System-analytic Safety Evaluation of the Hydrogen Cycle for Energetic Utilization

(Systemanalytische Sicherheitsuntersuchung des Wasserstoffkreislaufs für die energetische Nutzung)

Dissertation

zur Erlangung des akademischen Grades

Doktoringenieur
(Dr.-Ing.)

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geboren am 25.06.1965 in Ciamis, Indonesien

genehmigt durch die Fakultät für Verfahrens- und Systemtechnik
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eingereicht am: **9. März 2006**
Promotionskolloquium am: **4. Mai 2006**

ACKNOWLEDGMENTS

This dissertation was completed during my work as a research assistant at Department of Process Design and Safety, the Institute of Process Equipment and Environmental Engineering, the Faculty of Process and Systems Engineering, the Otto-von-Guericke-University Magdeburg, Germany, in the period of February 2002 to March 2006.

Foremost I would like to express my deep gratitude to the head of the department, **Prof. Dr.-Ing. Ulrich Hauptmanns.** He gave me suggestions to this work and opportunity to carry out of the research work at his department. His continual support and constructive criticism in numerous valuable discussions always inspired me in my technical and personal development. Professor Hauptmanns is not only as a university professor, but also as fatherly friend. He supports me and my family during our stay in Germany.

I would like to thank **Prof. Dr.-Ing. Uli Barth**, Bergische University Wuppertal, for being kindly agreeing to be referee for this dissertation, and his important advice which certainly improved the quality of this work.

I am also thankful to my host institution in Indonesia, Agency for the Assessment and Application of Technology ("BPP Teknologi"), for granting me study leave to pursue a doctor degree in Germany.

Furthermore, my personal sincere thank goes out to all my colleagues at the Institute of Process and Environment Engineering and at the department, especially to Dieter Gabel, Junior Prof. Dr. Markus Marx, Dariusz Jablonski, Sascha Grünbeck, Sören Omieczynski, and Alexander Bernhardt for inspiring discussions and, above all, for the pleasing work environment which I really enjoyed.

I thank also Mrs. Gabriele Fietz for her assistance with all organizational things.

A very important part of this work goes to my families and my wife Dedeh Ruhtika, also my daughters Nur Amalina Husna, Hanifah Nisrina, and Saskia Shafira, who have given me ongoing encouragement, trust and supports.

This work was financially supported by Goverment of Sachsen-Anhalt, Germany and Otto-von-Guericke-University of Magdeburg. Thank you for this support.

Magdeburg, 8. March 2006
Oo Abdul Rosyid

DANKSAGUNG (Acknowledgment in German)

Die vorliegende Arbeit entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Lehrstuhl für Anlagentechnik und Anlagensicherheit des Instituts für Apparate- und Umwelttechnik, Fakultät für Verfahrens- und Systemtechnik, der Otto-von-Guericke-Universität in Magdeburg, Deutschland, im Zeitraum von Februar 2002 bis März 2006.

Mein besonderer Dank gilt dabei dem Inhaber des Lehrstuhls für Anlagentechnik und Anlagensicherheit Herrn **Professor Dr.-Ing. Ulrich Hauptmanns.** Er gab die Anregung zu dieser Arbeit und mir die Gelegenheit zur Durchführung meiner Forschungsarbeiten an seinem Lehrstuhl. Seine fortwährende Unterstützung und seine fördernde Kritik in zahlreichen Fachdiskussionen inspirierten mich stets in meiner fachlichen und persönlichen Weiterentwicklung. Nicht nur als Hochschullehrer, sondern auch als väterlicher Freund unterstützte Prof. Hauptmanns mich und meine Familie während unseres Aufenthaltes in Deutschland.

Herrn **Professor Dr.-Ing. Uli Barth,** von der Bergischen Universität Wuppertal, danke ich für die Übernahme des Koreferates, und die guten Hinweise, die zur Verbesserung der Qualität dieser Arbeit beigetragen haben.

Ich bin auch dankbar zu meiner Hauptinstitution in Indonesien, „Agency for the Assessment and Applications of Technology (BPP Teknologi)“, denn im Bewilligen mir des Studie vom Doktor grad in Deutschland auszuüben.

Meinen Kolleginnen und Kollegen am Institut und am Lehrstuhl, vor allem Dieter Gabel, Junior Prof. Dr. Marcus Marx, Dariusz Jablonski, Sascha Grünbeck, Sören Omieczynski, und Alexander Bernhardt gilt mein besonderer Dank für die anregenden Diskussionen und vor allem für das angenehme Arbeitsklima, das ich während meiner Tätigkeit sehr genossen habe.

Weiterhin danke ich Frau Gabrielle Fietz für ihre Hilfe in allen organisatorischen Dingen.

Ganz herzlich möchte ich mich bei meinen Eltern und meiner Frau Dedeh Ruhtika sowie meinen Kindern Nur Amalina Husna, Hanifah Nisrina, und Saskia Shafira für ihre Geduld und Unterstützung bedanken.

Diese Arbeit wurde vom Land Sachsen-Anhalt und Otto-von-Guericke-Universität Magdeburg finanziell unterstützt. Auch für diese großzügige Förderung sei gedankt.

Magdeburg, 8. März 2006
Oo Abdul Rosyid

ABSTRACT

Hydrogen is considered as an energy carrier for the future. It is enabling sustainable clean efficient production of power and heat from a range of primary energy sources. It can be produced from water using a variety of primary renewable energy sources such as sunlight, wind power, biomass and hydroelectric power and also from nuclear energy. It can also be produced from hydrocarbons such as methanol and natural gas by a variety of reforming processes. When hydrogen is burnt directly as a fuel or converted to electricity, its principal by-product is water, which can be returned to the environment. Hydrogen can be used in wider ranges of energetic applications (e.g. as fuel for traffics, heat and power generation for household, etc).

In order to make hydrogen available at a large-scale as an energy carrier, an infrastructure covering the following steps must be built up: production, transportation, storage, filling station, and end-use. The technical installations used can fail, and the necessity of handling incidents may occur in many places. Therefore it is reasonable to determine the safety technological conditions and associated operating procedures for the realization of the hydrogen infrastructure at an early stage. This is the goal of the present work in which system-analytic methods, called “quantitative risk assessment (QRA)”, are used to estimate and to evaluate the risks, to identify possible weak points, and to make suggestions for improvement quantitatively.

In the present study, the QRA method is performed to evaluate the safety of the seven hydrogen study objects. They include hydrogen production, hydrogen storage, hydrogen filling station, and end-uses technologies (i.e. hydrogen private car, and fuel cells–combined heat and power for household). Firstly, accident scenarios of the hydrogen study objects are identified. Frequencies of the scenarios are estimated by using the probabilistic safety analysis-analytical approach, i.e. combination fault tree and event tree analysis. PHAST consequence model is used to predict the size, shape, and orientation of hazards zones that could be created by the scenarios. Finally, the consequence and frequency are combined to estimate the risk to the environment.

The estimated risk is compared with the existing standards, as well as with the systems having similar goals (e.g. LPG). The result shows that the risk level of the hydrogen objects lies in the risk reduction desired criteria. Should the plants be implemented for the public, the risk must be reduced as far as reasonable and practicable, typically subject to cost benefit analysis. Although, the individual risks of the hydrogen objects seem to be higher than that of LPG, but the societal risks are smaller. In other word, hydrogen poses smaller risk to the public than that of LPG.

KURZZUSAMMENFASSUNG (German Abstract)

Wasserstoff wurde als ein wichtiger Energieträger für die Zukunft gehalten. Er ermöglicht die saubere effektive und nachhaltige Herstellung von Energie und Wärme aus einer Reihe primärer Energiequellen. Er kann aus Wasser durch die zur Verfügung stehenden erneuerbaren Primärenergien, wie Sonnenlicht, Windenergie, Biomasse und Wasserkraft und aber auch aus Atomenergie produziert werden. Es kann auch aus verschiedenen Kohlenwasserstoffen, wie Methanol und Erdgas über Reformprozesse erzeugt werden. Wenn Wasserstoff direkt als ein Kraftstoff verbrannt oder in Elektrizität umgewandelt wird, ist das einzige Nebenprodukt Wasser, das problemlos in die Umwelt abgegeben werden kann. Wasserstoff kann in einem weiten Feld energetischer Anwendungen genutzt werden (z.B. als Kraftstoff für Verkehr, Wärme- und Stromerzeugung für den Haushalt, usw.).

Um Wasserstoff im großen Maßstab als Energieträger zur Verfügung zu stellen muss eine Infrastruktur aufgebaut werden. Diese umfasst die folgenden Stationen: Herstellung, Transport, Lagerung, Tankstelle und Endverwendung. Die technischen Installationen, die benutzt werden, können versagen, und die Möglichkeit von Handhabungszwischenfällen kann vielerorts vorkommen. Deswegen es ist sinnvoll schon im Frühstadium die technischen Randbedingungen und zugehörigen Arbeitabläufe für eine sicher Infrastruktur zu bestimmen. Dies ist das Ziel der vorliegenden Arbeit, in der systemanalytische Methoden - “quantitative risk assessment (QRA)” - benutzt werden um die Risiken auszuwerten, um mögliche Schwachstellen zu identifizieren und quantitative Vorschläge für Verbesserung zu machen.

In der vorliegenden Studie ist eine QRA-Methode ausgeführt worden, um die Sicherheit der sieben Wasserstoff-Studienobjekte auszuwerten. Sie umfassen Wasserstoffherstellung, Lagerung, Tankstelle und Endverwendungen (d.h. Wasserstoff-Auto, Brennstoffzellen - Kraft- Wärmekopplung für Haushalte). Unfallszenarien der Objekte werden erstens gekennzeichnet. Häufigkeiten der Szenarien werdengeschätzt, die probabilistic-sicherheits-analyse benutzt (d. h. Kombinations vom Fehler- und Ereignisbaum-Analyse). PHAST Konsequenz Modell benutzt vorauszusagen die Größe, Form, und Orientierung von Gefahren aufteilt das konn schaffte durch die Szenarien. Die Konsequenz und Häufigkeit wird sich schließlich dann verbunden, um das Risiko an der Umgebung zu schätzen.

Das geschätzte Risiko lässt sich mit den bestehenden Niveaus vergleichen und auch mit Systemen die ähnliche Ziele haben (z. B. LPG). Die Ergebnisse zeigen, dass das Risikoniveau der Wasserstoffobjekte in einem Bereich liegt, in dem man eine Reduzierung anstreben muss. Sollten die Anlagen für die Öffentlichkeit realisiert werden, muss das Risiko so weit sinnvoll möglich und umsetzbar reduziert werden, was typischerweise Gegentand einer Kosten-Nutzenanalyse ist. Obwohl, die individuellen Risiken der Wasserstoffobjekte scheinbar höher sind als die von LPG sind aber die sozialen Risiken kleiner. Anders ausgedrückt stellt Wasserstoff ein kleineres Risiko als das von LPG für die Öffentlichkeit dar.

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Chapter 1

INTRODUCTION

1.1 Problem Definition

In discussions about the future of our energy supply – particularly in connection with renewable energy sources – hydrogen is considered as an energy carrier. As a storage medium for energy, hydrogen fulfils several requirements concurrently, proving to be the most environmentally friendly energy carrier – because the only "waste gas" released when using it is water vapour. Moreover, hydrogen's special characteristics render it the ideal storage medium for electricity generated from renewable energy sources, making it the most important link in a sustainable energy value chain, which is completely emission free from beginning to end. Unlike fossil fuels such as crude oil or natural gas, hydrogen will never run out, because hydrogen is the element most commonly found in nature. Besides, the stored hydrogen can be used both to generate electricity or directly as a fuel, which makes it highly suitable for stationary as well as mobile applications. However, it must be kept in mind that it is only a medium for storage and not an energy source by itself, because it must be obtained from water or hydrocarbons by separation.

In addition, applications of hydrogen in energy sectors, especially for road vehicle and household uses are a promising avenue that must lead to an increased use of hydrogen technologies. Hydrogen used in fuel cells or as fuel in an internal combustion engine would result in reduced pollution. A rapid development of end-use technologies today will put hydrogen in the near future to be used as an energy carrier and fuels, called "hydrogen energy economy". A significant increase of hydrogen use as an energy carrier is, however only possible, if the risks of an accident in a production plant, during storage, transport, or end-use are controlled in order to avoid an increase of risk to the public as compared with well established procedures.

