THE INFLUENCE OF H_2 SAFETY RESEARCH ON RELEVANT RISK ASSESSMENT

Ustolin, F., Song, G., Paltrinieri, N., and Berto, F.
Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology NTNU, S.P. Andersens veg 3, Trondheim, 7031, Norway, federico.ustolin@ntnu.no

ABSTRACT

Hydrogen is a valuable option of clean fuel to keep the global temperature rise below 2°C. However, one of the main barriers in its transport and use is to ensure safety levels that are comparable with traditional fuels. In particular, liquid hydrogen accidents may not be fully understood (yet) and excluded by relevant risk assessment. For instance, as hydrogen is cryogenically liquefied to increase its energy density during transport, Boiling Liquid Expanding Vapor Explosions (BLEVE) is a potential and critical event that is important addressing in the hazard identification phase. Two past BLEVE accidents involving liquid hydrogen support such thesis. For this reason, results from consequence analysis of hydrogen BLEVE will not only improve the understanding of the related physical phenomenon, but also influence future risk assessment studies. This study aims to show the extent of consequence analysis influence on overall quantitative risk assessment of hydrogen technologies and propose a systematic approach for integration of overall results. The Dynamic Procedure for Atypical Scenario Identification (DyPASI) is used for this purpose. The work specifically focuses on consequence models that are originally developed for other substances and adapted for liquid hydrogen. Particular attention is given to the parameters affecting the magnitude of the accident, as currently investigated by a number of research projects on hydrogen safety worldwide. A representative example of consequence analysis for liquid hydrogen release is employed in this study. Critical conditions detected by the numerical simulation models are accurately identified and considered for subsequent update of the overall system risk assessment.

1.0 INTRODUCTION

Hydrogen is considered a clean fuel and could replace the fossil fuels in order to reduce environmental pollution. Potentially, its combustion produces only water and heat if the flame temperature is controlled or a catalyst burner is adopted. Moreover, hydrogen has a specific energy value (119.93 MJ/kg [1]) higher than other commercial fuels such as gasoline or natural gas. Despite these and other advantages, hydrogen is considered a dangerous fuel mainly due to its flammability and low ignition energy (0.017 mJ in air [2]). Hence, when the transportation and utilization of hydrogen is considered as an appropriate option, the safety aspects should be accurately evaluated and taken into account. Hydrogen has, in fact, a low density at normal temperature and pressure (0.0838 kg/m^3 at 293 K, 101.3 kPa bar [3]) compared with other fuels. Liquefaction increases the hydrogen density (70.9 kg/m^3 at 20.4 K, 101.3 kPa [4]) and this is why liquid hydrogen (LH_2) can be considered both for storage and transportation. In the case of road transportation, a truck with a tube trailer of compressed gaseous hydrogen can be filled with 300-400 kg of hydrogen at 200-250 bar, while a truck with a vacuum insulated tank can hold up to 3.5 tons of LH_2 [5]. On the other hand, when LH_2 is used, different hazards and related scenarios should be considered. Some of these have not been fully understood or forecasted yet.

Hydrogen is already widely used in several applications such as chemical industry (63%) and refineries (31%) for several processes [6]. In the last sixty years, hydrogen has been employed in the aerospace industry both as propellant [7] and to power fuel cell systems in order to produce electric energy [8]. For this purpose, hydrogen is stored in liquid phase. Usually, hydrogen production and utilization take place within the same industrial facility. This choice is driven by safety, logistic and economic aspects [6]. Both hydrogen production and consumption are expected to grow in the next years [9] mainly thanks to the energy storage capability of hydrogen coupled with renewable energies. In this case, the hydrogen safety aspects would become more important and atypical accident scenarios, that have not been considered yet for hydrogen, could arise.

