ENGINEERING SAFETY IN HYDROGEN-ENERGY APPLICATIONS

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ABSTRACT

Since a few years, hydrogen appears as a practical energy vector and some hydrogen applications are already on the market. However these applications are still considered dangerous, hazardous events like explosion could occur and some accidents, like the Hindenburg disaster, are still in the mind. Objectively, hydrogen ignites easily and explodes violently. Safety engineering has to be particularly strong and demonstrative; a method of precise identification of accidental scenarios ("probabilities"; "severity") is developed in this article. This method, derived from ARAMIS method, permits to identify and to estimate the most relevant safety barriers and therefore helps future users choose appropriate safety strategies.

1.0 INTRODUCTION

Since a few years, hydrogen appears as a credible alternative energy-vector and some hydrogen applications such as H_2-fuel cell cars are already on the market (Toyota Hydrogen Fuel Cell Vehicle: Mirai [1], for example). However hydrogen applications are still considered dangerous, indeed hazardous events like explosion could occur if a hydrogen-air mixture comes to be formed; and some accidents involving hydrogen, like Hindenburg disaster or more recently Fukushima Daiichi nuclear disaster, are still in the mind. And finally the full acceptation of them on the market will go through the public acceptation. And it should be recognised that hydrogen leaks can produce extended explosive clouds because of the broad flammability range, and that hydrogen-air mixtures ignite extremely easily and burn/explode fast and violently [2], [3]. As compared to other fuels (ex: hydrocarbons), the flammability range is 5-10 times larger, the minimum ignition energy is 5-10 times smaller and the maximum burning velocity is also about 5-10 times larger. In other words hydrogen-involved accident might lead to larger consequences. However, due to its physical properties, hydrogen may offer some appreciable advantages in terms of mitigation: because the flammable mixtures are much lighter than air, they disperse rapidly. Unfortunately, because of the very low minimum ignition energy, the ignition likelihood is much larger than for other common hydrocarbons. Design engineers have to face this reality and the logical consequence is that the safety demonstration has to be very strong and clearly understandable. To do so, experience shows that all the sequences of events leading to an hazardous situation (a leakage) need to be identified and ranked in terms of likelihood and consequences (explosions pressures, fire thermal fluxes). On this basis scenario-dedicated "safety barriers" can be chosen and engineered in terms of required reliability and efficiency (level of reduction of the consequences). In this paper, the various risk analysis methods used/developed so far in the field of hydrogen safety are reviewed and assessed. None of them seem to be fully adapted to engineer safety on a practical daily basis. An alternative is presented in the following.

2.0 STATE-OF-THE-ART OF EUROPEAN PROJECTS ON RISK MANAGEMENT

The definition of a major accident is, given into the SEVESO Directive [4], "*an occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment… and leading to serious danger to human health or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances*". The SEVESO directives are "translated" into national law. In France [5], the notion of major accident is the subject of an a priori classification of industrial installations on the basis of the nature of the products (clean hazards) and the nature of the transformation they are subjected to. For hydrogen applications, the border above which the installation enters into the scope of the regulation for the prevention of major accidents is 100 kg (>1000 kg for the SEVESO thresholds). However for many hydrogen applications, the quantity of stored hydrogen is often below 100 kg (typically 5 kg for the tank of Toyota Mirai) When an installation falls under the scope of the major accident regulation, a demonstration is required showing that the hazards are kept under control. The first step is always “risk assessment” but a number of very different methodologies (Table 1) exist to do this, which were benchmarked throughout Europe to highlight the performances/deficiencies.

Table 1. Definitions of the existing approaches for risk assessments. [6]

