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Abstract

Hydrogen is the most talked about topic today. Besides being able to reduce carbon dioxide levels with combustion products that do not produce carbon dioxide or known as green energy, its potential as a substitute for existing energy is needed. There are two important things that make hydrogen needed as a substitute for existing energy. The first is the limited availability of hydrocarbons based on (IEO, 2019) "*the global supply of crude oil, other liquid hydrocarbons, and biofuels is expected to be adequate to meet the world's demand for liquid fuels through 2050".* This must be kept in mind if future energy shortages are to be avoided. The second thing is concern for climate change. The use of hydrogen as a substitute for existing energy will reduce the level of carbon dioxide production. As we know in general that one of the factors for global warming is the increase in carbon dioxide in the atmosphere.

The higher the level of risk that is unknown and could arise over time as the use of hydrogen increases. Hydrogen-based systems, like any other technical system, will unavoidably include hazards connected with potentially dangerous conditions that endanger public safety, health, or the environment. Such as in this case, NORCE laboratories using hydrogen in their fermentation system. In order to ensure that connected products and systems are safe and perform as designed, safety issues must be addressed methodically for each equipment that involved hydrogen.

Risk analysis is the right step to make a detailed understanding of risk in an event. However, in the case of hydrogen use, risk analysis is not sufficient. Third party services are also available to help create hydrogen hazard prevention applications for each piece of equipment. However, this seems excessive and tends to be disproportionate to the costs incurred for a research lab that uses hydrogen below the LEL (low explosion limit).

The main objective of this thesis is to solve the problem of using hydrogen safely in the NORCE laboratory. Starting from a detailed understanding of the risk perspective in order to describe the risk of hydrogen accidental phenomena and consequences. This is important because it will relate to the selection of the right type of regulation and standard for designing risk reducing measures methods. In this case, the author uses the International Electrotechnical Commission (IEC 60079) series of explosive atmosphere standards and the International Standard Organization (ISO 15916) regarding basic considerations for the safety of hydrogen systems because the potential for explosions in hydrogen release often occurs. In addition, the principle of risk reducing measures and emergency response plan is based on the regulations of Petroleum Safety Authority Norway (PSAN) and NORSOK Z-013. As a result, this thesis provides several recommendations regarding risk reducing measures methods at NORCE Laboratories.

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1. Introduction

1.1. Background

Risk no matter how, whenever and whatever activities are always involved, and it is basically impossible to eliminate it completely unless it is accepted at some level. In general concept of risk management, risk can be managed in three ways; bear all the consequences or face the risks, take security measures to reduce potential risks and avoid risks by transferring them to other parties. The use of risk analysis especially quantitative risk analysis has an important role in making decisions in many activities such as oil and gas, medical, governance and policy, manufacturing, laboratories and others. There are several factors to improve the effectiveness of risk analysis including the strength of knowledge, information, data and expert opinion it all must be take into account when perform risk analysis.

However, the use of a comprehensive risk analysis can sometimes seem overkill in some cases, for example in research laboratories using hydrogen even below the Lower Explosion Limit (LEL) and sometimes it may even cost too much to implement a comprehensive risk assessment or use a third-party service. This makes the costs incurred not proportional to the results obtained, even seem futile. This is a challenge as well as the basic idea for this thesis from the point of view of the risk management discipline.

Scientists, companies and governments are increasingly interested in possible alternative energy sources because of concerns about global warming and climate change, as well as the depletion of fossil resources. Hydrogen has the potential to be an energy carrier and a viable substitute for hydrocarbons, especially in transportation. The advantages of hydrogen come from reduced carbon dioxide emissions or limited use of fossil fuels.

In line with this, to support the use of hydrogen as a substitute energy in the future. There needs to be support from the point of view of proper risk management for hydrogen handling so that it can be used safely, especially in this case is the NORCE research labs.

1.2. Problem Description

Along with the increased of hydrogen usage, risk analysis should be carried out to avoid the hazardous of hydrogen. According to (NASA, 1997), the hazards associated with hydrogen use can be categorized as physiological (frostbite, respiratory disease, and shortness of breath), physical (phase change, component failure, and embrittlement), chemical (ignition and combustion). The combination of hazards occurs in many cases. The main danger associated with any form of hydrogen is accidentally generating a flammable or explosive mixture, causing a fire or explosion. Safety will be enhanced if designers and operational personnel are aware of the specific hazards associated with handling and using hydrogen.

Generally, there are third party companies that help certify laboratories equipment according to applicable standards such as Ex-certified. However, cost plays a major role in decision making. As in this case, NORCE decided not to use Ex-certification in their laboratory due to necessity and cost. This is not a barrier to implementing safety management at NORCE labs. An understanding of the uncertainties of hydrogen accidental phenomena, hydrogen accidental consequences, and the application of principles based on international standards and regulations is key.

1.3. Purpose of thesis

The purpose of this thesis is to address the following:

- Discuss and defining the uncertainties of hydrogen accidental phenomena and hydrogen accidental consequences
- Discuss and understanding of regulation and international standard of related hydrogen accidental phenomena and consequences
- Suggest an appropriate risk reducing measures of hydrogen at NORCE laboratory following international standard and regulation

1.4. Limitation

The main focus in this thesis is to discuss an appropriate risk reducing measure at NORCE laboratories that using hydrogen in their fermentation process. International standard and regulation such as ISO, IEC, PSA and NORSOK that related to risk reducing principle for hydrogen has been use as basic idea with link to the uncertainties of hydrogen accidental phenomena and consequences. As a result, this thesis provides an appropriate risk reducing methods at NORCE laboratories such as detection measures, safety barrier and safety measures including emergency response plan.

1.5. Structure

This thesis is structured with an effective structure and has been evaluated to make it easier for users or readers to understand the focus of the research. The structure of this thesis is divided into the following sections:

Section two is the theocratical approach, this section divides into two sub section. The first sub section is discussing the risk perspective and the category, namely probability-based risk perspective and uncertainty-based risk perspective. Well understood of risk perspective is a key to describe or defined the uncertainty of some object for further analysis. And the second sub section is discussing the regulation (PSA Norway and NORSOK) and international standard (ISO and IEC) related to hydrogen and explosion atmosphere to better understanding of risk reducing and emergency response plan.

Section three is the hazard and risk of hydrogen. Discussing related hydrogen accidental phenomena and consequences has been discuss in this section with the aim of making it easy to determine the uncertainty of hydrogen.

Study case of this thesis is discussing in the **section four** including with discussion. Uncertainty of hydrogen as in this case is NORCE laboratories has been determine. As a result, suggestion of risk reducing measures and also emergency response plan related to the uncertainty is provides with following the related standard and regulation.

The **final section** is giving to the conclusion. better understanding of the suggestion risk reducing methods is mentioned in this section with link to the objective of this thesis.

2. Theoretical Approach

The theoretical approach is presented in the first portion of this thesis, which includes the most important words and concepts for this thesis. To distinguish between two major ideas that are crucial in this thesis, the theoretical approach has been separated into two subsections.

The first subsection contains a literature study that was chosen to better understand risk and risk perspectives based on probability and uncertainty. This goal is to show how the risk perspective is handled in case studies. We have chosen and illustrated the most crucial and relevant terminology and definitions.

The second concern is with Norwegian regulations, directives, and standards. The regulations must be followed, while the standards offer suggestions for how to comply with the regulations. The most important risk-related rules have been outlined. Furthermore, as in this case of thesis, the recommended norms are employed as an international standard for explosion hazard.

2.1. Risk

In early 1621, the Oxford English Dictionary (OED) first used the English word *risque*, which came from the French word "*risque*". while the word "*risque*" was first spelled as risk in 1655. According to OED 3rd edition, risk defined as.

"(Exposure to) the possibility of loss, injury, or other adverse or unwelcome circumstance; a chance or situation involving such a possibility".

A concise definition of risk is given by the Cambridge Advanced Learner's Dictionary (CALD), which defines it as *"the possibility of something bad happening"*.

Following (Wikipedia) there are various definitions of risk. However, there is no one definition that is appropriate for all issues, hence none is presented as the proper one. Rather, the definition is a political option, reflecting one's opinion on the relevance of many negative consequences in a given circumstances (Fischhoff, Watson and Hope, 1984). Thus, the Society for Risk Analysis (SRA) concludes that *"experience has shown that to agree on one unified set of definitions is not realistic"*. The solution is to take a different approach to the basic concept and distinguish between the overall qualitative definition and the measures that go along with it.

In other word, risk have different definition for different concepts like project risk, economic risk, environmental risk etc. but all of these refer to general definition by dictionary that was mentioned it above as "*the possibility of something bad happening*".

According to (Bellaby, Flyn and Ricci, 2005), risk is generally divided into three broad type. The first type is linked risk assessment practice. A risk is calculated by multiplying the effect of a hazard by the probability of it occurring and evaluated with uncertainty. The assessment is based on existing evidence and provides a "reasonable expectation" that applies as long as the conditions under which our current knowledge is based remain unchanged.

The second type of risk is associated with making decisions taking into account the likelihood that the consequences will be different. Uncertainty is not the only statistic in this case, and current knowledge is insufficient to serve as a guide. Thus, risk management is taken into account for emergency planning actions.

The third type is not about reasonable expectations or contingency plans for dealing with unintended consequences, but about people's perspectives on threats. This is exactly the same as one of the axioms from the black swan book, namely *'unknown-known'*. For example, we know that a terrorist act is a threat regardless of the danger that arises as a result or an emergency action to deal with it. But people do not realize it, or have not identified these events because the assessment was lacking thorough enough consideration (Aven, 2014).

Another semantic of risk is defined with linked to dictionary concept. It is "*the possibility of something bad happening*". Such as (Aven, 2015b), defined risk conceptually and provides an example related to activity.

Risk is related to future events A and their consequences (outcomes) C. Today, we do not know if these events will occur or not, and if they occur, what the consequences will be. In other words, there is uncertainty U associated with both A and C. How likely it is that an event A will occur and that specific consequences will result, can be expressed by means of probabilities P, based on our knowledge (background knowledge) K (Aven, 2015b) . In this term risk is defined technically as combination between consequences (C) and uncertainty (U) of some event (A) and based on this definition not only the possibility bad happening or negative consequences could be, but also could simulate with positive consequences for example spread of corona virus, this may negative for mostly all people in the world, but we do not know actually that there are positive consequences for others. Such an increasing face mask productivity that makes the company increase benefit, increasing benefit to the pharmacy or maybe this could be healing for the world from waste gas since travelling to anywhere is restricted and make the production of carbon dioxide is decrease especially from the transportation sector.