Boiling Liquid Expanding Vapour Explosion (BLEVE) and Rapid Phase Transition (RPT) are two physical explosions as consequence of a loss of containment and these are two atypical accidental scenarios. BLEVE is a very well-known phenomenon for different substances such as water, propane, Liquefied Petroleum Gas (LPG) and Liquefied Natural Gas (LNG). It can happen immediately after a catastrophic rupture of *"a vessel containing a liquid (or liquid plus vapour) at a temperature significantly above its boiling point at atmospheric pressure"* [10]. This definition has been given since Jones [11] stated that a Liquefied Natural Gas (LNG) vessel explosion cannot be identify as a BLEVE. In [11], Liquefied Petroleum Gas (LPG) BLEVE has been described as term of comparison, in which the tank is already at a pressure well above the atmospheric one. According to Jones, the pressure of the vapor in equilibrium with the liquid should be enough to produce a loss of containment. The pressure increases once the tank is heated by an external source such as a fire. Hence, this increase in pressure is sufficient in the case of LPG and also water (autoclave) but not for LNG [11]. It should be mentioned that a BLEVE can also occur without a fire when the tank is punctured or a defect in the material is present [12]. And as reported above, the main condition needed to reach a BLEVE is the presence of a superheated liquid inside the tank before its catastrophic rupture, making it a reachable phenomenon even for cryogenic fluids. An RPT can occur if LNG is spilled onto water *"due to the sudden boiling or phase change from liquid to vapor, usually in a way that the LNG penetrates into and mixes well with water"* [13]. In the case of LH_2, it is not clear yet if and under which conditions these phenomena can occur, and which is the impact of their consequences. In [14], the authors described the RPT as a possible phenomenon for cryogenic fluids spilled onto water, not only for LNG.

Several projects on hydrogen safety have been performed in the last decades. However, some of these studies have not considered BLEVE and RPT, such as the HyRAM tool [15]. However, this does not mean these phenomena cannot happen for LH_2. In fact, the IDEALHY project has been focused on the LH_2 risk assessment, considering BLEVE among the potential consequences [16]. In a recent JRC report on hydrogen safety, it has been concluded that wide knowledge gaps still exist in hydrogen BLEVE/fire resistance among all the other considered areas [17]. Moreover, LH_2 RPT has been theoretically predicted in a few studies such as in [18]. On the other hand, RPT has never happened for LH_2, while three past LH_2 BLEVE accidents have been identified in this study.

The present investigation is a preliminary introduction to the "Safe Hydrogen Fuel Handling and Use for Efficient Implementation" (SH_2IFT) project. This is a Norwegian project coordinated by the research institute SINTEF, in which the safety aspects of both liquid and gaseous hydrogen are carefully investigated. In the case of the LH_2, BLEVE and RPT will be analyzed carrying out experimental tests and developing numerical models both to assess the formation and estimate the related consequences.

The aim of this work is to integrate atypical accident scenarios, such as LH_2 BLEVE, into the standard risk assessment of LH_2 technologies. The DyPASI technique has been used to update the hazard identification phase, while relevant operational conditions of the LH_2 tank were considered as preliminary input to the consequence analysis phase. In Fig. 1, the phases described above have been summarized by means of a graphical sketch.

Looking at this scheme, it is worth of noting that to apply the DyPASI technique, other tools such as MIMAH (Methodology for the Identification of Major Accident Hazards) and MIRAS (Methodology for the Identification of Reference Accident Scenarios) are necessary. Furthermore, all the results obtained in this study will be confirmed during the SH_2IFT project (dashed lines).

In Section 2.0, the methodology employed in this work is described and in Section 3.0, the results of the consequence analysis are reported. The results have been discussed in Section 4.0.

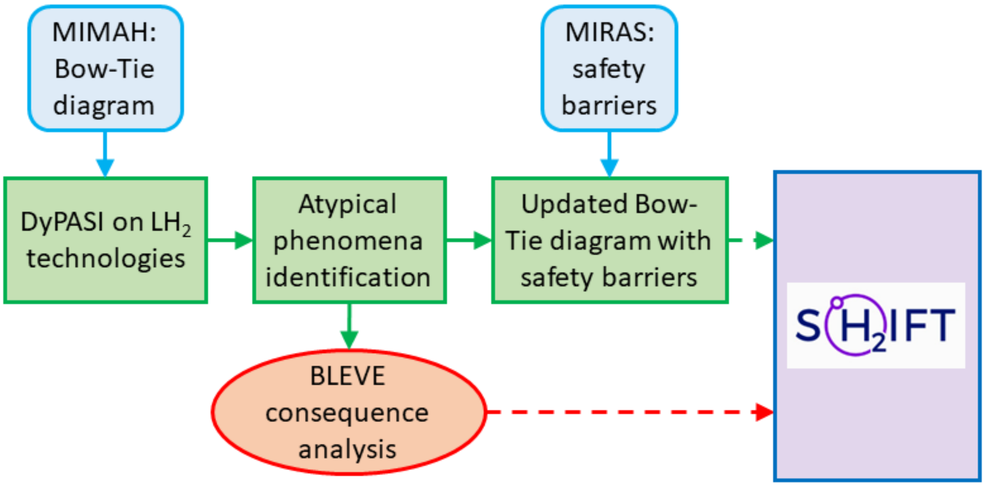

Figure 1. Scheme of the phases followed in this study. Dashed line indicates the results will be confirmed during the SH_2IFT project