Approach	Definition
Deterministic approach	The scenarios (ex: leak flow rate) are prescribed and often correspond to worst cases (ex: full bore rupture of the pipe). The scenarios may result from a brainstorming exercise (HAZOP, What-if ...) or may be imposed by the authorities. Only the consequences of the scenarios are estimated.
Probabilistic approach	The scenarios are identified using a brainstorming method (HAZOP, What-if ...) and are ranked according to their probabilities (fault tree for instance). Only those scenarios sufficiently probable and able to create a significant hazard are selected.
Quantitative risk assessment	In the quantitative risk assessment, after a brainstorming phase the consequences and probabilities of each scenario are assessed. The consequences (number of injured people; deaths (most often) or to damages) and the frequencies (number of occurrence per year) are based on facts, database. The QRA lead to the following results representation the individual risk (iso-risk curve) and the societal risk (frequency/severity curve). The QRA is a complicated and time consuming exercise.
Qualitative risk assessment	In the qualitative risk assessment scenarios, frequencies and consequences are extracted from the feedback for past accidents and existing knowledge about the hazards (good practices, hazardous potentials...). The ranking of the scenarios is qualitative (ex for the consequences: no effect minor effects; localized effects; important consequences outside). The result is presented in a risk matrix. The qualitative risk assessment is easy and fast exercise but may be subjective.
Semi-Quantitative risk assessment	A semi-quantitative approach is similar to a QRA but instead of precise frequencies, orders of magnitudes are used.

2.1 Benchmark Exercise on Major Hazards Analysis

For the first time in the project Benchmark Exercise on Major Hazards Analysis [7] (BEMHA) from 1988 to 1990, experts (from control authorities, research organizations, engineering companies or industry) could compare their methodologies. Eleven teams of experts analysed a typical ammonia storage facility located on a hypothetical site. The project resulted in a comprehensive overview of currently available methodologies for chemical risk assessment in Europe and highlighted the very strong influence of the assumptions made all along the risk assessment process such as the minimum lethal dose, source flow rates or hole sizes for process pipes. The project underlined the need to harmonize both the content and the format of the risk analysis as well as to establish a standardised language.

2.2 Assessment of the Uncertainties in Risk Analysis

Ten years later, the project ASSURANCE [8], [9] (Assessment of the Uncertainties in Risk Analysis of Chemical Establishment) (1998-2001) studied once again an ammonia storage facility in order to quantify the uncertainties associated with the risk analysis and in particular the incidence of the method of selection of the critical scenarios, the methods to estimate the consequences and the probabilities. It was found that the hazard identification phase was very critical. In particular, depending on the “filter” used (all probabilistic or all deterministic approaches) quite different ranking of the accidental scenarios were obtained (Table 2), particularly for scenarios with intermediate consequences. As for the scenarios’ frequency assessment, the estimates were also quite contradictory.

Table 2. Comparison of probabilities calculated in ASSURANCE project [9]. (Grey tanned cells contain the lower assessments. Black tanned cells contain the upper assessments)

#		3	5	7
Scenario		Rupture or disconnection between ammonia ship and unloading arm	Rupture of a ship tank	Rupture of 20" pipe (distribution line of cryogenic tank)
Partner	1	$4.8\ 10^{-4}$	$2.8\ 10^{-7}$	$6.0\ 10^{-6}$
	2	$4.8\ 10^{-6}$	$6.4\ 10^{-10}$	$1.0\ 10^{-6}$
	3	$8.0\ 10^{-3}$	$5.7\ 10^{-5}$	$5.0\ 10^{-6}$
	4	$5.0\ 10^{-3}$	---	$9.0\ 10^{-7}$
	5	$5.4\ 10^{-5}$	$2.3\ 10^{-6}$	$4.0\ 10^{-7}$
	7	$1.3\ 10^{-5}$	$4.9\ 10^{-6}$	$4.0\ 10^{-7}$
Range of deviation		$4.8\ 10^{-6}$ - $8.0\ 10^{-3}$	$6.4\ 10^{-10}$ - $5.7\ 10^{-5}$	$6.0\ 10^{-6}$ - $4.0\ 10^{-7}$

After this project, INERIS proposed to center the risk analysis onto the identification of “safety barriers” as a link between the probabilistic and deterministic approaches inasmuch the French authorities would accept a SEVESO plant only if safety barriers were indentified and could be maintained when time passes by. According to INERIS experience, the “safety barrier” approach offers a better transparency and a communication with a better perception by the general public.

2.3 Development of an integrated technical and management risk control and monitoring methodology for managing and quantifying on-site off-site Risks

I-RISK [10], [11] project (“Development of an Integrated technical and management risk control and monitoring methodology for managing and quantifying on-site off-site Risks” 1996-1998) illustrated the importance of safety barriers into the risk management process. The project I-RISK aimed at developing a safety management model for risk control and monitoring; i.e. a risk assessment method that will takes in consideration not only the technical aspects (identification of the events leading to loss of containment (LOC) and the associated fault and event trees), but also the management system (major hazard management system audit) and their interface (quantification of the effect of this risk management – safety measures – on the risk of LOC).