Let us use the hydrogen case as an example to make it closer to the current topic. Observed the fermentation process in a hydrogen-using laboratory. The sensor monitors and controls the hydrogen temperature and pressure during the fermentation process. In addition, the reactor is equipped with a mechanical independent pressure release device to ensure that the pressure limit is not exceeded. One possible outcome in this scenario is that the sensor fails to control the hydrogen temperature, resulting in over pressurization of the fermentation reactor. For simplified, fermentation process as an even A have the potential consequences C if the sensor fails to monitor the real temperature and pressure in the reactor. However, we do not know actually what the associated consequences will take place? is it the sensor will fail or not? This call uncertainty U and in this case, we only assess one uncertainty, and what about another uncertainty that could be influenced to lead an accident at laboratory? That is risk.

2.1.1. Risk perspective

The definition of risk as mentioned above is only considered as a dictionary and perspective. As a result, we could not have a conclusion to what an appropriate definition of risk for all events because risk has a different meaning for different discipline and application areas. Such as (PSA, 2011) defined risk as the consequences of the activities with associated uncertainty, (BS ISO 31000, 2018) defined risk as an effect of uncertainty on objectives, (NORSOK, 2010) defined risk as the combination of the probability of occurrence of harm and the severity of that harm, (Aven and Renn, 2010) defined risk refers to uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that humans value, Risk equals the expected loss (Willis, 2007), Risk is the probability of an adverse outcome (Graham and Weiner, 1995). All this perspective of risk is understood as an expected value, a probability distribution, as uncertainty and as an event and generally there is no universally accepted definition of risk. Based on these various definitions, it can be categorized between two perspectives. namely based on probability and based on uncertainty perspective (Aven and Renn, 2010).

2.1.2. Probability based risk perspective

The term of probability has been defined by (Kaplan and Garrick, 1981) into three different distinction, namely distinction between probability and frequency, distinction between probability and statistic, and the last is probability of frequency. Then, this distinction has been simplified by (Aven, 2011a) to interpreting probability into two different ways. That is (a) as a relative frequency and (b) the bayesian perspective.

a. Relative frequency

Risk (R) is described as (A, C, P), where (A) express as the number of events, (C) as the consequences of event “A” and P as the probability associated of event (A) and consequences (C). the probability in this term is interpreted as relative frequency probability or frequentist probability. As an example, consider at laboratory work and we can define event (A) (such as gas leaks) and associated consequences (C). The probability of event P_f (A) is the fraction of time the event (A) occur if the situation repeated with infinite number of time (Aven, 2011b).

P_f (A) in this term is unknown and need to describe. Risk analysis determines the estimate P_f* by using models and simulations to hypothetically repeat the situations (A). It is unknown how close the estimate P_f*(A) comes to the true value of P(A).

Risk description of relative frequency probability

$$R = (A, C, P_f^*, P (P_f), K)$$

K expressing the background knowledge on which the estimate P_f^* and probability distribution P are based. Second-order probabilities, such as “P” in the example above, are included in the description. This probability is based on a set of assumptions and could differ in a number of ways. As a result, a risk description must be able to reflect the uncertainty embedded in background knowledge and must look beyond subjective probabilities P (Aven, 2015a).

b. Bayesian perspective

In the bayesian perspective, the analyst expresses uncertainties using knowledge-based (subjective) probabilities. All probabilities are dependent on background data, available data, and the models being used (Aven and Renn, 2010).

Assume that the probability of event A occurring is 10%. There is no uncertainty in the assigned probability in this approach because it expresses the analyst's degree of belief in the event "A" based on background knowledge. This subjective probability can be compared to drawing a specific ball from an urn of ten balls.

An analysis based on historical data could easily become too narrow, implying that extreme outcomes are not taken into account. The problem is that, because such events are so unexpected, we don't always have the knowledge and insights to recognize them (Aven, 2015a).

2.1.3. Uncertainty based risk perspective

The risk perspective based on probability is a probability model that cannot always be meaningfully defined, as explained in Section 2.1.2, and we must thus go beyond the (A, C, P_f) perspective as a universal perspective. We get the (A, C, U) risk perspective by replacing the relative frequency probability P_f with uncertainty U. Because A and C are both subject to uncertainty, a "(A, C, U) perspective" is a natural contender. We want a framework that allows for different representations and expressions of uncertainty. As a result, risk is defined as a triplet comprising occurrences A, consequences C, and associated uncertainty U (will A happen, and what will be the repercussions C?). Various techniques, such as likelihood, possibility measurements, and others, could be used to describe the risk (Aven, 2011a).

Following (Aven, 2011b) risk description based on uncertainty :

$$R = (A, C, U, P, K)$$

There is P in this description, means as subjective probability expressing uncertainty U based on the background knowledge K. In this risk description, uncertainty is the most important component of risk rather than probability.

2.2. Regulation and standard

Every workplace entails a risk, and we have no way of knowing how significant the risk is. Working in the petroleum industry carries a high risk, but so does working in another industry, particularly when working with gas, which carries a high risk, such as working in a laboratory that uses hydrogen as a supporter for their work. However, it should not be an impediment to working effectively in a high-risk industry. To ensure a safe working environment, regulations and standards have been established. All regulations must be read and understood in the context of the governing laws in order to be consistent. Furthermore, the authorities advise that the guideline norms, which include the application of standards, be followed.

2.2.1. Norwegian regulation

The Petroleum Safety Authority (PSA) in Norway sets the rules for health, safety, and the environment in the petroleum industry and at onshore facilities. They show how to manage activities in the oil industry and at onshore facilities by demonstrating the basic requirements. These rules are divided into the following sections:

- The Framework Regulation

- The Management Regulation
- The Facilities Regulation
- The Activities Regulation
- Technical and Operational Regulation
- CO2 Safety Regulation
- The Working Environment Regulation

The regulations comprise a vast number of functional requirements, with standards and norms defining the level of prudence of the regulations. The Norwegian regulatory hierarchy is depicted in figure 1.

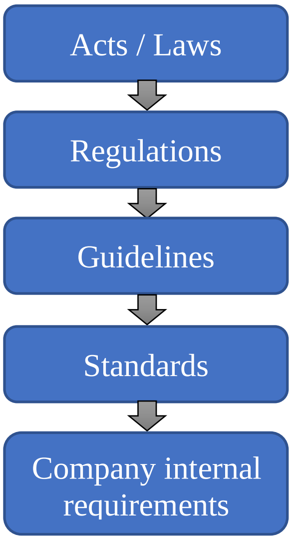


Figure 1. Norwegian regulatory hierarchy

The PSA is supposed to establish guidelines and monitor compliance to guarantee that industry, particularly in the petroleum industry, adheres to high standards of health, environment, safety, and disaster readiness, and therefore contribute to society's maximum benefit. The PSA is in charge of issuing and enforcing regulations as part of its role.

In terms of health, safety, and the environment, the PSA encourage high health, safety, and environmental standards in all activities covered by these rules and accomplish systematic execution of steps to meet requirements and meet the goals set out in workplace safety and health legislation.

Following (PSA, 2011), is explain regarding risk reduction principle. As it stated that *"Harm or danger of harm to people, the environment or material assets shall be prevented or limited* *in accordance with the health, safety and environment legislation, including internal requirements and acceptance criteria that are of significance for complying with requirements in this legislation. In addition, the risk shall be further reduced to the extent possible".* Risk must be minimized at all times, including throughout the selection of technical, operational, and organizational solutions. The potential harm to persons must be assessed and minimized in order to obtain the greatest possible outcomes, given that the expenses are not out of proportion to the risk reduction that will be achieved. To lower the risk as much as feasible, risk-reduction methods must be given. The actions and solutions that will lessen the uncertainty regarding the personnel's health and safety will be picked. Furthermore, elements that contribute to harm to people, assets, or the environment must be replaced with ones that pose a lower risk of harm.

There is uncertainty about which incidents will occur, how frequently they will occur, and what harm or loss of human life, health, the environment, and material assets the various occurrences will cause. In terms of the external environment, the uncertainty relates to the potential for operating discharges to cause environmental impact. There's also no way of knowing how much environmental damage the releases will create. As a result, the following (PSA, 2011) provides some guidelines relating to risk-reduction principles.

- Risk reduction must be further reduced beyond the established minimum level for health, safety and environment that follows from the regulations. The enforcement will be different based on whether it applies to high-risk operations and activities with major accident potential, or similar of lesser scope and with lower risk. This means that the risk shall be reduced if this can take place without unreasonable cost or drawback. The ALARP (As Low As Reasonably Practicable) principle is usually related for this concept.
- The BAT (Best Available Technology) principle, the party in charge of the activities must plan and operate using technology and procedures that, after a thorough evaluation, give the greatest and most successful results.
- Pre-cautionary principle, this provision is included to clarify a principle in the field of health, safety, and the environment that is recognized both nationally and internationally.
- Substitution philosophy, Alternative solutions that do not include the relevant risk elements must be chosen. The clause extends to the entire extent of the regulations and will also apply to matters that pose a health risk and fall under the jurisdiction of the health authorities, such as the duty to substitute products that contain chemicals that are harmful to human health and the environment.

These guidelines can be used as a basic in risk analyses to show the application of risk-reduction principles. Additionally, following (PSA, 2018) demonstrated the uses of acceptance criteria for major accident risk and environmental risk. Acceptance criteria define and indicate the top limit of what is considered an acceptable risk level in each category. Even if the results of risk studies or risk assessments suggest a level of risk that is within acceptable limits, additional risk reduction should always be addressed. The acceptance criteria must be written in such a way that they meet the requirements for appropriate risk and preparedness analyses and are acceptable for providing decision-making support in regard to risk analyses and risk assessments. In this acceptance criterion, a major accident is defined as an acute incident such as a major spill, fire, or explosion that results in multiple serious personal injuries and/or loss of human life, serious environmental harm, and/or loss of major financial assets immediately or later.

To make a decision, of course, these two parts of regulations are not enough to be used as supporting factors. There are still some regulations that need to be used as a basis for making decisions. For example, in the case of the fermentation process in the NORCE laboratory, the potential for fire and explosion hazards is a major problem that needs to be addressed. The handling must be in accordance with the applicable regulations, in this case, the PSA. Such as facility regulations, which govern the design of facilities as well as the primary safety functions including physical barrier and emergency preparedness. To ensure staff safety and reduce pollution, design facilities should be based on the most robust and simple solutions possible, and the main safety functions must be clearly specified. In addition, PSA's technical and operational regulations describe regulatory standards regarding fire and explosion protection in order to avoid risks and with respect to fires, explosions and other accidents as possible. In the event of a spill or leak, the necessary precautions must be taken to avoid the risk of fire or explosion, including fire and gas detection systems, control and monitoring systems and process safety systems to maintain safe conditions in the event of a fault that could prevent the system from functioning.

