses on the pipe. The temperature delta may not have to be very large by itself, but when applied for a long time thermal fatigue cracking will occur. An example of this is unbalanced fin-fan coolers.

Unbalanced fin-fan condition occurs when two or more fin-fan cooler banks operate in parallel, but the number of fans operating in each unit is not equal. Therefore the amount of cooling in each of the parallel coolers is unbalanced. To prevent this from happening, plants should run the fin-fan coolers so that the same number of fans are running per unit. A

temporary loss of a fan in one bank will not lead to a fatigue problem, assuming the fan imbalance problem is addressed quickly. Running fin-fan banks unbalanced for less than 2 days will not lead to fatigue damage.

Thermal Fatigue Cracking Incidents

Details of Incident A

A hydrogen / HyCO plant experienced a failure of the outlet piping of the fin-fan due to thermal fatigue cracking.

During operation at reduced rates, several of the fans were shut off, while syngas and process condensate continued to flow through all the fin-fan coolers.

The unbalanced fin-fan caused the gas coming out of each of the fin-fan banks to be a different temperature. The gas coming out of the fin-fan bank with all fans running was significantly cooler than the gas coming out of the fin-fan bank with no fans running.

This temperature delta increased the stress on the weld of the mixing points elbow, causing it to fail.

Details of Incident B

In another hydrogen / HyCO facility, a leak was found at the mixing point where the reverse osmosis makeup water and the process condensate combine. Upon inspection it was determined the source of the leak was a crack in the piping.

Due to the temperature difference between the reverse osmosis make-up water (21°C) and the process condensate (107°C), the stainless steel piping was subjected to thermal fatigue cracking.

Based upon a review of the operating conditions and the piping material of construction, it was determined that the piping should be replaced with Inconel 625 (>315°C) or Duplex SS (<315°C). These tougher materials are more resistant to thermal fatigue demands.

Lessons Learned

- Run fin-fan coolers balanced or minimize time unbalanced.
- Have the distributed control system (DCS) monitor the fans, to determine if the plant is operating with the proper number of fans per bank. It will issue an alarm and will totalize the number of hours that the fans have operated unbalanced.
- If there is a hot or cold mixing point where the difference in temperature between the combining water streams is $>50 \Delta T$, the material of construction should be changed to Inconel 625 or duplex SS. This mix point is usually where the make-up water system combines with the process condensate.

2. Stress Corrosion Cracking (SCC)

It is the cracking induced on “susceptible” metal, from the combined influence of tensile stress in the metal and exposure of the metal to a corrosive environment.

SCC is highly chemically specific, i.e. only certain alloys are susceptible to SCC, when exposed to a specific chemical environment. These chemicals react with the metal in a well defined temperature range.

Stress in the metal can be residual, applied or thermal. The most common is residual stress from welding or metal forming.

The three types of SCC that most concern about in a hydrogen plant are:

- Caustic induced
- Chloride induced
- CO/CO₂ induced.

Caustic induced SCC

This form of corrosion cracking can happen when austenitic steel is exposed to concentrated caustic environments (high pH) with the metal under a tensile stress.

Conditions needed for failure are:

- Susceptible metals like austenitic steel or more commonly known as series 300 stainless

- Potassium hydroxide migration from the nickel reformer catalyst, during normal operation
- Temperature where condensate will form in the syngas.

This is mainly a problem downstream of the reformer to the outlet of the first catalyst bed (HTS). This catalyst bed acts like a filter for the potassium hydroxide, so there is less concern of caustic-induced SCC downstream of the first vessel.

Chloride induced SCC

This form of corrosion cracking is a localized corrosion mechanism, which involves selective attack of the metal along grain boundaries, by any compound capable of donating free chlorine ions (Cl⁻); some common examples are salt (sodium chloride) and bleach (sodium hypochlorite). Susceptible metals are 300 series stainless steel.

Conditions for this to occur are:

- Chloride ions present
- Dissolved oxygen present
- Metal under tensile stress (usually at welds).

This is most likely to occur in make up water systems with chloride present. The chlorine ions could get into the process if reverse osmosis membranes fail.

CO/CO₂ induced SCC

This form of attack can occur in syngas process piping, where condensate containing CO/CO₂ is formed. Susceptible metals are stainless steel, carbon steel, CrMo.

The combination of the following conditions leads to CO/CO₂ induced SCC:

- Residual stress from welding following inadequate or lack of Post Weld Heat Treatment. Post Weld Heat Treatment is a stress-relieving procedure to improve the chemical/mechanical properties of welded surfaces.
- Condensate containing dissolved CO/CO₂ is present in the syngas piping. Cracking can readily occur at low concentration of CO and/or CO₂ in the presence of very low levels (ppb) of oxygen.
- A “Dead Leg” exists in the piping that provides a stagnant environment for oxygen. Dead-Leg is any size (diameter or length) piece of pipe that is dead-ended by either a manual block valve and/or a flanged component. There is normally no flow in a dead leg during operation. If a dead leg is not properly purged during SMR startup, it could

lead to oxygen being trapped. Small amounts of oxygen remaining in syngas dead leg piping will create an environment that can promote CO/CO₂ induced SCC while the plant is operating.

Stress Corrosion Cracking Incident

Details of Incident

A pipe rupture occurred in a SMR process that produces hydrogen and export steam. The rupture occurred in a 60cm diameter stainless steel pipe used to allow the process gas flow to bypass the high-temperature shift converter (HTS) during start-up. When the pipe ruptured, process gas contained in process equipment located upstream and downstream of the break vented into the SMR plant yard area. The vented process gas was a mixture of hydrogen, carbon monoxide, carbon dioxide, steam, and methane at 38bar and 343°C. The escaping high-pressure gas caused an energy release and subsequent fire. The fire was confined within the SMR plant, but equipment located near the pipe failure was damaged. The SMR plant distributed control system (DCS) worked properly to automatically shut down the process, thereby limiting the amount of process gas that escaped. Emergency response services were provided on the scene by the local county fire department within minutes of the incident and the fire was extinguished within 10 minutes. There were no injuries and no releases of any acutely hazardous materials covered by the Risk Management Prevention Plan (RMPP), EPA CERCLA, and SARA Title III regulations.

Metallurgical examination of the failed pipe segment revealed cracking on the pipe interior. The cracks were the result of stress corrosion cracking (SCC) of stainless steel, caused by the presence of caustic (potassium hydroxide). The most likely source of the caustic was small amounts of potassium promoter normally present in the SMR catalyst. The section of the HTS bypass piping where the rupture occurred was normally cool and non-flowing. The piping layout allowed water and potassium hydroxide condensed from the process gas stream to collect in a low point. The stainless steel material of construction of the bypass piping was susceptible to SCC from the concentrated caustic solution collecting in the bypass piping.

The incident was discovered during operations.

Lessons Learned

The stainless steel 60cm pipe that failed was replaced with 1-1/4 Cr 1/2 Mo alloy pipe that is corrosion-resistant to SCC. A revised HTS bypass piping layout was installed to prevent the hazardous conditions that lead to the failure. A detailed hazard review and evaluation of all of the materials of construction in the hydrogen plant process gas system led to preventively changing several other pieces of piping and equipment items in the SMR process to 1-1/4 Cr 1/2 Mo.

1.3.4 Alkaline water electrolysis – Case 1

Introduction

A certain hydrogen plant is designed to continuously produce hydrogen at a purity of 99.75% and at a rate of 510 m³ per day (~21m³/h). Hydrogen is produced in two banks of cells filled with a strong solution of caustic soda. Current is passed through the cells to produce hydrogen and oxygen. The oxygen is vented directly to the atmosphere, while the hydrogen is piped to the gasholder.

The gasholder is a low pressure storage vessel capable of storing 28 m³ of gas. It is constructed in two parts. The bottom section is a large round tank. The upper section is an inverted tank or bell that is free to move within the main tank as pressure increases or decreases. The main tank is filled with water to form a water seal. Hydrogen from the cells enters the gasholder above the water line, causing the bell to rise.

The purity of the hydrogen is monitored between the cells and the gasholder. If purity falls below 99.5%, the hydrogen is vented to the atmosphere.

The plant is installed with two compressors. Hydrogen is drawn from the gasholder by the compressor via the gas dryer and the filter. It is compressed to 12.4 MPa and delivered via high pressure (HP) dryers to the storage banks.

The plant contains four storage banks capable of storing 460 liters per bank. Each bank consists of 16 cylinders. Each cylinder is fitted with an overpressure protection device called a "bursting disc".

Details of Incident

One afternoon, an assistant operator attended the hydrogen generation plant as part of a routine plant inspection. The plant was functioning correctly and no obvious problems were noted.

Approximately one hour later, a large explosion was heard by a contractor in the contractor amenities area and the remaining staff in the administration building. Calls were received soon after by the duty shift manager advising him that there was a fire at the hydrogen generation plant.

The duty shift manager activated the site emergency plan. Calls were received by the local fire department and site fire-fighting teams were on the scene within a few minutes.

The fire was attended by a number of local fire departments and was declared under control the following morning.

Gassing of the in service units was suspended for the entire period of the emergency, as the gas up stations were in the fire area.

Plant Configuration at Time of Explosion

At the time of the explosion "A" and "B" banks of cells were in service filling the gasholder. The low pressure (LP) dryer and LP filter were in service. "A" H₂ compressor was in service delivering high pressure hydrogen via the "B" HP dryer to "B" and "C" storage banks.

Results of Inspections

Visual inspections of the plant found the high pressure pipe work had ruptured or parted at the following locations:

- Between two valves adjacent to a compressor
- At the pressure regulating valve near the compressor room
- Above the "B" HP dryer
- At the inlet to the "B" bank manifold
- At various bottle fittings in "B" bank.

In addition the following damage was noted:

- Pipe swelling at the compressor side of the HP regulating valve
- Pipe swelling at the HP Non Return Valve (NRV) (dryer side)
- Damage to a compressor blow-down pneumatic valve
- Damage to a HP dryer blow-down pneumatic valve.

Twelve of the sixteen B bank cylinders and six cylinders on C bank had been affected by the heat of the fire. Many of the copper vent pipes from the cylinders to atmosphere were discolored or melted indicating that many of the cylinder bursting discs had ruptured. The vacuum and purge pipe work around B and C banks had been destroyed by the fire.

The cladding at the eastern end of the building had been blown out above two storage banks. Debris from the site was distributed for 20 meters. Fire from a blown pipe at the rear of B bank impinged on the LP gasholder. Damage to the gasholder was superficial.

Incident Investigation

The damage to the HP pipe work suggested that the explosions occurred initially in the pipes between the compressor and the HP NRV. The swelling of the pipes indicated that a pressure wave had traveled along from the pipe from the direction of the compressors towards the storage bottles.

Such an explosion is possible if an explosive mixture of air and hydrogen existed in the pipes. Hydrogen will form an explosive mix with concentrations of hydrogen in air of 4% to 75%. Where pure oxygen is the contaminant the explosive limit is less than 5% oxygen in hydrogen. Hydrogen in an explosive mix is well known to ignite inside pipes.

The force of the explosions in the pipes had then caused consequential failures of fittings and joints at B and C storage banks. This released hydrogen into the storage shelter which subsequently ignited.

All possible points of air ingress were identified and checked as the possible cause of the explosive mixture. The main sources are dealt with in detail below:

1. **LP Filter** – The LP filter is fitted with a U bend water seal that is open to atmosphere. If the water seal is lost the air could be drawn into the line through the U tube. The seal is fitted with a clear plastic sight tube. The seal is checked regularly and topped up with colored water if the level is low. The seal was found to be dry after the incident. It is possible that the water had been blown from the tube during the explosion. The seal was dismantled and the elements were found dirty but not blocked. During the inspection it was confirmed that under blocked filter condition the compressor could not draw the seal water into the line.
2. **LP Dryer** – The LP dryer is also fitted with a U bend water seal that is open to atmosphere. This water seal is a steel tube and can only be checked by dipping the

open end. Because it is fed from the dryer it is generally spilling water when in operation. The bend was found full of water after the incident.

3. **LP Pipe low point drain at LP gasholder** – There are two pot style water sealed drains at the low point in the inlet and outlet pipes from the LP gasholder. These drains cannot be checked for water level visually or by dipping. The drains were opened and found full of water. The drain lines from the hydrogen pipes were found to be partially blocked.
4. **LP gasholder** – Mal-operation or sticking of the bell may allow air to enter the gasholder. Samples of gas were taken from the top of the gasholder and tested for oxygen and nitrogen. The results were 2.4% oxygen 4.6% nitrogen. As the proportions are not consistent with air a second test sample was taken from the inlet of the gasholder. The results of the second test showed 4.7% oxygen. Nitrogen was not identified in the sample. The operation of the gasholder was checked with nitrogen. The gasholder bell was found to operate smoothly with no stiction points. It also maintained pressure when filled with nitrogen. An internal inspection of the gasholder found that the inlet and outlet pipes extended only 12 to 15mm above the normal water level. Drawings indicated that this should have been at least 50mm above the water.
5. **Oxygen Ingress from Cells** – During operation the cells are designed to separate the oxygen from the hydrogen. Under abnormal conditions oxygen can enter the hydrogen system and cause contamination. The LP purity analyzer monitors the purity of the hydrogen and if it falls below 99.5% the analyzer opens a vent valve to prevent the contaminated hydrogen from reaching the gasholder. The LP purity monitor was checked. The 240 volt to 220 volt isolation transformer that powers the analyzer was found open circuit on the secondary winding. The operation of the LP Purity analyzer was confirmed as "non-fail safe". On loss of power or sample the analyzer output remains at the last recorded value. The indicated purity as found after the explosion was 99.8% with no power to the analyzer. The trip signal to operate the vent valve is driven by the indicator and would not have activated under these conditions. Supply supervision alarming was not connected to this part of the circuit. The hydrogen inlet pipe work and filter were found choked with water preventing hydrogen from passing to the monitor. These filters are regularly checked by office staff and no abnormalities were noted earlier on the day of the explosion. It is considered that the build-up of water occurred after the event due to residual water in the line. Once sufficient repairs had been carried out the cells were returned to service. On initial operation the cells attained a purity of 99.5% which then fell away to less than 92%. Investigations found that a number of cells had

low electrolyte levels. Once they were topped up to normal working level the purity returned to 99.5%. This operation was repeated a number of times with the same result. The cause of low electrolyte level was determined to be blocked water inlet pipes at the affected cells. Blockages were occurring at the inlets due to a build-up of magnetite and other contaminants. The low purity associated with low electrolyte levels may indicate that the dividing diaphragms between the oxygen and hydrogen generation cells has deteriorated allowing crossover of gases as the level drops. In addition 6 cells (3 on each bank) were found to produce gas at a purity below 99.5% with one on each bank below 97%. This again is thought to be a result of deterioration of diaphragms.

Plant Purging

Tests of gas in the LP gasholder indicated the presence of oxygen at a concentration of 4.7% and a small concentration of nitrogen. It was assumed that there was a possibility that the gas in the remaining A and D high pressure storage banks may have been contaminated. No attempt was made to sample the gas from the storage banks.

The LP gasholder was purged through the normal vent valves and filled with CO₂.

A detailed procedure involving nitrogen purging and remote operation of vent valves was developed for purging of the HP storage banks. The banks were successfully purged allowing repairs to the plant to begin.

In summary, explosions in the HP hydrogen feed pipes caused the failure of welds and connections at the storage banks, allowing hydrogen gas to be released in large quantities from B and C storage banks. The escaping hydrogen self-ignited, resulting in an explosion and fire.

The cause of the initial explosions was due to the spontaneous ignition inside the HP feed pipes of an explosive mix of hydrogen and oxygen.

It is concluded that the ingress of the oxygen to the system was from the hydrogen cells. The prime cause of the contamination was blockages in the water makeup lines to some cells, allowing high levels of oxygen to mix with the hydrogen as electrolyte levels fell.

The low purity hydrogen was not detected by the low pressure purity analyzer due to the failed isolation transformer.

There are a number of other potential air ingress points on the LP system that could have allowed contamination. These points are, however, considered unlikely to have been the cause of the contamination resulting in the explosion.

Lessons learned / Recommendations

A number of improvement options were identified.

1. Cells

Six cells are producing hydrogen at a purity below 99.5%. The inter chamber diaphragms are suspected as the source of cross contamination of hydrogen and oxygen. Five cells were overhauled in 1998 due to low hydrogen purity. In all cases the diaphragms were found to be in poor condition and replaced. Cells that were overhauled in 1998 were found to be producing at 99.8% during the post explosion testing.

Recommendation 1.1 – Overhaul and replace the diaphragms on all cells showing low purity results. Check on a routine basis the individual cell purity levels to monitor the deterioration of performance of individual cells.

Certain contaminants are produced as a result of the process that settle to the bottom of the cells. These contaminants, particularly magnetite, can block the water makeup ports and the drain valves. This was found to be the case on 6 makeup ports and on most drain valves. The blocked drain valves made it very difficult to clean the cells and to unblock the makeup ports.

Recommendation 1.2 – Replace the drain valves with open port ball valves to improve the drain operation and to allow effective cleaning of the cells. Instigate a routine for the yearly draining and cleaning of all cells.

2. Purity Analysis

Recommendation 2.1 – Replace the existing LP purity analyzer with a fail-safe model that ensures the vent valve is opened under the conditions described above. Carry out a risk assessment of the current LP purity analyzers to determine the level of risk associated with a loss of sample flow.

The plant is not fitted with HP purity analyzers to confirm the purity after the compressor. Given the number of possible air ingress points in the pipes under vacuum and the higher

probability of explosion of impure hydrogen in the HP system it is essential to be able to detect low purity after the compressors.

Recommendation 2.2 – Fit hydrogen purity analyzers that fail safe either between the stages of the compressor or immediately after the compressor. Carry out a risk assessment of the current LP and HP purity analyzers to determine the level of risk associated with a loss of sample flow failure.

3. Drain Piping

The drain piping installed at the hydrogen generation plant is of two types. The first is a simple U tube arrangement which is installed at the LP filter, LP dryer and before and after the LP vent pipes. The second type is a low volume closed pot style that can hold 2 to 3 liters of water. These are installed before and after the LP gasholder. In all cases the seal liquid level is maintained by the process. There is no external top up facility. With the exception of the LP filter U tube there is no visible means of checking the water level.

Recommendation 3.1 – Fit pot type water seals with open trough water makeup as a replacement for the existing U tube and pot-type seals. The original design drawings for the gasholder show the inlet and outlet pipes extend 50mm above the water line. The actual measured extension was less than 20mm. Small variations in the level control could allow water to enter the lines.

Recommendation 3.2 – Increase the pipe length to extend them to 50mm above the water level.

4. Building

The building is fitted with partially closed-in ends that can trap the gas under the roof. The current construction standard for this type of facility is to have the storage banks in an open area rather than inside a building of any kind. Any leakage will then quickly disperse into the atmosphere and not form an explosive mixture. This is not practicable at the current plant, but improvements are possible.

Recommendation 4.1 – Remove the end sheeting from the building to increase ventilation.

5. Compressor Suction Pressure

The investigative committee recommended investigating the installation of suction pressure trip devices to each compressor. The suction line of the compressors will operate under

vacuum for at least part of the system. An indication of a leak from atmosphere in these lines will be a decay in the vacuum at the suction of the first stage compressor.

This type of protection has proven unreliable in this application at this plant, causing spurious trips of compressors. The installation of HP purity analyzers under **recommendation 2.2** and improved drain pots under **recommendation 3.1** is considered to provide positive protection against the ingress of air on the suction pipe work.

6. Gassing Facilities for Generators

The gassing stations for the generators are located behind the HP storage banks and were inaccessible during the incident. The operating generator hydrogen pressures steadily decayed during this period but remained in-service. If however access into the plant had been delayed further all operational units may have been forced offline.

Recommendation 6.1 – Conduct an investigation into the feasibility of establishing a gas-up station away from the hydrogen generation plant, possibly near the CO₂ plant, to allow the units to be gassed from transportable pallets in an emergency.

1.3.5 Alkaline water electrolysis – Case 2

Introduction

A commercial facility utilizes an electrolysis system based on the electrolysis of a potassium hydroxide solution, to produce hydrogen for a hydrogenation process.

The electrolysis cells are circular with 1.5m in diameter and 25mm thick.

The design current for the electrolyser is 6,000 amps at 1.78 volts.

Operating temperature and pressure is 70-90°C and 30bar.

Hydrogen and oxygen product gases are separated from the electrolyte in separating drums.

Details of Incident

An explosion occurred in the electrolysis system.

The system had been operating at the plant for 13 years prior to the explosion. Operating experiences had been generally favorable except for the need to periodically flush the system with water to remove sludge formations.

A plant operator present in the electrolysis room at the time of the explosion was fatally burned by the caustic solution sprayed from the ruptured drum.

Incident Investigation

According to the investigative report, sludge deposits in the electrolyte passages started the following sequence of events, culminating in the explosion.

Reduced electrolyte flow rates caused by sludge blockage resulted in increased cell temperatures and electrolyte concentrations. The increased electrolyte concentrations and linear velocities (due to obstructed passages) eventually led to severe corrosion/erosion damage of the cell electrodes and separators. *Hydrogen embrittlement* may have also been a contributing factor.

The physical breakdown of the cell separators allowed hydrogen and oxygen to mix and hydrogen to enter the oxygen separator drum.

The gas mixture was ignited causing a violent explosion which ruptured the separator drum.

Lessons learned / Recommendations

The investigative report noted that the gas analyzer of hydrogen and oxygen product purity failed to work.

Recommendation 1 – The explosion could have been prevented by a continuous gas analyzer test of oxygen and hydrogen product purity. The continuous analyzer should be interlocked to shut the electrolyzer down when product purity falls below some nominally critical values.

Recommendation 2 – More widespread use of hydrogen analyzers and hydrogen detection equipment.

Recommendation 3 – Check on a routine basis the individual cell purity levels to monitor the deterioration of performance of individual cells and supply supervision alarming.

Recommendation 4 – Periodical flush the system with water to remove the sludge accumulation.

Recommendation 5 – Appropriate material selection to prevent from corrosion phenomena like hydrogen embrittlement.

Recommendation 6 – Adequate maintenance, taking into consideration the inverse relationship between hydrogen accidents and regular maintenance.

Recommendation 7 – Retrain personnel on emergency procedures and enhance their understanding and awareness of risky, flammable, explosive, and/or toxic substances. Avoid underestimation of the hazards and complacency.

Recommendation 8 – Refresh and re-enforce personnel training on their roles to ensure that non-essential personnel are cleared from the area during operation, protecting in this way the personnel and preventing from human losses.

1.4 Conclusions

Hydrogen plants are subject to Process Safety Management (PSM) regulations, covering the release or potential release of highly hazardous chemicals. PSM requirements include regular operator training, management of change, contractor safety, hot-work permits, accident-incident investigation and emergency planning and response. A Risk Management Program (RMP) must also be in place describing the “worst case” effects on the surrounding community of a product or other hazardous material release or spill. These are all elements that are addressed in a variety of ways through safety practices, adequate maintenance and inspection procedures in industrial hydrogen plants, successfully followed for decades. Despite all of this, mature technologies are not exempt of incidents.

But increased efforts need to be done on implementing regulations and safety best practices when moving hydrogen production technologies outside of the industrial fences into a wider public, with limited experience on handling hazards related to hydrogen, in a future hydrogen economy scenario. The answers of the stakeholders to the survey support this statement:

Hydrogen is perceived as a safe chemical when adequate measures are followed. Workers in H₂ plants are trained on the particularities of hydrogen handling, they are professionals who follow the recommendations to prevent incidents. Training is repeated periodically in order not becoming confident with repetitive tasks. Besides, mechanisms like BSP (Basic Safety Process) skill individuals and groups to be alert and to detect situations of risk or risky behaviors, focusing efforts on prevention activities to reduce incidents.

The neighbourhood is afraid about hydrogen production due to the lack or wrong information. After being informed, the public understands the process and feel confident that proper safety measures are taken, e.g. provision of H₂ detectors whose signals determine automatic Emergency Shut Down procedures of the production plants. Some stakeholders consider that there are no safety issues or even that the safety concern is too much magnified. However, isolated negative attitudes from only one neighbour can result in serious problems.

The perception of lack of safety results in over-sizing the safety measures. The main H₂ production safety issues are leaks and the risk to ignite. Explosions are in mind (due to the Hindenburg zeppelin incidents), despite until today no such events have happened in hydrogen production plants.

The first decision making criteria for introducing a new hydrogen production process is shared equally between safety and economics. The lack of dedicated RCS or, alternatively, the application of regulations not purposely designed to get these new systems approved is seen as a barrier; also the lack of a H₂ pipeline network to connect H₂ production centers with customers, whose availability would increase of the road traffic safety.

To set specific regulations for public H₂ infrastructure and harmonize them among countries, the need for prescribed safety zones for ATEX areas, to increase communication with authorities, more demonstration projects for instructing people, increase funding availability for H₂ applications, the need for skilled personnel working with hydrogen and related equipments, easy access to specific information on safety, to prove that the environmental benefits of the technology prevail over the perception of danger and, last but not least, to convince the technology sceptics, are listed among the needs to guarantee the maximum level of safety for an accelerated deployment of the hydrogen economy in Europe.

Deliverable No. 3.1

Chapter 2

Storage and distribution

2.1 Introduction

Hydrogen storage is a key element in the utilization of hydrogen fuel. The energy consumed in each step of the process of hydrogen production and distribution, including multiple storage options and transport, should be minimized for high energy efficiency.

Following the transmission of hydrogen gas through pipelines, there will be requirements for bulk storage at various local distribution centers. The quantity of hydrogen will be dictated by the application. Currently, the largest hydrogen storages are based on liquid hydrogen (LH₂) in insulated vessels. However, hydrogen liquefaction is a very energy-intensive process (the ideal liquefaction work is 12% of the heating value, and at least 20-30% of the energy content of hydrogen is used for liquefaction in real plants), and LH₂ storages are expensive and prone to product losses due to evaporation, which makes this process inefficient. The application of LH₂ is generally confined to high-purity applications in the chemical industry and aerospace applications (for instance, the external tank on the space shuttle has an aluminum LH₂ tank).

An alternative is storing hydrogen as compressed gas, for instance dealing with storage in vehicles. However, one kilogram of compressed hydrogen (CH₂) occupies around 11m³ of volume at ambient pressure and temperature and consequently compact pressurized storage requires compression at high pressures (e.g. 35-70 MPa). High strength steel or other metals are an option from a strength perspective; however, diffusivity of hydrogen through the steel and weight of the steel are major issues for vehicular storage, so that alternative lighter materials are considered like aluminum reinforced with carbon fibers.

As an example, storage of 5 kg of CH₂ at 34 MPa would require a volume of 212 L, which is substantially higher than the tank of conventional vehicles. However, only 8.5% of the energy content of the hydrogen is used in compression. The current challenge in CH₂ is to develop conformable pressure vessels that can optimize space in FCVs. In addition, continuing reduction in cost and lower weight will be the focus in future developments. The net energy utilized for CH₂ storage is the lowest as compared to LH₂, metal hydride, and all other storage options.

Dealing with hazards in storage, in normal conditions, hydrogen is a colourless, odourless gas much lighter than air. The low density in conjunction with the small particle size allows the penetration of hydrogen molecules in some metals and alloys such as cast iron and high carbon steel. The penetration may end in small hydrogen leaks, or, in the presence of cracks

within the wall, contribute to cracks spread, material strength decrease, and subsequent fracture. Hydrogen reacts violently with oxidizers such as nitrous oxide, halogens (especially with fluorine and chlorine), and unsaturated hydrocarbons (i.e., acetylene) with intensely exothermic reactions. Hydrogen gas forms combustible or explosive mixtures with the atmospheric oxygen over a wide range of concentrations as mentioned earlier. Hydrogen is nontoxic; however, besides the hazards of flash fire, jet fire, and gas cloud explosion presented in the case of an accidental release, hydrogen may act as an asphyxiant at sufficiently high concentrations by depleting the oxygen available in atmospheric air.

A brief listing of hazards in storage is listed below:

- Penetration in metals and alloys: H₂ leaks or cracks in walls /crack spread, material strength drop/fracture.
- Explosion of H₂ containers when exposed to high temperature or thermal radiation
- Heat supplied to the gas container may raise local wall temperature, thus weakening its strength.

Related to cryogenic storage:

- Embrittlement of service materials
- LH₂ spills: 1 L of liquid becomes 851 L of gas after evaporation
- Iron alloys at LH₂ temperature lose their ductility with risk of mechanical failure
- Cloud formation heavier than air ->increasing the risk of fires and explosions

Generally speaking, the ignition energy for hydrogen-air mixtures is extremely low, so that electrostatic sparks are sufficient ignition sources in case of leakages.

For this reason, storage is one of the biggest challenges with hydrogen and hazards in storage are mainly related to the risk of leaking which may result in mixing hydrogen with air in dangerous proportion.

Dealing with high pressure hydrogen safety, the potential risks of high pressure gaseous hydrogen (HPGH₂) include vessel explosion, gas leakage, temperature rise in fast filling process, and hydrogen embrittlement (HE). Currently, researches are mainly focused on the hydrogen embrittlement of metals at room temperature, temperature rise in fast filling process and potential risks such as diffusion, deflagration, and detonation after accidental hydrogen leakage.

Regarding Hydrogen embrittlement at room temperature, especially high-pressure high-purity hydrogen at room temperature is deemed to have significant deleterious effects on the mechanical properties of metals, a phenomenon generally known as high pressure embrittlement. The permeation of hydrogen atoms in the metal lattice promotes localized plastic processes and accelerates crack propagation rate. The degradation increases the risk of sudden failure for high pressure hydrogen components. Materials used in high pressure hydrogen systems are carbon and low alloy steels, high strength Cr-Mo alloys, austenitic steels, aluminum alloys and copper alloys.

Regarding temperature rise in fast filling process, fast filling of high pressure hydrogen gas results in a temperature rise within the vessel due to the released heat of compression and the Joule-Thomson heating of the fuel as it is throttled through the orifices. The Joule-Thomson coefficient for hydrogen is negative at the temperatures and pressures of filling; as a result, an isenthalpic expansion of the gas from the high pressure storage tank through the dispenser throttling device and into the low pressure cylinder results in an increase in gas temperature. The heat effect may deteriorate the carrying ability of carbon fibre reinforced tanks and leads to under-filling issues, since the pressure inside the vessel decreases as the gas cools down.

Regarding, diffusion, deflagration, and detonation after accidental hydrogen leakage, sudden mechanical failure of high pressure hydrogen storage devices or activation of pressure relief device (PRD) cause hydrogen leakage. High pressure hydrogen jet will form jet fire under certain conditions which can impinge on objects and emit thermal radiation. Systematic studies have been taken on the thermal properties of hydrogen jet flame and hot currents in the downstream region. The influence of flame shape and size by parameters such as nozzle diameter, gas pressure, jet flow rate, barrier, etc., has been investigated. Based on experimental data and numerical simulation results, the correlation between flame length and width with the hydrogen outlet pressure or flow rate, has been obtained which allows real-time prediction of the flame shape. Barrier walls are usually installed to protect people and facilities from the hydrogen jet flame or the thermal radiation. However, this confinement may increase the risk of hydrogen explosion and lead to disruptive overpressure in case of accidental combustions. When barrier walls are used to mitigate these hazards caused by hydrogen jet flame, it is important to ensure that they do not create unexpected additional hazards.

Hydrogen distribution and transport should combine safety with an attention to the cost-effectiveness and energy-efficiency of the method. There are three primary options for transporting hydrogen:

1. Pipelines and tube trailers for gaseous hydrogen, or a mixture of hydrogen and natural gas transportation.
2. Trucks, rails, barges, and ships with cryogenic tanks for liquefied hydrogen delivery.
3. High energy-density carriers such as ethanol, methanol and other liquids derived from renewable biomass that can be transported and reformed to hydrogen at the endpoint of use.

All transportation options are still under development but in any event, safe, cost-effective, and energy-efficient delivery technologies are needed. The main delivery barriers are those related to economic strategies and safety.

Regarding safety in pipelines, a pipeline network infrastructure is mostly used in transporting hydrogen in large quantities over a long distance, mainly due to its safety in operation, especially with small diameters and when operating at moderate and constant pressures.

Hydrogen transmission requires significantly greater power and energy for compressors with respect to other gases like natural gas. Also, lubricants used in normal compression applications can result in unacceptable contamination problems when hydrogen is used for fuel cells or other high purity applications. Reliable, low-cost, and efficient compression technologies for pipelines are needed. Alternatively, compressor-less hydrogen transmission pipelines are being explored based on the current technology of high-pressure-output electrolyzers.

Below appears a brief listing of the major hazard issues related to transmission in pipes:

- H₂ molecule diffuses rapidly and easily, with more challenging design of materials, seals, valves and fittings to avoid leakages.
- H₂ is odorless, colorless and tasteless so that it is undetectable by human senses; hence, odorants for leak detection should be used, with development of pipeline mechanical integrity sensors.
- Developing appropriate barriers (coating or surface treatment) to minimize H₂ penetration into metal materials.
- Pipeline damage tolerance depends on mechanical loading, material and H₂ pressure.

2.2 Document review and observations

Related codes and standards published are mainly drafted by the International Standard Organization (ISO), national standardization committees and international associations such as International Electrotechnical Commission (IEC), European Industrial Gas Association (EIGA), ASME, Society of Automotive Engineers (SAE), etc. To accelerate the pace of hydrogen standardization, special committees or project teams are usually built. ISO is developing fuel cell vehicle and hydrogen storage standards within technical committees TC22/SC21 and TC197. Below several codes and standards published are listed, dealing with hydrogen storage safety:

- ISO/TS 15869 (2009) "Gaseous Hydrogen and hydrogen Blends - Land Vehicle Fuel Tanks" .
- JARI S 001 (2004) "Japanese Regulation for Containers of Compressed Hydrogen Vehicle Fuel Devices" .
- CGH2R-12B Draft Revision 12 (2003) "Hydrogen Vehicles: On-board Storage Systems" Draft ECE. Compressed Gaseous Hydrogen Regulation Revision 12 .
- "Stationary Flat Steel Ribbon Wound Vessels for Storage of High Pressure Hydrogen". GB/T 26466-2011 China.
- ISO TR 15916:2004 "Basic Considerations for the Safety of Hydrogen Systems"
- AIAA G-095- 2004 "Guide to Safety of Hydrogen and Hydrogen Systems". American Institute of Aeronautics and Astronautics.

2.3 Interviews and case studies

In this section 6 case studies related to hydrogen distribution and storage are presented and summarized:

- OSSHY Project; On-Site Solid Hydrogen Storage , La Mote Fanjas (France)
- Hydrogen Filling Station in Huesca (Spain)
- Future Hydrogen Filling Station in Puertollano (Spain)
- Filling Station in Emeryville (USA).
- Incident at Filling Station (USA)
- “ZEROREGIO” Project (Europe)

Part of the information presented in the case studies come from interviews that took place with person listed below:

- Roman Guichon, Safety Engineer, McPhy Energy (France)
- Páblo Marcuello, senior engineer, Aragon Hydrogen Foundation (Spain)
- Monica Sanchez Delgado, Development and Validation of Systems Division Manager, Spanish National Hydrogen Center (Spain).
- Alberto Rota, member of scientific board for hydrogen activities in Regione Lombardia (Italy)

2.3.1 OSSHY Project

In the plant of McPhy Energy, in La Motte-Fanjas, a test platform has been built in order to operate and to test electrolyzers and solid storages. In this platform are installed :

- Electrolyser (10 m³ N/h)
- 100 kg H₂ solid storage
- Free areas for H₂ solid storage testing
- H₂ gas storage (4 hydrogen racks with B50 bottles)
- H₂ Compressor

The layout of the platform is described here (walls are in blue) :

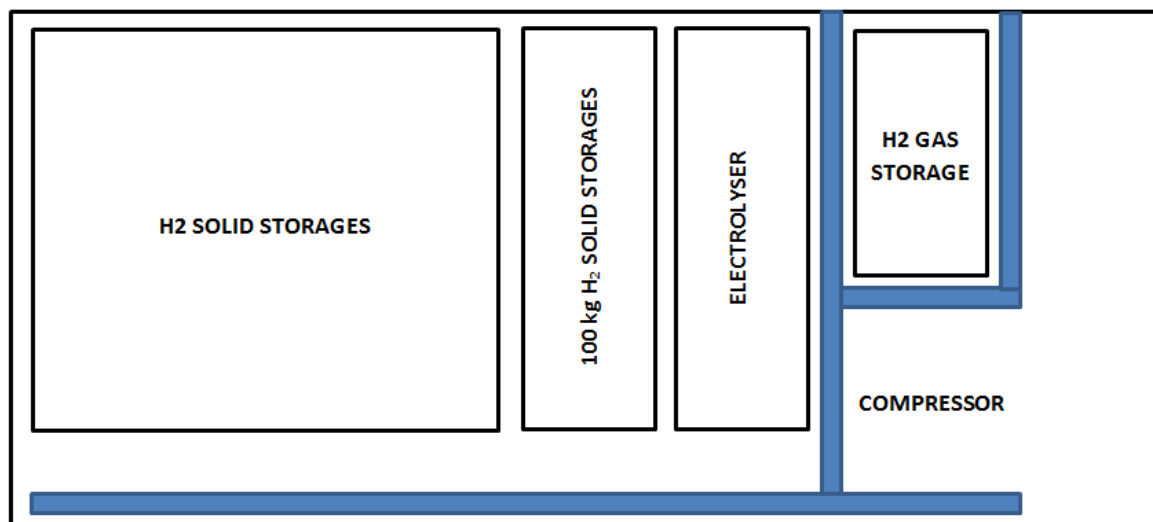


Figure 2.1. Layout of a McPhy Energy test platform in La Motte-Fanjas.

This platform is protected by a mesh and walls.



Figure 2.2. Protected area of the test platform in La Motte-Fanjas.

These walls have been built in order to protect the production building too. Near the access to the platform, we have boxes with keys in order to put the cell phones and other electrical equipment before to go into the platform.



Figure 2.3. Lockers at the entrance of testing platform for leaving cell phones and other electric equipments.

This platform is with controlled access. Only authorized people can enter in the platform. A list of these people is displayed near each door of the platform, since they have been trained to the related risks. It is important to take into account that a key is needed to open the doors, and nobody can go in the platform without gas detector.



Figure 2.4. Entrance of the testing platform; a key is necessary to enter the area.

If a person whom is not in the list needs to go in the platform, he has to obtain a work permit (which is delivered after an explication of the risk and a risk analysis for the operation) or to be accompanied by an authorized person. If a person has to do a hot point operation, he has to obtain a fire permit with a risk analysis before to do the operation.

On each door of the platform, an emergency shutdown is installed. It stop the electrical alimentation of the equipment of the platform and the hydrogen sources are isolated. For each more or less close space where hydrogen can be present, a H₂ detector is installed to detect any problem of the process. It is the case into the two areas of the storage.

In this platform, ATEX zones have been defined around the gas panel outside and where there are gas fittings. In these zones, only materials with an appropriate ATEX certification have been installed.

The HDS-100-S is an innovative storage developed by McPhy Energy. It stores 100 kg of hydrogen, using the reversible absorption properties of a magnesium hydride composite.

The different technical characteristics of the hydrogen storage are the following ones :

- Maximum input pressure of hydrogen: 10.4 barg
- Maximum temperature of hydrogen inlet: 60 ° C
- Minimum Temperature of hydrogen inlet: -20 ° C
- Hydrogen outlet pressure: 4 barg

- Maximum temperature of hydrogen outlet: 60 ° C
- Temperature minimum of hydrogen outlet: -20 ° C

In addition, the tank must be placed in a ventilated area (minimum 100 m³/h) at a temperature between 50°C and -20°C and only used with the N55 grade hydrogen. It means these maximum levels of impurity (ppm-mol) :

- H₂O : 2
- O₂ : 0,5
- CO₂ : 0,05
- CO : 0,05
- N₂ : 2
- CH₄ : 0,1

The storage is composed of two parts:

- Area with bottles with the magnesium hydride composite
- Area for the gas management (gas panel, ...)

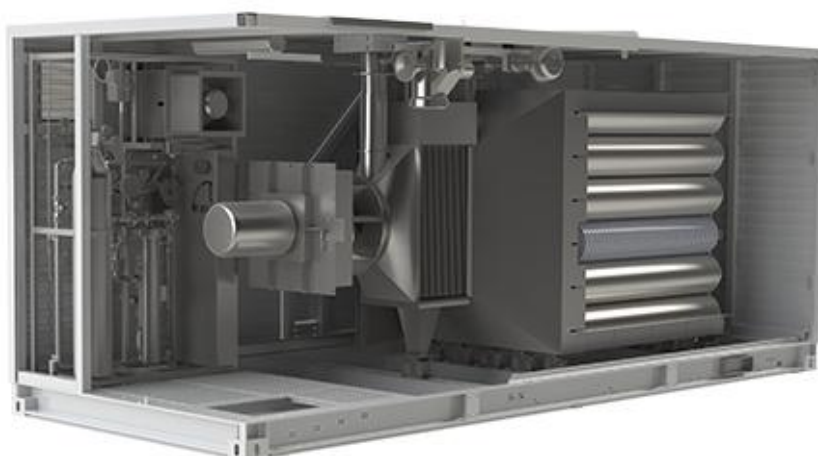


Figure 2.5. Layout of the storage system.

A pressure safety valve set at 12 bar is installed to protect the storage against an overpressure coming from the gas network.



Figure 2.6. Storage system from outside.

For the conformity of the solid storage, the following directives apply :

- Directive 97/23/EC : on the approximation of the laws of the Member States concerning pressure equipment
- Directive 94/9/EC : on the approximation of the laws of the Member States concerning equipment and protective systems intended for use in potentially explosive atmospheres
- Directive 2006/42/CE : on machinery, and amending Directive 95/16/EC
- Directive 2006/95/CE : on the harmonisation of the laws of Member States relating to electrical equipment designed for use within certain voltage limits
- Directive 2004/108/EC : on the approximation of the laws of the Member States relating to electromagnetic compatibility and repealing Directive 89/336/EEC

For the operation of these systems in France, the storage are subject to the following topics :

- 1416 : *Hydrogène (stockage ou emploi de l')* - Hydrogen (storage or use of).
- 1450-2 : *Solides facilement inflammables à l'exclusion des substances visées explicitement par d'autres rubriques (emploi ou stockage)* - Highly flammable solids excluding substances explicitly covered by other sections (use or storage).

- 1810 : *Substance ou préparations réagissant violemment au contact de l'eau (fabrication, emploi ou stockage des)* - Substances or preparations which react violently with water (manufacture, use or storage).

The list of the topics is available at the link:

http://www.ineris.fr/aida/sites/default/files/gesdoc/30296/BrochureNom_v33.1.1_20140327.pdf

or at the link :

<http://www.environnance.fr/pages/nomenclature-icpe.php>

For each topic, a law is applicable. The law which is applicable is given in the previous list of topics. It also depends on the quantity. You can upload them at:

<http://www.ineris.fr/aida/> or here : <http://www.legifrance.gouv.fr/>

In addition to the different laws described just before, as the storage is typically a pressure equipment, the following French law is also applicable to:

- Arrêté 15 mars 2000 : relative to the pressure equipment exploitation.

2.3.2 Hydrogen Filling Station in Huesca (Spain)

Aragon is a region located in the North of Spain who enjoys a great support from the local authorities on the development of renewable sources and hydrogen technologies. Following this line of work, the first Hydrogen Refueling Station (HRS) was built by Carbueros Metálicos - Air Products and opened in June 2008 in Zaragoza, the capital of Aragon, turning into the first public HRS in Spain. In June 2010 a new hydrogen filling station started operations in Huesca (Aragon), at the facilities of the Foundation for the Development of the New Hydrogen Technologies in Aragon. This new hydrogen station, built in the Foundation facilities located 70 km from Zaragoza, formed hereby the first "Hydrogen Highway" in Spain, with the final aim of the creation of a suitable infrastructure for the implementation of vehicles propelled by alternative and sustainable fuels, such as hydrogen, with zero emissions.

The station can be divided in different stages: production and purification, compression, storage and hydrogen dispensation. The electric power needed for the station operation comes from renewable origin, endowing the project with a global sustainable nature. The

Foundation has a mix of electrical renewable generation formed by wind farm, with a power of 638 kW using three different generator types, and a photovoltaic plant, is based on monocrystalline silicon, thin layer and polycrystalline sun followers with a power of 100 kW. Therefore, the hydrogen produced can be considered as “*green hydrogen*” without pollutants emissions, increasing in this way the high technological contents of the project. In the following photos, the wind farm and the sun followers are showed in the Foundation facilities.