In this project, Quantitative Risk Assessment (QRA) and management audits were used as 2 integrated tools. It was pointed out that “*the integrated technical and management model was very robust and helped audit organizations in a new way*” but that using the I-Risk method (QRA) on a full and complete site was much too demanding in terms of resources. I-RISK should be simplified to have a greater opportunity to be applied in the real life.

2.4 Accidental Risk Assessment Methodology for Industries ARAMIS

The project ARAMIS [12], [13], [14] (2002-2004) aimed at developing a new assessment method for major risks building on the preceding experiences. The ARAMIS project is based on an approach by barriers: identification of all conceivable major accident scenarios and the inventory of all safety equipment or barriers impeding the development of an accident because the final acceptability lies in the demonstration that the proper dimensioning (reliability, performances) of safety barriers is capable of keeping the identified risks under control. Besides, a significant evolution of the “risk perception/safety culture” is acknowledged:

- the unrealistic vision of “zero risk” hidden behind the deterministic approaches is ruled out;
- decision making is now open since a quantified line is drawn between acceptable and unacceptable accidents;
- safety management is possible since not only the technical performances of the barriers are accounted for but also their reliability which includes human/organisational aspects and thus involves responsibilities

This move is perceptible in several countries including France where the acceptance of a new industrial project is openly depending of the design and control of the safety barriers. The French regulatory system resembles ARAMIS methodology [15], [16].

ARAMIS [17] contains two methods. MIMAH (Methodology for Identification of Major Accident Hazards) helps identifying of all accidental scenarios physically conceivable. MIRAS (Methodology for the Identification of Reference Accident Scenarios) helps selecting the reference scenarios to be modelled and entered into the severity map.

The objective of MIMAH is the identification of major accidents i.e. all of the worst accidents likely to occur considering no safety systems and regarding the equipment, hazards and properties linked to substances used. MIMAH is based on the use of bow-tie diagrams (composed of a fault tree and an event tree, built around a critical event – an example is given Fig. 2); the bow-tie diagrams was chosen due their powerful mean of communication especially the visualisation of all causes and their relationship (necessary “AND” and sufficient “OR” conditions) allowing future probability calculations and identification of the potential safety barriers. In practise, the choice of the “critical event” may be difficult. It is formally, the point in the scenario were the succession of the elementary events switch from a causality organisation (event n°3 happens **IF** events n°1 **AND** 2 have occurred) to a temporal succession (event n°3 happens **WHEN** events n°2 **HAS** occurred). To help end-users, the structures of bow-tie were defined and potential critical events and the associated consequences were listed for typical equipment. It appears that critical events are often a loss of containment or, more generally a loss of physical integrity (leakage, spontaneous decomposition...). What happens AFTER the critical event is organised as an event tree. What occurs AHEAD is organised as a fault tree. In MIMAH, the probability aspect of the scenarios is not taken into account but the bow-tie is used to select the (suspected) required safety barriers, into the MIRAS method, which viability is tested analysing the organisation of the company.

In MIRAS, (the method of selection of reference accident scenarios (RAS)), the probabilities/consequences of each accident are calculated taking into account of the safety barriers. The MIRAS methodology takes into account the safety systems installed on and around the equipment, the safety management system and the frequency and consequences of the accident.

Firstly the calculation of the frequency (see Table 3) of the critical event is done through the analysis of the fault tree or with generic critical event frequencies (taking into account the safety barriers in the fault tree). Then the frequencies of dangerous phenomena are also calculated (taking into account the safety barriers in the event tree). The performances, efficiencies of the safety barriers influence both the frequencies and consequences. Secondly a qualitative assessment of the consequences of dangerous phenomena is done leading to four classes of consequences (Table 4). This assessment will serve in the selection of RAS using a risk matrix defined by three zones: negligible effects; medium effects and high effects. It turns out that RAS are dangerous phenomena located in the medium or large consequence zones. Finally for each RAS a quantitative assessment is made to calculate the Severity.

Table 3. Probability classes.

Probability		Quantitative estimation (per year)	Qualitative estimation
F4	Improbable	$< 10^{-5}$	Possible but extremely unlikely event
F3	Extremely rare	10^{-4} to 10^{-5}	Very improbable event
F2	Rare	10^{-3} to 10^{-4}	Improbable event
F1	Possible	10^{-2} to 10^{-3}	Likely event
F0	Occasional	$> 10^{-2}$	Common event

Table 4. Class of consequences.

