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Natural Hazard Triggered Technological Accidents Risk Assessment for Liquid Hydrogen Storage Systems

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Abstract

Hydrogen technologies are progressively vital in transportation and industry, necessitating feasible and secure storage and transfer methodologies to exploit hydrogen's exceptional energy storage capabilities. As the lightest and most abundant element in the universe, hydrogen has garnered substantial attention as a prospective solution to global energy and environmental challenges. Its high gravimetric energy density and eco-friendly attributes as a fuel position it as a promising alternative to fossil fuels for green energy production, transportation, and energy storage from renewables. However, ensuring the safe and efficient utilization of hydrogen remains a critical concern for its widespread and sustainable integration into energy solutions. Despite its higher gravimetric energy content compared to conventional fuels, liquid hydrogen (LH2) presents challenges and safety concerns, particularly in cases of accidental releases that could be triggered by natural hazards. This paper explores the ramifications of natural disasters on technological systems, specifically focusing on the potential risks and consequences of incidents involving LH2. It delves into historical incidents and adopts a literature review, with data on incidents related to gaseous hydrogen being available, since information on liquid hydrogen incidents caused by natural events is scarce. Understanding the intersections between natural disasters and liquid hydrogen storage facilities is vital for enhancing disaster resilience and fortifying LH2 storage systems. Key element to achieve this gain in disaster resilience is to adress risk. Therefore, a framework for risk analysis is presented and andaped for a case study, taking into account the lack of evidence-based data. Ultimately, this research endeavors to contribute to comprehensive disaster preparedness and resilience in the context of LH2 storage facilities and systems.

Keywords: liquid hydrogen, hydrogen storage, natural hazard, consequences of natech events

1. Introduction

Hydrogen technologies are playing an increasing role in transportation and industry. Feasible and safe hydrogen storage and transfer concepts are key for exploiting the great energy storage capacity of hydrogen. Hydrogen, the lightest and most abundant element in the universe, has garnered immense attention as a potential solution to address the growing energy and environmental challenges of the world. Its exceptional gravimetric energy density and environmentally friendly properties when used as fuel make it a promising alternative to fossil fuels for green energy production and transportation. Hydrogen has a higher energy content based on the mass when compared with other conventional fuels. This gravimetric energy density is 120 MJ/kg and therefore much higher than the energy content of gasoline (44 MJ/kg) ("Hydrogen Storage," 2023). The volumetric energy density on the other hand, is much smaller for liquid hydrogen (8 MJ/l) in comparison to gasoline (32 MJ/l) ("Hydrogen Storage," 2023). Also, hydrogen can be used to store energy produced by means of renewables. Ensuring the safety of hydrogen production, transportation, storage, and utilization is a critical prerequisite for its widespread adoption in a sustainable energy future. Liquid hydrogen (LH_2) might be used to store and transport large quantities of hydrogen and to power different types of vehicles (e.g. trucks, ships). Due to its cryogenic properties (-253°C close to atmospheric pressure) ("liquid hydrogen – Rocketology," 2016), double-walled vacuum insulated tanks are required to keep LH_2 cold for long periods of time until further distribution or use is due. LH_2 serves as a versatile and efficient fuel in various applications. One significant role is as a rocket propellant. The combustion of LH_2 with oxygen produces water vapor as the primary byproduct, making it a clean and environmentally friendly option compared to some other rocket propellants. Apart from space exploration, LH_2 is also being explored as a potential fuel for ground vehicles. In this context, LH_2 can be stored onboard and used in fuel cells in gaseous form to generate electricity, with water and heat being the only byproducts. This is part of efforts to develop cleaner and more sustainable transportation options. Overall, the role of LH_2 as a fuel extends beyond those applications and can contribute to more sustainable and environmentally friendly energy solutions. Although, a broad knowledge on hydrogen safety exists, there is limited knowledge for certain phenomena related to LH_2. A main concern when handling hydrogen are accidental releases that can lead to damage on structures and injury to personnel due to fires, and explosions. Natural Hazard Triggering Technological Disasters (Natech) incidents refer to industrial accidents sparked by natural phenomena like hurricanes, floods, earthquakes, and tsunamis. Over recent years, the likelihood of these occurrences has risen, prompting researchers to delve into innovative risk analysis methods (Mesa-Gómez et al., 2020). This paper explores various natural disasters such as earthquakes, floods, hurricanes, and their respective impacts on technological systems. It examines specific case studies to illustrate how natural disasters can trigger technological accidents, leading to disruptions in critical infrastructure, public safety concerns, economic ramifications, and environmental damage. For the successful implementation of a hydrogen-based society, it is indispensable to develop an infrastructure of LH_2 maritime terminals (bunkering infrastructures) and tanker ships. Assuming, that LH_2 infrastructure is worldwide deployed, LH_2 facilities might be located in areas which are particularly at risk from natural disasters. The aim of this paper is to provide critical insights on Natech in case of LH_2 technologies with focus on LH_2 maritime terminals.