Figure 2.7. The power for hydrogen production comes from solar panels and wind turbine.

Production and purification

The hydrogen is produced by water electrolysis in an alkaline electrolyzer of IHT company, with potassium hydroxide dissolution close to 30% in weight. The electrolyzer used has a discharge pressure of 32 bar which involves an important energy saving in the next stage of hydrogen compression. The electric consumption is close to 70 KW with a discharge flow of 10 Nm³/h and 99,7% (vol) of purity. It is important underline that the Foundation has been working together with the electrolyzer manufacturer in order to develop and optimize all the external components such us refrigeration system, gas separators or control system.



Figure 2.8. Alkaline electrolyzer for hydrogen production.

In order to use the hydrogen in a fuel cell, the hydrogen purity is increased in the purification unit, meanwhile the oxygen is vented to the atmosphere. The purification unit is composed of two condensers, a catalytic bed and two dryers bed. In this unit, the remains of water and oxygen must be removed so that the hydrogen purity reaches the value of 99,999% (vol) minimum necessary to operate a fuel cell. The two condensers remove the main part of the water contained in the flow; the oxygen reacts with the hydrogen in the catalytic bed to produce water which is finally removed in the two dryers bed operating at the same time. The first step consists of the oxygen elimination which is produced when the flow crosses through a catalyst bed, where the oxygen reacts with the hydrogen to produce water and a light rise of the temperature. In the reaction between the hydrogen and oxygen, the catalyst bed does not need to be regenerated, due to neither pollutant is produced. Subsequently, the water is removed by adsorption in two dryers towers that works in parallel. The water content is the sum of the water generated in the oxygen elimination and the water contained in the exit of the electrolyzer. When the flow goes through the dryer, the water is adsorbed in the particles bed and the purity increases up to the utilization in a fuel cell. In this case, the adsorption capacity of the tower is limited and when a tower is saturated of water, the control system changes automatically and the hydrogen flow begins to cross the other tower free of water. Therefore, the dryers towers must operate in parallel, while a tower is working (adsorbing water), the other is regenerating (desorbing water). The regenerating process can be realized with hydrogen or nitrogen.

Medium pressure hydrogen storage

There is a first hydrogen storage at 30 bar behind the purification unit where the hydrogen is stored so much for the fuel cells and different hydrogen demands of the workshops as for to keep a constant pressure in the compressor inlet. This storage contains up to 120 Nm³ of hydrogen at 30 bar.



Figure 2.9. First storage stage after hydrogen production; 120 Nm³ at 30 bar.

Compression

The compression stage is formed by a Hofer diaphragm compressor which increases the pressure from 30 bar to 350 bar in two stages, with a intermediate pressure of 100 bar. The compressor must be oil free in the mechanical parts that are in contact with the hydrogen so that the hydrogen flow is not contaminated when crosses each stage. After each compression stage, the hydrogen flow must be refrigerated to reduce the temperature so as to keep the hydrogen temperature in safe operation ranges and increase the efficiency of the unit. The maximum amount of hydrogen that can be compressed is 10,9 Nm³/h at 30 bar in the compressor suction head.



Figure 2.10. Two stages compressor, compressing hydrogen from 30 bar to 350 bar.

High pressure hydrogen storage

The high pressure hydrogen storage has a maximum capacity of 56 kg divided always in a three stage cascade system in order to increase the stored hydrogen efficiency. The hydrogen store is composed of high pressure stain steel cylinders in a steel bank. In the first stage of operation, the high pressure hydrogen storage will be close to 25 Kg. The cascade is formed by 18 cylinders with 6 bottles for each stage. In the middle of the next year is probable that the stored amount reaches the maximum according to the design.

For operating the cascade storage, the three stages are split into high, medium and low pressure. However, this differentiation is only to indicate the cascade operation, and not to the maximum pressure that can be stored in each stage. Initially the three stages are filled at the maximum pressure established of 350 bar.

Therefore, for filling process, the order of the stages used will be from low to high pressure with a certain pressure gradient between the cascade and the vehicle of 15 bar. Using this method the low and medium pressure stages provide most of the hydrogen supplied to the vehicle, and the high pressure stage is used to reach the target pressure of the vehicle's tank.

If the cascade storage system must be refilled, the operation order will be from high to low pressure. The first stage that is refilled is the one that has the hydrogen stored at maximum pressure in order to have the maximum amount of hydrogen to the maximum pressure

available if it is necessary to execute a filling. The cascade must be refilled when the pressure in one stage is below 330 bar. When this set point is reached the compressor begins to compress the hydrogen stored in the intermediate buffer and the electrolyzer begins to produce hydrogen. This operation is controlled by a PLC and the station keeps available to execute a filling if it is needed.



Figure 2.11. High pressure hydrogen storage at 350 bar.

Dispenser

The hydrogen dispenser is the final stage of the installation which connects the high pressure hydrogen storage with the fuel cell vehicle tank. The dispenser is able to fill buses and cars at 350 or 200 bar with a touch screen interface to select the fill pressure and visualize operation parameters such as filling time, variation pressure in the vehicle tank and in the high pressure storage, amount of hydrogen supplied and the price. The dispenser is activated by a pin code entered in the touch screen given just to the personal in charge of the station. The filling rate depends highly on the ambient temperature. Hereby, if the ambient temperature is higher than 30°C, the dispenser supplies hydrogen with a low filling rate in order to keep the temperature inside the vehicle tank below 85°C. This filling rate could vary

between 0.2 and 0.6 Kg/min. This is not the more efficient way of fill but it is a safety measure since there is no communication between the dispenser and the vehicle in order to know the temperature of the vehicle tank during the filling.



Figure 2.12. Hydrogen dispenser.

Control and monitoring

The station is controlled by a master PLC which oversees the installation for a safe operation and will be also used to record and send all the operation parameters such as pressures, temperatures, flows, time of fillings or electric consumptions so that these results can be analyzed in order to optimized the installation bottle necks, the station efficiency and to improve future designs of hydrogen stations.

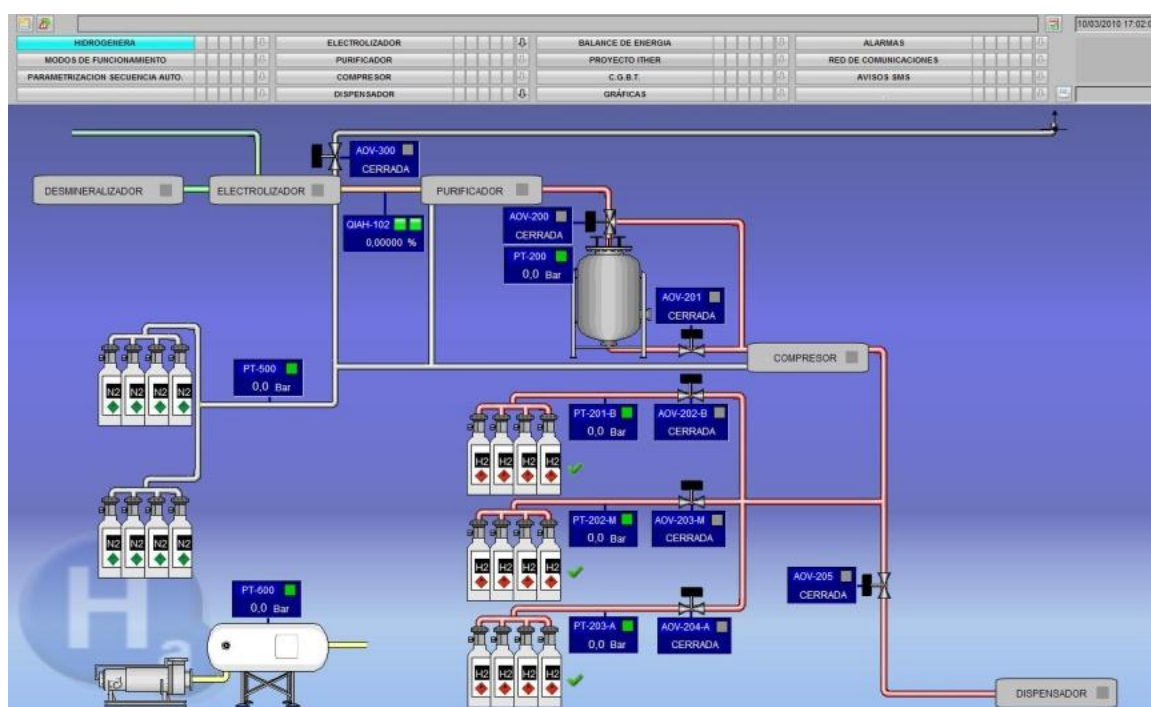


Figure 2.13. Monitoring and controlling display of the hydrogen dispenser.

PERMITTING AND SAFETY

For the permitting, there was a great collaboration by local authorities in order to speed up the procedures. All the permissions were granted by the local council of Huesca and by the regional government. It is important to evidence the great support of local and regional authorities in this project, which is very needed in order to develop these kinds of projects with a high cost of installation and a high uncertainty in the profits.

The main legislation that was applied is the following:

- Low voltage regulation R.D. 842/2002
- High pressure equipment regulation Directive 97/23/EC
- Construction technical code R.D. 314/2006
- Fire safety regulation R.D.2267/2004
- Chemical storage regulation R.D.379/2001,
- ATEX directive R.D. 400/1996
- Hydrogen rules recommended (but no obliged performance)

- UNE-ISO 14687 “Hydrogen as fuel. Product specifications”
- UNE-ISO 15916 “Safety considerations in hydrogen systems”
- EIGA. IGC Doc.15/05 “Gas hydrogen filling stations”
- EIGA. IGC Doc.121/04 “Hydrogen transportation in pipelines”
- EIGA. IGC Doc.134/05 “Explosive atmosphere ATEX”

In terms of safety, there has been no incident in the normal operation of the station. This includes a good safety record in the operation and filling process during maintenance. Some safety measures at the station are:

- Markings regard to best practices and prohibitions at perimetral fence
- Fence round the station so that people cannot come in to the station without authorization
- Fire sensor in the high pressure storage area
- Fire walls separating the high pressure storage area from the office and dispenser area. According to spanish regulation, this walls must be, at least, 50 cm higher than the highest point of the hydrogen storage
- Safety distance of at least 8 meters between hydrogen storage and nitrogen storage

2.3.3 Future Hydrogen Filling Station in Puertollano (Spain)

In the medium term, a Hydrogen Refueling Station (HRS) is planned to be installed in the Centro Nacional del Hidrógeno (CNH2) located in Puertollano (Ciudad Real), Spain. Nowadays, the project is in the design stage, and although neither European nor International specific standards for these kinds of facilities are available yet, standards from ISO and IEC bodies related to similar systems, and SAE and CSA documents are also being taking into account and the national regulatory framework.

The main objective, apart from the hydrogen supply, is the evaluation and optimization of the operation modes of the HRS. The refueling station should have the capability to fuel at least two 5 kg light vehicles storage system within a time span of 30 minutes and a maximum of 2 vehicles per day (10 kg/day). The stationary filling system can dispense hydrogen up to the 350 bars maximum. In this way, though only a small mass of hydrogen is produced daily, the

system offers opportunity to evaluate system reliability, cost, and safety. The capacities of all the storage vessels, the rate of hydrogen production, and the rate of compression must be coordinated and designed to achieve the required refueling demand.

The plant's hydrogen system consists of production, compression, storage and dispensing:

- ✓ The **hydrogen production system** is based on an electrolysis process that separates water into hydrogen and oxygen when an electric current is applied. The electrolyzer has a maximum production of 15 Nm³ of hydrogen per hour at 15 bars of pressure, being the quality of the hydrogen produced suitable for use in fuel cell-powered electric vehicles, according to the guideline SAE Technical Information Report J2719. The system includes a gas holder, which is a buffer tank installed between the electrolyser and the first compression stage. This tank allows storing hydrogen at the maximum working pressure of the electrolysis system and provides enough capacity when the hydrogen generator is not operating or is producing hydrogen in a low rate. The electrolyzer gets the energy from renewable sources, in particular, solar photovoltaic panels, enabling the refueling station to serve also as an electricity storage facility (hydrogen can be produced when there is excess electricity within the grid and stored until it is needed).
- ✓ The **first compression stage** consists on a gas booster pump driven by air, which is able to compress hydrogen gas up to 200 bars of pressure, using a simpler mechanism than a gas compressor with a single stage pressure arrangement. The performance will be function of the quantity of air available to drive it, the displacement per cycle of the booster and volumetric efficiency.
- ✓ The compressed hydrogen is stored in various cylinder bundles consisting of 16 upright 50-litre cylinders each one, with a total storage capacity of 560 Nm³. This storage, called **buffer storage**, provides hydrogen not only for the station, but for other pilot plants and laboratories located in the CNH2. Also, the facility includes commercial high purity hydrogen, as a "back up", if there is no electrolytic hydrogen available.

- ✓ In order to provide the desirable dispensing pressure, a **second compression stage** based on a diaphragm compressor is used. This compressor is capable of compressing the hydrogen up to 450 bars at a rate of 120 Nm³ per hour, filling the high pressure storage of the cascade storage system.
- ✓ The **cascade storage system** is divided into three reservoirs, which are low, medium and high-pressure reservoirs, at 250 bars, 320 bars and 440 bars of pressure respectively. The volume of cascade storage is approximately 550 Nm³, calculated to ensure that the hydrogen station can deal with the type and frequency of vehicles which will use the facility. This design also reduces the average applied differential pressure and hence the temperature rises during throttling due to the Joule-Thomson effect.
- ✓ The **hydrogen fuel dispenser** is capable of fueling 350 bars fuel system to 100% of targeted pressure without exceeding the specified limits according to SAE J2601. The dispenser used in this installation will be a Type D dispenser, which doesn't require cooling capability and the filling procedure is based on slower fueling rates than other dispenser types, in this particular case, up to a maximum flow rate of 2,5 kg/min. The dispenser will have two different nozzles, one for fueling light duty vehicles and other for fueling buses and trucks.

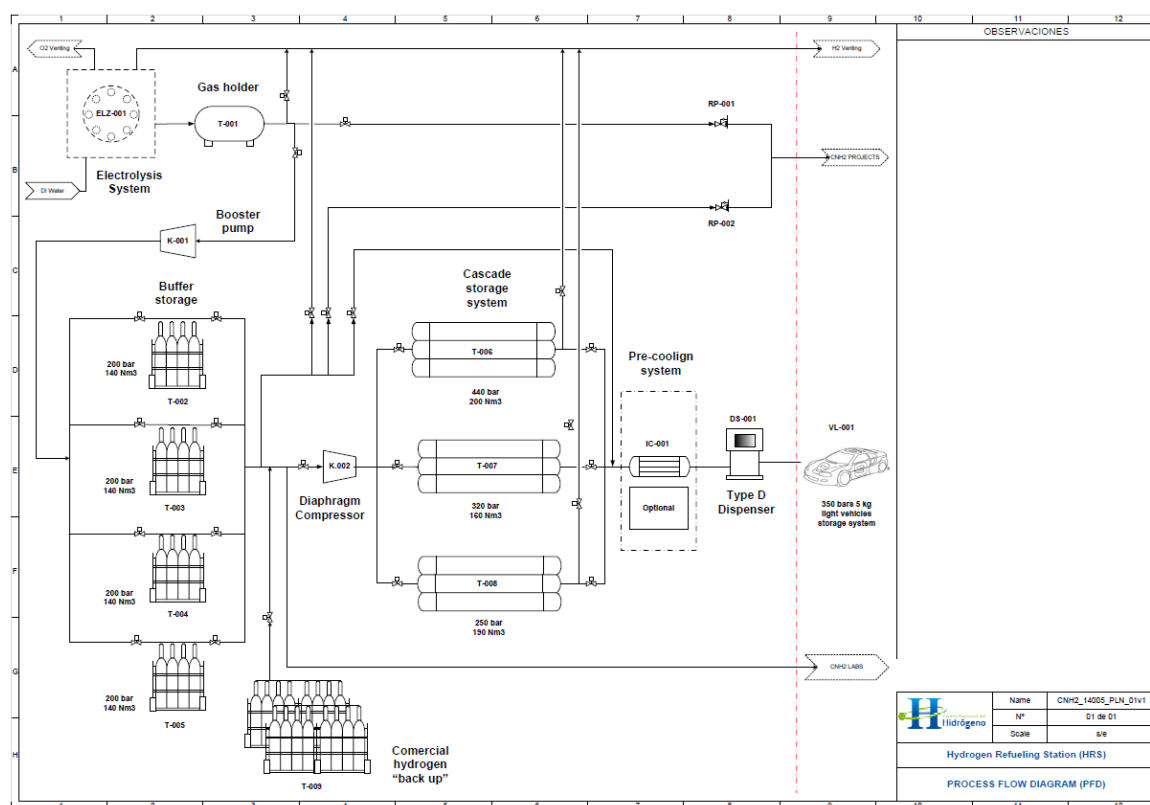


Figure 2.14. PFD of the Hydrogen Refueling Station (HRS) planned for Centro Nacional del Hidrógeno (CNH2) located in Puertollano (Ciudad Real), Spain.

Previously to the implantation and startup of the HRS it is necessary to prepare a safety study regarding to the national and international regulatory framework, focusing in separation distances requirements and storage facilities, taking into account that the safety requirements developed in the past for industrial applications are not necessarily adequate for these new facilities.

Summarizing, the most representative regulations and standards which are available and have to be taken as reference for the design and construction of the HRS are the following:

- **Spanish framework:**

- RD 379/2001, the regulatory framework for chemical products storage and its technical guidelines, concretely the MIE APQ 5, as it can be considered the most closed to the HRS requirements.
- RD 919/2006, the regulatory framework for distribution and utilization of gaseous fuels and its technical guidelines.

- **European framework:**

- Proposal of European Directive “Clean Power for Transport”. This Directive sets out minimum requirements on alternative fuels infrastructure build up, to be implemented through Member States' national policy frameworks, including common technical specifications for recharging points for electric vehicles and refueling points for natural gas (LNG and CNG) and hydrogen, and user information requirements.
- PED Pressure Equipment Directive 97/23/EC.
- ATEX Directive.
- Machinery guideline 89/392/EC
- Low Voltage guideline 93/68/EC

- **International Standards:**

- ISO 20100 Gaseous Hydrogen-Refueling stations, where priority is given to preventing escalation of small incidents into majors ones, with a focus on critical exposures such as places of occupancy.
- ISO 14687-2:2012 Hydrogen fuel -- Product specification -- Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles.
- ISO 17268:2012 Gaseous hydrogen land vehicle refuelling connection devices.
- SAE J2601 – Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles.
- CSA HGV 4.3-2012 – Test Methods for Hydrogen Fueling Parameter Evaluation.

Also, Local authorities and Industry Department of the Autonomous Community of Castilla La Mancha are involved in the design, construction and permitting process from the beginning of the project. Both of them are very important because environmental and building permits are required. Spanish authorities experience on the topic is not so high and they should participate in all the phases of the project for not extending too much the permitting lead time.

2.3.4 FILLING STATION - Emeryville, USA [8, 9]

The filling station of Emeryville (California, USA) is designed to fill both fuel cell cars and buses. The hydrogen is produced onsite by electrolysis or supplied as liquid hydrogen that is stored in a low-pressure tank. The station is capable of fueling 12 buses in a 24-hour period. The liquid hydrogen tank is replenished via truck delivery, typically every five to ten days. On average, the station contains about 1200 kg of hydrogen.



Figure 2.15. Hydrogen filling station of Emeryville (California, USA).

The station was put in service on August 31st, 2011 and refueled more than 1036 times before the first incident, which is here reported, on May 4th, 2012. The incident is described in detail in the report prepared by Sandia National Laboratories

Table 2.1. Technical data of the fuelling station in Emeryville, USA.

	Bus fuelling	Cars fuelling
Hydrogen source	Electrolyser (60 kg/day) / Liquid hydrogen tank	
Fuelling technology	Ionic compressor	Dry-running piston compressor
Fuelling pressure	350 bar	350/700 bar
Throughput	360 kg/day	240 kg/day
Fuelling couplings	350 bar	350/700 bar

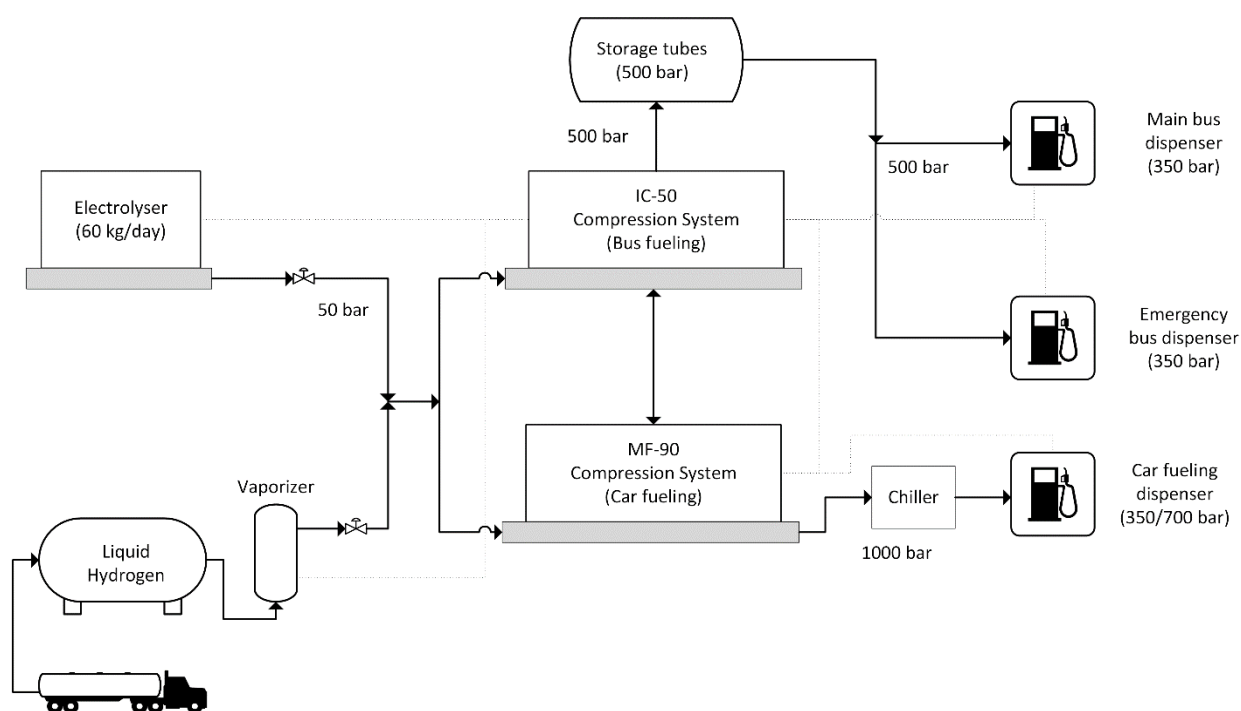


Figure 2.16. Scheme of the hydrogen filling station of Emeryville (California, USA).

In table 2.2 is summarized the sequence of the events related with the incident in the filling station. It started approximately at 7.45 AM on May 4th, 2012. The failure of a pressure relief valve figure below caused an immediate release of about 30 kg of hydrogen in the first minute; the incident escalated and led to an overall release of about 300 kg over 2.5 hours. The section of the plant involved in the incident is the high-pressure storage (i.e. “Storage tubes”).

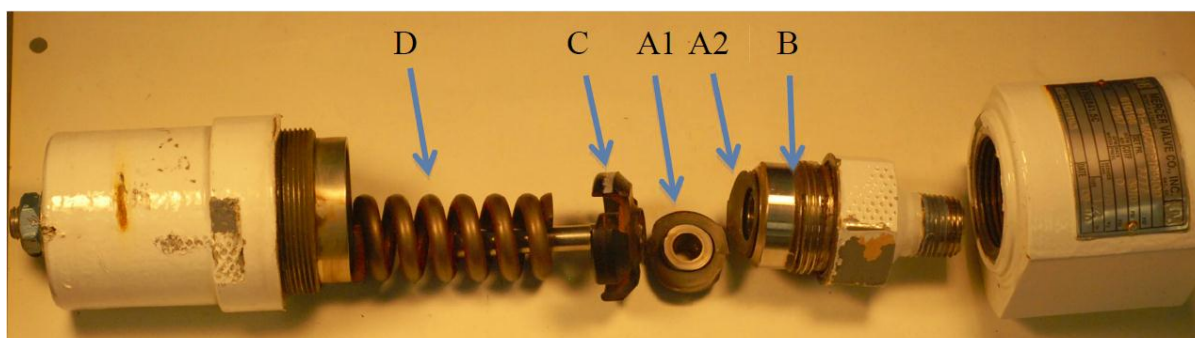


Figure 2.17. Pressure relief valve components: failed nozzle subassembly (A1, A2); inlet base (B); disk subassembly (C); set spring (D)

This kind of valves are designed to release gas in the event of an overpressure conditions; they are required by actual codes and standards on stationary storage systems that make use of pressurized gases. No overpressure was logged before the failure; the post-incident analysis of the component lead to the conclusion that the main factors that caused the incident are related with an improper selection of the materials and errors in the production process. A correct specification of the materials and a quality requirements check would have prevented this incident; further, widely accepted best practices about these components were available.

The first hydrogen release mixed with air in the vent tube and ignited producing a loud “boom” reported by eye and ear witnesses. A jet flame from the vent outlet stabilized and burned the top of the manual dispenser. The combusting paint and dust generated a yellow flame and smoke; after an unspecified time, the flame disappeared as the flammables, other than hydrogen, were consumed.

The emergency stop, activated by the plant operators, closed several valves and correctly insulated the high-pressure storage. The pressure measures indicated a decrease to about one third of the rated pressure corresponding to a release of about half of the hydrogen

content; the leakage is limited to the gaseous high-pressure section and no liquid hydrogen was released in the environment. From this point of view, the safety devices and procedures of the plant were sufficient and correctly operated in order to limit the effects of the incident.

Table 2.2. Sequence of events related with the incident in Emeryville Filling Station on May 4th, 2012.

Time	Event	Involved people
7.45 AM	Pressure relief valve failure - Immediate release of hydrogen. Emergency services contacted by phone. AC Transit employee activates the emergency stop.	Operators
7.57 AM	Emeryville Fire Department (EFD) classify the incident as “fuel tank on fire”.	First aid
8.17 AM	AC Transit Building evacuated by EFD.	First aid / Operators / Public
8.25 AM	Low pressure alarm in the storage that indicates an hydrogen vent from the system.	Operators
9.00 AM	Nearby public building (i.e. Secondary School) is evacuated.	First aid / Public
9.15 AM	AC Transit personnel gives the first update data to the EFD.	Operators
9.20 AM	EDF video surveillance reports multiple release points.	First aid
9.47 AM	EDF evacuates a 1 block radius.	First aid / Public
10.00 AM	Operators enter the area with thermal imaging equipment and confirms the leak from a vent stack and consequent fire. Storage in safety.	Operators
10.12 AM	Personnel close isolation valve on leaking vent stack.	Operators
10.58 AM	End of incident.	

Nevertheless, the escalation of the incident is mainly related to a missing communications among the involved peoples and to a wrong design of the vent. The emergency response was not sufficiently outlined in written procedures, and they were not executed as expected. Moreover, the fire alarm system was disabled by technicians that morning due to maintenance without communication to the fire department; this had no consequence in the incident, but it was a dangerous violation of the written procedures.

First responders, that had to face the situation, were not informed about the real situation in the plant. Information regarding the status of the system (pressures, temperatures, quantities of hydrogen) was available to the operators 15 minutes after the release started, but they were relayed to emergency operators only 1 hour and 35 minutes later. As a consequence, the measures taken by them were in favor of safety (i.e. school and plant surroundings evacuation). Both pressure and temperature level did not reach dangerous level in the system throughout the entire event. The situation is evaluated by means of the video surveillance: the report that supposed multiple release points was proved erroneous by the post-incident investigation. The internal communication in the plant and in the fire department worked fine, but the two entities failed to communicate with each other.

From the point of view of the design of the plant, two main mistakes were made. First of all, the position of the vent was too close to the dispenser; a free jet flame in the atmosphere would have generated no damages and avoided flames and smoke that could be dangerous for people. Vents would be designed in order to grant safe hydrogen release regardless its ignition. The dispenser was located after the tanks and the vent were already built without taking into account their presence; the lesson is that the design of such a plant must be comprehensive of all the details and has to be studied from a global point of view.

A second mistake was the design of the release system of the tank. A system that insulates the single hydrogen tube was missing. Therefore, as soon as the release valve activated, all the hydrogen in the whole tank was released (about 360 kg) and the leakage continues longer than if process isolation had been in place. The audible noise of the leakage was the only indication to the first responders that continued to escalate the incident.

The issues presented in this case study are lessons to be learned in order operate and design correctly hydrogen filling stations. Nevertheless, safety equipment was in general sufficient in order to grant the safety of people.

2.3.5 Incident at filling station (USA) [10, 11]

Near the end of the process of filling a gaseous hydrogen tube trailer at a liquid hydrogen transfilling station, a safety pressure-relief device (PRD) rupture disc on one of the tube trailer's ten tubes burst and vented hydrogen gas. The PRD vent tube directed gas to the top of the trailer where the hydrogen vented and ignited, blowing a flame straight up in the air. The operator filling the tube trailer heard a loud explosion from the sudden release of hydrogen gas and saw flames immediately. The operator closed the main fill valve on the tube trailer, stopping the hydrogen fill; however, the ten cylinders on the tube trailer were almost full (2500 psig/173 bar). The tube trailer involved in this incident was one of two tube trailers being filled simultaneously and was second in a line up of five tube trailers parked adjacent to one another at this location.

Emergency responders were dispatched to the scene. The facility deluge system was turned on. This system covers the trailer fill aisle with water and includes nozzles at the rear of the trailer and a fire cannon directed to the front. When the emergency responders arrived, they immediately began spraying the adjacent trailers to ensure that they stayed cool. The HazMat crews closed the 10 individual tube fill isolation valves located at the rear of the tube trailer and extinguished the fire. Total time to control the incident was less than 10 minutes and there was no property damage from this event.

Minor first aid was required for a mechanic working under the tube trailer during the filling process who bumped into the trailer several times during a hurried exit when the loud noise was heard.

The accident is caused by equipment failure. The hydrogen tube trailer involved in this incident was doing its first fill after requalification, where all the PRDs had just been replaced.

The PRD rupture disc designed for 3500 psig (241 bar) failed at about 1000 psig (69 bar) below rated pressure. The hydrogen tube trailer was grounded per procedure during the filling operation. Subsequent follow-up examination of the PDR rupture disc lot by the PDR manufacturer found that all of the lot conformed to specification.

- Specific response drills/exercises need to be conducted yearly. In this case, all safety systems worked as they should and outside emergency responders were not needed.

- Performing other tasks while filling hydrogen tube trailers, such as mechanic work, should be avoided. Most premature failures of hydrogen tube trailer PRD burst discs occur during the fill process.
- Grounding, as was done in the incident, should always be done during hydrogen filling. However, even when the fill vessel is grounded, it is not unusual for a hydrogen release to immediately ignite.
- The facility safety deluge water system should be checked periodically for coverage. In this case, a water cannon was a little off target from the last time it was operated and has now be repositioned and stabilized to ensure that it does not move in the future.
- Emergency responders assumed that adjacent tube trailers were heating up from single-cylinder vent flare as a 300°F (149°C) reading was obtained with a thermal device. This slightly delayed the closing of the cylinder isolation valves on the tube trailer. After-incident investigation found no paint discolored or burnt, so the temperature taken by the emergency responders was likely near the flaming vent discharge point.
- Securing hydrogen fill valve(s) at the back of the tube trailer was not dependent on the temperature at the vent stack, as this area was covered by deluge nozzles and located 40 feet (12.2 meters) away from the vent stack.
- Media involvement and resulting speculation can portray a situation as being much worse than it actually is.

2.3.6 “ZEROREGIO” - FP6 EU co-funded project [12]

Project “ZEROREGIO” started in 2004 and ended in 2010 [12]. Its objective was to improve the development of low-emission transport systems for European cities with demonstration activities. In order to reach this objective, different fields were investigated in the range of the project. First of all, use of hydrogen as an alternative motor fuel, produced as primary or waste stream in a chemical plant or alternatively through small “on-site” production facilities was evaluated. This activity required the development of infrastructure systems for hydrogen consisting of hydrogen production, compression, storage and distribution equipment and integration of these in conventional refueling stations. From the point of view of the vehicles,

demonstration of hydrogen as an alternative fuel was set up via automobile-fleet field tests at two different urban locations in the EU (Rhein-Main, Germany, and Lombardia, Italy). Both 350 bar and 700 bar onboard storages were tested.

Hydrogen sources were available at locations near the envisaged refueling stations. The conventional part of the refueling stations, already existing, was also made available for the project. The infrastructure for fuel transport from the source to the station was built in the project, as discussed further. Multiple solutions for infrastructure development for hydrogen were addressed: pipelining and trailers from a centralized production facility as well as local “on-site” H₂ production.

Car fleets were delivered and implemented by the automobile manufacturers DaimlerChrysler and Fiat. Field tests with the zero-emission fuel-cell vehicles were performed by respective city transport authorities in Mantova and the airport authority in the Rhein-Main region. The car fleets served for local deliveries, post distribution, taxi operations, passenger transfer etc. Technical as well as socio-economic evaluations of field tests led to suggestions and models for faster penetration of hydrogen as an alternative motor fuel over larger urban areas in the EU. A brief report of the infrastructure performances are shown in Table 2.3:

Table 2.3. Technical data of filling stations installed in the frame of “ZEROREGIO” project.

Number of filling stations	2
Number of dispensers	3 GH ₂ , 1 LH ₂
Average availability of dispensers	86.5%
Hydrogen refueled (gaseous)	1550 kg
Hydrogen refueled (liquid)	3700 kg
Number of accidents	4
Injuries to human or environment	None

Filling station design and safety features

The first filling station was located in Rhein-Main, Germany, where the following facilities were in operation:

- High pressure transport line for transporting hydrogen gas from the source (chemical plant producing hydrogen as a by-product) to the refuelling station;
- Compression and dispenser system for two pressures (350 and 700 bar);
- Storage and filler unit for liquid hydrogen;
- A multi-fuel conventional service station in the industry park Höchst in which the above hydrogen infrastructure is integrated.

The station started its activity on Nov. 17, 2006. The layout of the facility is shown below and the process is illustrated.

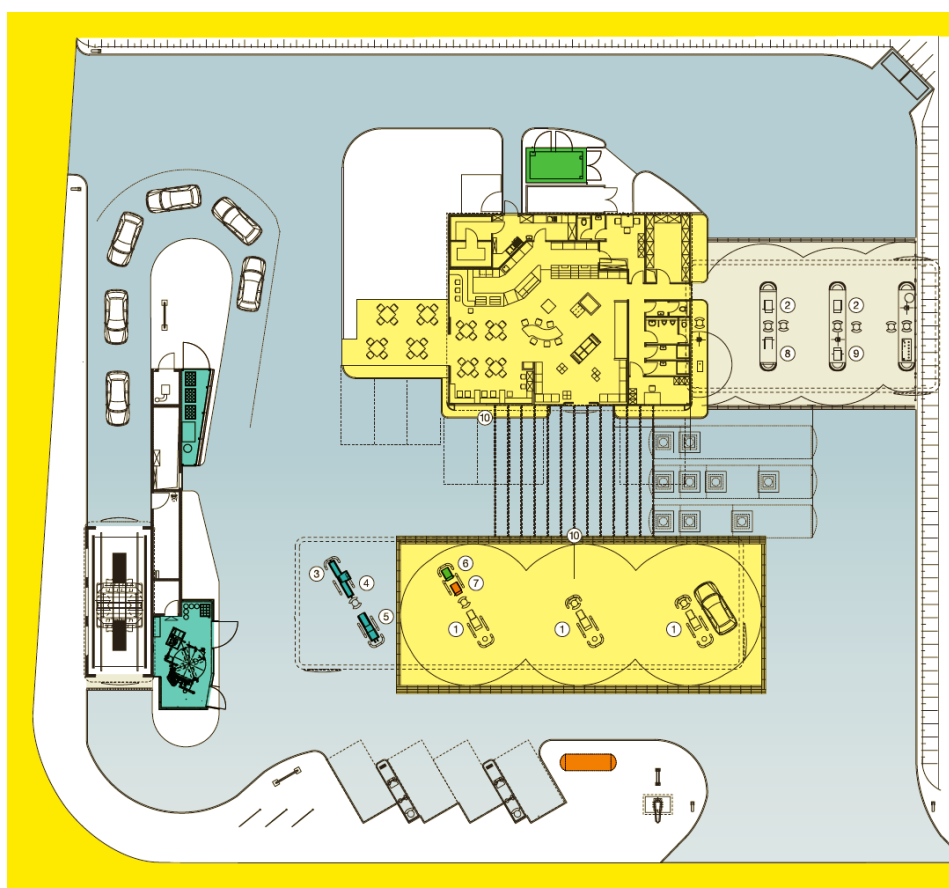


Figure 2.18. Layout of the filling station of Frankfurt, Germany (Höchst industry park): 1 - Regular fuel, 3-5 Hydrogen dispensers; blue - hydrogen infrastructure, green - natural gas infrastructure, yellow - photovoltaic plant.

The first section of the plant is located in a nearby chemical plant (chloralkali process) for which hydrogen is a by-product; after a first compression stage and a buffer, an innovative ionic liquid compressor increases gas pressure up to 900 bar. This component was one of its kind.

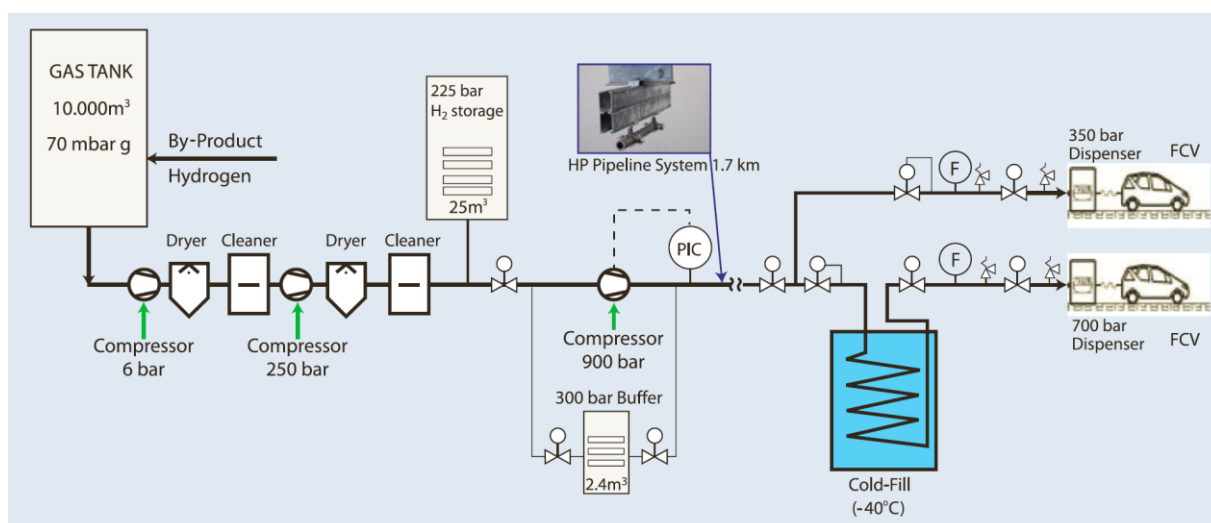


Figure 2.19. Process diagram of the Frankfurt filling station (gaseous hydrogen).

A pressurized pipeline delivers the hydrogen to the filling station (1.7 km in length, designed for a pressure up to 1000 bar); the solution chosen is a hanging pipeline that is buried when arrives in the filling station area. The hanging pipeline is a welded construction, leak-proof by definition, while the underground one is a tubing with PE sleeve in sand bed. A cold fill and two dispensers (one for 350 bar and one for 700 bar refueling) complete the layout. The dispensers are designed in order to achieve a 3 minutes refueling time as target for passenger vehicles. On the other hand, liquid hydrogen is supplied by means of trailers and compressed onsite (piston pump); a liquid hydrogen tank grants the adequate buffer (10 m³).

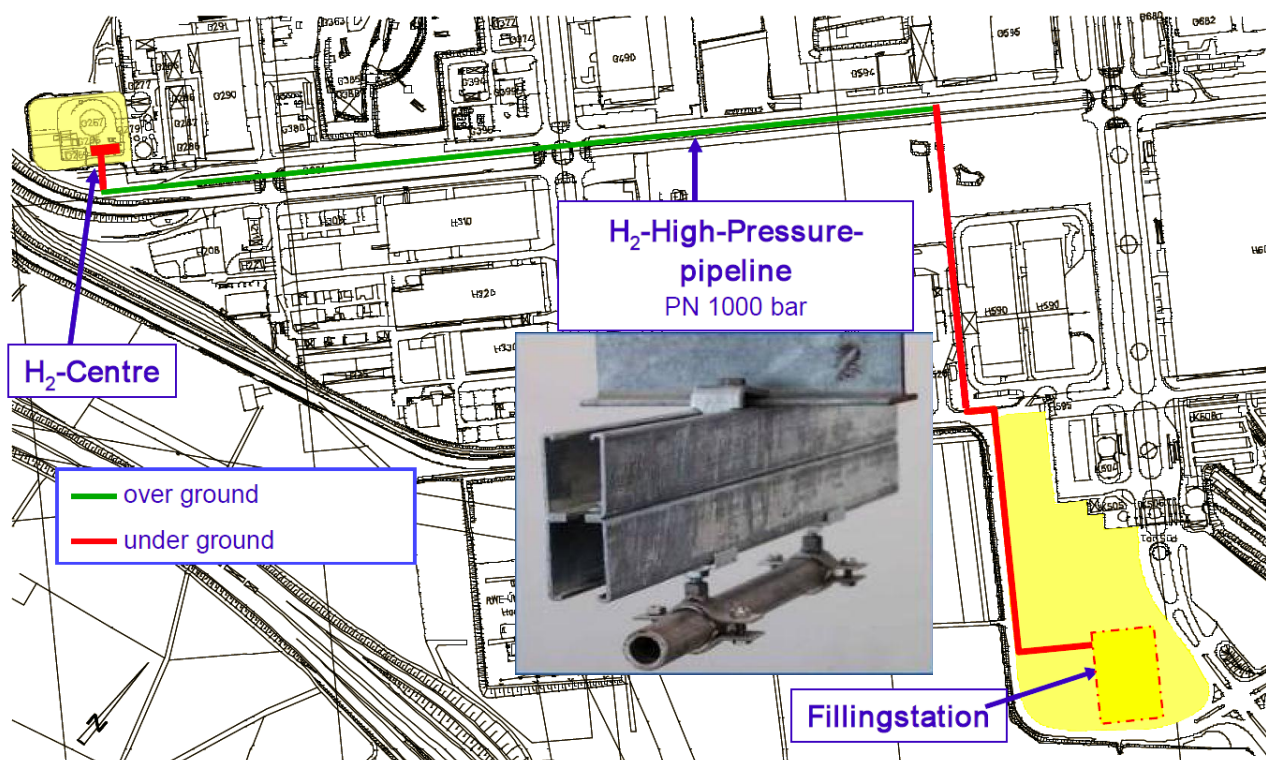


Figure 2.20. Layout of the transport line from the hydrogen source plant to the filling station.

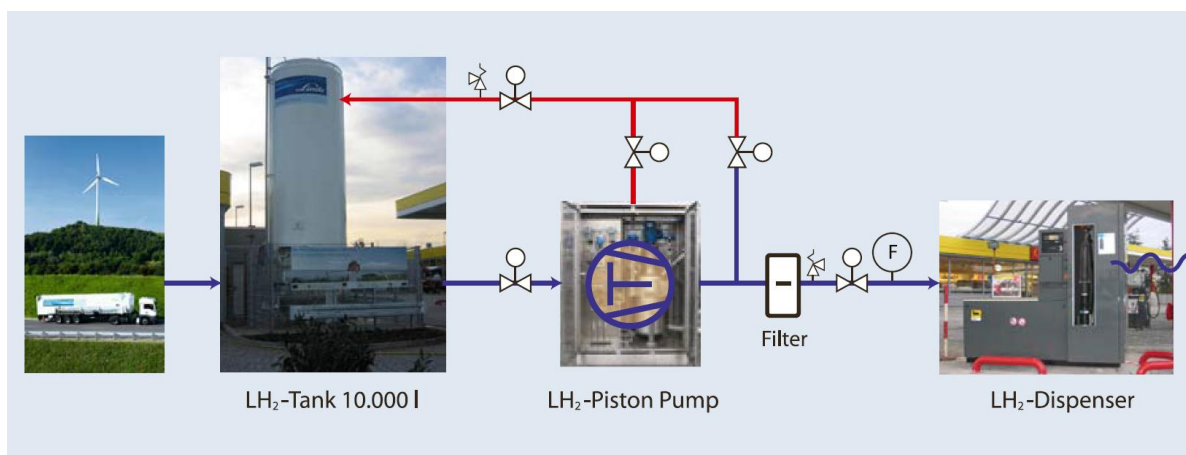


Figure 2.21. Process diagram of the Frankfurt filling station (liquid hydrogen).

