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Monitoring approaches for safe road transport of hydrogen

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Reliability, Availability, Maintainability and Safety Engineering
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Preface

The thesis is part of the two-year international master's degree program in Reliability, Availability, Maintainability, and Safety (RAMS) Engineering at the Norwegian University of Science and Engineering (NTNU). This work is carried out under the supervision of Professor Nicola Paltrinieri and Dr. Federico Ustolin as the co-supervisor during the spring semester of 2022.

Executive Summary

Hydrogen is the most promising candidate for replacing fossil fuels as during combustion it does not produce carbon dioxide as well as it is abundant in nature and contains high gravimetric energy density. It has the potential to be employed as a low emission fuel in transportation sector, depositing electrical energy, heating, and cooling purposes etc. This has led to the necessity of reinforcing hydrogen economy by developing all four sections, production, storage, transportation, and application described in hydrogen value chain. Hydrogen can be stored in different states for instance, in liquid, compressed gaseous and solid forms as well as can be transported to the end users through tube trailers, railway or ship. Though hydrogen has undoubtedly excellent properties as a source of energy, it unfolds several safety issues during its storage and delivery process. Hence, safe and reliable infrastructure is needed to convey hydrogen since it connects the demand and supply of the gas. In this report, transportation of hydrogen in compressed gaseous form using tube trailers is studied since it requires the simplest infrastructure and has economic benefit over other options.

The thesis presents a detailed risk analysis for tube trailer transportation of compressed gaseous hydrogen and identifies the potential accident scenarios developing from the initiating events to the end consequences. Since the initiating events are the first indicators of deviation from normal operating condition within a system, technologies to instantly detect the deviation by studying performance of different components are reviewed in this study. This will lead to early identification of any dangerous deterioration within the system which can timely be handled, and major accidents can be prevented as well. Process safety indicators are also mentioned in this report for the monitoring technologies of the initiating events to ensure dual assurance. Since there is no guideline about what physical quantities/ parameters are to be supervised while transporting hydrogen through tube trailers, a monitoring strategy is recommended for MCE company based on this research work that can be adopted to establish a safe compressed gaseous hydrogen tube trailer delivery method. Finally, comparison between the monitoring approaches adopted for hydrogen tube trailer and LPG, CNG transporting vehicles is conducted to study the differences. Moreover, future scope of work in this regard is also suggested in this report.

Acronyms

ADR	European agreement concerning the international carriage of dangerous goods by road
AEP	American electric power
ARAMIS	accidental risk assessment methodology for industries
CE	critical event
CGH_2	compressed gaseous hydrogen
CNG	compressed natural gas
DOT	US department of transportation
DP	dangerous phenomena
EQ	equipment type
HRA	human reliability analysis
IE	initiating event
LH_2	liquid hydrogen
LOC	loss of containment
LPG	liquified petroleum gas
MIMAH	methodology for the identification of major accident hazards
RCS	risk control system
SCE	secondary critical event
STAT	state of substance
TCE	tertiary critical event
UE	undesirable event
VCE	vapor cloud explosion

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1 Introduction

1.1 Background

In this time of energy transition, hydrogen is an ideal alternative to the fossil fuels (Kovač et al., 2021). The advantages of hydrogen as an energy carrier are well-known: it does not produce CO_2 during combustion (Rievaj et al., 2019), it has a high gravimetric energy content (120.1 MJ/kg (IEA, 2019))and it can be found in abundance in nature (Moradi & Groth, 2019). Some of the physical properties of hydrogen are compared with the ones of other conventional fuels (methane, natural gas and gasoline) in Figure 1.1.

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Figure 1.1: Physical properties of hydrogen (IEA, 2019)

Hence, hydrogen can function as a very low emission fuel for the transportation sector, heating and cooling purposes, depositing electricity, and providing the opportunity of using stored hydrogen for transport application (Moradi & Groth, 2019). The notion of hydrogen economy is driven by this flexibility offered by hydrogen. However, due to hydrogen's unique properties, such as, its wide range of flammability, low minimum ignition energy, and high burning velocity (see Figure 1.1) several safety concerns are associated with all four stages of hydrogen value chain which are production, storage, transportation, and application of the substance (Frankowska et al., 2022). In addition, the dangerous consequences resulted from hydrogen release were realized while investigating the experimental test results performed with hydrogen in specialization project.

Figure 1.2 depicts hydrogen life cycle that begins with manufacturing hydrogen and ends at applying it in various fields. There are multiple options available for each section. For instance, both fossil fuels like, coal and non-fossil fuels such as water, biomass can be utilized as feedstock for the production process of coal gasification, electrolysis, and biomass gasification, respectively (Li et al., 2019). In fact, hydrogen is considered as low or zero-emission fuel if made from the abovementioned non-fossil fuels (Ustolin et al., 2020). Furthermore, since hydrogen has very low gas density (0.08833 kg/m^3 at atmospheric conditions (NIST, 2022)), various storage approaches such as, liquefaction, compression, solid state etc. of hydrogen gas are adapted to increase the storage capacity (Barthelemy et al., 2017). However, since materials for solid-state hydrogen storage are still under development, transportation of compressed gaseous hydrogen (CGH_2) and liquid hydrogen (LH_2) has more practical implications (Ma et al., 2021).

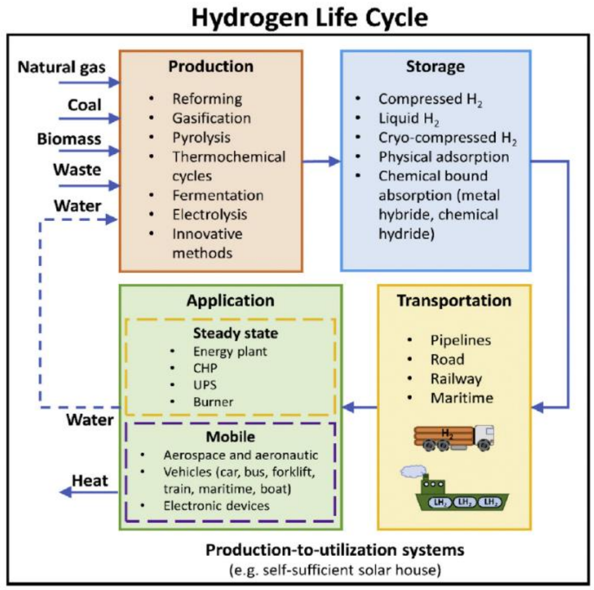

Figure 1.2: Hydrogen life cycle (Ustolin et al., 2020)

Thereafter, the hydrogen produced can be transported to the consumption sites via pipelines, trucks, trains, or ships which are also presented in Figure 1.2. However, the construction of pipeline supply network is a time consuming and costly job (Lowesmith et al., 2014). Besides, both the railway and maritime process includes transporting hydrogen in liquid phase (Ustolin et al., 2020). Energy loss during liquefaction of hydrogen is 300% higher compared to compressed gaseous form (Gardiner, 2009). Another difficult issue in cryogenic hydrogen storage is maintain the low temperature which is 20.3 K for LH_2 (Abohamzeh et al., 2021). Therefore, compressed gaseous hydrogen has become the most popular and common method for hydrogen storage and transportation system (Abohamzeh et al., 2021) since it requires the simplest infrastructure (Moradi & Groth, 2019) and can be transported via tube trailers, presented in Figure 1.3, which is an attractive and economical options (Reddi et al., 2018).

Figure 1.3: Tube trailer carrying CGH_2 (EERE, 2022)

The development of an efficient and reliable hydrogen value chain is required to reinforce the hydrogen economy and make this element one of the prime movers of the energy mix in future (Moradi & Groth, 2019). Along with the investment in production and the development of consumer markets, secured and effective infrastructure to store and transport hydrogen are also crucial elements (Gowdy, 2020). It is also a prerequisite to establish widespread use of hydrogen since it connects the supply and demand for the gas (European Commisison, 2020). Hence, this study focuses on the transportation section, particularly tube trailer transportation of CGH_2, of the hydrogen life cycle since failure of the pressure vessels can release all the stored hydrogen and can generate the highest consequences (Lasn & Echtermeyer, 2014). The study aims to provide a safe and reliable infrastructure by conducting risk analysis and investigating for the critical indications about the systems health so that different accident scenarios can be avoided.

To perform risk analysis for CGH_2 tube trailer transportation, relevant risks must be defined by answering three questions mentioned in (Kaplan & Garrick, 1981),

- What can go wrong?
- How likely is it to go wrong?
- If it does happen, what are the consequences?

The answer to the first question describes all the plausible accident scenarios that might arise while delivering hydrogen through tube trailers (Wall, 2011). The answer to the second question is the probability of the scenario whereas the third answer denotes the viable consequences resulted from them. However, in this study first and third questions are answered whereas the probability of the failure events are not assessed. The accident scenarios are determined by an initiating event (IE) and its path to a corresponding end result (Kaplan, 1997) . An IE is defined as a deviation from normal conditions that could, if not responded to in a correct and timely manner, lead to a hazardous event (Chisholm et al., 2020).

To achieve a complete risk picture of the CGH_2 tube trailer transportation technology, all the potential hazardous events and their primary causes are studied in this report. The causes leading to an accident can be classified into a small number of generic categories according to (Bubbico et al., 2016), which is demonstrated in Figure 1.4. For each of the general classes, additional subclass corresponds to the specific causes of a failure. For instance, third party activity includes failures due to any external mechanical interference conducted by third party operators. Specific causes of corrosion are degradation of the component material caused by external, internal or applied stress. When accidents occur due to defective maintenance operation or wrong replacement of a component, the failure origin fall into the category of operational/human errors (Bubbico et al., 2016).