2. State of the Art of Natech and Hydrogen Technologies

In this section relevant findings on Natech events, hazards and the properties of hydrogen are given. Also, risk assessment and the corresponding initial steps are explained.

2.1. Natech Events

Technological accidents caused by natural hazards, leading to the release of dangerous substances, are termed as Natech events. These incidents are classified as infrequent yet high-impact events, deviating from conventional risk evaluation and control methods. The repercussions stemming from these Natech accidents, along with others of similar nature, have underscored the susceptibility of contemporary societies to these increasingly intricate disasters. Multiple research endeavors have substantiated the rising occurrence and gravity of Natech accidents (Lanzano, 2017) intensifying the urgency to gain deeper insights into and effectively handle such occurrences. Consequently, there is a growing concern to enhance comprehension and management strategies concerning these specific types of events (Cruz and Suarez-Paba, 2019). Natech accidents necessitate the confluence of both natural and technological hazards. The ensuing section delineates the distinctive attributes and classifications of these natural and technological hazards.

2.1.1. Natural Hazards

Natural phenomena have the potential to impact the structural integrity of industrial facilities, leading to detrimental outcomes such as physical harm, operational disruptions, and subsequent financial setbacks. Moreover, these events can trigger severe accidents by discharging energy or substances into the environment. Within this context, phenomena such as earthquakes, floods, lightning, tsunamis, storms (including hurricanes and tornadoes), as well as other natural occurrences like intense precipitation or extreme temperatures (heat and cold waves), are noteworthy due to their inherent hazard. This hazard refers to their capacity to cause significant harm and potentially overwhelm both industrial and public emergency-response systems. Addressing these concerns is a priority for public authorities and communities at large. Throughout human history, endeavors have been made to forecast the onset of these natural events, acknowledging their potential impact and the imperative need to anticipate and mitigate their consequences (Lanzano, 2017).

2.1.2. Technological Hazards

The United Nations Office for Disaster Risk Reduction, as outlined in UNISDR (2015), defines a technological hazard as follows: "*a hazard stemming from industrial or technological conditions, encompassing accidents, risky procedures, infrastructure breakdowns, or specific human activities. These hazards have the potential to cause fatalities, injuries, illnesses, property damage, livelihood and service losses, social and economic disruptions, and environmental harm* (Cozzani, 2017)." This definition explicitly acknowledges Natech hazards, arising from the impact of natural events on hazardous industrial installations like nuclear power plants or chemical processing and storage facilities. As previously discussed, the occurrence of natural events can lead to the release of hazardous substances due to process disruptions or structural failures, impacting plant personnel, the local population, properties, and the environment both within and beyond the affected area. In the context of Natech risk assessment, evaluating technological hazards aims to identify potential sources of adverse effects resulting from the release of hazardous substances following natural event impacts (Cozzani, 2017). This evaluation begins with assessing the hazard posed by equipment containing hazardous substances, irrespective of the triggering event. However, when confronted with natural hazards, various limitations arise, particularly concerning the structural capacity. This refers to the inherent strength of the system beyond anticipated or designed loads -the system's structural vulnerability to natural events- an essential consideration in Natech risk assessment (Cozzani, 2017). When considering Natech risk, determining the hierarchy of potential technological hazards involves assessing process and storage equipment based on three fundamental criteria (Cozzani, 2017):

1. Evaluating the danger posed by the substance or combination of substances and the quantity present (whether stored, produced, or transported) within the specific unit or equipment (Cozzani, 2017).
2. Examining the physical state of the substances housed within the equipment (Cozzani, 2017).
3. Assessing the equipment's vulnerability to structural damage in the event of a natural occurrence (Cozzani, 2017).