Detailed reports of the operation are available. During the first year of operation, the two Zero Regio demonstration vehicles (F-Cell A Class cars) have filled hydrogen on a regular basis (at least once a day per car). In addition, other hydrogen vehicles including buses on

particular occasions have also used the refueling station. In all about 370 kg hydrogen has been refueled so far mostly at 350 bar vehicle tank pressure.

The transport system starts and operates automatically when at the station the hydrogen dispenser demands hydrogen. The system is monitored continuously in the control room and can be shut off by the control room operator in case of unexpected incidents. The compressor supplier can also monitor and control the compressor operation on line. The supplier can be contacted around the clock per hotline. In case of unexpected incidents and events, incident reports developed within the project are filled by the persons involved and on duty and the necessary information is communicated to the responsible personnel at the project coordinator.

The second Hydrogen Refueling Station was located in Mantova (Italy) and built by Sapio – Air Products. It started its activities on 21st September, 2007 after a long process to get all the permissions. The facilities in the station were an on-site hydrogen production facility based on a Catalytic Partial Oxidation process (CPO), that started in the second stage of the project, a hydrogen storage facility, a compression and distribution system for filling hydrogen at 350 bar. A layout of the plant and the process scheme are shown below.

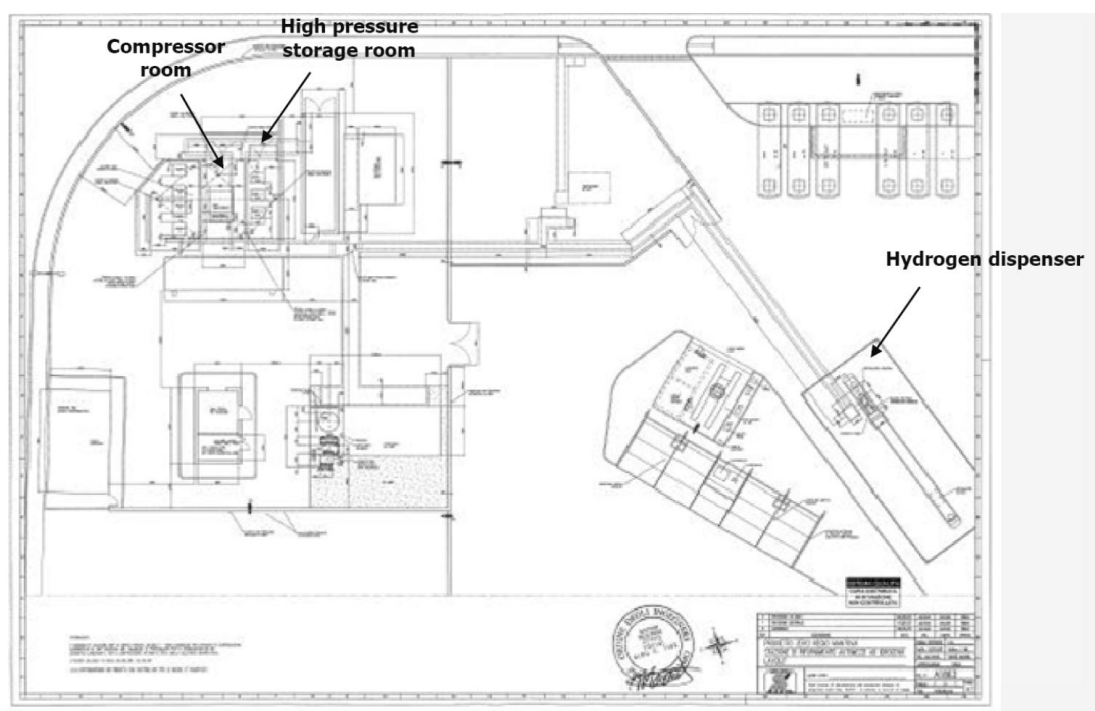


Figure 2.22. Layout of the filling station of Mantova, Italy

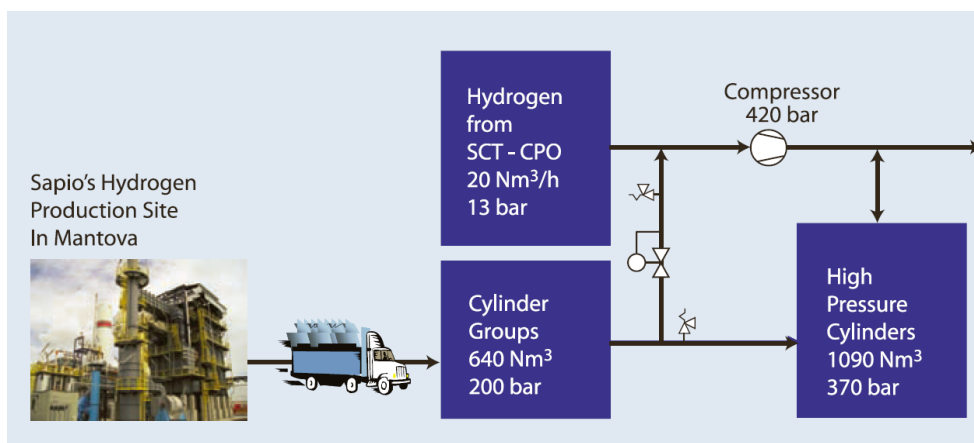


Figure 2.23. Process diagram of the Mantova filling station (gaseous hydrogen).

Before the startup of the onsite hydrogen production a cylinder group storage was built in order to feed the cars during the first phase of the fleet testing. Secondly this can be used as a back-up for refilling infrastructure. It was necessary to realise a pipe rack within the station, specifically designed to connect cylinders packs. A special one was designed to connect 4 cylinders packs. The pipelines are completely equipped with instrumentation which is designed to go in a “fail-safe” position in case of emergency of the plant. The compression is achieved by a two-stage membrane compressor and stored in a high-pressure storage unit.



Figure 2.24. Two-stage membrane compressor (left) and cylinders groups (right) for storage in Mantova filling station.

The building features and construction material (concrete) was chosen according to the Italian Fire Prevention rules, and a sprinkler system, automatically started up by a fire revealing system, was designed.

As can be seen in the figures, high concrete walls separated all the sections of the plant; a concrete wall was built in front of the dispenser, too in order to protect the structure from accidental impacts. Some of these precautions were not completely justified by safety analysis; a collateral effect was to give to the customers the impression of a very dangerous place, in addition to increase the costs and the building time. Due to the oversizing of the safety devices and structures, no significant accidents were observed in this station.



Figure 2.25. 350 bar dispenser in Mantova and concrete wall protection.

Reported accidents within Zero Regio Project

Some accidents occurred during the normal operation of the German HRS.

- Outflow of ionic liquid and hydrogen at one of the high pressure safety valves of the compressor was noticed on 12.04.2007. The safety valve including the copper washer ring were replaced.
- Compressor stop due to high pressure on the suction side was noticed on 19.04.2007. This incident was more dramatic as it sounds and damaged the safety exhaust line and valve and resulted in some hydrogen leakage. High pressure on the

suction side activated correctly the vent system. The valve on the pressure side was loose and caused the damaged.

- Compressor stop due to high temperatures was noticed on 11.09.2007 by the control room personnel. The cooler casing had a crack about 1 cm. long resulting in loss of the cooling water.
- On 06.12.2007 hydrogen was noticed by the monitoring sensors in the compressor room and the compressor was shut down automatically. The fault was discovered in the phase separator (separation of hydrogen and the ionic liquid) of the ionic compressor where the liquid level was not properly recorded. It must be mentioned that with the pipeline itself or with other components in the transport system no incidents were noticed.

About 620 kg of hydrogen was transported via the pipeline and refilled in the demonstration fleet of the project and other hydrogen vehicles outside the project during the reporting period.

The most relevant accident involved one of the dispensers. On 30.07.2007 a station customer from the conventional fuel side banged into the 700 bar dispenser while reversing his car. This damaged the housing and piping in the dispenser without resulting in any hydrogen leakage.

Figure below gives an impression of the damage. Technical and legal experts as well as insurance companies have been involved in clarifying this accident and the dispenser was replaced by a new one. This incident has been categorised, due to its very low probability, as an accepted risk by safety authorities in Germany. It opens up, however, some questions regarding the design of the protection barriers for the dispenser units; the barriers were slightly reinforced. In fact for all dispensers and not particularly for hydrogen dispensers. The accident did not affect the demonstration activities adversely.



Figure 2.26. 700 bar dispenser after the accident involving

Vehicle parking design and safety features



Figure 2.27. Garage for hydrogen vehicles into offices of SAPIO plant.

Specific attention was dedicated to the infrastructure required for parking the hydrogen FCV's, in particular for over-night parking. The garages were designed to be safe, ventilated

and kept above 1°C in winter. Covered garages have been employed at Fraport and Infraserv facilities in Germany meeting the above requirements.

In Italy, the base station of the vehicle fleet has been installed at the offices of SAPIO plant in Mantova city, where the vehicles were parked into a garage specifically built for them. The garage of the vehicles was built as a single room, containing all the three cars, equipped with a safety air circulating system, in order to avoid eventual hydrogen concentration.

Different components are intended to safety also onboard the vehicles. Safety and regulating valves are included both in the tank and in the hydrogen distributing line:

- Stop Valve (normally closed), placed in the tank, hermetically blocking the release of hydrogen in the event of collision, pipeline ruptures, user charges (engine or fuel cell) faulty or off, etc. Hermetic sealing also happens when the key is removed from the dashboard. The mass of hydrogen remaining in fuel lines is negligible;
- Calibrated-Diaphragm (pressure relief valve PRV) to a pressure of security, which comes into action in the event of abnormal surge;
- Fuse-Valve (PRD) calibrated to 104 ° C, which is intended to evacuate the gas in the event of fire, to prevent the rupture of the cylinder;
- Excess Flow Valve, that protects the mechanical system from failures due to excessive flow, for example, if experiencing a gas leak; the valve immediately detects the loss and reacts by stopping the flow.

Moreover, sensor of concentration / running hydrogen were included in the layout, in addition to the sensors of temperature and pressure. The vehicle is equipped with a hydrogen concentration sensor, placed in the rear of the passenger compartment. The sensor is positioned at the top because, hydrogen being much lighter than air will escape to the top of the passenger cabin. The concentration of hydrogen is measured in ppm (parts per million) and the signaling is both visual and acoustic: a special icon on the display begins to flash, while a beep is heard. When the hydrogen concentration sound alarm begins to operate (> 10,000 ppm) the control system activates the vehicle's automatic shutdown system. Similar systems are placed also in the filling station.

Regulatory and approval issues

From the point of view of safety best practices, this project is an interesting example. The first step of the process was an investigation for existing regulations and an assessment of

safety relevant incidents; Hazop studies have been carried out for all equipment. No specific technical standard existed referring to hydrogen filling station both in Germany and in Italy. The process in Germany lead to the implementation of a specific code of practice for hydrogen gas (*VdTUV Leaflet 514 04/2009*) that includes requirement for components, safety distances, measures against excess of pressure and other relevant indications.

Italian authorization process was slow because of many institutions involved, many steps to follow and many documents to produce; in absence of a reference standard the situation became very difficult and complicated to manage. A draft of a technical rule related to hydrogen vehicle refueling stations was prepared in 2004 and approved by institutions. Nevertheless, the final law took much more time to be approved and safety thresholds were increased without any evident justification. In the meanwhile, the filling station was built according to the approved standard and this caused some problems. Other similar issues were presented in the approval sequence of the vehicular fleet; the large number of involved authorities led to difficulties, for instance the vehicles were authorized to travel on A21 highway but not in tunnels, while another motorway society did not grant the authorization to transit. Moreover, despite an authorization for the dispenser to supply 350 bar hydrogen, the onboard storage was limited to 200 bar reducing the range of the vehicle.

One of the project results has been to evidence the importance of an harmonization of the legislation regarding the civil use of hydrogen across Europe, otherwise the technology and the safety measures are developed more according to the behavior of single authorities than to real scientific basis.

Altogether, no truly relevant accidents were observed in the filling stations and in the related storages, in addition to the ones that can be common with present plants where pressurized or dangerous gases (e.g. natural gas) are stored; none of the issues noticed was directly caused by hydrogen or by a wrong design of the components.

Comments - A. Rota - Regione Lombardia (project member)

The hydrogen dispensers were integrated in existing filling stations for conventional fuels (gasoline, diesel, LPG). The German station covered an area of about 4000 m² and in 2 years it was approved and completed. The innovative compressor was tested at 1000 bar in order to grant full efficiency at nominal pressure (900 bar); the debates were focused on the materials and the type of junctions for the high pressure pipeline. The main worries were related to possible leakages in this component that was located outside the areas of the

production plant and of the filling station, so the design was particularly accurate. Italian station covered an area of about 18000 m² and much of the worries were related to separate the hydrogen section from the other ones in order to prevent a hypothetical escalation of accidents. The innovative short-contact reformer used for onsite production had good performances in theory but was necessarily oversized (20 m³/h) for the real consumptions of the station, so the real performances were much lower both in terms of efficiency and of purity of hydrogen. Particular attention was given to the design of the garages, specifically built in Modena; the presence of the storage in the vehicle lead to particular requirements in terms of air circulation and the water in the cell to the setup of a temperature control system.

The project included also a study related to the efficiency of the energetic pathway of hydrogen that feeds the vehicles; emissions and environmental impact were more relevant than safety aspect according to some surveys that involved drivers and common people.

Another refueling station in Monza, dealing with hydrogen and methane mixtures, was not built due to discussions about safety issues and consequent lack of authorizations. An important point to be evidenced is that a European normative about hydrogen distribution and transport is mandatory: authorization procedures and lack of specific technical code of practice is the most relevant barrier. From the point of view of the public acceptance, there were no issues during the project. Anyway, for the customers of the filling in station in Mantova, the presence of high concrete walls and the isolation of the hydrogen dispenser gave a feeling of unsafety that was not justified by real and contingent dangers.

2.4 Conclusions

As main conclusions can be remarked:

- Hydrogen has physical hazards such as causing embrittlement of metals which leads to degradation and failure.
- Chemical hazards are related to: wide flammability and detonability ranges, low ignition energy, high flame velocity.
- Physiological hazards are related to asphyxiation, overpressure injury, thermal and cryogenic burns (hypothermia).
- There are hazards with storage, especially leaking and ventilation which result in mixing hydrogen with air hence, burning.
- Hydrogen has problems with transmission. It requires relatively more power to transmit. High pressure output electrolyzers have been recently used.
- Reliable and economic sensors are needed for detecting leak early.
- High degree of safety is essential to be achieved before any progress in applications toward hydrogen economy. Designs must take into account the intrinsic properties of hydrogen.
- Reliable and economic sensors are needed for hydrogen leak detection, in the overall storage installations and, in particular, in the dispensing area at the refueling stations. The use of these systems should always be recommended, if not mandatory, to safety interrupt the refueling process after any leak detection in order to prevent any major incident.
- High degree of safety is essential to be achieved before any progress in applications toward hydrogen economy. Designs must take into account the intrinsic properties of hydrogen. Particular attention should be put to the safe design of the future high capacity and high pressure (700 bar) refueling stations. These designs should retain at the same time the appearance of the current retail stations, avoiding as much as possible the use of very visible safety measures (e.g. high concrete walls, water fire extinction system excessive), for the widest public acceptance.

Deliverable No. 3.1

Chapter 3

Mobility and Vehicles

3.1 Introduction

In the framework of WP3, Task 3.3 focus on data collection about hydrogen safety related to mobility and vehicles.

The data collection process followed the methodological approach indicated in deliverable D2.4 “Mirror groups organization chart and data gathering procedures”.

Among the tools useful for data gathering the survey was considered the one with greater potential. The questionnaire was based on a website page where the stakeholders could write their answers. Despite this online tool the survey has not been successful and only a few answers were gathered. For this reason the work has been then more concentrated on literature review that gave the possibility to collect information about hydrogen safety aspects in vehicles and to find special case studies showing best and worse practice applied in the mobility sector.

In addition to the literature good information came also from direct discussions with people involved in activities with hydrogen fuel cell, especially people working on vehicles or components for them. Even if people in Solvay do not deal directly with hydrogen vehicles, they have anyway a good experience with PEM fuel cell or PEM electrolyzer testing, and their contribution was also important for writing this report.

In the following paragraphs information gathered through each tool are presented and discussed. The main deviation we had from the work plan is the relative weight of results coming from the survey, supposed to be quite relevant and resulted at the end almost negligible.

3.2 Interviews

According to the methodological approach defined in deliverable D2.4 a part of data collection activity was dedicated to interviews. We tried to get in contact with people involved directly or indirectly with activities related to hydrogen and mobility applications, which are mainly fuel cell powered vehicles.

A few people have been contacted, mainly people already in contact with our company for business reasons, and the discussion were held by telephone. People in general were open and at disposal for a good discussion even if it was not always easy to find the right time to talk, and the impression was that the safety topic was not the real priority in their activities. This does not mean that safety is not considered; it is a fundamental aspect for the success of hydrogen vehicles but not the limiting factor.

The main topics of the interviews were around general safety aspects related to hydrogen utilization, opinion about hydrogen hazards as obstacle to new technologies introduction and general perception from the public when approaching hydrogen powered systems.

Regarding hydrogen properties and associated risks we did not go into details because this information is available abundantly in literature and we focused mainly on personal opinions and feelings, coming from work experience. The main risk perceived in general is coming from the flammability of hydrogen even if the comparison with methane is often done and they are considered quite similar in term of hazard. The second important aspect is the risk of burst of high pressurized tank, which can reach 700 bar for having a good mileage of the vehicle.

Having always in mind that hydrogen is a fuel, and as such has intrinsic risks, in general people interviewed do not see the related safety issues an obstacle for new technologies introduction; the risks must of course be handled and mitigated but available technologies are considered at a good level for reaching an acceptable hazard level. Regulation and standard codes are important for best practice application in vehicle design and manufacturing; technologies are available for risk reduction but they must be correctly applied.

Apart the opinion of experts also the public perception is important to understand the potential of new hydrogen technologies. From the discussion held came out that in general the public is quite open in accepting hydrogen powered vehicles; for somebody hydrogen is

still automatically linked to dangerous explosion but with the correct information it is not difficult to show that hydrogen can be as safe as other common fuel used every day in normal life.

ANTONIO DELFINO and GINO PAGANELLI – MRT: Michelin Recherche et Technique - Switzerland

Dr. Antonio Delfino earned a PhD in Physics, he is at the Head of the Physics and Chemistry Department and has 12 years experience in PEM Fuel Cell

Dr. Gino Paganelli earned a PhD in Electrical Engineering and has 14 years experience in PEM fuel cell engineering

Michelin worked with hydrogen mainly for automotive applications, developing fuel cell systems and test cars based on hydrogen-air and hydrogen-oxygen fuel cells.

They worked also on a project with Airbus and DLR in 2008 performing flight evaluations of a fuel cell emergency power system within a A320 aircraft. In addition to these activities they evaluated a project for a fuel cell boat but they did not start working on that.

Talking about hydrogen safety in mobility applications the major risk is probably coming from the flammability of hydrogen when mixed with air, because it has a wide range of flammability. From their experience this aspect is not anyway considered an obstacle for car applications. With current technologies there are appropriate safety solutions that can reduce the risk of fire onboard, reducing the ignition sources and the risk of reaching a flammable mixture. Some properties of hydrogen, like lightness and diffusivity, help in this context because they reduce the chance to reach the LFL (low flammability level). This consideration is valid in open environment; in enclosed spaces, like in a garage, the situation can be different and in case of leak without correct ventilation the flammable concentration can be reached.

Michelin has developed a safety concept based on a dedicated hydrogen leak sensor. The leak sensor developed by Michelin was designed for very high sensitivity and reliability. It is able to deliver a built in test signal to ensure proper operation (Patents, FR2999811 (A1) and FR2999709 (A1)). This sensor has also very low power consumption; this allows the sensor

to be supplied even when the vehicle is parked in a garage in order to deliver alarm signals when hydrogen concentration reaches 10% of the LFL.

Another hazard related to hydrogen is its capacity to embrittle some materials, but also in this case it is not considered a big problem. The solution is simple and it is enough to select the right materials to avoid correlated risks; titanium has to be avoided for sure whereas materials like aluminum or composite can be applied without concerns.

The risk of tank burst has been well analyzed. The vessels can contain hydrogen highly pressurized (up to 700 bar) and in case of a rupture there is a big release of mechanical energy. They did not reach 700 bar in their experiences, working with a maximum of 350 bar. In case of tank rupture the risk comes from the release of energy in a very short time; releasing slowly the energy the destructive effects of the burst are reduced. Considering this aspect it is better to work with a composite tank because in case of a wall damage the rupture does not propagate and the gas takes a certain time to leak. On the contrary, with a metal tank the rupture propagates quickly and the vessel can split easily apart releasing gas and energy in a very short time. They did a lot of work on this topic and the solution that they adopted is a vessel composed by many smaller connected cylinders; the connections between the cylinders are properly calibrated to limit the velocity of gas transport from one cylinder to the other, so that in case of rupture the total amount of stored hydrogen takes more time to be released.

Other aspects taken in consideration to reduce the hazard of burst are the design of the chassis of the car and the installation of PRD/TRD (pressure and temperature release device). The chassis has to be designed to protect the tank from collisions and to constrain part of the energy in case of a burst. PRD/TRD is important to release hydrogen in a controlled way in case of increase of pressure or temperature of the vessel; they have developed a proprietary system for releasing hydrogen in case of temperature increase (Patent, EP1925864 (A1)).

The conclusion of this discussion is that safety issues will be not the limit for hydrogen usage in mobility applications. The risks associated are well known and they can be mitigated with the right technologies.

Apart the real risks it is important also to consider the perception of the people when talking about hydrogen utilization. In general from their experience, they see people quite skeptic about hydrogen safety. When talking about hydrogen people make an automatic connection to fires or explosions, even if they do not have technical knowledge or evidence for this fear.

This is not a rational conclusion but it comes from bad information. Michelin developed fuel cell systems also working with oxygen instead of air and people have no concerns in having an oxygen bottle onboard, even if it can be more dangerous than the hydrogen one. People that work regularly with hydrogen (for example a transporter) and know its properties are not particularly afraid of it; they work with hydrogen like with other flammable gases.

ALESSANDRO GHIELMI – R&D manager – SolviCore

Alessandro Ghielmi was researcher in the field of ionomers and membranes for fuel cells for over ten years in Solvay. He started his activity in this field back in 1999. From 2004 to 2010 he was responsible of the Fuel Cell Project in the Solvay R&D Center of Bollate (Milano), Italy. From 2010 to 2014 he was head of R&D at SolviCore, a leading company in the field of membrane-electrode-assemblies for fuel cells and PEM water-electrolysis applications.

SolviCore GmbH & Co. KG was founded on July 1st, 2006 by its parent companies Umicore and Solvay. The 50-50 joint venture is based in Hanau, at Umicore's main R&D site in Germany. SolviCore currently employs more than 50 people in research, development, production and sales of membrane electrode assemblies (MEA) and related compounds, to be used in fuel cells (FC) applications.

SolviCore is not working directly on systems for mobility applications but indirectly supplying MEA for fuel cells installed in these systems; they do not have specific experience in risk handling on vehicles but they work every days with hydrogen fuel cell in their test center for MEA evaluation.

During the interview the discussion was mainly focused on hydrogen properties and correlated risks and the people perception on hydrogen safety and utilization.

Hydrogen is considered a dangerous gas but not particularly worse than any other flammable fuels. Methane has similar properties to hydrogen, flammable and lighter than the air, and it is a commonly adopted fuel. A comparison with methane or natural gas powered vehicles is a good approach to understand the potential risk coming from hydrogen usage in mobility applications and to study the methodology for risk assessment and risk mitigation, considering of course the difference in properties of two gases.

The higher risk for hydrogen could come from its propensity to leak and flow (high diffusivity) and from its wide range of flammability, coupled with low ignition energy. The diffusivity and low density can have anyway some advantages because in open air hydrogen can escape quickly reducing the probability to reach the LFL. The low ignition energy in real cases is not making a great difference with other fuels because normal ignition sources, like a spark, have energy above the low limit of ignition for all of them.

The embrittlement caused by hydrogen is not considered a great hazard because it can be mitigated with the right selection of materials.

The other risk associated with hydrogen in vehicles is the high pressure needed to store the gas onboard. To reach a good mileage for a car the pressure inside the tank can reach 700 bar, which represents a big amount of mechanical energy that could be released in case of burst. The issue is not considered a big problem because with improvement in material science and building technologies the risk of tank burst can be reduced to acceptable values.

The real risks associated to hydrogen are important for the market evolution of related new technologies, but not to be underestimated is also the public perception of these risks. From his experience he thinks that the public acceptance will be not a great obstacle for the introduction of new hydrogen vehicles; talking with people in events like fairs or public presentations the safety aspects are always taken in consideration and there are often questions on the topic. People seem anyway not to have preconceptions against hydrogen and they are open to accept it especially after explaining hydrogen properties and making a comparison with gasoline and methane risks. People that work with hydrogen are aware of the related risks and they approach the gas without particular concerns; it is considered a flammable gas, like many others, and they know that the hazards can be managed with the correct handling.

In conclusion, even if he is not a real expert on safety countermeasures introduced onboard the vehicles, he believes that the technologies needed to mitigate the risks are available and that safety issues are not the obstacles for hydrogen introduction in mobility applications.

In his direct experience in fuel cell field over 15 years he never faced accidents or great risks associated with hydrogen utilization.

PAOLO DELZANNO – General manager – Dolomitech s.r.l.

Dolomitech (<http://www.dolomitech.com/>) is a newco founded in July 2010 in Trentino (Italy) with the aim of developing and commercializing environmentally friendly advanced propulsion systems (e.g. fuel cell propulsion systems).

They have a direct experience in fuel cell systems for mobility applications, having worked on fuel cell powered cars and buses. At the beginning of 2013 they put in service two small buses that work regularly every day; more details are described in one of the case studies reported in the dedicated paragraph.

We had a discussion on hydrogen and safety talking about hazards and countermeasures adopted to mitigate the risks.

In general hydrogen must be considered a dangerous gas but not more than other flammable fuels. They must be aware of the risks coming from hydrogen properties because they need to consider them during the design of the vehicle and of the fuel cell system. Hydrogen can be dangerous but if best practices are applied in the design, building and service phases of the vehicle the risk can be managed and reduced properly. They build their vehicles in conformity with the European Regulation nr. CE 79/2009; again more details on the bus design are given in the case study paragraph.

The main risks related to hydrogen are the possibility of ignition in case of leak and the burst of high pressurized tank. The technology has anyway reached a good grade of maturity and the residual risk is considered low and acceptable. The vehicle is designed to reduce hydrogen accumulation in case of leak; dedicated sensors can detect hydrogen below the LFL and trigger safety procedures; the tank, the only part of their system containing pressurized hydrogen, is tested in extreme conditions to verify its mechanical resistance.

Hydrogen, thanks to its high diffusivity, unlikely creates flammable mixture in open environments. A higher risk of ignition could be present in enclosed space, like a garage, but also in this case with the right precautions such risk can be minimized. The countermeasures used for methane works also for hydrogen, and consist mainly in the correct aeration to avoid accumulation under the ceiling of the buildings. In their building where the buses are parked they have sensors that open the doors for complete ventilation in case of hydrogen detection.

In conclusion at Dolomitech they do not think that safety issues are limiting the diffusion of hydrogen vehicles. The main problem encountered for market introduction is the high cost of components for the propulsion system, which lead to a high price of the vehicle.

Their two buses have been in service for more than one year; they travel every day and they did not faced till now any trouble related to hydrogen safety. They did not find resistance from people in using this public transport; people know that the buses are powered by hydrogen but they consider them simply like electrical vehicles.

ANGELO MORENO - Hydrogen activities coordinator - ENEA

From 1995, Angelo Moreno deals with hydrogen technologies and fuel cells, at ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) research center; mainly in the field of high temperature fuel cells and of stationary applications. Coordinator of several European and national projects, he is member of the European Hydrogen and Fuel Cell Technology Platform and of many other national and international boards.

He is often involved in dissemination activities addressing both common people and technicians. Until some years ago, the idea of hydrogen safety was strongly related with catastrophic event; nowadays, this preconceived approach is somehow outdate and a discussion can be hold on more reliable basis. The perception of a highly dangerous substance related with hydrogen is mainly due to lack of education and to fear of change. In the past, our cities were lightened with “town gas” (i.e. a syngas with an high content of hydrogen) that was distributed in a gas network; it cannot be appreciated a sensible increase in accidents with respect to actual natural gas grid. If that technology was applied some decades ago, why we cannot use it now that the technology had been improved? For sure, hydrogen is a hazardous gas and has to be handled consequently.

In the vehicular sector, we currently have methane vehicles that store onboard pressurized gases. Hydrogen storage requires higher pressures (i.e. 700 bar); nevertheless, the technological progress led to new types of tanks (multilayer, carbon fiber, ...) that in case of injuries limit the leakages and don't fragment in dangerous splinters. Moreover, the experiment that compares the flames from vehicles tanks, originated by hydrogen or gasoline

in consequence of an accident, it's an example of advantages of hydrogen technology. Without pointing out which is the hydrogen car, people would indicate it as the safest. Fuel cell electric vehicles are efficient; so, the energy globally stored, and therefore released in case of accidents, is lower than in traditional cars.

Technicians are aware that some properties of hydrogen makes it in principle more dangerous, but real life conditions usually makes no difference between hydrogen and other gaseous fuels (i.e. the activation energy of both hydrogen and methane mixtures are lower than the one that can be supplied by sparks or electric contacts).

A very important concept is that the choice about safety devices cannot be delegate to single person or safety personnel; a strong and homogeneous regulation has to be provided in order to avoid wrong practices. In fact, if the responsibility is left to the single (technician or emergency operator), safety devices could be oversized or, in exceptional cases, the project would stop due to the amount of excessive barriers.

An example can be the design of a refilling station for hydrogen fuelled cars or buses; a correct approach can lead to a full operating station (e.g. the one located in Berlin), whereas a preconceived approach to safety can strongly slow down the projects and increase the costs (e.g. RIVIERA project in Liguria, Italy).

The training of operators (i.e. technicians, firefighters, ...) is mandatory; but it's also mandatory the preparation of people involved in the authorization process. Sometimes people can also on purpose stress the hazards of hydrogen, in order to give a negative view of the technology; in this case, the correct information must be efficiently underlined to avoid erroneous perceptions.

The point is to disseminate the valuable contribution that hydrogen technologies could give in order to solve issues as global warming, local pollution (due to vehicles and domestic heating) and security of supply. Moreover, they can be coupled with renewable energy sources, increasing the positive environmental effect. This aspect must be emphasized together with the safety aspects when the technology is discussed and evaluated.

In addition, a clear roadmap has to be defined in order to favor and make uniform the effort to create a solid hydrogen market; unlike other well-established technologies, both the demand and the offer on the market have to be built and safety aspects, together with public opinion, have a strong influence on this process.

SOLVAY INTERNAL FOCUS GROUP

In Solvay Alternative Energy research group, we organize every month an internal meeting to address safety issues in work places. We took the chance of this event to dedicate a part of the last meeting to a discussion around a case study presented later in this report.

The meeting was held on May 27th, in Bollate R&D center. About 20 people from Alternative Energy R&D group were present. People were mainly researchers and technicians working in the fields of Li batteries, photovoltaic, fuel cells and H₂ electrolyzers.

The selected case study for discussion was on a CNG tank burst, happened in California in 2007 (see the dedicate paragraph for details). The accident has been described and analyzed to understand what went wrong and how the fatal event could have been prevented. A dedicated presentation was done to illustrate data and pictures.

The experience was positive and people were involved in the discussion. The case analysis showed that the main cause of the accident was due to a lack of good practice around the vehicle, whose tank burst during a fueling. Bad practices were applied during the aftermarket conversion of the vehicle, during a maintenance phase that followed a rear impact and during the fueling operation done by the driver.

Without going in technical detail the main conclusion of the discussion is that working with high pressure gases or flammable substances is always hazardous, but this risk can be mitigated and reduced if a proper handling of materials and devices is applied. In the specific case we noticed a lack in the formation of the personal working with hazardous conditions; vehicle converters and also the driver did not have the correct perception of the risk coming from highly pressurized cylinders, leading them to bypass good practice that are fundamental in handling the risk.

The formation of personal working on hydrogen vehicles and also the end-users is fundamental to prevent fatal accident.

3.3 Document review and observations

Document review and observations are tools used to collect information from literature and internet. There are a lot of documents and papers describing the topic of hydrogen safety. Many of these documents describe hydrogen properties and hazards, giving general information useful for any kind of applications. Other documents found are more specific for automotive applications, describing the risks associated specifically to car or bus powered with hydrogen. We found articles about safety countermeasures to be adopted to mitigate the risk, other on theoretical study and experimental study on accidents involving hydrogen.

The following part of this report is the resulting summary of all documents reviewed during the project and contains more detailed information on topics listed above. The paragraph contains information coming from bibliography reference [13] to [39].

Hydrogen in mobility applications.

Hydrogen is considered a good candidate to be the fuel for future mobility applications. Hydrogen is the most abundant element in the universe and it is very abundant on the earth. Hydrogen is not a source of energy but an energy carrier because there is virtually no “free” hydrogen on our planet; all of it is combined with other elements (mostly oxygen or carbon) in other substances.

Hydrogen could be used in the future to feed internal combustion engine, very similar to NGV or to power electric cars through the usage of fuel cells. An ICE working with hydrogen derives from gasoline or natural gas engine that is adapted to work properly with the new fuel. This solution reduces the pollutants emission and cut to zero the CO₂ produced onboard by the vehicle. The NO_x emission anyway is not avoided because this comes from the nitrogen contained in the air during the combustion. The usage of a fuel cell in electric cars is the best solution because the fuel efficiency in this type of vehicles is higher and the emission at the tailpipe is only water.

There are several fuel cell technologies but the most promising for mobility applications are the PEM FC (polymer electrolyte membrane fuel cell), working approximately around 70-90 °C and low pressure, generally between atmospheric and 3 bar.

We said that free hydrogen is not present on our planet so in order to directly use it as a fuel (both in a fuel cell or in an internal combustion engine), it must be separated from other

elements. The hydrogen fuel used in vehicles is either derived from water (by electrolysis) or from a gaseous or liquid hydrocarbon fuel (by reforming). After being separated it must be stored, first at the fuel station and then on the vehicle.

In theory hydrogen could be produced directly onboard from hydrocarbon fuel through a reforming process, avoiding the problem of storing hydrogen on the vehicle. Most of these reforming processes are anyway still too energy intensive, hot or voluminous to be installed in vehicles, particularly in passenger cars, and for this reason is not currently the applied technology.

Hydrogen can be stored onboard in four main ways: compressed, as a liquid, in hydride form bound to metals, or on the surface of solid porous materials or carbon nano-tubes.

The energy density of hydrogen per mass unit is high, about three times higher than gasoline or diesel, but it becomes very low if considered per volume unit at ambient pressure and temperature. For this reason hydrogen must be stored onboard at high pressure (up to 700 bar) or at low temperature (-253°C) to get it liquid and increasing in this way the energy stored on the vehicle to reach an acceptable mileage.

The metal hydrides could be a good solution for hydrogen storage because they allow hydrogen accumulation at low pressure but they are not used for mobility applications because the too high weight.

The forms of storage that are currently being tested are mainly compressed hydrogen and liquid hydrogen.

Years ago the hydrogen tank was mainly based on steel and to reach high operating pressure its weight was too high to be a good solution for onboard storage. Liquid hydrogen was then considered a better solution and applied on some vehicles. Tanks for LH₂ are typically made of stainless steel and basically have a tank within a tank with a vacuum seal between the inner and outer tanks. This forms a thermoslike insulating protection to reduce the rate of boil-off of the cryogenic hydrogen. The boil-off is one drawback of this technology; to prevent pressure build up in the cryogenic tank hydrogen is time to time safely vented. Depending on the use and building technology of the vehicle the expected leakage of stored hydrogen is 1-3% per day.

Today the new tank technologies for compressed gas are mainly based on lighter solutions than steel, consisting in aluminum or composite tank wrapped with carbon fibers and liquid hydrogen is not considered anymore an attractive solution for vehicles. This remains a more common technology to store hydrogen at fuel stations.

For compressed hydrogen gas the maximum pressure level used on a given vehicle type depends on the fuel tanks installed. Currently, storage tanks on the vehicles hold hydrogen at either 350 bar or 700 bar when completely full. The actual pressure depends on the amount of hydrogen in the tank and the allowable working pressure. Vehicles and tanks are extensively tested and are designed to maintain their integrity in the event of an impact.

Compressed gaseous hydrogen containers are normally categorized into the following four types [31] (see Figure 3.1):

Type 1 - Metallic container

Type 2 - Hoop wrapped container with a metallic liner

Type 3 - Fully wrapped container with a metallic liner

Type 4 - Fully wrapped container with a non-metallic liner

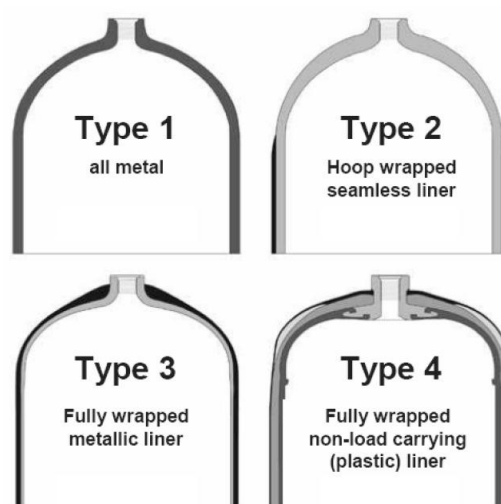


Figure 3.1. Types of Compressed Gaseous Hydrogen Containers [31]

In Type 3 and Type 4 containers, the main purpose of the liner is containment of the hydrogen gas, while the overwrapping provides the structural strength of the container. Current Type 4 containers use a polymer as the liner, e.g. HDPE, typically overwrapped with carbon fibers set in a resin matrix. Type 3 tanks have normally an aluminum liner with carbon fibers wrapped on the outside. Other fibers such as glass or aramid may also be used, but most automotive hydrogen applications use carbon fibers. The overwrap varies in thickness around the container depending on the stresses, as does the direction of the fibers. Type 3

or increasingly Type 4 containers are used for almost all current automotive compressed gaseous hydrogen applications.

Due to its small molecular size, hydrogen permeates through the containment materials found in compressed gaseous hydrogen storage systems. Permeation increases with storage pressure, material temperature and number of pressure cycles that the container is exposed to. For metallic containers or containers with metallic liners the permeation rate is considered to be negligible. However, hydrogen permeation is an issue for containers with non-metallic liners (the Type 4). Proposals for vehicle regulations and standards for hydrogen systems give limits on the allowable rate of permeation for Type 4 containers during approval tests.

For city buses compressed gaseous hydrogen storage systems are usually roof mounted, with the fuel cells either mounted on the roof or at the back of the vehicle, with both locations offering good ventilation that maximizes the use of the strong buoyancy characteristics of hydrogen in the event of leaks. Roof mounted systems are also outside of the impact zones of traffic accidents.

For passenger cars, hydrogen storage systems are usually mounted near the rear axle as this position offers the best protection in the event of a traffic accident, with the fuel cells mounted in the “engine” compartment or underneath the car.

Hydrogen properties and related risks.

In its pure form, a hydrogen molecule is composed of two hydrogen atoms (H₂) and is a gas at normal temperatures and pressures.

Hydrogen is a flammable gas with a wide range of flammability, between 4 and 75% in air. Also the ignition energy is small, being only 0.02 mJ.

To have a better perception of the level of risks associated with hydrogen is a good practice to make a comparison with gasoline and/or diesel fuel. These are the usual fuels used every day for vehicles and people accept their intrinsic risks; making a comparison with them we can better evaluate the level of acceptance for hydrogen introduction as a common fuel for mobility.

A first important comparison is between the flammability ranges; the following table shows the upper, lower and ignition energy for hydrogen, gasoline and methane.

	Hydrogen	Methane/Natural Gas	Gasoline
LFL (% in air)	4.0	5.3/3.8	1.0
UFL (% in air)	75.0	15.0	7.8
Min. Ignition energy (mJ)	0.02	0.29	0.30

Just looking at the wide range of flammability we could conclude that the hazard of hydrogen is higher than of gasoline or methane, but if we focus the attention on the low limit of ignition the conclusion can be different. In many practical situations the lower limit is the most important parameter; considering a case of slow leak the ignition will take place when the LFL is reached and in case of hydrogen this is 4 times greater than gasoline.

Also the low ignition energy in practical situation is not so critical because the value is valid only for stoichiometric concentration (25-30% H₂ in air); with concentration till 5% the ignition energy is comparable to that of methane and can be higher than that of gasoline (see Figure 3.2). Another consideration that reduce the practical risk of low ignition energy is that a common ignition source, like a spark from weak static electricity, has an energy of 10 mJ, which is much higher of all fuel ignition energies. Moreover, the LFL limit is applicable to laboratory conditions and marks the transition from the region where no ignition is possible to the region where ignition is barely possible under some conditions. Considering dynamic and usual automotive environmental conditions, the actual sustainable ignition threshold is significantly above the 4%.

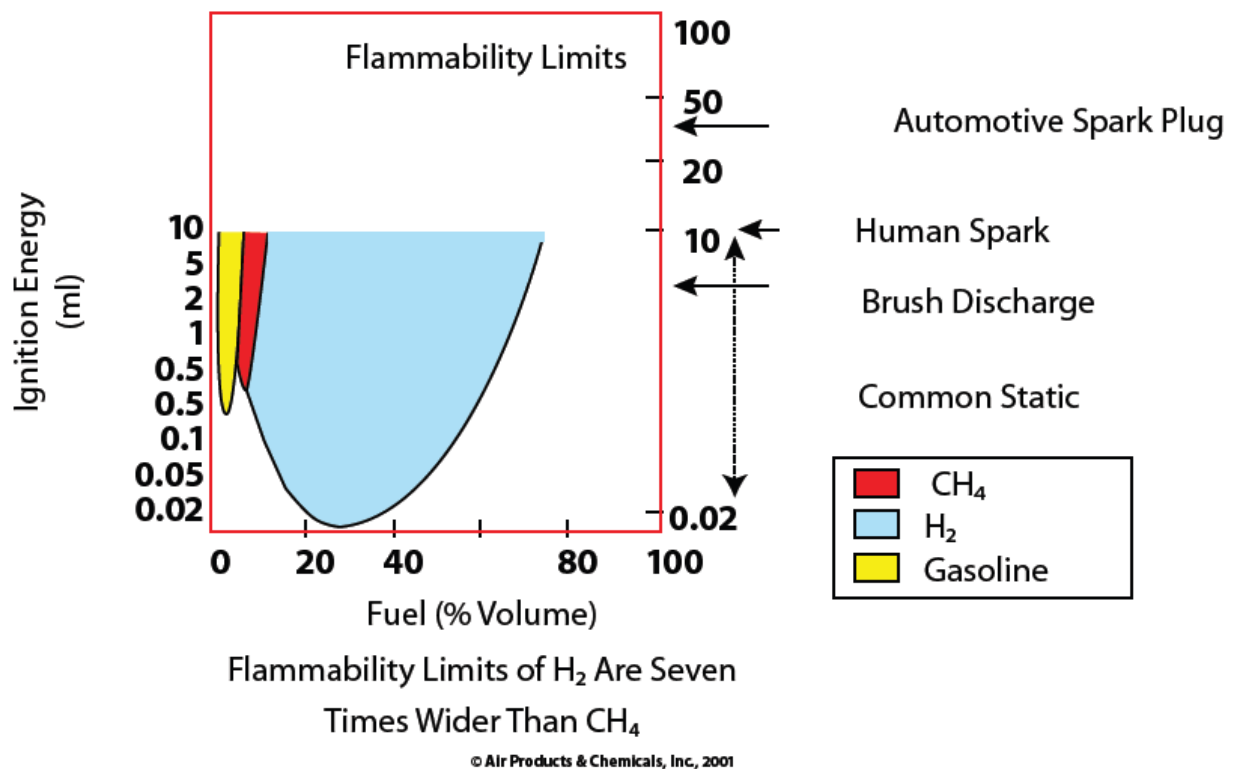


Figure 3.2. Flammability limits and ignition energy of hydrogen, methane and gasoline [23].

