HYDROGEN REFUELLING STATIONS
Example of a safety study for a hydrogen – natural gas refuelling station

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ABSTRACT:

The assessment of risks related to the operation of public and non-public hydrogen refuelling stations is a key step in the sitting approval process by legal authorities and eventually fire-department. Present work is underway at European level to facilitate approval procedures in order to ease technology deployment across Europe. In France, the ALTHYTUDE project co-ordinated by Gaz de France, deals with the use of a bus fleet fuelled with a mixture of hydrogen and natural gas in two different cities. Dunkerque in the North of France (two busses) and Toulouse in the South of France (three busses) have been selected. Refuelling stations will be built in each city. So as to get the sitting approval of the refuelling stations, risks analyses have been performed for each station. These risk assessments are in line with the new French regulation related to major accidents and somehow compatible with the health & safety at work regulation regarding explosion hazards. Methodology and first results of the risk analysis of the Dunkerque refuelling station are reviewed in this paper: hazardous scenarios have been proposed, safety barriers have been listed for each scenario, intensity quotation has been performed and scenario have been chosen for hazard quantification.

KEYWORDS : *Hythane®, refuelling station, risk analysis, hydrogen, natural gas*

1. Programme description

This paper presents the ALT-HY-TUDE project lead by the Research Division of Gaz de France, which intends to demonstrate the use of Hythane® as an environmental friendly fuel. The objectives are to:

- assess the relevance of Hythane® as a short term transition fuel towards hydrogen,
- provide immediate benefits with reduction of urban pollution and greenhouse gas emissions,
- take advantage of synergy with NGV infrastructure and vehicle technologies.

1.1. General description

Topics studied in the project deal with:

- hydrogen production and related Hythane® refuelling stations,
- improvement of the NGV[1] engine and buses for hydrogen/natural gas blend,
- technico-socio-economic assessment of Hythane® as clean fuel,
- bus and refuelling stations safety issues.

The ALT-HY-TUDE project is running from mid-2005 to 2008. The launch of the effective stations and buses operation is planned for the end of 2006.

[1] Natural Gas Vehicle

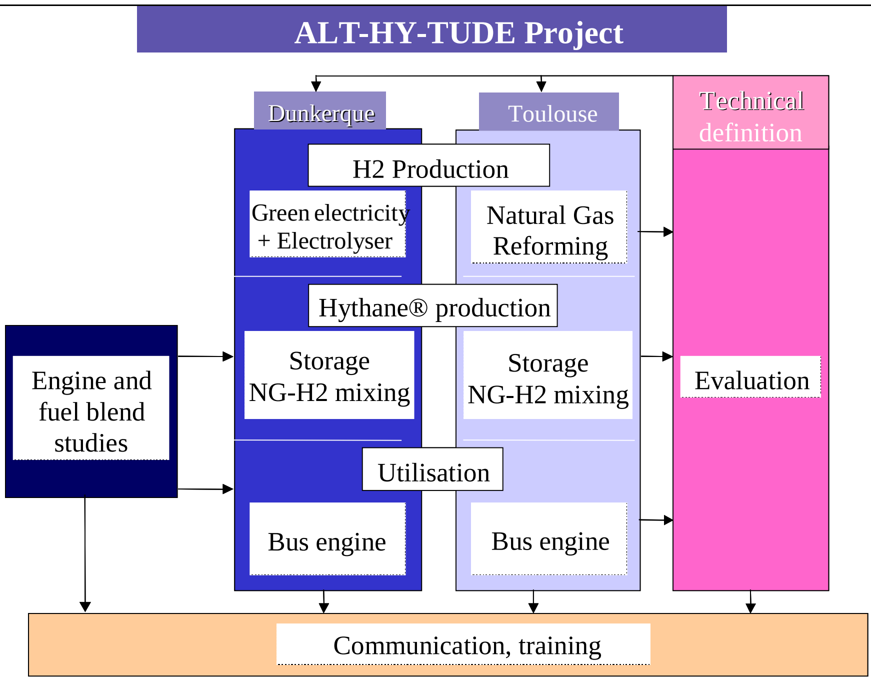

Figure 1: Programme description

The project is taking place in two cities in France that have a strong environmental policy and wish to lead the path of innovation towards hydrogen: Dunkerque, in the North of France and Toulouse in the South-West. The demonstration takes place in relation with existing NGV stations in order to take advantage of the NGV infrastructures, e.g. the compressed NG and the bus depot. The NGV stations are modified to integrate the new Hythane® refuelling stations by adding the H2 generator, the mixing equipment, the filling terminal, and the measurement and safety devices:

- Dunkerque: the great potential of wind power as renewable energy resources will be used for the production of H2 by means of a small, 4Nm3/h electrolyser manufactured and provided by Hydrogenics Europe NV, and operated with that "green" electricity. Therefore a reduction of CO2 emissions compared to NGV are induced considering the whole energy chain analysis.
- Toulouse: the reformer provided by Air Products and Gaz de France will have small H2 production capacity designed for filling the three Hythane® buses. The reforming of NG is considered as the best solution to provide H2 in the transition phase while the market of the H2-energy is growing.