Generic cause	Specific cause
Third party activity	Vehicles/other equipment not related to excavation activity
	Excavation machinery
	Heavy loads
	High-voltage electrical
	Shipping traffic in river
	Pipe resting on rock
Corrosion	External corrosion
	Internal corrosion
	Stress corrosion cracking
Mechanical failure	Ageing
	Construction defects
	Material defects
	Overpressure
	Supports failure
	Weld failure
Operational/human error	Decommission
	General operations
	Hot tapping
	Maintenance
	Pigging operations
	Pressure testing
	Repair/replacement
	Shutdown
	Start-up
	Valve operations
Natural hazard	Cold weather
	Erosion
	Floods
	Land slides
	Heavy rains
	Lightning
Equipment failure	Buckle in pipe
	Control system
	Flange
	Isolation valves
	Pumps/compressor
	Relief valves

Figure 1.4: Generic and specific causes of failure (Bubbico et al., 2016)

An important starting point for good safety assessment is a comprehensive analysis of the initiating events which have the potential to result in undesirable consequences (Chisholm et al., 2020). As a result, this study focuses on monitoring the initiating events so that any deviation from normal operating conditions can be reported instantly to prevent the development of accident scenarios. However, safety barriers are defined as physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents (Sklet, 2006). According to their function, barriers can be classified into two categories (Liu, 2020),

- Preventive/proactive barriers – It is used to reduce the likelihood of occurrence of the hazardous event.
- Reactive/mitigating barriers – It is used to minimize the consequences of any hazardous event.

Therefore, the monitoring techniques adopted for the initiating events act as preventive safety barriers while delivering CGH_2 using tube trailers. MCE AS is a production company, equipped with modern production facilities located in Etne municipality. MCE has extensive expertise in building large vehicles' bodywork, production and installation of steel structures and distribution of industrial gases such as, nitrogen, acetylene and oxygen. Moreover, the company intends to contribute to the clean energy market by providing transportation facility for CGH_2. In this study, state-of-the-art monitoring technologies are analyzed for the identified initiating events to recommend a strategy for the company since there is no specific guideline regarding this issue. This strategy can be employed during tube trailer transportation of CGH_2 in order to build a safe and reliable infrastructure to contribute to the emerging field of hydrogen economy.

1.2 State-of-the-art hydrogen transportation

Regarding transportation continuity, methods adopted for delivering hydrogen can be divided into two classes (Takahashi, 2009).

- Continuous transport
- Batch transport

1.2.1 Continuous transport

The only manner to achieve a continuous supply of hydrogen is through pipelines which can be employed for both compressed gaseous and liquid hydrogen (Takahashi, 2009). Typically, the pipelines are installed within the hydrogen production facility or until the hydrogen consumption plant. However, the length covered by the pipelines are short to limit the capital and variable costs required by the maintenance which is 550 km for compressed gaseous hydrogen (Takahashi, 2009) and 0.5 km for liquid hydrogen (Peschka, 1992).

1.2.2 Batch transport

The batch transport of hydrogen is conducted by storing it in vessels that are loaded onto mobile units such as, trucks, rail cars and ships etc. (Takahashi, 2009). The railroad is not commonly used to transport hydrogen due to unavailability of liquid hydrogen tank cars (Ustolin et al., 2020) . Similarly, ships for carrying liquid hydrogen for long distances are yet to be built. On the other hand, when road transport is adopted, hydrogen can be stored on board trucks in both compressed gaseous and liquid forms. Compressed gaseous hydrogen is transported using on board pressure vessels installed in the tube trailers for short distances, whereas liquid hydrogen is delivered by road tankers stored in a double walled tank for mid-range distances.

All the transportation methods of hydrogen with their respective storage techniques which are listed in Table 1.1. This also shows distance covered by each transportation method, storage pressure and hydrogen amount for each of the cases.

Table 1.1: Hydrogen transportation methods (n.a.: not available) (Ustolin et al., 2020)

Transportation method	Hydrogen storage method	Transport distance (km)	Pressure (bar)	Hydrogen amount
Pipelines	CGH_2	Up to 550	Up to 100	n.a.
	LH_2	Up to 0.5	Up to 7	n.a.
Road	CGH_2	Short distance	250	600 kg per truck
	LH_2	Mid-range distance	Up to 7	4 tons per truck
Railway	LH_2	$>10^3$	Up to 7	7 ton per rail car
Maritime	LH_2	Transoceanic delivery	Up to 7	60 ton per tank

It is mentioned in (Yang & Ogden, 2007) that the most suitable transportation method is selected based on the specific geographic and market characteristics (e.g., city population and radius, population density, size, and number of refueling stations and market penetration of fuel cell vehicles) of a territory and the selection of the state of hydrogen is influenced by multiple factors such as storage capacities, demand volumes, and transport distances. Since, transporting CGH_2 through tube trailers is considered in this report, state-of-the-art tube trailer transportation is presented further. Generally, a tube trailer consists of pressure vessels designed to store hydrogen at a rated pressure, packaged in a container, and mounted on it to transport CGH_2 from production site to the consumers (Reddi et al., 2018). Currently there are 5 types of pressure vessels, which are described in Figure 1.5.

Types of pressure vessels	Weight	Cost	Pressure
Type I: Full metal pressure vessels	Heaviest	the lowest cost	up to 200 bar
Type II: Steel vessel with a glass-fibre composite layer added around the steel	30–40% lighter than Type I	50% more than Type I	300 bar
Type III: Fully- wrapped vessels with composite and metal liner	70% lighter than Type I	about twice the cost of Type II	350–700 bar
Type IV: Full composite	80% lighter than Type I	Higher cost than Type I - III	up to 1000 bar
Type V: linerless fully composite pressure vessel	85% lighter than Type I	–	–

Figure 1.5: Different types of pressure vessels for hydrogen storage (Abohamzeh et al., 2021)

Type I vessels are the most traditional and heaviest ones, made from steel or aluminium (Abohamzeh et al., 2021). Type II vessels are manufactured from composite and metal which weighs 30-40% less than the previous one. Metal liner is used in Type III cylinders with a composite structure which makes it 70% lighter than Type I. Further improvements have been made in Type IV, which is made with carbon-glass composites or carbon fibres and can contain the highest amount of pressure. The modifications are still going on to develop Type V vessel, a linerless fully composite pressure vessel, which is still pre-commercial (LeGault, 2012).

Commercial tube trailers, mostly contain 12-20 long steel cylinders placed on the trailer bed following the regulations proposed by US Department of Transportation (DOT) (Yang & Ogden, 2007). Typically, a container carries nine tubes each with a volume of 91.8 ft^3 (Chen, 2010). The type of pressure vessels mounted on the trailer affect the maximum possible payload and hence the economics of hydrogen delivery (Reddi et al., 2018). Tube trailer with type I pressure vessels can transport up to 250 kg of hydrogen at pressures of 200 bar, while type III and type IV pressure vessels can transport up to 1000 kg of hydrogen at pressures of 500 bar.

1.3 Previous accidents

Hydrogen has been carried to different places as CGH_2 through tube trailers from the previous century and due to the hazardous properties of the substance several accidents have occurred. Some of the accidents associated with tube trailer transportation of CGH_2 are presented below.

In December 1969, improper purging procedure allowed oxygen gas to flow into a partially filled hydrogen cylinder installed on a tube trailer which resulted in a storage tube explosion (H2Tools, 2022). Initially an ignition occurred in the manifold which was followed by deflagration that eventually transitioned to a detonation rupturing the tube. The gas in the tube was estimated to have around 42 vol% hydrogen at the time of ignition, with the rest being oxygen. The far end of the tube was deformed, and the tube fragments were thrown quite far. A 20 kg piece of hydrogen tube was found 425 m away from the place of explosion. Besides, several employees of the facility suffered severe burns and other injuries from the accident.

Another accident happened in the Unites States on May 2001 when a tractor-semitrailer with horizontally mounted tubes filled with CGH_2 at approximately 166 bar collided with a northbound pickup truck (Lam et al., 2019). The tractor-semitrailer went out of control and left the roadway which resulted in the damage of the tubes, valves, piping along with the rear side fittings of the trailer. This caused the release of hydrogen gas that ignited apparently. The driver of the pickup truck received non-life-threatening injuries whereas the tractor-semitrailer driver died due to blunt force trauma.

In March 2003, an accident occurred in Italy involving multiple vehicles and a CGH_2 tube trailer on a rural highway (Pilo et al., 2005) . Figure 1.6 shows the tube trailer condition after the accident. This resulted in leakage in the hydrogen plumbing system and deformed one of the hydrogen tubes with a 10-centimeter longitudinal crack, depicted in Figure 1.7, from which hydrogen began to leak. The conventional vehicles which were trapped under the tube trailer caught fire and subsequently ignited leaked hydrogen along with the combustible components of the tube trailer such as, tires, fuel etc. However, there were no fatalities or injuries due to the accident.