Comparing other properties of hydrogen with gasoline we can observe that the first has:

- Wider flammability range
- Lower ignition energy
- Greater propensity to leak
- Higher flame velocity
- Greater propensity to detonate
- Greater diffusion coefficient
- Greater buoyancy
- Lower explosive energy per unit volume

From these characteristics it seems again that gasoline is far better than hydrogen in terms of safety but again in real circumstances the conclusions are different. Hydrogen vehicles safety is judged potentially better than the demonstrated safety record of gasoline and equal to or better than that of natural gas. This conclusion derives from the positive safety attributes (higher buoyancy, greater lower flammability limit and higher lower detonation

limit), which are more important than the negative ones (low ignition energy, wide flammability range, high flame velocity and resultant tendency to detonate) in case of vehicle accident scenarios.

Hydrogen has 52 times greater buoyancy and 12.2 times greater diffusion coefficient than gasoline. The buoyancy is so high because the hydrogen density is only 7% that of air; thanks to this property in case of a leak hydrogen rises rapidly in air. On the other hand gasoline vapors are 3.4-4 times heavier than air and they will tend to remain at ground level in case of fuel spill. Also horizontal dispersion of hydrogen is faster than gasoline fumes because of the greater diffusion coefficient.

Ford tried to compare the risk of hydrogen and gasoline leak from a car for a DOE report. From their evaluation in open air the hydrogen car is less hazardous than gasoline because the lower probability of leak and lower probability of ignition since the gas rise away.

Diesel and gasoline are liquid fuels and this change the scenario in case of a leak if compared with hydrogen gas. Leaking liquid fuel can puddle and spread over a large area, and the puddles will persist because they evaporate slowly. Diesel fuel is not very volatile, and the risk that accumulated vapors will result in an explosion is small, even for large leaks. Gasoline, however, is very volatile and vapors from leaks can create the risk of an explosion if they collect in an enclosed space on the vehicle or in a building.

Several tests have been done to compare a fire in case of hydrogen or gasoline fueled vehicle. Figure 3.3 shows a simulation of a fire in case of fuel leak from the tank; in case of hydrogen the flame rises and burns until all hydrogen is vented from the vessel whereas in case of gasoline the fuel puddle beneath the vehicle and the entire car took fire.

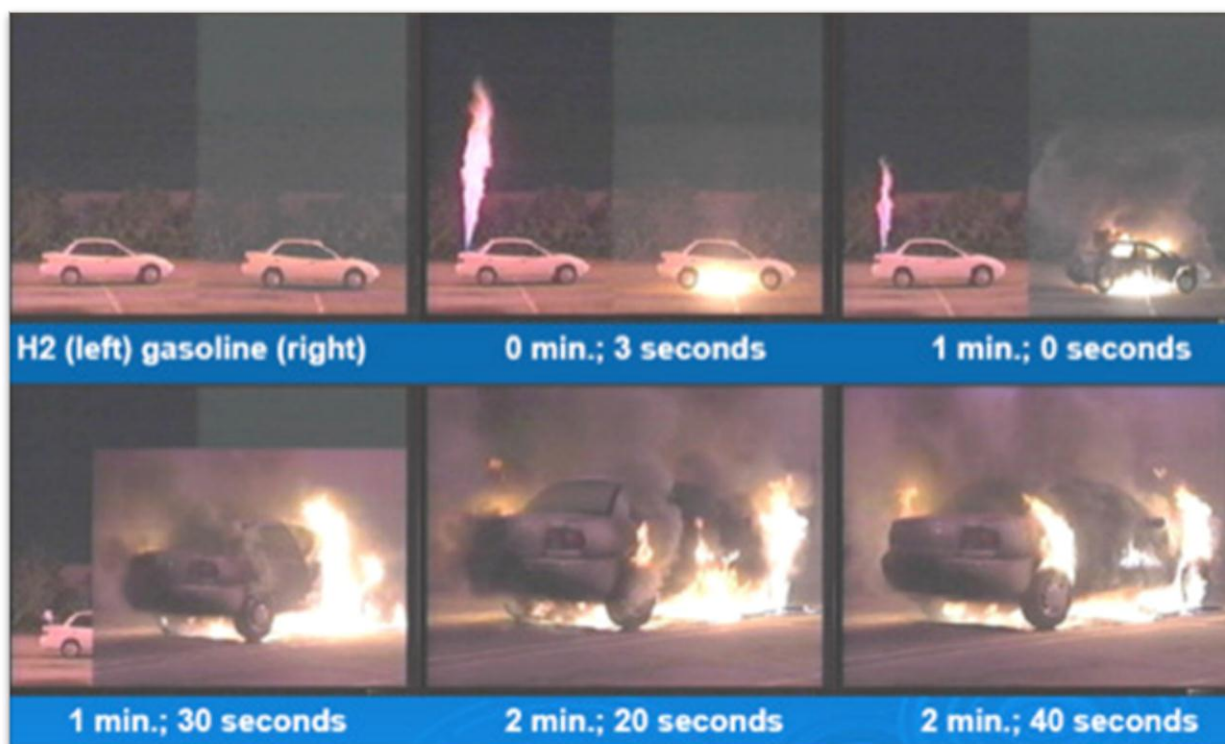


Figure 3.3. Direct comparison of ignited fire on hydrogen (left) and gasoline (right) leaking cars.

The maximum height of the hydrogen flames was higher than the maximum height of flames of the gasoline-fueled vehicle, but the gasoline-fueled flames were wider and persisted longer (from growing to diminishing flame). Radiated heat levels around the vehicle were also lower for the hydrogen-fueled fire than for the gasoline-fueled fire, and total damage to the vehicle was less. This is only one of many vehicle fire scenarios, but is illustrative of the differences between hydrogen-fueled fires and those fueled by gasoline or diesel fuel.

A hydrogen flame can occur when hydrogen is released from pressurized storage. The hydrogen may exit a leak location in a pressurized stream, or jet. The jet will have air at its edges and can combust in a jet flame, which is another name for a diffusion flame. A jet flame is similar to a Bunsen burner flame. Hydrogen gas can also experience a “flash fire” as it is mixing in air. A flash fire is a combustion event with little or no overpressure, and, as the name implies, it proceeds in a very fast time scale until the hydrogen is consumed.

As hydrogen gas is released into air, typically its concentration is very high near the release point and it is not well mixed in the air. If the gas ignites at that time, generally the result is a flash fire. Flash fires consume escaping hydrogen so it is not available for further mixing in

air. In one viewpoint, a hydrogen jet fire can be beneficial. If the area around the leak is confined (that is, within a building, a tunnel, a viaduct, a trench, a valley, etc.), then the jet fire reacts the hydrogen and does not allow hydrogen to pre-mix in the confined space. Without a pre-mixed system, an explosion cannot occur. Extinguishing the jet fire without isolating the hydrogen supply leads to venting unburned hydrogen. The hydrogen could accumulate and results in formation of an explosive mixture.

When the hydrogen gas has been well mixed with air, as in a gas cloud release into the air, the gas can have a deflagration explosion or a detonation explosion. Of these two pre-mixed combustion reactions, a deflagration explosion is less severe than a detonation explosion. The detonation has much higher overpressure, a shock wave, and much higher heat energy release than a deflagration.

A deflagration explosion is also a combustion event, where the combustion wave front is subsonic in the unreacted medium (typically air ahead of the wave front). The sound speed in air at normal temperature and pressure is 350 m/s. For gas deflagrations, the combustible material and the oxidizing agent (oxygen in air) are pre-mixed; that is, well dispersed and mingling together. This mixing assures adequate oxygen to hydrogen fuel ratios for combustion. The entire flammable zone, between 4% and 75% concentration of hydrogen in air, can support a deflagration event. A deflagration is typically a modest time scale and modest energy release event.

Deflagrations can undergo a transition to detonation under conditions where the combustion wave is increased past the sonic velocity in the unreacted medium. Factors that affect the possibility of a deflagration to detonation transition (DDT) in air are the hydrogen concentration (the gas concentration detonation range is 18-59%), the degree of confinement of the gas, the presence of obstacles or conditions that promote turbulence in the burning gas, and the strength of the ignition source. In open air is very unlikely that a deflagration transit to a detonation. Igniting a detonation in a gas cloud is more difficult, since the minimum volume concentration is 18.3% in air and the ignition energy is in the 10 kJ range.

A detonation is also a combustion event, where the combustion wave front is supersonic in the unreacted medium. A detonation is typically a fast time scale event with high energy output. Fortunately, most authors agree that even though hydrogen has a high flame speed and consequently high overpressures from deflagrations, a transition to detonation is not possible in an unconfined area. Since turbulence is required, the difference between the lower flammable and lower explosive limits exists for hydrogen, and ignition energies for

deflagrations are small, deflagrations are considered to be much more likely than detonation events, making deflagrations the safety significant events.

From the analysis above we can conclude that in open air the risk of hydrogen combustion is quite low thanks especially to the high buoyancy and diffusivity, which helps to keep the hydrogen concentration below the LFL of 4%. In case of ignition is then unlikely that the combustion or deflagration transforms in a detonation. The consequences of hydrogen leak can be different in closed environments, where hydrogen can accumulate and easily create a flammable or explosive mixture. Hydrogen leaks in indoor cases represent the most risky situation for this gas.

Having high diffusivity hydrogen in closed environments can dilute quickly but being in a confined space sooner or later it will reach the flammable composition in air; in this case the volume of flammable mixture can be also quite big increasing the probability of reaching an ignition point. With high volume of reactants the destructive effects in case of ignition are also more important.

Confined areas associated with automobiles themselves could be the passenger compartment, trunk or other cargo area, or engine compartment. Other confined areas common to automobiles could be a repair garage bay, a tire servicing bay, a parking garage, a residential garage or protective structure, a car wash building. Explosion confinement areas could be also a narrow street between tall buildings, a tunnel, under a bridge.

The greatest potential risk to the public would appear to be a slow leak of hydrogen in an enclosed environment without ventilation (passive or active) and leak detection, how could be a home garage.

The same risk of gaseous fuel accumulation in enclosed area is present with gasoline or natural gas but in this case the leak is easily detected because of the distinctive odor that they have; natural gas has no odor itself but it is added with odorant, something that now cannot be done with hydrogen. Odorants commonly used are organics containing sulfur and sulfur is known to be a strong poisoning elements for the catalyst used in fuel cells. At the moment there are no known substances that can be added to hydrogen without affecting the fuel cell performance. In case of hydrogen the only indication of a gaseous leak may be a whistling noise similar to escape of other high-pressure gases.

Another particular characteristic of hydrogen is that its flame is invisible and also in this case there are now no additives to color it. In case of a jet fire the risk is to get burned because a person can go closer to the flame without seeing it. The flame has also low irradiation energy

so it is more difficult to feel the heat from distance. The low irradiation energy has anyway positive effects because it reduces the risk of secondary fires when hydrogen burns.

A typical fire can still threaten personnel safety by smoke inhalation and heat exposure. However, hydrogen-air mixtures burn without any smoke, so smoke inhalation is only a concern if the fire ignites other materials. Inhalation of hot combustion products from hydrogen-air reactions and fire heat exposure are important since they can damage a person's lungs and burn the skin.

The high diffusivity of hydrogen is not considered a real problem for permeation through materials because the right wall thickness is the simple solution. The high hydrogen mobility can be a problem because it increases the leakage speed in openings (e.g. puncture in the hydrogen tank). Compared to methane the diffusivity of hydrogen is 3.8 times greater but the leak rates is only 1.26 or 2.83 higher depending on the flow regime, laminar or turbulent (so depending if the leak is on low or high pressure section of the circuit). On the other hand the energy leak is lower for hydrogen than methane because of different energy density (methane has about an energy density 3 times higher than hydrogen). Different leak rates are linked to different sonic velocity. Due to higher sonic velocity (1308 m/s) hydrogen would initially escape much faster than natural gas (sonic velocity of natural gas is 449 m/s).

Hydrogen embrittlement is another property often mentioned as hazard in case of its usage; this is actually a well know characteristic for hydrogen but is not an issue when proper materials are chosen for tank or BOL component (e.g. aluminum or composite). Materials known to be subject to hydrogen embrittlement are titanium alloy and high resistance steel.

The material selection is fundamental for the high pressurized tank used to store hydrogen onboard. To have a good mileage for the vehicles hydrogen must be compressed at high pressure (up to 700 bar) and this introduce a mechanical risks derived from structural failure and the subsequent release of mechanical energy.

An alternative to onboard compressed gas is the storage of liquid hydrogen, introducing risks connected to very low temperature (-252°C). Liquefied hydrogen has the additional concern of extremely cold temperatures that can lead to cryogenic burns, frostbite, hypothermia, and lung damage from inhalation of cold vapor. The eyes are a special concern for tissue damage from cryogen contact. Cryogen contact can also fail mild steel due to ductile-to-brittle transition and thermal contraction at low temperatures.

Additionally, in the case of emergency release, super-cooled components such as pressure release devices, pipes and valves, can "burn" the skin upon contact. A white cloud formed

by condensed water vapor (and sometimes liquid oxygen) may indicate venting or leaking LH₂. These clouds may, because of the higher density of cold gases, move horizontally or even downwards and contain cold GH₂. The hydrogen cloud may extend beyond the visible portion of a vapor cloud. This hydrogen will, however, warm up within seconds and quickly disperse upwards.

The largest amount of hydrogen present onboard a vehicle is inside the tank, hence the leak from tanks represent the highest risk situation for a vehicle. Several tank failure modes may be considered in both normal operation and collision, such as:

- Catastrophic rupture, due to manufacturing defect in tank, a defect caused by abusive handling of the tank or stress fracture, puncture by a sharp object, external fire combined with failure of pressure relief device to open;
- Massive leak, due to faulty pressure relief device tripping without cause or chemically induced fault in tank wall; puncture by a sharp object, operation of pressure relief device in a case of fire (which is the purpose of the device).
- Slow leak due to stress cracks in tank liner, faulty pressure relief device, or faulty coupling from tank to the feed line, or impact-induced openings in fuel line connection.

On the other hand the onboard fuel cell poses the least hazard, although hydrogen and oxygen are separated by a very thin (~20-30 µm) polymer membrane. In case of a membrane rupture hydrogen and oxygen would combine, but in that case the fuel cell would lose its potential which should be easily detected by a control system. In that case the supply lines should be immediately disconnected. The fuel cell operating temperature (60° to 90°C) is too low to be a thermal ignition source even if hydrogen and oxygen may combine on the catalyst surface and create ignition conditions. However, the potential damage would be limited due to a small amount of hydrogen present in the fuel cell and fuel supply lines.

Public perception of hydrogen safety and related risks.

By definition any fuel or energy carrier concentrates energy in a small volume, thereby creating a potential hazard.

Society has accepted this risk for fossil fuels considering the benefits that derive from them, so hydrogen should be considered acceptably safe if it is equal or less risky than gasoline. Gasoline is therefore a good reference point to judge safety.

Hydrogen vehicles are judged potentially less hazardous than gasoline or propane ones but public perception is different.

When hydrogen is proposed as a future fuel, the average person may ask the question about the Hindenburg, the Challenger, or even the hydrogen bomb disasters. The Hindenburg accident is often connected to hydrogen unsafety even if the main problem of that accident was related to the highly flammable covering of the dirigible, made of cellulose nitrate added with aluminum flakes, which are ingredients of rocket fuel. Another association is with the hydrogen bomb even if there is zero probability of having a fusion reaction of hydrogen in normal conditions.

Clearly, consumers will not accept hydrogen or any new fuel unless it is as safe as our current fuels.

The main reason why people can be scared by hydrogen is because they do not really know it. People do not recognize that hydrogen is already used extensively in industry (coolant, ammonia production, sulfur reduction in crude oil) and that it has been used for over 40 years as home heating fuel (town gas). Town gas is still used today in China and the main risk of this gas is not linked to hydrogen flammability but to the CO content (up to 5-6%). Hydrogen has been also used widely in the space programs.

The public is averse to the risks associated with unknown events, even while accepting the equivalent risks of common activities. For this reason hydrogen would probably have to meet a very stringent risk level. One approach to minimize unknown-fear phenomenon is to compare hydrogen directly with more common fuels (comparative risk assessment). We do not need an absolute evaluation of the risk and we do not need to define the acceptable risk level because the reference is given by the common fuel: hydrogen has to be risky like gasoline or better.

To address this perception problem crash tests with cars and high pressurized tanks of hydrogen could be executed, to demonstrate the safety of new vessels.

Risk reduction and management.

Both mechanical and chemical release of energy from the catastrophic failure of a cylinder would have a devastating effect on an automobile and its passengers. Failure of hydrogen cylinders must therefore be prevented.

Countermeasures to avoid a tank rupture for overpressure are always applied; there are three common options available: burst disks, fusible plugs and spring loaded valves. The most probable cause for tank overpressure is the increase of temperature of the contained gas, due for example to a fire. In the event of a fire impinging on the hydrogen storage tank, a temperature-activated pressure-release device (PRD/TRD) will open to rapidly release hydrogen, usually within a few minutes. The PRD/TRD is integrated into one end of the tank assembly and is sometimes routed through a vent stack. In vehicles with multiple tanks, each tank has its own PRD/TRD. If a PRD/TRD activates, you will usually hear a “bang” followed by a loud hissing sound, similar to the sound of a high pressure air hose. The tank will empty in 2-3 minutes.

The ventilation should be dimensioned to minimize the additional fuel supplied to the fire. The ventilation direction should minimize the potential contact with people and avoid of hydrogen accumulation. The cylinder opening can also be equipped with an excess flow control valve, which limits the maximum flow in case of the hydrogen line is broken.

One problem that can occur, and has been demonstrated with fire burst test, is that the wall of the tank can fail before the PRD/TRD is activated. In some experiments the pressure inside the cylinder did not rise sufficiently so that a pressure-activated pressure relief device would have activated to prevent rupture. The temperature inside the cylinder also did not climb sufficiently to activate a thermally-activated pressure relief device if it has been present. Thermally-activated pressure relief devices must, therefore, be exposed to a sufficient external heat source to guarantee activation.

In the most extreme case, a pressure relief device would prove ineffective when a cylinder is exposed to a point source of heat or flame. This can happen especially with type III and IV cylinders, which utilize aluminum or polyethylene liners, which unlike steel liners are not designed to provide integrity. The mechanical strength for these cylinders comes from the wrapping fiber; in case of an impinging fire the wrapping could be damaged before the activation of PRD/TRP and a catastrophic rupture occurs. Furthermore for type IV vessel the polyethylene liner provides thermal insulation for the contents of the cylinder. Therefore,

when exposed to fire, the temperature and pressure inside this cylinder will not climb as quickly as for a type I, II or III cylinder.

The installation of more pressure release devices in one cylinder can reduce the risk of catastrophic failure as well as the incorporation of one or multiple layers of thermal insulation with a debris shield, as demonstrated in some experimental tests.

Another important device for risk reduction in case of hydrogen usage is the sensor able to detect the presence of hydrogen gas in the air. Hydrogen is odorless and sensors are very important to warn the occupant of the vehicle or people around it in case of leak. H₂ sensors should also activate countermeasures like ventilation, FC system shut-down or valves shut-off.

An example found in literature [20] shows the sensors position on board the HydroGen4 fuel cell vehicle, which has seven sensors for hydrogen leakage supervision (see Figure 3.4). If the onboard supervision system detects hydrogen concentrations exceeding the threshold values, a hydrogen warning mode is enabled. The vehicle driver is notified by visible and audible signals, and fuel supply from the hydrogen storage system is shut down by closing shutoff valves.

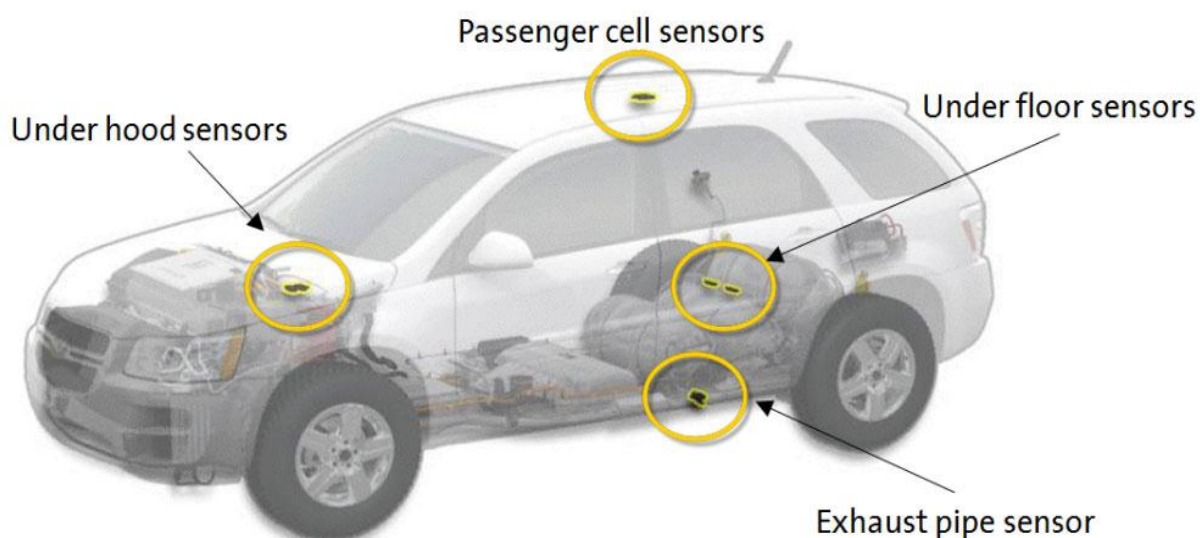


Figure 3.4. Locations of hydrogen sensors onboard the HydroGen4 [20]

In addition to hydrogen sensors also inertial switch can be installed on vehicles, which should again be connected to the control system and activate all safety procedures in case of collision: safety valves will shut off the flow of hydrogen and the electrical power will be cut from the battery. The principle is similar to that applied to air-bugs. These switches are activated above a preset “g” level (normally set between 5 and 10).

For preventing hydrogen related accidents the design aspects for the vehicle are fundamentals. Of the three legs of the fire triangle (fuel, oxidant, ignition source), the hydrogen system designer has the most control over the fuel source; hence it is important to minimize all potential for hydrogen to leak into the passenger compartment, trunk, cargo space, wheel wells, and other enclosed spaces. This is done through careful placement of fuel tanks, lines, and connections. It may also be advisable to provide ventilation openings in locations that might not otherwise require them, specifically to vent any leaked hydrogen.

The tank and the high pressure line should be installed into the vehicle in a place with the minimum risk of rupture in case of collision. Protections installed around the tank and lines should also be considered. Particular attention should be posed on the cylinder input port, which is the weakest point in case of collision.

A debris shield can be designed to protect against rocks and materials with specified velocities. There may be disadvantages, however. The shield will change the heat transfer to and from the tank or component. That could be good or bad. If it protects the tank from a pool fire, that would be good. If it prevents the thermally actuated-pressure release device from working as intended, it would have a bad outcome.

In addition to leak risk reduction also the ignition sources must be limited. On vehicle an ignition source can derive from the electric circuits, which can generate sparks; separating in the design the electric parts from the hydrogen circuit is a good practice for safety on FCV.

Onboard there are several leak sources that are installed on purpose, which are the outlets of all PRDs/TRDs placed on the vehicle. These outlets should be at the top surface of the vehicle and pointed away from the passenger or cargo compartment.

Material selection is of course very important. Materials subjected to embrittlement must be avoided. Hydrogen line should in metal materials. To be considered also the durability of materials, paying attention to the possible chemicals that could contact the parts causing a chemical degradation; for example a critical part could be the glass fibers wrapping the high pressure tank, which can be corroded by acidic solutions.

Finally it is important for people to recognize easily when a vehicle is fuelled by hydrogen, using the correct labeling according for example to SAE J2578 (see Figure 3.5).

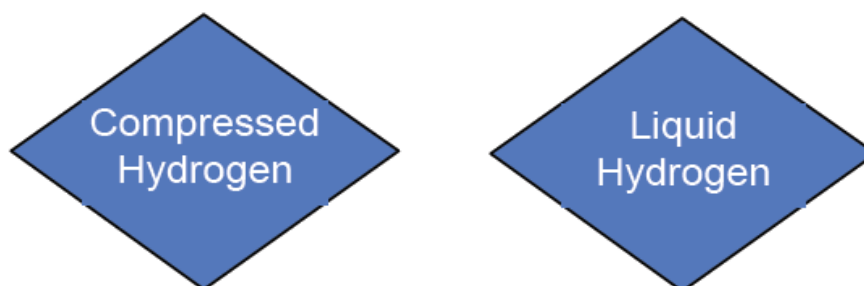


Figure 3.5. Labeling for vehicles fuelled with compressed or liquid hydrogen [23].

CFD for simulation of diffusion of hydrogen [28, 29, 30].

To understand the ignition risk of an air-hydrogen mixture caused by a localized leak an experimental test can be carried out. In this type of experiments a leak of hydrogen is simulated in a closed environment, like a cabin of a vehicle or a home garage, and with well localized H₂ sensor the diffusion of the gas is monitored to understand how and where the LFL is reached or passed. In some cases the mixture is also ignited to study the fire evolution.

This type of experiments are anyway expensive and time consuming, especially when the fire involve real cars.

A good approach to perform these studies consuming less resource is the utilization of CFD. With this computer simulation is possible to study the evolution over time of an air-hydrogen mixture cause by a fixed leak. The results can show where the hydrogen concentration reaches the ignition level and also the timescale of the diffusion. The main advantage compared to the experimental approach is that, once the model has been validated, it is possible to study many types of leaks and many types of environment with relative low effort.

The model is generally validated comparing calculated results with real data, simulating the real experiment conditions. Extensive CFD modeling has been conducted and validated

against experimental results in hopes that CFD modeling can be used as a reliable prediction tool for evaluating the safety of situations in which reliable experimental data is not available.

Since conventionally fuelled vehicles often are stored inside garages and travel through tunnels, it is natural to assume that the same situations will apply to hydrogen fuelled vehicles. For this reason, several studies have been performed to evaluate hydrogen releases within an enclosed or partially enclosed area such as a garage or tunnel.

A specific example for CFD found in literature focus the attention on existing home garages to understand if they are suitable for hydrogen fuelled vehicle or must be modified. The order of preference for garage modification was modification of garage door without using forced ventilation, modification of garage without using forced ventilation (addition of a passive vent at the garage ceiling) and last modification of garage using forced ventilation and addition of a hydrogen leak detection system. The results show that with opening in the garage door the concentration of hydrogen goes above the LFL only in the zone close to the leak source (see Figure 3.6).

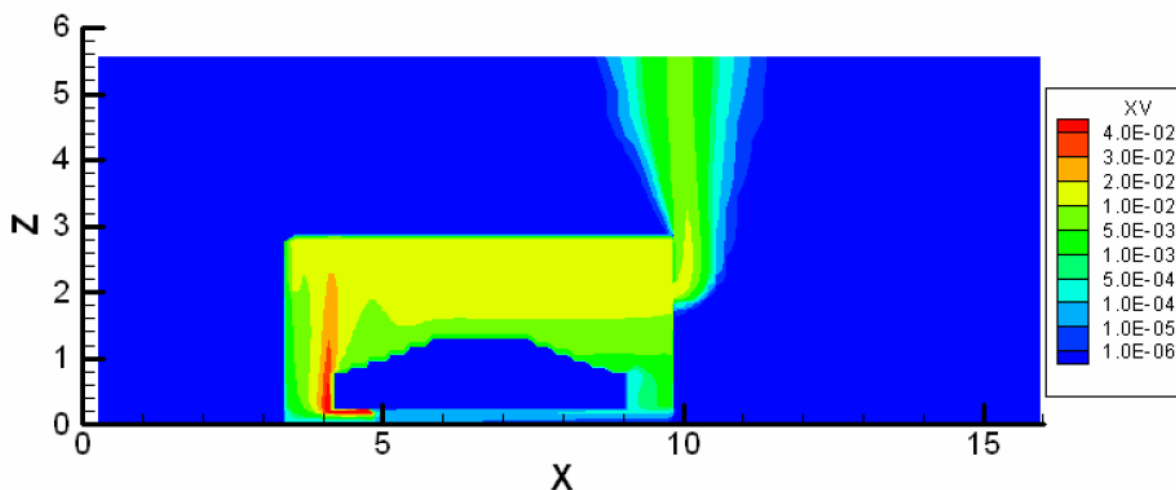


Figure 3.6. Contours of He concentration at symmetry plane at $t=3600$ sec [28].

3.4 Case studies

In previous paragraphs, through literature study, interviews and group discussions, we have seen a lot of information related to hydrogen properties, hydrogen hazards, methods of risk mitigation and also other less technical topics like the public perception and opinions on hydrogen utilization in new generation of vehicles.

In this paragraph using the case study tool, described in deliverable D2.4, we will move from a more general and/or theoretical view to realist scenarios, describing practical examples of best or worse practice applied in the field of hydrogen safety vehicles.

In our company we do not have meaningful experience with fuel cell vehicles and we have selected a few case studies found in literature or analyzed a real case contacting an external company.

First good news is that we wanted to start showing worse case examples, describing car or bus accident caused by onboard hydrogen, but we have not been able to find significant cases in literature or accident database. We searched for example in <http://h2incidents.org/> and found a few accidents involving fuel cell cars but none of them were related to hydrogen or fuel cell system. The idea was to describe real accidents to analyze and understand the causes, in order to give valuable information for future risk mitigation, but we could not do this. Of course this should not be considered an upsetting finding since the aim of our project is to show that hydrogen can be handled and used safely. Statistical data are maybe not relevant yet but, as described in following case studies, already thousands of operational hours or millions of kilometers have been collected by hydrogen buses or cars and no significant accidents have been recorded.

As said there were no accidents related to hydrogen in database records but we found a detailed description of a fatal event occurred on a van powered with CNG. In this case the accident consisted in the burst of one of the pressurized tank installed onboard. The tank was containing natural gas but since the cause was a mechanical failure the same event could have been happened with hydrogen. This example shows that the risks are always present, but in this case a series of bad practice caused the fatality that could have been avoided with appropriate behavior.

Other three cases reported are examples of good practice. We analyzed the operational data, kilometers and hours, of car or bus fleet demonstrating that millions of kilometers can be driven without particular concern regarding safety. Two cases are based on funded

projects demonstrating the operability of bus and car fleet (HyFLEET:CUTE and PROJECT DRIVEWAY) and the analysis come from project reporting documents. A third example relates to an Italian startup that is operating two small hydrogen fuel cell buses; for this case we had the chance to visit the company, talk with the personnel and also make a tour around the valley in Trentino where the buses are in service. For this particular study we had the chance to gather more details and information on the vehicles and their operation.

Finally we reported briefly a case of training for operators that have to work with hydrogen vehicles. We have seen in previous discussions that technology is fundamental to improve safety of vehicles but people training and formation are equally important. This is for sure an example of best practice because everybody who has to work or simply to drive an hydrogen fueled vehicles should be aware of the risks associated and the basic safety concepts to be followed in case of accident.

3.4.1 HyFLEET:CUTE: Bus Technology and Fuel for TODAY and for a Sustainable Future [40, 41].

This case study comes from the analysis of a funded project called HyFLEET:CUTE; the project brings together 31 partners from industry, Government, academic and consulting organizations.

HyFLEET:CUTE has been established under and is financially supported by the European Commission's 6th Framework Research Program. The European Union's Energy Policy aims at diversifying and security energy sources while reducing CO₂ (Carbon Di Oxide - a gas that contributes to the world's Climate Change) and other emissions harmful to the environment and human health. Hydrogen is a key element in this future strategy for road transport.

The HyFLEET:CUTE project has involved the operation of 47 hydrogen powered buses in regular public transport service in 10 cities on three continents. The Project started in 2006 and concluded at the end of 2009. Its aim was to diversify and reduce energy consumption in the transport system by developing new, fuel efficient hydrogen powered bus technology, plus clean, efficient and safe production and distribution of hydrogen as a transport fuel. No

accidents causing harm to people, assets or environment occurred during the project, which represents for us a good case study or best practice.

All the buses tested and operated within this project can be divided in two main categories: electrical buses with power coming from fuel cell technology and more conventional buses based on Internal Combustion Engine powered with hydrogen. More precisely 33 buses had a fuel cell power train and 14 buses had a hydrogen ICE power train.

Fuel Cell (FC) Power Train.

Thirty three hydrogen powered FC buses continued operations for at least one year in Amsterdam, Barcelona, Beijing (China), Hamburg, London, Luxembourg, Madrid, Perth (Australia) and Reykjavik.

The operation of the 33 fuel cell buses within HyFLEET:CUTE was a very successful continuation of the CUTE, ECTOS, STEP and FCB Beijing projects.

The main FC bus fleet was equipped with a pure fuel cell power train, as schematically shown in Figure 3.7.

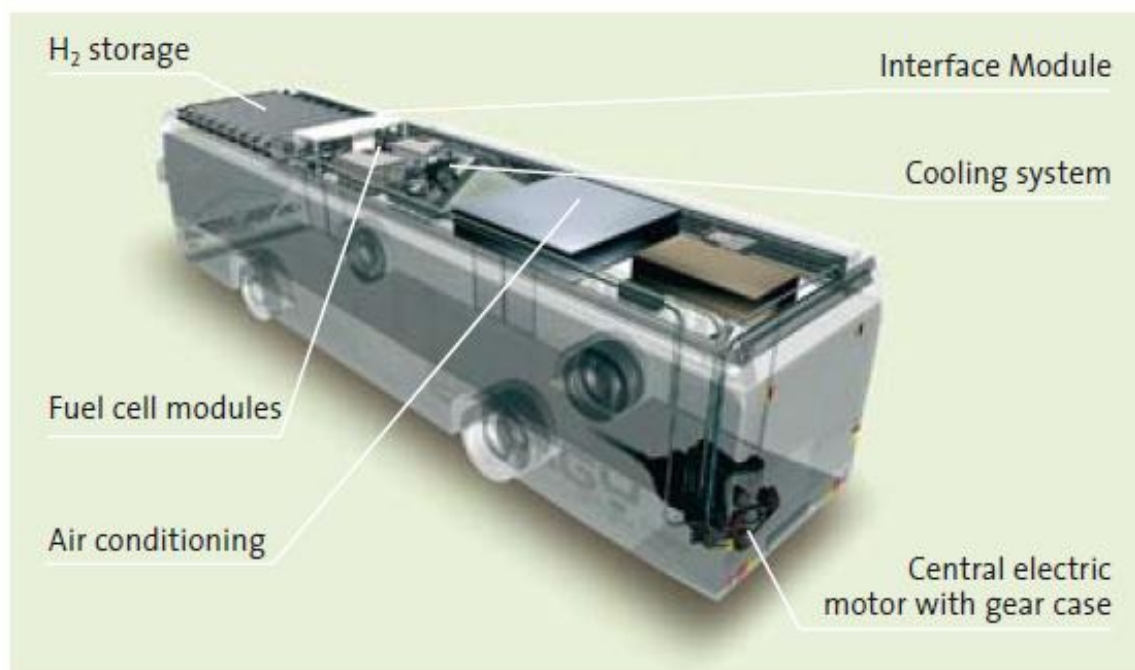


Figure 3.7. Technical design of the fuel cell buses.

During the project also a prototype next generation FC/battery hybrid bus with greater fuel efficiency was developed, tested and demonstrated.

The key technical data for the Fuel Cell buses is provided in Table 3.1. This table includes also the data for the FuelCELL-Hybrid Bus developed and demonstrated during the project.

Table 3.1. Key technical data of the fuel cell bus fleet and FuelCELL-Hybrid.

Vehicle	Fuel Cell Bus Fleet	FuelCELL-Hybrid
Label	Mercedes-Benz	Mercedes-Benz
Model	Citaro	Citaro
Length	12 m	12 m
Height	3,67 m	3,40 m
Max. Weight	19 t	18 t
Net Weight	14,2 t	13,2 t
Transport Capacity	70 passengers	76 passengers
Driving Range	ca. 200 km	> 250 km
Power Fuel Cell System	250 kW	120 kW
HV-Battery	–	26,9 kWh, max 180 kW
Drive power	205 kW for 15–20 secs	220 kW for 15–20 secs
Fuel Cell Tanks	9 cylinders, > 40 kg, 350 bar	7 cylinders, 35 kg, 350 bar

The goal of the new generation of hybrid bus was the reduction of fuel consumption by up to 50 % through improvement in energy efficiency while maintaining or, if possible, increasing the overall vehicle reliability. Lifetime and cost have also been key drivers in the development.

The fuel consumption reduction goal of 50 % was reached. The warranty is expected to increase from a minimum of 2.000 hours to 12.000 hours.

The battery energy storage introduced in the hybrid power train is based on lithium-ion battery technology. The advantages of this type of battery are:

- High energy capacity
- Predictable performance– State of charge– Battery status
- Closed battery, – Maintenance-free
- Low self-discharge (< 5 % per month)

The hydrogen storage system has been downsized as a result of the improved efficiency of the drive train. This has led to the reduction in the overall weight of the bus. The 350 bar system incorporating proven components from the HyFLEET:CUTE buses has been maintained in the new bus. The reliability and maturity of the system has also been enhanced through improved gas piping.

Figure 3.8 shows the design of the new FuelCELL-Hybrid prototype bus.

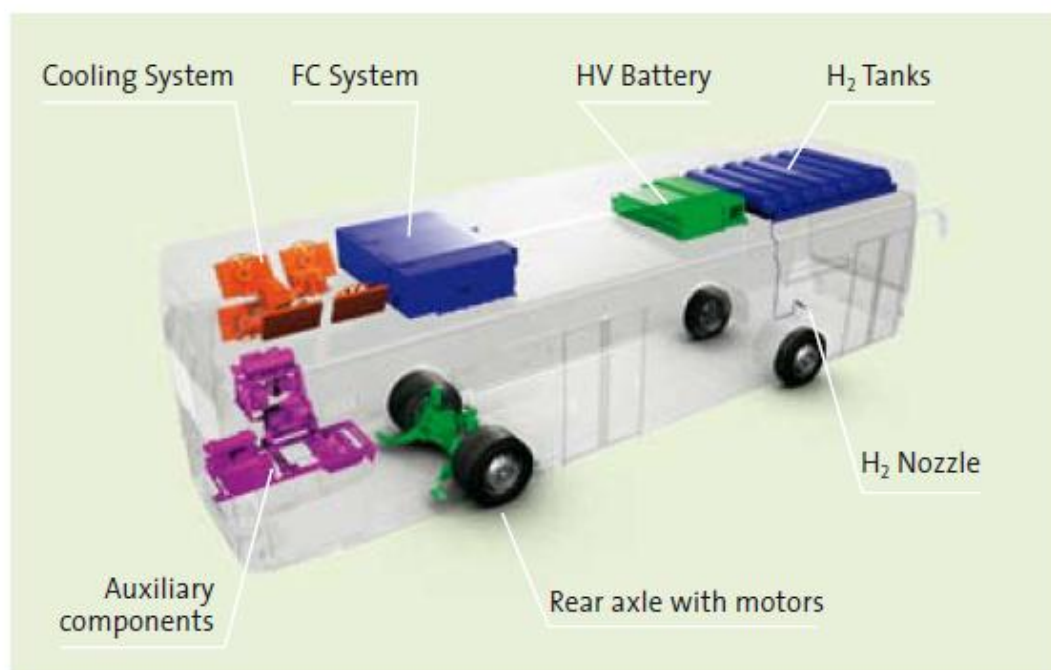


Figure 3.8. Key components of the Citaro FuelCELL-Hybrid prototype bus.

In term of operations the overall fleet of buses performed very well in an extremely wide range of climatic conditions; from hot and dry in Madrid to cold and humid in Reykjavik; from flat in Hamburg to hilly in Luxembourg; from congested in London to full speed in Perth. The ambient air temperatures ranged from - 5 °C to 36 °C.

There were no major breakdowns or problems caused by the fuel cell technology and their components or of the buses themselves.

Within the HyFLEET:CUTE project, the H2FC buses in Hamburg covered the largest distance of 341.046 km. This was due to its operation of 9 buses over an extended period.

The buses operating in Barcelona covered the least distance due to problems with the hydrogen infrastructure.

The average daily operation was approximately 7 hours; ranging from approximately 9 hours in London down to Beijing with 5,5 hours per day.

The global performance of the FC bus fleet of 33 buses, within the HyFLEET:CUTE project is summarized in Table 3.2.

Table 3.2. Results for H₂FC buses within the HyFLEET:CUTE project.

Parameter	Fuel Cell Buses (HyFLEET:CUTE)
Kilometres driven	1.081.485 km
Hours of operation	66.038 h
Average speed	16,4 km/h
Average fuel consumption	21,9 kg/100 km (72,9 l/100 km Diesel Equivalent)
Bus availability ¹⁾	92,6 %

The cumulative kilometers driven are divided by cities and showed in Figure 3.9.

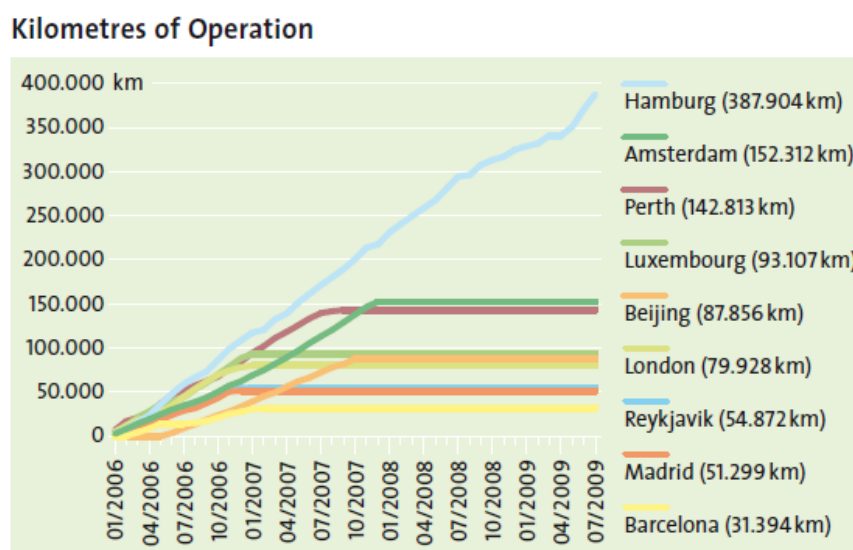


Figure 3.9. Cumulative distance driven per FC bus site with HyFLEET:CUTE.

Very important for our study are the safety related problems during operation. The positive conclusion is that there were no major safety related incidents in the operation of the 33 FC buses. This good result validates both the vehicle design and the maintenance concept used.

Internal Combustion Engines (ICEs)

Different types of ICE buses were developed and operated for HyFLEET:CUTE Project.

MAN Nutzfahrzeuge AG (MAN) developed a fleet of fourteen buses powered by two different hydrogen Internal Combustion Engine (ICE) technologies for operation in regular public transport service. The buses were operated throughout the HyFLEET:CUTE Project by the Berlin Bus Company (BVG – Berliner Verkehrsbetriebe).

All the buses were based on the standard low floor MAN City Bus Lion's City model.

The first four buses had naturally aspirated ICE (NA ICE) technology with 150 kW of power. This technology has been progressively developed and improved over the last decade.

MAN also developed ten buses for the project with turbo-charged ICE (TC ICE) technology with 200 kW of power.

And finally a fifteenth prototype bus was based on the turbo-charged bus technology and incorporated a fuel cell to provide auxiliary power for the bus systems. This bus was constructed in order to demonstrate the possibilities of this technology and was not operated in regular public transport service.

The key vehicle data are summarized in Table 3.3.

Table 3.3. Summary of key vehicle data for MAN ICE buses.