The two cities are providing new NGV buses from IRISBUS-HEULIEZBUS for the demonstration (figure 2). These NGV buses are equipped with the new stochiometric engine CURSOR 8 from Iveco.

Figure 2: Future Hythane® bus in Toulouse, operated by Tisséo Réseau Urbain.

The use of Hythane® implies an adaptation of the NGV buses to the new fuel which includes a modification of the mapping of the engine: bench tests are carried on in order to find the best engine performance trade-off in term of emissions, efficiency and reliability, for several hydrogen contents in the blends. The optimised tuning will be applied to the buses' engine. Laboratory results will be checked through road trial tests. At an early stage, these tests will take place without in order to assess performance and reliability.

In the meantime the necessary approval process of this new type of Hythane® buses and the new refuelling stations will be accompanied by the French Administration.

Regulatory file including safety studies on the refuelling stations and the vehicles is a major issue that is already being worked on in relation with local authorities.

1.2. Partnership

Key stakeholders have been incorporated into the project; urban communities, utility suppliers, refuelling station operators, technology developers, bus operators, bus manufacturer, universities, engineering companies and safety experts (Table 1). The goal is not only to gather the right competencies to achieve the various parts of the project but also to start building a hydrogen expert community covering all aspects of the energy chain.

<table>
<tr><td colspan="2" align="center">Gaz de France: coordinator
GNVert: refuelling station studies, modification, operation & maintenance
INERIS: regulatory aspects, safety studies
EGIM: engine studies
IRISBUS: vehicles modification & validation
CONNEX: pollutant measurements</td></tr>
<tr><th>Dunkerque</th><th>Toulouse</th></tr>
<tr><td>H2 Développement: local coordinator & green H2 production</td><td>IMFT: local coordinator & engines studies</td></tr>
<tr><td>Communauté Urbaine de Dunkerque</td><td>SMTC-Tisséo: public transport Authority</td></tr>
<tr><td>DK Bus Marine: bus operation</td><td>Tisséo Réseau Urbain: bus operation</td></tr>
<tr><td>Hydrogenics: H2 generation (electrolyser), station design and supply</td><td>Air Products: H2 generation (reformer), station design and supply, back-up</td></tr>
</table>

Table 1: List of ALT-HY-TUDE partners.

2. Regulatory framework

2.1. French regulatory framework related to major accidents

The ALTHYTUDE project falls within the French Environmental regulation framework because hazardous substances handled and associated Hydrogen Refuelling Station processes belong to a hazardous or so called nomenclature edited by the French Environment Ministry.
These main items are:

- item 1411, corresponding to flammable substances. Thresholds are based on the total quantity likely to be stored.
- item 1415 corresponding to the hydrogen production. Thresholds are based on the quantity of hydrogen produced.
- item 1416, corresponding to storage and use of hydrogen. Thresholds are based on the total quantity likely to be stored.
- item 2910, corresponding to combustion. Thresholds are based on the thermal power of the installation. This item is particularly suitable for the reforming system.
- item 2920 corresponding to compression. Thresholds are based on the absorbed power of the installation running at an effective pressure higher than 1 bar.

The applicable items thresholds should be compared with characteristics of the foreseen hydrogen systems in order to define under which category it falls. Three different categories (and associated constrains) exist in the French legal framework:

- “Declaration” category (D): for installations that do not present serious hazards or inconveniences. They must comply with general national safety measures. Application file should be sent to the local authority (so called Préfet),
- “Authorisation” category (A): for installations that present serious hazards or inconveniences. Application file should be sent to the local authority (so called Préfet). Authorisation is issued if the applicant demonstrate that hazards or inconveniences are under control. Specific legally binding safety measures are set by local authorities.
- “Authorisation and public easement” or Seveso category (AS): for some A installations which can generate very important hazards. This status integrates the transposition under the French law of the European Seveso Directive. One again, application file should be sent to the local authority (so called Préfet).

Since hydrogen producing equipment are classified at least under an authorisation regime, a safety study has to be performed and sent to the local authority.