Figure 1.6: CGH_2 tube trailer after the accident (Pilo et al., 2005)

Figure 1.7: Longitudinal crack on one of the cylinders (Pilo et al., 2005)

A hydrogen leak and subsequent explosion occurred due to the failure of fixing straps leading to the cylinders containing hydrogen gas at 200 bar fall of the tube trailer onto the road, illustrated in Figure 1.8, on December 2003 in Italy (Pilo et al., 2005). Tie-down strap weakness or error in properly securing it were assumed to be the probable causes of the accident. The event caused leakage to some of the cylinders and damaging the plumbing system as well. The released hydrogen ignited and caused explosion that damaged a car which was following the trailer and broke windows of a nearby house. Nevertheless, nobody was injured due to the accident.

Figure 1.8: CGH_2 cylinders fallen onto the road (Pilo et al., 2005)

One more accident occurred in Italy in February 2004 when a CGH_2 tube trailer, carrying hydrogen at 200 bar pressure, overturned on its side during runtime which broke valve of a single hydrogen tube (Pilo et al., 2005). The damaged tube was positioned on the bottom tier. The ignition status of the leaked hydrogen was uncertain. Also, no news of injuries or fatalities were reported.

Hydrogen gas explosion occurred while filling storage cylinders at the American Electric Power (AEP) Muskingum River plant in Ohio in January 2007. The explosion occurred after generating a loud noise similar to high pressure gas venting through a relief valve. Over pressurization of the rupture disk attached to the cylinders instigated hydrogen release which accumulated and form a large cloud that finally ignited and exploded. As a result of this accident, one fatality and nine injuries were reported (OSHA, 2022).

The consequences resulted from these accidents raised concern about the credibility of conveying CGH_2 using tube trailers on road and provoked the investigation of means to improve safety of the tube trailers. In this report, a framework regarding the monitoring of the initiating events is presented to be adopted for this particular case to establish a safe and efficient transportation system for CGH_2.

1.4 Motivation and objective

The main motivation behind this thesis is lack of a definitive guideline regarding what are the parameters to be monitored to provide instant detection of deviation from normal operating condition while transporting CGH_2 using tube trailers. Therefore, investigating the initiating events and the corresponding supervising technologies to provide critical information is a necessity to improve safety during hydrogen transportation. The thesis is dedicated to specifying the triggering events and the respective monitoring techniques so that early detection of any irregularities can be conducted to prevent the hazardous events. Hence the main objectives of the thesis are the following –

- Study all the potential accident scenarios and their corresponding initiating and end events to get a complete picture of the development of the accident scenarios.
- Study the cutting-edge monitoring methods of the initiating events. The report is intended to provide an overview of the techniques that can be used to supervise the performance of the components within the system.
- Suggest a strategy that can be adopted by the MCE company while transporting CGH_2 via tube trailers to ensure safe and reliable delivery process.

1.5 Scope and limitations

The thesis focuses on providing indication on the parameters to be monitored using right technologies so that any deterioration can be observed quickly to prevent accidents. This is only performed for tube trailers carrying CGH_2. Other means of transportation such as, pipelines, road tankers etc. and storage techniques like, LH_2 are not considered here. While performing the risk analysis, only hazard identification is done, and accident scenarios are developed. No indication about the probability of occurring a critical event is presented in this report. Besides, monitoring approaches for technical related issues, such as, mechanical failure, equipment failure and failure due to operational error are documented. Hence, studying monitoring techniques for human error is out of the scope of this thesis. However, only current monitoring technologies are reviewed in this report and no suitable equipment to supervise the initiating events are suggested for the company.

1.6 Report structure

The rest of the report maintains the following structure. Chapter 2 discusses the methodology used for identifying the accident scenarios, initiating events during tube trailer transportation of CGH_2. Chapter 3 is the main part of the report which contains the results of this study. The chapter discusses the findings of the risk analysis conducted for the particular case in detail. Overview of the current monitoring technologies for the initiating events are presented here. Also, this chapter contains the monitoring strategy recommended for the MCE company. Chapter 4 has the discussion part where the significance of the findings is presented. Chapter 5 concludes the study and lists future scopes in the subject area.

2 Methodology

Monitoring can be defined as any kind of acquisition or collection of data on a certain activity using technical devices, observation, or surveying methods to assess if targeted outputs are proceeding as planned so that timely corrective measures can be taken before the project is affected (FAO, 2006). In accordance with the definition, several technologies can be used to acquire information of the performance of the studied system to detect any deviation and thus helps to attain desire outcome by avoiding risks. For this purpose, the six steps of performance measurement described in (HSE, 2006) has been adopted as the methodology of the thesis work. Figure 2.1 depicts the steps with a brief description of each of the steps. These steps aid to develop performance indicators, by conducting risk analysis, which are essential to ensure that major risks are under control as early warning of dangerous deterioration within system provides an opportunity to avoid major accidents (HSE, 2006). The procedure of implementing these steps in the thesis is narrated further in this chapter.

Step 1	Establish the organisational arrangements to implement the indicators	Appoint a steward or champion
		Set up an implementation team
		Senior management should be involved
Step 2	Decide on the scope of the measurement system. Consider what can go wrong and where.	Select the organisational level
		Identify the scope of the measurement system: ■ Identify incident scenarios - wnat can go wrong? ■ Identify the immediate causes of hazard scenarios ■ Review performance and non-conformances
Step 3	Identify the risk control systems in place to prevent major accidents. Decide on the outcomes for each and **set a lagging indicator**	What risk control systems are in place?
		Describe the outcome
		Set a lagging indicator
		Follow up deviations from the outcome
Step 4	Identify the critical elements of each risk control system, (ie those actions or processes which must function correctly to deliver the outcomes) and **set leading indicators**	What are the most important parts of the risk control system?
		Set leading indicators
		Set tolerances
		Follow up deviations from tolerances
Step 5	Establish the data collection and reporting system	Collect information - ensure information/unit of measurement is available or can be established
		Decide on presentation format
Step 6	Review	Review performance of process management system
		Review the scope of the indicators
		Review the tolerances

Figure 2.1: Overview of the six steps to setting performance indicators (HSE, 2006)

Step 1 - This step is about setting up an implementation team engaging the management committee (HSE, 2006) which is closely related to industrial aspect rather than conducting an individual thesis. Therefore, this step is disregarded in this work.

Step 2 – While performing this step, performance indicators are selected from the plant organization level since it provides information about the system's design as well as inspection and maintenance of the operations conducted within it (HSE, 2006). Afterwards, methodology for the identification of major accident hazards (MIMAH) is applied to identify the major hazards susceptible to the studied system since it involves the development of fault and event trees based on the equipment type (EQ) and state of the substance (STAT) (Delvosalle et al., 2005). This method is mainly based on bow-tie approach which is depicted in Figure 2.2 (Salvi & Debray, 2006). The bow-tie is centered on the critical event (CE), the left part of it is named fault tree which identifies the possible causes of the CE, and the right part is known as event tree, which describes the viable consequences of the CE (Delvosalle et al., 2005).

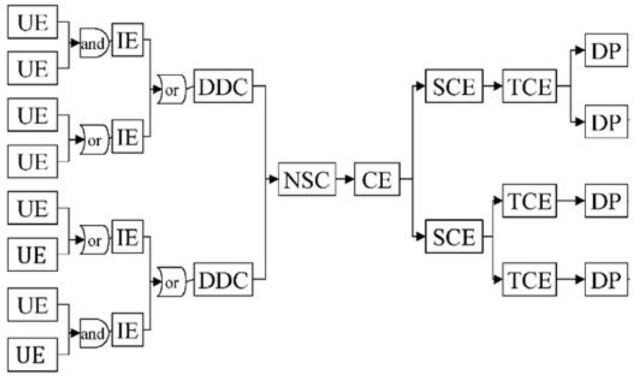

Figure 2.2: The bow-tie approach (Delvosalle et al., 2005)

To apply MIMAH methodology for hazard identification, it is necessary to analyze the system along with the equipment involved. The description of all the components used in a generic hydrogen transportation system is studied by analyzing (ISO, 2015).
Since the phase of the material and the typology of equipment is known for the system, guideline for building generic fault and event trees provided by accidental risk assessment methodology for industries (ARAMIS) project can be utilized. According to (Delvosalle et al., 2004a), critical events suitable for the system is selected by using two matrices given for equipment type and state of the substance handled. Thereafter, the secondary critical event (SCE) is determined with the help of the matrix linking the critical events and the state of the substance. The tertiary critical event (TCE) is retrieved by using the matrix developed for SCE and TCE in the report. Finally, dangerous phenomena (DP) are pointed out by studying TCE-DP matrix as well as keeping the hazardous properties of hydrogen in mind. The whole process of developing the event tree can be presented in a flow chart displayed in Figure 2.3.