2.2. Characteristics of Hydrogen

Effective storage of hydrogen plays a pivotal role in establishing an adequate hydrogen infrastructure. Various methods exist for storing hydrogen, with pressurized gaseous hydrogen and liquefied hydrogen being the most prevalent forms. Additionally, alternatives such as metal hydrates or organic liquid hydrogen carriers (LOHC) are also viable options for hydrogen storage. The high volumetric energy density of liquid hydrogen (compared to pressurized gaseous hydrogen) makes it the preferred choice for storing significant amounts for long-haul transportation operations and large-volume terminal bunkering. One of the primary challenges associated with widespread hydrogen utilization is its exceptionally low density (0.0883 kg/m³ at standard atmospheric temperature and pressure (NIST Chemistry WebBook, 2023)), necessitating vast storage volumes. Consequently, hydrogen is either compressed or liquefied post-production. Liquid hydrogen (LH_2) boasts a density three orders of magnitude greater (70.9 kg/m³) compared to standard atmospheric conditions. Storing and handling LH_2 poses a significant challenge due to its extremely low temperature (-253°C at atmospheric pressure), rendering it one of the coldest cryogenic fluids (NIST Chemistry WebBook, 2023). In contrast to conventional fuels such as gasoline and natural gas, hydrogen exhibits higher energy content per unit mass, broader flammability range, lower minimum ignition energy and density, faster flame speed, and diffusion coefficient. Furthermore, hydrogen lacks odor, is colorless, and its flame might be nearly imperceptible in daylight. Table 1 presents a comparison of hydrogen, gasoline, and natural gas concerning some relevant hazard parameters (Vudumu, 2010).

Table 1. Relevant hazard parameters of hydrogen (Vudumu, 2010).

Relevant Hazard	Hydrogen	Natural Gas	Gasoline
Flammability limits in air (vol%)	4-74	5-15	1-7
Minimum ignition energy in air (mJ)	0.02	0.30	0.30
Stoichiometric flame speed (m/s)	2.1	0.4	0.3
Diffusion coefficient in air (cm^2 /s)	0.61	0.16	0.05

Within the scope of utilizing LH_2, several primary risk elements surface prominently. Firstly, the occurrence of spills and leakages emerges as critical events during accidents involving LH_2. Despite their relatively smaller scale and shorter duration compared to LNG (liquid natural gas) spills, the extreme low temperature of LH_2 (-253°C) necessitates specialized release models due to its higher density compared to compressed hydrogen (Ustolin et al., 2022). Secondly, both LH_2 and LNG exhibit potential explosion hazards. In particular LH_2 displays higher susceptibility to Deflagration to Detonation Transition (DDT) necessitating specific conditions such as hydrogen concentration above 12% (Ustolin et al., 2022) in air, presence of ignition sources, and turbulence-inducing obstacles. Thirdly, the combustion properties of LH_2, despite its wider flammability range, demonstrate unique characteristics. LH_2 fires exhibit higher flame speeds than LNG but burn for shorter durations. Additionally, both

LH_2 and LNG vapors ignite with weak thermal sources (Ustolin et al., 2022). Fourthly, careful material selection becomes crucial for LH_2 storage equipment to avert issues of low-temperature embrittlement. This necessitates the avoidance of carbon steels, known to succumb to embrittlement in LH_2 environments (Ustolin et al., 2022). Fifthly, potential explosion phenomena such as Boiling Liquid Expanding Vapor Explosions (BLEVE) and Rapid Phase Transitions (RPT) require attention. While BLEVE can occur due to vessel ruptures containing superheated liquids, the occurrence and characteristics of RPT in LH_2 remain ambiguous, warranting LH_2-specific experimental tests (van Wingerden Kees et al., 2022a). Lastly, the risk associated with the condensation or solidification of air components (nitrogen and oxygen) due to LH_2's extremely low temperature stands as a unique safety concern, unlike LNG, which exhibits a boiling temperature higher than that of air. Overall, the implementation of LH_2 technologies necessitates careful consideration of these various risks, emphasizing the need for tailored safety measures, extensive risk assessment, and ongoing investigation into potential emerging hazards especially when it comes to Natech events (Ustolin et al., 2022).

2.3. Interaction of Natural Hazards and Hydrogen

A Natech event arises when a natural hazard intersects with facilities containing hydrogen or with the hydrogen substance itself. Concerning the risk posed by natural hazards affecting a liquid hydrogen tank, potential outcomes include leakage or damage to insulation. Additionally, the boil-off gas (BOG) might lead to risks associated with tank pressurization and ignition. Natural hazards such as earthquakes, strong winds, and flooding possess the potential to cause significant harm to a large-volume liquid hydrogen tank. Earthquakes have the capability to compromise the tank's structural integrity. Strong winds and floods may carry debris that can inflict damage upon the tank. Moreover, depending on the tank's filling level and consequent weight, flooding and strong winds might displace the tank, potentially resulting in damage. Lightning during inclement weather poses a risk, particularly if there is preexisting hydrogen leakage or if the lightning ignites the boil-off gas released through the vent mast. Additionally, unrelated fires stemming from natural hazards, when near the tank, could cause damage and prompt a rapid pressure surge due to the insufficient heat resistance of the tank's superinsulation.