Hydrogen has a long history of safe use in the chemical, manufacturing, and utility industries, which are predominantly operated by highly trained people. However, as a large-scale energy carrier in the hands of the general public, where untrained people will deal with hydrogen, it may create safety issues unique to energy projects. In order to make hydrogen available at a large-scale as an energy carrier, an infrastructure covering the following steps must be built up: production, transportation, storage, filling station, and end-use. The technical installations used can fail. Furthermore, the possibility of handling incidents may occur in many places. Therefore it is reasonable to determine the safety technological conditions and associated operating procedures for the realization of the hydrogen infrastructure at an early stage. This is the goal of the present work in which system-analytic methods are used to evaluate the risks quantitatively, to identify possible weak points, and to make suggestions for improvement. The determined risk will be compared as far as possible with systems having similar goals, e.g. use of LPG.

1.2 Objective

The objective of the study is to establish the safety technological conditions for the safe use of hydrogen as an energy carrier, to determine the risk connected with hydrogen uses at large-scale, and to compare this risk associated with similar technologies. The emphasis of the work is on the development of accident scenarios for the technical plants and the interfaces to humans.

1.3 Methodology

Safety evaluation is performed by safety analysis methods, which means that a systematic examination of the structure and function of a process plant system aimed at identifying potential accident contributors, evaluating the resulting risk, and finding risk-reducing measures [107]. The study uses a quantitative risk assessment (QRA) method to calculate and evaluate risk quantitatively. The method mainly consists of five elements, i.e. hazards identification, probabilistic safety analysis, consequences analysis, risk estimation, and risk evaluation.

Firstly, one or more realistic representatives system of hydrogen energy cycles from [200, 212, 187, 181, 78, 79, 199, 96, 171, 176] had been evaluated and selected as basis for the work (study objects). Safety-relevant of hydrogen properties and incidents relating to hydrogen were also compiled and evaluated. Appropriate technical components and equipments of the selected hydrogen study objects were then assigned, and the appropriate process flow of the system was also determined. Hazard identification methods had been carried out to determine some conceivable accident scenarios and definitions of the top events. Based on the above information the associated event tree and fault tree diagrams were developed. The failure data of the technical plants and human error probabilities for quantitative evaluation were collected and evaluated. It continues with quantitative evaluation of fault tree and event tree to calculate the expected frequencies of the initial events and the associated accident outcomes. The weak point analysis is elaborated on a basis for technical improvements. Its validity is proved by further probabilistic evaluation. The consequences of the accident outcomes (i.e. end points of the event tree diagrams) are simulated with existing consequence models (e.g. PHAST). They include discharge and dispersion modelling, fire and explosion effects modelling, and the estimation of incident impacts on people. The risk is estimated by combining the potential consequences and the expected frequencies of the accident outcomes. Finally, the risks are evaluated which may be done by comparing with legally required risk criteria, and/or comparison with the similar technologies.

1.4 Scope of the Study

Scope of the study was performing a QRA study on the hydrogen cycle for energetic applications in traffic and households sectors. The Seven study objects representing the hydrogen energy cycle were identified and analysed. They include hydrogen production, storage at depot, filling station, end-use technologies (e.g. hydrogen private car and fuel cell-combined heat and power for households), and hydrogen transportations (e.g. hydrogen road truck and hydrogen pipeline). The QRA study was focused on their storages where most of the time a large amount of hydrogen is available.

1.5 Barriers to Introduction

Some obstacles that must be overcome to achieve the goals and objectives of the study include:

- Difficult access to industry proprietary data. Hydrogen technologies, systems, and components are still in the pre-commercial development phase. As such, only limited data are available on the design and the operational and safety aspects of these technologies.
- Limited historical database for components. Only a small number of hydrogen technologies, systems and components are in operation. As such, only limited data are

available on the operational and safety aspects of these technologies, and the materials from which they are fabricated.
- Relevant accident data have been difficult to obtain for information of risk due to the following reasons: (1) confidentially aspects among the companies, (2) the availability information is not detailed enough to develop detailed scenarios, and (3) existing hydrogen accidents data/statistics relate to an industrial use rather than private customers..

1.6 Structure of the Dissertation

This dissertation focuses on quantitative risk assessment of the hydrogen cycle for energetic uses. It is divided into six chapters. The first chapter discusses for study background, goals, methodology, scope of work, and barriers of the study. The second chapter provides a brief introduction to a hydrogen energy economy. Chapter 3 describes in detail the hydrogen study objects considered in the study. Chapter 4 describes how to estimate the risk by introduction of a quantitative risk assessment (QRA) method. This chapter is divided into five main sections, hazard identification method, estimating frequency, consequence modelling, risk estimation and risk evaluation. In Chapter 5 the QRA results and risk evaluations are presented. It includes frequency estimation results, consequence modelling results, and the estimated risks in the form of individual and societal risk. This chapter introduces the term “tolerable risk”. Any risk assessment must compare the risk analysis result with tolerable risk levels accepted by society. Chapter 6 contains summary of the results and the outlooks.

The dissertation has eight appendices. The first appendix (Appendix A) presents table of hydrogen properties. It includes leak properties, combustion properties, and hydrogen embrittlement. The Appendix B presents a brief description of the hydrogen production technologies. Summary of the hydrogen related accidents are presented in the Appendix C. Appendix D presents standards, codes, and regulations related to hydrogen. The brief description of the consequence model used in the study is presented in Appendix E. Appendix F presents the fault tree method (analytical approach) used in the study. The Appendix G presents fault tree analysis (FTA) of the hydrogen study objects. Finally, the last appendix (Appendix H) presents the summary of the risk calculation results.

Chapter 2

HYDROGEN ENERGY ECONOMY

2.1 INTRODUCTION

The term, "hydrogen energy economy" refers to global economy hydrogen, using hydrogen for energy carrier. It is a vision for future in which economic system is based on the use of hydrogen as an energy storage and transport medium. It is important for the advancement of humanity for several reasons. First, the fossil fuel economy is fraught with problems: limited supply, global warning, and pollution [74, 81]. Fossil fuels are, indeed, running out. There is a finite supply of oil to be found on the planet, and once that oil is consumed, it simply cannot be recreated without waiting hundreds of thousands of years for nature to create more. By burning the fossil fuels to obtain energy a number of air pollutants and CO_2 are released. The release of CO_2 into the atmosphere may bring about significant global climate changes; CO_2 is a called a greenhouse gas due to its physical characteristic of acting like a layer of glass in the atmosphere allowing the heat from the sun to penetrate but not escape thus contributing to global warming. The air pollution is worsening to an extent where major cities around the world are being forced to restrict car use and introduce measures to encourage cleaner vehicles.

The advantage of a hydrogen energy economy is that it could completely eliminate the problems created by our present fossil fuel economy. Hydrogen as a secondary energy carrier offers the best alternative solutions. Hydrogen produced from renewable energy provides an alternative fuel free of all carbon emissions, and offers a sustainable energy supply. Hydrogen fuel cell vehicles produce no emissions except for water vapour, creating a solution to current urban air pollution problems.

The concept of using hydrogen as an energy system is not new; it has previously been used both industrially and domestically. In the first half of this century the entire gas supply in Germany consisted of town gas, a coal gas made up of more than 50% hydrogen. Only with the discovery of oil and natural gas reserves was hydrogen gradually forced out of the public supply system. As recently as in 1992, almost 3 billion m^3 of town gas (a third of that in the former East Germany) was still in use in the private household and small industry sector [212]. The hydrogen energy economy mainly consists of four functional steps: production, storage, transport, and end-use [31].

The prospect of hydrogen energy economy, however, often raises concerns about safety due to hydrogen accidents in the past. As hydrogen technologies developed, safety issues should be addressed. The public's perception and willingness to accept hydrogen as an energy carrier and fuel could be a significant barrier to the construction of a hydrogen economy. Whether used for transportation or in stationary applications the public will have to be encouraged to adopt new technologies as they begin to become commercially available.

This chapter discusses hydrogen safety basics, hydrogen energy technologies, and the vision use of hydrogen in energetic applications. At the end of this chapter, two realistic end-use scenarios considered in the study are presented.

2.2 HYDROGEN SAFETY

Like all fuels, hydrogen has inherent hazards and must be handled carefully. However, hydrogen has gained an undeserved reputation as a highly dangerous substance. In fact, hydrogen has been used for years in industrial processes and as a fuel by NASA, and has earned an excellent safety record. “Town gas,” a near 50-50 mixture of hydrogen and carbon monoxide, was also widely used earlier in this century before it was replaced by natural gas. A recent study suggests the Hindenburg accident was not caused by a hydrogen explosion. It was likely caused by paint used on the skin of the airship, which contained the same component as rocket fuel.

Safe practices in the production, storage, distribution, and use of hydrogen are essential components of a hydrogen economy. A catastrophic failure in any hydrogen project could irreparably damage the entire transition strategy. Like most energy carriers, however, hydrogen can be handled and used safely with appropriate sensing, handling, and engineering measures.

2.2.1 Hydrogen Safety Properties

Hydrogen is the simplest element, has three isotopes: hydrogen at wt 1.008 (H), deuterium at wt 2.0141 (D), and tritium at 3.0161 (T). Hydrogen is very abundant, being one of the atoms composing water. Whereas hydrogen atoms exist under certain conditions, the normal of pure hydrogen is the hydrogen molecule, H_2, which is the lightest of all gases [190]. The hydrogen molecule exists in two forms, ortho-hydrogen and para-hydrogen, depending on the nuclear spins of the atoms.

A phase diagram of hydrogen is shown in Figure 2.1. In normal conditions (20°C, 0.1 MPa) hydrogen is a colourless, tasteless, non-poisonous, and flammable gas. At low temperature, hydrogen is a solid with a density of 70.6 kg/m^3 at -262°C, and a gas at higher temperature with a density of 0.089886 kg/m^3 (i.e. 7% of the density of air) at 0°C and a pressure of 0.1 MPa. Hydrogen as a liquid in a small zone between the triple and critical points with a density of 70.8 kg/m^3 at -252.87°C (Appendix A). As temperature decreases, the hydrogen gas can be transformed into liquid state, which requires an energy in amount of 670 J/g [190].

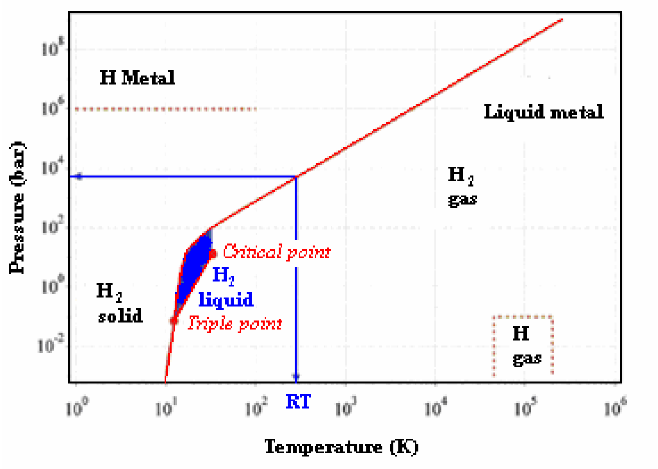


Fig. 2.1 Simple phase diagram of hydrogen [213]

Nothing what humans do is without risk, consequently, also each energy poses its specific safety risks which have to be taken care of. Hydrogen can be safer than conventional fuels in some situations, and more hazardous in others [12]. The relative safety of hydrogen compared to that other fuel must therefore take into consideration the particular circumstances of its accidental release. Hence a meaningful comparison must be based on comparing all relevant situations. Cadwallader and Herring [36] quote the National Hydrogen Energy Association as having qualitatively determined that methane was less dangerous than hydrogen and that hydrogen was less dangerous than propane. The following subsection gives a brief overview of the hydrogen safety properties, and compared with those of methane, propane and gasoline.

2.2.1.1 Leak Propensity

Hydrogen gas has the smallest molecule and has a greater propensity to escape through small openings than liquid fuels or other gaseous fuels. For transfer through a membrane the relative rate is governed by the relative diffusion coefficients of the materials. For subsonic releases through openings the rate is dependent on whether the flow is laminar or turbulent. For laminar flow the relative molar leak rates of two gases are theoretically inversely proportional to the ratio of their dynamic viscosities. For turbulent flow the molar leak rates are theoretically inversely proportional to the square root of the relative gas densities. For sonic releases the molar leak rates are proportional to the sonic velocity of the gases. For perfect gases the ratio of molar flow rates equals the ratio of volumetric flows.