Ranking	Definition	
	Domino effect	Effect on human target
C1	To take into account domino effects, the class of consequences attributed to the studied dangerous phenomenon will be increased to the class of the secondary dangerous phenomenon that the first can bring about by domino effects	No injury or slight injury with no stoppage of work
C2		Injury leading to an hospitalisation > 24h
C3		Irreversible injuries or death inside the site, reversible injuries outside
C4		Irreversible injuries or death outside the site

As conclusion the ARAMIS methodology is a composite of a deterministic and a probabilistic method. ARAMIS follows the suggestions from INERIS formulated at the end of the project ASSURANCE.

At the European level ARAMIS is a "*recommended and harmonised tool used by risk experts and recognised by the risk decision-makers in the European Union*" [18], covering the requirements of the SEVESO Directive.

2.4 International Energy Agency - Hydrogen Implementing Agreement

At the international level, the tasks 19 and 31 of International Energy Agency (IEA) Hydrogen Implementing Agreement (HIA) [19], [20]; started in 2004; are devoted to the implementation of safety in hydrogen-based applications consecrated to a commercial use. During that period of time, IEA worked in close cooperation with Europe and joined the following projects both in view of selecting an appropriate risk assessment method and of identifying knowledge gaps: HyQRA (third internal project of HySafe: Safety of Hydrogen as an Energy Carrier; 2004-2009) and HyApproval (Handbook for Approval of Hydrogen Refuelling Stations; 2006-2008).The aim of the project HyQRA was the development of a reference QRA methodology applicable to the hydrogen systems; which however used simplified calculation methods for having acceptable answer times. Additional work was also performed to reduce the uncertainties (scenario selection, leak and ignition probabilities …).

The overall outcomes of IEA HIA Task 19 are:

- Because of the specificities of hydrogen; specific ignition probability, low radiant heat… for instance, the use of off-shore or HydroCarbon Release database for hydrogen systems is irrelevant;
- But the database HIAD (Hydrogen Incident and Accident Database); established by HySafe; is a valuable tool to estimate the hydrogen-associated event frequencies.
- Oil and gas industries risk analysis reflects the importance of safety barriers. Hydrogen systems risk analysis should also reflect the importance of the safety barriers. Taking into account the safety barriers should be included as a best practice for risk assessment. Using fault and event trees can highlight the barriers' importance.
- For hydrogen applications safety barriers must: avoid releases, detect gas leak, remove ignition source and/or shut down and isolate part of the process.
- For the hydrogen applications, not only those with interface between public users and the technical system, have to include the public risk perception in the risk analysis and risk communication.
- The human factors and so the safety culture had to be integrated into risk assessment.

About the methodologies to carry out the risk assessment, QRA exercises stressed out the possibility to calculate the efficiency of safety barriers but full QRA is often too complicated in everyday practise and somewhat "unstable" because of the dependency of the final outcome from the inputs (cf. 5.0)[1] and assumptions. A qualitative approach would be more tractable and offers in addition the possibility to present the results in a consequence risk matrix where each scenario is represented as point into the matrix and can be easily compared to the others. Moreover the influence of mitigation measures can be efficiently illustrated. Task 31 of the same project pointed out again the need to adjust the traditional approaches and the leak, failure, ignition frequencies data and to tailor the risk assessment methods and the use of safety measures (prevention and mitigation) to fit hydrogen applications. Especially, the attention is drawn on the importance of evaluating the prevention and mitigations measures.

More recently a JRC report on hydrogen safety [24] identified the state-of-the-art and the knowledge gaps for hydrogen risk assessment, dispersion or combustion, etc. The report highlights that deterministic and engineering methods prevail over probabilistic methods and consequently are currently used for hydrogen safety of particular system or facility. They take over the conclusions of previous projects, i.e. the leak of hydrogen specific data available and the fact that even though the QRA is a useful tool, its application on a system, in the case of a full probabilistic QRA, could be a very expensive practise. Deterministic or probabilistic studies of parts of the system are preferred.