2.0 METHODOLOGY

In Fig. 2, the green boxes show a generic risk analysis process. If the risk analysis is carried out for emerging technology, there are some limitations during the hazard identification and consequence analysis phases. The results from the application of DyPASI and the consequence analysis to the emerging technology can be used as integration of the traditional risk analysis. These integrations are represented by the blue boxes in Fig. 2, and these are connected by a double arrow since they influence each other.

Hydrogen is usually considered as an emerging technology [19]. For this reason in this study, DyPASI has been applied to LH_2 technologies following the methodology reported in [20] and a LH_2 BLEVE consequence analysis has been carried out. The results of this study aim to be used as updates of a risk analysis on hydrogen technologies.

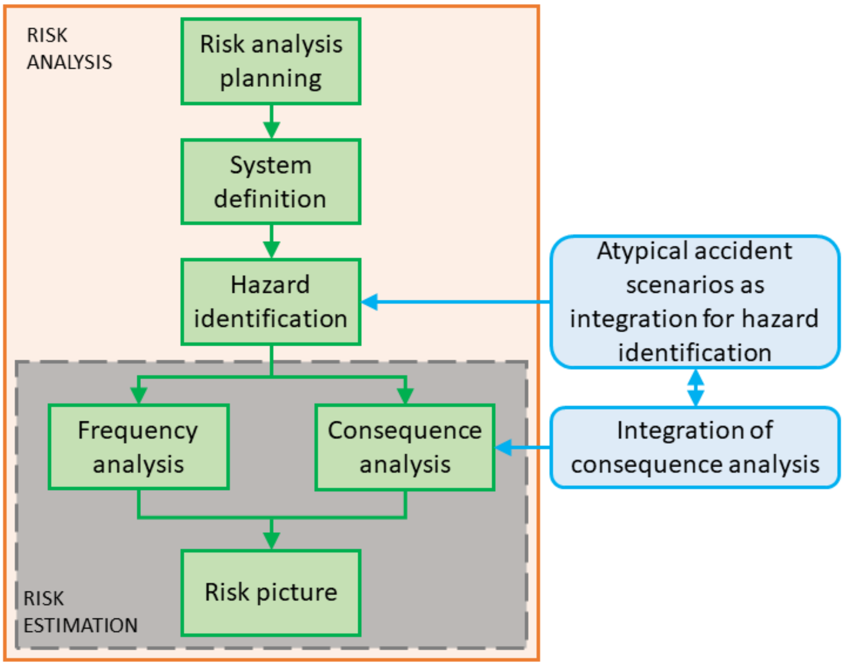

Figure 2. Integration of atypical accident scenarios and consequence analysis in a typical risk assessment

In the following, DyPASI and its procedure are briefly described. Furthermore, the methodology adopted to carry out the LH_2 BLEVE consequence analysis has been reported.

2.1 Integration of hazard identification: application of DyPASI technique to LH_2 technologies

DyPASI is a hazard identification technique usually coupled with a Dynamic Risk Assessment (DRA) in order to update it taking into account atypical accidental scenarios which are not considered by traditional hazard identification processes [21]. MIMAH methodology has been used to develop the conventional bow-tie diagram used as input of the first DyPASI step [22]. DyPASI procedure is structured in different steps and these are described in Table 1. MIRAS methodology has been used to define the safety barriers for the atypical scenarios in the step 4 of DyPASI [23], [24].

Table 1. DyPASI procedure steps, adapted from [20].