Predicted theoretical flow rates of methane and propane relative to hydrogen are given in Table 2-1. The high pressure systems of hydrogen storage the flow from any leaks is likely to be sonic [12]. Therefore hydrogen would leak approximately 3 times faster than natural gas and 5 times faster than propane on a volumetric basis. However the energy density of hydrogen is lower than that of methane or propane such that for sonic flow its energy leakage rate would be 0.34 times that of methane and 0.2 times that of propane.

Leaks of liquid hydrogen evaporate very quickly since the boiling point of liquid hydrogen is so extremely low. Hydrogen leaks are dangerous in that they pose a risk of fire where they mix with air. However, the small molecule size that increases the likelihood of a leak also results in very high buoyancy and diffusivity, so leaked hydrogen rises and becomes diluted quickly, especially outdoors. This results in a localized region of flammability that disperses quickly. As the hydrogen dilutes with distance from the leakage site, the buoyancy declines and the tendency for the hydrogen to continue to rise decreases [12]. Very cold hydrogen, resulting from a liquid hydrogen leak, becomes buoyant soon after is evaporates.

Table 2-1. Leakage properties of hydrogen and other fuels [12].

Leakage Properties	**Hydrogen**	**Methane**	**Propane**
- Diffusion coefficient in air at NTP (cm^2/s)	0.61	0.16	0.12
- Viscosity at NTP (g/cm.s x 10^5)	89	11.7	80
- Density at NTP (kg/m^3)	0.08938	0.6512	1.87
- Ratio of specific heats, Cp/Cv at NTP	1.308	1.383	1.14
Relative leak rate (Subsonic flow):			
- Diffusion	1	0.26	0.20
- Laminar flow	1	7.60	1.11
- Turbulent flow	1	0.35	0.21
Relative leak rate (Sonic flow):	1	0.34	0.20

2.2.1.2 Hydrogen Embrittlement

Prolonged exposure to hydrogen of some high strength steels can cause them to loose their strength, eventually leading to failure. This effect is termed hydrogen embrittlement (HE). The study of HE mechanisms [56] includes large number of pertinent variables such as time of exposure to hydrogen, stress state, pressure, temperature, hydrogen concentration, purity of hydrogen, mechanical properties of the metal, and so on. According to [56] HE is divided into three classes: hydrogen reaction embrittlement, internal hydrogen embrittlement, and environmental hydrogen embrittlement (Appendix A). Liquid hydrogen (known as cryogenic liquids) poses additional brittle failure called low-temperature embrittlement. The increase in strength as the temperature is lowered does not make all material satisfactory for use in cryogenic applications. If the structural materials lose ductility or become brittle, they can break suddenly and unexpectedly under normal stress conditions. Proper choice of materials to avoid these risks is required.

2.2.1.3 Dispersion

Hydrogen gas is more diffusive and under most conditions more buoyant than gasoline, propane or methane and hence tends to disperse more rapidly if released. The one exception is for cryogenic releases of hydrogen where the very cold vapour cloud initially formed can be denser than the surrounding air [12].

2.2.1.4 Flammability and Ignition

Hydrogen has much wider limits of flammability in air than methane, propane or gasoline and the minimum ignition energy is about an order of magnitude lower than that of other combustibles (Table 2-2). The wide range of flammability of hydrogen-air mixtures compared to other combustibles is in principle a disadvantage with respect to potential risks. A hydrogen vapour cloud could potentially have a greater volume within the flammable range than a methane cloud formed under similar release conditions. In practical release situations the lower ignition energy of hydrogen may not be as significant a differentiation between the fuels as it first seems. The minimum ignition energy tends to be for mixtures at around stoichiometric composition (29 vol.% for hydrogen). Figure 2.2 shows that at the LFL the ignition energy for hydrogen is similar to that of methane.

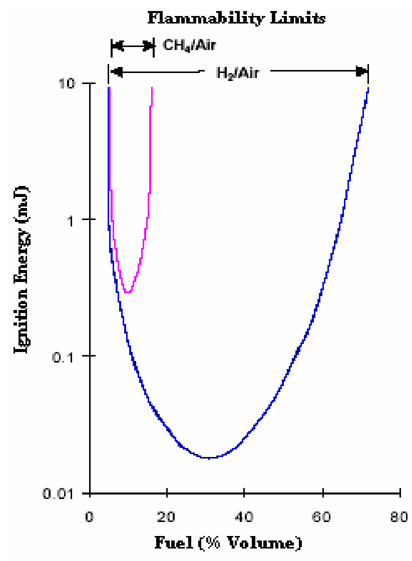


Fig. 2.2 Minimum ignition energy of hydrogen compared with that of methane [17].

The minimum autoignition temperature of hydrogen is higher than that of methane, propane or gasoline (Table 2-2). However the autoignition temperature depends on the nature of the source. The minimum is usually measured in a heated glass vessel, however if a heated air jet or nichrome wire is used the autoignition temperature of hydrogen is lower than that of other fuels.

2.2.1.5 Deflagration and Detonation

Hydrogen gas can burn as a jet flame with combustion taking place along the edges of the jet where it mixes with sufficient air. In the open flammable mixtures undergo slow deflagration. Where the flame speed is accelerated e.g. by extreme initial turbulence, turbulence from obstacles, or confinement, the result is an explosion. An extreme example is a detonation where the flame speed is supersonic.

An explosion is always accompanied by a fireball and a pressure wave (overpressure). The fireball can ignite combustible materials in the vicinity or fuel released by the explosion so that a fire may follow an explosion. If the flammable mixture is partially or totally confined the explosion may propel fragments of the enclosure material over great distances. A detonation explosion is more severe than a deflagration explosion, the overpressures generated are higher and hence much greater physical damage is possible. Direct detonation of a hydrogen gas cloud is less likely than a deflagration explosion as the ignition energy required is in the 10 kJ range, the minimum concentration is higher and the detonable range is narrower than the flammable range.

A deflagration can make the transition to a detonation (called deflagration to detonation, DDT) if the concentrations in the flammable cloud are within the detonable range and the flame front can accelerate to a speed above the sonic velocity in air. This can occur if the dimensions of the cloud are large enough to provide sufficient run-up distance for the flame to accelerate, and if there are turbulence promoting structures to accelerate the flame or there are pressure wave reflecting bodies such as walls. The turbulence in an emerging high pressure hydrogen gas jet release coupled with its exceptionally high burning velocity may also provide the conditions for detonation rather than deflagration to occur on ignition.

Table 2-2. Deflagration and detonation properties of hydrogen and other fuels [46]

	Hydrogen	Methane	Propane	Gasoline
Lower flammability limit (LFL, vol.% in air)	4	5,3	2,1	1
Upper flammability limit (UFL, vol.% in air)	75	15	9,5	7,8
Minimum ignition energy (mJ)	0,02	0,29	0,26	0,24
Auto-ignition temperature (°C):				
- Minimum	585	540	487	228-471
- Heated air jet (0.4 cm diameter)	670	1220	885	1040
- Nichrome wire	750	1220	1050	
Adiabatic flame temperature in air (K)	2318	2158	2198	2470
Quencing gap at NTP (mm)	0,6	2	2	2
Lower detonability limit (LDL, vol.% in air)	11-18	6,3	3,1	1,1
Upper detonability limit (UDL, vol.% in air)	59	13,5	7	3,3
Maximum burning velocity (m/s)	3,46	0,43	0,47	
Concentration at maximum (vol.%)	42,5	10,2	4,3	
Burning velocity at stoichiometric (m/s)	2,37	0,42	0,46	0,42
Concentration at stoichiometric (vol.%)	29,5	9,5	4,1	1,8

2.2.2 Hydrogen Accidents

The prospect of hydrogen as an energy carrier often raises safety question, in part because of its association with the Hindenburg, the German airship whose explosion in 1937 took 36 lives. For years, it was widely believed that the cause of the explosion was ignition of the hydrogen gas used for lifting the ship. In 1997, a NASA investigator Dr. Addison Bain, however, published his surprising finding that the highly combustible varnish treating the fabric on the outside of the vessel most likely caused the tragedy.

The study collected 75 incidents related to hydrogen (Appendix C), excluding the NASA incidents. It found that 30.7% of the incidents resulted in fires such as jet fire, fire ball, etc. Explosion (including with vapour cloud explosion) accounted for 20% of the incidents. Both of fire and explosion accounted for 4%, and the rests of incidents (45.3%) involved hydrogen release without ignition. A report on incidents with hydrogen in aerospace operations studied by [148] involved 96 incidents of releases of hydrogen, both gaseous and cryogenic. This study was performed at the National Aeronautic and Space Administration (NASA) facilities. Twenty-six percent of the accidents were caused by work area deficiencies, such as inadequate work conditions during installation or maintenance, or lack of training. Procedure deficiencies accounted for 25% of the mishaps. Design deficiencies accounted for 22% of the events. Planning deficiencies, such as test plans and hazard studies, resulted in 14% of the events. Component malfunctions (accountable to the component) resulted in 8% of the events. Material incompatibility and material failures accounted for 3% of the events. These events were not catastrophic failures, and few events resulted in fires. A summary of the accidents is presented in Appendix C.

2.2.3 Hydrogen Standards, Codes, and Regulations

Development of hydrogen codes, standards, and regulations are essential when hydrogen becomes a significant energy carrier because they are required to establish a market-receptive environment for commercializing hydrogen-based products and systems. Several studies on hydrogen safety as well as expert opinions stated that hydrogen's safety has been shown to be on a par with the current fuels when proper regulations, codes and standards, and best practices are followed. Tables of codes, standards, and regulations for hydrogen (International, EU, Germany, and USA), are presented in Appendix D.

2.2.3.1 Codes and Standards

A standard is a set of technical definitions, guidelines, and instructions for designers and manufacturers. It is typically voluntary, but has been agreed upon to ensure consistency, compatibility, and safety. Developing a standard is a consensus process involving a number of experts in the field. Once developed, standards are usually incorporated into codes that, in turn, must be adopted by State and local jurisdictions to become legal and binding. Standards are developed by international or national standard organisations, such as ISO, IEC, NFPA, ASME, DIN, etc. Standards are considered as very important by the industry to support the free exchange of goods and services.

The International standards are considered to be the best way to promote the development of a safe “hydrogen society”, and a very important standard organisation in this context is the International Organization for Standardization (ISO). For example is the ISO/TC 197. It was created in 1990, and is the technical committee of the ISO responsible for the standardization in the field of systems and devices for the production, storage, transport, measurement, and use of hydrogen. The standards related to fuel cell technologies are prepared by the International Electrotechnical Commission, IEC TC 105. IEC is a global organization that prepares and publishes international standards for all electrical, electronic and related technologies. These serve as a basis for national standardization and as references when drafting international tenders and contracts. The scope of IEC TC 105 is to prepare international standards regarding fuel cell (FC) technologies for all FC applications such as stationary FC power plants, FC for transportation such as FC propulsion systems and auxiliary power units and portable FC power generation systems.

2.2.3.2 Regulations

Regulations are normative documents giving general requirements to secure that construction and use of the application is carried out safely. However, regulations do not say how this should be achieved in practice. Standards give more practical rules/guidelines on how safe construction and operation should be carried out. On a national basis regulation includes requirements of a general character, focused on functional requirements, such as the protection of workers, protection of third party and property, etc. There exist International (UN), continental (USA, Europe, Asia etc.) and national regulations.

In the U.S. Federal regulations on the transportation and use of hydrogen there are rules or orders intended to promote safety, compatibility, and efficiency. The two principal regulatory areas regarding transportation safety are both under the Department of Transportation (DOT). Under 49 CFR (1995), the DOT Research and Special Programs Administration regulates pipelines and hazardous materials shipments. The 29 CFR (1996), under the jurisdictions of the Occupational Safety and Health Administration (OSHA) regulates the safe handling of hydrogen in the work place, where hydrogen is classified as a hazardous material.

EU directives are very important regulations. They are considered as normative when they are adapted to national regulations in the different European countries, and they are enforced by national regulatory authorities. So far there are no regulations that specifically address hydrogen applications, and this is also the case for other types of hazardous materials [135]. Safety regulations usually address groups of materials, classified as flammable, explosive, toxic, oxidizing etc. However, requirements given in regulations related to hazardous materials; risk reduction, protection of workers, environment and material values etc. are also normative for hydrogen applications.