The repercussions of a Boiling Liquid Expanding Vapor Explosion (BLEVE) can be severe and historically have resulted in fatalities due to the impact of blast waves, the generation of fragments, and, if the contents are flammable, the occurrence of a highly radiating fireball (van Wingerden Kees et al., 2022b). BLEVE incidents involving flammable liquids have been observed for various fuels, including liquefied natural gas (LNG), the effects of which have been studied by Betteridge and Phillips (Betteridge and Phillips, 2015). The BLEVE phenomenon has been extensively investigated and reviewed in several works (see, for instance, Center for Chemical Process Safety (CCPS, 2016)). Consequently, contemplating a BLEVE scenario involving a vessel containing liquid hydrogen (LH_2) becomes essential. Nonetheless, experimental examinations of LH_2 BLEVEs have been notably limited. This lack of empirical data might be associated with the restricted use of liquefaction or the perception that an LH_2 BLEVE hazard was not plausible, given its storage at cryogenic temperatures and relatively low pressure. LH_2 is typically stored in double-walled vacuum insulated vessels, which have been shown in experiments to mitigate the likelihood of BLEVEs (van Wingerden Kees et al., 2022b). As of now, there have been no recorded LH_2 BLEVE incidents linked to natural disasters. However, a fire in proximity to a liquid hydrogen tank as an initiating event remains a plausible scenario. A self-ignition phenomenon was discovered during the SH_2IFT tests when LH_2 was released onto and into water. On the other hand, RPT (rapid phase transition) was not recorded during this test (van Wingerden Kees et al., 2022a).

2.4. Risk Assessment

The traditional method of quantitative risk analysis (QRA) can be adapted for Natech risk assessment. This adaptation involves expanding the QRA methodology to encompass specific equipment damage models and accounting for the potential occurrence of multiple simultaneous loss-of-containment incidents across different units, a critical aspect commonly seen in Natech accidents (Krausmann, 2017). While there are simple damage models accessible for select equipment types like storage tanks and certain process equipment, particularly for situations involving earthquakes, their incorporation into QRA case studies highlighted the significance of factoring in accident scenarios triggered by earthquakes (Krausmann, 2017). This revelation underscores the importance of ensuring the safety of not only the facility but also the surrounding population and environment. Hence, it's crucial to adequately consider natural hazards as significant contributors to risk at hazardous facilities within the risk-analysis process (Krausmann, 2017). Assessing Natech risks demands a substantial quantity of input data to assess how the natural hazard interacts with the industrial system and its potential outcomes. The subsequent list offers an outline of the data essential for Natech risk analysis (Krausmann, 2017):

1. Parameters indicating the severity of natural hazards which can cause potential for damage.
2. Identification of target equipment, prioritizing the most hazardous equipment types based on the quantity and nature of stored or processed dangerous substances, as well as the operating conditions of the equipment.
3. Understanding damage states resulting from the severity of the natural event, often accomplished through studies of past incidents or numerical modeling to correlate the intensity of damage.
4. Employing equipment damage models such as probit models or fragility curves, which establish the likelihood of damage concerning its intensity.
5. Utilizing consequence-analysis models to estimate the aftermath of a loss-of-containment event, including evaluations of substance concentrations (toxic release), heat radiation (fires), or overpressure (explosions).
6. Assessing the likelihood of occurrences by estimating frequencies, probabilities, or using qualitative assessments for all potential event combinations.
7. Gathering data on risk receptors, such as population distribution in the vicinity of hazardous installations, to comprehend potential impacts (Krausmann, 2017).

Empirical models for equipment damage, either developed or currently in development, have been partially derived from the examination of historical accident data. The primary constraint of this methodology lies in the lack of comprehensive equipment damage models, resulting in significant uncertainty. Further efforts in this realm are necessary to mitigate uncertainties inherent in both data and models used for analysis. Certain natural hazards, such as severe earthquakes or floods leading to Natech accidents, have the potential to simultaneously impact both on-site and off-site lifelines and utilities necessary for accident prevention and mitigation. The disruption of these utilities can initiate a Natech accident or impede emergency response measures aimed at mitigating its consequences. Consequently, adopting a worst-case risk-analysis approach seems prudent, wherein the scenario-building process for Quantitative Risk Assessment (QRA) assumes the failure of internal and external safety and mitigation measures (Krausmann, 2017).