2.2.2. NORSOK Z-013

The Norwegian Technology Standards Institution (NTS) has established NORSOK standards for the petroleum industry, which address both technical and operational aspects of safety (NORSOK, 2010). The PSA has recommended that the majority of the NORSOK criteria should be followed. As a result, knowing and applying these standards can help to comply with the rules. The risk analysis employed in this thesis must adhere to the rules, but it should also incorporate the recommended standards. (NORSOK, 2010) is based on the following elements:

- Prior to conducting a risk analysis, establish risk acceptability criteria.
- The relationship between risk and the Environmental Protection Agency (EPA), particularly the integration of the two types of analysis into a single overall analysis process
- Analyses preparation and execution
- Additional risk and EPA requirements for various activities and life cycle phases.
- Establishing regulations based on risk and the Environmental Protection Agency's guidelines

As a result, throughout the risk analysis for the case studies, this standard was employed and referred to. The standards primary goal is to demonstrate the recommended steps that must be included in a risk assessment. Furthermore, because risk and emergency preparedness plans are emphasized, it overlaps and complies with PSA rules. These aspects should be considered while making the risk analysis.

2.2.3. International standard for explosion hazard

The International Organization for Standardization (ISO) is a global federation of national standard-setting organizations. Technical committees are typically responsible for preparing international standards. Each member body with an interest in a particular topic has the right to have a representative on the committee. On all aspects of electrotechnical standardization, ISO works closely with the International Electrotechnical Commission (IEC). Like the NORSOK standard, ISO/IEC is a recommendation that needs to be involved in making a risk analysis. however, Unlike the NORSOK standard, the international standard, in this case, ISO/IEC, explains the guidelines related to the problems in this thesis, in this case, the hazard and risk of hydrogen, in greater detail. The two standards that will be presented in this chapter are ISO/TR 15916 regarding Basic considerations for the safety of hydrogen systems, and then IEC 60079-10-1 related to the discussion on Classification of areas – Explosive gas atmospheres.

a. ISO/TR 15916: Basic considerations for the safety of hydrogen systems

(ISO/TR 15916, 2004) is an international standard or technical report regarding basic considerations for the safety of hydrogen systems and cover all aspect of hydrogen safety. The extent to which these standards are followed will vary depending on the application (such as the conditions and quantity of hydrogen involved, and the way in which the hydrogen is used). Good appliance design, combined with proper installation care, is expected to reduce the degree of safety considerations to levels that are judged acceptable by the public for common appliances in use today. Manufacturers of hydrogen appliances will need to take these principles into account in order to tailor enough specific information for their appliance's operation, the environment in which they will be utilized, and the audience who will use them. Hydrogen has been utilized safely in a variety of applications for many years. Following the concepts outlined in this technical report can help to ensure that hydrogen is used successfully in the future.

b. IEC 60079: Classification of areas - Explosive gas atmospheres

(IEC 60079-10-1, 2015) is concerned with the classification of area where flammable gas or vapour hazard may occur, which can then be used to support the correct design, building, operation, and maintenance of hazardous area equipment. It is meant to be used in situations where flammable gas or vapour is mixed with air and could provide an ignite hazard. This standard's strategy entails analysing and classifying the environment in which a potential explosion could occur, as well as making it easier to choose, install, and operate appropriate equipment for safe use in that environment. The ignition characteristics of gases or vapours, such as ignition energy and ignition temperature, are also taken into account in the classification. The determination of the type of hazardous zone and the zone's area are the two basic goals of area classification.

This standard is the most commonly used in terms of protection from explosion hazards and usually we have known as IECEx. Additionally, this standard has been used as a requirement in terms of planning, design, and installation for explosion protection. The Ex-standard covers both primary and secondary protection. Primary protection explains the basis for an explosion, including factors, hazardous areas, prevention of an explosion, and the method of primary explosion protection itself. While on secondary protection, it explains the relevance and advantages of the area classification in workplaces, explosion parameters, ignition temperature and fundamental matters, including maximum experimental safe gap (MESG) and minimum ignition current ratio (MIC).

2.3. Risk reduction measures

The main purpose of risk reducing measures is to mitigate or reduce the risk or consequences of certain activities, including safe operation and reducing consequences as well as emergency preparedness action (HSE, 2006). Another purpose is provided in the standards (NORSOK, 2010) that the risk reducing measures should take into account the reliability and the vulnerability of the risk reducing measures and the possibility of documenting and calibrating the evaluated measures of risk reduction. The steps taken to reduce the risk in each scenario are an important part of the risk analysis process for preventing, optimizing, or mitigating the effects of an accident, for example. Expert judgment and expertise can be used to evaluate risk-reduction techniques during the planning phase. It is critical to recognize the circumstances that may need a departure from earlier practices, norms, and standards. Following framework regulation (PSA, 2011), the risk reducing principle involved risk acceptance criteria (RAC) and As Low As Reasonably Practicable (ALARP) as the recommended methods to follow.

The main purpose of RAC is to keep the risk associated with particular activities to an acceptable level, which should be as low as possible (Aven *et al.*, 2004). With respect to a particular amount of time or phase of the activity, RAC determines the overall risk level that is defined as tolerable. The RAC serves as a reference for estimating the need for risk mitigation measures, thus it should be ready before the risk analysis begins (Aven, Vinnem and Vollen, 2006).

ALARP principle states that the risk should be reduce as low as reasonably practicable, a risk reducing measure should be implemented provided it cannot be demonstrated that costs are high in comparison to the benefits achieved (HSE, 2001). The general consensus is that all reasonable precautions will be taken in the event of a risk that falls within the so-called acceptable range. This is accomplished by gradually lowering them until the expense of further risk reduction is roughly excessive to the benefits that can be realized. When determining the RAC and risk-reduction strategies, the ALARP concept is critical in ensuring that the risk is reduced beyond the regulatory minimum.

3. Hazard and Risk of Hydrogen

Hydrogen is a valuable resource with limitless possibilities. The utilization of hydrogen technology has exploded in popularity during the last decade. Unfortunately, as usage grows, so does the risk of an incident. Despite the fact that some people think of hydrogen as a dangerous fuel, it has been utilized safely for generations in a variety of businesses. Some of hydrogen's qualities make it safer to handle and use than many conventional fuels today (e.g., hydrogen is non-toxic and much lighter than air, allowing leaks to dissipate quickly). However, on the other hand, necessitate unique engineering considerations in order to avoid an accident. Three important variables that apply to all flames adequately describe what is required for a fire to occur: fuel, oxidizer, and ignition. What we call fire is a "combustion" reaction, which is a chemical reaction of a fuel in which, in this case, hydrogen combines with an oxidizer such as oxygen. This extraordinary reaction can be harnessed for good under regulated conditions. Volatile hydrogen flames, on the other hand, can be very destructive in the wrong circumstances. Therefore, understanding the hazard and risk of hydrogen is the first step toward safety (WHA, 2021).

3.1. Hydrogen safety property

Due to the environmental and energy security benefits of hydrogen as a primary energy vector compared to conventional fossil fuels in terms of emissions and supply availability, the concept of hydrogen as a primary energy vector has received a lot of attention. The most prevalent element on the planet is hydrogen. Many scientists believe hydrogen will be an ideal future energy source, serving as both a future fuel and an energy carrier for electricity. Furthermore, hydrogen has other advantages, including being the most abundant element with a high energy content per mass (Dagdougui *et al.*, 2018). The table below shows the property of hydrogen compared to other gases that are important in terms of safety.

	Hydrogen	**Methane**	**Gasoline**
Flammability limits (vol%)	4.0–75	5.3–15	1.0–7.6
Auto-ignition temperature (°C)	572	632	440
Ignition energy (mJ)	0.018	0.280	0.25
Deflagration index (bar m/s)	550	55	100–150
Limits of detonation in the air (vol%)	13–65	6.3–13.5	1.1–3.3
Coefficient of diffusion in the air (cm/s)	0.61	0.16	0.05
Max flame speed in the air (cm/s)	3.06	0.39	–

Table 1. Property of hydrogen (http://www.nrel.gov)

Aside from its excellent burning qualities and high energy output per unit of mass, hydrogen has a number of disadvantages that could threaten its safety and acceptance by the general people. Traditional fuels have physicochemical qualities that are vastly different from hydrogen as mentioned in table 1. The low ignition energy, fast flame speed, poor flame visibility, colourless and odourless nature, and wide flammability range which means highly flammable and very easily ignited are all major concerns. In addition, because hydrogen is a lighter gas than air, it has a tendency to ascend and spread swiftly in the atmosphere, depending on the direction, rate, and pressure of the release. Therefore, a hydrogen economy must include safe methods for the production, storage, distribution, and use of hydrogen with respect to its property. Any hydrogen project that fails catastrophically could threaten the entire transition approach. Hydrogen, like most other energy carriers, can be handled and used safely with the right sensing, handling, and engineering methods (Rosyid, 2006).

3.2. Application of Hydrogen

The search for alternative fuels has grown in recent years as the world's energy needs have grown, with hydrogen being a clear possibility. Because it provides more energy per unit of mass than current fuels, hydrogen is a clean energy vector that can be utilized as a substitute fuel. Hydrogen is being used in a variety of applications. They range from large-scale uses in the chemical and oil industries to small-scale applications in portable devices or laboratories (in gas chromatography) and others (Ruiz, 2015).

Following (HySafe, 2007b), hydrogen application can be group into three sectors:

- Transport
- Stationary (industrial and residential)
- Portable

One advantage of hydrogen as an energy carrier is that it can easily power vehicles, locomotives, ships, and planes. In the transportation industry, the most advanced usage of hydrogen is in motor vehicles, particularly cars. This is why automobile manufacturers around the world are pouring money into hydrogen research and development. Internal combustion engines (ICEs), fuel cells, and gas turbines can all use hydrogen to power cars. ICEs, on the other hand, are a well-established technology that converts common liquid fuels to hydrogen with relative ease. As a result of these factors, some automakers are developing hydrogen-specific ICEs. Small hydrogen-fuelled gas turbines suitable for road cars are the subject of research in Germany and the United States. Gas turbines, according to some, may be the winning technology for using hydrogen for transportation applications. Hydrogen has been used for transportation in both aviation and a variety of other modes of surface transportation (Larsen, Feidenhans’l and Sønderberg Petersen, 2004)

The first sector deals with mobile applications for a hydrogen economy, as well as the stationary applications required to establish the infrastructure needed to support these mobile applications, such as hydrogen filling stations. According to (HySafe, 2007b), stationary application divide into two parts. Namely, industrial application (above or equal to 50 kW) and residential (small applications using below or equal to 5 kW and large applications using under 250 kW). In the short-medium term, it seems unlikely that direct hydrogen consumption for industrial or residential purposes will play a significant role. However, a growing amount of hydrogen for use as an energy buffer may be required in the long run. The essential infrastructure will have to be modified to the changing needs of the decentralized energy markets as they develop.