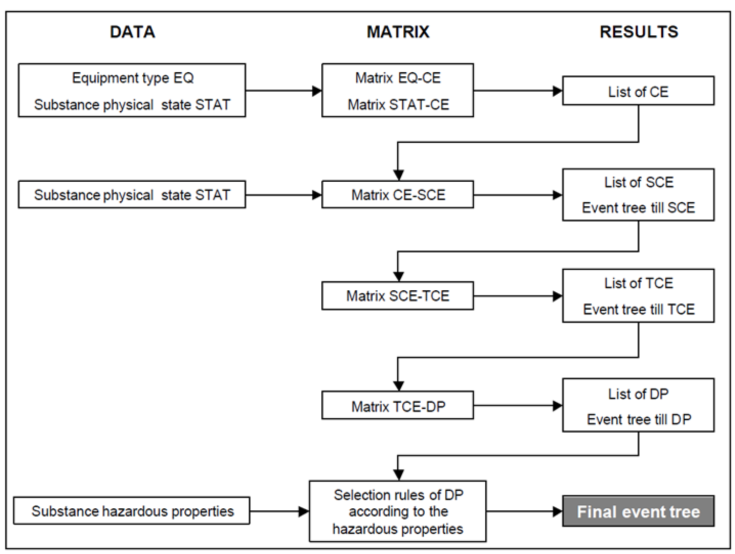

Figure 2.3: Summary of the steps for building event tree (Delvosalle et al., 2004a)

Furthermore, to develop fault trees for each of the critical events, generic fault trees provided by (Debray et al., 2004), are used as a guideline to know about the causes leading to the critical events. However, the fault tree analysis is performed only to know about the undesirable event (UE), related to the systems components, which are the root causes of triggering the critical events (Sakar et al., 2021). Thus, logical gates used to connect detailed direct causes, necessary and sufficient conditions in fault tree are not presented in the final bow-tie diagram of this study.

Step 3 – The state-of-the-art of the monitoring technologies for all the relevant undesirable events are reviewed which are regarded as risk control system (RCS). Besides, desired safety outcomes and lagging indicators for all risk control systems are recognized analyzing scientific literatures, technical reports, and suitable standards. Desired safety outcome is defined as successful prevention of hazard scenario by each risk control system. This outcome can be assured by introducing lagging indicator since it reveals weaknesses within the associated risk control system.

Step 4 - Leading indicator manifests the input that are necessary to deliver the desired safety outcome by the risk control systems. In step 4, leading indicator is set for each risk control system to ensure their continuous effectiveness. Both the leading and lagging indicators provide dual assurance by confirming that risk control systems are operating as intended and providing a warning when problems start to develop as well.

Step 5 and 6 - These two steps described in (HSE, 2006) are dedicated to documentation, availability and reviewing the work which is more logical to perform in an organizational level. Hence, step 5 and step 6 are not considered in this study.
By applying this methodology, process safety indicators for CGH_2 tube trailer transportation are determined which will assist in developing a safe infrastructure by providing critical information about the initiating events.

2.1 Case study

Road transportation of hydrogen is subject to the European agreement concerning the international carriage of dangerous goods by road (ADR) which provides regulations about the packaging and labelling of dangerous goods as well as construction, equipment and operation of the vehicle carrying them. In addition, the standards in ISO/TC 197 specifies directives in the realm of hydrogen production, storage, transportation, and measurement systems and devices. However, there are no indications on what should be monitored to ensure safe delivery of hydrogen. Therefore, this calls for the formulation of a guideline on the monitoring system of transporting hydrogen to receive information of any anomaly within the system.

To aid MCE company for transporting CGH_2 using tube trailers, different accident scenarios that can arise during road transport is investigated. To fabricate efficient monitoring approaches for the triggering events, a strategy is formulated based on the analysis performed using the methodology described in previous section. Besides, comparative study is performed to compare the monitoring approaches adopted for hydrogen trucks and other dangerous goods carrying vehicles.

3 Results

This report recommends a monitoring strategy for MCE company by discussing the system's components, accident scenarios and state-of-the-art monitoring technologies as well. In the beginning of this chapter, equipment involved in conveying CGH_2 via tube trailers is presented. Possible accident scenarios are described using MIMAH methodology and cutting-edge monitoring techniques for all the listed undesirable events are presented as well further in this chapter. Finally, a monitoring strategy is suggested for the company by introducing important parameters to observe for establishing a safe transportation system for CGH_2. These are presented elaborately in the following part of the report.

3.1 System description

In accordance with step 2 described in (HSE report), investigation is performed on the equipment involved in CGH_2 transportation. Figure 3.1 shows a schematic representation of CGH_2 delivery process where hydrogen is compressed by using a compressor and loaded into the storage vessels mounted on the tube trailer (Elgowainy et al., 2014) . The filled tube- trailer is then transported from the distribution gas terminal to the fueling station or other plants, where CGH_2 is needed. CGH_2 is then discharged from the tube-trailer pressure vessels and compressed further to store in a high-pressure buffer storage system.

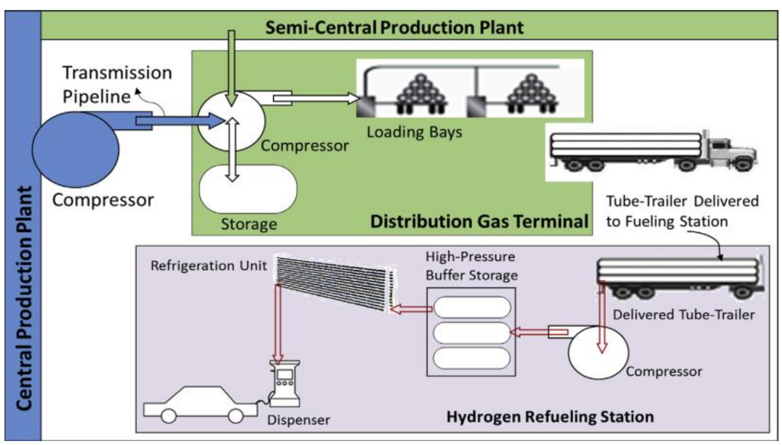

Figure 3.1: Schematic representation of compressed gaseous hydrogen tube-trailer delivery (Elgowainy et al., 2014)

According to (ISO, 2015), in a generic hydrogen system, there are primary and auxiliary components relevant for the intended application. For the system examined here, internal combustion engines perform the primary function for road transportation of CGH_2 and auxiliary components that provide essential support for primary functions are listed in Table 3.1. It is found that, storage vessel along with welded joints, pressure relief systems are relevant for transportation process whereas along with these components delivery pipes, flow control devices are used while transferring the gas in storage tanks. After the identification of the components involved in the considered hydrogen system, the MIMAH methodology was applied to determine the major hazards of the system.

Table 3.1: Equipment used in hydrogen transportation and transferring system

Hydrogen system components	**Description**
Storage vessel	The design, function, and applied construction materials of the storage vessels should comply with modern technology and reflect the type of service, for example, CGH_2 vessel.
Delivery pipes, joints, and seals	Piping used for transporting CGH_2 must satisfy the requirements described in (ISO, 2015). In case of joints, seals, welded joints are preferred due to hydrogen's high tendency for diffusion and permeation.
Flow control systems	A variety of mechanical components for instance, valves, check valves, regulators, pressure gauges, flow meters etc. are employed to control hydrogen flow while loading/unloading the vessels.
Pressure relief systems	In order to protect on-board storage vessel and piping against over pressure, pressure-relief valves and rupture disks are used within the system.

3.2 Identification of hazards within the system

To identify all the possible hazards and accident scenarios, MIMAH methodology has been used to investigate the critical events associated with the system. Event tree and fault tree are also formulated to comprehend the accident scenarios and undesirable events responsible for them respectively. The identified critical events, event trees and undesirable events are discussed in the following sections. The investigation done in this section meets the description of step 2: identification of the hazard scenarios mentioned in (HSE, 2006).

3.2.1 Identification of critical events

In (Delvosalle et al., 2004b), the on-board storage vessel and piping of the studied system is categorized as EQ 8: pressure transport equipment and the state of CGH_2 tones with STAT 4: gas mentioned in the literature. Studying the two matrices given for EQ 8 and STAT 4, illustrated in Figure 3.2, in total four critical events associated with the system are found.

EQ8	**Pressure transport equipment**
STAT4	**Gas / Vapour**

		CE 1 Decomposition	CE 2 Explosion	CE 3 Materials set in motion (entrainment by air)	CE 4 Materials set in motion (entrainment by a liquid)	CE 5 Start of a fire (LPI)	CE 6 Breach on the shell in vapour phase	CE 7 Breach on the shell in liquid phase	CE 8 Leak from liquid pipe	CE 9 Leak from gas pipe	CE 10 Catastrophic rupture	CE 11 Vessel collapse	CE 12 Collapse of the roof
Pressure transport equipment	EQ8					X	X	X	X	X	X		
Gas / Vapour	STAT4					X	X			X	X		
Results						**X**	**X**			**X**	**X**		

Figure 3.2: Critical events retained according to the equipment type and state of the substance (Delvosalle et al., 2004b)

The critical events which are suitable for on-board storage vessel and piping are listed in Table 3.2. The critical events presented here are generally defined as loss of containment (LOC) (Delvosalle et al., 2006).

Table 3.2: Critical events associated with considered hydrogen system

CE 5: The start of a fire
CE 6: A breach on the shell
CE9: Leak from gas pipe
CE10: Catastrophic rupture

3.2.2 The event tree

After establishing the critical events, matrices for constructing the event tree for each of the critical events are used. Besides, the risk phrase associated to hydrogen is also studied and it is found that risk phrase R12 is attributed to CGH_2 (Publications Office of the European Union, 2008) . R12 corresponds to the hazard statement H220 ‘flammable gas, hazard category 1’. Here, category 1 indicates that CGH_2 is extremely flammable. Figure 3.3 presents the event tree for all the critical events and depicts the sequential development of the consequences as well. From the event built for CE 5 which is the start of fire, it can be said that the dangerous phenomena for this case is fire. For both the critical events CE 6: Breach on the shell and CE 9: Leak from gas pipe, the same end events occur , immidiate ignition leads to jet fire whereas vapor cloud explosion (VCE)/ flashfire results from delayed ignition (Abohamzeh et al., 2021). CE 10: Catastropic rupture can result in overpressure and missile ejection since the vessel explodes. The released CGH_2 ignites and burns in the fireball or VCE/falshfire form.