2.2.3.3 Status and Development of Hydrogen Standards in Germany

In Germany, there is no particular regulation as well as standardization for the construction and operation of hydrogen installations [168]. These are covered by the existing standards (e.g. DIN) and regulations (e.g. TRG, BImSchG). For example, construction and installations of hydrogen plants are regulated in the Federal Immission Control Act (Bundesimmissionsschutzgesetz, BImSchG). The German standards institute (DIN) involves in the development of the technical committee (TC) of the International Standard Organization (ISO) for hydrogen, i.e. ISO TC 197 ("Hydrogen Technologies"). This includes ISO 14687 (“Airport hydrogen fuelling station”), and ISO 15916 (“Basic requirements for safety of hydrogen system”). Hydrogen as a flammable gas, which is stored either as a compressed gas or as a cryogenic liquid falls under the relevant general regulations. Based on this background in Germany - e.g. compared to France it is comparatively simple to obtain the permission required by hydrogen plants [168, 53].

2.3 HYDROGEN ENERGY CYCLE

Conceptually, the purpose of a hydrogen energy economy can be categorized as the: (1) production, (2) storage and transport, and (3) use of hydrogen. Some applications may involve all three categories. Figure 2.3 illustrates a structure of an energy supply system for an industrialized country (e.g. Germany) with import “clean” hydrogen (i.e. hydrogen energy economy), proposed by Winter and Nitsch [200]. In the system, hydrogen is fed into the supply system in a similar way as today natural gas. In the case of Germany, the required hydrogen will be mainly imported through a gas pipeline or LH_2 tanker from neighbouring countries, where hydrogen is produced from cheap renewable energies [201]. It is similar to the current fossil fuel economy, where most of the oil and gas are imported from other countries. The country has limited energy resources to self generate hydrogen in large quantities. However, a small part of the hydrogen may be produced domestically from off-peak period of regional power plants (fossil fuels, or renewable energy power based), as domestic gas, to guarantee high efficiency of the power stations. The imported hydrogen (both liquid and gas) is then stored in a large-scale stationary storage at terminals to obtain a seasonal balance. Underground storage may be used to store a large amount of gaseous hydrogen, and a large-scale LH_2 stationary storage for liquid hydrogen.

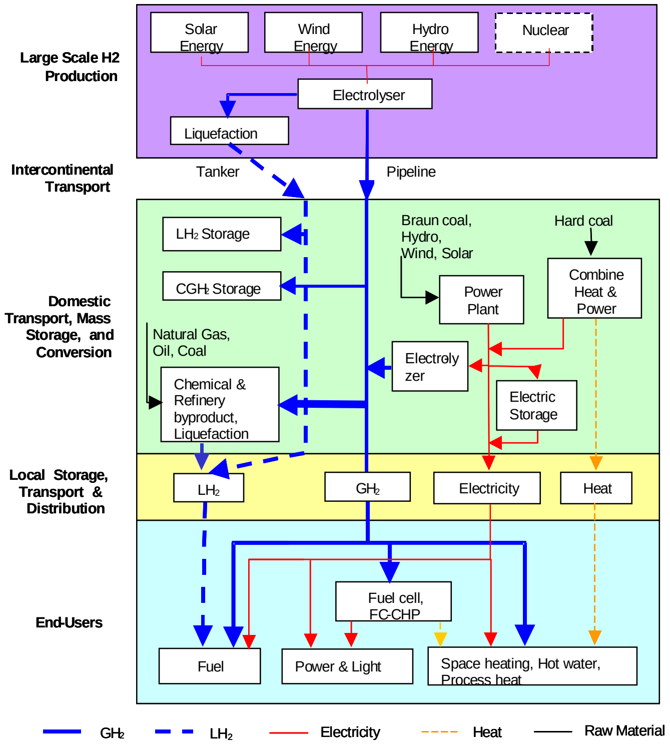


Fig. 2.3 Structure of a hydrogen energy economy for an industrial country [200].

2.3.1 Hydrogen Production

Although hydrogen is the most abundant element in the Universe, it does not exist in free state in any significant amount on the Earth. It is found almost always chemically bound to other elements such as water, biomass, or fossil fuels. Molecular hydrogen, therefore, must thus be extracted from compounds such as water or organic molecules. Various methods of production have unique needs in terms of energy sources (such as heat, light, electricity) and generate specific by-products. Figure 2.4 shows a pathway of hydrogen production from different resources and technologies. One can distinguish between productions using a primary energy carrier and productions using a secondary energy carrier. Primary energy production presently means hydrogen production from fossil fuels via natural gas reforming as well as the partial oxidation of heavy fuel oil (or Diesel) and coal. Along with these further processes are in the research and development phases. The leader among these is the gasification of biomass, but also worth mentioning is the direct production of hydrogen from algae subjected to solar radiation. It is, however, only the biomass gasification process whose development phase is so developed, that its transformation into a market competitive product within the next few years can be expected.

Electricity is presently the only secondary energy carrier used to produce hydrogen, either by the electrolysis of water or as a by-product resulting from the chlorine-alkaline electrolysis. Water electrolysis is independent of primary energy use and as such is seen as the essential element of hydrogen based energy sector. As another secondary energy based production method, the reforming of methanol in mobile applications could play a role in the near future. About 95% of today's hydrogen is produced from fossil fuels using high-temperature chemical reactions that convert hydrocarbons into a synthetic gas, which is then processed to make hydrogen [96]. In many areas of the world, including Germany, large-scale natural gas reforming is currently the lowest cost method for hydrogen production. Hydrogen could also be produced at large scale by the gasification of feedstock such as coal, heavy oils, biomass, wastes or petroleum coke. In regions with plentiful, low-cost biomass resources, biomass gasification could become an economically attractive method of hydrogen production. Limiting factors are likely to be land availability and competing uses for low-cost biomass feedstock in the electricity sector.

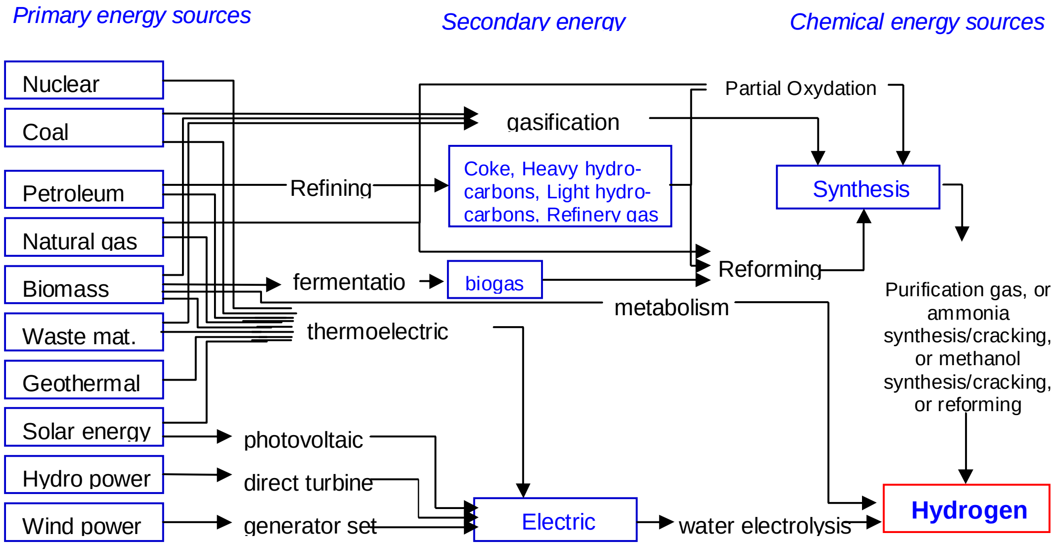


Fig. 2.4 Hydrogen resources and production technologies [96]

Hydrogen production by the above processes (e.g. electrolysis, reforming or else) is a process of energy transformation. Electrical energy or chemical energy of hydrocarbons is transferred to chemical energy of hydrogen. Unfortunately, the process of hydrogen production is always associated with energy losses. This section discussed briefly the two methods of hydrogen production mostly commercially today. Description of several hydrogen production technologies are presented in the Appendix B.

2.3.1.1 Electrolysis

In electrolysis, electricity [46, 211] is used to decompose water into its elemental components: hydrogen and oxygen. Electrolysis is often considered as a preferred method of hydrogen production as it has high product purity, and is feasible of small and large scales. Electrolysis can operate over a wide range of electrical energy capacities, for example, taking advantages of more abundant electricity at night. At the heart of electrolysis is an electrolyzer. An electrolyzer is a series of electrolysis cells (Figure 2.5) each with a positive and negative electrode. The electrodes are immersed in water that has been made electrically conductive, achieved by adding hydrogen or hydroxyl ions, usually in the form of alkaline potassium hydroxide (KOH).

The rate of hydrogen generation is related to the current density (the amount of current divided by the electrode area measured in amps per area). In general, the higher the current density, the higher the source voltage required, and the higher the power cost per unit of hydrogen. However, higher voltages decrease the overall size of the electrolyzer and therefore result in a lower capital cost. State-of-the-art electrolyzers are reliable, have energy efficiencies of 65 to 80% and operate at current densities of about 2000 A/m^2 [46].

For electrolysis, the amount of electrical energy required can be somewhat offset by adding heat energy to the reaction. The minimum amount of voltage required to decompose water is 1.23 V at 25 ºC. At this voltage, the reaction requires heat energy from the outside to proceed. At 1.47 V (and same temperature) no input heat is required. At greater voltages (and same temperature) heat is released into the surroundings during water decomposition. To be truly clean, the electrical power stored during electrolysis must derive from non-polluting, renewable sources. If the power is derived from natural gas or coal, the pollution has not been eliminated, only pushed upstream. In addition, every energy transformation has an associated energy loss. Consequently, fossil fuels may be used with greater efficiency by means other than by driving the electrolysis of hydrogen. Furthermore, the cost of burning fossil fuels to generate electricity for electrolysis is three to five times that of reforming the hydrogen directly from the fossil fuel.

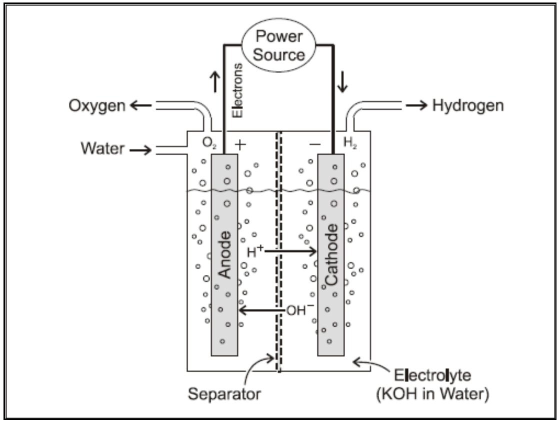


Fig. 2.5 Work principles of a typical electrolysis cell [46]

2.3.1.2 Reforming

Reforming [46, 211] is a chemical process with the reaction of hydrogen-containing fuels in the presence of steam, oxygen, or both in a hydrogen-rich gas stream. When applied to solid fuels the reforming process is called gasification. The resulting hydrogen-rich gas mixture is called reformate. The equipment used to produce reformate is known as a reformer or fuel processor. The specific composition of the reformate depends on the source fuel and the process used, but it always contains other compounds such as nitrogen, carbon dioxide, carbon monoxide and some of the unreacted source fuel. When hydrogen is removed from the reformate, the remaining gas mixture is called raffinate. In essence, reforming a fossil fuel consists of the following steps: (1) Feedstock purification (including sulfur removal); (2) Steam reforming or oxidation of feedstock to form hydrogen and carbon oxides; (3) Primary purification—conversion of carbon monoxide to carbon dioxide; (4) Secondary purification—further reduction of carbon monoxide.

Any hydrocarbon or alcohol fuel can serve as a feedstock to the reforming process [46, 211]. Naturally, fuels with existing distribution infrastructures are the most commonly used. For example, natural gas has a well-established infrastructure and is the most economical of all reforming feedstock. Natural gas contains low levels of sulfur compounds that must be removed, as they would block active catalyst sites in the reformer and fuel cells. These sulfur compounds require fuel purification prior to reforming.

At the heart of reforming is a reformer. There are three basic types of reformers: steam reformers, partial oxidation reactors and thermal decomposition reactors. A fourth type results from the combination of partial oxidation and steam reforming in a single reactor, called an auto-thermal reformer. The steam reformers are currently the most efficient, economical and widely used technique of hydrogen production [46] Steam reforming is based on the principle that hydrogen-containing fuels decompose in the presence of steam over nickel-based catalysts to produce a mixture of hydrogen and carbon monoxide. The steam reforming process is illustrated schematically in Figure 2.6.