2.2. Some Regulatory changes after the Toulouse disaster (2001)

After the major accident in Toulouse (21/09/2001, AZF explosion), the national regulation was updated by the law of the 30th July, 2003 and its different orders of applicability in 2005.
These changes concern basic requirements for safety studies under the perspective of major accidents and risk management. The main requirements behind a safety study are:

- to demonstrate that a site reach, in acceptable technological conditions, a risk level as low as possible, given the state-of-the-art, the good practices and the vulnerability,
- to characterise for each hazardous phenomena (explosion, fire, toxic release):
  - occurrence probability: Three possible approaches: quantitative, semi-quantitative, and qualitative associated with a scale
  - kinetics : slow or fast
  - intensity: damage distances with reference thresholds
  - and severity of the major accident associated with the phenomena (mix of damage and vulnerability of surrounding)

The basic element and related interactions in the process to demonstrate that an appropriate safety level is reached is illustrated by the figure below:

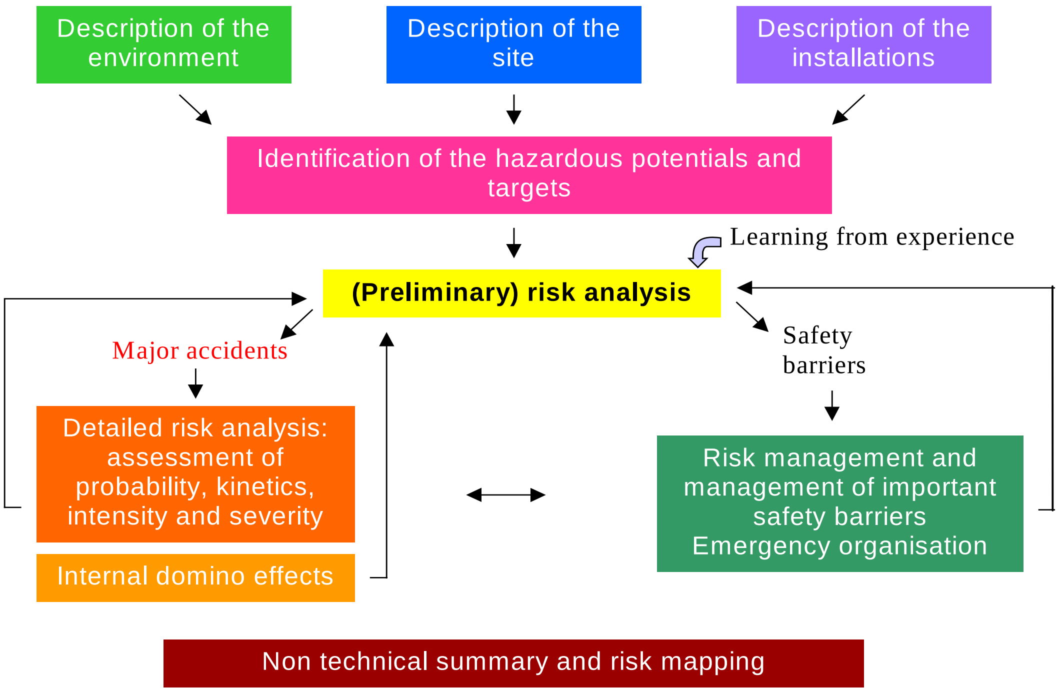

Figure 3: Basic elements for risk control and risk communication

The guidance of the 25th June 2003 defines, according to the above figure, the general framework for a safety study on a Seveso site.

2.3. French regulation related to health and safety protection of workers

As pure or blended hydrogen are handled by workers (driver, bus deposit worker, …), the regulation related to the safety and health protection of workers potentially at risk from explosive atmospheres (1999/92/EC Directive also called ATEX Directive) is applicable.
This Directive has been transposed in the French Labour Code and requires employers to:

- Evaluate risks associated to explosive atmospheres. This process includes zone classification,
- Select and install appropriate electrical and mechanical equipment and protective systems to control ignition sources in explosion zones,
- Edit an explosion protection document to demonstrate that explosion risks have been adequately evaluated and are under control.

The ATEX regulation requires employers to perform a thorough risk analysis in order to identify situations that can lead to the formation of an explosive atmosphere, to its ignition, and to harmful effects on workers.

The regulatory texts do not propose a risk assessment method, but the French decree 2002-1553 (art. R 232-12-26), by transposition of the European Directive, indicates that:
« *the employer shall assess the specific risks arising from explosive atmospheres, taking account at least of:*

- the likelihood that explosive atmospheres will occur and their persistence,
- the likelihood that ignition sources, including electrostatic discharges, will be present and become active and effective,
- the installations, substances used, processes, and their possible interactions,
- the scale of the anticipated effects. »

During the risk analysis, frequency of unwanted events will be estimated as a combination of likelihood of an explosive atmosphere to be present and ignition likelihood. Explosion consequences will also be evaluated. Effects of an explosion are either mechanical effects (pressure effects, missiles) and thermal effects. So as to evaluate these effects, it is necessary to consider:

- The location of the explosive atmosphere in relation with potential confinements (the greater the confinement the more severe effects will be),
- The explosive volume (the larger the volume the greater the effects).
- And workplace locations.