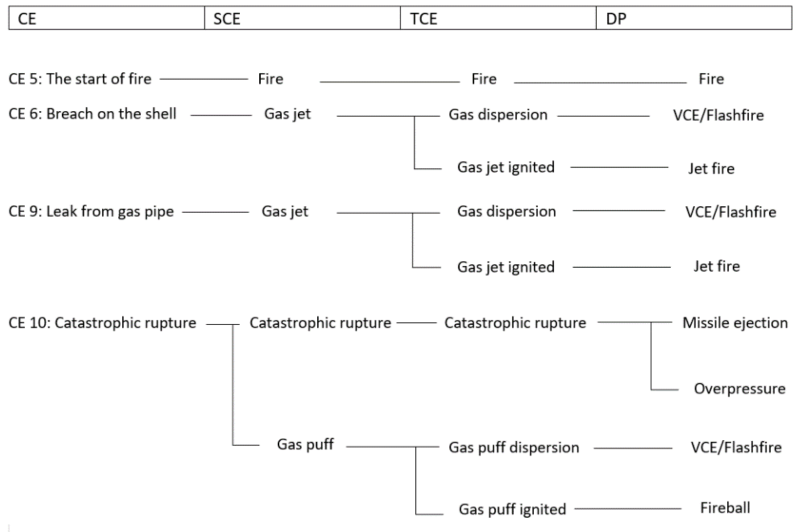

Figure 3.3: Event tree analysis of release of compressed gaseous hydrogen (Delvosalle et al., 2004b)

3.2.3 The fault tree

Fault tree analysis is conducted to find out the triggering events of all the critical events aiming to detect them using proper technologies in advance. The specific causes retrieved from (Debray et al., 2004) are grouped into six generic categories as per the description given in (Bubbico et al., 2016) which stimulates the understanding of the type of causes leading to the critical events. Table 3.3 depicts all the initial causes under suitable categories with which research is conducted further in this report.

3.2.4 The bow-tie diagram

After completing both the event tree and fault tree analysis of LOC of CGH_2 equipment while transferring and transporting it, the bow-tie diagram is generated, depicted in Figure 3.4. At the center of the diagram, four critical events, retrieved from (Delvosalle et al., 2004b) mentioned in Section 3.2.1, are placed. At the left of the bow-tie, only the generic classes of the undesirable events are presented whereas on the right side dangerous phenomena caused by unintentional release of CGH_2 are shown. This bow-tie diagram provides a quick review of the generic causes which results in the critical events. It also describes all the possible outcomes that might arise due to the LOC of CGH_2 components.

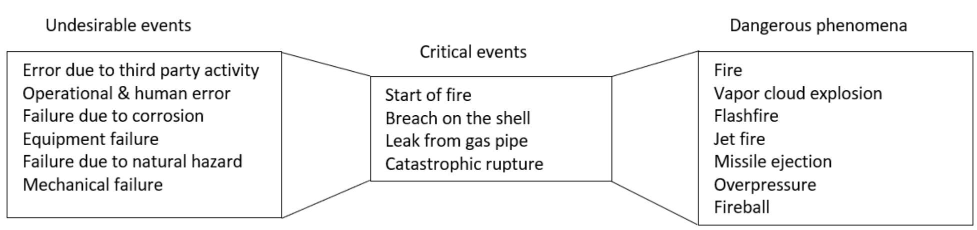

Figure 3.4: Bow-tie diagram of LOC of CGH_2 equipment

Table 3.3: Generic and specific causes of the critical events

Third party activity	**Operational/human error**	**Corrosion**	**Mechanical failure**	**Natural hazard**	**Equipment failure**
Error ordering the product	Human error	Corrosive environment	Design fault	Natural causes (snow, wind etc.)	Compressor overspeed
Delivery error	Lacking/defective maintenance	Corrosive product	Badly designed procedure	Earthquake	Blockage in pipeline
Inappropriate labelling of the product	Forgotten material	Stress related corrosion	Internal flammable mixture	Cold weather	Pressure regulation fails
Inappropriate labelling of the storage	Installation error		Presence of ignition source	Erosion	Incorrect sensor signal
Wilful disobedience	Conception error		Overfilling		Safety valve failure
Dangerous driving	Abnormal use conditions		Transmission error		
Contamination	Interpretation error		Hydrogen cracking sensitive material		
Manufacturing error	Lacking/deficient checking procedure		Wrong welding procedure		
Obstacles on the way	Human error in setting temperature target		Unauthorized welding		
Malicious intervention	Valve opened in wrong direction		Lacking/defective protection		
Wrong substance introduced	Wrong valve opened		Aging		
Substance introduced in the wrong form/ratio	Flow stop control not accessible				
Bad quality due to transport/storage	Flow stop control difficult to operate				
Bad quality delivered	Presence of fine material				
Electrical failure	Substance has too much speed/turbulence				

3.3 Human reliability analysis

Human reliability analysis (HRA) identifies various types of human errors that can occur in each activity, as well as the variables that may cause them, and to offer ways to reduce human mistakes (Morais et al., 2022). Maintenance, installation, driving the vehicle, operating different components are some of the tasks that require human involvement while transporting and transferring CGH_2 and so subjected to human errors. For the considered CGH_2 system, relevant mishaps done by human are listed under the categories named 'third party error' and 'operational/human error' in Table 3.3 which includes mistakes such as, wrong operation of valves, setting incorrect temperatures for the pressure vessel, defective maintenance work, bad driving, ordering wrong product etc. According to (ISO, 2015), human error is the primary cause of accidents with hydrogen systems. So, special consideration must be given to HRA of CGH_2 system.

However, HRA is a multidisciplinary approach which requires knowledge of psychology, medicine and engineering field to analyze the reliability of a human operator (Ciani et al., 2022). Therefore, monitoring of human errors is extremely complex and belongs to a different research field which is out of the scope of this thesis work. Therefore, in this report no further work is accomplished regarding this field.

3.4 Monitoring technologies

To perform step 3 described in (HSE, 2006), risk control systems which are the cutting-edge monitoring technologies of the specific causes are reviewed. In case of natural hazards for instance, snow, wind or adverse weather condition, forecast is known in advance and so can be avoided efficiently. On the other hand, successful prediction of earthquake is still a study area, making it difficult to suggest any system to inspect this (Yousefzadeh et al., 2021). Since CGH_2 is stored at 298K (Hjeij et al., 2022) and it is assumed that it is operating within the designed stress limit, the effect of corrosion is neglected as well. Therefore, three generic classes, equipment failure, mechanical failure, and failures due to wrong operation of the components are investigated. State-of-the-art monitoring technologies are studied for the specific causes under these categories to facilitate early detection of deteriorating performances. Furthermore, desired safety outcome and lagging indicator for each of the risk control system are mentioned as per the requirements of step 3. Besides, leading indicator for the selected risk control systems are determined as well according to step 4 indicated in (HSE, 2006).

3.4.1 Contamination

Hydrogen stored in the on-board pressure vessel can possess impurities left by the production process or introduced during storage and post-production handling (ISO, 2015). The quantity and type of impurities adversely affect hydrogen consuming systems which can eventually lead to critical events mentioned in Table 3.2. Hydrogen gas can possess contaminants such as, nitrogen, argon, helium, methane, carbon dioxide, sulfur, ammonia, water etc. (PST, 2022).

- **Monitoring system**: Different types of gas analyzers and impurity analyzers can be used to trace contaminants within the gas (PST, 2022). For example, LDetek HyDetek system is an advanced tool, developed specifically for hydrogen production, to monitor the presence of impurities. This involves a combination of plasma emission detector, thermal conductivity and quartz crystal microbalance sensors to monitor all potential contaminants in the hydrogen. Another method is 'Representative sampling of hydrogen gas' (Bacquart et al., 2021). This allows taking a small amount of stored hydrogen gas from the vessel to analyze the contaminants present in it.
- **Desired safety outcome**: Successful detection of the presence of any sort of impurities in the CGH_2 system.

- **Lagging indicator**: Number of losses of containment due to the presence of other unexpected gases.
- **Leading indicator**: The gas and impurity analyzers must be in good working condition to monitor the impurities. For the sampling method, caution should be taken while sample from stored CGH_2 is collected.

3.4.2 Fine material present in H_2 storage

Fine materials coming from manufacturing process, containment etc. can lead to erosion which results in loss of containment of CGH_2 storage (Debray et al., 2004).

- **Monitoring system:** Filters are useful for preventing hazards resulted from solid particle impurities (ISO, 2015). Clogging of the filters should be monitored to ensure the removal of solid particles from hydrogen gas (ISO, 2020). This may be done by periodic maintenance, by regular operational checks, or by monitoring pressure drop using pressure gauges, pressure transducers etc. across the equipment.
- **Desired safety outcome:** Absence of fine material in the CGH_2 system is identified as a desired safety outcome.
- **Lagging indicator:** Number of cases of LOC caused by fine material present in the CGH_2 system.
- **Leading indicator:** Filters should operate according to systems requirements during operational check or regular maintenance. For pressure gauges and transducers, they should be in proper operating condition to read the pressure drop across the filters.