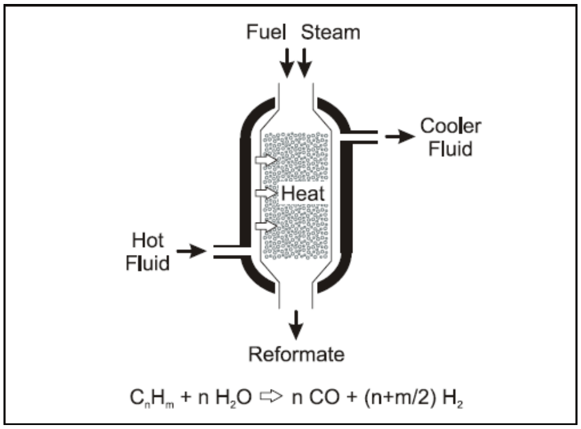


Fig. 2.6 Steam reforming process [46]

2.3.2 Hydrogen Storage and Transportation

2.3.2.1 Compression and Liquefaction (Packaging)

Hydrogen still requires further preparation according to the demands of the intended end use. Firstly, cleaning of the hydrogen is required in order to ensure that the required quality is met. Following this it must be compressed, whereby the pressure level is dependent on either the end application or the intermediate storage method. Alternatively, liquefaction may be the reasonable option if transport over long distances is required or if the end users require a high energy density (small storage volume).

2.3.2.1.1 Compression of Hydrogen

Compression of hydrogen is carried out in the same way as for natural gas, though as hydrogen is less dense the compressors need better seals. It is sometimes even possible to use the same compressors, as long as the appropriate gaskets (e.g. Teflon) are used and provided the compressed gas can be guaranteed to be oil free. Energy is needed to compress gases. The compression work depends on the thermodynamic compression process. The ideal isothermal compression cannot be realized. The adiabatic compression equation [31, 190]:

$$w = \left[\frac{g}{g-1}\right] p_o \cdot v_o \left[\left(\frac{p_1}{p_o}\right)^{(g-1)/g} - 1\right] \qquad (2\text{-}1)$$

where

w = specific compression work [J/kg]
p_o = initial pressure [Pa]
p_1 = final pressure [Pa]
v_o = initial specific volume [m^3/kg]
g = ratio of specific heats, adiabatic coefficient [-]

The energy consumed by an adiabatic compression of Helium, hydrogen and methane from atmospheric conditions (1 bar = 10^5 Pa) to higher pressures is shown in Figure 2.7. Clearly, much more energy per kg is required to compress hydrogen than methane. Isothermal compression follows a simpler equation:

$$w = p_o \cdot V_o \ln(p_1 / p_o) \qquad (2\text{-}2)$$

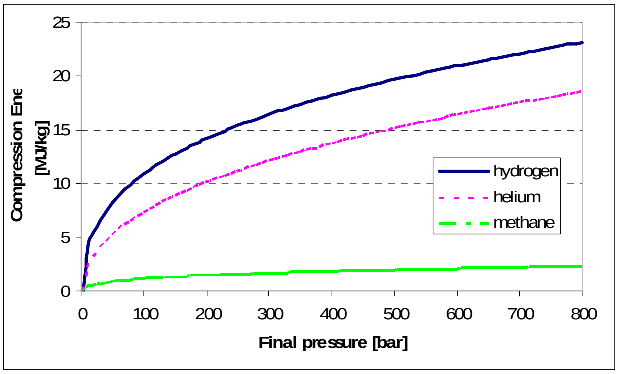


Fig. 2.7 Adiabatic compression work for hydrogen, helium and methane

The compression work is the difference between the final and the initial energy state of the hydrogen gas.

Figure 2.8 illustrates the difference between adiabatic and isothermal ideal-gas compression of hydrogen. Multi-stage compressors with intercoolers operate between these two limiting curves. Also, hydrogen readily passes compression heat to cooler walls, thereby approaching isothermal conditions. Numbers provided by a leading manufacturer [31] of hydrogen compressors show that the energy invested in the compression of hydrogen is about 7.2% of its higher heating value (HHV). This number relates to a 5-stage compression of 1,000 kg of hydrogen per hour from 1 to 20 MPa. For a final pressure of 80 MPa the compression energy requirements would amount to about 13% of the energy content of hydrogen. This analysis does not include electrical losses in the power supply system.

Since hydrogen compression is carried out in the same way as the compression of natural gas, the procedure is well tested and readily available. New developments are mainly associated with the optimization of the individual units within the total concept, with the primary application here being the high pressure compression at service stations. Typical pressure levels are 3 - 4 MPa for pre-compression stages for filling of collecting tanks, and 25 – 30 MPa for storage tanks in fast fill applications. The fast fill process is achieved by an over pressure over the pressure level in the vehicle tank being filled (20 or even 25 MPa). The choice of the highest pressure level is primarily dependent on the maximum permitted pressure that the storage tank can withstand (modern tanks constructed from composite materials are rated for up to 700 bar). Because of the logarithmic relationship between pressure and work required for the isothermal compression, the increased energy required for a higher filling pressure is not that great. Thus the compression from 1 to 30 MPa needs only 10% more energy than the compression from 10 to 20 MPa [31].

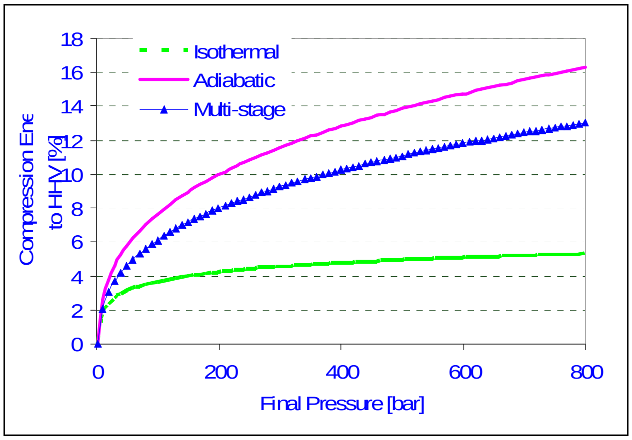


Fig. 2.8 Energy required for adiabatic and isothermal ideal-gas compression of H_2 [31].

2.3.2.1.2 Liquefaction of Hydrogen

In order to reduce the volume required to store a useful amount of hydrogen - particularly for vehicles - liquefaction may be employed. The advantage of liquid hydrogen is its high energy: mass ratio, three times that of gasoline. It is the most energy dense fuel in use (excluding nuclear reactions). That is why it is employed in all space programmes. Since hydrogen does not liquefy until it reaches -253°C (20 degrees above absolute zero), the process is both long and energy intensive. Up to 30% of the energy content in the hydrogen can be lost. Theoretically only about 14 MJ/kg (3.6 kWh/kg) have to be removed to cool hydrogen down to 20K (-253°C). The real energy needed to liquefy the hydrogen is about 40 MJ/kg (11 kWh/kg), compared to its energy content (high) of 142 MJ/kg.

But cryogenic refrigeration is a complex process involving Carnot-cycles and physical effects (e.g. Joule-Thomson) that do not obey the laws of heat engines. For the refrigeration between room temperature (T_R = 25°C) and liquid hydrogen temperature (T_L = -253°C) one obtains a Carnot efficiency of

$$h_c = \frac{T_L}{T_R - T_L} = \frac{20K}{298K - 20K} = 0.072 \tag{2-3}$$

or about 7%. The assumed single-step Carnot-type cooling process would consume at least 57 MJ/kg or 40% of the HHV energy content of hydrogen. This simple analysis does not include mechanical, thermal, flow-related or electrical losses in the multi-stage refrigeration process. But by intelligent process design the Carnot limitations may be partially removed. But the lower limit of energy consumption of a liquefaction plant does not drop much below 30% of the higher heating value of the liquefied hydrogen. As a theoretical analysis of the complicated, multi-stage liquefaction processes is difficult, we present the energy consumption of existing hydrogen liquefaction plants [31]. The liquefaction energy requirement depends on the process itself, the process optimization, the plant size, and on other parameters. Figure 2.9 shows typical energy requirements for the liquefaction of 1 kg hydrogen as a function of plant size and process optimization. The plants have a capacity between 1 to 10,000 kg of liquid hydrogen per hour.

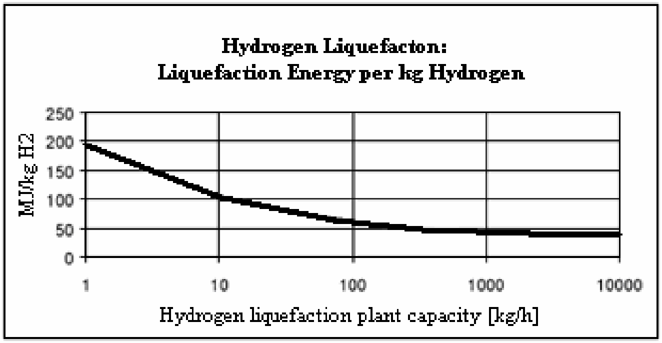


Fig. 2.9 Typical energy requirements for the liquefaction [31, 212]

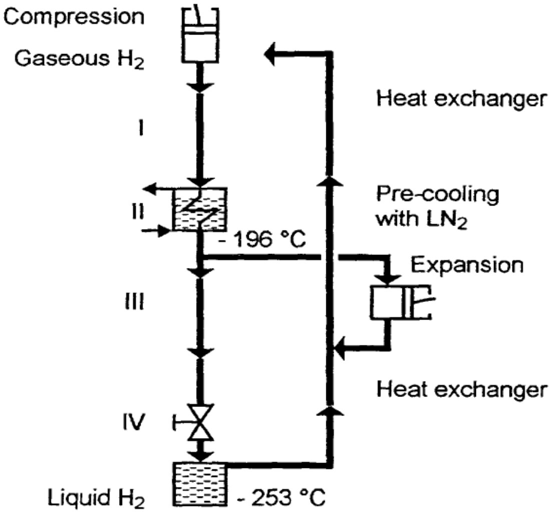


Fig. 2.10 Schematic of the Claude process for hydrogen liquefaction [96]

A commonly applied method in large-scale liquefaction plants is the Claude process (Fig.2.10). The necessary refrigeration is provided in four principal steps leading to the liquefaction of hydrogen [96]: (1) compression of hydrogen gas, removal of compression heat; (2) pre-cooling with liquid nitrogen (80 K); (3) expanding and thus cooling of a part of the hydrogen in an expander resulting in a further pre-cooling of the residual hydrogen (80-30K); and (4) expanding of residual hydrogen in a Joule-Thomson valve until liquefaction (30-20K). The method is now implemented in the Ingolstadt (Germany) liquefaction plant. The liquefaction plant supplied by Linde AG, has a capacity of 4.4 t/d. Today there are about 10 medium sized plants with production capacities of 10 - 60 t/d, in operation around the world. Liquefaction plants in USA, Japan and Europe with capacities in the range of 3 - 12 t/d are more recent [78].

2.3.2.2 Hydrogen Storage

As seen in Section 2.2, hydrogen has the lowest gas density and the second-lowest boiling point of all known substances, making it a challenge to store them as either a gas or a liquid. As a gas, it requires very large storage volumes and pressures. As a liquid, it requires a cryogenic storage system. Hydrogen's low density, both as a gas and a liquid, also results in very low energy density. Stated otherwise, a given volume of hydrogen contains less energy than the same volume of other fuels. This also increases the relative storage tank size, as more hydrogen is required to meet a, for example, given vehicle's range requirements. The amount of hydrogen needed for fuel cells is offset somewhat by the fact that it is used more efficiently than when burnt in an internal combustion engine, so less fuel is required to achieve the same result.

Despite its low volumetric energy density, hydrogen has the highest energy-to-weight ratio of any fuel. Unfortunately, this weight advantage is usually overshadowed by the high weight of the hydrogen storage tanks and associated equipment. Thus, most hydrogen storage systems are considerably bulkier and/or heavier than those used for gasoline or diesel fuels.