3. Methodology

The study adopts a literature review approach conducted on 10.11.2023, analyzing relevant scientific journals and technical reports detailing technological accidents involving hydrogen caused by natural disasters such as lightning strike. The research methodology also involves the systematic collection and analysis of data, aiming to identify patterns, key factors, and implications associated with these incidents. Past hydrogen-connected accidents with natural disaster as triggering events were sought in the HIAD 2.0 database. An interface for the HIAD 2.0 database was used to filter possible accident causes related to natural hazards, or to environment in general (Campari et al., 2023). Additional research was performed by retrieving information from the Japanese source HGPS (High-Pressure Gas Safety Institute database) regarding natural hazard connected incidents with hydrogen refueling stations (Tzioutzios et al., 2023). The findings could then be applied to a specific case study such as the liquid hydrogen storage tank installed in the hydrogen terminal in Kobe, Japan. Different technical characteristics of the liquid hydrogen tank concerning the system-layout, components and capabilities of the liquid hydrogen terminal in Kobe are not publicly available. Therefore, it is currently challenging to perform an analysis on this case study without knowledge on previous accident scenarios. Although, assumptions were made regarding key components and vulnerability to specific natural hazards. Finally, a framework for a risk analysis for Natech events is provided and adapted to hydrogen related incidents based on the results obtained from the literature review on Natech accidents involving hydrogen technologies and the assumptions made on LH_2 components.

4. Results

This section will provide an overview of the existing data concerning Natech incidents involving hydrogen. Additionally, it will outline and explain the pertinent components found in liquid hydrogen terminals and the natural hazards that could affect a liquid hydrogen terminal at a specific site.

4.1. Historical Incidents

Records of natural hazard triggered accidents involving liquid hydrogen were not found. Although, information on such accidents involving gaseous hydrogen was found in different databases. A first revision of the accident-database HIAD 2.0 (Campari et al., 2023) has led to the conclusion, that there are only two incidents known where a natural event (weather lightning) has been a cause for a hydrogen-related accident. In both casas the scenario was an ignition of intentionally released hydrogen through a venting system. In the first case a chemical plant experienced a fire outbreak during a severe thunderstorm, originating at the top of the flare stack. This stack is utilized for releasing hydrogen produced during the reactivation of chlorine electrolysis cells. Despite the deliberate injection of steam and nitrogen to prevent ignition, the fire ignited. On-site firefighters promptly cooled the flare stack while technicians shut down the electrolysis cells to cease the hydrogen supply fueling the flames. These cells had been restarted after a power outage at the onset of the storm. The fire was successfully extinguished after about three hours, allowing for the restarting of the electrolysis unit (Campari et al., 2023). The introduction of steam and nitrogen aims to dilute the hydrogen stream and elevate the minimum ignition energy of the hydrogen-oxygen mixture. However, this strategy does not entirely eliminate the ignition risk as the hydrogen concentration remains above the minimum ignition level. Notably, a lightning strike at the flare stack proved sufficient to initiate the fire (Campari et al., 2023). In another instance, a mixture of hydrogen released via a venting pipe was ignited at a facility in Hamburg following a lightning strike (Campari et al., 2023). The gathered information is shown in Table 2. The table contains a description of the accident referring to what triggered the physical consequences. The state or phase of the released hydrogen is shown as well as the natural event that led to the full development of the consequence.

Table 2: Accidents listed in the HIAD 2.0 accident database (Campari et al., 2023).

No.	Description	Physical consequences	Hydrogen release type	Natural event
1	Ignition of hydrogen discharged through a venting pipe	Jet fire and explosion	Gas	Weather lightning
2	Ignition of a hydrogen mixture released through a venting pipe	Jet fires and explosions	Gas mixture	Weather lightning

Japanese sources (HGPS) (Tzioutzios et al., 2023) show three relevant incidents where refueling stations for gaseous hydrogen were effected. In all three cases shown, a failure in the pipework was the source of a hydrogen leakage. In two of the cases this was caused by earthquakes, in one case strong wind led to the failure of the structure. Only during the scenario triggered by strong winds an ignition happened and resulted in the development of a jet fire and explosions. Similarly, to the accidents found in the HIAD database, the events gathered from the HGPS database are collected in Table 3 following the same logic.

Table 3: Accidents listed in the HGPS accident database (Tzioutzios et al., 2023).