According to these consequences evaluation, scenarios' severity will be estimated.
For the ALT-HY-TUDE project health & safety at work explosion related scenarios will be taken into consideration in the course of the risk assessment. Therefore, both aspects of land use planning and health & safety at work will be looked at although relevant scenarios and targets are different.

2.4. Targets to be considered for risk assessment

Risk assessment is always a matter of hazards associated with unwanted events and a matter of targets who can suffer from the identified hazards. Targets could be people, infrastructures or the environment. When considering human targets along with refuelling stations, it is possible to classify people into three categories: plant personnel, customers and off site lay people (pedestrians, people in buildings, inhabitants…). Depending on the approach, either occupational health, customer protection or external safety, different people can be at concern. However, the tolerable risk level for all three categories is the same. The main differences depending on who is considered will be on investigated scenarios as well as on the nature of the proposed safety barriers.
As an example, when dealing with external safety, a focus on 'low frequency - severe consequence' scenarios is necessary since their outputs will play an important role in land use planning as referred in Seveso Directive 96/82EC. On the other hand, when dealing with plant workers or even with customers, we will rather be interested in «high-frequency - low consequence» scenarios such as those we would consider when implementing the ATEX 99/92EC requirements. As far as safety barriers are concerned, it is necessary to make sure that the customer interface is idiot proof whereas we would rely on plant personnel training and procedures as a contribution to risk control.
Since various type of people (inhabitants, workers…) are considered within the same risk assessment, it is necessary to make sure that both severity and frequency scale allow covering the all range of relevant scenarios.

3. Risk analysis methodology

The risk analysis, heart of the safety study, consists in two main steps:

- the preliminary risk analysis: this first helps to identify and rank hazardous phenomena according to a criticity matrix and then to select most hazardous ones,
- the detailed reduction risk study: this second step is an in-depth study of the selected hazardous phenomena and associated risk reduction measures including their performance.

As explained above, risk analysis is required both by the Major Accidents and ATEX regulations. The preliminary risk analysis can take into accounts both expectations. However, we only present in this paper the risk assessment results that fall within the framework of Major Accidents regulation.

3.1. The preliminary risk analysis

The preliminary risk analysis consists in:

- Identifying, as much as possible, the **dangerous phenomena** likely to lead to major accidents through various scenarios identified. Each dangerous phenomenon (physical phenomena like fire, explosion, toxic dispersion, etc.) can be the result of many undesired events, themselves induced by different causes.
- Quoting the **likelihood of occurrence** (F) of each cause (without initially considering the technical or organisational safety) according to a quotation scale.
- Listing the **safety barriers** (technical and/or organisational) whatever prevention or protection that contribute to mitigate major accidents identified.
- Quoting the identified dangerous phenomena in terms of **intensity** (I) in accordance with the intensity scale. This step aims at selecting dangerous phenomena that can lead to damage distances beyond site boundaries. So there will be dangerous phenomena with hazardous consequences limited to site boundaries and some expanding outside the site boundaries. This classification is one of the key criteria when choosing scenario to compute for quantification.

The table below is the one which is used for the risk assessment of the refuelling station.

Unwanted event	Causes	F	Dangerous phenomena	Local effects	Final effects	I	Scenario to be modelled	Safety functions	Technical safety barrier	LC[2]	Organisational safety barrier	LC	P	G	Additional measures

Table 2: Risk analysis table

a. *Frequency of occurrence and intensity*

Below are examples of quotation scales for cause occurrence frequency and for dangerous phenomena intensity.