Hydrogen also plays an important role in the portable application sector. A portable application in this case is the use of hydrogen as the main material supporting fuel cells or better known, as hydrogen fuel cells. Small fuel cells can be used in portable electronic equipment (up to 100 W) and portable generators to replace batteries and internal combustion engines. Due to the weight of the fuel cell, the upper limit for a portable generator is around 5 kW. Portable electronic devices such as cell phones, laptops, cameras, etc. are one of the main applications for low-power fuel cells. Fuel cells can provide significantly more power per unit of space or weight than batteries but have lower output voltages and a slower response to transients. Portable generators, uninterruptible power supplies (UPS), auxiliary power units, power tools, and light vehicles such as electric trolleys, lawn mowers, and roadside equipment use fuel cells up to 5 kW(Larsen, Feidenhans’l and Sønderberg Petersen, 2004).

Furthermore, hydrogen is also used in a variety of industrial operations. Apart from the applications listed above, its use as a raw material in the chemical industry and as a reductor agent in the metallurgic sector are noteworthy. Hydrogen is a key component in the production of ammonia, which is used to make fertilizers, and methanol, which is used to make numerous polymers.

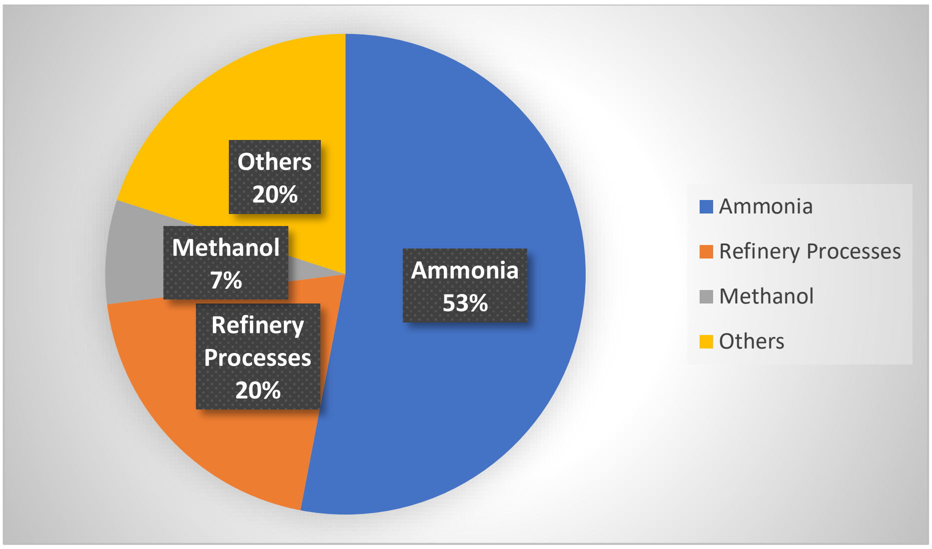


Figure 2. Pie chart of hydrogen uses

The use of hydrogen in the ammonia industry is more than in other industries, as shown in the pie chart above. Hydrogen is used as the main raw material in the formation of ammonia. Hydrogen is reacted with nitrogen to form ammonia according to the following equation.

$$3H_2 + N_2 \Rightarrow 2NH_3 \qquad (1)$$

While in the oil and gas industry, hydrogen is utilized in the refinement of crude oil into refined fuels like gasoline and diesel, as well as the removal of impurities like sulphur from these fuels (Ruiz, 2015).

3.3. Hydrogen accidental phenomena and consequence

In this subsection, the author will briefly describe the accidental phenomena and accidental consequences of hydrogen. Along with the rapidly growing use of hydrogen, as described in the previous chapter, the higher the risk that will be faced. Therefore, discussing this topic is important for knowledge to support hydrogen as a substitute for energy that is safe and environmentally friendly.

3.3.1. Accidental phenomena

The accidental phenomena in hydrogen are the same as in gases in general, it can be divided into three parts:

- Release of hydrogen
- Dispersion of hydrogen
- Hydrogen ignition

The result of a positive pressure difference between a container and its surroundings is gaseous hydrogen leaks through a hole or channel. A nozzle is commonly used to represent the aperture. A flow via a convergent nozzle to a lower downstream pressure can be chocked (sonic) or subsonic, depending on the upstream pressure. The ratio of constant volume to constant pressure specific heat determines the crossover pressure (Hanna and Strimaitis, 1989). In this case, the storage of hydrogen in the NORCE laboratory needs special attention to avoid this type of hydrogen release (sonic or subsonic release) due to the smallest molecule in hydrogen gas may enhance the likelihood of leakage through small pores and materials. In other words, because of its low viscosity, hydrogen is significantly more likely than other hydrocarbons to leak from piping connections. On a volumetric basis, hydrogen would leak three times faster than natural gas and five times faster than propane (Rosyid, 2006). The other way to hydrogen release that related to accidental phenomena is pool spreading and vaporization. The release of liquefied gas usually leads to the accumulation and creation of a liquid pool on the ground, which grows radially away from the releasing point, depending on the volume spilled and the rate of release, and which also begins to evaporate immediately. The pool's surface area expands during the initial release phase, implying a faster vaporization rate. Eventually, a state is attained in which the entering mass is equal to the evaporated mass. The cooling of the solid ground causes a reduction in heat input, resulting in a progressively growing pool size at a constant spill rate. Despite the ice development, the pool area and vaporization rate for the water surface are maximum and largely constant, as determined by lab-scale tests (HySafe, 2007a).

The second accidental phenomena are dispersion of hydrogen. The types of gas dispersion that need to take into account for in general are the dispersion in the open atmosphere, dispersion in obstructed environment and dispersion in confined environment. Forces coming from the internal energy of the gas and/or energy inside the system are primarily responsible for the formation of a gas cloud in the atmosphere. If there is not any early ignition, density variations, atmospheric conditions, and terrain all play a role in the structure of the vapour cloud. Density disparities between cloud and ambient air will be balanced out in the final phase due to atmospheric dispersion, and concentrations will eventually fall below flammability standards. When analysing hydrogen dispersion in a blocked environment, keep in mind that the dispersing cloud behaviour for gaseous and liquefied hydrogen spills is fundamentally different. When hydrogen escapes from the liquid state to the atmosphere, it disperses as a heavier-than-air gas with horizontal movement and extended dilution times, whereas hydrogen is a buoyant gas in its gaseous state. Some of the results reported for the dispersion of other flashing liquids may be applied to hydrogen dispersion in this way. The last type dispersion is dispersion in confined environment, the leakage in a confined environment differs from the open atmosphere and semi-confined situations in that it occurs in a room. The hydrogen is discharged into the room atmosphere, where it either builds up or disperses externally through venting holes. For low-momentum, gaseous hydrogen leaks, buoyancy has a greater impact on gas motion than diffusivity. The direction of the release determines the gas motion in high-pressure systems; however, in low-pressure systems, a jet is formed, which minimizes the gas's inertia (Venetsanos *et al.*, 2003).

The last accidental phenomenon of hydrogen is the ignition of hydrogen. We need to take into account variations in the ignition timing of the release of hydrogen, the aim of which is to reduce the consequences of the release of hydrogen. For flammable hydrogen-oxidant combinations, there are a variety of potential ignition sources. Flames, electrical sparks, fused wires, hot surfaces, heating, rapid adiabatic compression, shock waves, and catalytic materials are only a few examples. All of these processes raise the temperature of a piece of the combustible mixture to a point where the surrounding uncombusted layers react as well, resulting in a flame. A jet flame can be formed, for example, if hydrogen is ignited instantly (Pasman and Rogers, 2010).

3.3.2. Accidental consequences

Fire and explosion hazards can occur as a result of hydrogen phenomena such as release or dispersion, just as they do with gases in general. Based on the report (HySafe, 2007a), there are two type of explosion: chemical explosion and physical explosion. In chemical explosions, the developing blast wave transports a large percentage of the combustion energy uniformly dispersed in all directions. This impact is strongest at ground level (hemispherical) explosions, when the yield ratio might be twice that of a spherical explosion due to reflection. Overpressures, thermal radiation, debris or missile throwing, and the damage degree or vulnerability of the receiving items must all be taken into account. In the other hand, a bursting or rocketing pressure vessel, which can occur as a result of a fire induced BLEVE (Boiling Liquid Expanding Vapor Cloud Explosion), is the most common type of physical explosion. The BLEVE becomes increasingly damaging as the liquid density increases. A fireball will form if the liquid is combustible. A BLEVE generates many pressure spikes: from the flashing liquid, expanding vapor phase, and, if suitable, burning. However, an explosion cannot occur in a tank containing only hydrogen because an oxidizer, such as oxygen, must be present in a concentration of at least 10% pure oxygen or 41% air for an explosion to occur (Ruiz, 2015).

Same as explosion, fire hazard of hydrogen in general divide into two type: hydrogen flash fire and jet fire. Hydrogen will spread within its flammable range for many meters from the discharge, depending on the pressure of release, weather conditions, and the size of the smallest internal diameter of pipework. When a cloud of hydrogen in the open air comes into contact with an ignition source, it can cause a flash fire. The flame is returning to the source of the problem. A flash fire is a nonexplosive vapor cloud combustion that occurs when hydrogen gas is released into the open air (Pasman and Rogers, 2010).

Jet fires are usually smaller than pool fires (with liquid hydrogen) or flash fires, although depending on the fuel discharge rate, they can be rather enormous. Jet fire is the consequence of the continual combustion of a flammable fuel. A leak's flames are almost completely unidirectional (Houf and Schefer, 2007).

4. Study Case

4.1. Background

NORCE or Norwegian Research Centre AS was founded in July 2017 to create a powerhouse for research that will lead the way in innovation, value creation and research. NORCE is a Norwegian government-owned research institute and it is one of the biggest research organization of Norway. The presence of NORCE is to convey new knowledge and innovative solutions that will be essential and fruitful–regionally, nationally and globally.

Currently, NORCE has an ongoing analysis project in the laboratory. The ongoing process involves hydrogen as a support for the fermentation process. As a reminder that hydrogen is a gas that requires more attention as a hazardous gas because it is a flammable material, and which is often encountered in hydrogen accidents is an explosion hazard.

Generally, there is international standard for explosive equipment such as an ISO or IEC/Ex certification. that applies to protective systems against explosions as well as all equipment used in or related to explosive atmospheres, such as electrical and non-electrical equipment, components and safety devices, control and adjustments necessary for the safe operation of this equipment and protective systems. This usually used for company that involves explosive gas in their process operation such as offshore installation, petrochemical, smelter etc. NORCE, in this case does not use this certification due to EX-certification is commonly not used in experimental settings such as research laboratories with reference to the regulations. It is a challenge for risk management field to analyse this process to make safety management and control measure based on risk perspective at NORCE laboratory.