No.	Description	Physical consequences	Hydrogen release type	Natural event
1	Dispenser/pipe joint damage	Hydrogen leakage	Gas	Earthquake
2	Pressure relieve valve, Ignition during pipe discharge	Jet fire and explosions	Gas	Strong winds/Typhoon
3	Compressor pipework, joint failure	Hydrogen leakage	Gas	Earthquake

Based on the details of each incident, assumptions for similar scenarios with liquid hydrogen technologies are made. Weather lightning is presumably the most likely trigger for ignition of (intentionally or unintentionally) released hydrogen. Regarding liquid hydrogen, it is of high importance to note the different nature of the discharge due to the thermodynamic particularities. Liquid and gaseous hydrogen carry the potential for physical explosions which can occur even without an ignition source such as weather lightning. Natural events like earthquakes, floods and tsunamis are likely to damage large liquid hydrogen tanks resulting in a release and dispersion of different magnitude depending on the size of the leakage. However, an ignition source can cause fire and chemical explosions in all scenarios of a liquid hydrogen loss of containment. The knowledge gathered form analyzing past incidents and the properties of liquid hydrogen could enable to draw conclusions for safety barriers such as mitigative, procedural and preventive measures when considering the design of facilities such as the terminal in Kobe in the future.

4.2. Operation of Liquid Hydrogen Terminals and Vulnerability to Natural Hazards

The temperature differential between the stored liquid and the ambient environment inevitably results in heat transfer into the LH_2, leading to its evaporation. This vapor, known as boil-off gas (BOG), contributes to an increase in pressure within the storage tank, a process termed self-pressurization. To alleviate pressure buildup, venting of the tank into the atmosphere becomes necessary, albeit resulting in the loss of valuable hydrogen. This discharge maintains a constant temperature within the tank, a phenomenon referred to as auto-refrigeration (Verfondern, 2008). The rate of BOG generation varies depending on factors such as insulation quality and the tank's surface-to-volume ratio. For instance, a 50 m^3 cryogenic tank may experience BOG generation at a rate of approximately 0.4%vol/day, whereas a larger 20,000 m^3 LH_2 tank may experience a lower rate of around 0.06%vol/day (Verfondern, 2008). Furthermore, heat ingress causes the vapor temperature to rise more rapidly than that of the liquid, resulting in heat conduction across the vapor-liquid interface. This temperature disparity leads to thermal stratification within the liquid phase, where the interface exhibits a higher temperature than the bulk liquid (Kang et al., 2018). The phenomenon of self-pressurization is of significant importance in ensuring efficient LH_2 storage. When the pressure within the storage tank exceeds a certain threshold, it becomes imperative to release hydrogen to prevent overpressure and potential loss of integrity. Such a scenario could lead to catastrophic consequences due to loss of containment. Hence, the tank's design plays a pivotal role in determining the opening pressure of the relief valve. Furthermore, comprehending the dynamics of self-pressurization is crucial to mitigate hydrogen loss through boil-off, which translates to a loss of stored or transported energy. Armed with knowledge of self-pressurization, hydrogen can be extracted from the tank for conversion into electricity via a fuel cell or combustion in an internal engine. This extraction process may occur either just before the release of boil-off gas through the overpressure valve or continuously to maintain a specific pressure level. Moreover, predictive pressure adjustment techniques can be employed to establish optimal conditions during limited time periods when economical hydrogen utilization is not feasible. Modeling the pressurization process remains essential for obtaining a comprehensive understanding of the phenomenon. In cryogenic applications, insulation materials must fulfill several essential criteria to ensure optimal performance and safety. Fire resistance stands as a primary concern, necessitating insulation materials with properties that deter ignition and retard flame propagation in the event of a fire, thereby enhancing overall safety measures. Durability holds equal importance, requiring insulation materials to endure harsh environmental conditions and resist degradation over time to uphold their effectiveness and longevity. Cost considerations significantly influence decision-making, encompassing both initial investment and long-term cost-effectiveness. While initial expenses are noteworthy, assessing the overall cost-effectiveness of insulation materials throughout their lifespan is imperative, considering factors such as maintenance needs and potential energy savings. Thermal conductivity serves as a foundational characteristic directly influencing insulation performance. Materials with lower thermal conductivity are favored, as they effectively impede heat transfer, aiding in the maintenance of stable temperatures and minimizing heat loss in cryogenic settings. Cryogenic tanks, frequently employed for storing substances such as LH_2 or LNG, usually feature double-walled containers with insulation material placed between the outer and inner walls to reduce heat transfer. There are various insulation materials available for containing and storing LH_2, including Multi-Layer-Insulation (MLI), glass microspheres, aerogel, foams, and perlite. Among the most widely employed in mobile applications and smaller vessels is multi-layer insulation (MLI). MLI represents a type of insulation system comprised of numerous layers of thin reflective materials, each separated by spacers. These spacers establish voids or pockets of vacuum between the layers, thereby minimizing heat transfer via radiation. For instance, an insulation system might entail 70 layers of aluminum foils or aluminized polymers, interspersed with glass fibers or polymer spacers, resulting in an overall thickness of approximately 30 mm suitable for mobile applications like the automotive sector (Ustolin et al., 2022). Terminals for storing LH_2 in large quantities consist of multiple elements like storage tanks, transfer system including transfer lines, valves, and piping, (eventually cryogenic pumps), safety systems, control- and monitoring systems. This equipment can be described as critical equipment due to the fact, that it can be affected by natural hazards to trigger an Natech incident. Special attention should be paid to equipment that, in case of failure, carries the potential to cause a loss of containment (LoC). Table 4 shows each piece of equipment and its corresponding description and components.