Step	**Input**	**Output**	**Description**
0	Input to conventional bow-tie technique	Generic bow-ties describing potential accident scenarios	DyPASI needs a preliminary application of the conventional bow-tie technique to identify relevant critical events
1	Information from accident databases	Risk notions on undetected potential	A search for relevant information concerning hazards that may have not been considered in conventional bow-tie development is performed
2	Risk notions from step 1	Early warnings triggering further analysis	A determination is made as to whether the data are significant enough to trigger further action and proceed with risk assessment
3	Bow-ties from step 0 and early warnings from step 2	Bow-tie diagrams considering also atypical scenarios	Atypical scenarios are isolated from the early warnings; cause–consequence chains are built and integrated into the generic bow-ties
4	Integrated bow-ties from step 3	Safety barriers for the atypical scenarios	Safety measures are defined for the atypical scenarios identified

2.2 Integration of consequence analysis: LH_2 BLEVE

DyPASI technique can identify different kind of consequence scenarios of an accident but other tools are needed to estimate the entity and impact of these consequences. Hence, a LH_2 BLEVE consequences analysis has been carried out herein for this purpose.

The BLEVE consequences are the overpressure of the blast wave, the missiles (debrides formed after the vessel rupture) that fly away owing the explosion and the thermal radiation, if a fireball occurs due to an ignition source outside the tank, such as fire [25]. In the present study, only the evaluation of the overpressure of the blast wave has been considered.

The superheat limit temperature theory [26] assumes that the liquid contained in the vessel must be superheated, otherwise the yield of the explosion cannot be compared with a BLEVE. To estimate the superheat temperature of a substance, several formulas have been developed by different authors. One of the most common equation used is the one proposed by Reid [27]:

$$\mathrm{T_{shl}} = 0.895 \cdot \mathrm{T_c} = 29.66\ \mathrm{K}, \tag{1}$$

where T_c – critical temperature, K. Eq(1) is a simple formula that depends only on the critical temperature. According to Eq(1), the superheat temperature of hydrogen is 29.66 K. There are other methods to estimate the superheat temperature, but these are more conservative. Casal et al. [10] explained that this theory is valid only at small scale but not at large scale where a non-homogeneous distribution of the heat is always present around the vessel. Nevertheless, the superheat limit temperature is an important parameter because at this temperature the adiabatic energy transfer between the liquid and vapor interface reaches its maximum value [28]. In this study, the inputs for the estimation of the consequence analysis have been chosen in order to reach a temperature higher than 29.7 K inside the tank. Furthermore, a correlation between the hydrogen mass contained in the tank, its pressure and the yield of the LH_2 BLEVE has been searched. The mass and pressure of hydrogen are operational parameters, and in the case of a storage facility, they might vary during the day.

A representative BLEVE consequence analysis has been carried out using the software PHAST 8.11 developed by DNV-GL. In this software, a BLEVE is simulated as a standalone model, hence the simulation is not time-dependent. The chosen tank has a volume of 1 m^3, a cylindrical shape with a diameter of 1.13 m and 1 m of length. The elevation of the tank is 1 m over the ground. The tank contains hydrogen in both phases, liquid and vapor. Three different pressure levels, 9, 11.9 and 31.2 bar gauge (bar_g) have been chosen to simulate the BLEVE. The first pressure, 9 bar_g, is approx. 1.21 times 7.4 bar_g, that is the pressure at which the first pressure relief valve (PRV) of the LH_2 vessel opens [29]. The same approach is suggested in [30]. Then, the yield of the BLEVE have been estimated when the vessel has a pressure of 11.9 bar_g, which is a value close to the hydrogen critical pressure (12.96 bar). The burst pressure of the LH_2 tank has been estimated to calculate the yield of the BLEVE in case of PRVs failure without fire engulfment of the tank (cold BLEVE). In this case, the value of the pressure inside the tank before its failure is the highest compared with hot BLEVE. When the tank is exposed to fire, the tank material is subjected to thermal stress and the estimated bursting pressure has a lower value than the considered case. To evaluate the bursting pressure, the tank wall thickness has been calculated following the ASME Boiler and Pressure Vessel Code (BPVC) Sec. VIII [31]. This code is used to design also cryogenic vessels. Eq(2) is used to calculate the tank wall thickness, t:

$$\mathrm{t} = \frac{\mathrm{P \cdot R}}{\mathrm{\sigma \cdot e - 6 \cdot P}} = 2.76\ \mathrm{mm}, \tag{2}$$