3.4.3 High speed and turbulence of CGH_2

Hydrogen flow rate during loading the pressure vessel needs to be monitored and kept within a suitable predetermined value as higher speed and turbulence will lead to erosion which can result in loss of containment (Debray et al., 2004).

- **Monitoring system:** A flow control valve is a system to regulate fluid flow by responding to signals from other devices like flow meters, temperature gauges etc. (Emerson Automation Solutions, 2005). Hence, flow rate measurement equipment such as, flow meters and flow control devices like, valves, check valves, regulators etc. can be installed in the hydrogen system to monitor flow rate of CGH_2 while transferring it to the pressure storage vessel (ISO, 2015).
- **Desired safety outcome:** Maintaining a predefined flow rate of CGH_2 while filling the pressure vessel as well as emptying it.
- **Lagging indicator:** Number of times flow rate is not at the specified level due to malfunctioning of the flow control devices.
- **Leading indicator:** Equipment involved in flow control process are working as intended.

3.4.4 Internal flammable mixture

It is necessary to prevent ingress of air to the compressor during loading and transportation of hydrogen gas since presence of oxygen can form flammable mixture.

- **Monitoring system:** Gas density meter is currently used to measure the presence of oxygen in hydrogen cooled turbine which can also be installed in the studied system to monitor the percentage of air in hydrogen gas (Yokogawa, 2022). Furthermore, several gas detection technologies such as, trace oxygen analyzers are also in practice of measuring hydrogen percentage in power generators (PST, 2022).
- **Desired safety outcome:** Identification of the presence of oxygen in the CGH_2 pressure vessel.
- **Lagging indicator:** Number of cases where LOC of CGH_2 equipment developed because of the flammable mixture.
- **Leading indicator:** Appropriate functioning of equipment involved in detecting flammable mixture.

3.4.5 Presence of ignition source

Many electrical, thermal, and mechanical sources of ignition are possible (ISO, 2015). Deposition of static electric charge can act as an electrical ignition source. Ignition can occur from different thermal sources such as, open flames, hot surfaces etc. Also, mechanical sources of ignition include mechanical impact, friction, mechanical vibration.

- **Monitoring system:** Temperature sensors can be used in the hydrogen system to detect hot surfaces. Fire detectors can be used to identify open flames (ISO, 2015). The grounding method of the tube trailer should be monitored prior to transfer to reduce the risk of static discharge. In case of outdoor environments, this will help to prevent lightning strikes also. Visual inspection and vibration measuring devices are used to monitor mechanical vibration of the components.

- **Desired safety outcome:** Recognizing all possible ignition sources within the system.

- **Lagging indicator:** Number of times where ignition is initiated by any of the abovementioned sources which results in the LOC of CGH_2 equipment.

- **Leading indicator:** Installed temperature sensors, fire detectors and vibration measuring devices are operating as per the design. For visual inspection and ensuring grounding of the tube trailer, competent operators should be given the responsibility.

3.4.6 Overfilling

It is reported in (Hjeij et al., 2022) that the pressure of CGH_2 can be 20 MPa or 70 MPa but the storage temperature for both the cases is 298 K. When the specified pressure and temperature is reached the supply of hydrogen is stopped and any deviation from this situation is considered as overfilling which can generate overpressure.

- **Monitoring system:** To monitor appropriate filling of the tanks, pressure, and temperature of the gas inside the storage tank should be investigated. Pressure after compression should be studied along with the storage inlet pressure of the gas (ISO, 2020). Pressure gauges or pressure transducers can be used in this purpose. Gas temperature in the tank can be monitored using temperature sensors, thermocouples etc.
- **Desired safety outcome:** Identifying any pressure and temperature deviation of the on-board storage vessel while packing it with CGH_2.
- **Lagging indicator:** Number of occurrences of LOC of CGH_2 component because of overfilling.
- **Leading indicator:** The installed pressure and temperature sensors are functioning accurately to provide information about the storage facility.

3.4.7 Wrong welding procedure/ Unauthorized welding

Any leakage in the welded joints can lead to unintentional release of hydrogen gas which must be inspected using suitable technologies as hydrogen is a colorless, odorless flammable gas and its flame cannot be seen through naked eyes (Hübert et al., 2011).

- **Monitoring system:** Hydrogen gas sensors, hydrogen flame detectors can be used to identify release of hydrogen gas due to leakage (ISO, 2015). In addition, visual inspection can be performed to detect any damage of the welding joints (Compressed Gas Association, 1999).
- **Desired safety outcome:** Successful detection of any type of leakage in the welding joints with the help of hydrogen gas and flame detectors.
- **Lagging indicator:** Number of incidents happen because of venting of hydrogen gas through welding joints.
- **Leading indicator:** The hydrogen gas sensors and flame detectors should work as intended and be placed within the proximity of vulnerable joints. Moreover, the welding joints must meet the design requirements in time of visual inspection.

3.4.8 Blockage in gas delivery lines

While filling the storage tanks with CGH_2 installed on the tube trailer, the delivery lines used must be free from any damage, leak and blockage and meet the requirements described in (ISO, 2020).

- **Monitoring system:** Monitoring inlet and outlet pressures of the hydrogen gas using pressure gauges or pressure transducers can help to detect blockage in the delivery lines. Monitoring the CGH_2 flow rate can provide information of this issue (Bacquart et al., 2021). Also, regular visual inspection of the transferring system must be conducted to check that the assembly is free from damage and periodically tested for leaks by an appropriate method, such as bubble testing or pressure decay testing.
- **Desired safety outcome:** Early identification of blockage and any sort of damage in the transferring lines.
- **Lagging indicator:** Number of failures occur as a consequence of blockage, damage in the delivery lines.
- **Leading indicator:** All the equipment employed to detect hindrance in the pipeline such as, pressure gauges, pressure transducers, flow rate measuring system etc. are in good operating condition. The functioning of the delivery system should meet the design specifications.

3.4.9 Pressure relief system fails

Pressure relief system is implemented as a safety barrier which vents the excess hydrogen in case of over pressurization of the tank. Catastrophic rupture of the containment can occur due to defective pressure relief system.

- **Monitoring system:** To identify defective pressure control devices, visual inspection, periodic maintenance can be performed (Compressed Gas Association, 1999).
- **Desired safety outcome:** The pressure regulation devices respond to the variation of CGH_2 pressure while in storage or transferring and act accordingly to reduce the impact.
- **Lagging indicator:** Number of cases of LOC of CGH_2 because of inappropriate pressure regulation actions.
- **Leading indicator:** The installed pressure regulation devices need to be within the design requirements while visual inspection or periodic maintenance is performed.

3.4.10 Incorrect sensor signals

Different types of sensors for instance, pressure sensors, temperature sensors, hydrogen gas sensors are used to detect irregularity in the transportation operation. Wrong information due to the incorrect measurements of the sensors can compromise the normal operating process of the system and can decline safety of the system (Li et al., 2018).

- **Monitoring system:** Periodic maintenance, testing and physical redundancy of the sensors are needed to implement as risk reducing measures of incorrect sensor signals (Li et al., 2018).
- **Desired safety outcome:** Sensors provide exact information about the systems condition during runtime.
- **Lagging indicator:** Number of situations where LOC of CGH_2 and false alarm condition is created because of inaccurate sensor signals.
- **Leading indicator:** During maintenance and testing, sensors should comply with the system's requirements.

3.4.11 Flow stop control not working

Shut off valve is used as a protective fitting to stop fluid flow in case of emergency situations such as, high pressure, excess fluid flow etc. (Chinyaev et al., 2016). It is important to ensure this flow control system works as intended.

- **Monitoring system:** Any impairment can be detected by visual inspection and periodic maintenance (Compressed Gas Association, 1999).
- **Desired safety outcome:** The on-board pressure vessel is filled with right quantity of CGH_2.
- **Lagging indicator:** Number of failures of the pressure vessels where controlling the gas flow is the main contributor.
- **Leading indicator:** The valves installed for controlling flow works within the system requirements during maintenance and inspection.

A risk control matrix is presented in Table 3.4 as described in step 3 of (HSE, 2006)to find the interconnection between different risk control systems as well as to see if there exists a common RCS for several undesirable events.

Table 3.4: Risk control matrix

	Undesirable events										
Risk control systems	Contamination	Fine material present in the stored CGH_2	High gas speed and turbulence	Internal flammable mixture	Presence of ignition source	Overfilling of storage vessel	Defects in welded joints	Incorrect sensor signals	Malfunctioning of flow stop control devices	Failure of pressure relief system	Blockage in delivery lines
Gas analyzer	X										
Representative sampling of stored CGH_2	X										
Periodic maintenance		X						X	X	X	
Visual inspection		X			X				X	X	X
Pressure gauge, pressure sensors		X				X					X
Flow meter			X								
Flow control device			X								
Gas density meter				X							
Trace oxygen analyzer				X							
Temperature sensors					X	X					
Grounding method					X						
Vibration measuring devices					X						
Hydrogen gas sensors							X				
Hydrogen flame detectors							X				

3.5 Monitoring strategy for MCE company

The investigation on the initiating events indicated that risk control systems of some of the undesirable events should be activated prior to the road transportation. For instance, presence of fine material or any contaminant gas should be monitored in the time of loading the pressure vessel. Also, the pressure and temperature of the storage tank must be investigated during the filling process as well as the run time. These risk control systems ensure safe transferring and storage of CGH_2 which will eventually increase the safety level. Besides, visual inspection of most of the components are done even prior to the transferring process. All these procedures work together as preventive safety barriers for avoiding the critical events. As a result, a strategy to monitor operating condition of the components of the considered system is proposed for three operational modes, before filling process, during filling of the pressure vessel and during the transportation process where on-board storage vessel is used. This can be applied as a checklist to ensure all the components are functioning as intended and to implement risk control systems to inspect any deviation instantly.