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[1] For instance, within the context of the project HyQRA, a benchmark exercise [21] was done in order to estimate the differences and similarities in the quantitative risk assessment methodology. In this paper, a summary (Table 5) of the adopted values for ignition probabilities for the consequence modeling showed that the probabilities vary considerably, for instance the "no-ignition" probability varies from $p = 0$ to $p = 0.85$, while using the same sources (i.e. the deliverable n°71 of HySafe [22] or the Purple Book [23]).

To conclude considering the new hydrogen technologies, a quantitative risk assessment should be too time-demanding and difficult to achieve because of the lack of information such as leak frequencies or ignition probability. A mixture of both might be proposed, producing a semi-quantitative analysis, closed to what is currently done in France. A semi-quantitative analysis would be less demanding than a quantitative risk assessment and the representation of results through a risk matrix is a better mean of communication.

3.0 TENTATIVE APPLICATION OF ARAMIS METHOD TO A HYDROGEN APPLICATION

This case study will help to illustrate the risk assessment methodology. This study focuses on a hydrogen-based energy storage system, the Greenergy Box^{TM} as showed in the Figure 1. The Greenergy Box^{TM} is a containerized hydrogen chain comprising an electrolyser, a fuel cell, a water and heat management, and electrical converter systems coupled with a hydrogen and oxygen storages installed aside of the container. The Greenergy Box^{TM} is an integrated modular system that can offer a power from 50 to 500 kW with a storage capacity from 0.2 to 2 MWh. Several systems can be coupled to increase the power and the energetic capacity.

The Table 5 presents the input data used for the next steps of the risk assessment.

Table 5. Input data for risk assessment.

Storage	Pressure	35	bar
	Volume of hydrogen	6	m^3
	Volume of oxygen	3	m^3
Pipe	Pipe diameter	9.5	mm
	Pipe length inside container	45	m
	Pipe length outside container	6	m
	Fuel cell pressure	9 to 2	bar
	Electrolyser pressure	40	bar
Container	Free volume	20	m^3
	Ambient temperature	288	K

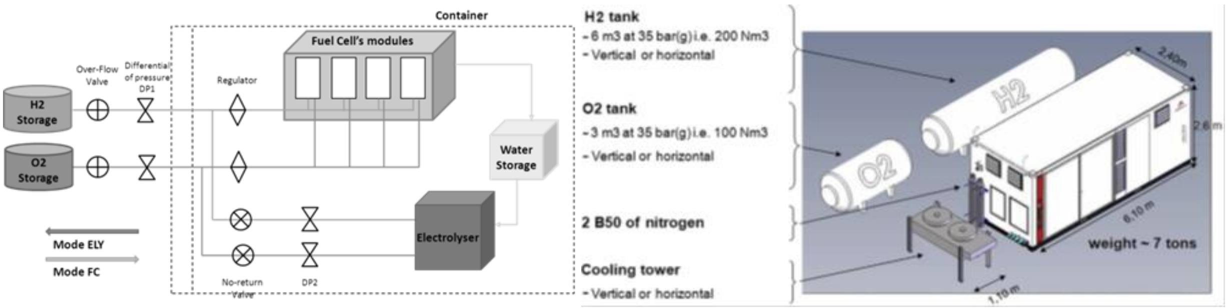

Figure 1. Illustration of the Greenergy Box^{TM} [25]

3.1 Identification of accident scenarios

The method used for the identification of the scenarios is based on MIMAH (. This intuitive method is composed of three steps:

- Selection of the potential hazards present in this application due to their properties (flammable, oxidant … or not) or their conditions of use (operation pressure for example). Here are considered three gases i.e. hydrogen; oxygen and nitrogen.
- For all of those substances, identification of the potential hazardous equipment i.e. pipes, pressure storage or process equipment (pump, physical separator, energy production equipment).
- Selection of the critical event, also called central event. According to the ARAMIS methodology, the central event is defined as a loss of containment; in this case, the central event is either the formation of an explosive atmosphere due to a leak, either the busting of equipment under pressure (collapse of a capacity) for the different hazardous equipment identified.

Table 6. Initiating and critical events and their associated phenomena.