where P – design pressure, psi_g; R – tank radius, mm; σ – allowable stress, psi; e – weld joint efficiency. In this case, the value of P is 107 psi_g (7.4 bar_g), R is 500 mm, σ is 20,000 psi for the AISI Stainless Steel 304 [32] and e is equal to 1. To estimate the burst pressure P, Eq(3) has been used [25]:

$$\mathrm{P} = \mathrm{P_0} + \frac{\mathrm{S_M \cdot t}}{\mathrm{R + 0.6 \cdot t}} = 3.22\ \mathrm{MPa} = 32.2\ \mathrm{bar}, \tag{3}$$

where P_0 – atmospheric pressure, MPa; S_M – mechanical strength of the material, MPa. In this case, P_0 is equal to 0.1 MPa, S_M value is 565 MPa for AISI Stainless Steel 304 [25]. Eq(3) has been used for LH_2 tank because it is applied for cylindrical vessels with the pressure ($P - P_0$) lower than 0.385 times S_M [25].

In [33], the authors distinguished a subcritical BLEVE from a supercritical. The difference is that in the subcritical BLEVE, the tank pressure is lower than the hydrogen critical pressure, while the opposite occurs in a supercritical BLEVE. The authors analyzed the two different BLEVE types in the near field and they attempted to predict the blast effect from different experimental tests. In this study, both sub- and super-critical BLEVE have been analyzed, since the hydrogen critical pressure is almost 13 bar and the initial conditions of the consequence analysis were 9, 11.9 and 31.2 bar_g as tank pressure.

To simulate the BLEVE using PHAST, it is possible to set the pressure inside the tank, the temperature of the substance and the bubble point. The mass of the substance contained inside the tank is not an input, hence, to reach its desired value the other conditions such as pressure, temperature and liquid mole fraction should be changed. When the substance is in the supercritical state, only the temperature can be varied to set the mass at fixed pressure. When the pressure is 11.9 barg inside the tank, the minimum and maximum values of the mass that can be reach are almost 26 and 40 kg respectively, due to the density of the vapor and the liquid at this pressure. For this reason, 26, 30 and 40 kg have been chosen as values of the hydrogen mass contained in the tank. In Table 2, the initial conditions of the different simulation have been collected.

Table 2. Initial conditions of the different BLEVE consequence analysis scenarios.

Tank pressure (bar_g)	**Mass (kg)**	**Temperature (K)**	**Liquid mole fraction**	**Liquid mass fraction**
9	26	31.3	0.33	0.64
	30		0.44	0.74
	40		0.71	0.90
11.9	26	33.0	0.05	0.08
	30		0.35	0.46
	40		0.97	0.98
31.2	26	43.0	0	0
	30	40.7	0	0
	40	36.7	0	0

3.0 RESULTS

3.1 Results of DyPASI application to LH_2 technologies

In the original bow-tie diagram obtained with the MIMAH tool, the catastrophic rupture of the cryogenic tank has been chosen as critical event. MIMAH suggests generic logic trees to build the bow-tie diagram. This methodology considers BLEVE as a domino effect, being the critical event of a secondary event tree.

In the following, a brief literature review on the LH_2 BLEVE accidents has been reported. In 1974, a LH_2 tank with a volume of 20,000 gal blew up as a result of an improper firefighting technique. The firefighters sprayed the vent stack with water in order to extinguish the fire. The water froze inside the vent stack sealing it. The remain hydrogen inside the tank warmed up, causing an overpressure with a consequent BLEVE explosion [34]. The main cause of the Challenger Space Shuttle disaster was an O-ring rubber seal failure installed in one solid rocket booster [35]. The lack of sealing allowed the hot gases to escape and be ignited. In this way, a flame was directed toward the external tank that contained the LH_2 and LOX vessels. The vessels breached and exploded due to the flame [1]. Prugh [36] identified this explosion as a BLEVE. Also Abbasi and Abbasi [37] confirmed this theory describing an accident occurred on 28th January 1986 at the Kennedy Space Centre, Florida (USA) where a tank containing 115 t of LH_2 exploded killing 7 people. In [38], another LH_2 tank explosion accidents has been reported. The accident dynamics was similar to the first explosion described before. In this case, a 9,000 gal LH_2 double walled tank exploded the day after a fire erupted on the controls end of the tank [38]. The day of the explosion, there was not presence of fire and nitrogen was injected in the tank in order to empty it. The vacuum valve was opened 35 minutes before the explosion since the pressure in the vacuum jacket was rising and the nitrogen purge was stopped since it was too slow [38]. In that study, a model to carry out the consequence analysis of this accident has been developed.