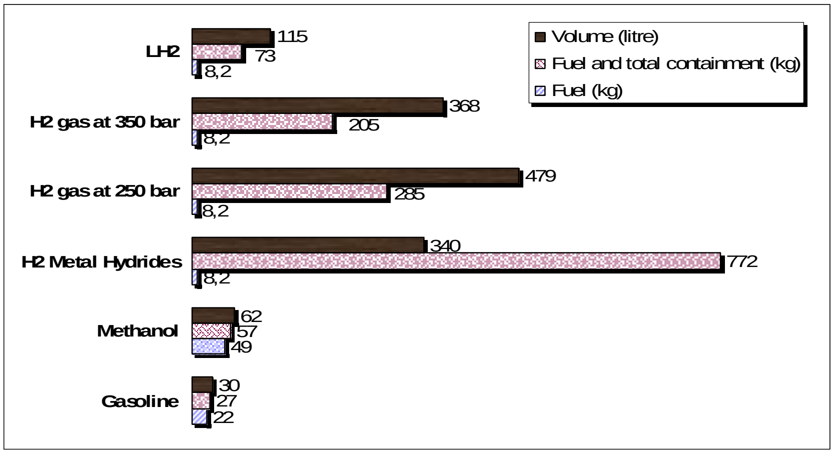


Fig. 2.11 Storage volume and weight of comparative fuels [31]

For all practical purposes, hydrogen can be stored as either a high-pressure gas, a liquid in cryogenic containers, or a gas chemically bound to certain metals (hydrides). The volume and weight of each of these systems is compared to gasoline, methanol and battery storage systems (each 1,044.5 MJ of stored energy; equivalent to 30 litres of gasoline) in Figure 2-11. Ironically, the best way to store hydrogen is in the form of hydrocarbon fuels although it requires additional systems to extract it.

2.3.2.2.1 Compressed Gas (CGH$_2$) Storage

The traditional way of storing hydrogen is in gaseous form in pressure vessels. Gaseous hydrogen can be stored either in above ground (in portable or stationary containers) or in underground (i.e. different kinds of earth caves) storages.

a. Above Ground Storage

Compressed gaseous hydrogen is stored above ground in a high pressure gas cylinder. It is classified based on material compositions, i.e. metal and composite (Table 2-3). In general, the less metal is used, the lower is the weight. For this reason, type 3 cylinders are usually used in hydrogen applications, and type 4 cylinders will likely gain prominence in the future. Specific weights depend on individual manufacturers, but as a point of reference, a 100 l type 1 (steel) cylinder weighs about 100kg, a type 3 (aluminum/composite) cylinder weighs about 65 kg, and a type 4 cylinder weighs about 30 kg. Type 3 cylinders derive most of their strength from the composite overwrap that is wound around the inner liner. This composite consists of high-strength fibers (usually carbon) that are wrapped around the cylinder in many layers and glued together by a resin such as epoxy.

In the industrial sector a standardization of type has already occurred. As a result, cylindrical tanks with a maximum operating pressure of 5 MPa and 2.8m diameter are now available in the following lengths (or heights): 7.3 m (max. capacity at 4.5 MPa: 1305 Nm3), 10.8 m (max. capacity 2250 Nm3) and 19m (max. capacity 4500 Nm3). Bottle type storage can also be used as stationary storage as long as the volume is sufficient. Such bottles are available in steel in sizes ranging from 2 to 50 l (corresponding to 0.35 - 8.9 Nm3 and weights of 5.3 - 68 kg) with operating pressures of 20 MPa. In these cases, calculations for energy density by weight (gravimetric) and volume (volumetric) including the storage device itself result in figures of 0.9 – 1.1 MJ/kg and 0.5 MJ/l, respectively. Gravimetric energy density of hydrogen is largely dependent on the material of the container since light materials usually do not tolerate pressure as well as heavier ones. The theoretical gravimetric energy density of hydrogen can be calculated with the molar mass of hydrogen molecule (2.016 g/mol) to be 141.8 MJ/kg [31, 212].

Table 2-3. High pressure gas cylinder classifications [190]

Design	Description	% Metal/ Composite	Weight (kg) for 100 l
Type 1	A cylinder made wholely of steel or aluminum	100/0	100
Type 2	A cylinder with a metal line of steel or aluminum and a hoop-wrapped composite overwrap	55/45	-
Type 3	A cylinder with a thin metal liner of steel or aluminum and a fully wound composite overwrap	20/80	65
Type 4	A cylinder with a plastic liner and a fully wound composite overwrap	0/100	30

Note: % Load taken by metal vs. composite.

b. Underground Storage

Underground caves are an easy and relatively cheap method for large seasonal storage of hydrogen. This storage technique is already in use for natural gas. There are several kinds of caves that can be used, such as salt caverns, mined caverns, natural caves, and aquifer structures. For example, the city of Kiel in Germany has been storing town gas containing 60 – 65% of hydrogen in a gas cavern at a depth of 1330 m since 1971 [96; 207].

Salt is often found in the form of layers that can be hundreds of meters thick. These layers are practically impermeable to water and air. The cavity is made in the salt by dissolving and the surface is cemented before feeding the gas. Aquifers are located in porous geological formations. The gas is injected into the rock pores, initially filled with water, in which the gas is accumulated. The use of this technique requires special geological conditions and can thus be used only in certain regions. The pressure in the earth caves varies between 8 – 18 MPa and thus the volumetric energy density is about 900 – 1674 MJ/m^3. In aquifer structures, the energy density is naturally significantly smaller. The losses caused by the leaks in the earth caves are about 1-3% of the total volume per year [31].

2.3.2.2.2 LH_2 Storage

Liquid hydrogen (LH_2) storage systems overcome many of the weight and size problems associated with high-pressure gas storage systems, albeit at cryogenic temperatures. Liquid hydrogen can be stored just below its normal boiling point of –253 ºC (20 K) at or close to ambient pressure in a double-walled, super-insulating tank (Dewar). This insulation takes the form of a vacuum jacket, much like in a thermos bottle. Liquid hydrogen tanks do not need to be as strong as high-pressure gas cylinders although they do need to be adequately robust if used for automotive purpose.

As compared with pressurized gas storage, this method is more expensive, because of the high cost of insulation. Despite the high price, however, in the case of large tanks the increased storage density of liquid hydrogen outweighs the benefit of reduced material costs associated with compressed gas storage. The containers usually combine different kinds of insulating methods. These include vacuum insulation, vapour-cooled radiation shields (VCS), and multi-layer insulation (MLI). A schematic of an insulated vessel is given in Figure 2.12. Larger containers are to some extent produced with perlite vacuum insulation.

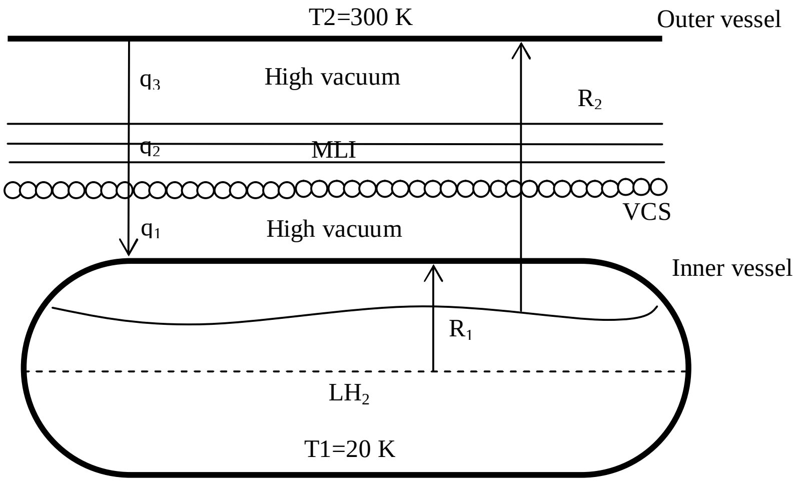


Fig. 2.12 Combined insulation of vacuum, MLI, and VCS techniques [170]

Hydrogen cannot be stored in liquid form indefinitely. All tanks, no matter how good the insulation, allow some heat to be transferred from the ambient surroundings. The heat leakage rate depends on the design and size of the tank — in this case, bigger is better. This heat causes some of the hydrogen to vaporize and the tank pressure to increase. Stationary liquid hydrogen storage tanks are often spherical since this shape offers the smallest surface area for a given volume, and therefore presents the smallest heat transfer area. For example, the largest LH2 tank belongs to NASA located at Cape Canaveral is a spherical tank with a storage volume of 3800 m^3 (approx. 270 t LH_2) and the outer spherical diameter of 20 m. The evaporation rate is under 0.03% per day, allowing for a storage period of several years.

Although liquid hydrogen storage systems eliminate the danger associated with high pressures, they introduce dangers associated with low temperatures. A severe frostbite hazard exists in association with the liquid hydrogen, its vapour and contact surfaces. Carbon steel exposed to temperatures below –30°C, either directly or indirectly becomes brittle and is susceptible to fracture. Air may liquefy on the outside of exposed liquid hydrogen lines or under insulation resulting in an oxygen concentration that poses a fire or explosion hazard if it drips onto combustible materials.

The gravimetric energy density of liquid hydrogen including the storage container is about 25.9 wt% (5 MJ/kg), and the volumetric energy density about 9936 MJ/m^3. Improvements in insulation techniques and the pressurization of the vessel will have some effect on these figures [31].

2.3.2.2.3 Metal Hydride

Metal hydride storage systems are based on the principle that some metals readily absorb gaseous hydrogen under conditions of high pressure and moderate temperature to form metal hydrides. These metal hydrides release the hydrogen gas when heated at low pressure and relatively high temperature. In essence, the metals soak up and release hydrogen like a sponge. The advantages of metal hydride storage systems revolve around the fact that the hydrogen becomes part of the chemical structure of the metal itself and therefore does not require high pressures or cryogenic temperatures for operation. The high weight of a metal hydride storage device is its disadvantage. Since hydrogen is released from the hydride for use at low pressure (0.25 to 1 MPa depending on material choice), hydrides are the most intrinsically safe of all methods of storing hydrogen. At the same time it gives a high volumetric storage density of approx. 0.8 – 1.4 MJ/kg and 3.6 – 5.4 MJ/l.

There are many types of specific metal hydrides, but they are primarily based on metal alloys of magnesium, nickel, iron and titanium. In general, metal hydrides can be divided into those with a low or high hydrogen release temperature [213]. The high temperature hydrides may be less expensive and hold more hydrogen than the low temperature hydrides, but require significant amounts of heat in order to release the hydrogen. Low temperature hydrides can get sufficient heat. In Germany, metal hydride storage is being further developed and supplied by GfE (Gesellschaft für Elektrometallurgie) [207].

2.3.2.3 Transport and Distribution

Hydrogen transportation issues are directly related to hydrogen storage issues. In general, compact forms of hydrogen storage are more economical to transport and diffuse forms are more costly. The technologies for routine handling and delivery of large quantities of hydrogen have been developed in the chemical industry. Liquid hydrogen is delivered by truck or rail over distances of up to several hundred miles. Compressed gas hydrogen pipelines (up to several hundred kilometers in length) are used commercially today to bring hydrogen to large industrial users like refineries. For a large-scale hydrogen energy system, it would probably be less expensive to transport a primary energy source (like natural gas or coal) to a hydrogen plant located at the “city gate,” rather than making hydrogen at the gas field or coal mine and piping it to the city. In the long term, transcontinental hydrogen pipelines seem unlikely, unless there were a compelling reason to make hydrogen in a particular location far from demand.

2.3.2.3.1 Road Transport

A hydrogen economy also involves hydrogen transport by road. There are other options for hydrogen distribution (such as rail, barge, etc.), but road transport will always play a role, be it to serve remote locations or to provide back-up fuel to filling stations at times of peak demand.

a. Liquid Transport

Hydrogen can be transported on the road by truck as a cryogenic liquid in double-walled, super-insulated vacuum-lined tanks. Transporting liquid hydrogen is far more efficient than transporting a high-pressure gas, particularly where larger quantities are needed. On the downside, maintenance costs are much higher for liquid transportation. Today, LH_2 is transported in cryo-containers or trailers of typically up to 41 m^3 or 53 m^3 at cryogenic temperatures of - 253°C. Larger quantities of LH_2 have been transported in NASA's space program in barges over distances of about 100 km. LH_2 road transport in large cylindrical containers of 270 m^3 and 600 m^3 has been performed in the framework of ESA's Ariane space program. In most cases the transport is weight-limited, it is limited by volume for liquid hydrogen. For example, the useful volume of a LH2 tanker truck with dimension of 2.4 m wide, 2.5 m high and 10 m long, is 60 m^3. Only 4.2 tons of liquid hydrogen can be filled into this box, because the density of the cold liquid is only 70 kg/m^3 or slightly more than that of heavy duty Styrofoam. The rest of the space is needed for container, thermal insulation, equipment etc. In fact, there is room for only about 2.1 tons of liquid hydrogen on a large-size truck.

b. Gas Transport

Hydrogen as a high-pressure gas can be transported in cylinders at pressures ranging from 15 to 40 MPa. For trucks, specially designed tube trailers carry a number of large, high-strength steel tubes linked together through a common manifold. This design works well in providing small quantities of hydrogen, but is very inefficient in terms of transport energy. The weight of the cylinders required is such that the gas is only 2 to 4% of the cargo weight. A hydrogen pressure tank can be emptied only from 20 MPa to about 4.2 MPa to accommodate for the 4 MPa pressure systems of the receiver. As a consequence, it delivers only 80% of its freight, while 20% of the load remains in the tanks and is returned to the gas plant. Today, at 20 MPa pressure only 320 kg of hydrogen can be carried and only 288 kg are delivered by a 40-ton truck. This is a direct consequence of the low density of hydrogen, as well as the weight of the pressure vessels and safety armatures.