		Buses 1–4 naturally aspirated	Buses 5–14 turbo-charged
Vehicle	Label	MAN low floor bus	
	Model	Lion's City	
	Length total	12 m	
	Height; Width	app. 3,4 m; 2,5 m	
	Max. Weight	18,0 t	
	Net. Weight	12 t	12,9 t
	Transp. Capacity	80 Persons	77 Persons
	Driving Range	> 200 km	> 250 km
Engine	Model	MAN Aspirated-Engine (H 2876 UH01)	MAN Turbo-Engine (H 2876 LUH01)
	Engine Output	150 kW at 2.200 RPM	200 kW at 2.000 RPM
	Torque	760 Nm at 1.000–1.400 RPM	1100 Nm at 1.400–1.600 RPM
Storage Unit	Model	Hydrogen-high-pressure Light-weight construction	
	System, Capacity	10 vessels, type III, Dynetek 10 x 205 l = 2.050 l (app. 50 kg H ₂)	
	Compression	max. 350 bar (@ normal conditions)	
Basics	Air Conditioning	Driver's cab only	Passenger compartment

The naturally aspirated ICE technology developed 150 kW of power and was adequate for normal city bus operations. This technology proved very reliable during the operation in Berlin, with no major breakdowns. Apart from normal service work, very few repairs were necessary.

The turbo-charged ICE technology was developed to provide increased power. This enabled the entire bus to be air conditioned, as well as giving improved acceleration away from bus stops and smoother integration of the vehicle into traffic flows. A second development goal was to improve the fuel economy to give a greater operating range for the buses. This enabled the easier integration of the buses into regular day to day fleet operation, avoiding returning to the base for refuelling during the day.

The performance of the turbo-charged ICE technology reflected its development status with a number of issues being highlighted and overcome as the program progressed.

The major issue to be addressed was the performance of the fuel injectors which caused the engines to under-perform and a consequent series of issues and failures with the buses. The end result was that the anticipated improved fuel economy was not observed, overall bus performance was not in line with design criteria and the availability was comparatively low.

In term of operation Table 3.4 reports the total kilometers driven by the fleet and other data like the total hours of operation. Figure 3.10 shows cumulative driven kilometers and operating hours of the fleet.

Table 3.4. Results for H₂-ICE buses within the HyFLEET:CUTE project.

Parameters	ICE buses HyFLEET:CUTE ^{1]}
Kilometres driven	360.099 km
Hours of operation	25.638 h
Average speed	13,1 km/h
Average fuel consumption	21,6 kg/100 km (71,9 l/100 km Diesel Equivalent)
Bus availability ^{2]}	89,0 %

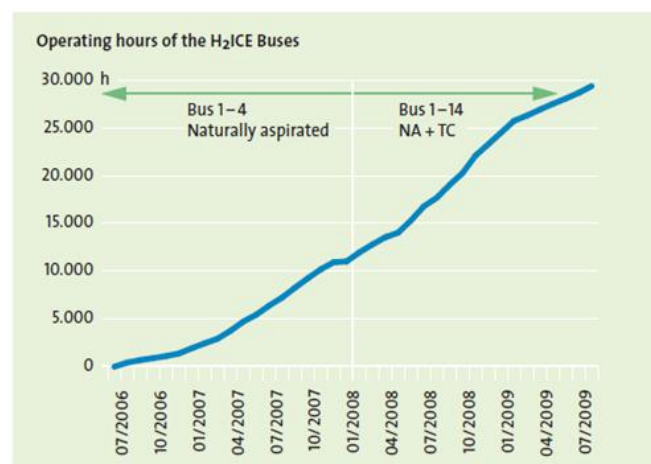
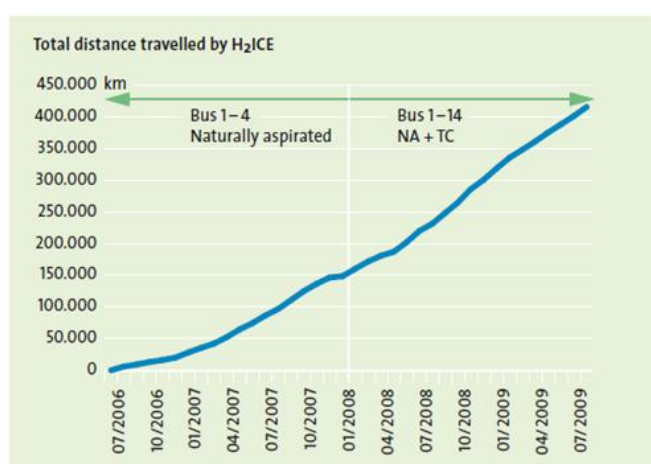


Figure 3.10. Cumulative driven distance and operating hours of H₂-ICE buses within the HyFLEET:CUTE project.

An important part of the project was the monitoring of the quality and safety aspects related to the overall operation of the bus fleets. This activity was done with two reporting tools; one incident reporting scheme for monitoring and discussion (called the Task Force) and one web-based system.

A distinction was made between incidents and accidents:

Minor or Near Miss Incidents: A sudden unintended event with no consequences, but that affected the quality of the operations or had the potential to become an accident

Accidents: An undesired and unplanned event that has caused harm to people, assets or environment.

From January 2006 through to June 2007, a total of 279 independent performance incidents were reported through the web-based system. The table below (Table 3.6) shows the top five performance incidents by indicator and % frequency.

About 1/3 of the records relating to indicator # 5 were computer errors at one of the stations. These errors did not affect safety at the station but they affected the quality of the operation.

Related to hydrogen the only incident recorded was an unexpected release of gas occurred when a check valve within the tank nozzle failed. The component was replaced and the problem did not re-occur.

Table 3.5. Top 5 incidents reported through web-based system.

Q. & S. indicator no.	Description	% of Records ¹⁾
5	Interrupted operation of hydrogen station	50,56
6	Emergency shut-down	8,61
7	Gas or liquid leakages	7,78
3,3	Vehicle failure affecting vehicle operation	7,22
3,1	Technical failure in dispenser or filling equipment affecting vehicle operation	6,11

One of the conclusions related to safety is that training is a key word. Having skilled personnel knowing the technology and the systems was crucial. Team responsibilities and

coordination of actions across organizational boundaries, including suppliers, was important in establishing common “best operational practices” respected by all parties involved.

It is notable that the quality and safety records in HyFLEET:CUTE relate mainly to technical irregularities and incidents. Industrial experience suggests more than 80 % of all incidents are related to human errors. The reason why the experiences in HyFLEET:CUTE (< 1 %) were different from this would benefit from further evaluation. Quality, safety and training were a continuous focus in the project. The emphasis put on the reporting of incidents as a tool for further improvement was a key driver in the partners continuing to report.

To conclude we can add as final comments that HyFLEET:CUTE has shown unequivocally that:

- Hydrogen can be a low or even emission-free transport fuel;
- Fuel cells are a practical propulsion system for transport;
- Today's technology – internal combustion engines – can run efficiently and very cleanly on hydrogen;
- Hydrogen can be produced efficiently and with virtually zero atmospheric pollutant and carbon emissions when renewable primary energy sources or nuclear energy are utilised;
- Infrastructure to produce, supply and distribute hydrogen for transport can be implemented efficiently and with no fundamental obstacles; and, most importantly
- A hydrogen based transport system can be implemented and can operate safely, delivering substantial long term public benefits.

Also an investigation on the level of acceptance in the Community of the H₂ technologies has been carried out.

2.833 people were personally interviewed in eight cities (Amsterdam, Barcelona, Berlin, Hamburg, London, Luxembourg, Madrid and Reykjavik) between September and October 2006. In addition, 519 people participated in online interviews between August and September 2006.

The main results from the Acceptance Study were as follows:

- Associations with the word hydrogen were positive or neutral in 92 % of the cases.

- 78 % of the interviewees were aware that hydrogen can be used as a fuel and 72 % of participants agreed that there is a need to find alternative fuels for vehicles.
- The substitution of conventional buses by hydrogen buses in the cities was supported by a large majority of respondents and opposed by only 1 %. The remainder stated that they were indifferent or needed more information to come to a decision (see Soc – Figure 1).
- Assuming that people have the choice between a conventional bus and a hydrogen bus under the same conditions (route and ticket price), 76 % would choose the hydrogen bus and 1 % the conventional one. 21 % would have no preference (2 % did not respond).
- Asked “Would raised (ticket) prices for hydrogen buses be justifiable?” overall 44 % responded ‘yes’ and 57 % ‘no’. However, some cities showed a greater than 50 % willingness to accept higher prices.

3.4.2 “PROJECT DRIVEWAY” - USA/Germany [42-47]

General Motor's "Project Driveway" fuel cell vehicle demonstration used a fleet of over 100 fuel cell electric vehicles in order to demonstrate in the field the feasibility of hydrogen-based mobility. In Europe, the project was developed in collaboration with Opel. Project started in autumn 2007, and between 2007 and 2008 were produced about 170 vehicles. 119 vehicles are handed over to private and commercial customers all over the world (i.e. in the US and in Germany). More than 80 drivers have used these vehicles for extended periods of about 2/3 months; moreover, thousands of common people had driven them occasionally. On March 2010 over 1'900'000 cumulative kilometers have been travelled, as of mid-2012, the experience reached 4'000'000 km. One fuel cell stack already reached an operational life of more than 1600 hours; three cars travelled more than 110'000 km.

In order to grant the correct maintenance level, several facilities were adequately equipped and provided of refueling capability (Figure 3.11). The personnel were trained to manage hydrogen safely and to provide both routine and emergency maintenance to the vehicles.



Figure 3.11. Personnel of FSS Facility (Ardsley, NY, USA) and hydrogen production unit for refueling.

Moreover, first aid responders were specifically trained; fuel cell cars have many different characteristics (hydrogen tanks and piping, high voltage batteries and wiring) in comparison with common ones. In case of accidents, they have to know the structure of the car for their own safety (Figure 3.12).



Figure 3.12. First aid responders training to manage hydrogen cars

The vehicles developed for this project are the HydroGen4 variant of the Chevrolet Equinox; they were approved according to U.S. Federal Motor Vehicle Safety Standards (FMVSS).

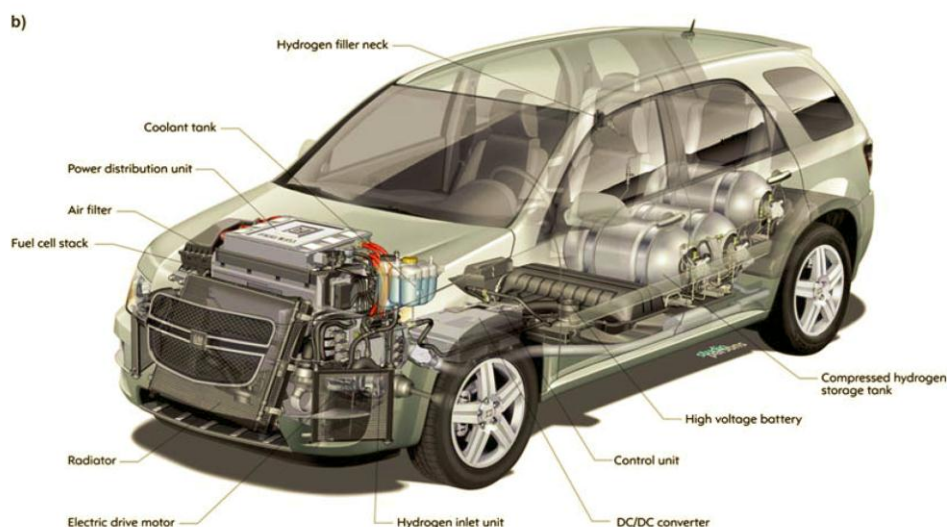


Figure 3.13. FCEV GM HydroGen4 Equinox

The electric motor can supply a steady power of 73 kW (corresponding at about 160 km/h of maximum speed); the maximum performance is 93 kW. The performances of these vehicles are very similar to the one of a common diesel vehicle; they can accelerate from 0 to 100 km/h in 12 s (corresponding to a maximum torque of 320 N). The cars can be both operated and started at very low temperatures (down to -25°C). The onboard storage systems are three pressurized (700 bar) carbon-fiber tanks that can and enable a range of about 320 km. An additional battery (about 1.8 kWh, 35 kW) was introduced in order to enable energy recovery and improve efficiency.

A relevant aspect, from the point of view of safety, is that the huge number of hydrogen fuel cells cars on the road and the large distances accumulated made certain that these cars would be involved in common accidents. Press releases report that five GM fuel-cell vehicles have been involved in accidents up to 2010, and none has resulted in any sort of catastrophic hydrogen explosion.

Pictures in Fig. 3.14 refer to an accident in Washington D.C. on February 22nd, 2010. The vehicle was being driven in the traffic when it was involved in a three-car accident: struck from behind by a pickup, it was forced forward into another pickup. No hydrogen was released and no people injured, in spite of the extensive damages on both front and rear side. The passive safety devices and the controls operated as designed.



Figure 3.14. FCEV Chevrolet Equinox involved in accidents during the 'Project Driveway' demonstration project

The cars are designed so that the tanks will leak in a jet flame if ruptured and ignited, in order to avoid an explosion. Seven hydrogen sensors are located on the car (in the passenger compartment, under the hood and on the tanks). A warning signal warns the driver when a quantity of hydrogen above 12% of lower flammability limit is detected, while an evacuation signal is given when the threshold of 50% of lower flammability limit is reached. Hydrogen flow is interrupted automatically if the hood is not fully latched. The high voltage (and consequently the fuel cell) is shut off immediately when an air bag deploys, the hood is opened or the rear crash sensor is activated.

3.4.3 Dolomitech FC Buses.

Another *positive case study* or *best practice* has been selected from an Italian experience, consisting in the operation of two minibuses that have been working for more than one year, with a regular daily operation since their start of service. During this period no accidents have been recorded, showing that hydrogen can be safe is properly managed.

These buses have been designed and assembled by Dolomitech and are operated by Trentino Trasporti in Fiemme and Fassa valleys in north of Italy.

Dolomitech (<http://www.dolomitech.com/>) is a newco founded in July 2010 in Trentino (Italy) with the aim of developing and commercializing environmentally friendly advanced propulsion systems (e.g. fuel cell propulsion systems).

Its main mission is:

- R&D of terrestrial, marine and air propulsion systems with high efficiency and low environmental impact
- Development of prototype vehicles and vehicles for niche markets
- Scientific consulting and engineering services to support the implementation of projects with renewable and alternative energy
- Assessment, design and project of plants for production, transport and transformation of renewable energy

Its knowledge and expertise are:

- Fuel Cell stack development and characterization for custom application
- Fuel Cell Systems analysis and development
- Thermal fluid dynamic and structural analysis
- Hardware and software control development
- Development and characterization of power electronic components
- Development and characterization of traction battery packages

The buses analyzed for this case study, model “Fuel Cell Dominant” (FCD), are derived from the Iveco Daily platform, a Diesel bus that has been converted in an electric vehicle with 17 seats, included the driver (see figure 3.15 and 3.16).



Figure 3.15. Fuel Cell Dominant bus white (s/n 1001).



Figure 3.16. Fuel Cell Dominant bus grey (s/n 1002).

The power for the three phase asynchronous electric motor comes from a hybrid system composed by a hydrogen fuel cell stack and a lithium ion battery. The hybridization helps to enhance the total mileage of the vehicle improving the fuel efficiency and also thanks to the plug-in function for battery charging. The main dynamic power comes from the battery pack and the fuel cell generates a more constant power that keeps the charge of the battery; with this approach the fuel cell can work under more controlled conditions optimizing fuel efficiency and life time. The bus is also equipped with a regenerative braking system that allows the charging of battery during the deceleration phase, recovering energy otherwise lost in a pure fuel cell power train. If necessary the bus can work solely with the battery pack, switching off completely the fuel cell system.

The hydrogen is stored in two tanks in gas compressed form; the nominal pressure of storage is 350 bar and the total storage capacity is around 7 kg.

The total mileage of the vehicle, given by stored hydrogen and charged battery, is around 300 km.

More technical data are reported in Table 3.6 and 3.7.

Table 3.6. Technical specifications of Hybrid Fuel Cell Bus.

Urban and suburban Hybrid Fuel Cell Bus	
Vehicle Platform	IVECO Daily (7 mt)
Weight (full load)	5600 kg, cat. M3
Maximum weight	5600 kg
Seats	16 + driver, B class
Architecture	Hybrid (Fuel Cell + batteries)
Electric motor	three phases asynchronous (power 80 kW _{max})
Fuel Cell	PEM automotive (power 50 kW _{max})
Batteries	Lithium ion
H ₂ storage	carbon fiber@ 350 bar, volume 300 lt, H ₂ capacity 7 kg
FCS	Suitable for low temperature operation
	Electric heating and air conditioning
	"Plug-in" functionalities
	Braking system with kinetic energy recovery
	Suitable for mountain roads

Table 3.7. Performances of Hybrid Fuel Cell Bus.

Urban and suburban Hybrid Fuel Cell Bus	
Max speed	80 km/h
Max slope	20%
Refueling time	<10 min.
Range	300 km
Use	Suitable for mountain roads
FCS	Suitable for low temperature operation

Since we are using this application as case study for hydrogen and safety we will focus more on details around the FC system and the countermeasures adopted to reduce the risk related to the hydrogen utilization. Also details on total operation of the buses are important for our evaluation.

The main components of the FC system are two FC stacks, two hydrogen tanks, first and second stage of pressure regulation, recirculation loop. Very schematically the FC system is summarized in figure 3.17.

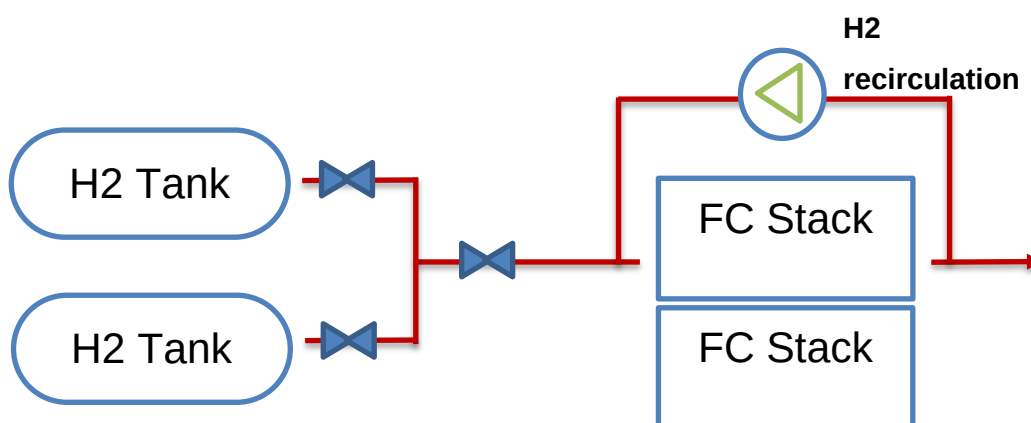


Figure 3.17. Simplified scheme of the FC system.

The FC stacks are composed by 128 cells each, they operate at low pressure with dry air and hydrogen; hydrogen is recirculated for membrane self-humidification, recovering the water produced by the electrochemical reaction.

The two vessels for hydrogen storage are type 3 tanks produced by Dynetek, with aluminum liner wrapped in carbon fibers. The nominal pressure is 350 bar but they can reach 438 bar during filling operation. Each tank contains up to 3.5 kg of hydrogen for a total storage of about 7 kg.

Figure 3.18 reports the specification of the tank installed, which is the model W150.

 Dynetek Industries Ltd. DyneCell® Lightweight Fuel Storage Systems										
350 bar/5075 psi Hydrogen @ 15°C/59°F										
Series	Internal Volume		Outer Diameter		Length		Weight		Capacity	Port
	litres w.c.	cubic inches	mm	inches	mm	inches	kg	lb	kg H2	
L026	25	1,526	280	11	655	25.8	15	33	0.61	G5, G8
L039	39	2,380	280	11	926	36.5	20	44	0.94	G8
L043	43	2,624	280	11	1,000	39.4	22	49	1.04	G8
L043	43	2,624	280	11	1,066	42	22	49	1.04	G5N8N
L047	47	2,868	280	11	1,090	42.9	23	51	1.14	G8
M039	39	2,380	295	11.6	906	35.7	21	46	0.94	G5N8N
V074	74	4,516	399	15.7	900	35.4	36	79	1.79	G8, G8N*
V174	174	10,618	399	15.7	1,890	74.4	73	161	4.21	G8
W150	148	9,032	413	16.3	1,534	60.4	65	143	3.58	G8
W205	205	12,510	416	16.4	2,030	79.95	90	198	4.96	G8N*
ZM180	178	10,862	602	23.7	972	38.3	92	203	4.31	M8C

* Add 80 mm or 3.15 inches to cylinder Length for Neck Mounted cylinders.

Maximum fast fill pressure: 6344 psi / 438 bar	
Port Sizes	N: Neck Mount G5: Dual Port - 1.125-12 UN w/O-Ring G8: Dual Port - 2.000-12 UN w/O-Ring
	DyneCell cylinders have been certified under: ISO 11439, NGV2, CSA B51, and Reijikijun Betten-9 And approved by: TUV and KHK

Specifications

Figure 3.18. Technical specifications of hydrogen tank.

The tanks are installed on the roof of the bus. This is a usual setup for buses because of availability of space in this position and because in case of hydrogen release it can be easily vented away reducing the risk of combustion or explosion.

A series of safety devices and countermeasures have been adopted to reduce the risk of accidents related to the onboard hydrogen.

The tanks are equipped with PRD (pressure release device), activated above 100°C, that can release the hydrogen in case of a temperature increase, like in the event of a fire. This is fundamental because the high temperature causes the increase of pressure inside the tank and a decrease of mechanical properties of the tank wall. In addition there is also an excess flow valve that limits the maximum hydrogen flow in case of a rupture of a line or device in the hydrogen system. Above a certain release velocity the flow is completely shut off.

On intermediate and low pressure line there are PRV (pressure relief valve) that prevent the pressure to go above the nominal values, 5.5 and 1.7 bar respectively.

All the venting openings are positioned on the top of the vehicle to facilitate the hydrogen dissipation in case of activation of release devices.

The FC system is enclosed in a box fixed under the vehicle in rear position (see figure 3.19). Inside the box is installed a hydrogen sensor that is able to shut off the tank valves of hydrogen and shut down the FC system in case of a leak detection. There is a hydrogen sensor also in the cabin of the bus and the full system is designed to avoid hydrogen leak and accumulation in this volume: i) there are no devices or line connections involving hydrogen inside the cabin; ii) the high and medium pressure section of the system is positioned on the roof of the bus.

In addition to safety devices and system design there are also a series of software controls, monitoring pressure, temperature and gas flow values, which can shut down the FC system (and close the hydrogen valves) in case of deviation from defined range.

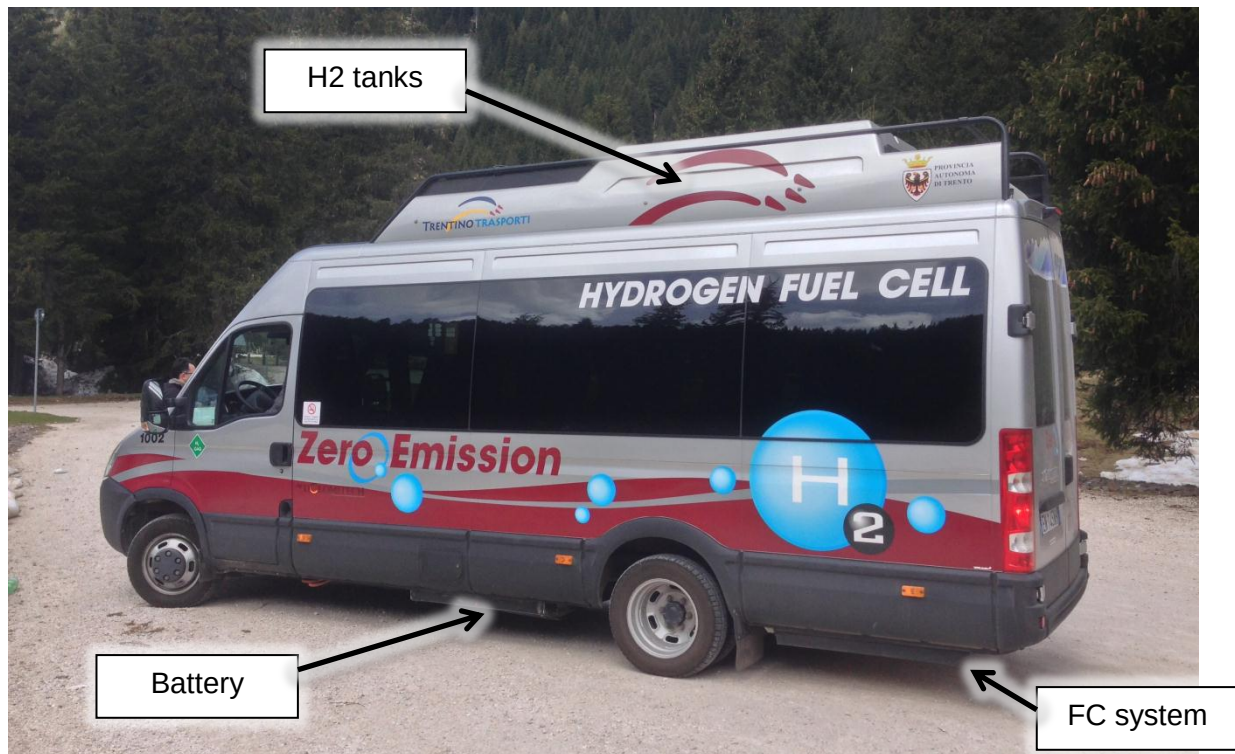


Figure 3.19. Fuel Cell Dominant bus.

As final general comment regarding safety we can add that all the directions indicated in CE N. 79/2009 [21] has been followed and applied to the buses under analysis.

Finally, to conclude the case study analysis we have to look at the data of operation of the two vehicles. The buses have been delivered to Trentino Trasporti on January 2013 and they started their service in occasion of Nordic World Ski Championships in Val di Fiemme (from February 2nd, 2013). During this period they covered every day the route Tesero/Cavalese/Veronza, 230 km long, for a total of 2800 km for each vehicle.

After the World Championships the buses have been put in service on the route 113 in Val di Fiemme till June 06th, 2013. This rout was covered three times each day for a total of 100 km. Figure 3.20 and 3.21 show the route followed by the buses in this period.

TRENTINO TRASPORTI ESERCIZIO

Servizio Extraurbano
Orario in vigore dal 11/09/2013 al 27/06/2014

113 Cavalese - Daiano - Carano - Tesero - Cavalese

Frequenza	★	★	☒	☐	☐	★	☐	☐	☐						
Note di corsa						①		②	③						
									④						
Percorso di Andata	445	77	49	66	62	212	68	32	64						
CAVALESE (Autostaz.) Part.				8.23	11.00	13.20	14.30	17.00	17.30						
VARENA				8.33	11.10	13.30	14.40	17.10	17.40						
Varena (Via Alpini)				8.35	11.12	-	14.42	-	17.42						
Daiano				8.41	11.18	13.35	14.48	17.15	17.48						
CARANO				8.46	11.23	-	14.53	-	17.53						
CARANO (Municipio)				8.46	11.23	13.43	14.53	17.23	17.53						
CAVALESE (Autostaz.)				8.53	11.30	14.03	15.01	18.00							
Masi di Cavalese			7.35	9.02	11.51		15.10	18.21							
Stava	Part.	7.20	-	-	-	-	-	-	-						
Lago di Tesero		-	7.41	9.08	11.45		15.16	18.15							
Tesero		7.39	7.40	7.45	9.12	11.39	15.20	18.09							
CAVALESE (Autostaz.) Arr.		7.48	7.54	9.21	11.58		15.29	18.28							

Note di Corsa

☐ Solo nei gg. Feriali

☒ Feriale non Scolastico

★ Nei gg. Scolastici

① Transita per Aguai

② La corsa prosegue per V. Veronza

③ Servizio svolto da autonoleggiatore privato

④ La corsa prosegue per l'Ospedale

Figure 3.20. Bus route 113 in Val di Fiemme [48].

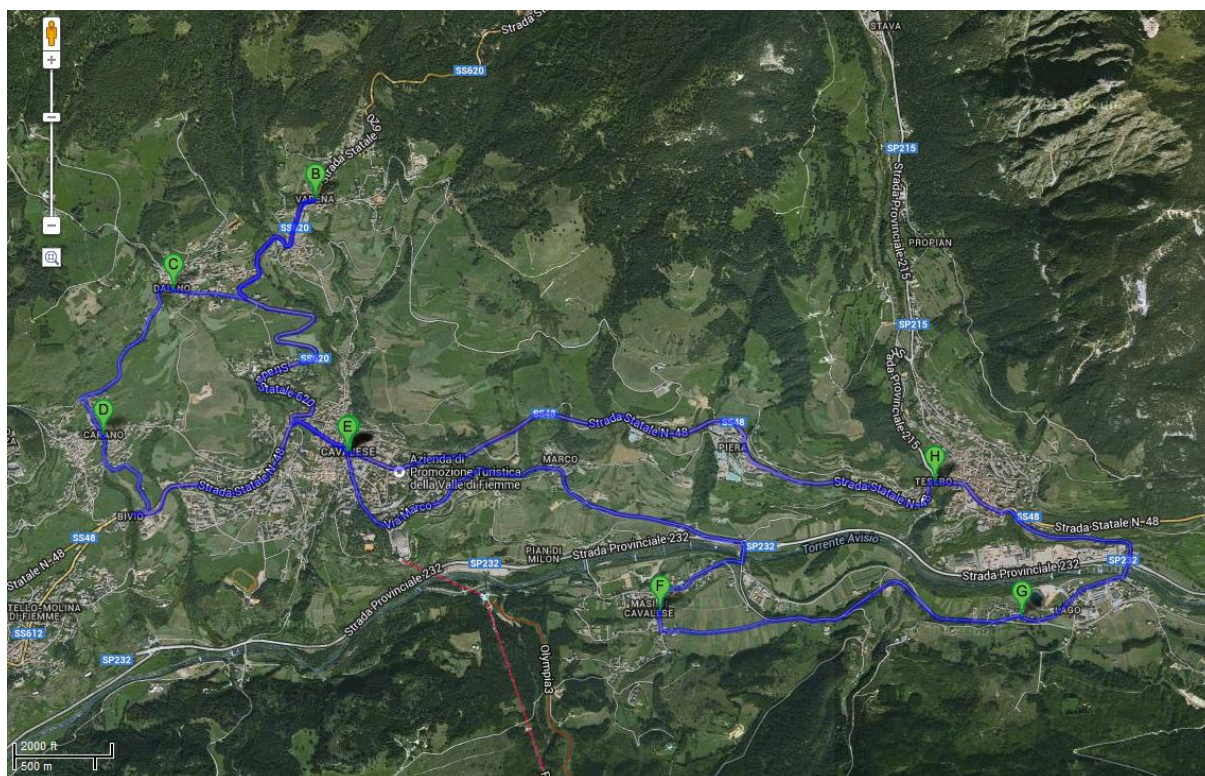


Figure 3.21. Map view of bus route 113 in Val di Fiemme.

During the summer period (July, August and September) the two buses have been moved on the route 122 in Val di Fiemme (Predazzo/Passo Rolle/Fiera di Primiero) (see fig. 3.22) covering 120 km each day with a delta of altitude of 2000 m.

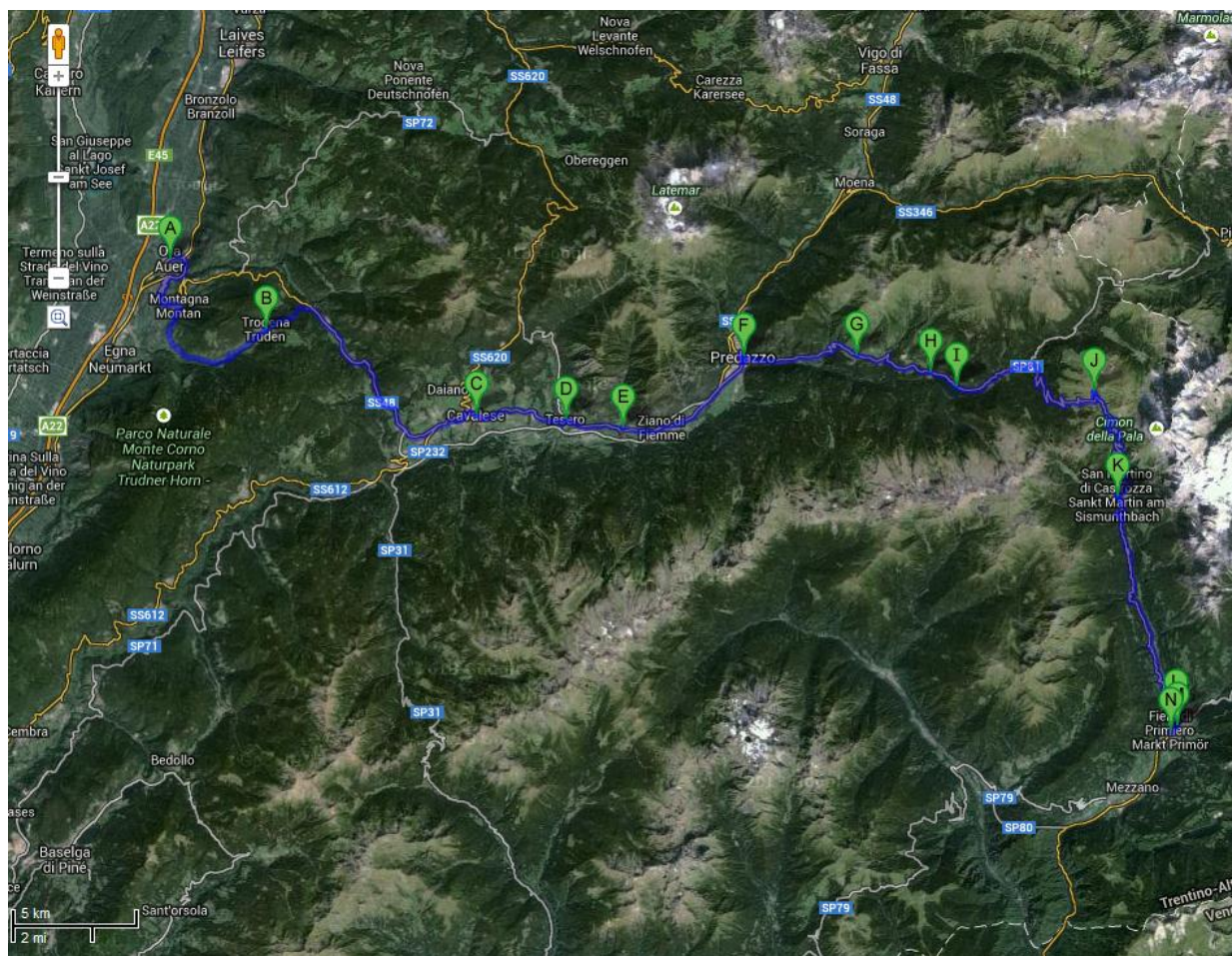


Figure 3.22. Map view of bus route 122 in Val di Fiemme.

From October 2013 the buses went back to the winter route 113, where they are still in service.

Figure 3.23 reports the cumulative distance traveled by the two buses from February 2013 to March 2014 showing quite a constant utilization of the two vehicles over more than one year.



Figure 3.23. Distance traveled by the two buses from February 2013 to March 2014 [44].

The last update with data of operation is from May 14th, 2014.

In term of distance we have:

- minibus white (s/n 1001): ~ 18.000 km
- minibus grey (s/n 1002): ~ 16.500 km

In term of hours we have about:

- minibus white (s/n 1001): ~ 900 hours
- minibus grey (s/n 1002): ~ 825 hours

In the end of this analysis we can conclude that the considered case is indeed a good example of application of hydrogen and fuel cell technology for transport applications. During the entire period of operation there were no accident recorded involving the vehicles and there were no failure connected to the fuel cell system, demonstrating that this hydrogen technology can substitute the standard one based on Diesel engine and, also important, without introducing higher safety risk if the correct methodologies of operation are followed.

3.4.4 CNG Vehicle tank burst during filling [49].

The third case study represents a worse case because it describes a fatal accident occurred to a driver in California in 2007. To be precise the accident was not linked to a hydrogen vehicle but to a van powered by CNG (compressed natural gas). This case has been anyway selected because the accident was caused by a burst of the pressurized tank, so it could have been happened also in case of hydrogen utilization instead of natural gas.

The case has been described and analyzed by R. Rhoads Stephenson from Motor Vehicle Fire Research Institute.

The unfortunate event happened on May 26th, 2007; during filling operation of the vehicle, an airport shuttle van, his CNG tank burst and the driver was killed. The case has been initially investigated by the sheriff and coroner and the vehicle was turned over to the pressure vessel experts in California Dept. of Occupational Safety and Health.

The vehicle more precisely was a 2001 Ford van – E350 Super Club Wagon XL (see figure 3.24). It was OEM manufactured with 3 CNG tanks and then two additional tanks were added in the aftermarket to extend the range:

- one tank was installed longitudinal on passenger side
- one white tank was installed behind rear axle, right in front of rear bumper. This tank was manufactured by Comdyne.

The Comdyne tank was a Type 3 one with aluminum liner and wrapped with glass fiber. It was manufactured under DOT exemption. Most of these tanks were manufactured in 1990s; early tanks were white and later ones were black due to a protective external coating.

The nominal pressure of the tanks was 3600 psi except for the longitudinal aftermarket one, which was rated at 3000 psi and it was expired at the time of the accident.



Figure 3.24. Ford van – E350 Super Club Wagon XL.

The filling station where the accident happened was owned and located on the property of the LA County Sanitation District. It was quite new (November 2006) and operated by Clean Energy Station.

There was a surveillance camera installed at the station but it was not recording at the time of the accident.

Analyzing the fill data from the station and the measured OEM tanks pressure it came out that the station did not over-pressurize the tank during the filling operation. The cause of accident cannot be linked to the filling station malfunctioning.



Figure 3.25. CNGF filling station.

Before the fatal event, on May 6th, 2007, the van was involved in another accident, a rear impact with minor damage; the van was hit from behind by a Honda Accord and only the rear bumper was visibly damaged, like shown in figure 3.26-left.

On the other hand the Honda was extensively damaged like shown in figure 3.26-right; an important information for our study is that the car battery was damaged and spilled its acid on the rear of the van.



Figure 3.26. Ford van damage (left) and Honda Accord (right) damage after rear impact accident.

After this accident the driver had tanks “looked at” by an alternative fuel conversion company, which recommended him to replace the rear tank and not fill it. This conclusion was taken based on accident description and not on a real inspection: the vehicle was not put on lift and the tank was not removed for a deep checkup. The tank may have been isolated by closing mechanical valve during this control.

The van has been repaired and returned to the driver the evening before the incident. The rear bumper has been replaced but no work was done on the fuel system.

The burst occurred the day after the van went back to service, during the fueling while the driver was behind the vehicle and he was thrown about 30 feet away reporting a massive trauma. He died instantly.

The fueling that caused the tank burst was not the first after the rear-end accident; just after this event a first filling was done without tragic consequences.

The burst broke three windows of the vehicle, the bumper blew off and the tank showed a “fish mouth” shaped rupture (see figure 3.27). The aluminum liner tore open in several pieces.



Figure 3.27. The rear van tank after the burst.

The possible causes of the tank burst could have been a mechanical damage coming from the rear impact or an over-pressurization of the tank by the station. Both these possibilities have been discarded from tank inspection and station data analysis.

The other possibility, that has been then confirmed, was a chemical degradation caused but the battery acid spilled on the rear van by the Honda.

The tank inspection was performed at SEAL Laboratories, Torrance, CA and the conclusion was that the tank lost strength due to Stress Corrosion Cracking (SCC) caused by the battery acid. The burst happened two weeks after the rear impact because SCC takes both stress and time to occur.

The same type of Comdyne tanks were used by GM and Chrysler. GM had two tank bursts on pick-up trucks and the investigation showed susceptibility to corrosive fluids, one case due to battery acid and the other due to a corrosive wheel cleaner (Fluoride). The problem was studied by SwRI and Failure Analysis Associates and GM recalled circa 2200 vehicles and destroyed tanks. Comdyne is no longer in business.

The conclusion of this case study is that risk of fatal accident is always present when working with dangerous gases or conditions, the high pressure in the specific event. The case shows also that the accident occurred because bad practices were applied, both during the aftermarket modification of the van and during the inspection after the first rear impact accident.

The finale inspection showed that the aftermarket tank that did not burst was rated at 3000 psi and not 3600 like all the others; in addition to that it had exceeded its lifetime one year before the burst.

Another bad practice was the position of the white tank, behind the rear bumper; this is a critical position in case of a rear impact accident with other vehicles.

The inspection of the vehicle and tanks after the rear impact was also done too superficially, without detecting the risk linked to the presence of acid on the exterior of the white tank.

All these bad practices and unfortunate linked events led to the fatal incident that could have been avoided following appropriate procedures.

3.4.5 EMERGENCY OPERATORS TRAINING and HANDBOOKS

A point of primary importance in hydrogen devices safety is the training of the emergency first responders; the availability of specific information related with the situation would limit the damages to property and people or avoid excessive measures. In general, theoretical and practical courses were organized to train first emergency responders where demonstrative projects involving fuel cell vehicles were carried out.

An example is the course “Introduction to Hydrogen Safety for First Responders” organized by the U.S. Department of Energy [50]. It is developed to help first responders to:

- Understand the properties of hydrogen in comparison with other fuels and safety mechanisms
- Recognize and identify hydrogen vehicles, stationary power generators, storage containers and refueling equipment
- Identify typical ignition sources and other potential hazards
- Execute initial “awareness-level” response actions

The course is given both as online presentation and in presence.

In the course of demonstrative project “Project Driveway” developed by General Motors, in which more than one hundred hydrogen cars were delivered to privates and companies, particular attention was given to the training of emergency first responders [51]. In order to prepare for the market test, GM worked with first responders in the “Project Driveway” test areas to detail vehicle specifics in the event of an emergency, and program participants will be trained in safe fueling practices (Figure 3.31). Over 1500 people were trained in 3 cities. Training was delivered on site or via Distance Learning system. All service engineers have completed this training comprehensive of 10 day classes that cover key areas:

- Theory of operation
- Procedures
- Hands on Exercises
- Troubleshooting Exercises

First Responder Training was implemented at the completion of each station and averaged 100 participants for each of five stations, including over 200 in Washington, D.C. First Responder Training was also completed by GM at various levels: at the launch of Project Driveway, at events requested by various organizations (such as California Fuel Cell Partnership), and at station openings.

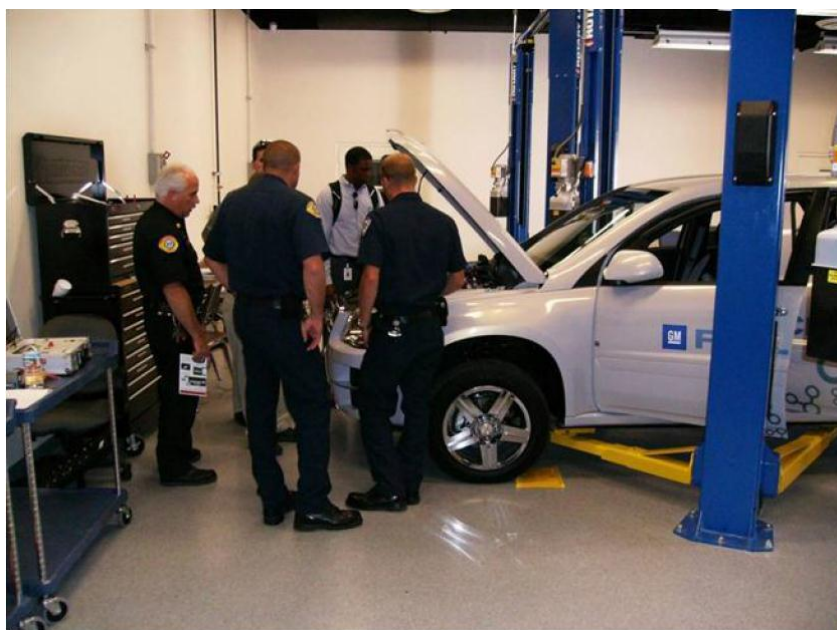


Figure 3.28. First responder Training Session [51]

In Europe, the project HyResponse started in April 2013 and is currently ongoing [48]. It targets to create a European Hydrogen Safety Training Platform (EHSTP). This training platform will develop a tool box for European First Responders to help them assessing status and decision making not only for the implementation of a new hydrogen project but also on the emergency response level in case of incident/accident on site. The existing Fire Fighter pedagogic training approach will be followed to train First Responders on all safety aspects in dealing with not only transport but also stationary hydrogen applications i.e. passenger vehicles, buses, forklifts, hydrogen refueling station, materials handling, decentralized hydrogen production, hydrogen storage and distribution systems, backup power generation, stationary fuel cells for combined production of heat and power. The release of an “Emergency Response Guide” is forecasted in April 2016.