Applying DyPASI, with the available information regarding the three past BLEVE accidents, this phenomenon becomes an event in the updated bow-tie diagram. Moreover, in the fault tree “improper firefighting technique” has been added as an escalation factor, following the procedure used in the software BowTieXP. This escalation factor triggers the PRV failure, leading to internal overpressure.

In the updated bow-tie diagram, three safety barriers have been added by using the MIRAS methodology. These safety barriers are the “training” of the fire fighters and the “PRV” in order to prevent the PRV failures when the LH_2 tank is exposed to a fire and the increase in over-compression inside the tank respectively. The other safety barrier is the “blast walls”, usually utilized to mitigate the consequence of an explosion such as the overpressure of the blast wave. Only with the experimental tests that will be carried out during the SH_2IFT project, the effectiveness of these safety barriers will be properly estimated.

In Fig. 3, the updated bow-tie diagram is shown. The black branches form the bow-tie diagram developed using the MIMAH methodology, while the blue branches have been integrated after the DyPASI application. The red boxes in the figure are the safety barriers. BLEVE can be sub- or super-critical as mentioned in the Sec. 2.2. For this reason, the first branch of the event tree stated both types of BLEVE and the sub-critical BLEVE is indicated as BLEVE.

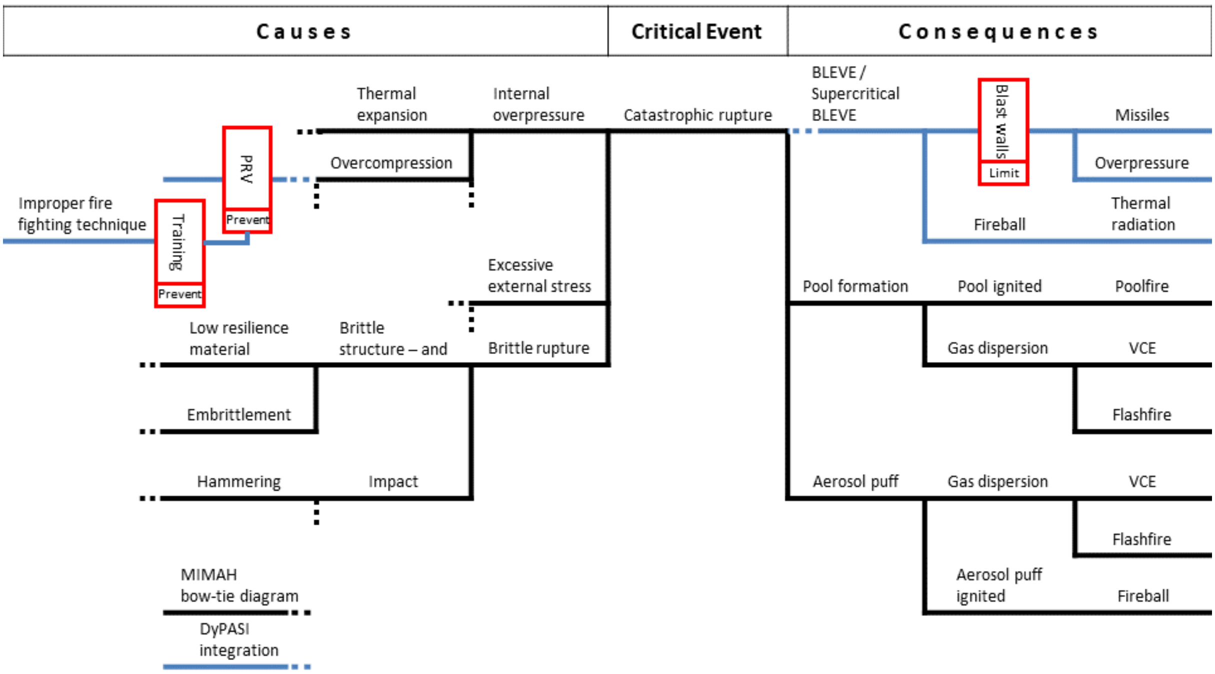

Figure 3. Bow-tie diagram updated with the DyPASI integrations (light blue dotted line) adapted from [20]. Safety barriers in red boxes to avoid the critical event or to limit the consequences