2.3.2.3.2 Pipeline Delivery

Gaseous hydrogen can be transported by pipeline in a similar fashion as natural gas. Hydrogen, being less dense than natural gas, results in less mass transport for a given pipeline size and operating pressure. In addition, the energy density of hydrogen is only one third that of natural gas on a volumetric basis; hence, three times the amount of hydrogen gas must be pumped through a pipeline to transmit an equivalent amount of energy. To compensate for both of these properties, hydrogen pipelines need to be designed to operate at higher pressure in order to be practical. All pumps and other equipment must be hydrogen compatible. Furthermore, hydrogen pipelines must be resistant to hydrogen embrittlement in order to prevent cracking.

Existing hydrogen gas pipelines operate in some parts of the world. In the US there are 725 km of pipelines, including those in Texas, Indiana, New Jersey and Louisiana. In Europe, pipelines are operated in Germany (210 km) and between Belgium and France (400 km), among several others. Compared to pipelines for others gases, these lengths are very short. However, they indicate that the high cost of transporting hydrogen by gas pipeline is already worth while in some areas [207].

The theoretical pumping power requirement N [W] is presented by [31]:

$$N = V_o \Delta p = A_p \, v \Delta p = p \, / \, 4 \, d^2 \, v \Delta p = p \, / \, 4 \, d^2 v \, \tfrac{1}{2} \, r \, v^2 e = \tfrac{1}{8} p \cdot d^2 \cdot v^3 \cdot r \cdot e \qquad \text{(2-4a)}$$

$$\text{with} \quad \varepsilon = 0.31164/Re^{\mathrm{n}}; \text{ and } \quad \mathrm{Re} = r \cdot v \cdot d \, / \, h \qquad \text{(2-4b)}$$

where,

V_o = volumetric flow rate [m^3/s]
A_p = cross section of pipe [m^2]
v = flow velocity of the gas [m/s]
Dp = pressure drop [Pa]
d = pipeline diameter [m]
ε = resistance coefficient

r = density of the gas [kg/m^3]
Re = Reynolds number
n = 0.25, for turbulent pipe flow (Blasius equation)
η = dynamic viscosity [kg/(m s)]

2.3.3 Hydrogen Energetic Applications

Hydrogen has many potential energy uses, including powering non-polluting vehicles, heating homes, and fueling aircraft. Energetic applications of hydrogen can be classified into two main categories, i.e. direct combustion (e.g. internal combustion engine) and fuel cells.

2.3.3.1 Internal Combustion Engine

An internal combustion engine (ICE) transforms chemical energy contained in a fuel into mechanical energy through combustion in a piston or rotary engine. Modified ICE can utilize hydrogen in place of gasoline. Optimized hydrogen engines can be run at higher compression ratios than those with unleaded gasoline. It makes hydrogen-powered engines 15-25 % more efficient than gasoline engines. Advantages of the ICEs are mainly relatively mature technology, relatively low cost when compared to a fuel cell, and potentially low greenhouse gas emissions. Depending on the source of the hydrogen gas the greenhouse gas emissions will be lower than gasoline. If renewable energy is used to generate the hydrogen they may approach zero. However, the disadvantages of the ICE are: lower efficiency than a fuel cell, and some pollutant emissions from the engine remain (e.g. Nitrogen oxides).

2.3.3.1.1 The Engine

The properties of hydrogen (vid. in Section 2.2.1) that contribute to its use as a combustible fuel are wide range of flammability, low ignition energy, small quenching distance, high autoignition temperature, high flame speed at stoichiometric ratios, high diffusivity, and very low density. The theoretical or stoichiometric combustion of hydrogen and oxygen is given as $2H_2 + O_2 = 2H_2O$; where 2 moles of H_2 and 1 mole of O_2 are needed for complete combustion. Because air is used as the oxidizer instead oxygen, the calculations showed that the stoichiometric or chemically correct air to fuel (A/F) ratio for the complete combustion of hydrogen in air is about 34:1 by mass. This means that for complete combustion, 34 kg of air are required for every kg of hydrogen. This is much higher than the 14.7:1 A/F ratio required for gasoline [46].

Since hydrogen is a gaseous fuel at ambient conditions it displaces more of the combustion chamber than a liquid fuel. Consequently less of the combustion chamber can be occupied by air. At stoichiometric conditions, hydrogen displaces about 30% of the combustion chamber, compared to about 1 to 2% for gasoline. Figure 2.13 compares combustion chamber volumes and energy content for gasoline and hydrogen fuelled engines. Depending on the method used to meter the hydrogen to the engine, the power output compared to a gasoline engine can be anywhere from 85% (intake manifold injection) to 120% (high pressure injection).

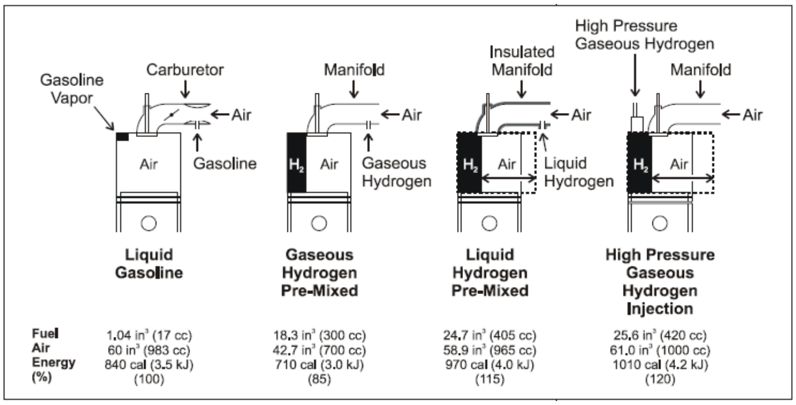


Fig. 2.13 Combustion chamber for gasoline and hydrogen fuelled engines [46]

2.3.3.1.2 Thermal Efficiency

The theoretical thermodynamic efficiency of an Otto cycle engine is based on the compression ratio of the engine and the specific-heat ratio of the fuel as shown in the equation [46]:

$$h_{th} = 1 - \frac{1}{(V_1 / V_2)^{g-1}} \qquad (2\text{-}5)$$

where

V_1/V_2 = the compression ratio; γ = ratio of specific heats; and
η_{th} = theoretical thermodynamic efficiency

The higher the compression ratio and/or the specific-heat ratio are the higher the indicated thermodynamic efficiency of the engine. The compression ratio limit of an engine is based on the fuel's resistance to knock. A lean hydrogen mixture is less susceptible to knock than conventional gasoline and therefore can tolerate higher compression ratios. The specific-heat ratio is related to the fuel's molecular structure. The less complex the molecular structure, the higher the specific-heat ratio. Hydrogen (γ = 1.4) has a much simpler molecular structure than gasoline and therefore its specific-heat ratio is higher than that of conventional gasoline (γ = 1.1).

2.3.3.1.3 Emissions

The combustion of hydrogen with air (instead of oxygen), however can also produce oxides of nitrogen (NOx) [46]:

$$H_2 + O_2 + N_2 = H_2O + N_2 + NO_x$$

The oxides of nitrogen are created due to the high temperatures generated within the combustion chamber during combustion. This high temperature causes some of the nitrogen in the air to combine with the oxygen in the air. The amount of NOx formed depends on the air/fuel ratio; the engine compression ratio; the engine speed; the ignition timing, and whether thermal dilution is utilized. Compared to fossil fuel ICEs, however, NOx emissions of lean-burn hydrogen ICEs for road vehicles are very low.

2.3.3.1.4 Power Output

The theoretical maximum power output from a hydrogen engine depends on the air/fuel ratio and fuel injection method used [46]. As mentioned before that the stoichiometric air/fuel ratio for hydrogen is 34:1. At this air/fuel ratio, hydrogen will fill 29% of the combustion chamber leaving only 71% for the air. As a result, the energy content of this mixture will be less than it would be if the fuel were gasoline (since gasoline is a liquid, it only occupies a very small volume of the combustion chamber, and thus allows more air to enter).

Since both the carburator and port injection methods mix the fuel and air prior to entering the combustion chamber, these systems limit the maximum theoretical power obtainable to approximately 85% of that of gasoline engines. For direct injection systems, which mix the fuel with the air after the intake valve has closed (and thus the combustion chamber has 100% air), the maximum output of the engine can be approximately 15% higher than that for gasoline engines. Therefore, depending on how the fuel is metered, the maximum output for a hydrogen engine can be either 15% higher or 15% less than that of gasoline if a stoichiometric air/fuel ratio is used [46]. However, at a stoichiometric air/fuel ratio, the combustion temperature is very high and as a result it will form a large amount of nitrogen oxides (NOx), which is a pollutant. Since one of the reasons for using hydrogen is low exhaust emission, hydrogen engines are not normally designed to run at a stoichiometric air/fuel ratio. Typically hydrogen engines are designed to use about twice as much air as theoretically required for complete combustion. At this air/fuel ratio, the formation of NOx is reduced to nearly zero.

Unfortunately, this also reduces the power out-put to about half that of a similarly sized gasoline engine. To make up for the power loss, hydrogen engines are usually larger than gasoline engines, and/or are equipped with turbochargers or superchargers.

2.3.3.1.5 Current Status

A few auto manufacturers have been doing some work in the development of hydrogen-powered vehicles (Ford has recently announced that they have developed a production ready of hydrogen-powered vehicle using an ICE and BMW has completed a world tour displaying a dozen or so hydrogen-powered 750i vehicles). However, it is not likely that any hydrogen-powered vehicles will be available to the public until there is an adequate refuelling infrastructure and trained technicians to repair and maintain these vehicles.

2.3.3.2 Fuel Cells

The fuel cells are devices that convert hydrogen gas into low-voltage, direct current electricity by combining hydrogen and oxygen electrochemically. In a fuel cell, a fuel gas is converted into electrical energy in an electrochemical process. Some fuel cells use methane and a few use liquid fuels such as methanol, but most of the fuel cells use hydrogen as the fuel. Besides, oxygen (usually obtained from air) is also needed by fuel cells. Fuel cells can be made in a wide range of sizes. They can be used to produce small amounts of electricity for portable devices, as well as the very high power electric power stations.

The efficiency of a fuel cell is as high as 75 % [46]. There are no NOx, CO, HC emissions, because hydrogen is not burnt in air. Fuel cells potentially produce low greenhouse gas emissions. Depending on the source of the hydrogen gas the greenhouse gas emissions will be lower than those of a current internal combustion engine. If renewable energy is used to generate the hydrogen greenhouse gas emissions may approach zero. Types of fuel cells have been developed usually classified according to the electrolyte used. In the Figure 2.14, fuel cell types are presented including their operating temperature and anode/cathode reactions.

2.3.3.2.1 Operation Principles

A fuel cell is an energy conversion device that converts the chemical energy of a fuel directly into electricity without any intermediate thermal or mechanical processes. Energy is released whenever a fuel reacts chemically with the oxygen in air. In an internal combustion engine, the reaction occurs combustively and the energy is released in the form of heat, some of which can be used to do useful work by pushing a piston. In a fuel cell, the reaction occurs electrochemically and the energy is released as a combination of low-voltage DC electrical energy and heat. The electrical energy can be used to do useful work directly while the heat is either wasted or used for other purposes.