Qualitative :	« Highly improbable event »		« Very improbable event »	« Improbable event »	« Probable event »	« Usual event »			
Semi--quantitative :	10^{-6}		10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10
Probability classes (from -2 to 6)	6	5	4	3	2	1	0	-1	-2

Figure 4: Example of a frequency quotation scale

[2] Level of confidence, see paragraph b)

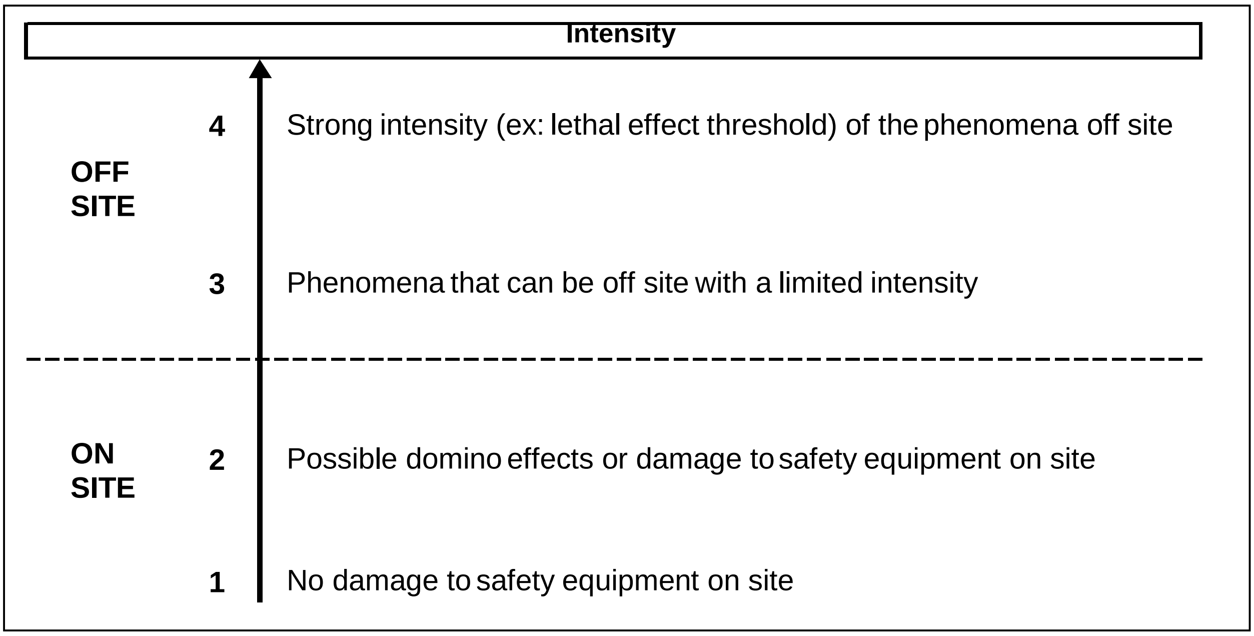

Figure 5: Example of an intensity quotation scale

Criteria, which could be considered for the intensity quotation are, for example:

- Product intrinsic hazards,
- Installation localisation compared with site boundaries.

b. Safety barriers

Safety barriers can contribute to mitigate risks through by:

- either removing/ reducing causes of initiating events leading to an undesired event or reduces its frequency of occurrence,
- or reduce the consequences associated to the dangerous phenomena.

To estimate the probability level of a dangerous phenomenon, only the safety barriers having sufficient performances to mitigate risks can be taken into account. This "safety barrier approach" enables to make a direct and logical link with risk management.

Safety barrier should be independent from the process, the other safety barriers participating to risk reduction as well as to the initiating event consequences. Safety barrier performance can then be assessed according to its efficiency, its response time and its level of confidence in terms of reliability (LC).

The performance of barriers should be assessed in the framework of a given scenario. Indeed, a safety barrier can be ranked very efficient for a given scenario but can be inefficient for another.
Safety barriers level of confidence helps to determine the residual probability of a dangerous phenomenon. The table below gives an example of level of confidence quotation.

Level of confidence	Performance of the safety barrier
0	limited
1	medium : at least one permanent control is necessary
2	High : at least one efficient safety barrier is independent
3	maximum

Table 3: Example of quotation for safety barriers level of confidence

3.2. Detailed risk reduction study

This step aims at examining in detail the selected dangerous phenomena considered as critical after the preliminary risk analysis and at concluding about the risk reduction level on site.

3.2.1. Modelling of dangerous phenomena

Modelling of the scenario quoted with an intensity of 3 or 4 (effects off site) should be performed with computer code or software. Scenarios with a level 2 intensity can also be considered. These scenarios can be computed either mitigated or non-mitigated. This helps to appreciate the risk reduction potential of safety barriers and therefore the positive action of safety measures taken.

The main calculation tool, which is being used for atmospheric dispersion modelling is PHAST (Process Hazard Analysis Software Tool - version 6.4). It is a software, which relies on an integral model. Dispersion is resolved through the UDM model (Universal Dispersion Model). This method combines various models:

- jet dispersion,
- droplet evaporation and rainout, touchdown,
- pool spread and vaporisation,
- heavy gas dispersion,
- passive dispersion.