3.2 LH_2 BLEVE consequence analysis results

The results of the BLEVE consequence analysis obtained with the PHAST software are the overpressure of the blast wave at different distances and the overpressure radii. The latter indicates at which distance the overpressure has a value of 0.02068 bar_g, which is the lowest value considered. In the presented study, the same overpressure values considered by PHAST that correspond to 3, 2 and 0.3 psi_g (0.2068, 0.1379, 0.0207 bar_g respectively) have been analyzed. In the following, these values have been indicated as Overpressure 1, 2 and 3 respectively.

In Table 3, the results of the BLEVE consequence analysis have been collected. In particular, the estimated distances at which the 3 values of overpressure occurred have been reported.

As expected, when the hydrogen mass contained inside the vessel increases, the distance to overpressure increases as well. It is possible to note that the increase of mass influence more the distance when the tank pressure is 11.8 bar_g (+12.4 %). Instead, when the hydrogen is in supercritical conditions, the mass has a weak influence on the results of the consequence analysis. The worst-case scenario is the third one, when the tank pressure is 31.2 bar_g, equal to the estimated bursting pressure of the tank.

For the considered cases, it seems that the tank pressure has a higher influence than the hydrogen mass on the consequence results. Comparing the same amount of hydrogen (26 kg) increasing the pressure from 9 to 31.2 bar$_g$, the distance to overpressure increase up to 19.8 %.

These results will be confirmed during the SH$_2$IFT project when the experimental tests will be carried out to validate this model.

Table 3. Results of the BLEVE consequence analysis at different conditions.

Tank pressure (bar$_g$)	**Mass (kg)**	**Distance downwind to Overpressure 1 (m)**	**Distance downwind to Overpressure 2 (m)**	**Distance downwind to Overpressure 3 (m)**	**Increasing of the distance to Overpressure 1**
9	26	7.65	10.15	40.25	
	30	7.90	10.47	41.55	+3.2 %
	40	8.45	11.20	44.43	+10.4 %
11.9	26	8.38	11.02	43.31	
	30	8.74	11.49	45.14	+4.2 %
	40	9.43	12.39	48.71	+12.4 %
31.2	26	9.64	12.60	48.20	
	30	9.74	12.75	48.74	+1.1 %
	40	9.85	12.88	49.27	+2.2 %

4.0 DISCUSSION

The application of DyPASI to LH$_2$ technologies allowed to highlight a specific and atypical accident scenario such as BLEVE, not considered as direct consequence of the critical event but as a domino effect. In this study, the catastrophic rupture of a LH$_2$ tank was the only critical event that has been analyzed. Applying DyPASI to different critical events for LH$_2$, other accident scenarios could be identified. In [20], DyPASI has been applied to LNG regasification technologies and RPT, BLEVE, cryogenic burn, cryogenic damage and asphyxiation have been identified. These accident scenarios were not considered by MIMAH. A loss of containment of a LH$_2$ tank could have the same consequences. For example, frostbites and asphyxiation are already considered in [39]. There are no records on RPT after a LH$_2$ spill onto water. The probability to reach an RPT for LH$_2$ will be analyzed during the SH$_2$IFT project, together with the BLEVE phenomenon. It has been demonstrated that the combination of the results from the employment of the DyPASI technique with those from the standard application of MIMAH allows to capture the accident scenarios related to emerging technologies.

5.0 CONCLUSIONS

In this study, an atypical accidental scenario, such as LH$_2$ BLEVE, has been integrated into the standard risk assessment of LH$_2$ technologies. This has allowed by defining the appropriate safety barriers to avoid, control, limit or prevent causes and consequences of the critical events. With this aim, a preliminary consequence analysis has been carried out. The results of this analysis have showed that there is a clear correlation between the hydrogen mass contained in the vessel, its pressure and the distance to BLEVE overpressure. The tank pressure has been found to influence more the yield of the BLEVE explosion. This result represents the very first sound basis to design robust safety barriers. The suggested safety barriers and the results of the BLEVE consequence analysis will be confirmed and validated soon by the experimental tests that will be carried out during the SH$_2$IFT project which is now under progress.

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