3.5.1 Before the filling process

There are some risk control measures which need to act prior to the filling process to fill the storage vessels with proper safety level. In this phase the components that must be checked are listed below.

- Investigation to identify blockage in the delivery lines, presence of ignition sources must be undertaken.
- Proper operating condition of the shut of valves, pressure relief devices and sensors should be assured.
- Visual inspection needs to be performed to check damage, leak etc. in the lines and storage vessel.
- Grounding of the tube trailer must be done.

3.5.2 During the filling of the storage tanks

While transferring CGH_2 into the pressure vessels, the parameters need to monitor are presented below.

- Delivery lines and storage vessels are to be checked for leakages, block etc. To detect leakage in the delivery lines or tank, reading from hydrogen gas sensors and flame detectors should be monitored all the time.
- Presence of impurities must be checked to maintain the defined purity level. For instance, hydrogen supplied for fuel cell of road vehicles should have 99.97% purity and the maximum concentration of other contaminants are also presented in (ISO, 2019).
- Pressure across the filters needs to be monitored to make sure proper functioning of the filters.
- Velocity of CGH_2 should be monitored while filling the storage tank to ensure operation within the design envelope.
- Pressure and temperature of the storage tank must be monitored continuously to prevent overfilling. The pressure should be within the range provided in (Reddi et al., 2018) depending on the type of the vessel. For instance, type I vessel can carry upto 250 of hydrogen at 200 bar and the temperature should be maintained at 298 K at the given pressure (Hjeij et al., 2022).
- Presence of oxygen needs to be checked and kept under the lower flammability range.

3.5.3 During road transportation

Since the on-board pressure tanks are a confined system, there is little chance that contaminant gases, fine material will penetrate inside them. Therefore, the company can disregard these two causes when it comes to the monitoring of on-board pressure vessels. However, there are several things to be monitored to provide a secured delivery process which are given below.

- Presence of oxygen should be monitored continuously to avoid formation of flammable mixture and kept under the lower flammability range.
- On-board temperature and pressure sensors must be installed to monitor the temperature and pressure respectively of the storage vessel.
- To conduct early detection of leakage in the welding joints, storage vessel etc., reading from hydrogen gas sensors and flame detectors should be investigated continuously.
- Proper working condition of the pressure relief devices should be assured before the start of the delivery process.

Figure 3.5 illustrates all the operational modes along with the parameters, components that must be checked to allow safe CGH_2 delivery process via tube trailers.

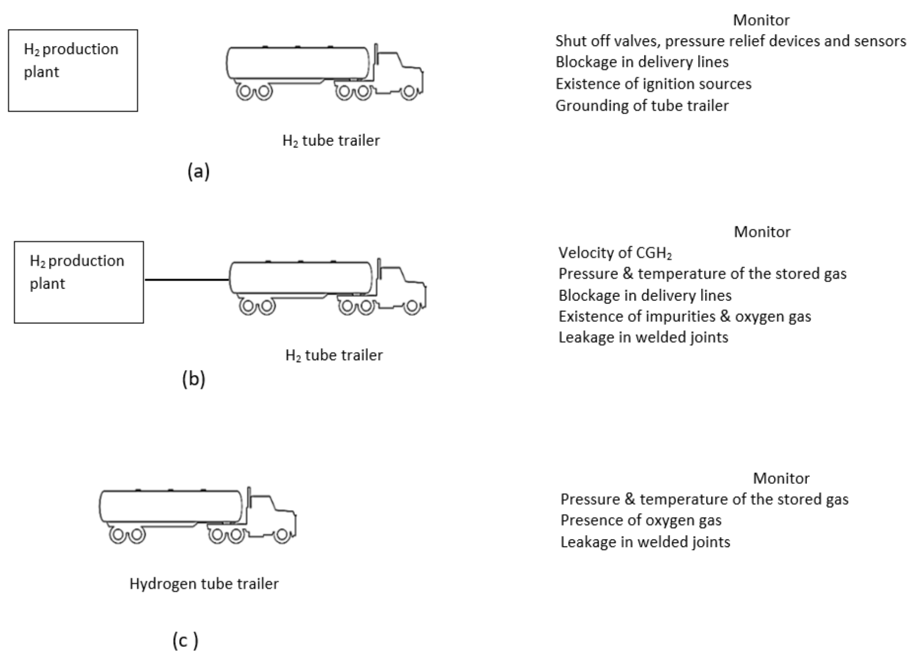

Figure 3.5: Timeline of applying monitoring approaches (a) before filling the tube trailer; (b) during the filling process; (c) tube trailer on road

3.6 Monitoring trucks carrying other dangerous goods

To present a comparative study, monitoring approaches for vehicles carrying liquified petroleum gas (LPG) and compressed natural gas (CNG) are studied and presented below.

3.6.1 Monitoring approaches for LPG carrying road tankers

LPG is transported through road tankers (Bubbico et al., 2000) and (Standard Norge, 2014) specifies both mandatory and optional equipment that are necessary to ensure that conveyance is carried out safely. According to (Standard Norge, 2014), LPG storage vessel should possess content gauge to supervise the amount inside as well as pressure gauge needs to be installed to monitor the pressure. The reading from these gauging devices must be studied continuously during the filling operation to confirm that the road tanker is not overfilled (Standard Norge, 2013). The filling area needs to be inspected for any source of ignition source and grounding of the tanker must be fulfilled. LPG sensors must be installed to identify leakage in storage vessel by detecting the presence of LPG in the atmosphere (Singh et al., 2022). All the valves installed in the road tanker should be monitored to check if it is operating as intended (Standard Norge, 2014). Pressure vessels of the road tankers and the equipment are required an initial inspection before being put into service to ensure all the items are functioning as specified.

3.6.2 Monitoring approaches for CNG carrying tube trailers

Compressed natural gas is loaded in cylindrical or spherical storage containers and can be transported onshore by truck (Heerden et al., 2020). To ensure safe handling and transportation of CNG, several physical quantities need to be monitored during filling the storage vessels and transportation. During filling operation, presence of any of ignition sources must be identified. In addition, grounding of the tube trailers should be adopted prior to the transferring process (ISO, 2018). Presence of moisture and other foreign material should be identified efficiently in the stored tank. To avoid over pressurization of the on-board containment, pressure and temperature of the tank must be monitored (Tractebel Engineering S.A., 2015). Sensors must be installed on cylinders to identify leak by detecting the presence of CNG (Christian, 2021). Furthermore, visual inspection and periodic maintenance should be performed to look for corrosion or other damages of the components including the tank (ISO, 2007).

4 Discussion

To recommend monitoring approaches for safe road transport of CGH_2, the components used in transportation of CGH_2 were studied. It is found that typically a hydrogen system is consisted of storage vessel, delivery pipes, welded joints, flow control and pressure relief devices. The components involved in the system can be classified into two parts, for transportation where storage vessel with the welded joints and pressure relief devices are used, another part is transferring which involves all the previously mentioned components along with delivery pipes and flow control devices. While performing risk analysis according to MIMAH for CGH_2 tube trailer transportation system, four critical events - start of the fire, breach on the shell, leak from pipeline and catastrophic rupture were identified for the given equipment type and state of the substance handled. The study suggests that all the critical events demonstrate different forms of LOC of CGH_2 components which can lead to different dangerous consequences. From the event tree analysis, fire, VCE, overpressure, missile ejection, fireball etc. were recognized as the possible dangerous phenomena which has severe impact over the human beings and properties. A variety of initial causes, responsible for the critical events, are found from the fault tree analysis and are further divided into six different categories. It can be seen that human error, faulty equipment, mechanical failure, natural hazards etc. contribute to the LOC of CGH_2 tube trailer delivery system. Though human faults are identified as the cause of the majority of undesirable events, these are not studied further is since human error is addressed in HRA which is an interdisciplinary research area and outside the scope of this thesis. Furthermore, triggering events resulting from natural hazards are not considered as these can be avoided by knowing the weather forecast beforehand.

As a result, state-of-the-art monitoring technologies for the initiating events under mechanical failure, equipment failure and operational failure categories are investigated. The study suggests that it is critical to monitor the temperature and pressure of the stored CGH_2 during the transportation process. Any deviation from the specified temperature and pressure (298 K at 200 bar) can lead to over pressurization of the containment which can result in harmful end events. Besides, monitoring presence of oxygen, detecting leakage in the joints must be done as well. In the time of filling the pressure vessels with CGH_2, supervision like, inspecting flow stop control devices, leakage in the delivery pipes, grounding of the tube trailer etc. must be conducted to increase safety level. The current monitoring technologies to conduct the previously mentioned inspection processes are mostly comprised of sensors that measure different physical quantities such as, pressure, temperature, velocity of CGH_2, presence of oxygen and other unwanted gases etc. This allows for fast diagnosis of system deterioration and prompt corrective action, thus considered as risk control system. The desired safety outcome of the mentioned sensor system is described as the exact reading of the corresponding parameter which helps to comprehend successful operation of such a RCS. Both the process safety indicators, lagging and leading indicators presents an effective method to ensure proper functioning by discovering weaknesses within the RCS followed by an accident as well as during routine checks.