4.2. Process description

Bacterial biomass utilization become a source of protein, fat and vitamins has been going on since the 1960s. this is commonly known as microbial protein or single cell protein. Single cell protein (SCP) has been suggested as one of the potential alternatives to meet the rising global protein demand (Garc, 2021). For SCP production, a variety of feedstocks can be used, ranging from human edible products like sugar to waste products like wastewater resources. Whether the final food product is intended for animal or human consumption determines the feedstock used. Additionally, SCP may be made from a number of microorganisms, including microalgae, bacteria, and fungi (Pander *et al.*, 2020).

Autotrophic bacteria that fix carbon dioxide into their cellular biomass provide one of the most sustainable forms of SCP because it can produce cell biomass without generating any significant by-products. The following is a generalized reaction for aerobic CO_2 fixation through H2 oxidation:

$$H_2 + O_2 + CO_2 \Rightarrow \text{Biomass} + H_2O \qquad (2)$$

Another reference of chemical reaction is the one proposed for *Cupriavidus necator* based on culture estimates by (Ishizaki and Tanaka, 1990) as shown in equation below:

$$21.36\ H_2 + 6.21O_2 + 4.09\ CO_2 + 0.76\ NH_3 \Rightarrow C_{4.09}H_{7.13}O_{1.89}N_{0.76} + 18.7H_2O \quad (3)$$

Equation (3) is similar with NORCE fermentation process. H_2, O_2, and CO_2 are fed to the bioreactor, along with ammonia and minerals, for cell growth in a continuous fermentation system. The fermentation broth represents the liquid effluent from the bioreactor, which is typically characterized by 1-3 percent dry weight biomass (i.e., bacterial cells) and some unutilized nutrients. The effluent is sent to the downstream processing section, where it is mechanically dewatered and dried to remove the water. Finally, the SCP product will be spray dried into a powdered form that can be easily stored. Heat treatment of the effluent fermentation broth, alkaline treatment, or chemical extraction can all be used to reduce the nucleic acid content of the product (Wiebe, 2017).

4.3. Risk reduction priority of hydrogen at NORCE laboratory

The most serious risk associated with hydrogen use is a leak into the laboratory environment, which would raise the hydrogen concentration to dangerous levels. In the air, hydrogen has a lower explosive limit (LEL) of 4%. As a result, by emptying two 50L Hydrogen cylinders, the LEL of a small hermetically sealed laboratory with a volume of 500m3 can be reached. This can be accomplished in minutes if the leak is large enough. When high-pressure hydrogen is rapidly released from a cylinder, it can self-ignite.

Explosions of hydrogen pose a significant threat. Over a wide range of concentrations in the range of 4.0 percent –75 percent and 18 percent –59 percent, respectively, hydrogen gas forms combustible or explosive mixtures with atmospheric oxygen. Vapor cloud explosions occur when a large amount of hydrogen is released into the atmosphere and mixes with the air to form a large flammable cloud before being ignited (Pasman and Rogers, 2010). The strength of the explosion is determined by the magnitude of confinement, which is determined by the degree of confinement, and can result in a blast wave that damages nearby buildings and people (Baraldi *et al.*, 2009). Many studies on hydrogen stations have focused on hydrogen explosions, deflagrations, or detonations (Fukuda, 2004).

Based on the uncertainty of hydrogen hazard as mentioned above, it is important to implement risk reduction measures in order to safely use hydrogen in the laboratory. The core concepts of risk reduction, such as preventing, identifying, controlling, and/or minimizing the risk involved, as well as establishing an emergency response plan, must be followed when determining risk reduction steps. As a result, method selection is critical for a successful risk reduction strategy. Risk-reduction measures must follow the following priority, according to the standard (NORSOK, 2010).

4.3.1. Probability reducing measure

According to the standard (NORSOK, 2001) that reducing the probability of accidents should be favoured over reduction of consequence whenever this is technically, operationally and economically feasible. Which means reducing the probability of occurring related to hydrogen accidental phenomena such as release, or dispersion must be avoided or even eliminated rather than controlled.

Due to the property of hydrogen having a very low viscosity compared to other gases, the tendency to release hydrogen is difficult to prevent. Pressure testing using nitrogen on pipes that have "leak tight" will find leaks when testing using hydrogen. However, if installed by a competent person, the use of the correct sealing interface and suitable components in the hydrogen system will greatly limit the possibility of this happening. On the other hand, the low energy density of hydrogen means that it results in a much lower energy leakage rate. Nevertheless, a high priority should be given to preventing the probability of hydrogen release. Therefore, to limit the likelihood and size of any leak, special attention should be paid to the design, installation, operation, and maintenance of hydrogen handling equipment (Pritchard, Royle and Willoughby, 2009).

Another technique that can be used in terms of probability reducing measures is inherently safer design. Prevent accident rather than controlling is the main focus of this method. The table below shows the basic principle of inherently safer design that using in the chemical industry as recommendation.

Type	Typical techniques
Minimize (intensification)	• Change from large batch reactor to a smaller continuous reactor • Reduce storage inventory of raw materials • Improve control to reduce inventory of hazardous intermediate chemicals • Reduce process hold-up
Substitute (substitution)	• Use mechanical pump seals vs. packing • Use welded pipe vs. flanged • Use solvents that are less toxic • Use mechanical gauges vs. mercury • Use chemicals with higher flash points, boiling points, and other less hazardous properties • Use water as a heat transfer fluid instead of hot oil
Moderate (attenuation and limitation of effects)	• Use vacuum to reduce boiling point • Reduce process temperatures and pressures • Refrigerate storage vessels • Dissolve hazardous material in safe solvent • Operate at conditions where reactor runaway is not possible • Place control rooms away from operations • Separate pump rooms from other rooms • Acoustically insulate noisy lines and equipment • Barricade control rooms and tanks
Simplify (simplification and error tolerance)	• Keep piping systems neat and visually easy to follow • Design control panels that are easy to comprehend • Design plants for easy and safe maintenance • Pick equipment that requires less maintenance • Pick equipment with low failure rates • Add fire- and explosion-resistant barricades • Separate systems and controls into blocks that are easy to comprehend and understand • Label pipes for easy "walking the line" • Label vessels and controls to enhance understanding

Table 2. Inherent safety technique (Daniel and Joseph, 2011)

In practice, however, it may be difficult to verify the risk reduction features since they rely on operational methods that are seen as less trustworthy, such as preventing gas leaks from operations. The probability reduction measures in risk analysis are difficult to calculate. Evaluations of consequence-reducing measures, on the other hand, are simpler and more reliable (Vinnem, 2014).

4.3.2. Consequences reducing measure

Fires and explosions are the most common consequences of the release of hydrogen. Therefore, before that happens, it is necessary to assess the uncertainty of the hydrogen release in order to avoid having major consequences. In this case, the consequence of reducing measure is divided into two parts. The first is the consequences of reducing the measure of hydrogen release and the second is the consequences of reducing the measure of fire and explosion.

a. Consequences reducing measure of hydrogen release

The result of the continuous release of hydrogen is the formation of a cloud of combustible gas that can quickly burn when it encounters an ignition source. This needs to be anticipated to avoid greater consequences such as fire and explosion.

Because an explosive gas atmosphere can only exist if a flammable gas or vapour is present with air, it's important to figure out where a flammable atmosphere can form inside process equipment, or where a release of flammable substances can cause a flammable atmosphere to form outside process equipment. Gaseous hydrogen has no distinct colour or odour. It has the smallest and lightest molecule of any gas. As a result, gaseous hydrogen is more permeable to materials, has fewer leak routes, diffuses more quickly in the environment, and has greater buoyancy than other gases. As a result of these characteristics, released hydrogen rises and diffuses quickly, but if confined, it can concentrate in high spots. (IEC 60079-10-1, 2015). Therefore, detection measures are mandatory to be installed, especially in areas that have the potential for hydrogen release or leakage as a notification or alarm to immediately take precautions to prevent the accumulation of hydrogen release. However, it should be noted that the properties of hydrogen are not the same as those of hydrocarbon gases, so the selection of the right detector for hydrogen should be of particular concern and must comply with international standards.

Furthermore, ventilation design in confined areas also plays an important role in preventing the formation of combustible mixtures of hydrogen. Deflagration venting is widely considered as the most common and cost-effective method of explosion mitigation. The following observations/assumptions underlying the methods (HySafe, 2006):

- The less confinement of a room, the lower general overpressure is seen
- The more reactive gas, the more vent area is required for pressures to remain low

Generally, gas or vapour released into the environment may dilute due to turbulent mixing with air and, to a lesser extent, diffusion due to concentration gradients, until the gas disperses completely, and the concentration is basically zero. Dispersion will be aided by air movement caused by natural or artificial ventilation. Dispersion or diffusion of a gas or vapour into the atmosphere is an important factor in lowering the gas or vapour's concentration below the lower flammable limit (IEC 60079-10-1, 2015).

b. Consequences reducing measure of fire and explosion

The rate at which energy is released is the key distinction between fire and explosion. Explosions release energy quickly, usually in a couple of microseconds, whereas fire releases energy slowly. Fire can also result from explosions, and explosions can result from fire. A common thing that is used as a basic principle to avoid fire or explosions is the fire or explosion triangle. To start a fire or an explosion, three conditions must be met in the fire triangle. There must first be a flammable or explosive element present. Second, to promote the combustion reaction, oxygen or an oxidant must be present. Finally, an ignition source must be supplied to start the reaction. In simple term, if one of the fire or explosion triangle's components is removed, the triangle is broken, and a fire or explosion will not occur (Daniel and Joseph, 2011).

A number of mitigation methods applied to limit the effects of fires and explosions have been provided in international standards and the relevant literature. (National Fire Protection Association and American National Standards Institute, 2015) Recommends the use of fire alarm systems, automatic fire extinguishing systems and portable fire extinguishers. Whereas in terms of explosion mitigation, international standards (ISO/TR 15916, 2004) suggest preventing unwanted hydrogen/oxidizing mixtures (such as purging, a system must be purged with an inert gas to remove air before introducing hydrogen into the system, and the system should be purged of hydrogen before being opened to the air), the use of the ventilation system as referred to in point (a) and minimize the sources of ignition (electrical, mechanical, and thermal ignition sources) so that a fire triangle does not occur.