In the field of hydrogen vehicles, the producers release guides and handbooks in order to clarify the structure of their own vehicles. Hydrogen cars deals with both pressurized gaseous fuel and high voltage lines, the features and specifications of which may not be familiar to emergency responders.

In general, the main topics addressed are:

- Identification of a fuel cell vehicle (exterior graphics, under-hood structure, ...)
- Location of the main components (fuel cell, electric motor, tanks, battery, ...) and related hazards (high-voltage, hydrogen content, ...) (see Figure 3.29)
- Propulsion system and power disabling procedure
- Hydrogen sensors and related icons on the instrument panel
- Position of the vent system of the tanks
- Identification of “no-cut” zones, due to high voltage and fuel lines (see Figure 3.30)

Among the available guides, we can mention:

- HONDA FCX Clarity - Emergency response guide [53]
- TOYOTA FCHV - Emergency response guide [54]
- CHEVROLET Equinox Fuel Cell - Emergency Response Quick Reference [55]

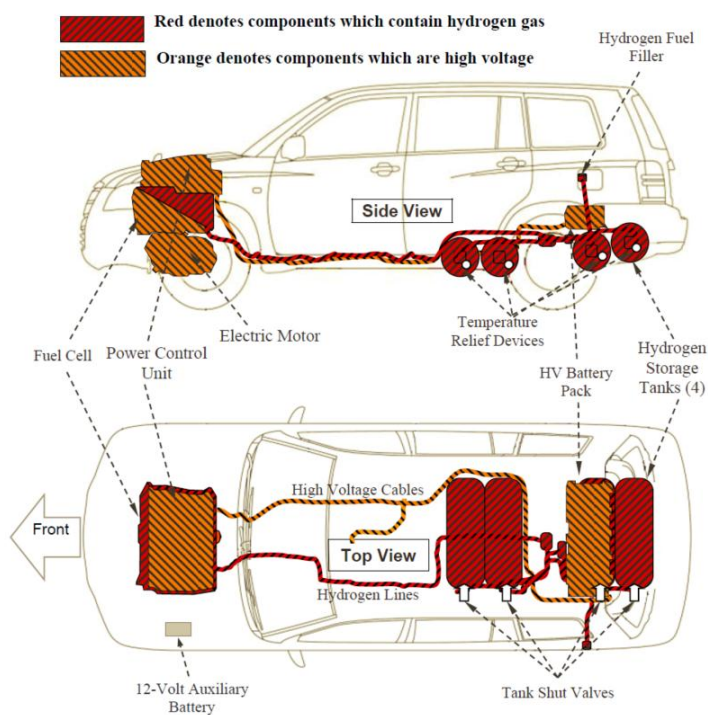


Figure 3.29. Location of the main components in a fuel cell car [54]



Figure 3.30. Example of “no-cut” zones in a fuel cell car [55]

Similar material is currently available for hybrid vehicles. All these information have to be disseminated and available to all the people involved in safety and emergency management, in addition to car owners.

3.5 Conclusions

Task 3.3 in the framework of Workpackage 3 (WP3) had the goal of collecting data about hydrogen safety related to mobility and vehicles.

The data collection process followed the methodological approach indicated in deliverable D2.4 “Mirror groups organization chart and data gathering procedures”.

The survey was supposed to be the main tool for gathering data, distributing a questionnaire to all stakeholders and expecting a good level of responsiveness. Unfortunately the participation to this survey has been lower than expected and major importance has been given to literature and documents review and to direct discussion with people through interviews or focus group.

The main problem encountered during this work has been the difficulty to find a quick response from stakeholders. Some of them, especially industries, are not very open in sharing all the information they have, mainly because often the safety countermeasures on the vehicles are strictly connected with their design.

In general through some interviews and document reviews the information collected were able to give a good overview of safety aspects in mobility applications and final results is relatively complete. What is maybe missing is a statistic evaluation of the risks coming from hydrogen vehicles because of the limited amount of information available. Fleets of hydrogen cars or buses are still not very common and this is the main limit for statistical analysis.

Through this work we analyzed the main risks associated to hydrogen utilization in transport means and which are the main technological solutions to mitigate these risks. Hydrogen hazards are not considered limiting factors for diffusion of new vehicles even if the countermeasures to reduce the risks are fundamental. The main concerns are not related to vehicle itself but to the garage where the car can be parked, especially home garage where hydrogen can accumulate in case of leak.

Some case studies presented show with real examples how hydrogen can be used already in a safe way, even if they could be not statistical valuable to make a direct comparison with standard fueled vehicles.

Technology is considered mature to be used safely but some stakeholders indicated that more demonstrative projects could help in showing the potential of these new means of transport. No safety issues are foreseen that would warrant cessation of hydrogen use as a

vehicle fuel. Also more uniform safety rules, at least at European level, could help the industries in developing easily their systems and vehicles.

While there are still mishaps with hydrogen in various industries, it is clear that hydrogen can be handled safely if its physical properties are understood and appreciated by those using the gas, and if proper precautions are taken.

The most important safety principle in any situation is education; anyone who will operate or maintain hydrogen-fueled vehicles should receive hydrogen safety training. At a minimum, this training should cover the characteristics of hydrogen, operation of onboard safety systems, hydrogen fueling operations, and actions to take in case of an emergency. In case of private vehicles also the end-users must be adequately trained to prevent simple and dangerous mistakes.

Deliverable No. 3.1

Chapter 4

Non-vehicles and residential power generation

4.1 Introduction

In the framework of WP4, Task 3.4 focus on data collection about hydrogen safety related to non-vehicles and residential power generation.

The work has analyzed to main group of application:

- small or medium application with fuel cells (from hundreds of Wh to few kWh)
- big plant for energy production (from hundreds of kWh to MWh)

Concerning the first group, the main sectors of application are residential power and heat generation, grid support units, small back-up and off-grid systems. Demonstration chargers for personal computers or mobiles and also educational kit can be included in this group whereas they are commercially available since many years.

In the second group we included the increasing number of installation regarding Solid Oxide Fuel Cells (SOFC), Molten Carbonate Fuel Cells (MCFC), Proton Exchange Membrane Fuel Cells (PEMFC) and the big energy generators like experimental turbogas burning hydrogen (ex.: Enel Research demonstration project in Fusina - Venice province).

In both cases, we encountered many difficulties in focus on safety aspects of the different applications: concerning these topic the international situation appear to be particularly heterogeneous, there are no specific framework within these initiatives can be developed synergically (as opposed to what happens in the field of mobility) and, at present stage, the higher expectations are directed towards increasing of efficiency and reducing the cost of such systems.

The data collection process followed the methodological approach indicated in deliverable D2.4 “Mirror groups organization chart and data gathering procedures”. In the following paragraphs information gathered through each tool are presented and discussed.

4.2 Questionnaire and interviews

In this chapter the main results of the questionnaires are resumed, reporting where possible, the completed answers. Note that, as mentioned in Chapter 1, the first and third sections of the questionnaire were common to all mirror groups. Therefore, some answers that were already reported in Chapter 1 are repeated here, for respondents of both questionnaires.

1.1. In what sector, or sectors, are you mainly interested in relation to the hydrogen technologies and fuel cells safety matters (H₂ Production, Storage and Distribution, Mobility and Vehicles, Non-vehicles and residential power generation, Regulations, Codes and Standards (RCS)).

Most part of the respondents belongs to industries. Except for one case, all were interested in more than one specific group of safety matters.

1.2. Could you provide an estimate of the hydrogen/fuel cells market related to your specific sector in Europe and globally (market share)?

The question was understood in very different ways by the various participants.

Here is a picture of the answers:

Safety is about 10% of the FCH market share.

In terms of number of units more than 20000 fuel cells have been shipped globally for stationary applications by all vendors. Keep in mind that NTUA is only involved in research and not in the manufacturing of fuel cells.

1.3. Could you provide an estimate of the hydrogen/fuel cells market related to your specific sector in Europe and globally (competitors)?

Also in this case the question was not understood in the expected meaning. The answers were copied by the previous one.

1.4. How do you think the H₂ safety is perceived among your suppliers?

The main differences in the answers seems to depend if the participant:

- is focused on the relationship with other companies or institutions already connected with hydrogen activities:

H₂ safety is well looked after by suppliers. Safety is ensured with off-the-shelf technology though special care must be taken.

- is considering a wider range of stakeholders

In a primitive way due to lack of education/training and insufficient investment in hydrogen safety research. Mistakenly hydrogen safety is treated by many not as technological issue but as psychological.

1.5 How do you think the H₂ safety is perceived among your customer?

The situation seems to be more variegated.

Variable perception. Some are still afraid of potential safety issues related with H₂ whilst some already understand that even if potentially dangerous, safety is currently ensured.

With doubts, but after explanation it becomes positive

Customers still afraid hydrogen as there is no way to demonstrate safety by experiments and videos. Instead attempts to push 'safety' by repetition of words 'it is safe' continue.

Customers consider H₂ as a safe fuel

1.6 How do you think the H₂ safety is perceived among your own workers?

Safety training on hydrogen issues has been taken in serious consideration:

All researchers involved adhere to guidelines set by NFPA (50A, 55), EIGA IGC 15/06/E, PED and specific risk assessment and HAZOP studies based on application.

Safety regulations and recommendations are in place and the procedures have been implemented by the workers

It is not more dangerous or safe. It is different and should be dealt with professionally.

1.7. How do you think the H₂ safety is perceived among your subcontracted workers, which work in this issue?

This question, like numbers 1.8 and 1.9 has been usually overpassed by the respondents.

Specific questions on Non-vehicles and residential power generation

5.1. What sub-category best identifies your interests? i) Decentralized power generation; ii) Remote back-up power

60% of the respondents were interested in decentralized power generation; 20% on remote back-up power and the remaining in both. No relation has been highlighted between the sub-category and the belonging organizations.

5.2. What are the decision making criteria within your organisation when introducing new processes, products or services related to hydrogen production?

In this case was quite clear that environmental and economical criteria were the key factors, at the same level of importance.

5.3. What order of importance does your company give to the following hazards?

Unimportant = 1; Very Important = 5; Do not know = 0

Hazards related to hydrogen	% of 1	% of 2	% of 3	% of 4	% of 5	% of 0
<i>Ignition when mixed with oxygen</i>					80%	20%
<i>Propensity to leak and flow</i>			40%		40%	20%
<i>Ability to embrittle certain materials</i>	20%	20%	20%		20%	20%
<i>Invisible flame</i>			20%	20%	40%	20%
<i>Very cold in liquid form (-253°C)</i>	40%		20%			40%
<i>Highly pressurised (70 Mpa)</i>		20%		20%	40%	20%
<i>Asphyxiant</i>	40%		40%			20%
<i>Hazards linked to H₂ colourless/ odourless nature</i>	20%		60%			20%

The hazard of hydrogen to ignite is by far the most important one, followed by its propensity to leak, the invisible flame and it at high pressures. It is important to note that in this topic, the use of high pressure storage and liquid hydrogen is not so common.

5.4. What risks, hazards related to hydrogen mostly affect your organization and clients and what are the consequences you face?

The participant to the questionnaire answered to this question in line with the question 2.3: only the risk of explosion was added, that is an aspect to be noted.

The only consequence revealed is the need of redundancy of safety measurement.

5.5. What are the main barriers to the introduction of new H₂ production plants, in particular considering H₂ safety?

Most of the respondents mentioned economics aspects as main barrier; then two elements have been reported: absence of regulation and lack of hydrogen infrastructures.

5.6. Are there any solutions to overcome these barriers?

According to the previous questions, two solutions has been clearly identified:

EU common regulations in safety and regular seminars, exhibitions and shows about hydrogen technologies

Expansion of the H₂ supply network and commercial storage solutions

5.8. What solutions and measures were adopted by your organisation and how are they effective?

Concerning this question, only one participant defined as main solution the redundancy of safety measures. For the others the theme is still work in progress.

5.9. What are your needs in relation of the H₂ production safety?

As for what answered in question 5.6, the main topic is related to the EU common regulations.

5.10. How the aforementioned measures are perceived by your academic collaborators, customers and suppliers?

The measures are perceived positively.

5.11. How safe use of hydrogen in non-vehicles and residential power generation and your measures are perceived by workers / employees / collaborators in your organisation?

The measures are perceived positively.

5.12. How do you think safe use of hydrogen in non-vehicles and residential power generation is perceived by EU citizens and citizens in your region?

The applications are still perceived with some doubts.

5.13. Are you aware of promising technologies that might reduce safety issues in your sector?

Only one participant answered positively, but he didn't detail them.

5.14. Are you aware of promising practices that reduce or might reduce safety issues in your sector?

Similar answers like before:

EU common regulations in safety and regular seminars, exhibitions and shows about hydrogen technologies

Supplementary questions

7.1. What aspects do you think should be improved regarding H₂ safety (incl. regional, national and EU aspects)?

- The implementation of common RCS across all Europe is a “common” answer.

EU common regulations in safety, standards

Development and enforcement of uniform standards and legislation regarding H₂ applications

- Increase the number of demonstration projects for instructing people, as well as easy access to specific information on safety.

Dissemination plans to raise people's awareness of the safe nature of H₂ utilisation today

- Building a common and available infrastructure:

Expansion of the public infrastructure to avoid private installations that are potentially riskier

7.2. What recommendations on hydrogen safety do you have for the EU institutions (incl. regional and national aspects)?

Similar answers like before.

7.3. Do you have any H₂ related actors and stakeholders that you wish to suggest for the present interview?

In addition to suggesting some well known entities working in this sector, it has been recommended to organize more regular seminars, exhibitions and shows about hydrogen technologies.

7.4. Do you think is there any lack of funding in relation to the development of hydrogen and fuel cell technologies, and H₂ safety. Please, justify.

A sort of lack in funding is confirmed by the respondents:

There has been a transition from a decade when substantial funding was devoted to fuel cell development to a decade when fuel cells, in particular some technologies, seem to have disappeared from earth. The difficulties of the European industry might have contributed but, even if this were the case, my feeling is that there is a lack of official support to the technology

7.5. Do you think the hydrogen stakeholders are not efficiently connected to technology transfer centres and hydrogen clusters/platforms? Please, justify.

Answers were clearly in favor of “Yes” (not efficiently connected).

According to the methodological approach defined in deliverable D2.4 a part of data collection activity was dedicated to interviews.

Some difficulties were encountered in identifying collaborative stakeholders, despite the fact that we have contacted primarily SOL consolidated partners.

The first one, was related to the possibility to reach experts on the requested topics, while very often the reference person has a different role in his organization (i.e. administration or sales); second, many Companies and Institutions have very strict policies in terms of external communications, which sometimes discourage the participation to such activities. Third, in the recent years many project – at European and Worldwide levels – have been deployed to collect data related to “hydrogen application”: the background noise generated has probably made the opportunity to participate in similar initiatives less attractive.

Eventually, we tried focus on people belonging to organization involved directly on the topic of this WP.

Professor MARCO N. CARCASSI – University of Pisa

Professor Marco N. Carcassi has focused his research studies, in last thirty years, in Hydrogen Risk in Nuclear and Conventional plants. He is member of several associations, both scientific and institutional, focused on hydrogen risk and technology development. Presently he is associate Professor at University of Pisa in the Civil and Industrial Engineering department.

Starting from his experience in hydrogen safety field, initially applied on nuclear plants, Prof. Marco Carcassi had develop a very deep knowledge on hydrogen feature when used in industrial plants.

The foundation of his experience came from the experimental analysis of hydrogen burning process and releases. Subsequently he was deeply involved on embrittlement studies and explosion simulation.

Since the 2000 years he has started an effective dissemination action, he worked as member of Italian Ministry of Interior Ad-Hoc Group created by the Italian Fire Corps to draw up the fire prevention regulations for hydrogen and methane applications, as member of ISO/TC

197, WG11. and IEA Task 19 “Hydrogen Safety” Moreover he is member of the Board of the International Association on the Hydrogen Safety (IA-HYSAFE).

His feeling regarding hydrogen safety is that there is no unsolvable technical issues or too dangerous technical compromises able to justify the common fear in using H₂. Perhaps the market size, that is still small, impedes the diffusion of an actual hydrogen safety awareness. In support of this thesis we can consider that methane is commonly used despite it is even more dangerous.

The reason of that difference in common awareness is clearly derived by the market dimension, in fact the methane market is not considered as innovative as the hydrogen one; from that, methane is considered more reliable and more tested in comparison with the hydrogen that is considered too innovative and not so known.

The experience of Prof. Carcassi led to think that to avoid the different approach on safety, the support of empirical data is essential. An example is the way in which the Italian fire brigades defined the safety regulation for the use of hydrogen: their conservative approach has been overcome thanks to a comparative jet fire test for hydrogen and methane.

ILARIA ROSSO - Chief Innovation Officer - Electro Power Systems

Ilaria holds a PhD in chemistry from University of Torino and is an expert in both fuel processing techniques and fuel cells technology. Co-founder of Electro Power Systems, since 2002 Ilaria published more than 50 scientific papers at industry conferences and within international journals focusing on the chemical processes involved in hydrogen technologies.

In 2011 Ilaria received the first ever EU Prize for Women Innovators from the European Commissioner for Research Innovation and Science. She now serves as Chief Innovation Officer, with responsibilities for the ideas and technology innovation development, leveraging the right incentives, and building/running an effective, transparent, and efficient innovation process together with the stakeholders and EU policymakers.

Electro Power System (EPS) is a company deeply involved in developing equipments able to transform hydrogen into electrical power. In particular they developed a commercial PEM fuel cell integrated with a PEM electrolyzer.

The main applications for that kind of technologies are back up systems, grid support, energy storage and off grid applications.

An example of that application has been the installation of back up system able to guarantee the power supply stability to telecommunication infrastructure (200 installation up to now). In particular it was made by an electrolyser, a fuel cell and a small gas storage. Some of that installation had been carried out in urban location. In that case the biggest problem they had to face was the bureaucracy needed. An important aspect that have to be highlighted is the difference between the approach to hydrogen from citizen and institutional actors.

Concerning the action implemented by EPS to decrease the dangerous perceived by citizen, the first task defined has been the visual definition of dangerous area and the access restriction to unauthorized person.

PAOLO FRACAS - Chief Executive Officer - Genport North America Corp.

Electrical engineer, post graduate international studies at MIT, 21 years managerial experience in multinational companies, 10 years experience in FC.

The genport company is involved in testing, developing and commercializing portable system that use hydrogen for producing electrical power. Considering the genport experience two different but related aspects have to be considered in order to increase the hydrogen diffusion.

The first is a marked grow busted by the introducing of less expensive technologies. The second is the standardization of hydrogen features, *e.g. physical state, purity grade*, so as to define a unambiguous regulation.

Regarding the hydrogen safety, one of the biggest issue to face is the wrong feeling that led to consider hydrogen more dangerous that others technologies commonly used. An example of this aspect is the difference in safety perceived between lithium ion battery and solid state hydrogen; in fact the first, since it is well defined and regulated, is considered safety despite the accidents occurred, the second is considered more dangerous even if there was no significant accidents occurred.

Another example of that wrong feeling is the policy applied by insurance company, in fact in some cases there was not possible stipulate a insurance agreement for lab in which hydrogen is used.

Concerning the technical aspect that is more relevant if the aim is to minimize the hydrogen danger, Genport company identified the leakage as critical aspect of their products. Related to this point are: the high cost of hydrogen tested hardware and detector for hydrogen release. Also the electrical hardware have to be safe as established by ATEX regulation.

JURI RICCARDI - Researcher – ENEL S.p.A.

Juri Riccardi is a researcher at ENEL Engineering Research Division (Enel is Italy's largest power company and Europe's second listed utility by installed capacity. It is a leading integrated player in the power and gas markets of Europe and Latin America, operating in 40 countries across 4 continents overseeing power generation from over 98 GW of net installed capacity and distributing electricity and gas through a network spanning around 1.9 million km to serve around 61 million customers).

At the present his research activity is mainly focused on renewable energy, smart grids and distributed generation systems. Since 2000 his researches have been also focused on the hydrogen applications in large scale industrial combustor and on the development of hydrogen energy storage tanks coupled with renewable generation systems (photovoltaic and wind turbine).

In his experience the main safety critical issues concerning large scale hydrogen applications (energy generation, energy distribution and energy-storage) can be summarized as follows:

- hydrogen losses by diffusion phenomena through valves and containment walls;
- materials damaging at temperature environment (corrosion, stress corrosion cracking, hydrogen embrittlement);
- materials damaging at high temperature (attack from hydrogen, hydrogen disbonding of bimetallic stainless alloys, hydrogen embrittlement).

Despite the numerous literature papers already published on this subject, further exhaustive studies concerning hydrogen interaction with metallic structures should be recommended,

especially to investigate the effects in large scale innovative applications, using hydrogen as energetic carrier. In fact, due to its high capacity to produce breaks deferred in time, hydrogen induced cracking and hydrogen embrittlement phenomena should be considered the two relevant safety issues in chemical plants as well as energetic and mobility applications.

CARLO TREGAMBE - R&D Manager ICI_LAB - ICI CALDAIE S.p.A.

ICI_LAB, a proper self-standing department established in the company in 2005, is specialized in research on micro-cogeneration with "fuel cells" for local production of electricity and heat with power up to 100 kW.

Carlo Tregambe underlines that his experience is limited to "field tests" at the site of a selected number of customers, in order to improve their technology. Then, they can be ranked in a post-laboratory demonstrative stage, still not available to public customers. Moreover, safety issues are limited due to the intrinsic layout of the technology that includes a reforming reactor directly coupled with a fuel cell, without any intermediate hydrogen storage. The system is operated at ambient pressure. In case of significant leakages or malfunctions, the control system insulates the components by means of valves and shut-down the reactor, limiting the potential hydrogen dispersions; the methane feed is immediately interrupted.

Ahead the installation and setup of the equipment an analysis of the surrounding is realized, aiming at put to use the best practices. Outdoor installation is the better solution in order to improve the safety. On the other hand, indoor plants can be realized; current solutions for indoor thermal power stations, which could be substituted by micro-cogeneration residential plants, already requires by law some safety precautions (i.e. a minimum air replacement rate, ATEX standard application). In theory, they would be sufficient for the micro-cogeneration plant; anyway, in order to guarantee a higher level of safety, the setup of the plant takes into account additional safety factors (about 1.3) and hydrogen gas detectors are introduced in the balance of plant. Weld joint will substitute, in the development of the device, the internal flanges in order to minimize the possibility of hydrogen leakages. These adaptations are mainly due to the great role that safety plays in hydrogen applications, supported by final users perception.

With respect to the barriers to introduction of residential hydrogen applications, lack of education is the most relevant. In his experience, when he worked with technicians,

hydrogen did not lead to particular safety issues or prejudice. Therefore, once the boundaries of the problem was defined and reasonable solutions was discussed, the work went on. On the contrary, in public events (e.g. fairs) where common people or not expert in the field technicians face the technology, much more barriers and preconceptions are present. Therefore, he highlights the strong impact of demonstrative public plants in order to solve such issues. The way to improve the H₂ safety perception is to make hydrogen technologies everyday things, as well as nowadays natural gas based technologies.

RICHARDO CHACARTEGUI - Associate Professor - University of Seville

He holds a PhD in Energy Engineering and a Msc Mechanical Engineer. He is currently Professor of the Energy Engineering Department at the University of Seville. From this position he has participated in more than 60 R&D collaborative projects developing different commercial technologies for the energy and transport industries from his R&D group.

He collaborates with companies active in the field of hydrogen systems; a lot of studies and projects are ongoing in order to assess feasibility of hydrogen plants. Nevertheless, due to the early stage of the hydrogen market, companies are much more concerned about reduction of costs; safety is important, but they assume that issues related of this aspect would be solved meanwhile and that perception would be positive after demonstration in the field. Research is focused on innovative technologies and layouts, so safety aspects are usually not directly addressed and given to following detailed design step.

Each safety issue can be faced with the current technology; the level of complexity of the solution depends on the single application and, for sure, implies additional costs. The higher the perception of the risks, the higher the requirement in terms of additional instruments and devices aimed at safety.

About the applications, domestic cogeneration is nearest to the market than fuel cells vehicles; it would be competing with natural gas that has anyway safety issues. So, an accurate design, a correct placement and a real maintenance is already required. Actually, these technologies are still not economic so a fast spread is not realistic. An alternative could be the use of mixtures of hydrogen and other gases (i.e. syngas). Syngas is currently stored in plants, easier to handle, to store and cheaper; moreover, the perception of the risk is

lower. So it could be a starting point in the short-term as a substitute of natural gas for the applications.

FOCUS GROUP

Considering the difficulties to find significant case studies to the topic of this chapter, the focus group theme suggested to the participant was the perception of the danger related to Hydrogen and the attendees experience in the field.

Attendees: Ilaria Rosso, Marco Carcassi, Juri Riccardi, Paolo Fracas.

The discussion started with some considerations about the perceived danger of hydrogen. As already noted during the face to face interview, the bigger issues are not related to actual lack of safety but are strongly connected to the complexity of regulation in effect.

All the focus group members agreed with the fact that hydrogen is not danger as perceived and, vice versa it is less dangerous than gases commonly used such as methane. Moreover they explain how a correct way to inform citizen or a visual advice on a site in wich hydrogen is used could actually decrease the danger perceived.

Prof Carcassi highlighted another important aspect connected to the way in which the hydrogen safety matter is faced. He noted that the states in which the responsibility of hydrogen installation safety is directly assign to the technician who designed it, have a larger diffusion of hydrogen technologies while, when an independent monitoring organization is in charge of safety control, a lot of time more have to be spent to be able to operate the potential hydrogen installation even if it has been already completed. This drives the hydrogen costs up, impeding a large scale diffusion.

So two different but related aspects has been defined in the first part of focus group; a more complex regulation means a more complex system of safety monitoring that impede the hydrogen diffusion causing an increasing of installation costs. Furthermore the present distorted representation of hydrogen could be modified implementing the communication on hydrogen features.

Obviously the hydrogen market is deeply affected by the regulation difference from each country. The only way feasible if the aim is developing a Europe hydrogen market is nullifying those difference and an effective solution able could be an over national regulation. Even in this case the possibility to reintroduce specific national directives have to be avoid preventing the application of national sub-directives. Exemplification of that, are definitely the PED and the TPED directives whom are over national but applied through national sub-directives thus in very different way.

In the second Ilaria Rosso, Juri Riccardi, and Paolo Fracas explained their particular experience regarding the non vehicles power generation from hydrogen.

Ilaria Rosso is involved in the installation of PEM fuel cell, integrated with a PEM electrolyser and a compressed gas storage system, for grid support, electrical back up and off grid application.

Some of those installation has been carried out mainly in industrial zones but even in residential areas, in every case the safety requests form the monitoring organization have been focused on storage system an not to the production or fuel cells systems. This is simply because of the small volume that contain hydrogen in fuel cell or electrolyser apparatus, from that each problem that occurs on that apparatus can not be considered as incident but only al malfunction.

Paolo Fracas, that is involved in testing, developing and commercializing portable system that use hydrogen for producing electrical power, state that he had an experience very similar to the one of Ilaria Rosso.

In fact the fuel cell in the apparatus made by his company have high safety level, while the storage system is considered the dangerous part even it works at ambient pressure and temperature since it is based on solid state storage technology,

Regarding that point Mr. Fracas means to underline the fact that the lithium batteries are definitely more dangerous than an hydrogen storage system based on metal hydride but none of the company that usually transport Li-battery are willing to transport them.

Eventually Mr Ricciardi, that is researcher of ENEL researcher division, expose the experience had with the first worldwilde turbine used to burn hydrogen and produce lectrical power.

Also in this case, the storage has been considered as the dangerous part of the plant. In fact all the demands of safety implementation have been focused on control valves used to control the storage tank and to control the high pressure electrolyzer.

4.3 Document review and observations

Related codes and standards published are mainly drafted by the International Standard Organization (ISO), national standardization committees and international associations such as International Electrotechnical Commission (IEC), European Industrial Gas Association (EIGA), National Fire Protection Association (NFPA), Canadian Standards Association (CSA) etc. To accelerate the pace of hydrogen standardization, special committees or project teams are usually built. Below several codes and standards published are listed, dealing with hydrogen storage safety:

- IEC 62282-3-100 Stationary Fuel Cell Systems – Safety (International)
- BS EN 62282-3-100:2012 Stationary Fuel Cell Systems – Safety (International)
- GB/T 27748.1-2011 Stationary fuel cell power system - Part 1: Safety (China)
- ANSI/NFPA 853 Installation of Stationary Fuel Cell Power Plants (United States)
- BS EN 62282-3-3:2008 Stationary Fuel Cells Power Systems – Installation (European Union & UK)
- Stationary Fuel Cell Power Requirements: ANSI/CSA America FC 1-2004
- Portable Fuel Cell Power Systems ANSI/CSA America FC 3-2004
- CAN/BNQ 1784-000 Canadian Hydrogen Installation Code (Canada)
- NFPA 853 Standard for the Installation of Stationary Fuel Cell Power Systems
- HSE - Installation permitting guidance for hydrogen and fuel cell stationary applications (UK version)
- IEC 62282-3-1 (2007-04) Ed. 1.0 Fuel cell technologies – Part 3-1: Stationary fuel cell power systems – Safety
- IEC 62282-3-2 (2006-03) Ed. 1.0 Fuel cell technologies – Part 3-2: Stationary fuel cell power systems – Performance test methods
- IEC 62282-3-3 (2007-11) Ed. 1.0 Fuel cell technologies – Part 3-3: Stationary fuel cell power systems – Installation

- IEC 62282-5-1 (2007-02) Ed. 1.0 Fuel cell technologies – Part 5-1: Portable fuel cell power systems – Safety
- IEC 62282-6-100 (2010-03) Ed. 1.0 Fuel cell technologies – Part 6-100: Micro fuel cell power systems – Safety
- IEC 62282-6-200 (2007-11) Ed. 1.0 Fuel cell technologies – Part 6-200: Micro fuel cell power systems – Performance test methods
- IEC 62282-6-300 (2009-06) Ed. 1.0 Fuel cell technologies – Part 6-300: Micro fuel cell power systems – Fuel cartridge interchangeability
- IEC/TS 62282-7-1 (2010-06) Ed. 1.0 Fuel cell technologies – Part 7-1: Single cell test methods for polymer electrolyte fuel cell (PEFC)

4.4 Case studies

4.4.1 DUDLEY, United Kingdom

This case studies has been extracted by HYPER Project reports (www.hyperproject.eu).

A verification model of SOFC had been installed in Dudley West Midlands (UK) to demonstrate the effectiveness and reliability of domestic heat and power co-generation (one family unit).

The whole systems was CE marked.

The authorization process passed through the following step:

- Hazop performed and Risk Assessment with HSE
- Planning authority consulted but they said it was outside their control
- Building control advised to treat it as an outside experiment
- Supply of gas (BOC) covered by Gas Regs
- Fire Brigade did not have a procedure – one was written specifically by third parties and they adopted it. They were involved in the installation process: a special telephone number was issued in case of emergency



Figure 4.1. SOFC CHP system.

The system was housed in a wooden shed –indoor installation – and in the end it was treated more as a natural gas system would have been treated, fitted with leak detectors.

Main parameters of the installation are resumed in the table 4.1.

Table 4.1. Technical data of SOFC CHP system.

Nominal power [kW _{AC}]	1.5
Nominal heat [kW _{th}]	3.0
Fuel gas supply pressure [mbar]	18 to 25
Voltage [V]	230

The fuel cell was in the end connected to the grid.

In this case studies, the main challenges were the following one:

- public perception of hydrogen was not good and many actors involved was feared from its application;
- the lack of standards and guidelines, created many difficulties in the authorization process since it was not clear which institutions should have been responsible for the different procedures.
- Moreover, this kind of application that could have been easier managed in an industrial installation required more time due to the authorization complexity

4.4.2 Danish micro-CHP project [56, 60]

The project aims at the demonstration on field of the effectiveness and reliability of domestic heat and power co-generation based on Danish Fuel cells. The project is scheduled in three phases: during the first one (2006-2007), micro combined heat and power (μ CHP) prototypes were developed and tested and the results from these first tests provided valuable input for improvements of the next versions of the devices. The second and the third phases (2008-2014) are demonstrations at end users (9 prototypes during phase 2 and a larger quantity during phase 3). Private householders as well as firms and public buildings tested the units during the routines of the everyday life.



Figure 4.2. Household of the first μ CHP test unit.

The units allow for distributed generation of heat and power at the end users location at a minimum of CO₂ emission and, at the same time, providing grid balancing capacity and energy storage functionalities for future smart grid operation. From this point of view, the Verstenkov village on Lolland Island was chosen for the field test due to the large excess of annual wind energy locally produced (about 500% of the total load). The village is situated in heating district 4, with 540 inhabitants (about 150 single family houses). In the past, in case of leak of wind the missing heat and power were produced by domestic systems mainly fed by oil. The idea is to replace them with μ CHP fed by hydrogen produced from the large excess of wind; hydrogen is produced by electrolysis and distributed by means of a dedicated H₂-grid infrastructure.

Different technologies were selected for the project: LT-PEM (low temperature PEM fuel cells), HT-PEM (high temperature PEM fuel cells), SOFC, CPO- μ CHP (local production of hydrogen from methane through catalytic partial oxidation) and LT-PEM coupled with small scale methane reforming unit. They were lab tested and, if ready, brought to field tests.

In this report, we will focus on phase 2 and 3 field tests and, in particular, on LT-PEM systems that are the most proved technology and therefore the one with a large number of tested units (5 in phase 2 and 35 in phase 3). Different units were developed in the project by the partners of the project (IRD fuel cells, DGC, SEAS NVE, Danfoss), named α , β and γ ; their characteristics are reported in the table. Main difference in the first step is the improvement of efficiency, while γ - μ CHP strongly reduced the costs (about 60%) and size.

Table 4.2. Technical data of Low Temperature PEM systems.

	α - μ CHP	β - μ CHP	γ - μ CHP
Nominal power [kW _{AC}]	1.5	1.5	1.5
Power range [kW _{AC}]	0.9 ÷ 2.0	0.9 ÷ 2.0	0.9 ÷ 2.0
Nominal heat [kW _{th}]	1.1	1.5	1.6
Heat range [kW _{th}]	0.5 ÷ 1.1	0.8 ÷ 2.0	0.5 ÷ 2.0
Efficiency (H ₂ to P _{AC} , LHV)	43%	47%	44%
Combined efficiency	75%	94%	94%
			

It was relatively simple to allocate the first five test families (phase 2); all installation sites were different and the users were without special knowledge of the used technology. The requirements and wishes from the customers have a high priority in this work. As a results, three of the installations were made indoors (garage or utility room) and two were outdoor solutions (sheds). All the installations comprised a β - μ CHP unit and a 200 liter heat storage. The units were operated on heat demand and, for additional peak heating during the coldest part of the year, an electrical cartridge heater is integrated in the heat storage. All the hydrogen fuelled micro CHP units at Vestenskov are connected to the internet; this enables remote control, if needed, and data transmission. Some examples of installations are shown in the following figures.



Figure 4.3. Examples of indoor installations and sheds for outdoor solutions.

The hydrogen is produced by two electrolysis unit (Hydronics, PEM, 4 kW) linked to the wind power plant. Nominal hydrogen production is 16 Nm³/h (max 20 Nm³/h, max electric consumption 104 kW) at 8 bar_g; due to the unpredictable nature of the energy source and the mismatching with the loads, hydrogen is stored in a 25 Nm³ tank at 6 bar_g. A dedicate underground pipeline distributes hydrogen to the customers. This infrastructure was built in two phases: the grid for the first field test houses was made in coated stainless steel, while the piping for the succeeding grid in Vestenskov was made with PE-80 tubing.



Figure 4.4. Electrolyser and storage unit.



Figure 4.5. Building of the hydrogen grid infrastructure.

Safety aspects were very important in this project, due to the not-restricted zone in which the units are located (households, public buildings, ...). First of all, each unit needs a CE certification (test and evaluation of the documentation has been completed at DGC). The certificate was issued after an inspection of each μ CHP unit, until the development of the CHP manufacturing facilities at IRD has been completed. Two safety valves (e.g. solenoid valves) are added to the original design in order to fulfil the CE-marking requirements and a barrier diagram (HAZAP) is associated with the unit.

The phase 2 and 3 μ CHP units are intended to be used in an ordinary household, and therefore regulated by the Gas Appliance Directive (GAD). The standards and directives applied in this project are:

- Gas Appliance Directive 2009/142/EC
- DS/EN 62282-3-1:2007 Fuel cell technologies Part 3-1: Stationary fuel cell power systems – Safety
- DS/EN 437+A1:2009 Test gases – Test pressures – Appliance category
- DS/EN 50465:2009 Gas appliance – Fuel cell gas heating appliance – Fuel cell gas heating appliance of nominal heat input inferior or equal to 70 kW

According to the normative, a risk analysis was developed in order to identify any significant foreseeable safety issue and to ensure a safe operation in any working point and during the whole lifetime of the device. Leakage tests were made before the first start up and repeated at the end of the CE tests, in order to check that the system will not leak flammable gases. Moreover, a test of personal safety shutdown was performed in order to show that the system will shutdown before there will be a safety issue.

In general, in the case of stationary fuel cell plants for CHP operation it's also recommended that the installation comply with the requirements of the local fire protection authorities. A number of international standards are being prepared to facilitate compliance with the above mentioned directives. The standards are primarily aiming to describe a standardized way to comply with the Gas Appliances Directive. It is DGC's recommendation to respect not only the legislation in force, but also the standards that CEN and IEC's TC105 are drafting; some of which have already been published.

Many Gas Regulations requirements severely affect the construction and design of the plant. To achieve efficient implementation of the requirements of the Gas Appliances Directive it is necessary to acquaint oneself with these requirements very early in the process - e.g. when entering into the actual design phase from the conceptual phase. Correspondingly, experience shows that it is necessary to involve relevant authorities in the installation work very early in the process and, at any rate, prior to any practical installation work.

In Denmark the most important authorities in connection with hydrogen and fuel-cell plants are the Danish Working Environment Authority, the Danish Safety Technology Authority and the Danish Emergency Management Agency. Besides these, the regional and local authorities must approve the physical location in accordance with district and regional planning.

According to the opinion of manufacturers, system integrator and energy/service suppliers, it's suggested a "gas background" (e.g. the Danish "A-certificate") for installers and service personnel. Additional general training in piping and fittings work for hydrogen piping is required. Moreover, product training for the specific devices is also essential.

For the demonstration plant, hydrogen is present in the main process equipment container, in the hydrogen storage and in the outdoor pipe systems. The content of hydrogen in the main process equipment container is less than 5 grams and is considered to be below the triviality limit. For the piping system, there will only be a demand for zone 2 classification for locations with assembled pipes or flanges. The hydrogen storage contains maximum 13.5 kg hydrogen and has to be fenced in (about one meter away from the installation) and this area is also classified as zone 2, which implies that all equipment must be approved according to ATEX.

The safety system of the CHP is strongly linked to the gas ramp component, that reduces the pressure from 4÷6 barg of the hydrogen grid to the 0.4 bar entering the house; in case of an event activating the CHP safety system, the main valve in the gas ramp will close.

Several operation stops occurred mainly caused by different subsystems and not the fuel cells (control-error from the heat storage, bad internet connections, limited lifetime of the stack).

Several conclusions can be summarized after this field test. Hydrogen units and installations need solid regulations and standards for the authorities to act smoothly. It took one year to acquire the necessary legal authorizations in Vestenskov, mainly because the responsibility of the approval of hydrogen installations in private households was not clearly defined.

Public acceptance is mandatory for the technology success; the field test hosts have proven to be very good ambassadors for the acceptance as they often talk to many tourists and journalists of their experience. Moreover, shortly after the end of phase 2, it was found that more than 90% of the inhabitants of the nearby village Vestenskov were willing to act as host for fuel-cell cogeneration demonstration plants.

From the technologic point of view, many optimizations are required in order to improve the aimed stability and lifetime (over 40,000 hours)

The field test has attracted a lot of interest and visits amongst industries, politicians and NGO's. SEAS-NVE and Lolland municipality have established an energy exhibition in Vestenskov, H2interaction (<http://www.h2interaction.dk/>), to accommodate the energy-tourists need for information without stressing the 'test'-families with too many showings.

4.4.3 Case study 3 – Testing of hydrogen-based CHP units within a dedicated laboratory

Introduction

In the last years, Politecnico di Milano has dedicated an effort to set up a new Laboratory of Micro-cogeneration (LMC) [61]. The laboratory is a structure developed for testing up to 100kW_{el} combined heat and power (CHP) units fueled by natural gas, hydrogen, synthetic gas or any mixtures of the previous, depending on the thermal power range and type of syngas composition. The laboratory can test also trigeneration or Combined Cooling Heating

and Power (CCHP) systems using heat pumps or thermal absorption chillers and boilers. The laboratory is designed to recreate most plausible operating condition, changing independently the water flow rates and temperatures of hydraulic circuits, flow rate and chemical composition of the fuel gas supply, temperature of the ambient air and the electric load. It aims at characterizing a micro-CHP in terms of realistic energy and environmental performance, improving where necessary the control logic; secondly, it aims at developing innovative systems and components in the context of specific research projects.

We discuss here briefly the Lab features by the point of view of testing of Fuel Cell systems using hydrogen either taken from a feeding circuit or generated locally with a fuel processor and by the point of view of safety requirements and equipment.

Testing of a hydrogen-based PEM CHP system

Activities at LMC lab have included testing of 20 kW PEM fuel cell CHP systems, which is considered here as an example. Hydrogen was generated locally within a natural gas reformer and purified through a water gas shift and preferential oxidation reactor loop. After installation at the laboratory, testing has been performed within R&D activities on the development and tuning of the fuel processor and hydrogen purification line, the heat recovery loop for cogeneration purposes, the FC stack integration and electrical connection as well as to verify the system mass and energy balances and emissions. Heat recovery allows producing 60°C hot water by cooling the FC and the fuel processor. Details about the laboratory and the tests are discussed in [62]

The simplified diagram of the FC unit with fuel processing and heat recovery loop is shown in the next figure.

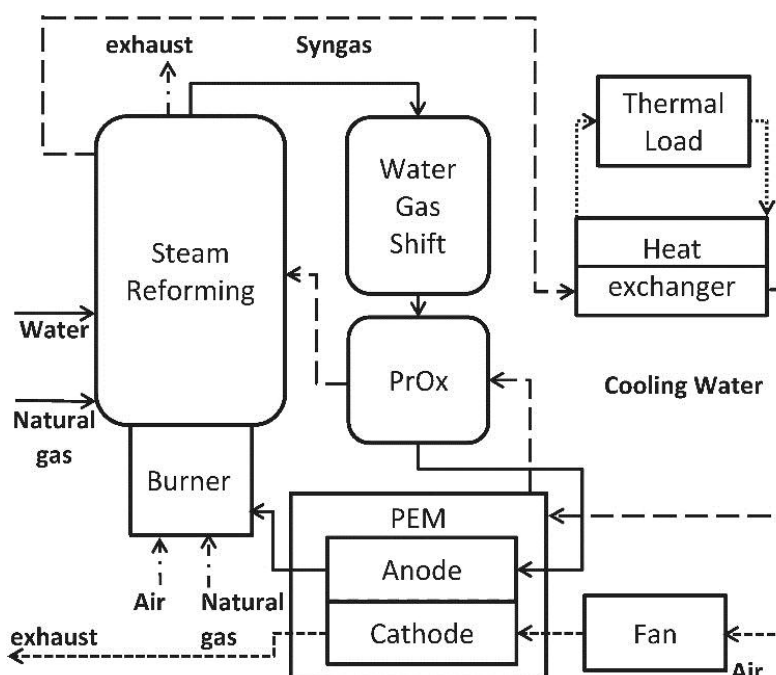


Figure 4.6. Simplified diagram of the PEM FC unit: the fuel supplied is natural gas, transformed into the fuel processor in a stream with a high content of hydrogen that feeds the PEM cells.