Initiating event
Leak on a pipe
Rupture of a pipe
Failure of a component
Increase of the pressure
Sudden variation of pressure
Premature ageing of the membrane
Perforation of the membrane
Mechanical aggression
Natural aggression
Mechanical weakening
External fire
Human error (maintenance)

Critical event
Collapse of capacity
Formation of an explosive atmosphere

Hazardous phenomena
Jet fire
Explosion
Fire
Missiles
Blast wave
Flashfire
Fireball

For a breach or a leak, three size are considered as a percent or size of the diameter hole (values from ARAMIS project)

Size	*Breaches on containers*	*Leaks on pipes*
Large	*100mm*	*Full rupture*
Medium	*35-50mm*	*22-44%*
Small	*10mm*	*10%*

After the identification of critical events (Table 6), the bow-ties can be built associating the fault tree built using the initiating events (left part of Table 6) and the event tree built using the identified hazardous phenomena (right part of Table 6). For each critical event (depending also on the hazardous substances and equipment), a bow-tie is associated (ex: Figure 2 is the bow-tie of a “small leak of hydrogen into the container” scenario). At this stage, the safety barriers are inserted in the bow-tie and are represented by vertical bars (see Figure 2).

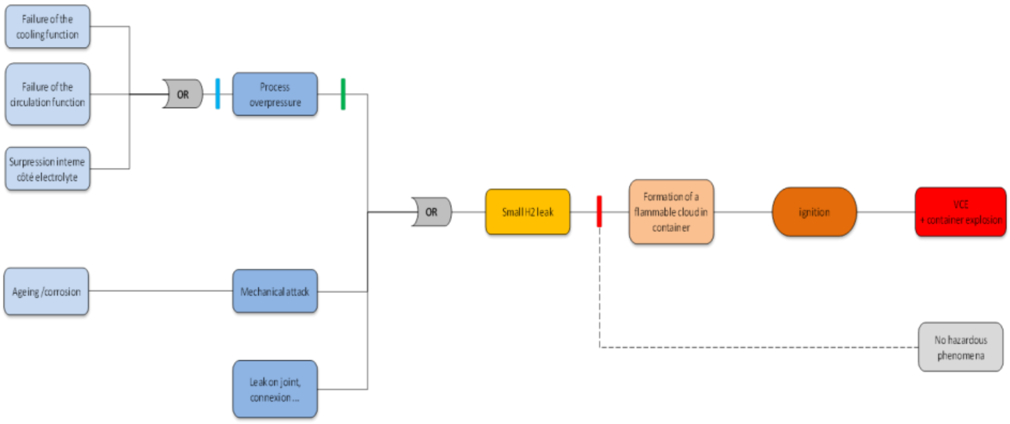

Figure 2. Bow-tie of “small leak of hydrogen in the container” scenario

3.2 Selection of the reference scenarios

For the selection of reference scenarios, a method similar to MIRAS (calculation of the frequencies and estimation of the consequences) can be used. Nonetheless some changes must be taken into account; the ARAMIS methodology had been created to evaluate the risk of major accidents on industrial sites and is not specific to hydrogen.

The frequencies are estimated via the bow-tie diagrams and taking into consideration the safety barriers. Due to the lack of information about event frequencies or ignition probabilities, some assumptions had been made:

- Ignition probability is equal to 1 (ignition happens in all of cases)
- For the initial event frequencies, orders of magnitudes are used instead of precise values ($f_{(\text{small leak})} = 10^{-5}$; $f_{(\text{large leak})} = 10^{-6}$ [26]; $f_{(\text{valve failure})} = 10^{-2}$ [27]), as well for the critical event frequencies. Such a choice can qualify the method used as a semi-quantitative risk assessment.
- Only the fully developed dangerous phenomena are taken into account (conservative)

Given the ignition probability equal to 1 and the lack of information about the explosion and/or jet fire probabilities in the case of hydrogen ignition, the frequencies of the hazardous phenomena will be equal to the frequencies of the critical events. This is of course an accepted and conservative approach for a risk assessment since the worth case will be considered (largest distances of effects). For the assessment of the consequences, the definition of the four classes differs from the ARAMIS method due to the size of the object studied (here the Greenergy Box^{TM}). In this case, the borders of our system corresponds to the footprint of the whole system i.e. the container and the storage area (Table 7). Using such classes for the assessment of the consequences illustrate the choice of a semi-quantitative risk assessment.

Table 7. Definition of consequences class used in the case of a containerized hydrogen application.