The model of jet dilution is based on the theory of Ricou and Splading. The combustion is not modelled with PHAST. PHAST's results regarding the flammable cloud are the LFL[3] distance and the flammable mass.

Concerning the calculation of consequences associated with unconfined explosion scenarios, INERIS calculate overpressures likely to be generated in the environment, by using the "Multi-Energy" method. This method has been developed by TNO. It calculates overpressures according to expected flame velocity and explosion volume.

This modelling step enables to complete the risk assessment tables with a quotation in severity according to the severity scale shown below.

Level of severity	Internal or external human targets	*Material targets (for information)*
4	Death of one or several people	*Loss of the CNG station or destruction of vehicles or external goods (of which personnel's vehicles) or destruction of several vehicles or on site goods*
3	Encounter/aggression of one or several people with irreversible effects	*Temporary unavailability of the NVG station or long term unavailability of the HRS without any possible bringing back into service or destruction of some on site vehicles or goods (except personnel's vehicles)*
2	Wounds with reversible effects	*Long term unavailability of the HRS with possible bringing back into service*
1	No significant effect on the personnel of the site	*No effect on the equipment with temporary loss of the H2 production function*

Table 4: Severity Levels

Then, a "bow-tie" graph can help to picture the scenarios and the expected contributions of safety barriers taken. "Bow-tie" is a combination of a fault tree and an event tree. It merges in a single graph most severe scenarios leading to a given hazardous phenomenon (explosion, fire…). It is a useful tool to demonstrate that risk is under control. "Bow-tie" combining causes and barriers can help to estimate the residual frequency of scenarios.

[3] Lower Flammability Limit

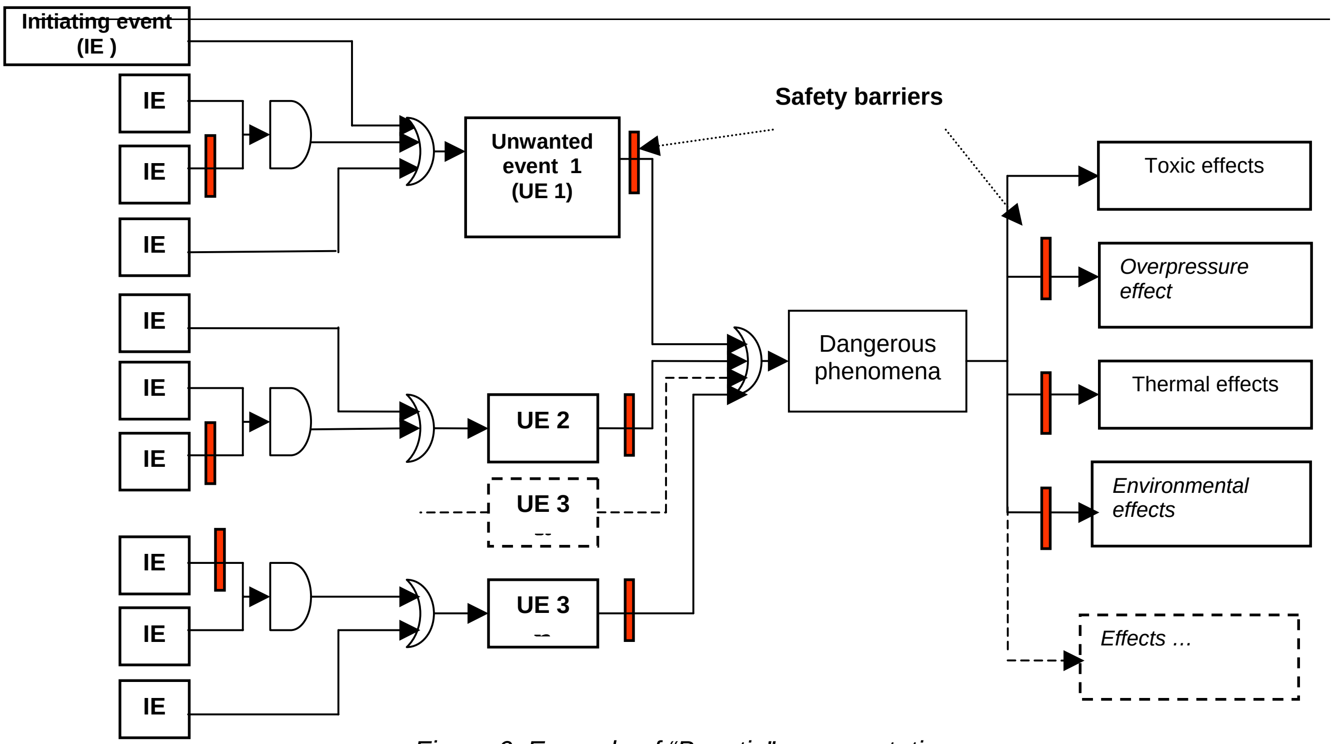

Figure 6: Example of "Bow-tie" representation

Finally, once the residual probability and the severity of relevant hazardous phenomena is known, the risk level can defined according to the criticity matrix (see below) in order to evaluate whether risks are acceptable or not.