The lab is organized into three areas: (i) the test room ; (ii) the control room (about 40 m², hosting the control panel and data acquisition, as well as auxiliary instrumentations); (iii) the plant area, placed above the ceiling of the test room, hosting all the hydraulic circuits, air treatment unit and the electrical panels.

The test room, fuel supply and safety infrastructure

The gas distribution network includes low pressure natural gas from local distributor pipelines, as well as compressed natural gas from a dedicated screw compressor (up to 30 Nm³/h at 10 bar); other gases are stored in bottles (CO, CO₂, N₂, H₂, O₂), with the additional possibility of producing hydrogen and oxygen through a dedicated electrolyzer. The latter features a hydrogen flow rate capacity of 6 Nm³/h at 30 bar, and a connection to a storage system with 1 m³ pressurized vessels.

The test room is a 25 m² cell where the hydraulic, electrical and gas circuits can be connected to the unit under test. Room walls and internal doors are fire resistant according to the REI120 class.

A redundant leakage monitoring system on flammable and toxic gases (CO, H₂, O₂, CH₄), together with a large capacity ventilation system (1200 Nm³/h) and permanent external openings ensures the possibility to comply with ATEX standard requirements and carry out tests on unclassified units and components. Exhaust gases can be sent to two external stacks (one of which is designed for hot, dangerous and corrosive gases).



Figure 4.7. Test room with a prototype CHP plant (PEM FC system by ICI Caldaie SpA with hydrogen generated locally through a NG reformer). Hydraulic and electrical connections are on the left side, gas connection on the right. An HVAC unit and a safety ventilation system continuously refresh the room atmosphere during the tests.

Within the cell, the gas lines are organized with a measurement and control section (for pressure and flow rate) yielding the possibility of being mixed for syngas simulation. In that case, dosing is controlled through a closed loop control based on periodical chemical analysis through a micro-gas chromatographer.

More specifically, the test room receives the following gas lines:

- natural gas at 20 mbar (diameter 50 mm);
- natural gas at 10 bar (diameter 12.5 mm)
- hydrogen at 25 bar (diameter 12.5 mm)
- carbon monoxide at 25 bar (diameter 12.5 mm)
- CO₂, N₂ and O₂ at 25 bar (diameter 12.5 mm)

Gas lines are manufactured with AISI304 stainless steel; the pressurized lines are tested and certified for an operating pressure up to 30 bar. Before entering the test room, the gas lines are equipped with valves with actuators (normally closed) controlled by the gas detection system (see next figure).



Figure 4.8. Gas lines feeding the test room from the external side, with automatically actuated valves (controlled by the gas detection system) on the right.

The lines of flammable gases are received within the test room through a ventilated gas box. Emergency buttons are installed outside the test room and in the building to interrupt the electrical connection of the power lines.

Aiming to avoid the risk of formation of explosive gas mixtures and reduce the ATEX classification of the test room from level 2 to 'not dangerous', each cell is equipped with an atmosphere detection system with adequate availability and manufacturing features, according to CEI 31-35 and EN 61779-1 - EN 61779-5 and with permanent ventilation. Gas detectors are redundant (2 for each dangerous gas, i.e. H₂, CO, CH₄) and installed according to Ex-n specifications.

The gases can enter the room provided that the gas detection system does not reveal any dangerous gas in the atmosphere and the room ventilation (forced ventilation with flow rate 1200 m³/h) is active. Pre-alarm level is set at 15% of LEL (for hydrogen 0,6% in air), full alarm level is set at 30% of LEL (for hydrogen 1,2% in air).

4.5 Conclusions

There are a wide range of applications for non-vehicles and stationary technologies of Hydrogen and Fuel cells: from small systems to charge mobiles equipment to big energy production plant. Specific products or technologies may involve industries, research centers and final consumers.

Despite the increasing number of applications around the world, the research activities highlights a lack of documentation concerning safety issues. Many case studies were available regarding different installations, but there was no results concerning accidents reports. According to the interviews, this has to be related mainly to the operative conditions of the FC, where the connectes storage is typically minimized (otherwise can be considered as a separate system) and working pressure is close to ambient (usually lower than 5 barg).

Moreover, it still miss a normative framework concerning this topic: up to now this kind of applications have been managed in accordance to similar standards and regulations that appear to be closer to the application (*i.e.*: Natural Gas codes and standards, traditional co-generation systems). This solution maybe has seemed to be practical for the earliest installations, but these could become a barrier for the long term development of these systems.

In many countries is still unclear the Institution that has to approve the installations and between two cases, even in similar conditions, safety requirements can be very different.

Big installations, managed by industrial stakeholders that already have confidence with authorization procedure management, probably are less impacted by this criticality. On the other hand, residential installations and small energy systems may incur in some problems due to the specific aspects of this technology (*i.e.*: is it possible to bring or send by post an hydrogen cartridge?) .

Deliverable No. 3.1

Chapter 5

Regulators, 1st Responders,

Consumers

5.1 Introduction

Regulations have important roles in supporting and promoting innovations and newly developing markets. In the framework of WP3, Task 3.5 focuses on data collection about regulators, first responders, consumers areas to identify the main safety matters in FCH.

A relevant list of stakeholders in the areas regulators, 1st responders, consumers were prepared in deliverable D2.4. Collecting the data using the questionnaire was not successful and no data has been collected so far. The direct communication was the most powerful tool therefore the interviews were successful. Regarding the observations and the documents reviews, the results have been summarized in table under the document review section 5.4. The organization of the focus groups has been carried by task 3 leader for the mirror groups due to the difficulties and the high cost for organising different focus groups. Among the contacted persons in the area of regulations and first responders, they did not have case studies focusing on the safety issues regarding the hydrogen applications.

The following sections are including the data gathered by each data collection tool.

5.2 Interviews

Following the methodological approach described in deliverable D2.4 interviews with high relevant stakeholders to the project have been done. The questions of the interviews have been prepared following the following the outlines:

- Collect further details starting from the answers to the questionnaires.
- Regarding practices and hazards related to hydrogen technologies, what recommendations do the stakeholders have?
- Details about infrastructure, processes and applications.
- Feedback on current policies and enforcements.
- Recommendations on training of personnel and regulations.

The interview took place with the persons listed below:

- Angelo Moreno, President of Italian association of Hydrogen and fuel cells (Italy).
- Antonio Pugliano, Lombardia Regional Firefighters (Italy).
- Chiara Milanese, Chemistry Department of the University of Pavia, coordinator of Pavia Hydrogen Lab (Italy).
- Erwin Mayr, Istituto per Innovazioni Tecnologiche (Italy).
- Marco Migliavacca, Board member of Italian association of Hydrogen and fuel cells (Italy).
- Rita Saiu, Italian Ministry of Health (Italy).

It was difficult to find the right time for the interviews and two of the interviews conducted by phone while four interviews conducted in one-to-one meetings.

Below is full text of the interviews:

1. According to you, how deep is the awareness concerning the use of hydrogen and its safety among the different levels of society? (politics, schools, general public..)? Which kind of means would you propose in order to improve the consciousness and raise awareness on this issue?

- Making exception of the experts on hydrogen issues, there is a lack of awareness among the general public, even though during these last years a slight improvement of knowledge, mostly regarding the safety of hydrogen compared to that of other gases, has been perceived. A spread of knowledge concerning hydrogen is needed, in particular at schools and in the media, where demonstration campaigns can be promoted in order to normalize the use of hydrogen.
- In the specific sector where our Unit is involved, training and knowledge are good. In general, I think that the level of awareness regarding hydrogen issues is quite low. To raise awareness, a greater diffusion of installation and a greater spread of demonstration campaigns to inform citizens are needed, as it is already done to increase awareness concerning other gases.
- I believe that in Italy, the degree of knowledge and awareness of hydrogen issues is unfortunately quite low at every level of society. I think that young people are curious enough on this topic, but neither the media nor schools play a significant role in spreading information. Politicians and administrators are, maybe intentionally, very poorly informed. As regard the level of awareness concerning safety, I think this is probably the lowest, since the general feeling is still that hydrogen is dangerous and difficult to manage. In order to increase consciousness I would propose to organize trainings and seminars at high schools and college, but also courses and conferences addressed to adults. These last might serve as demonstrations and encourage people to visit research centers and laboratories where experts work on different aspects of hydrogen. I would also propose to give hydrogen more relevance through initiatives and publications on magazines (good examples : “M’illumino di meno” published on RadioRai and a publication on Topolino for children).
- There is surely a spread interest concerning hydrogen, but this does not mean that there is a real knowledge about this topic. Administrators are more

involved on financial issues linked to hydrogen use and application. Regarding the citizens, the feeling of danger of hydrogen persists. The best mean to overcome this situation is showing solutions, such as those we are proposing with demonstration projects, with hydrogen buses and transports in Bolzano.

- In general the awareness on hydrogen issues is very low. It would be useful to organize training courses at different levels, seminars, exhibitions and spread information also through the media.
- Politicians: no knowledge. Administrators: lack of investments. Schools: teachers are not well prepared on the topic. Media: partial information. Citizens: citizens want simple and straight information. Up to now, information are just for experts.

2. What is the state-of-the-art in regulations/environmental protection, certification and incident handling? (barriers/solutions?)

- At the national level, there is no harmonization with regards to authorization and regulation processes, this because of the lack of a national set of normative that establishes clear and uniform laws and directives. It is necessary in this sense, a greater alignment between national and European regulation.
- Regulation in the field of hydrogen safety is sufficient to assure the efficiency and face the urgencies. Our Unit is able to tackle every issue concerning the efficiency and safety of installations. Safety on mobile installation is not our concern. First response does not need a specific regulation, it rather needs a set of prevention rules and trainings for the safety operators, as it is already done for other gases.
- As far as I know, at the national level institutions and entities are in charge of developing regulation. In particular, the Ministry of Environment, the Ministry of Economic Development, the Ministry of Transport and Infrastructure and the Ministry of the Interior through the Firemen Body, the CTI, CUNA and CIG. The normative in force are: Ministerial Decree of 16 February 1982 concerning the activities for fire prevention; the Ministerial Decree of 24 November 1984

concerning security measures in case of fire for transport, distribution, collection and use of natural gas with density until 0,8.; the Ministerial Decree of 31 August 2006 concerning the approval of the technical rule for fire prevention for design, construction and use of distribution installations of hydrogen. These norms should be respected by every operator dealing with every hydrogen aspect.

- Regulation is inadequate and date back to 2006. There are a lot of diversities among EU countries with regard to application and implementation of EU directives. Information for users and operators is also inadequate and should be improved.
- Regulation is very good since hydrogen is used as a gas since several years ago.
- Environmental protection: fire control regulation does not take into account hydrogen installation. Certifications: we are just at the beginning. First response management: regulation is scarce. It is needed that the legislation is generated by experts.

3. Do you think there are some obstacles in the determination of rules on hydrogen safety? If yes, which kind of measures would you propose to implement at the European, national and local level in order to improve the quality of the normative process?

- It would be interested , as already established by the new FCH JU2, implementing a system to collect data and information for the entities appointed to the standardization and regulation, in order to be facilitated in the pre-normative phase. They should consider, besides the issues connected to safety, also the issues related to consumption, such as the normative to measure purity and quality of hydrogen.
- It would be desirable a greater interaction among various entities in order to coordinate in a comprehensive way the interventions regarding various aspects of hydrogen. A typical case is that linked to mobility problems, that is in my opinion, should be managed in a more integrated way.

- I do not think that there are obstacles in the determination of rules on security. I believe that a normative at the European level could be useful.
- Regulation is sufficiently clear, but a coordination at the local level on the implementation of directives is lacking. In general, we can say that in Italy there are more restrictions than in Germany.
- It would be useful comparing the different normative of European countries concerning different issues regarding hydrogen, and take the most efficient and effective ones as an example. In my opinion, German legislation is the best in this sense.
- At the national level, it seems that information are aligned with the level of competence of our politicians and administrators

4. *Have you specific recommendation for European or national institutions with regards to safety in the use of hydrogen?*

- Except the distinction between mobile and stationary applications, there is always a problem of standardization of components such as the components of the distribution. As regard safety, systems to manage odors would be needed, similar to those used for methane.
- Under the technical point of view we are able to interact with others' countries regulations. It still remains, however, a problem of harmonization among the various national regulations, that should homogeneously adopt European directives.
- I do not have specific recommendations.
- As already said, my recommendation would be that of favour all the activities that could improve the uniformity of reception of directives in the different EU countries.
- New recommendations are not needed: the only thing that is needed is the efficient application of the normative already existent (ex JRC).
- It is always necessary favor trainings in places where hydrogen is produced and used.

5. *How do you get informed and updated on news regarding regulation, codes and standards that could reduce problems related to safety in various sectors (distribution, storage, mobility and transport, RCS)?*

- Personally, as a representative of a research entity, I take part to the working groups on hydrogen, but I do not enjoy a direct information.
- We rely on our official information channels, that are communications sent to the various Units sometimes also sent as drafts to be modified, commented and integrated with suggestions.
- I get informed through the websites and the network of contacts that I have working in this field, because from our entity are not foreseen specific refresher courses. Days spent studying or researching on this topic are auto financed or paid with funds of the research group.
- For us, the principal channel of information is represented by the strict collaboration with hydrogen installation producers, that are always updated concerning regulation and any other type of news on this issue.
- Internet, literature and seminars.
- Being an expert also in the field of prevention, I acknowledge that is difficult finding information concerning prevention and early warning systems.

6. *Do you think that the stakeholders operating in the field of hydrogen are enough connected to the centers of technology transfer and/or related associations?*

- Stakeholders and the centers of technology transfer are not in strict connection or in any case this happens very seldom since there are no national programs that favour the dialogue between enterprises and research centers on the issue of hydrogen. At the same time, in a period of economic crisis as this one, enterprises are not very much keen in investing without having clear and well defined long-term objectives and programs.
- A greater activity of confrontation and interaction, especially with the academic world has to be underlined, however, that this practice is already in place both with institutions and with personal contacts and has already

produced an important Conference on hydrogen safety, organized at our premises in Rome in 2008, in collaboration with the University of Pisa.

- I think that from the part of associations operating in the field there is a good commitment in trying to involve stakeholders. Networks work well. I believe that stakeholders should show a greater interest and enthusiasm in the proposed activities.
- There is inadequate information from Associations, that should play a more active role in spreading information especially in the field on safety measures.
- There is a connection between the two entities, but the problem is the effective transfer of information from one to the other.
- They are not connected because valuable channels of connection between them still lack.

7. *Do you think there is a lack of funds to support hydrogen technology and fuel cells as concerns the aspects of safety?*

- A great differentiation of funding can be appreciated in Italy from Region to Region. This is because of the lack of a coherent financing plan at the national level that could facilitate the cooperation among local excellences.
- A new technology, such as hydrogen and fuel cells, does always require additional funds in order to be launched and developed.
- I think that funds allocated to the hydrogen sector are scarce, both those appointed to security aspects and those appointed to research and development of new technologies for hydrogen production and storing.
- Funds are available, but they seem to be managed especially from the producers. I think it should be desirable beginning a pre-commercial phase where public financing should decrease and private investment should increase. This would require, however, a stability in the contents of the normative that regulate fiscal aspects for new installations.
- At the European level, funding are available and sufficient, even though it is not always clear their destination.

- In Italy there are not enough funds for research and new technologies. Technological gap between Italy and other European countries is becoming bigger and bigger.

8. (addressed to politicians and administrators) Do you have the impression that there are some difficulties in finding information or that there is a lack of information?

- With regards to interactions with technical offices and local administrations, or with those municipalized companies interested in the use of hydrogen, technical problems are successfully tackled and solved.
- There is inadequate specific information and in particular there are not enough channels to spread information. More in general, in order to create an efficient network, it is necessary having competent persons.

5.3 Document review and observations

The document review and observations aim to collect information from literature and internet articles on hydrogen technologies, fuel cells and safety.

The summary files here below are meant to give the reader an overview concerning the content and the most relevant information on some selected papers on hydrogen issues.

These papers have been chosen from different sources, such as periodical reviews, publications or minutes of workshop and conferences.

Most of the articles deal with hydrogen technology and safety, and analyze these two topics under different points of view (first response, policies etc.). The majority of them are addressed to experts, since the level of information that they provide is, in most cases, very deep and technical. Other papers are addressed to policy makers.

The types of papers taken into consideration are quite different: they can be guidelines, technical papers, case studies, normative and so on. This variety can give the reader a wide choice and the possibility to deepen different arguments.

1	Title	HYDROGEN REGULATIONS, CODES AND STANDARDS FOR ROAD VEHICLES AND THEIR REFUELING INFRASTRUCTURE IN EUROPE
	Summary	Presentation overview: • Safety Implications of Hydrogen Use in Road Transport • Why Harmonized Regulations and Standards ? • EIHP's Involvement in H2 • Regulations and Standards Work • Globally Harmonized Vehicle Approval • Recommendations
	Main Topic	Hydrogen technologies
	Author	Reinhold Wurster
	Date and source of publication	14 -15 June 2004, London, CUTE – Bringing a fuel cell bus fleet on the road in European cities, http://www.eihip.org/public/documents/CUTE_15JUN2004/CUTE_R&S_RWurster-LBST_15JUN2004.pdf
	Intended audience	Policy makers, Experts
	Type of paper	Guidelines
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)

2	Title	HSE HORIZON SCANNING REPORT THE HYDROGEN ECONOMY
	Summary	Hydrogen can be used to generate energy by burning in a boiler or internal combustion engine, or by reaction with oxygen in a fuel cell. Free hydrogen does not occur in nature, so hydrogen is not strictly a fuel, but an energy carrier. Hydrogen can be produced by a variety of means, for example by the electrolysis of water or by algae. Since the residue from hydrogen is just water, it provides energy that is very clean at the point of use. If the primary energy source is a fossil fuel, much of the advantage is lost, but if the primary source is renewable, then a hydrogen based system can provide both a very clean energy source and a means of storing the fluctuating outputs associated with renewable sources such as wind and solar systems
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Sam Bradbrook Futures Team, HSL
	Date and source of publication	2011, Health and Safety Executive UK, http://www.hse.gov.uk/horizons/assets/documents/sr025.pdf
	Intended audience	Policy makers, Hydrogen operators, Experts, Safety operators
	Type of paper	Guidelines
3	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	OVERVIEW OF EUROPEAN AND INTERNATIONAL REGULATION AND STANDARDISATION ACTIVITIES
	Summary	International technical committees have been created inside the ISO and IEC organisations so as to facilitate the world-wide industrialisation and commercialisation of hydrogen systems and fuel cells. The working group ISO TC 197 entitled Hydrogen Technologies has already published international standards and is very active in the edition of standards for all the hydrogen chain from production to end use. The working group IEC TC 105 focuses on fuel cell technologies. It is also currently drafting many standards for fuel cell applications (mobile, stationary, portable and micro fuel cells). At an international level, the UNECE is actively working for the publication of two Global Technical Regulations for vehicles fuelled with gaseous or liquid hydrogen. And, finally, many European projects intend to facilitate the implementation of a harmonized.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	INERIS (National Institute of Industrial Environment and Risks) Parc Technologique Alata - BP 2 – 60550 Verneuil en Halatte (France) E-mail : samira.chelhaoui@ineris.fr 2CEA (French Atomic Energy Commission) Centre de Grenoble – 17 rue des Martyrs – 38054 Grenoble Cedex 9 (France) Email : pierre.serre-combe@cea.fr
	Date and source of publication	2006, 16th World Hydrogen Energy Conference (WHEC2006), Lyon : France http://halineris.ccsd.cnrs.fr/docs/00/97/25/37/PDF/2006-104_hal.pdf
	Intended audience	Policy makers, Hydrogen operators, Experts, Safety operators
4	Type of paper	Guidelines
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
4	Title	RISK INFORMED SEPARATION DISTANCES FOR HYDROGEN

		REFUELLING STATIONS
	Summary	The lay-out requirements developed for hydrogen systems operated in industrial environment are not suitable for the operating conditions specific to hydrogen refuelling stations (service pressure of up to 95 MPa, facility for public use). A risk informed rationale has been developed to define and substantiate separation distance requirements in ISO 20100 Gaseous hydrogen – refuelling stations. In this approach, priority is given to preventing escalation of small incidents into majors ones, with a focus on critical exposures such as places of occupancy (fuelling station retail shop), while optimizing use of the available space from a risk perspective, a key objective for being able to retrofit hydrogen refuelling in existing stations.
	Main Topic	Safety, Hydrogen technologies
	Author	Frederic Barth Air Liquide Hydrogen Energy, BP 126, 78354 Jouy en Josas, France frederic.barth@airliquide.com
	Date and source of publication	2013, International Conference on Hydrogen Safety
	Intended audience	Experts, Safety operators
	Type of paper	Academic, Technical, Guidelines
5	TYPE OF INFORMATION	Quantitative (graphs, tables, data..)
	Title	HYDROGEN SAFETY: R&D WORK IN THE HORIZON HYDROGEN ENERGY PROGRAM
	Summary	The energy industry is undergoing an important transformation (global warming, dependence of the energy supply, depletion of energetic resources); our societies will have to develop solutions that are sustainable and more environmentally-friendly. In the frame of those global challenges, hydrogen can play a key role in the development of new energy alternatives. As a carrier that is compatible with other types of energies, it can be produced from a wide variety of sources including renewable, while presenting unique storage options and, combined to a fuel cell, efficiently produces electricity with zero direct pollution. Energy and environment being major growth drivers, Air Liquide decided to lead the Horizon Hydrogène Energie (H2E) program. This ambitious French program represents a global investment of 190 million Euros over 7 years in research and technology development and federates 19 partners in order to implement new industry for hydrogen energy. Competitive solutions are already available and Air Liquide deploys them onto four main “early” markets – off-grid sites, backup power, special vehicles and mobile energy – with a fully dedicated supply chain as illustrated in Figure 1. In order to establish a market-receptive environment for hydrogen-based products and have development/modification of relevant codes and standards that will ensure the safe operation, handling and use of hydrogen technologies, it is essential to implement a specific safety strategy during the product design phase. A scientific basis for providing realistic risk assessment and possible mitigation means is required to reach the safety objective.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Sidonie Ruban, Simon Jallais, Deborah Houssin, Valérie Naudet, Claire Weber, Air Liquide, Jouy-en-Josas, France Jérôme Daubech, Christophe Proust, INERIS, Verneuil-en-Halatte, France Alain Bengaouer, CEA, Gif-sur-Yvette, France
	Date and source of publication	2010, 18th World Hydrogen Energy Conference (WHEC2010), Essen : Allemagne
	Intended audience	Hydrogen operators, Experts, Safety operators

	Type of paper	Technical
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
6	Title	SAFETY STANDARD FOR HYDROGEN AND HYDROGEN SYSTEMS
	Summary	The course is an introduction to the procedures for safe handling of hydrogen, flammable and toxic gases by small users working in the field of hydrogen and fuel cells. Theoretical and practical aspects are emphasized, aiming at identifying the main hazards and reduce the risks associated with the use of these gases. Topics: 1. Market, hydrogen production, fuel cells, and energy storage; 2. International System of Units, Comparison between the ideal gas and real gases; 3. Safety of gases and hydrogen; 4. Cylinders, fittings and valves for gases and hydrogen; 5. Purge of gases; 6. Infrastructure for gases and hydrogen; 7. Accidents with hydrogen.
	Main Topic	Safety
	Author	Neves Jr, N.P. Laboratório de Hidrogênio, Universidade Estadual de Campinas, P.O.Box 6039, 13083-970, Campinas - SP, Brazil, nevesjr@ifi.unicamp.br
	Date and source of publication	2013, http://www.ichs2013.com/index.php/conference-presentations-and-papers
	Intended audience	Hydrogen operators, Experts, Safety operators
	Type of paper	Guidelines
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..), Qualitative (descriptions, overview..)
7	Title	DISCUSSION OF LESSONS LEARNED FROM A HYDROGEN RELEASE
	Summary	Just in-line with any emerging alternative transportation fuel incidents involving hydrogen used as transportation fuel are learning opportunities for this new and growing industry. This paper includes discussion of many topics in hydrogen safety surrounding the installation, operation and maintenance of commercial hydrogen stations or compression, storage, and dispensing systems.
	Main Topic	General, Safety, Hydrogen technologies
	Author	Harris, A., Kashuba, M. Sandia National Laboratories 7011 East Ave Livermore, CA 94550 California Air Resources Board, P.O. Box 2815, Sacramento, CA 95812
	Date and source of publication	2013, International Conference on Hydrogen Safety
	Intended audience	General public, Experts
	Type of paper	Academic, Guidelines
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
8	Title	HYDROGEN SAFETY RESEARCH: STATE-OF-THE-ART
	Summary	This paper is an attempt to give a concise overview of the state-of-the-art in the recent hydrogen safety research, mostly within the framework of activities performed by the European Network of Excellence HySafe "Safety of Hydrogen as an Energy Carrier" and related projects. The up-to-date knowledge, recent progress and future research are discussed in brief. The large eddy simulation (LES) model.
	Main Topic	Safety, Fuel cells, Hydrogen technologies

	Author	Molkov, V. Hydrogen Safety Engineering and Research (HySAFER), University of Ulster, Jordanstown, Block 27, Newtownabbey, BT37 0NL, Co. Antrim, UK
	Date and source of publication	2007, 5th International Seminar on Fire and Explosion Hazards, Edinburgh, UK
	Intended audience	Hydrogen operators, Experts, Safety operators
	Type of paper	Academic
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
9	Title	HYDROGEN SAFETY STANDARDS AND THE HYPER PROJECT
	Summary	Presentation overview: • Introduction • Why there is a need for standards • Range of relevant standards. • Hydrogen Codes and Standards • Activities of ISO, IEC, EIGA etc • HyPER Project • Project aims • Links to standards • Summary
	Main Topic	Safety, Hydrogen technologies
	Author	STUART HAWKSWORTH, HAZARD REDUCTION GROUP HEALTH AND SAFETY LABORATORY BUXTON
	Date and source of publication	http://www.ukhfca.co.uk/wp-content/uploads/2011/03/hydrogen-safety-standards-hyper.pdf
	Intended audience	Policy makers, Experts
	Type of paper	Guidelines
10	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	LET'S GO GREEN WITH HYDROGEN! THE GENERAL PUBLIC'S PERSPECTIVE
	Summary	It is well known in socio-economics that the success of an innovation process depends to a great extent on public acceptance. The German HyTrust project analyzes the current state of public acceptance in hydrogen technology in the mobility sector. This paper focuses on cutting-edge results of interviews, focus groups and a representative survey. Based on these results, almost 80% of the Germans are in favor of introducing hydrogen vehicles. But from the perspective of the general public, it is important that hydrogen is produced in an environmentally friendly way. HyTrust is the socio-scientific research project that accompanies the German Federal Government's National Innovation Programme.
	Main Topic	General, Hydrogen technologies
	Author	Zimmer, Rene Resource Protection & Landscape Ecology, Independent Institute for Environmental Issues, Greifswalder Strasse 4, Berlin, 10405, Germany, rene.zimmer@ufu.de

		Welke, Joerg Resource Protection & Landscape Ecology, Independent Institute for Environmental Issues, Greifswalder Strasse 4, Berlin, 10405, Germany, joerg.welke@ufu.de
	Date and source of publication	2012, International Journal of Hydrogen Energy
	Intended audience	General public, Hydrogen operators, Experts
	Type of paper	Case study
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
11	Title	ESTIMATION OF UNCERTAINTY IN RISK ASSESSMENT OF HYDROGEN APPLICATIONS
	Summary	Hydrogen technologies such as hydrogen fuelled vehicles and refuelling stations are being tested in practice in a number of projects (e.g. HyFleet-Cute and Whistler project) giving valuable information on the reliability and maintenance requirements. In order to establish refuelling stations the permitting authorities request qualitative and quantitative risk assessments to show the safety and acceptability in terms of failure frequencies and respective consequences. For new technologies not all statistical data can be established or are available in good quality causing assumptions and extrapolations to be made. Therefore, the risk assessment results contain varying degrees of uncertainty as some components are well established while others are not. The paper describes a methodology to evaluate the degree of uncertainty in data for hydrogen applications based on the bias concept of the total probability and the NUSAP concept to quantify uncertainties of new not fully qualified hydrogen technologies and implications to risk management.
	Main Topic	Safety, Hydrogen technologies
	Author	Markert, F., Krymsky, V. and Kozine, I. Safety, Reliability & Human Factors section, Technical University of Denmark, Management Engineering Department, Produktionstorvet building 426, DK-2800 Kongens Lyngby, Denmark fram@man.dtu.dk Ufa State Academy of Economics and Service, 145 Chernyshevsky Street, Ufa, Bashkortostan, 450078, Russia vikrymsky@mail.ru
	Date and source of publication	2011, 4th International Conference on Hydrogen Safety
	Intended audience	Experts, Safety operators
	Type of paper	Academic, Technical, Guidelines
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..)
12	Title	CONNECTICUT HYDROGEN AND FUEL CELL DEPLOYMENT TRANSPORTATION STRATEGY
	Summary	In summary, information in this Plan suggests that a transition to a hydrogen economy and the deployment of zero-emission, hydrogen fuel cell buses state-wide will increase transportation efficiency, improve environmental performance, increase economic development, and create new jobs. The technical and financial arrangements needed for such a transition from conventional vehicles and bus fleets will require initial investment

		by the state and federal government and private industry; however, such investment is well justified and will become a necessity as concerns about public health and climate change increase and the supply of conventional fuels becomes more limited. Furthermore, the use of domestic fuel and technology manufactured in Connecticut rather than fuel primarily produced overseas and bus engines manufactured out of state will provide value to Connecticut's economy and Connecticut's workers. The Plan also suggests that there are many specific locations for hydrogen refueling stations along state highways or at locations that could potentially be utilized by state fleets or other public or private-sector fleets.
	Main Topic	Safety, Hydrogen technologies, Fuel cells
	Author	Connecticut Department of Transportation 2800 Berlin Turnpike Newington, CT 06111
	Date and source of publication	2011, http://www.chfcc.org/Publications/reports/CT%20Hydrogen%20Trans%20Strategy1-1310%20Final%20Plan.pdf
	Intended audience	Experts, Safety operators
	Type of paper	Report
13	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
	Title	FIRE FIGHTER SAFETY AND EMERGENCY RESPONSE FOR ELECTRIC DRIVE AND HYBRID ELECTRIC VEHICLES
	Summary	As the use of alternative energy proliferates, the fire service has identified a number of areas of concern with hazard mitigation and emergency response. This includes electric and hybrid electric vehicles, which are introducing new and unexpected hazards to fire fighters and other emergency responders. The goal of this report is to assemble and disseminate best practice information for fire fighters and fireground incident commanders to assist in their decision making process for handling electric and hybrid electric vehicles. Specifically, this study focuses on vehicles intended for roadway passenger use involving fire and/or rescue emergency situations, either on the roadway or at charging/docking stations (e.g., garages). The project deliverables will be in the form of a written report, which will include best practices that can serve as the basis for training program development by others. The deliverables for this project collectively review the available baseline information, identify the fundamental principles and key details involving fire/rescue tactics and strategy, provide a summary of core basics, and address and clarify related issues such as training needs.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Casey C. Grant, P.E. Fire Protection Research Foundation
	Date and source of publication	2010, The Fire Protection Research Foundation, One Batterymarch Park , Quincy, MA, USA 02169-7471
	Intended audience	Experts, Safety operators
	Type of paper	Guidelines, Report
14	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	HYDROGEN AND FUEL CELL TECHNOLOGIES FOR SUSTAINABLE FUTURE
	Summary	This paper discusses some crucial energetic, environmental and sustainability issues and the role of hydrogen and fuel cell technologies as one of the potential solutions to these

		issues. The commercialization plans in various industrialized countries (USA, Canada, Japan, etc.) for these technologies have started by identifying the most likely early markets for hydrogen as an energy carrier and fuel cells as power producing devices from micro- to macro-applications, and set realistic near-term and mid-term goals for selected market penetration. The plans outline the major barriers to achieving those goals and recommends activities to capitalize on the incentives and overcome the market barriers. The paper also presents possible future hydrogen energy-utilization patterns for better environment and sustainable development, and shows how the principles of thermodynamics via energy can be beneficially used to evaluate hydrogen and fuel cell systems and their role in sustainability. Throughout the paper, current and future perspectives regarding thermodynamics and sustainable development are considered.
	Main Topic	General , Safety, Hydrogen technologies , Fuel cells
	Author	Ibrahim Dincer Faculty of Engineering & Applied Science, University of Ontario Institute of Technology, North Oshawa, Canada
	Date and source of publication	2008, JJMIE
	Intended audience	Experts, Safety operators, Hydrogen operators
	Type of paper	Academic
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
15	Title	HYDROGEN SAFETY ENGINEERING: WHAT DO WE KNOW AND WHAT ARE KEY ISSUES TO BE RESOLVED
	Summary	Presentation contents: • Introduction. • Hydrogen Technologies. - o 2.1 Standard of Hydrogen Technologies. • Cryogenic Vessels. • Combustible Gases (lighter than air). • Voltage regulations. • Electrical Noise. • ISO TC 197. • IEC TC 105 Fuel cells. • SAE Standards for automotive fuel cell. • Hydrogen fuelling and fuelling stations.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Vladimir Molkov Hydrogen Safety Engineering and Research Centre (HySAFER)
	Date and source of publication	2014, Future Powertrain Conference, http://futurepowertrains.co.uk/2014/presentations/vladimir-molkov.pdf
	Intended audience	Experts, Safety operators, Hydrogen operators
	Type of paper	Technical, Presentation
16	TYPE OF INFORMATION	Quantitative (graphs, tables, data..)
	Title	SAFETY ASPECTS AND STAKEHOLDERS' RESPONSIBILITIES
16	Summary	Presentation contents: • NoE HySafe - Integration of the EU H₂ Safety Research • HySafe NoE achievements

		• International Association for Hydrogen Safety • Development needs • Recommendations • Summary
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Gerd Petra Haugom, DNV/International Association for Hydrogen Safety (HySafe)
	Date and source of publication	2009, http://www.ivt.ntnu.no/docs/norways/Workshop_2009-05-13/14_10%20Haugom.pdf
	Intended audience	Experts, Safety operators
	Type of paper	Presentation
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
17	Title	THE HYDROGEN ECONOMY, FUEL CELLS, AND ELECTRIC CARS
	Summary	Hopes have again been raised about developing a “hydrogen economy”, in which hydrogen could be expected to replace oil and natural gas for most uses, including transportation and heating. It is again being claimed that hydrogen will be a widely available, clean, safe fuel. This article argues that such expectations are almost certainly illusory. Hydrogen, like electricity, is not an energy resource but an energy carrier. It takes more energy to extract hydrogen from water than burning the hydrogen can ever provide. There are also inevitable losses in storage, transmission, and final mechanical or heating applications. The question then turns on the efficiency—and safety—of the entire chain of conversion, from the energy source (fossil, solar, or other) to the final use. Moreover, energy sources (preferably renewable, for the long term) can be used for the direct creation of electricity, which can be introduced into the existing grid without requiring a vast investment in a new hydrogen distribution system. In addition, a hydrogen-based system would be unacceptably dangerous. This report will present a detailed technical and economic analysis of the problems with the proposed hydrogen economy and the advantages of some alternatives, principally electricity-based. A hypothetical case of what would be required for a hydrogen filling station serving the general public is closely examined.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Reuel Shinnar Department of Chemical Engineering, The City College of New York, Steinman Hall, T-316, New York, NY 10031, USA
	Date and source of publication	2003 Elsevier
	Intended audience	Experts, Safety operators, Hydrogen operators
	Type of paper	Academic
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
18	Title	SAFETY OF HYDROGEN AS AN ENERGY CARRIER
	Summary	The primary goal of the HySafe permeation study has been to assist the safe introduction of hydrogen road vehicles with the minimum of restrictions for manufacturers and customers by avoiding the restrictions imposed by some countries on alternative fuel vehicles in parking facilities. The HySafe activity was initiated as the rates proposed in the draft ECE compressed gaseous hydrogen regulation and the various versions of ISO/DIS15869 (Gaseous Hydrogen And Hydrogen Blends - Land Vehicle Fuel Tanks)

		were believed to be overly restrictive. As a result HySafe undertook a scientifically based study to investigate if the existing rates could be relaxed safely. Discussions also took place with the SAE Fuel Cell Safety Working Group. The focus of this work is on providing an allowable permeation rate for the draft EC regulation for type-approval of hydrogen powered motor vehicles and the container requirements in the UN ECE WP29 GTR proposa
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Paul Adams, Volvo Contributing Authors: Alain Bengaouer (CEA) Benjamin Cariteau (CEA) Dmitriy Makarov (UU) Vladimir Molkov (UU) Efi Papanikolaou (NCSRD) Jean-Bernard Saffers (UU) Isabelle Tkatschenko (CEA) Alexandros Venetsanos (NCSRD)
	Date and source of publication	2009, http://www.hysafe.net/download/1855/HySafe%20D74%20Permeation%20Rev7%20Final%20Corr%201.pdf
	Intended audience	Experts, Safety operators, Hydrogen operators
	Type of paper	Report
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
19	Title	CHAPTER 10 REGULATIONS-CODES-AND-STANDARDS
	Summary	Presentation contents: • Introduction. • Hydrogen Technologies. • Cryogenic Vessels. • Combustible Gases (lighter than air). • Voltage regulations. • Electrical Noise. • ISO TC 197. • IEC TC 105 Fuel cells. • SAE Standards for automotive fuel cell. • Hydrogen fuelling and fuelling stations.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	
	Date and source of publication	H2training.eu
	Intended audience	Experts, Safety operators, Hydrogen operators
	Type of paper	Guidelines
20	Title	LIGHTHOUSE PROJECT FOR THE DEMONSTRATION OF HYDROGEN FUEL CELL VEHICLES AND THEIR REFUELLING INFRASTRUCTURE IN SCANDINAVIA
	Summary	The H2moves Scandinavia project has been a unique opportunity to showcase the reliability and hence marked preparedness of hydrogen operated fuel cell cars under daily driving conditions, even in harsher climate conditions pertinent to Oslo and Copenhagen. The project is going to adapt a safety and emergency plan for hydrogen refuelling

		stations plan.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Ulrich Büniger, Peter Bremer, Sofia Capito, Tim Faber, Teresa Fickler, Sae Hoon Kim, Steffen Møller-Holst, Martin Svensson, Flemming Wennike, Mikael Sloth, Federico Zenith
	Date and source of publication	2013, http://www.scandinavianhydrogen.org/sites/default/files/h2ms_report_final_publicreport_v09.pdf
	Intended audience	Experts, Safety operators, Hydrogen operators
	Type of paper	Report
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
21	Title	WEB-BASED RESOURCES ENHANCE HYDROGEN SAFETY KNOWLEDGE
	Summary	List of online hydrogen safety resources.
	Main Topic	General, Safety, Fuel cells, Hydrogen technologies
	Author	Steven C. Weiner, Linda L. Fassbender, Chad Blake, Salvador M. Aceves, Brian P. Somerday and Antonio Ruiz
	Date and source of publication	2011, HYPOTHESIS http://www.hypothesis.ws/HYPOTHESIS%20IX/Presentazioni/HYP_011.pdf IX
	Intended audience	Experts, Safety operators, Hydrogen operators
	Type of paper	Report
22	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	INSTALLATION PERMITTING GUIDANCE FOR HYDROGEN AND FUEL CELL STATIONARY APPLICATIONS: UK VERSION
	Summary	The HYPER project started on 1 November 2006 and ended in February 2009. The work programme of the HYPER project was structured around the development of an installation permitting guide (IPG) which includes: • An assessment of current knowledge on installation requirements of small stationary H₂ and FC systems; • Detailed case studies of representative installations; • Modelling and experimental risk evaluation studies to investigate fire and explosion phenomena. The IPG was developed in response to the growing need for guidance to facilitate small hydrogen and fuel cell stationary installations in Europe. This report is a revised version of the IPG intended for the UK market, reference being made to UK national regulations and standards as opposed to European as appropriate. This document is not a standard, but is a compendium of useful information for a variety of users with a role in installing these systems, including: • Design engineers; • Manufacturers; • Architects; • Installers; • Operators/Maintenance workers; • Regulators.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	D K Pritchard, M Royle & D Willoughby
		Health and Safety Laboratory

		Harpur Hill Buxton Derbyshire SK17 9JN
	Date and source of publication	2009, Health and Safety Laboratory for the Health and Safety, http://www.hse.gov.uk/research/rrpdf/rr715.pdf
	Intended audience	Policy makers, Hydrogen operators, Experts, Safety operators
	Type of paper	Guidelines
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
23	Title	HYDROGEN REGULATION
	Summary	Existing hydrogen installations have been built to a number of different codes & standards, primarily based on national and local specific requirements. Some codes and standards applied have been derived from experiences with the CNG industry. Hydrogen specific international codes and standards (e.g. ISO) are presently still under development. The purpose of regulations, standards and codes is to ensure safe and reliable design and operation of a product or facility.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Date and source of publication	www.ika.rwth-aachen.de/r2h/index.php/Special.../Hydrogen_Regulations
	Intended audience	Policy makers, Hydrogen operators, Experts, Safety operators
	Type of paper	Guidelines
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
24	Title	PERCEPTIONS OF HYDROGEN FUELLING SAFETY
	Summary	Analyst view regarding hydrogen fuelling accident.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Jonathan Wing Market Analyst jonathanwing@fuelcelltoday.com
	Date and source of publication	2012, Fuel Cell Today, http://www.fuelcelltoday.com/analysis/analyst-views/2012/12-07-18-perceptions-of-hydrogen-fuelling-safety
	Intended audience	General public, Hydrogen operators, Experts, Safety operators
	Type of paper	Opinion
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
25	Title	BOOK REVIEW: "TOMORROW'S ENERGY: HYDROGEN FUEL CELLS AND THE PROSPECTS FOR A CLEANER PLANET"
	Summary	The safety of hydrogen is discussed in one chapter, This chapter looks at the misconceptions surrounding hydrogen as a fuel and the rigorous testing it has gone through to determine its safety for public use
	Main Topic	General, Safety, Fuel cells, Hydrogen technologies
	Author	Dan Carter Manager dancarter@fuelcelltoday.com

	Date and source of publication	2012, Fuel Cell Today, http://www.fuelcelltoday.com/media/1738778/hoffmann_tomorrow_s_energy.pdf
	Intended audience	General public, Policy makers, Hydrogen operators, Experts, Safety operators
	Type of paper	Opinion
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
26	Title	HYDROGEN FUEL CELL CODES & STANDARDS
	Summary	Hydrogen Fuel Cell Codes & standards vehicle applications
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	
	Date and source of publication	2014, Hydrogen/Fuel Cell Codes & Standards, http://fuelcellstandards.com/Vehicle%20Matrix.pdf
	Intended audience	General public, Hydrogen operators, Experts, Safety operators
	Type of paper	Guidelines
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..)
27	Title	NEW ENERGY, NEW HAZARDS, THE HYDROGEN SCENARIO
	Summary	For the last ten years and more, INERIS has acquired a practical experience on hydrogen safety. Among others, the following experimental topics have been dealt with : confined hydrogen explosion, liquid hydrogen leak and subsequent dispersion in air phenomenon, hydrogen jet release, dispersion and inflammation, measurement of hydrogen concentration in air-hydrogen atmospheres, pressurised hydrogen tank testing. In parallel risk assessment have been carried out on hydrogen-related equipment (reformers, electrolyzers...). This long lasting experience is now invested in hydrogen technologies. In this field, INERIS is involved in several European and national projects as well as in standardization working groups focusing on the safe handling of hydrogen.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Lionel PERRETTE, Samira CHELHAOUI Institut National de l'Environnement Industriel et des Risques Direction des Risques Accidentels
	Date and source of publication	2003, Riso International Energy Conference, Roskilde : Netherlands http://hal.archivesouvertes.fr/docs/00/97/24/21/PDF/2003-055_hal.pdf
	Intended audience	Hydrogen operators, Experts, Safety operators
	Type of paper	Academic
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
28	Title	SAFETY ISSUES REGARDING FUEL CELL VEHICLES AND HYDROGEN FUELED VEHICLES
	Summary	The current discussion on dependence on foreign oil imports and the President's "Freedom Car" initiative has brought alternatively fueled vehicles and hydrogen to the attention of the public. Even though all current fuel cell and hydrogen vehicles are experimental and only being tested in low numbers on public roadways, several states have mandated zero emission vehicles to be introduced (ZEV) in the near future. As new technologies, fuel cells and hydrogen have some associated safety concerns that have to

		be addressed. Although some of the concerns raised are similar to those encountered with substances such as compressed or liquid natural gas (CNG or LNG) and technologies such as electrically powered vehicles, the combination of different technologies in new vehicles and the addition of new and unproven technology warrant special attention. First responders should be informed of the potential risks of newly developed vehicles before they are commercialized, and measures should be put in place to minimize the hazards to the general population.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	The International Consortium for fire safety, health and environment
	Date and source of publication	2003 https://dps.mn.gov/divisions/sfm/programsservices/Documents/Responder%20Safety/Alternative%20Fuels/FuelCellHydrogenFuelVehicleSafety.pdf
	Intended audience	Hydrogen operators, Experts, Safety operators
	Type of paper	Guidelines
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
29	Title	SAFETY CONSIDERATIONS FOR HYDROGEN TEST CELLS
	Summary	The properties of hydrogen compared to conventional fuels such as gasoline and diesel are substantially different requiring adaptations to the design and layout of test cells for hydrogen fuelled engines and vehicles. A comparison of hydrogen fuel properties versus conventional fuels in this paper provides identification of requirements that need to be adapted to design a safe test cell. Design examples of actual test cells are provided to showcase the differences in overall layout and ventilation, safety features, fuel supply and metering, and emissions measurements. Details include requirements for ventilation patterns, the necessity for engine fume hoods as well as hydrogen specific intake and exhaust design. The unique properties of hydrogen, in particular the wide flammability limits and nonvisible flames also require additional safety features such as hydrogen sensors and flame cameras. properly designed and implemented fuel supply system adds to the safety of the test cell by minimizing the amount of hydrogen that can be released. Apart from this the properties of hydrogen also require different fuel consumption measurement systems, pressure levels of the fuel supply system, additional ventilation lines, strategically placed safety solenoids combined with appropriate operational procedures. The emissions measurement for hydrogen application has to be expanded to include the amount of unburned hydrogen in the exhaust as a measurement of completeness of combustion. This measurement can also be used as a safety feature to avoid creation of ignitable hydrogen-air mixtures in the engine exhaust. The considerations provided in this paper lead to the conclusion that hydrogen IC engines can be safely tested, however, properly designed test cell and safety features have to be included to mitigate the additional hazards related to the change in fuel characteristics.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Weiner, S.C., Fassbender, L.L. and Quick, K.A. Pacific Northwest National Laboratory, Washington, DC 20024, sc.weiner@pnl.gov

		Pacific Northwest National Laboratory, Richland, WA 99352
	Date and source of publication	2011, International Journal of Hydrogen Energy
	Intended audience	General public, Policy makers, Hydrogen operators, Experts, Safety operators
	Type of paper	Guidelines
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
30	Title	USING HYDROGEN SAFETY BEST PRACTICES AND LEARNING FROM SAFETY EVENTS
	Summary	A best practice is a technique or methodology that has reliably led to a desired result. A wealth of experience regarding the safe use and handling of hydrogen exists as a result of an extensive history in a wide variety of industrial and aerospace settings. Hydrogen Safety Best Practices (www.h2bestpractices.org) captures this vast knowledge base and makes it publically available to those working with hydrogen and related systems, including those just starting to work with hydrogen. This online manual is organized under a number of hierarchical technical content categories. References, including publications and other online links, that deal with the safety aspects of hydrogen are compiled for easy access. This paper discusses the development of Hydrogen Safety Best Practices as a safety knowledge tool, the nature of its technical content, and the steps taken to enhance its value and usefulness. Specific safety event examples are provided to illustrate the link between technical content in the online best practices manual and a companion safety knowledge tool, Hydrogen Incident Reporting and Lessons Learned (www.h2incidents.org), which encourages the sharing of lessons learned and other safety event information.
	Main Topic	Safety, Fuel cells, Hydrogen technologies
	Author	Weiner, S.C., Fassbender, L.L. and Quick, K.A. Pacific Northwest National Laboratory, Washington, DC 20024, sc.weiner@pnl.gov Pacific Northwest National Laboratory, Richland, WA 99352
	Date and source of publication	2011, International Journal of Hydrogen Energy
	Intended audience	General public, Policy makers, Hydrogen operators, Experts, Safety operators
	Type of paper	Guidelines
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
31	Title	SAFETY OF HYDROGEN POWERED INDUSTRIAL TRUCKS, LESSONS LEARNED AND EXISTING CODES AND STANDARDS GAPS
	Summary	This paper provides an introduction to the powered industrial truck application of fuel cell power systems, the safety similarities with the automotive application and safety lessons learned. Fuel Cell niche markets have proven their value to many early adopters. How has the automotive market provided a springboard for these niche application? How are niche markets revealing gaps in current safety approaches? What is different about the powered industrial truck application and what new codes and standards are needed to accommodate those differences?
	Main Topic	Hydrogen technologies
	Author	Harris A., Rao P.
	Date and source of publication	2011, http://conference.ing.unipi.it/ichs2011/papers/188.pdf .