Besides, from the risk control matrix, presented in Table 3.4, it is evident that visual inspection, and periodic maintenance are the most significant risk control systems for CGH_2 tube trailer transportation since highest number of undesirable events can be identified by performing well planned maintenance and inspection operation. Number of LOC of CGH_2 component due to defective maintenance and irregular inspection is determined as the lagging indicator and the leading indicator is defined as the accurate functioning of the components during maintenance and inspection. By applying both indicators efficiently, required safety outcome for this RCS can be achieved.

A checklist is recommended for MCE company based on the analysis performed in this report. The strategy of adopting suitable monitoring approaches includes three distinct operational modes such as, before filling process, during filling process and during transportation through tube trailers. From the proposed strategy, it can be seen that, prior to loading the pressure vessels, some preliminary work such as, supervising the components involved in the filling process are in right operating condition, identifying all the potential ignition sources, grounding of the tube trailer etc. must be done. On the other hand, during the filling process top priority is given to fill the tank maintaining safe pressure and temperature limit of the stored gas with required purity level. Hence, continuous monitoring of the pressure, temperature, and percentage of unwanted gases inside the cylinder should be performed. However, it can be noticed that, more physical quantities and components need to be monitored during the filling process than the runtime since during delivery, CGH_2 is stored in a confined space which results in no entrainment of contaminant gases and a smaller number of equipment is involved then. While the tube trailer is on road, detecting unintentional release of hydrogen gas due to leakage on the vessel or the other components is given significant importance since released hydrogen can lead to dangerous consequences like, jet fire, VCE etc. Furthermore, continuous measuring of the pressure and temperature of the stored gas is also incorporated to prevent over pressurization of the tank. The recommended strategy suggests that the transportation scenario would be seriously affected if all the initiating events of an operational mode are not monitored. For instance, over pressurization of the storage tanks can occur if the pressure and temperature during the loading of the storage tanks are not monitored. Hence, this would also affect the tube trailer during run time and can lead to catastrophic rupture of the tank. Similarly, before the start of the filling process, potential ignition sources must be identified. Otherwise, this can lead to fire or explosion in case of sudden release of hydrogen gas in the time of loading the pressure vessel. In short, it can be said that monitoring indications suggested for all three operational modes are tied together to facilitate preventive safety barriers for CGH_2 tube trailer transportation system to provide a robust, safe, and efficient infrastructure of hydrogen delivery process.

Monitoring methods for CGH_2 tube trailers and other dangerous goods such as LPG and CNG carrying vehicles are also investigated in order to identify similarities and differences. It was found that all the three cases possess similar type of physical quantities to be monitored for example, inspecting pressure and temperature of the storage tanks for all three sorts of substances are given significant importance due to the potential of over pressurization. The reason behind this might be the cylinders used for storing the gases falls under the same supervision of gas cylinders provided by (ISO, 2007). In addition, for all the gases, identifying the presence of impurities need to be performed during loading the storage vessels. Since CGH_2, LPG, CNG are flammable gases, all the potential ignition sources need to be identified and grounding of the vehicle must be done earlier to the filling process. Furthermore, unintentional release of gas is detected using suitable gas sensors to identify leakage in the vessel, joint etc. However, release of LPG and CNG gas through a leak is less severe than hydrogen leakage since hydrogen flammability range is (4 – 77 vol%) which is wider than both LPG (2.2 – 9.5 vol%) and CNG (5.3 -15 vol%) (NREL, 2009). Also, minimum ignition energy of hydrogen is very low approximately one-tenth of natural gas and petroleum gas (NREL, 2009). As a result, a little amount of hydrogen can ignite effortlessly and cause serious harm. Besides, hydrogen flame can't be seen through naked eyes unlike LPG and CNG flames. Therefore, monitoring hydrogen release using sensors and flame detectors is crucial. Visual inspection and periodic maintenance of the components involved in the transporting such as, storage vessels, valves etc. are equally important for all the gas types. It is evident that the monitoring approaches for CGH_2 trucks are not completely different than LPG or CNG transportation vehicles. Therefore, the common approaches adopted for the LPG and CNG conveying vehicles can be applied to the CGH_2 tube trailers as well with a little bit of modification according to the unique properties of hydrogen.

This study only focuses on reviewing the current monitoring technologies used to supervise the performance parameters of the components to study deviation from the intended operating conditions. However, no suggestions are made regarding the suitability of the techniques for MCE company, which can be studied further as a continuation of this work. Again, the lagging and leading indicators presented here are purely qualitative. Hence, efforts can be given to establish quantitative process safety indicators since it will give more accurate verification of the proper functioning of risk control systems. Besides, only one delivery mode is considered in this study. CGH_2 delivery using pipelines and hydrogen delivery in different forms such as, liquid, solid can also be studied to ensure safe delivering process. Furthermore, human reliability analysis holds major importance in transferring and transporting hydrogen. Therefore, research should be conducted in this particular field to improve the situation by reducing faults performed by humans.

5 Conclusions

Hydrogen is the main candidate to replace fossil fuels due to being an abundant, renewable, potentially clean energy carrier containing high energy in per unit mass. The specific properties like- wide range of flammability (4-77 % in air by volume), minimum ignition energy (0.02 mJ) and high burning velocity not only make hydrogen an excellent fuel but also unfolds several safety issues related to the stages of hydrogen value chain. Among the four sections of the value chain, transportation is studied in this report since it connects the demand and supply for the gas as well as to boost hydrogen economy good infrastructure is essential. Though it can be beneficial to deliver hydrogen in both compressed gaseous and liquid state, compressed gaseous form is preferred due to less energy loss compared to the liquefaction process and no handling of cryogenic temperature. Moreover, CGH_2 can be transported using tube trailers which is an economic and simplest approach. Therefore, in this report total accident scenarios that might arise from tube trailer delivery of CGH_2 is studied along with the triggering events and viable end consequences. A risk analysis of the considered system is performed by answering two questions from the risk triplets mentioned in (Kaplan and Garrick), what can go wrong and what are the consequences. MIMAH methodology is adopted to perform the risk analysis and it is found that the four critical events, start of fire, breach on the shell, leak from the pipe and catastrophic rupture, retrieved from (Delvosalle et al., 2004b) refers to different forms of loss of containment. The dangerous phenomena caused by these critical events are dependent on ignition conditions. In case of immediate ignition, gas jet ignited occurs whereas delayed ignition leads to VCE/flashfire. For catastrophic rupture of containment, the end events are denoted as overpressure, missile ejection and fireball.

The initiating events for all the critical events are studied and classified into six generic categories – third party activity, operational/human error, corrosion, equipment failure, natural hazard, and mechanical failure. It is found that most of the causes responsible for the hazardous critical event are related to human error. However, in this study, three types of causes, mechanical failure, equipment failure and failure due to operational error are studied since human reliability analysis is a complex and multidisciplinary field which is out of the scope of this work. The state-of-the-art monitoring technologies are studied for each of the initiating causes to find out which physical parameters can provide information about the deviation from normal operating condition. By monitoring the parameters, early detection of any dangerous deterioration can be achieved and thus it is regarded as risk control system. It can be seen that periodic maintenance and visual inspection are the most used risk control systems for the highest number of the causes. Desired safety outcomes for all the risk control systems are mentioned also so that the result due to proper functioning of the RCS are clear enough to understand. Lagging and leading indicators are also presented to propose the ways how double verification for the risk control systems can be undertaken.

Thereafter, a monitoring strategy for MCE company is recommended based on this analysis. The strategy was divided into three parts, before the transferring operation, during transferring CGH_2 in storage tank, and transportation when the vessel is on-board the tube trailer. Before starting the transferring process, shut off valves, pressure relief valves and installed sensors should be checked for any type of malfunctioning. In addition, blockage of the delivery lines, existence of ignition source in close proximity and proper grounding of the tube trailer must be investigated. During loading the pressure vessel, velocity of the gas entering the vessel along with the pressure and temperature of the storage tank should be monitored continuously to prevent overfilling. Presence of any contaminant gas as well as oxygen must be checked using proper technologies. Any type of leakage in the pipeline or welded joints should be searched using hydrogen gas sensors, flame detectors and visual inspection. In the time of transportation, consideration must be given to continuous monitoring of temperature and pressure of the tank and detecting released hydrogen gas due to leakage in the system by implementing hydrogen gas sensors and flame detectors. Presence of oxygen inside the tank also needs to be checked due to the wide flammable range of hydrogen gas.

However, the monitoring approaches adopted for LPG and CNG transportation are also studied, and it is found that most of the physical parameters that to be monitored are same for all the three cases. For instance, pressure and temperature of the storage tank, any sort of leakage of the components, presence of ignition source etc. One important aspect for hydrogen is that due to its wide flammable range and minimum ignition energy, leakage of hydrogen gas needs to be detected as soon as possible. So, any type of release of hydrogen is considered harmful whereas release of LPG and CNG are not as dangerous as CGH_2. Since there is no guideline of the monitoring approaches regarding CGH_2 transportation, this report presented a framework that includes the parameters needs to be monitored to ensure safe CGH_2 delivery process through tube trailers. However, this study only focuses on one delivery mode, monitoring approaches for other means for instance, LH_2 delivery, hydrogen delivery using pipeline etc. can be performed to formulate a complete guideline of all the processes. Also, this study suggests that human reliability analysis is crucial to provide a safe framework for CGH_2 transportation.

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