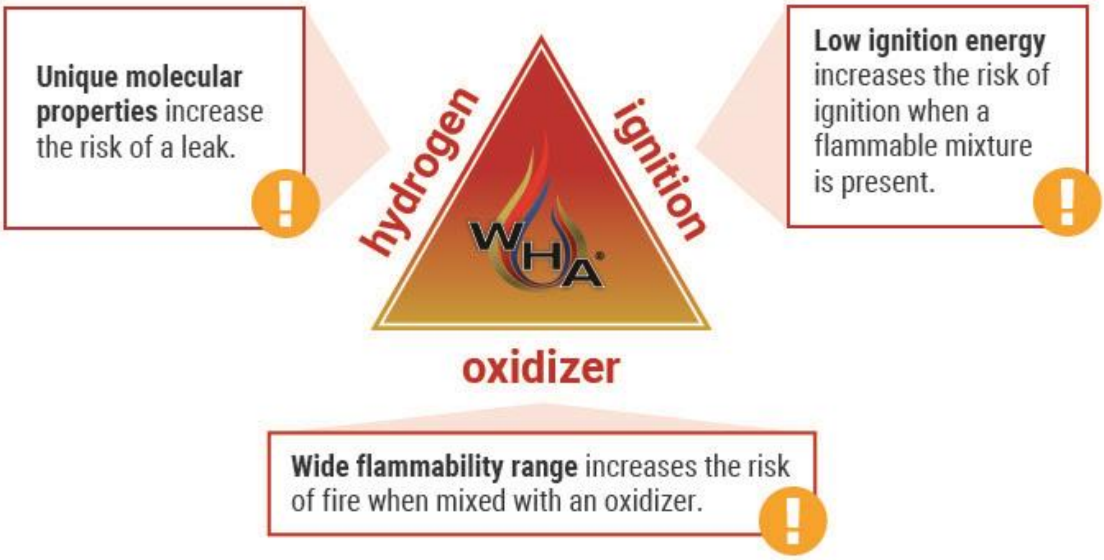


Figure 3. fire or explosion triangle of hydrogen (https://wha-international.com/hydrogen-fire-risk-management/)

In addition, because of hydrogen's high reactivity and the limited benefits predicted from active measures, considerable attention should be paid to finding the best passive protection strategies. Guidelines about gas explosions can be found in (Bjerketvedt, Bakke and van Wingerden, 1997). Here are some recommendations for passive protection design:

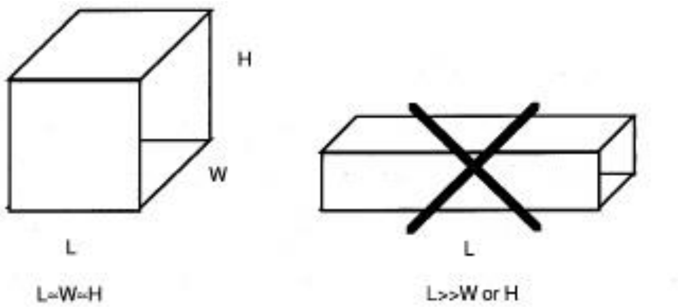
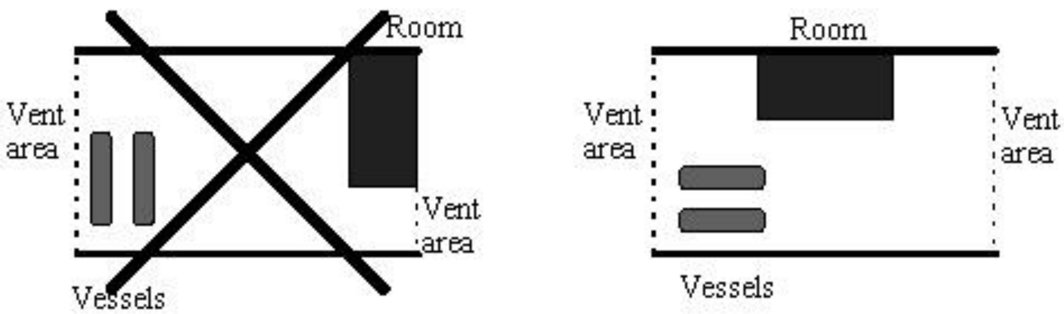


Figure 4. shape of compartment

A cubical box is the best design for a compartment with explosion venting on two end walls. A comparatively low explosive pressure can be expected in such a design.



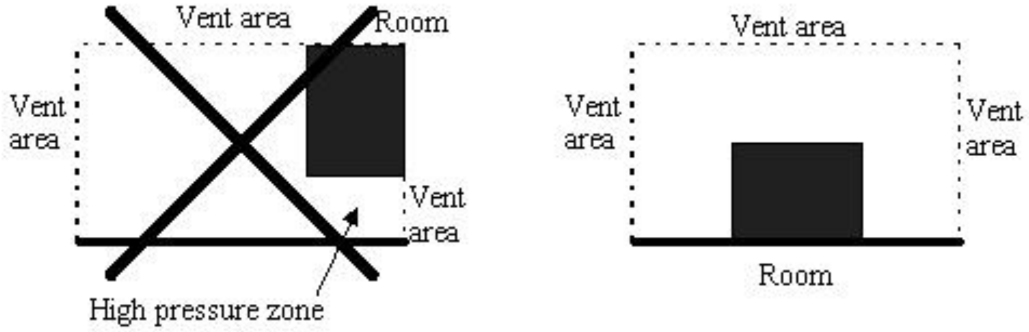


Figure 5. The effect of congestion and obstructions

Top view of two compartments. In the layout on the left side the room blocking the vent area and the vessels are generating turbulence by acting as repeated obstacles. The right side show an improved layout.

Furthermore, if fire and explosion cannot be avoided, then action to reduce the consequences of fire and explosion must be implemented. The use of an emergency response plan related to this event has been suggested in international standards (ISO 13702, 2015) with the aim of minimizing the impact of fire and explosion hazards, including on humans, preventing escalation to other buildings and minimizing the impact on the environment.

4.4. Suggestion risk reduction measure of hydrogen at NORCE laboratory based on international standard and regulation perspective

As we know generally in the industry and have explained in the regulations in the previous section, risk reduction measures usually related to the ALARP (As Low As Reasonably Practicable) principle to keep risk at an acceptable level. That means risk reduction measures have been implemented. If the topic of this thesis is the fermentation process in the NORCE laboratory using hydrogen as a supporting process, risk reduction measures must be considered in order to reduce or avoid the potential consequences of accidental hydrogen phenomena such as hydrogen release, dispersion, or even ignition. Based on the explanation of the effect of hydrogen in the section three, there are two consequences that will occur if one of the hydrogen phenomena happens. Namely explosion hazard and fire hazard. Therefore, it is necessary to pay more attention to these two consequences as discussed in this subsection namely, how to detect potential explosion hazards or fire hazards and suggestions regarding safety barriers and safety measures based on international standards and regulations.

4.4.1. Detection measure of explosive atmosphere and hydrogen flames

As discussed in the chapter on risks and hazards of hydrogen, the main danger of the accidental release of hydrogen is the hazard of explosions and fire. Because of its wide flammability and detonability ranges, as well as its low ignition energy, hydrogen is potentially more hazardous than other conventional fuels (methane, propane) or their vapours (gasoline) in most enclosed environments (Cracknell *et al.*, 2003). Although the risks associated with an unwanted release are likely to decrease quickly in outdoor situations and/or in the presence of adequate ventilation due to its high buoyancy, the deployment of an adequate system for the detection of explosive atmospheres and fire should always be considered as a possible safety measure. Other methods of detecting hydrogen are required due to the limits of human senses. To detect the presence of hydrogen, a range of methods and detector types are commercially available. Many of these detectors can be used in automatic warning and control systems.

a. Detection of explosive atmosphere

The substances likely to be present, the location of the sources, maximum source strength, and dispersion conditions must all be adequately known as major prerequisites for the use of alarms, and the instrument performance must be appropriate to the conditions of use, particularly in terms of response time, alarm level, and cross-sensitivity. Individual gas alarm system failures should not result in dangerous conditions, and the number and position of measuring stations should be designed so that the expected mixtures can be recognized quickly and reliably. According to standard and regulation, gas alarms for use in hazardous environments must be licensed and adequately identified as safe electrical equipment.

Depending on the working conditions, different types of hydrogen sensors are used. Electrochemical, catalytic, and thermal conductivity sensors are primarily utilized in industries where there is a risk of hydrogen contamination. Semiconductor-based sensors are most commonly employed in research labs, whereas MEMS (micro-electro-mechanic system) sensors are used in the aerospace and space industries (HySafe, 2006).

As stated above, semiconductor-based sensors are most often used in research labs. Due to the high cost for certified Ex for explosive-atmosphere every equipment at the NORCE labs and based on ALARP principle that the risk reducing measures should be implemented if the cost is not disproportionate relative to the benefits of risk reduction. It is appropriate that the NORCE laboratory install a sensor of this type as the risk reducing tools.

There are two types of MOXs (semiconductor metal oxide), namely n-type MOXs (zinc oxide, tin dioxide, titanium dioxide or iron oxide responding to reducing gases (H2, CH4, CO, C2H2, and H2S) and p-type MOXs (nickel oxide, cobalt oxide responding to oxidizing gases (O2, NO2, and Cl2). MOXs (semiconductor metal oxides) have attracted a lot of attention because of their low cost, high and fast reaction, and relative ease of use, as well as their ability to detect a wide range of gases (Phanichphant, 2014).

Following international standard (ISO/TR 15916, 2004), have recommended the use of hydrogen detectors wherever hydrogen is used. The locations listed below are some of the best places to put hydrogen detectors:

- *locations where hydrogen leaks or spills are possible.*
- *at hydrogen connections that are routinely separated (for example, hydrogen refuelling ports).*
- *locations where hydrogen could accumulate.*
- *in building air intake ducts, if hydrogen could be carried into the building.*
- *in building exhaust ducts, if hydrogen could be released inside the building.*

The following suggestions from (NASA, 1997) have been offered in order to develop a reliable hydrogen detection and monitoring system:

- *Evaluate and list all possible sources to be monitored (valves, flanges, connections, bellows, etc.) and provide valid justification for sources not monitored.*
- *Evaluate the expected response time of the leak detection system to ensure compatibility with the responding safety system.*
- *Provide visual and audible alarms as necessary when the worst allowable condition (red line) is exceeded. The allowable condition must still be in the safe range, but a warning indicates a problem.*
- *Provide portable detectors for field operations or isolated areas and permanently installed detectors for remote-automated operations.*
- *Utilize a program to maintain and periodically recalibrate detectors to ensure acceptable performance.*
- *Determine the number and distribution of sampling points in the hydrogen detection system based on the possible leak rate, ventilation amount, and area size. Consideration should be given to methods of routing hydrogen to the detector.*

As recommended above, a personal hydrogen detector is required in addition to the installed hydrogen detector for use by each laboratory worker in and around the hydrogen system. The most typical warning concentration level is 1% hydrogen (volume fraction) in the air, which is comparable to 25% of the lower flammability limit. This level should normally enable enough time to respond appropriately, such as by shutting down the system, evacuating workers, or taking other necessary actions.

b. Detection of hydrogen flame

Hydrogen is a colourless, odourless, and tasteless gas that emits relatively little light and colour when burned. Without specialized technology, hydrogen and hydrogen flames are extremely difficult to detect. Furthermore, as the smallest element on the periodic table, hydrogen is well-known. In practice, this means that the H2 molecules are extremely vulnerable to leakage. They can pass through many things that are thought to be "airtight". Hydrogen can even soak into metals, making them brittle and cracking (a process known as hydrogen "embrittlement").