	Intended audience	General public, Experts
	Type of paper	Technical, Propaganda
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
32	Title	VALIDATION STRATEGY FOR CFD MODELS DESCRIBING SAFETY-RELEVANT SCENARIOS INCLUDING LH ₂ -GH ₂ RELEASE AND THE USE OF PASSIVE AUTOCATALYTIC RECOMBINERS.
	Summary	An increase in use of hydrogen for energy storage and clean energy supply in a future energy and mobility market will strengthen the focus on safety and the safe handling of hydrogen facilities. The ability to simulate the whole chain of physical phenomena that may occur during an accident is mandatory for future safety studies on an industrial or urban scale. Together with the RWTH Aachen University, Forschungszentrum Julich (JULICH) develops numerical methods to predict safety incidents connected with the release of either LH ₂ or GH ₂ , using the commercial CFD code ANSYS CFX. The full sequence from the release, distribution or accumulation of accidentally released hydrogen, till the mitigation of accident consequences by safety devices is considered. The paper describes the current development status, gives examples of the validation and concludes with future work to provide the full range of hydrogen release and recombination simulation.
	Main Topic	Safety, Hydrogen technologies
	Author	C. Jakel, S. Kelm, E. Reinecke, K. Verfonden, H.-J. Allelein.
	Intended audience	Experts
	Type of paper	Academic, Technical
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
33	Title	STATE-OF-THE-ART AND RESEARCH PRIORITIES IN HYDROGEN SAFETY
	Summary	On October 16-17, 2012, the International Association for Hydrogen Safety (HySafe) in cooperation with the Institute for Energy and Transport of the Joint Research Centre of European Commission (JRC IET Petten) held a two-day workshop dedicated to Hydrogen Safety Research priorities. The workshop was hosted by Federal Institute for Materials Research and Testing (BAM) in Berlin, Germany. The main idea of the Workshop was to bring together stakeholders who can address the existing knowledge gaps in the area of the hydrogen safety, including identification and prioritization of such gaps from the standpoint of scientific knowledge, both experimental and theoretical including numerical. The experience highlighting these gaps which was obtained during both practical applications (industry) and risk assessment should serve as reference point for further analysis. The program included two sections: knowledge gaps as they are addressed by industry and knowledge gaps and state-of-the-art by research. In the current work the main results of the workshop are summarized and analysed.
	Main Topic	Safety, Hydrogen technologies
	Author	Kotchourko A., Barladi D., Bernard P.; Jordan T., Kessler A., LaChance J., Steen M., Tchouvelev A., Wen J.
	Date and source of publication	2013, International Conference on Hydrogen Safety (HySafe)
	Intended audience	General public and Experts
	Type of paper	Technical, Propaganda
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)

34	ION	
	Title	HYDROGEN EMERGENCY RESPONSE TRAINING FOR FIRST RESPONDERS
	Summary	The U.S. Department of Energy supports the implementation of hydrogen fuel cell technologies by providing hydrogen safety and emergency response training to first responders. A collaboration was formed to develop and deliver a one-day course that uses a mobile fuel cell vehicle (FCV) burn prop designed and built by Kidde Fire Trainers. This paper describes the development of the training curriculum, including the design and operation of the FCV prop; describes the successful delivery of this course to over 300 participants at three training centers in California; and discusses feedback and observation received on the course. Photographs and video clips of the training session will be presented.
	Main Topic	Safety, Hydrogen technologies, First Response
	Author	Elmore M.R, Fassbender L.L., Hamilton J.J., Weiner S.C.
	Date and source of publication	2012, Hydrogen and Fuel Cells Program, U.S. Department of Energy.
	Intended audience	Experts, Safety operators, Hydrogen operators
	Type of paper	Technical, Propaganda, Case study
35	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	CFD AND VR FOR RISK COMMUNICATION AND SAFETY TRAINING
	Summary	This paper will describe possibilities with VRSafety and give examples of use. In cooperation with Statoil, Christian Michelsen Research (CMR) and GexCon have developed the VRSafety Application. VRSafety can visualize simulation results from FLACS (and another Computational Fluid Dynamics (CFD) – tool KFX) in an immersive virtual reality (VR) lab or on a PC. VRSafety can further be used to interactively control and start new CFD-simulations during the sessions. The combination of accurate CFD-modelling, visualization and interactive use through VRSafety, represents a powerful toolbox for safety training and risk communication to first-responders, employees, media and other stakeholders. It can also be used for lessons learned sessions studying incidents and accidents, ad to demonstrate what went wrong and how mitigation could have prevented accidents from happening.
	Main Topic	Safety, Safety trainings
	Author	Hansen O.R., Ulvang D.M., Langeland T., Middha P.
	Date and source of publication	
	Intended audience	General public, Hydrogen operators, Experts, Safety operators
	Type of paper	Academic, Technical, Propaganda, Report of a seminar/conference
36	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	HYDROGEN SAFETY TRAINING FOR RESEARCHER AND TECHNICAL PERSONNEL
	Summary	The paper presents the structure and program of two hydrogen safety classes each respectively directed to laboratory researchers and technical operators. Laboratory researchers who need basic hydrogen safety information will be able to benefit from a 4-hour web-based hydrogen safety class (free online access at http://www.h2labsafety.org/) addressing hydrogen fundamentals: properties, pressure and cryogenic safety, emergency response and codes and standards. Technical operators in charge of building and testing experimental hydrogen equipment will also benefit from a more

		comprehensive 3-day hand-on safety class that will present detailed information for installation, testing and operation of hydrogen pressurized systems. The hands-on class includes a full day of classroom.
	Main Topic	General, Hydrogen technologies, Safety
	Author	Aceves S.M, Espinosa-Loza F., Petitpas G., Ross T.O., Switzer V.A.
	Date and source of publication	2011, International Conference on Hydrogen Safety, San Francisco.
	Intended audience	Hydrogen operators, Experts, Safety operators
	Type of paper	Academic, Technical, Propaganda
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
37	Title	EUROPEAN HYDROGEN SAFETY TRAINING PLATFORM FOR FIRST RESPONDERS: HYRESPONSE PROJECT
	Summary	The paper presents HyResponse project i.e. a European Hydrogen Safety Training Platform that targets to train First Responders to acquire professional knowledge and skills to contribute to FCH permitting process as approving authority. The threefold training program is described: educational training, operational level training on mock-up real scale transport and hydrogen stationary installations, and innovative virtual training exercises reproducing entire accident scenarios. The paper highlights how the three pilot sessions for European First Responders in a face to face mode will be organized to get a feedback on the training program. The expected outputs are also presented i.e. the Emergency Response Guide and a public website including teaching material and online interactive virtual training.
	Main Topic	Safety, First Responders, Hydrogen technologies
	Author	Verbrecke F., Vesly B., Lopez M., Molkov V., Rejjalt M., Dey R., Maranne E.,
	Date and source of publication	
	Intended audience	Hydrogen operators, Experts, Safety operators
	Type of paper	Technical, Propaganda
38	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	Validation Testing in Support of Hydrogen Codes and Standards Development
	Summary	New codes and standards are being developed to facilitate the safe deployment of emerging hydrogen technologies. Hydrogen markets will benefit from standards that address the specific properties of hydrogen, hydrogen effects on strengths of materials and hydrogen compressed gas storage at pressure up to 70 MPa. The need for validation of new hydrogen requirements has been identified by codes and standards technical committees. The US Department of Energy (DOE) office of Energy Efficiency and Renewable energy (EERE) has tasked the National Renewable Energy Laboratory (NREL) with the role of supporting hydrogen codes and standards research and development needs. NREL has provided validation test support to several new standards development efforts. Validation test are presented for these four specific standards development needs.
	Main Topic	Codes and Standards, Hydrogen technologies
	Author	Burgess R.M., McDougall M., Newhouse N.L., Rivkin C., Buttner W.J., Post M.B.
	Date and source of publication	2011, http://conference.ing.unipi.it/ichs2011/papers/150.pdf .

	Intended audience	Policy makers, Experts
	Type of paper	Technical, Propaganda
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
39	Title	DEVELOPMENT OF AN ITALIAN FIRE PREVENTION TECHNICAL RULE FOR HYDROGEN PIPELINES
	Summary	This paper summarizes the current results of the theoretical and experimental activity carried out by the Italian Working Group on the fire prevention safety issues in the field of the hydrogen transport in pipelines. From the theoretical point of view a draft document has been produced beginning from the regulations in force on the natural gas pipelines; these have been reviewed, corrected and integrated with the instructions suitable to the use of hydrogen. From the experimental point of view an apparatus has been designed and installed at the University of Pisa; this apparatus has allowed the simulation of hydrogen releases from a pipeline with and without ignition of hydrogen-air mixture. The experimental data have helped the completion of the above mentioned draft document with the instructions about the safety distances. The work on the text contents is concluded and the document is currently under discussion with the Italian stakeholders involved in the hydrogen applications.
	Main Topic	Safety
	Author	Mattei N, Carcassi M.N, Ciannelli N, Pilo F.
	Date and source of publication	2011, http://conference.ing.unipi.it/ichs2011/papers/111.pdf .
	Intended audience	Experts
	Type of paper	Academic, Technical
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
40	Title	REGULATIONS AND RESEARCH ON RC&S FOR HYDROGEN STORAGE RELEVANT TO TRANSPORT AND VEHICLE ISSUES WITH SPECIAL FOCUS ON COMPOSITE CONTAINMENTS
	Summary	Developers interested in high pressure use and especially in mobile use of hydrogen rely on composite vessels for dangerous goods transport and onboard storage. Based on this review, origins of different regulations for the storage of Hydrogen as dangerous good and as propellant for vehicles will be examined. Both categories started out using steel and sometimes aluminium as cylinder material. With composite materials becoming more common, a new problem emerged: vital input for regulations on composite pressure systems was initially derived from decades of experience with steel vessels. As a result, both regulatory fields suffer somewhat from this common basis. Only later developments regarding requirements for composite vessels have begun to go more and more separate ways. Thus these differences lead to some lacks in regulation with respect to composite storage systems. Here, different aspects of uncertainties and relevant approaches to solution will be explained.
	Main Topic	Safety, Regulations for storage, Hydrogen technologies
	Author	Mair G.W., Poschko P.
	Date and source of publication	2011, http://conference.ing.unipi.it/ichs2011/papers/244.pdf .
	Intended audience	General public, Policy makers, Experts
	Type of paper	Academic, Case study, Technical

	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
41	Title	LICENSING A FUEL CELL BUS AND HYDROGEN FUELLING STATION IN BRAZIL
	Summary	The Brazilian Fuel Cell Bus Project is being developed by a consortium comprising 14 national and international partners. The projects was initially supported by the GEF/UNDP and MME/FINEP Brazil. The national coordination is under responsibility of MME and EMTU/SP, the Sao Paulo Metropolitan Urban Transport Company that also controls the bus operation and bus routes. This work reports the efforts done in order to obtain the necessary licenses to operate the first fuel cell buses for regular service in Brazil, as well as the first commercial hydrogen fuelling station to attend the vehicles.
	Main Topic	Fuel Cell Buses, Hydrogen technologies, Fuel cells
	Author	Neves Jr. N.P., Pinto C.S.
	Date and source of publication	2011, http://conference.ing.unipi.it/ichs2011/papers/228.pdf .
	Intended audience	General public, Policy makers, Experts
	Type of paper	Technical, Propaganda, Case study
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
42	Title	SAFETY ASSESSMENT OF UNIGNITED HYDROGEN DISCHARGE FROM ONBOARD STORAGE IN GARAGES WITH LOW LEVELS OF NATURAL VENTILATION
	Summary	This study is driven by the need to understand requirements to safe blow-down of hydrogen onboard storage tanks through a pressure relief device (PRD) inside a garage-like enclosures with low natural ventilation. Current composite tanks for high pressure hydrogen storage have been shown to rupture in 3.5-6.5 min in fire conditions. As a result a large PRD venting area is currently used to release hydrogen from the tank before its catastrophic failure. However, even if unignited, the release of hydrogen from such PRDs has been shown to result in unacceptable overpressures within the garage capable of destroying the structure. Thus, to prevent collapse of the garage in the case of a malfunction of the PRD and an unignited hydrogen release there is a clear need to increase blow-down time by reducing PRD venting area. The conclusion is drawn that PRDs currently available for hydrogen-powered vehicles should be redesigned along with a change of requirements for the fire resistance rating of onboard storage as hydrogen-powered vehicles are intended for garage parking. Regulation, codes and standards in the field should address this issue.
	Main Topic	Safety, Hydrogen technologies
	Author	Brennan S., Molkov V.
	Date and source of publication	2011, http://conference.ing.unipi.it/ichs2011/papers/238.pdf .
	Intended audience	General public, Experts, Safety operators
	Type of paper	Technical, Propaganda, Proposal
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
43	Title	HIGH PRESSURE HYDROGEN FIRES
	Summary	In the scope of the French national project DRIVE and European project HyPER, high pressure jet flame of hydrogen were produced and instrumented. The experimental technique and measurement strategy will be presented. Many points are original developments like the direct measurement of the mass flowrate by weighing continuously

		the hydrogen container, the imaging processing to extract the flame geometry, the heat flux measurement device, the thermocouples.. Flame have been produced from 900 bar down to 1 bar through orifices ranging from 1 to 10 mm. Thus an original set of data is now available not only about the flame but also about the thermodynamic properties of high pressure hydrogen (since the pressure and the temperature in the container were continuously monitored during the release). A comparison with other published data is proposed and a discussion of some available models.
	Main Topic	Safety, Hydrogen fires, Hydrogen technologies
	Author	Christophe Proust, Didier Jamois, Etienne Studer.
	Date and source of publication	2010, Science Direct.
	Intended audience	General public, Experts
	Type of paper	Academic, Technical
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
44	Title	A NATIONAL SET OF HYDROGEN CODES AND STANDARDS FOR THE UNITED STATES
	Summary	In 2003, the U.S. Department of Energy (DOE) initiated a project to coordinate the development of a national template of hydrogen codes and standards for both vehicular and stationary applications. The process consisted of an initial evaluation to find any gaps in the existing hydrogen codes and standards, and to define the codes and standards required to fill these gaps. These codes and standards were to be developed by several standards development organizations (SDOs). This article describes the three levels of codes and standards that address hydrogen technologies for the built environment. (level 1: primary adopted building and fire codes; level 2: hydrogen-specific codes and standards references in primary adopted code; level 3: hydrogen-specific component standards referenced in hydrogen-specific codes).
	Main Topic	Hydrogen technologies
	Author	Carl Rivkin, Chad Blake, Robert Burgess, William J. Buttner, Matthew B.Post
	Date and source of publication	2011, International Journal of Hydrogen Energy 36.
	Intended audience	Experts, Policy makers
	Type of paper	Normative, Propaganda
45	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	DEVELOPMENT OF KOREAN HYDROGEN FUELING STATION CODES THROUGH RISK ANALYSIS
	Summary	When hydrogen fueling stations were constructed first time in Korea in 2006, there were no standards for hydrogen fueling stations. Hence the CNG (Compressed Natural Gas) station codes were temporarily adopted. In last three years, from 2006 to 2009, the studies for the development of hydrogen fueling station standards were carried out, with the support of Korean government. In this study, three research groups cooperated to develop optimized hydrogen fueling station codes through risk analysis of hydrogen production and filling systems. Its results were integrated to develop on the one hand the codes for off-site type hydrogen fueling stations and on the other hand the codes for on-site type hydrogen fueling stations. These were applied from September 2010.
	Main Topic	Safety, Hydrogen technologies
	Author	Eunjung Kim, Kwangwon Lee, Jongsoo Kim, Younghee Lee, Jaedeuk Park, Il Moon.

	Date and source of publication	2011, International Journal of Hydrogen Energy 36.
	Intended audience	Experts, Policy makers
	Type of paper	Academic, Technical
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
46	Title	HYDROGEN SAFETY ENGINEERING FRAMEWORK AND ELEMENTARY DESIGN SAFETY TOOLS
	Summary	The viability and public acceptance of Hydrogen and Fuel Cell (H ₂ FC) systems and infrastructure depends on their robust safety engineering design and on education and training of the workforce, regulators and other stakeholders in the state-of-art in the field. This can be provided only through building up and maturity of the Hydrogen Safety Engineering (H ₂ SE) profession. H ₂ SE is defined as an application of scientific and engineering principle to the protection of life, property and environment from adverse effects of incidents/accidents involving hydrogen. This paper describes a design framework and overviews a structure and contents of elementary design safety tool for carrying out H ₂ SE.
	Main Topic	Safety, Hydrogen technologies
	Author	J.-B. Saffers, V.V. Molokov
	Date and source of publication	2014, International Journal of Hydrogen Energy 39.
	Intended audience	Experts, Policy makers
	Type of paper	Academic, Technical, Propaganda
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
47	Title	NORTH AMERICAN AND INTERNATIONAL HYDROGEN/FUEL CELL STANDARDS
	Summary	The commercialization of fuel cells is dependent on the development of performance based standard methods to evaluate safe performance and provide a basis for comparing similar products. Standards utilize the knowledge gained during research and development to provide criteria to evaluate products to a minimum level of safety. Aligning national standards with international requirements facilitates international trade, and provides the basis for international-to-regional harmonization of standards. CSA America, Inc., (CSAA) a nationally recognized and accredited United States Standards Development Organization (SDO), is one of many SDOs leading the effort to facilitate U.S. interests toward national and international development of standards for fuel cell and hydrogen technologies. This paper will provide an overview of the U.S. standards activities and issues as they relate to the development of standards activities.
	Main Topic	Codes and Standards, Hydrogen technologies, Fuel cells
	Author	Julie Cairns
	Date and source of publication	2010, International Journal of Hydrogen Energy 35.
	Intended audience	General Public, Experts, Policy makers
	Type of paper	Normative, Propaganda
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)

48	Title	PERMITTING OF A PROJECT INVOLVING HYDROGEN A CODE OFFICIAL'S PERSPECTIVE
	Summary	Recent growth in the development of hydrogen infrastructure has led to more requests for code officials to approve hydrogen-related projects and facilities. To help expedite the review and approval process, significant efforts have been made to educate code officials on permitting hydrogen vehicle fueling stations and facilities using stationary fuel cells (e.g., backup power for telephone cell tower sites). Despite these efforts, project delays continue because of several factors, including the limited experience of code officials with these types of facilities, submittals that lack the required information (including failure to adequately address local requirements), and submission of poor quality documents. The purpose of this paper is to help project proponents overcome these potential roadblocks and obtain timely approval for a project. A case study of an actual stationary application permitting request is provided to illustrate the value addressing this issue.
	Main Topic	Safety, Hydrogen technologies
	Author	Kallman R.A., Barilo N.F., Murphy W.F
	Date and source of publication	2012, published by Elsevier Ltd.
	Intended audience	General public, Experts
	Type of paper	Propaganda, Case study
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
49	Title	QUALITY SPECIFICATION AND SAFETY IN HYDROGEN PRODUCTION, COMMERCIALIZATION AND UTILIZATION
	Summary	For decades, the issue of hydrogen quality specification has been a source of complexity and confusion in particular for end users, especially because of the jargon spoken by different providers and clients in varied and diverse areas of application. Virtually every requirement was established within the customer – supplier relationship. The rise of new hydrogen technologies, the emergence of new devices like fuel cells and the spread of knowledge, together with the growing need for uniformity has pushed the specialists to solve this problem. As a result, standardization seems to be the key to accomplish with quality goals at the lowest cost possible. This article discusses the traditional concepts used in the past, the current situation, the standards used today and future developments in hydrogen quality requirement to simplify and facilitate the use and the application of hydrogen and blends with a careful respect for the quality of the product and safety.
	Main Topic	Safety, Quality Standard
	Author	José Luis Aprea.
	Date and source of publication	2014, International Journal of Hydrogen Energy 39.
	Intended audience	Experts
	Type of paper	Technical, Normative
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
50	Title	WEB-BASED RESOURCES ENHANCE HYDROGEN SAFETY KNOWLEDGE
	Summary	The U.S. Department of Energy's Fuel Cell Technologies Program addresses key technical challenges and institutional barriers facing the development and deployment of hydrogen and fuel cell technologies with the goal of decreasing dependence on oil, reducing carbon emissions and enabling reliable power generation. The Safety, Codes &

		Standards program area seeks to develop and implement the practice and procedures that will ensure safety in the operation, handling and use of hydrogen and hydrogen systems for all projects and utilize these practices and lessons learned to promote the safe use of hydrogen. Web-based resources play a key role in reaching, educating and informing stakeholders whose contribution will help enable the deployment of new hydrogen and fuel cell technologies. This paper surveys eight web-based tools, each targeted to a specific stakeholder audience, that are integral resources for information on hydrogen-related safety, codes and standards work in the Fuel Cell Technologies Program.
	Main Topic	General, Safety, Best practices
	Author	S.C. Weiner, L.L. Fassbender, C. Blake, S.M. Aceves, B.P. Somerday, A. Ruiz.
	Date and source of publication	2013, International Journal of Hydrogen Energy 38.
	Intended audience	Policy makers, Experts, Safety operators
	Type of paper	Academic, Technical, Propaganda
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
51	Title	RENEWABLE HYDROGEN ENERGY REGULATIONS, CODES AND STANDARDS CHALLENGES FACED BY AN EU CANDIDATE COUNTRY
	Summary	The European Union is one of the most important players in the field of world energy with an integrated and well-organized energy market. However, energy policies in the EU are not sustainable. The EU is the world's largest importer of fossil fuels and is leading global action in accelerating the transition to renewable energy and low-carbon economy at present. Renewables make the second-largest contribution to domestic energy production after coal. This paper focuses on the institutional, public policy and business practice aspects in terms of hydrogen energy infrastructure development and the regulations in the context of planning and construction for hydrogen energy infrastructure. This paper also analyzes the current state of the regulation of the hydrogen energy sector in the EU and its candidate country, Turkey.
	Main Topic	General , Renewable energy
	Author	Sudi Apak, Erhan Atay, Gungor Tuncer.
	Date and source of publication	2012, International Journal of Hydrogen Energy 37.
	Intended audience	General public, Policy makers, Experts
	Type of paper	Academic, Technical, Normative
52	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	HAZARDS OF LIQUID HYDROGEN
	Summary	In the long term the key to the development of a hydrogen economy is a full infrastructure to support it, which include means for the delivery and storage of hydrogen at the point of use, ex at hydrogen refuelling stations for vehicles. As an interim measure to allow the development of refuelling stations and rapid implementation of hydrogen distribution to them, liquid hydrogen is considered the most efficient and cost effective means for transport and storage. The Health and Safety Executive have commissioned the Health and Safety Laboratory to identify and address issues relating to bulk liquid hydrogen transport and storage and update/develop guidance for such facilities. This position paper, the first part of the project, assesses the features of the transport and storage aspects of the refuelling stations that are now being constructed in the UK, compares

		them to existing guidance, highlights gaps in the regulatory regime and identifies outstanding safety issues. The findings, together with the results of experiments to improve our understanding of the behaviour of liquid hydrogen, will inform the development of the guidance for refuelling facilities.
	Main Topic	Safety, Hydrogen technologies, Fuel cells
	Author	D K Pritchard, M Royle & D Willoughby Health and Safety Laboratory Harpur Hill Buxton Derbyshire SK17 9JN
	Date and source of publication	2010, Health and Safety Laboratory for the Health and Safety, http://www.hse.gov.uk/research/rrpdf/rr769.pdf
	Intended audience	Policy makers, Hydrogen operators, Experts, Safety operators
	Type of paper	Guidelines
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
53	Title	ADVANCING THE HYDROGEN SAFETY KNOWLEDGE BASE
	Summary	The International Agency's Hydrogen Implementing Agreement (IEA HIA) was established in 1977 to pursue collaborative hydrogen research and development and information exchange among its member countries. Information and knowledge dissemination is a key aspect of the work within IEA HIA tasks, and case studies, technical reports and presentations/publications often result from the collaborative efforts. The work being conducted in hydrogen safety under Task 31 and its predecessor, Task 19, can positively impact the objectives of national programs even in cases for which a specific task report is not published. The interactions within Task 31 are illustrating how technology information and knowledge exchange among participating hydrogen safety experts are serving the objectives intended by the IEA HIA.
	Main Topic	General, Safety, Hydrogen research and development
	Author	S.C. Weiner
	Date and source of publication	2013, International Conference on Hydrogen Safety (Brussels).
	Intended audience	Policy makers, Experts
	Type of paper	Technical, Propaganda
54	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	DROP-IN HYDROGEN FUELING (2014)
	Summary	The website is covering many safety issues regarding the hydrogen: https://processdesign.mccormick.northwestern.edu/index.php/Dropin_Hydrogen_Fueling_(2014)#Safety_Codes_and_Standards
	Main Topic	General, Safety, Hydrogen technologies, Fuel cells
	Author	Authors: Matthew Ardagh, Michael Ashley, Alex Chandel, Eric Jiang, Minwook Kim, Todor Kukushliev, William Lassman (ChE 352 in Winter 2014) Steward: David Chen, Fengqi You
	Date and source of publication	2014, https://processdesign.mccormick.northwestern.edu/index.php/Dropin_Hydrogen_Fueling_(2014)#Safety_Codes_and_Standards
	Intended	Hydrogen operators, Experts, Safety operators

	audience	
	Type of paper	Report
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
55	Title	DEVELOPMENT OF AN ITALIAN FIRE PREVENTION TECHNICAL RULE FOR HYDROGEN PIPELINES
	Summary	This paper summarizes the current results of the theoretical and experimental activity carried out by the Italian Working Group on the fire prevention safety issues in the field of the hydrogen transport in pipelines. From the theoretical point of view a draft document has been produced beginning from the regulations in force on the natural gas pipelines; these have been reviewed, corrected and integrated with the instructions suitable to the use of hydrogen. From the experimental point of view an apparatus has been designed and installed at the University of Pisa; this apparatus has allowed the simulation of hydrogen releases from a pipeline with and without ignition of hydrogen-air mixture. The experimental data have helped the completion of the above mentioned draft document with the instructions about the safety distances. The work on the text contents is concluded and the document is currently under discussion with the Italian stakeholders involved in the hydrogen applications.
	Main Topic	Safety,Best practices
	Author	Mattei N, Carcassi M.N, Ciannelli N, Pilo F.
	Date and source of publication	2011, http://conference.ing.unipi.it/ichs2011/papers/111.pdf .
	Intended audience	Experts, Safety operators
	Type of paper	Academic, Technical
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
56	Title	HYDROGEN & FUEL CELLS INTERAGENCY ACTION PLAN
	Summary	The Hydrogen and Fuel Cells Interagency Action Plan lays out an integrated plan for coordinating U.S. federal agency efforts to research, develop, demonstrate, and deploy these important technologies. Section 1 of the plan provides the context for and status of federal hydrogen and fuel cell activities and Section 2 presents the action plans for five broad activity areas: • Address technical challenges through research and development. • Support development and adoption of codes, standards, and regulations. • Validate technologies in real-world operating conditions. • Adopt hydrogen and fuel cell technologies in federal government operations. • Track and communicate results
	Main Topic	Safety, Hydrogen technologies, Fuel cells
	Author	U.S. department of energy
	Date and source of publication	2011, http://www.hydrogen.gov/pdfs/hydrogen_fuelcell_interagency_action_plan.pdf
	Intended audience	Policy makers, Hydrogen operators, Experts, Safety operators
	Type of paper	Technical, Report
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
57	Title	SAFETY STANDARD FOR HYDROGEN AND HYDROGEN SYSTEMS

	Summary	The handbook is a document containing guidelines for safely storing, handling and using hydrogen in gaseous, liquid or slush form, whether used as a non-propellant or propellant. It contains chapters on properties and hazards, facility design, design of components, material compatibility, detection, and transportation. The purpose of the Hydrogen Safety handbook is to provide a practical set of guidelines for safe hydrogen use. The intent is to provide enough information that it can be used alone, but at the same time, reference data sources can provide much more detail if needed.
	Main Topic	Safety
	Author	The National Aeronautics and Space Administration (NASA), the agency of the United States government that is responsible for the nation's civilian space program and for aeronautics and aerospace research.
	Date and source of publication	2005, http://www.hq.nasa.gov/office/codeq/doctree/canceled/871916.pdf .
	Intended audience	Hydrogen operators, Experts, Safety operators
	Type of paper	Technical, Guidelines
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
58	Title	PROJECT ON MINIMUM STANDARDS AND NON-BINDING GUIDELINES FOR FIRST RESPONDERS
	Summary	The aim of the response guidelines is to establish procedural guidelines for mid-level strategic/tactical planners responsible for CBRN preparedness and response. The response guidelines provide generic advice and guidance on procedures, capabilities and equipment required to implement an effective response. They are designed to improve multi-agency interoperability in first response to a CBRN incident and provide guidance on when regional, national or international assistance may be required. The guidelines have been prepared to help planners in EAPC nations determine their own level of capability through self-assessment. They serve as a checklist. Implementation of the guidelines is optional.
	Main Topic	Safety, First response
	Author	NATO
	Date and source of publication	2002, http://www.nato.int/docu/cep/cep-cbrn-response-e.pdf .
	Intended audience	General public, Safety operators
	Type of paper	Guidelines
59	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	REGULATIONS AND RESEARCH ON RC&S FOR HYDROGEN STORAGE RELEVANT TO TRANSPORT AND VEHICLE
59	Summary	Developers interested in high pressure use and especially in mobile use of hydrogen rely on composite vessels for dangerous goods transport and onboard storage. Based on this review, origins of different regulations for the storage of Hydrogen as dangerous good and as propellant for vehicles will be examined. Both categories started out using steel and sometimes aluminium as cylinder material. With composite materials becoming more common, a new problem emerged: vital input for regulations on composite pressure systems was initially derived from decades of experience with steel vessels. As a result, both regulatory fields suffer somewhat from this common basis. Only later developments regarding requirements for composite vessels have begun to go more and more separate ways. Thus these differences lead to some lacks in regulation with respect to composite

		storage systems. Here, different aspects of uncertainties and relevant approaches to solution will be explained.
	Main Topic	Safety, Regulations for storage, Hydrogen technologies
	Author	Mair G.W., Poschko P.
	Date and source of publication	2011, http://conference.ing.unipi.it/ichs2011/papers/244.pdf .
	Intended audience	General public, Policy makers, Experts
	Type of paper	Technical, Academic
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
60	Title	INTENTION TO CONSTRUCT AND OPERATE A PUBLIC H ₂ FUELLING STATION
	Summary	The paper provides information about the necessary steps to follow in order to construct and operate a public H ₂ fuelling station. It gives guidelines about the process of construction, the right authorities to identify and contact, permits to obtain, stakeholders to engage, the license application and submission, regulations to apply, communication to the public.
	Main Topic	General, Hydrogen fuelling station, Hydrogen technologies
	Author	National Organization Hydrogen and Fuel Cell Technology.
	Date and source of publication	http://www.h2-genehmigung.de/leitfaden/
	Intended audience	General public, Experts
	Type of paper	Technical, Guidelines
61	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	LOW EMISSIONS IN PORT AND AT SEA
	Summary	The first fuel cell applications on seagoing vessels will be competitive with diesel engines as early as 2020. A market survey, conducted by Germanischer Lloyd (GL) on "Fuel Cell Systems in Shipping", explains this mainly by the rise in fuel costs and the introduction of CO ₂ levies.
	Main Topic	General, Hydrogen technologies
	Author	
	Date and source of publication	http://www.europeanenergyreview.eu/site/pagina.php?id=2943&zoek=hydrogen%20safety
	Intended audience	General Public
62	Type of paper	Propaganda
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
	Title	HYDROGEN AND FUEL CELLS ON THEIR WAY TO THE MARKET
	Summary	Hydrogen and fuel cells are well on track for market. This trend can be seen at H ₂ Expo, to be held in Hamburg for the eighth time on 8 and 9 June.
	Main Topic	General, Hydrogen technologies
	Author	
	Date and source of publication	http://www.europeanenergyreview.eu/site/pagina.php?id=3030&zoek=hydrogen%20safety

	publication	y
	Intended audience	General public, Experts
	Type of paper	Propaganda, Report of a seminar
63	Title	HYDROGEN: USE AND FIRE PREVENTION IN ITALY
	Summary	Presentation overview: • From the beginning to nowadays • The industrial production of H₂: potential risks • Hydrogen and renewable energy sources • Legislation and safety aspects
	Main Topic	Safety, Hydrogen technologies, Fuel cells
	Author	Fabio Dattilo
	Date and source of publication	2013, ICHS
	Intended audience	Experts, Safety operators
	Type of paper	Technical, Guidelines
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..) and Qualitative (descriptions, overview..)
64	Title	Chapter VI: LEGAL REQUIREMENTS, STANDARDS, AND OTHER CODES
	Summary	The energy industry is undergoing an important transformation (global warming, dependence of the energy supply, depletion of energetic resources); our societies will have to develop solutions that are sustainable and more environmentally-friendly. In the frame of those global challenges, hydrogen can play a key role in the development of new energy alternatives. As a carrier that is compatible with other types of energies, it can be produced from a wide variety of sources including renewable, while presenting unique storage options and, combined to a fuel cell, efficiently produces electricity with zero direct pollution. Energy and environment being major growth drivers, Air Liquide decided to lead the Horizon Hydrogène Energie (H2E) program. This ambitious French program represents a global investment of 190 million Euros over 7 years in research and technology development and federates 19 partners in order to implement new industry for hydrogen energy. Competitive solutions are already available and Air Liquide deploys them onto four main “early” markets – off-grid sites, backup power, special vehicles and mobile energy – with a fully dedicated supply chain as illustrated in Figure 1. In order to establish a market-receptive environment for hydrogen-based products and have development/modification of relevant codes and standards that will ensure the safe operation, handling and use of hydrogen technologies, it is essential to implement a specific safety strategy during the product design phase. A scientific basis for providing realistic risk assessment and possible mitigation means is required to reach the safety objectives.
	Main Topic	Safety, Hydrogen technologies, Fuel cells
	Author	Sidonie Ruban, Simon Jallais, Deborah Houssin, Valérie Naudet, Claire Weber, Air Liquide, Jouy-en-Josas, France Jérôme Daubech, Christophe Proust, INERIS, Verneuil-en-Halatte, France Alain Bengaouer, CEA, Gif-sur-Yvette, France
	Date and source of publication	2010, 18th World Hydrogen Energy Conference (WHEC2010), Essen : Allemagne
	Intended	Hydrogen operators, Experts, Safety operators

	audience	
	Type of paper	Technical
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
65	Title	SAFETY DISTANCES: COMPARISON OF THE METODOLOGIES FOR THEIR DETERMINATION
	Summary	In this paper, a study on the comparison between the different methodologies for the determination of the safety distances proposed by Standard Organizations and national Regulations is presented. The application of the risk-informed approach is one of the methodologies used for the determination of safety distances together with the risk-based approach. One of the main differences between the various methodologies is the risk criterion chosen. In fact a critical point is which level of risk should be used and then which are the harm events that must be considered. The harm distances are evaluated for a specified leak diameter that is a consequence of some parameters used in the various methodologies. The values of the safety distances proposed by Standard Organizations and national Regulations are a demonstration of the different approaches of the various methodologies, especially in the choice of the leak diameter considered.
	Main Topic	Safety, Hydrogen technologies, Fuel cells
	Author	M. Vanuzzo, M. Carcassi Department of Mechanical, Nuclear and of Production Engineering, University of Pisa, Via Diotisalvi 2, Pisa 56126, Italy
	Date and source of publication	2011, ICHS
	Intended audience	Hydrogen operators, Experts, Safety operators
	Type of paper	Academic, Technical
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..)
66	Title	TWO SAE STANDARDS TO HARMONISE GLOBAL HYDROGEN FUELING
	Summary	SAE International's Fuel Cell Standards Taskforce has completed two technical standards that aim to support the impending rollout of hydrogen fueling infrastructure and fuel cell electric vehicles (FCEVs). The standards have been created to harmonise hydrogen fueling worldwide for both 350 and 700 bar (5000 and 10 000 psi) stations.
	Main Topic	Safety, Hydrogen technologies, Fuel cells
	Author	SAE
	Date and source of publication	April 2014, Fuel Cells Bulletin
	Intended audience	General public, Hydrogen operators, Experts, Safety operators
	Type of paper	News
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)

	INFORMATION	
67	Title	COMPARISON OF NFPA AND ISO APPROACHES FOR EVALUATING SEPARATION DISTANCES
	Summary	The development of a set of safety codes and standards for hydrogen facilities is necessary to ensure they are designed and operated safely. To help ensure that a hydrogen facility meets an acceptable level of risk, code and standard development organizations (SDOs) are utilizing risk-informed concepts in developing hydrogen codes and standards. Two SDOs, the National Fire Protection Association (NFPA) and the International Organization for Standardization (ISO) have been developing standards for gaseous hydrogen facilities that specify the facilities have certain safety features, use equipment made of material suitable for a hydrogen environment, and have specified separation distances. Under Department of Energy funding, Sandia National Laboratories (SNL) has been supporting efforts by both of these SDOs to develop the separation distances included in their respective standards. Important goals in these efforts are to use a defensible, science-based approach to establish these requirements and to the extent possible, harmonize the requirements. International harmonization of regulations, codes and standards is critical for enabling global market penetration of hydrogen and fuel cell technologies.
	Main Topic	Safety, Hydrogen technologies, Fuel cells
	Author	LaChance, J.L., Middleton, B., and Groth, K. M. Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM, 87104, USA,
	Date and source of publication	2012, International Journal of Hydrogen Energy
	Intended audience	Hydrogen operators, Experts, Safety operators
	Type of paper	Academic, Technical
	TYPE OF INFORMATION	Quantitative (graphs, tables, data..)
68	Title	LATEST FUELING STATION STANDARD IN GERMANY
	Summary	Guidelines for Hydrogen fueling station standard in Germany
	Main Topic	Safety, Hydrogen technologies, Fuel cells
	Intended audience	General public
	Type of paper	Guidelines
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
69	Title	GENERAL INFORMATION ABOUT HYDROGEN, HYDROGEN FUEL STATIONS AND FUEL CELL VEHICLES (FCHV)
	Summary	General information about Hydrogen and Hydrogen fuel stations
	Main Topic	General information
	Intended audience	General public
	Type of paper	Guidelines
	TYPE OF INFORMATION	Qualitative (descriptions, overview..)
70	Title	INTRODUCTION TO HYDROGEN SAFETY ENGINEERING

Summary	Presentation contents: • Definition and scope • Glossary • Deterministic versus probabilistic approach • Basic process of hydrogen safety engineering (HSE) • Main three steps of HSE: • Benefits of HSE • RCS and HSE • Examples
Main Topic	General, Safety, Hydrogen technologies, Fuel cells
Author	Vladimir Molkov, Jean-Bernard Saffers Hydrogen Safety Engineering and Research Centre (HySAFER) University of Ulster
Date and source of publication	2011, 4th International Conference on Hydrogen Safety
Intended audience	Hydrogen operators, Experts, Safety operators
Type of paper	Guidelines
TYPE OF INFORMATION	Quantitative (graphs, tables, data..), Qualitative (descriptions, overview..)

5.4 Conclusions

The common problem that has been highlighted by the majority of the interviewed regards the low level of awareness among different levels of society on hydrogen related issues. According to the interviewed, this scarce information leads to a lack of interest, and also the politicians seem not to give a particular attention to the topic.

Another aspects the majority of the interviewed agreed on, is the lack of a set of normative that regulate hydrogen use and safety at the national level. An harmonization and a greater alignment with the European regulation would be desirable.

Funds represent another topic of interest when talking about hydrogen: the interviewed underlined that research in the field of the use of hydrogen and its safety is strictly linked to the financial resources allocated, and very often these resources are too scarce. For this reason, progresses are slow.

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