Table 4: Relevant elements of liquid hydrogen terminals.

Relevant equipment	Description	Key components
Storage Tanks	Liquid hydrogen is securely stored within cryogenic tanks, insulated to maintain low temperatures, and prevent hydrogen evaporation.	Vacuum insulated storage tanks equipped with essential safety features like pressure relief valves.

Transfer system	Required to transfer LH_2 efficiently transferred from storage tanks to designated distribution points. This system ensures a dependable and regulated flow of liquid hydrogen to various users or transport vehicles.	Consisting of transfer lines (rigid or flexible), valves, and pressurization system including heat exchangers. loading arms. Eventually, cryogenic pumps might be utilized.
Safety systems	Due to its flammable nature, liquid hydrogen terminals integrate safety systems aimed at preventing and mitigating potential hazards. These include leak detection, fire suppression, and emergency shutdown systems.	Comprising safety sensors, alarms, safety valves, breakaways, emergency shutdown systems, fire suppression systems such as sprinklers, dikes, blast walls.
Control and Monitoring Systems	Advanced control and monitoring systems play a pivotal role in overseeing terminal operations, ensuring safety protocols, and optimizing overall efficiency by providing real-time data on various parameters like temperature and pressure.	Encompassing distributed control systems, supervisory control and data acquisition and safety instrumented systems

The Hydrogen Energy Supply Chain Technology Research Association (HySTRA) Liquid Hydrogen Terminal in Kobe is believed to be equipped with these components as well. The stationary storage tank is an essential element of the terminal. HySTRA aims at the distribution of hydrogen in liquified form by ship from Australia to Japan. However, due to the lack of detailed information regarding layout, capabilities, and risk assessment, assumptions must be made. Situated on the airport island in Kobe, the terminal faces potential risks from natural disasters. Its proximity to coastal waters increases the possibility of surges or tsunamis. Moreover, the region frequently experiences seismic activity in the form of earthquakes. Additionally, specific weather conditions like strong winds, heavy rainfall, and lightning also pose threats, albeit not site-specific. The terminal faces risks associated with Natech events involving liquid hydrogen, ranging from hazards due to cryogenic temperatures to potential fires, explosions, and material damage, including embrittlement.

5. Discussion

To date, there is only little data on Natech events involving LH_2 available. Also, regulations and standards are not widely defined. Some could be derived from petrol industries like the American Petroleum Institute (API). API 2003 "Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents" refers to a recommended practice which offers guidelines and recommendations to prevent and mitigate potential ignitions caused by static electricity, lightning, and stray currents in facilities associated with the refining, petrochemical, and related industries. This practice aims to enhance safety measures by providing strategies to manage and reduce the risks associated with such ignition sources in these industrial settings (American Petroleum Institute, 1998). Also, specific standards for hydrogen storage facilities were developed. For example, ISO 19880-1:2018 specifies requirements for the design, operation, maintenance, and safety aspects of hydrogen storage systems (Schneider et al., 2016). However, further research and regulations for Natech risk are necessary to be assessed sufficiently.

5.1. Risk Analysis

Fig. 1 shows the 9 steps for quantitative Natech risk analysis described by Antonioni et al. (Antonioni et al., 2007). In section 5.1.1 the in Figure 1 shown flowchart is explained in more detail. Furthermore, the contained information is projected on risk analysis for a liquid hydrogen terminal.