		Probability level				
		5	**4**	**3**	**2**	**1**
Severit y level	**4**					
	3					
	2					
	1					

Table 5: Example of an acceptability matrix

	Major risk not managed – Not acceptable
	Major risk managed – Reduce as low as possible, maintain safety barriers performances
	No major risk

4. Main results of the risk analysis for the Dunkerque Hythane® refuelling station

4.1. General description of the refuelling station

The refuelling station will be located in a bus depot, which already accommodate a NGV refuelling station. The general process of the refuelling station is illustrated below.

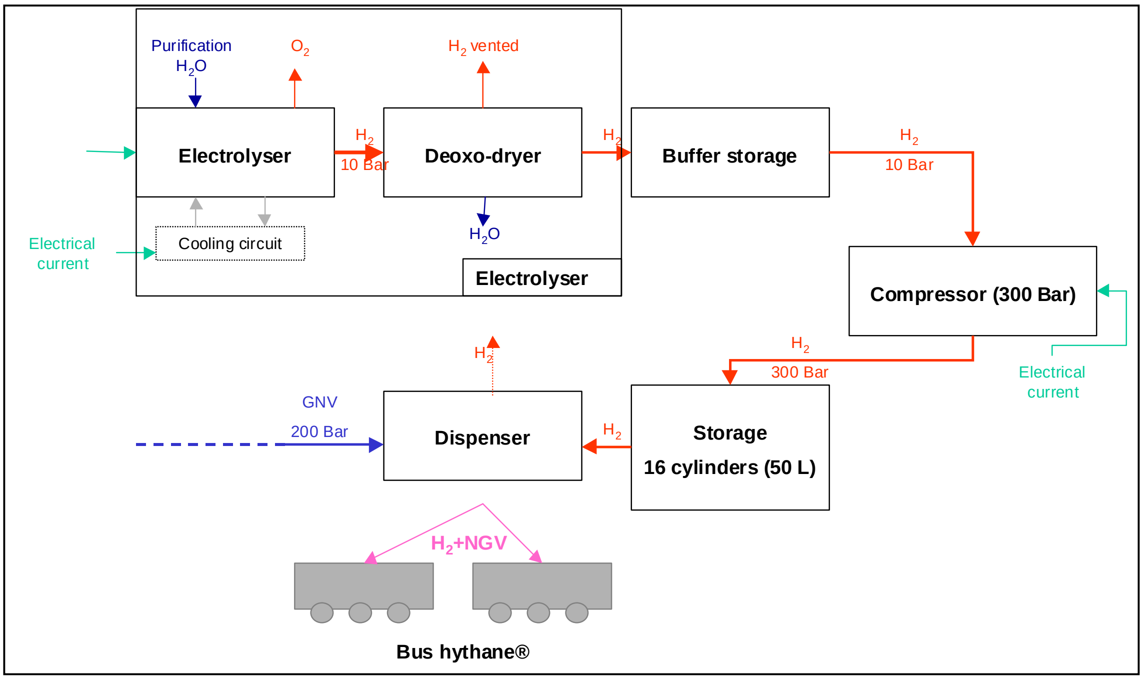

Figure 7: General process of the Dunkerque refuelling station

The electrolyser and the Deoxo-dryer will be installed in a closed container. The electrical equipment will be separated from the electrolyser and the Deoxo-dryer by a wall. Near the container, there will be a concrete room which will contain the buffer storage (10 Bar), the compressor (300 bar) and the high pressure hydrogen storage (16 cylinders containing 50 m^3 of hydrogen each). Electrical equipment will also be separated from gas equipment by a wall.
The container and the room will be equipped with a gas detection system. The ventilation in the electrolyser container will be mechanical, whereas in the room the ventilation will be ensured by the compressor: if the compressor does not run, the ventilation will be natural.
Hydrogen and natural gas will be fed by pipes in duckboard to the dispenser. Hydrogen and natural gas will be introduced in the bus tanks sequentially.

4.2. Most critical scenarios

The following most critical scenarios likely to induce effects and eventually damages beyond the boundary of the refuelling station have been identified. These scenarios' intensity has been earlier ranked either level 4 or 3. Some level 2 scenarios have also been kept due to the uncertainty regarding their intensity potential. These scenarios address the following sub-systems: the electrolyser, the 10 bar buffer tank, the compressor, the compressed hydrogen storage, the hydrogen feed line, the natural gas feed line and finally the dispenser.