Hydrogen flames emit far less heat than hydrocarbon flames, therefore human physical awareness of this heat does not occur until direct contact is established with the flame. As a result, a hydrogen fire in a place where hydrogen can leak, spill, or build and produce potentially combustible mixes may go undetected and spread despite any human direct monitoring. In these cases, hydrogen fire detectors can assist in taking immediate action. Fixed hydrogen fire detectors can be used to monitor remote operations continuously, or portable detectors can be used in the field.

The following is an explanation scenario of the occurrence of the hydrogen fire made by (Beeson and Woods, 2003):

- *Hydrogen is released, mixes with an oxidizer, and forms a combustible mixture. The mixture contacts an ignition source and ignition occurs.*
- *The hydrogen system is contaminated with an oxidizer as a result of improper purging and/or in leakage of an oxidizer, such as air. The hydrogen and the oxidizer form a combustible mixture, the combustible mixture contacts an ignition source, and ignition occurs.*
- *Hydrogen or an oxidizer leak from one part of a system into another part of the system where a combustible mixture is formed and ignited.*

And the following are some significant considerations to consider while choosing a hydrogen flame detector (ISO/TR 15916, 2004):

- *detection distance and area covered.*
- *susceptibility to false alarms from sources such as the sun, lightning, welding, lighting sources and background flare stacks.*
- *response time.*
- *sensitivity to appropriate radiation spectrum.*

Based on the suggestion above, we need to take it into consideration to have such a clear understanding as a guide related to the hydrogen flame detector to be installed at the NORCE labs. There are several types of hydrogen flame detector technology recommended by (NASA, 1997) and can be used as a reference for the installation of hydrogen flame detectors at NORCE labs.

- *Thermal fire detector classified as rate-of-temperature-rise detector and overheat detector have been manufactured for many years and are reliable. Thermal detectors need located at or very near the site of a fire.*
- *Optical sensor for detecting hydrogen fires fall into two spectral regions: ultraviolet (UV) and infrared (IR). UV system are extremely sensitive; however, they are susceptible to false alarm and can be blinded in foggy condition. Infrared system typically are designed for hydrocarbon fires and are not very sensitive to hydrogen fires.*
- *Imaging system mainly are available in the thermal IR region and do not provide continuous monitoring with alarm capability. The user is required to determine if the image being viewed is a flame. UV imaging system require special optic and very expensive. Low-cost system, using low-light silicon charge coupled device (CCD) video technology with filters centred on the 940- and 1100-nm emission peaks. Have been used at some facilities.*
- *A broom has been used for locating small hydrogen fires. The intent is a dry corn straw or sage grass broom easily ignites as it passed through a flame. A dry fire extinguisher or throwing dust into the air also causes the flame to emit visible radiation. This technique should be used with care in windy, outdoor environments in which the light hydrogen flame can easily be blown around.*

Detection could include keeping an eye on an unattended site or looking for signs that are not visible to on-site staff in order to take action before the accident gets out of hand. Detection addresses both needs in the case of hydrogen flames. However, we have noted that distinguishing hydrogen-related signals from parasitic signals may be difficult. As a result, it may be preferable to prioritize human analysis and actions above automatic ones in order to avoid false alarms and related automatic actions.

4.4.2. Safety barriers and safety measures

The usage of hydrogen carries a number of risks, not all of which are well understood or known. However, there is no reason why hydrogen should not be considered as an energy substitute in the future. The use of proper safety barriers and safety measures helps to significantly reduce risks and potential consequences. There are two types of actions in this subsection: mitigation measures and emergency response. In this case, NORCE labs, international standards and regulations for hydrogen systems can be used as guidance to acquire an acceptable safety barrier and safety measures. Various worldwide organizations and researchers have undertaken various efforts in this area over the last decade with the goal of making hydrogen a safe future energy.

a. Mitigation measure

When working with hydrogen, there are a lot of unintended consequences that can occur. The hazard will vary greatly depending on the situation and surroundings. In an unconfined process facility, a large leak of hydrogen gas may be safe, but if ignited within a building, a much smaller leak could be disastrous. Loss of life or harm to persons, property, reputation, and other consequences are all possible consequences. This chapter will go through several approaches and strategies for potentially lowering the risk of undesirable events (i.e., lowering the frequency and/or severity).

Hydrogen mitigation measures should take into account the accidental hydrogen phenomenon as described in part two of this thesis. There are three accidental phenomena that must be monitored and mitigated: dispersion (limiting the amount of flammable), fire hazard (limiting fire load and consequences), and explosion hazard (limiting pressure generation and consequences). The following is a proposed example of a protective measure for this accidental phenomenon created by (HySafe, 2006)

- Dispersion (limiting the amount of flammable)
  - ⇒ *Confine leak exposed area either by solid casing or by soft barriers (polyethylene sheets). This may limit flammable cloud size, by physically limiting the cloud or reducing the momentum of a jet release.*
  - ⇒ *Reduce confinement near leak-exposed area to allow buoyancy driven dispersion transporting hydrogen away.*
  - ⇒ *Natural ventilation, forced ventilation, emergency ventilation to remove hydrogen*
  - ⇒ *Removal of ignition sources to reduce explosion frequency.*
  - ⇒ *Igniters (or continuous burners) to ensure that gas clouds are ignited before they grow too large to limit consequences.*
  - ⇒ *Catalytic recombiners to remove unwanted hydrogen.*
  - ⇒ *Inert gas dilution after release but prior to ignition, reducing the reactivity.*
  - ⇒ *Fine water-mist dilution to reduce flammability, or sprinklers to improve mixing/dilution*
  - ⇒ *Rapid injection of dense hydrocarbon gas (e.g., butane) with much lower reactivity than hydrogen.*
  - ⇒ *Detection, activate shut-down (ESD), pressure relief, and safety measures, move people to safe place.*
- Fire hazard (limiting fire load and consequences)
  - ⇒ *Proper design against heat loads*
  - ⇒ *Passive fire protection to protect equipment and increase time before escalation*
  - ⇒ *Sprinkler systems and water deluge to cool equipment and control flames*
  - ⇒ *Inert gas systems or fine water mist to dilute oxygen and reduce heat generation.*
  - ⇒ *Avoid feeding oxygen into fire by proper confinement, limit ventilation.*
- Explosion hazard (limiting pressure generation and consequences)
  - ⇒ *Proper design against pressure loads, particular focus on manned areas and control rooms, as well as structures that can give escalation when failing.*
  - ⇒ *Explosion vents allowing overpressure to be vented*
  - ⇒ *Layout optimisation to limit turbulence generation*
  - ⇒ *Water deluge or mist generation ahead of flames cooling the flame*
  - ⇒ *Suppression systems quickly putting up inert atmosphere (powder, inert gas, water mist or too rich flammables) ahead of flame*

- ⇒ *Flame isolation by fast acting closing valves or flame arresters (Maximum Experimental Safe Gap, MESG)*
- ⇒ *The use of large balloons to prevent flammable mixtures in certain regions, but still give volume for gas expansion during explosion. Similar "soft barriers" could be used to limit combustion near ceiling (in flame accelerating beams) or other places with significant congestion.*
- ⇒ *Separation distances to avoid incidents to escalate to other parts of plant or to protect neighbours.*
- ⇒ *Absorbing/collapsing walls to reduce reflected shockwaves.*
- ⇒ *Introduce heat absorbing material, like porous elements made of thin aluminium foils or similar*

Because the list of probable circumstances is so extensive, this selection will not include all risk-reduction options. One thing to keep in mind is that some of the actions may appear to be paradoxical from a risk perspective, and it is not always clear whether risk is decreased or raised. For example, in the mitigation step of hydrogen dispersion above, removal of the ignition source vs ignition on purpose. If small gas clouds are always ignited, the frequency of explosions may grow, but the consequences are expected to be lessened, resulting in a risk that is presumably acceptable. Increased confinement, for example, can lower cloud size while also increasing pressure and the likelihood of unfavourable outcomes.

Another issue with mitigation devices is that they are typically tested in idealized scenarios (empty spherical vessel with central ignition), but then used in real-world scenarios where geometry will affect performance.

Logically in the three accidental phenomena above, we have to take into consideration at the hydrogen dispersion. We can eliminate the further consequences such as explosion and fire hazard when we can prevent hydrogen dispersion occur. Another way is to mitigate if the dispersion when it occurs. Based on the international standard of explosion (IEC 60079-10-1, 2015) and (ISO/TR 15916, 2004) have addressed of design of ventilation system to mitigate the further consequences of hydrogen dispersion. Generally, gas or vapour released into the atmosphere can be diluted by turbulent mixing with air and, to a lesser extent, diffusion driven by concentration gradients, until the gas disperses completely, and the concentration is basically zero. Dispersion will be aided by air movement, whether from natural or manmade sources. Due to higher evaporation on an exposed liquid surface, increased air movement may also speed up the discharge of vapour.

The following are basic functional that must be achieved in ventilation design based on international standards (IEC 60079-10-1, 2015):

- *To increase the rate of dilution and promote dispersion to limit the extent of a zone.*
- *To avoid the persistence of an explosive atmosphere that may influence the type of a zone.*

The following are some other considerations for ventilation systems (ISO/TR 15916, 2004):

- *Ventilation should be established prior to hydrogen being introduced into a confined space and continue until hydrogen is removed from the confined space.*
- *Ventilation should not be shut off as a function of an emergency shutdown procedure unless the source of hydrogen is outside the confined space.*
- *Suspended ceilings and inverted pockets in confined spaces should be avoided or adequate ventilation of these spaces should be ensured.*
- *Electrical equipment in the ventilation system should meet appropriate provisions for operation in a combustible environment.*

In a non-ventilated enclosed location, hydrogen leaks or spills can easily generate ignitable gas mixes. As a result, active or passive ventilation should always be present in confined spaces including equipment for handling or storing hydrogen. This ventilating system should be supported with hydrogen detectors especially in the restricted space such as NORCE labs to detect the presence of hydrogen and prevent the formation of a flammable mixture due to the diffusion of a gas or vapour into the atmosphere is an important factor in reducing the concentration of the gas or vapour below the lower flammable limit.