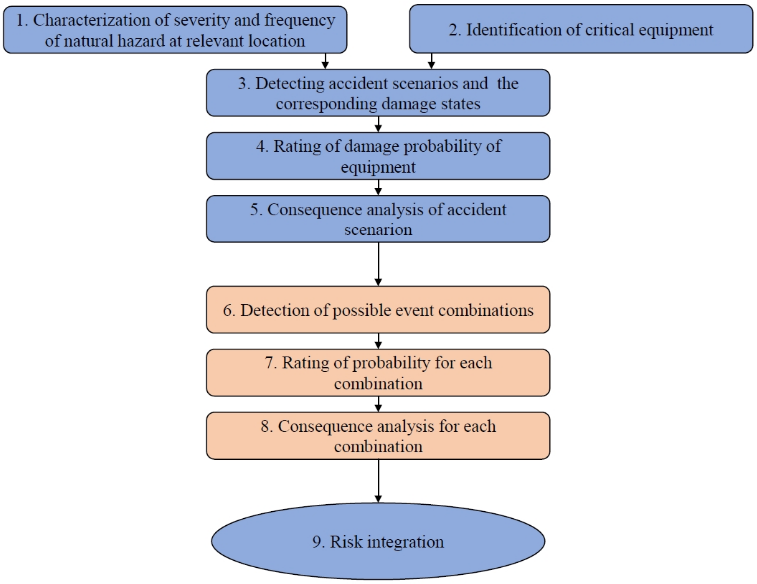

Fig. 1. Flowchart for Natech risk analysis (adapted from (Krausmann, 2017)).

5.1.1. Natech Risk Analysis for the Kobe LH_2 Terminal

A quantitative Natech risk assessment for the hydrogen terminal in Kobe would follow the steps outlined in the flowchart in Figure 1. Step one involves characterizing the relevant natural hazard in terms of its severity and frequency within the specific area, requiring substantial data on natural events in Kobe. In step two, critical equipment susceptible to natural events, potentially resulting in a Natech incident, is identified, and cataloged in Table 4 for an LH_2 terminal. Step three involves identifying potential accident scenarios and their corresponding equipment damage states. Step four estimates the probability of damage to this critical equipment, while step five delves into analyzing the consequences of these possible scenarios. Steps three to five are reiterated, focusing on various event combinations in step six, rating their probability in step seven, and conducting consequence analyses for each event combination in step eight. Step nine marks the integration of risks, estimating and visualizing the risk for each identified scenario (Krausmann, 2017). This methodology could be applied to LH_2 terminals such as the Kobe one developed by the HySTRA consortium previously described. However, a comprehensive risk analysis for Natech accidents at the Kobe site necessitates a wealth of additional data, particularly concerning critical equipment at the installation and information on natural events occurring in the area.

5.1.2. Safety Barriers

Following the risk analysis, a comprehensive risk evaluation can be executed, thereby concluding the risk assessment. Subsequently, measures for addressing risks may emerge. In the future, companies should benefit from Natech risk assessment through establishing safety berries for LH_2 storage applications. Safety barriers for facilities storing liquid hydrogen can either be mitigative or preventive in nature. Preventive measures aim to restrict the impact of natural hazards on the Kobe installation. Options include constructing tsunami protection walls or earthquake-resistant structures. Mitigative safety measures, on the other hand, aim to minimize consequences following a technological accident. Implementations such as pressure relief valves, sprinkler systems, or emergency protocols would be put into effect. These safety barriers must be tailored to the specific site's likely hazards. Collecting and assessing data on the type, severity, and frequency of natural events becomes imperative. A detailed risk assessment focusing on the accidental release of cryogenic hydrogen, encompassing contributing factors like vulnerabilities in technological infrastructure, human errors, regulatory gaps, and insufficient disaster preparedness measures, is essential. Future studies should focus on that in more detail.

6. Conclusions

Natural hazards may provoke accident scenarios that lead to the loss of containment of hydrogen storage equipment resulting in catastrophic consequences. Some of these may be exposure of structures and personnel to extreme low temperatures, fires, and explosions. The findings highlight the multifaceted nature of technological accidents triggered by natural disasters and the involved elements of storage facilities. Risk management is a key capability to ensure an effective utilization of liquid hydrogen technologies. Therefore, the process of risk assessment and risk analysis is adapted to Natech events in the context of LH_2 technologies. Although, more data is needed to provide a sufficient risk assessment. The study also emphasizes the need for measures to limit or eradicate vulnerabilities in technological systems such as large volume liquid hydrogen terminals and enhance disaster preparedness in the context of liquid hydrogen storage ultimately. This research aims to contribute to a better understanding of this critical intersection and provide recommendations for enhancing disaster resilience in technological systems.

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