Ranking	Definition
C1	Light effect inside
C2	Moderate to Important effect inside, no effect outside
C3	Important effect inside and light effect outside
C4	Important effect outside, leading to dominos effects

The consequences of the different events are assessed according to the feedback given by international online databases: HIAD [28], BARPI [29] or H2tools.org [30]. Accidents related into those online databases can give some idea of the severity of the selected events like, for example the following accidents extracted from the H2tools.org database, “Water Electrolysis System Explosion” [31] or “Small Fire in Fuel Cell Test Stand” [32].

For instance between a large and a small leak into the container not only the frequency will change but also the class of consequences because the mass flow rate of the leak (i.e. also the quantity of hydrogen released into the container) will also differ. This is also true when the operation pressure change from 35 barg (ELY process pressure) to 2 barg (FC process pressure); the mass flow rate at 2 barg is twenty times smaller than the mass flow rate at 35 barg. Those differences will lead to different levels of consequence.

Knowing the frequencies F and the classes of consequences C of each critical event (identified scenario) are possible to put those one into the risk matrix (Fig. 3 and Table 8) and consequently to determine the reference accident scenarios which are the following ones:

- Ignition inside the process (Electrolyser size)
- Ignition of an explosive atmosphere – storage

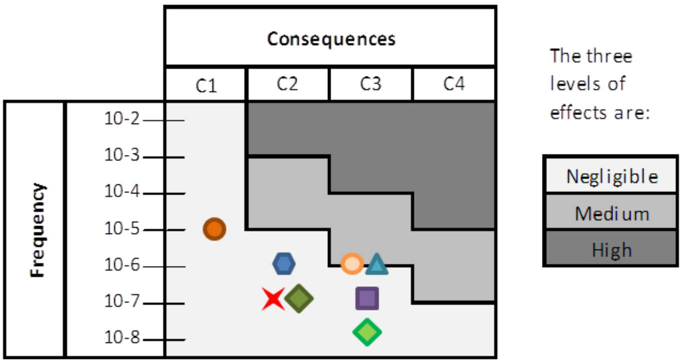

Figure 3. Risk Matrix

Table 8. Frequencies and classes of consequences of each identified scenario.

#	Symbol	Hazardous phenomena	F	C
1	◆	Ignition of an explosive atmosphere (large leak) – container	10^{-8}	C3
2	◆	Ignition of an explosive atmosphere (small leak) – container	10^{-7}	C2
3	●	Ignition inside the process (Electrolyser)	10^{-6}	C3
4	●	Ignition inside the process (Fuel Cell)	10^{-5}	C1
5	▲	Ignition of an explosive atmosphere – storage	10^{-6}	C3
6	■	Bursting	10^{-7}	C3
7	✕	Fire due to Oxygen	10^{-7}	C2
8	⬢	Fire with an electric origin	10^{-6}	C2

4.0 DISCUSSION

Thus ARAMIS methodology can be implemented on H2 applications. However, some limitations may jeopardize its usefulness.

In particular, the frequencies of the various events in the bow tie depend very much on the past experience of incidents, defaults or accidents. The available databases are either not relevant or too limited and may not represent the state of the art of the technology. This point is particularly crucial when a similar piece, such as valve, is used in a large number inside the same area. A valve for instance can leak. If then of them are used and if the individual frequency of a leakage is 10^{-4}/year, the total leak frequency inside the container is 10^{-3}/year. If the technology is such that the individual leakage is smaller or if the number of them is much less that ten, then the global frequency of the event “leakage inside the container” could vary by two orders of magnitude. This would depend very much on the architecture of the system and, to be fully operational, the fault-tree needs to be more detailed to accommodate this level of information.

A similar comment could be done about the classes of consequences. Available accident database is limited and may not represent the state of the art. For instance, the severity of the explosion (especially for hydrogen) is known to depend very significantly from the volume/turbulence of the atmosphere and thus from the size of the system and pressures. Consequence models may be used instead to account for the process and environmental conditions.

For example, the event n°5 is classified C3 for the consequences nevertheless the conditions of pressure of the Greenergy Box^{TM} are different from feedback. As shown hereafter, the distance for potential domino effects d3 (Table 9) calculated for the event n°5 (Table 10) is around 10 m and consequently potential domino effects on the container would have to be considered.

Table 9. Effects distances in function of the hazardous phenomenon and thresholds.