We must also acknowledge the threats that can develop from flames and hot combustion products that will come out of the ventilation system must be considered when building the ventilation system. They must be disposed of in a secure location, away from personnel and without causing damage to the surrounding equipment. This is especially true for ventilated equipment that is inside building such as NORE labs. Installing ducting on the ventilation system to divert the discharge to a safe region, ideally outside the building, is one solution to this problem. However, the installation of ducting will increase flow resistance, and any unburned gas discharged into the duct could cause a secondary explosion. The overall impact is that the flow through the vent is reduced, resulting in a reduction in the explosion pressure. To reduce vent inefficiency, ducting should be kept as short as possible, with no bends or excessive radius bends, and a cross-sectional area at least as large as the vent itself (NFPA 68, 2002).

b. Emergency Response

Essentially, the same emergency response methods that are available for gas can also be used for hydrogen-related accidents. However, because hydrogen is more reactive than other hydrocarbons, existing methods must be modified. Active firefighting, for example, is less effective than for other hydrocarbons, so a greater emphasis will be placed on comprehensive emergency response planning. The emergency response plan should take into account the key dangers that are expected and should try to reduce the risk to individuals. Furthermore, the emergency plan must be in writing and include the specific activities that employers and employees must follow to protect employee safety in the event of a fire or other emergency.

There are no specific standards governing emergency response methods for hydrogen. Therefore, they may be extracted from other areas where extensive emergency planning is seen as essential. (NORSOK, 2010), for example, covers both risk assessment performance and environmental preparedness assessment. The standard is organized in such a way that it is simple to identify the requirements that apply to each process separately. As a result, the standard can be applied when only one of the two processes is required. If/when both procedures are to be conducted "simultaneously", or during the same period of a project, the two processes should be integrated and/or coordinated to the greatest extent practicable. In many circumstances, the input data and outcomes generated by one process will be used as input to the other process, and vice versa. As a result, the two processes have merged to some extent.

Another international standard for reference guidelines of emergency response is (ISO 15544, 2010). Generally, the main principle of this standard is slightly similar to NORSOK. The systematic identification of hazards, followed by appraisal and risk management, is a core principle in emergency planning. The emergency response strategy, which describes the general philosophy of how the organization, procedures, equipment training, and other measures are supposed to work together to deal with foreseeable incidents – even if an emergency response measure fails. For example, direct mitigation measures for a hydrogen leak could include the shutdown of ignition sources upon gas detection to prevent ignition. This precaution may not be effective and may even cause ignition. Hence, warning and escape measures, as well as evacuation routes, must be included in the strategy. Furthermore, because all of these methods rely on the detection and notification of a hydrogen leak, the detection and communication systems must be extremely reliable.

NORSOK and ISO both explain communication methods. This is one of the critical components of the emergency response plan. Technical measures, organization, processes, and training will all be tailored to each other and the overall plan for effective communication. Effective emergency response is impossible if communication fails. Technical communication methods could trigger automatic activities such as prevention and mitigation actions like cutting off electrical power or initiating an alarm, emergency ventilation, allowing for manual intervention or even escape. Mobilization and communication within the emergency response organization, as well as mobilization of external resources, will require technical communication measures. All of these measures must be extremely reliable, and in circumstances when human action is required (mobilization, intervention, or escape), the recipient's ability to receive the message and interpret the critical information must also be taken into account. In addition, an organization designed and prepared for emergency response is also required for effective emergency response. The lines of communication should be fully understood and practiced, preferably on a regular basis. Within the organization, emergency procedures should be known and tested, particularly the function and use of communication technology.

c. Response to fires and explosions

Gas or hydrogen leakage is generally difficult to extinguish. The appropriate action for hydrogen ignition is to keep the surrounding area as safe from fire and explosion effects as possible and to avoid escalation. According to international standard (ISO 13702, 2015), the purpose of this section is to develop facilities that will allow people to deal with fire and explosions. The functioning and position of the equipment provided to allow workers on the installation to manage fires and explosions can have a big impact on how well they can use it in an emergency situation. As a result, the fire and explosion system (FES) will consider limiting the exposure of employees involved in fire and explosion management. Below are several considerations must be followed to obtain an effective response to fire and explosion:

- *Automating shutdown and control actions to limit the need for staff on the location to make complex decisions in an emergency situation. When manual initiation is used, the systems shall be simple to operate and shall not require operators to make complex or non-routine decisions. Once initiated, all control actions shall occur automatically.*
- *Presenting critical information at a control station so that personnel involved in managing an emergency have the information they need.*
- *Providing the functions and controls that will allow those on the location to initiate any emergency actions they decide is needed.*
- *Locating any emergency controls or equipment that are required for operation in a fire or explosion, such that there is a good prospect of being able to use them under emergency conditions.*
- *Limiting the amount of physical and mental effort required to perform their emergency response role effectively.*

In addition, those who are responsible for safety-critical actions must have demonstrated ability to do their duties in emergency situations. To maintain the required skill levels, regular training, workouts, and drills must be used. Other than that, reliable means of communication between sites that can be occupied, or must be occupied, must be provided.

4.5. Discussion

This section will include a discussion and recommendations for future work on risk-reduction measures in the context of hydrogen use at NORCE labs according to international standards and regulations. The main issue is how to address and identify the risk of using hydrogen in NORCE labs. As a result, risk-reduction measures were implemented in accordance with regulations and in order to achieve proper risk management. The discussion refers to a related journal article, book, regulation and international standard as a basis thinking for problem solving and recommendations in the risk management of hydrogen at NORCE labs.

Basically, the safe use of hydrogen is possible if the property of this energy carrier is taken into consideration. The related safety management, as with any other flammable gas, requires understanding from multiple disciplines. Material compatibilities, CFD (Computational Fluid Dynamics) calculations for dispersion, detailed chemistry for ignition, reactive flows in transitional states like flame acceleration and deflagration-detonation-transition and structural integrity considerations encounter new applications, operational modes and new materials in the hand of the public user.

The safety factor of the use of hydrogen should not be a barrier to using hydrogen as a substitute for energy. The use of hydrogen, particularly in the transportation sector, should be encouraged because it is a good step toward reducing carbon dioxide emissions from the combustion of existing fuels. This is due to the fact that hydrogen does not emit carbon dioxide during combustion, making it a clean energy source.

In fact, hydrogen has long been used safely in the chemical, manufacturing, and utility industries. But only limited to people who have done a series of training on the operation and handling of hydrogen. Of course, this is a barrier that makes hydrogen limited to general use. One step toward making hydrogen safe for general use is to adhere to the principle of risk reduction measures based on regulations and international standards.

Risk analysis for hydrogen specifically is still very limited and not yet available. For example, the ignition behaviour of especially cold clouds under atmospheric conditions is not well understood. The same applies to transition phenomena such as flame acceleration and the deflagration to detonation transition are well studied under ideal conditions (perfect premix, simple geometry), but for realistic scenarios (with inhomogeneous mixtures, realistic geometries), there is a lack of knowledge.

The discussion in section three regarding the hazard and risk of hydrogen is only based on the journal literature, regulations and international standards. When applied to hydrogen, many of the particular or general guidelines that have been successful in assessing risks associated with typical gas energy carriers have not been shown to be entirely conservative. This gap immediately involves difficulties in designing appropriate mitigation, including sensor techniques, ventilation systems and emergency response plans. Of course, this becomes a problem if risk reducing measures only link up to one guideline. As a result, the authors combine a number of related standards and regulations, as well as lessons learned from the hydrogen accident, to create appropriate risk management.

The main thing that is of concern in handling hydrogen is to understand the accidental phenomena and accidental consequences of hydrogen as discussed in section three. Hydrogen release, hydrogen dispersion and hydrogen ignition are hydrogen accidental phenomena that need to be understood before designing hydrogen handling measures. Fire and explosions are the most frequent accidental consequences in terms of hydrogen accidents.

Based on the discussion of section three related to accidental phenomena and accidental consequences of hydrogen, the authors decided to use the ISO 15916 and IEC 60079 standards by complying with the general rules of regulations such as PSA Norway and NORSOK Z-013 to make recommendations for risk reducing measures in the context of NORCE labs, such as those which have been discussed in section three. As a result, a comprehensive risk analysis is needed considering that hydrogen is very reactive compared to other hydrocarbons. However, in the case of NORCE labs, a comprehensive risk analysis seems too much for a research lab. In addition, data management related to hydrogen properties such as statistical approach, calculation of dispersion, detailed chemistry for ignition is still rare and not yet available. Therefore, the author concludes that the main thing that needs to be understood in the context of a research lab is a detailed understanding of the hydrogen accidental phenomenon. Because, in general, the consequences of hydrogen accidents are the same as other hydrocarbons, namely fire and explosion. Therefore, a detailed analysis of hydrogen accidental phenomena such as uncertainties or probability related to hydrogen accidental phenomena needs to be carried out to determine the appropriate risk reducing method.

From a risk perspective point of view, the hydrogen accidental phenomenon is an event (A), and the hydrogen accidental consequence is (C). There are uncertainties (U) related to (A) and (C) about whether event (A) will occur and what the consequences will be (C). The author limits the analysis of uncertainties to focus on accidental phenomena (A) and makes mitigation or emergency response plan when consequences (C) occur to reduce the impact of explosion or fire propagation.

uncertainties on hydrogen accidental phenomena based on lessons learned that occurred on Jun 28, 2010 (hydrogen explosion in university biochemistry laboratory). This condition is somewhat the same as that discussed in this thesis, namely the fermentation process using hydrogen in the NORCE lab. There are several uncertainties based on this incident, ranging from non-technical such as human error or misunderstanding related to standard operating procedures for hydrogen handling and technical such as equipment design. As a result of combining international standards with regulations and lessons from hydrogen accidents, the following recommendations have been discussed in this section:

- In terms of preventing the occurrence of accidental hydrogen phenomena, it is highly recommended to carry out periodic checks of the hydrogen lines before, during and after operation.

- Detection measures (both installed and portable) and ventilation design are important in planning risk reduction actions.
- Based on regulations applicable to the Norwegian Petroleum safety authority and the NORSOK Z-013 standard, discusses the importance of emergency response plans as part of risk management.
- Fire and explosion mitigation such as response is one part of the action to minimize the danger from accidents to equipment, personal and or the environment.
- Training of personnel should contain standard safety measures and a more specific examination of the hazards associated with working with hydrogen.

5. Conclusion

The release of hydrogen in laboratory fermentation processes can easily cause fires and explosions given that ignition sources can be found in the equipment involved. To prevent their occurrence and reduce the consequences of hydrogen release, key among these are principles of safer design, use of effective safety management systems, and inspection of prior incidents for learning. All of these link to the risk reducing methods in this thesis.

Basically, international standards and regulation are based on lessons learned from past incidents and accidents, a scientific approach and public expectation. Therefore, understanding the uncertainty of hydrogen accidental phenomena and consequences with the use of international standards and regulation is an appropriate way to design risk-reducing methods.

Since the use of hydrogen in the fermentation process in the NORCE laboratory is below the LEL (Lower Explosion Limit), the detection measure is critical to anticipate any unwanted hydrogen release with the assumption that a standard emergency response plan must be implemented. In addition, communication is essential in supporting an effective emergency response. As mentioned in section four, technical communication methods could trigger automatic activities such as prevention and mitigation actions like cutting off electrical power or initiating an alarm, emergency ventilation, allowing for manual intervention or even escape.

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