Station Sub-systems	Scenario description	Intensity ranking
Electrolyser	Hydrogen explosion inside production housing. Explosive atmosphere caused by hydrogen leakage (leak fed by back flow from buffer)	2 or 3
	Hydrogen explosion inside production housing. Explosive atmosphere caused by hydrogen major loss of confinement (human error, guillotine break)	3
Pressurised Hydrogen storage	Hydrogen explosion in open air. Explosive atmosphere induced by fittings' leakage on storage tanks.	2 or 3
	Hydrogen explosion in open air. Explosive atmosphere caused by voluntary or accidental hydrogen release through release devices.	2 or 3
	Rupture of pressurised hydrogen tank caused by external fire	3
Hythane® dispenser	Hythane® explosion in open air. Explosive atmosphere caused by leakage during refuelling (bad nozzle connection, accidental disconnection, back flow from the vehicle after disconnection…)	3
	Hythane® jet flame at nozzle connection (bad connection,…)	2 or 3
	Hythane® explosion in open air. Explosive atmosphere caused by leakage of Hythane® hose (hose wear, break-away leakage…)	2 or 3
	Hythane® fire or explosion inside dispenser unit (ageing, mechanical aggressions)	3
	Accidental disconnection and hazardous whirl of refuelling hose and nozzle	2 or 3

Table 6: List of level 4 and 3 scenarios for the electrolyser, the pressurised storage and the dispenser

4.3. Example of refuelling station safety features

In order to mitigate identified scenarios, the following safety barriers have been selected in the course of the risk assessment.

System or sub-system	Safety features
Hydrogen production compartment (electrolyser and hydrogen buffer)	▪ Fire proof walls (2 hour rated), ▪ Explosion venting, ▪ Hydrogen (alert at 20% LFL and shut down at 40% LFL) and fire detection, ▪ Controlled ventilation (ventilation is only turned off in case of a fire) ▪ Electrical equipment segregation ▪ Restricted access
Hydrogen storage	▪ Bottles are placed vertically, ▪ Storage located outdoor, ▪ Storage surrounded with two hours rated fire walls, ▪ Protection of storage tanks against impinged fire jet, ▪ Thermal fuse 100°C rated to empty the storage in case of a fire, ▪ Manual emergency storage emptying also possible, ▪ Fire and gas detection, ▪ Emergency shut down valve downstream, ▪ Pressure monitoring, ▪ Eventually, water deluge system.
Hythane® dispenser	▪ Standardised nozzle, ▪ Dispenser and refuelling in open air, ▪ Dispenser on elevated floor and crash barriers, ▪ Emergency button on dispenser, ▪ Gas and fire detection, ▪ Non return valve, ▪ Emergency shut down valve upstream / Excess flow valve, ▪ Isolation valve always shut down when not in use, ▪ Break away on dispensing line, ▪ Leak test before refuelling, ▪ Refuelling by trained personnel only and refuelling procedure, ▪ Natural ventilation of dispenser casing.
Hythane® station	▪ Fences or fire proof wall around the station, ▪ Safety distances computed based on mitigated scenarios (fire proof walls help to reduce safety distances), ▪ Non mitigated scenarios also computed in order to assess the importance of proposed safety barriers (emergency shut down valve for instance),

Table 7: Example of safety features selected for the selected equipment of the refuelling station

We shall also mention that ATEX zoning has been carried out. Whenever possible, weld has been favoured and pipes have been protected against mechanical aggressions. Periodic controls are planned and safety experiences will be recorded. Efficiency, reliability and response time of safety barrier has been taken into account to demonstrate risk control. Performance over time of these safety equipment will be checked.

As far as emergency shut downs are concerned, two emergency levels will be enforced. That includes:

- Emergency stop: isolation of equipment plus partial depressurisation. This stop is triggered by a critical drift of key parameters (temperature, pressure)
- And ultimate shut down: isolation of equipment, plus total depressurisation and eventually shut down of installations in the vicinity (NGV station). This stop is triggered by critical gas or fire detection and eventually by manual action of trained people

5. Conclusions

Being the first refuelling stations ever built in France in the framework of hydrogen related demonstration project, this work should pave the way in terms of methodology and legal expectations to further French initiatives. ALT-HY-TUDE learning contribute to the European Hyapproval project.

6. Acknowledgements

The ALT-HY-TUDE project is supported by the ADEME (French Agency for the Environment and the Energy Management) and the FEDER (European Funds for the Regional Development) for the Dunkerque operation.

7. References

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