Distance	Explosion	Thermal (Fire)
d1	20mbar	1,8 kW/m²
d2	50mbar	3 kW/m²
d3	140mbar	5 kW/m²
d4	200mbar	8 kW/m²

In case of an ignition of a leak near or in the storage area (Table 10), the most likely event might be the ignition of a jet, resulting in a jet fire and in an explosion. The characteristics of the jet; considering a supersonic release; are a mass flow rate of 0.11 kg/s, after ignition the flame length is 7 m, the flame diameter 1.2 m and the distance to Lower Flammable Limit (LFL) is 1.1 times the flame length that is to say 7.7 m. The jet explosion is calculated considering the largest sphere into the jet. Given the fact this event happens in an open space (storage is outdoor); the index used for the Multi-Energy Method (index of explosion severity) is 6. For the thermal effects calculation, the percent of the radiation flux is equal to 30% (conservative calculation). No domino effects are possible with other capacities due to the presence of protection wall between capacities. The models used for the calculations are drawn from [33]

Table 10. Results of the effect distances for the event n°5.

Effect Distance	Jet Explosion	Thermal (Jet Fire)
d1	32 m	14 m
d2	16 m	11 m
d3	7 m	8 m
d4	5 m	6 m

Lastly, the question of the “safety barriers” is raised. Again a “strong” demonstration of the safety is required for hydrogen-energy. And this depends on the perceived efficiency of the safety barriers. The latter influences both the frequency of the critical events and, often, their consequences. It is known that limitations exist on both aspects. For instance, a safety barrier may reduce the frequency by two orders of magnitudes but rarely more [34], [35]. To make the demonstration, it would be better to start from the situation without barriers and then to add the barriers to demonstrate the performances.

On that specific point, three criteria need to be specifically addressed: the independency of the barrier against the scenario for which it is designed, the failure on demand rate (comparable to the Safety Integrity Level for automatic systems), the response time within the context of the scenario and the efficiency which measures the reduction of the consequences. Good practises were developed, even for human barriers [34], [35].

5.0 FUTURE WORK

As mentioned above, there is a lack of information concerning the hydrogen-associated probabilities. In one hand, Astbury and Hawksworth [36] compared ignitions of hydrogen releases with non-hydrogen releases. They showed that on 81 incidents inventoried for hydrogen releases, all of them ignited (4 of them were delayed ignition) in comparison with non-hydrogen releases (around 1440 releases) where 1.5% of them did not ignite. In other terms, the ignition probability is equal to 1. The difference might come from both the low minimum ignition energy (17µJ for hydrogen) and the large flammable range of hydrogen (from 4%vol. to 75%vol in the air).

In another hand, into the project HyQRA leads to the following conclusion about the ignition probability which varies from $p = 1$ to $p = 0.15$, while using the same sources. Feedback can be a mean to improve the gaps such as the ignition or leak probabilities. A work through the feedback from accidents and incidents, done via online database as BARPI [28], ODIN/HIAD [29] or H2incidents [30] created by the international hydrogen safety community, will permit to highlight the sequence of events leading to accidents and so to calculate most realistic probabilities.

6.0 CONCLUSION

Using and adapting the ARAMIS method permits to use a demonstrative method and to incorporate and to take into account the safety barriers. Indeed the ARAMIS method, based on an approach by barriers which can be defined as an approach that identifies of all conceivable major accident scenarios and inventories of all safety equipment or barriers impeding the development of an accident, proposed a systematic methodology of identification and selection of scenarios and also the generic calculation of the frequencies via the bow-ties.

However due to and considering the quantity and size of hydrogen applications (often below 100kg), the ARAMIS method should be modified. First such an application can not lead to major risk, due to as previously mentioned the quantity of hydrogen involved. Secondly the current databases (of frequencies and consequences), often extracted from off-shore or hydrocarbons databases, are unsuitable for the hydrogen applications. And finally the central character of the barriers is not sufficiently rested on, and particularly the assessment of efficiency (level of reduction) of the safety barriers.

Future works should be done on the calculation of the frequencies via a generator of probabilities with more detailed bow-ties and the establishment of a specific database to hydrogen gathering information on initiating events probabilities (ignition probabilities for example). Before a work on the criteria evaluation of the barriers, should be effectuate in order to assess their influence on both frequencies and consequences. For example the evaluation of the barriers can be based on the evaluation of independence of barriers and the probabilities of failure on demand. Finally the calculations of the effects should also review in order to have a better estimation of the consequences knowing the conditions of use.

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