In a fuel cell, the fuel and the oxidant gases themselves comprise the anode and cathode respectively. Thus, the physical structure of a fuel cell is one where the gases are directed through flow channels to either side of the electrolyte. The electrolyte is the distinguishing feature between different types of fuel cells. Different electrolytes conduct different specific ions. Electrolytes can be liquid or solid; some operate at high temperature, and some at low temperature. Low-temperature fuel cells tend to require a noble metal catalyst, typically platinum, to encourage the electrode reactions whereas high-temperature fuel cells do not. Most fuel cells suitable for automotive applications use a low temperature solid electrolyte that conducts hydrogen ions.

In principle, a fuel cell can operate using a variety of fuels and oxidants. Hydrogen has long been recognized as the most effective fuel for practical fuel cell use since it has higher electrochemical reactivity than other fuels, such as hydrocarbons or alcohols. Even fuel cells that operate directly on fuels other than hydrogen tend to first decompose into hydrogen and other elements before the reaction takes place. Oxygen is the obvious choice of oxidant due to its high reactivity and its abundance in air.

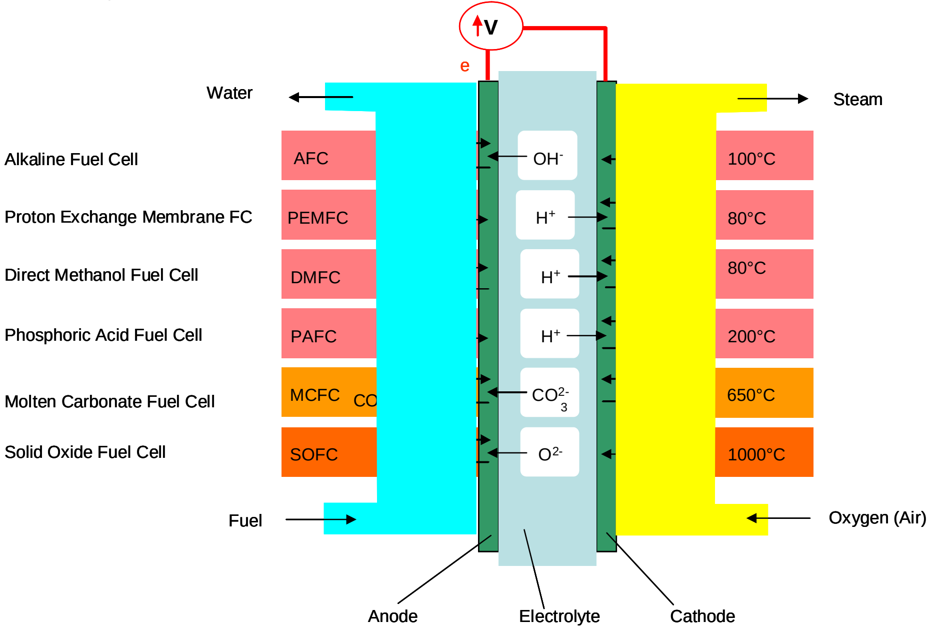


Fig. 2.14 Principles and types of fuel cells [33]

2.3.3.2.2 Types of Fuel Cells

Types of fuel cells differ primarily by the type of electrolyte they employ (Figure 2.14). The type of electrolyte, in turn, determines the operating temperature, which varies widely between types. High-temperature fuel cells operate at temperatures higher than 600 °C. These high temperatures permit the spontaneous internal reforming of light hydrocarbon fuels — such as methane — into hydrogen and carbon in the presence of water. This reaction occurs at the anode over a nickel catalyst provided that adequate heat is always available. This is essentially a steam reforming process (see Section 2.3.2.2). Internal reforming eliminates the need for a separate fuel processor, and can use fuels other than pure hydrogen. These significant advantages lead to an increase in overall efficiency by as much as 15%. During the electrochemical reaction that follows, the fuel cell draws on the chemical energy released during the reaction between hydrogen and oxygen to form water, and the reaction between carbon monoxide and oxygen to form carbon dioxide.

High-temperature fuel cells also generate high-grade waste heat, which can be used in downstream processes for co-generation purposes. They react easily and efficiently without an expensive noble metal catalyst, such as platinum. On the other hand, the amount of energy released by the electrochemical reaction degrades as the reaction temperature increases. They also suffer from severe materials problems. Few materials can work for extended periods without degradation within a chemical environment at high temperature. Furthermore, high-temperature operation does not lend itself easily to large-scale operations and is not suitable where quick start-up is required. As a result, current high-temperature fuel cells applications have focused on stationary power plants where the efficiencies of internal reforming and co-generative capabilities outweigh the disadvantages of material breakdown and slow start-up. The most prominent high-temperature fuel cells are molten carbonate and solid oxide.

Low-temperature fuel cells typically operate below 250 ºC. These low temperatures do not permit internal reforming, and therefore require an external source of hydrogen. On the other hand, they exhibit quick start-up, suffer fewer materials problems and are easier to handle in vehicle applications. The most prominent low-temperature fuel cells are alkaline; phosphoric acid, and proton exchange membrane (or solid polymer).

2.3.3.2.3 Advantages and Disadvantages of Fuel Cells

Fuel cell systems are usually compared to internal combustion engines and batteries. They offer unique advantages and disadvantages with respect to them, as summarized in Table 2.4.

a. Advantages

Fuel cell systems operate without pollution when operated with pure hydrogen, the only by-products being pure water and heat. When using hydrogen-rich reformate gas mixtures, some harmful emissions result although they are less than those emitted by an internal combustion engine using conventional fossil fuels. Thermodynamic efficiency of the fuel cell is higher than that of heat engines. Since fuel cells do not use combustion, the efficiency is not linked to their maximum operating temperature. As a result, the efficiency of the power conversion step (the actual electrochemical reaction as opposed to the actual combustion reaction) can be significantly higher. The efficiency characteristics of fuel cells compared with other electric power generating systems are shown in Figure 2.15.

Table 2-4. Advantages and disadvantages of fuel cells [77]

Fuel cell	Electrolyte	Op. temp. (°C)	Applications	Advantages	Disadvantages
PEM FC	Solid organic polymer poly-perfluorosulfonic acid	60 -100	Electric utility, portable power, transportation	Solid electrolyte reduces corrosion & management problems Low temperature Quick start up	Low temperature requires expensive catalysts High sensitivity to fuel impurities
AFC	Aqueous solution of potassium hydroxide soaked in a matrix solution	90-100	military space	Cathode reaction faster in alkaline electrolyte — so high performance	Expensive removal of CO2 from fuel and air streams required
PAFC	Liquid phosphoric acid soaked in a matrix	175 - 200	electric utility transportation	• Up to 85 % efficiency in co-generation of electricity and heat • Impure H2 as fuel	• Pt catalyst • Low current and power • Large size/weight
MCFC	Liquid solution of lithium, sodium and/ or potassium carbonates, soaked in a matrix	600 - 1000	electric utility	High temperature advantages	High temperature enhances corrosion and breakdown of cell components
SOFC	Solid zirconium oxide to which a small amount of ytrria is added	600 - 1000	electric utility	• High temperature advantages* • Solid electrolyte advantages (see PEM)	High temperature enhances breakdown of cell components

b. Disadvantages

Fuel cells require relatively pure fuel, free of specific contaminants [46]. These contaminants include sulfur and carbon compounds, and residual liquid fuels (depending on the type of fuel cell) that can deactivate the fuel cell catalyst effectively destroying its ability to operate. None of these contaminants inhibit combustion in an internal combustion engine. Fuel cell systems are heavy. Fuel cells themselves are not excessively heavy, but the combined weight of the fuel cells, their support systems and their fuel storage is presently greater than that of a comparable internal combustion engine system. Fuel cell systems are generally lighter than comparable battery systems even though the battery systems require less support equipment.

Despite their weight, existing fuel cell prototype vehicles have shown that systems can be made sufficiently compact for automotive use.

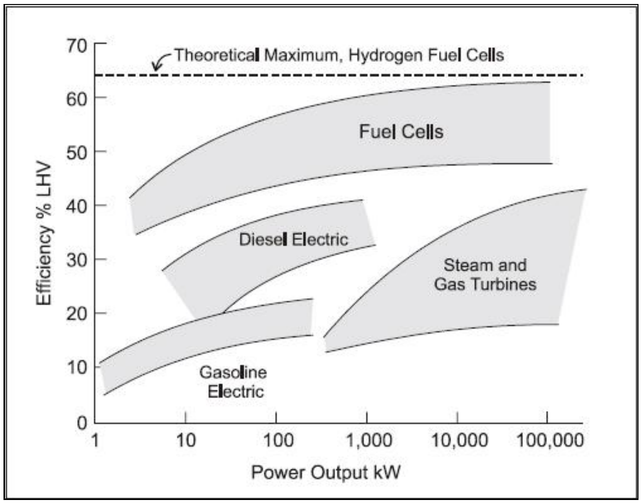


Fig. 2.15 Power generating systems efficiency comparison [46]

2.3.3.2.4 Applications

Fuel cells are inherently modular and therefore lend themselves to a wide range of applications, from large stationary power plants to small portable power packs.

a. Stationary Power plants

Stationary power plant applications have been demonstrated in a number of pilot projects using a variety of fuel cell technologies over the past decades. The largest power plant to date is the Ballard Generation System's 250 kW natural gas fuelled proton exchange membrane fuel cell power plant currently operating at a number of sites worldwide. Although 250 kW is a small amount of power compared to conventionally powered generating stations, it is adequate to service isolated neighbourhoods or to provide emergency backup power to critical facilities, such as hospitals. Stationary power plants are obvious candidates for operation using conventional fuels, such as natural gas, which can be piped to the power plant and reformed on site. Overall size and warm-up time are less critical issues than in smaller, mobile applications. In addition to the high operating efficiency, low emissions and good transient response characteristic of fuel cell systems, stationary applications also produce copious amounts of hot water and waste heat that can be used directly in the surrounding community, further in-creasing the overall system effectiveness.

b. Traffic Applications

Fuel cells systems are attractive for traffic applications due to their low noise, and zero emissions. Buses are the most commercially advanced of all fuel cell applications to date. For example, a successful demonstration program has been carried out by XCELLSiS Fuel Cell Engines, Inc., with the introduction of three buses each in Vancouver and Chicago. All of these buses use pure hydrogen stored as a high-pressure gas; other demonstration vehicles have used liquid fuels and incorporate on-board reformer systems. Buses are a logical starting point for the introduction of fuel cell technology into the transportation sector for several reasons: they offer a reasonably large platform for system components and fuel storage, they can be fuelled at a central fuelling station, and they are regularly maintained by trained personnel.

Cars represent the ultimate market for fuel cell manufacturers due to the quantities involved worldwide. While cars provide the major stimulus for fuel cell development, as they are a major contributor to air pollution, they also pose some of the greatest challenges to commercialization. These challenges include their relatively small size, the vast fuelling infrastructure required, and the inconsistent maintenance habits of the public at large. In addition, performance and reliability expectations are high, while cost expectations are low. Many major car companies are engaged in automotive fuel cell programs including Daimler-Chrysler, Ford, General Motors, Nissan, Mazda, Subaru, Toyota, Honda and Hyundai. Some of these companies have built prototype vehicles using fuel cells with or without auxiliary batteries, and fuelled using either pure (gaseous or liquid) hydrogen or reformate.

2.4 THE HYDROGEN SCENARIOS CONSIDERED

Germany, the world fifth largest consumer of energy, depends heavily on energy import to meet energy demand. Nearly all petroleum and about 80% of natural gas used are imported [176]. About one fourth of final energy consumption of the country (1990-1999) is demanded by industry. The traffic sector has nearly 30 % followed by households with 28.5 %. Small businesses hold a share of 16 % of the final energy consumption. The military is below one percent. It is also shown that the energy consumption of business dropped and industry and rose for **households** and **traffic** sectors (Figure 2.16).

Germany has relatively insignificant domestic energy sources and is heavily import-reliant to meet its energy demands. Coal accounted for 47% of the domestic energy production in 1999, nuclear power 30%, natural gas 14%, renewable sources (including hydro) 6%, and oil 2%. However, oil accounted for 38% of the energy consumption.

Germany has a strong commitment to protect its environment. For example, under the Kyoto Protocol of December, 1997, the country would have to go even further by reducing carbon emissions 8% by 2008-2012. Unfortunately, there have been continuing pollution problems in the country. For example, the total CO_2 emissions in Germany decreased about 15 % during the 90s from 1014 Mio.ton to 859 Mio.ton. However, **traffic** and **households** sectors heightened their emissions. They increased by 12 % and 6 %, for traffic and households, respectively (Figure 2.17).

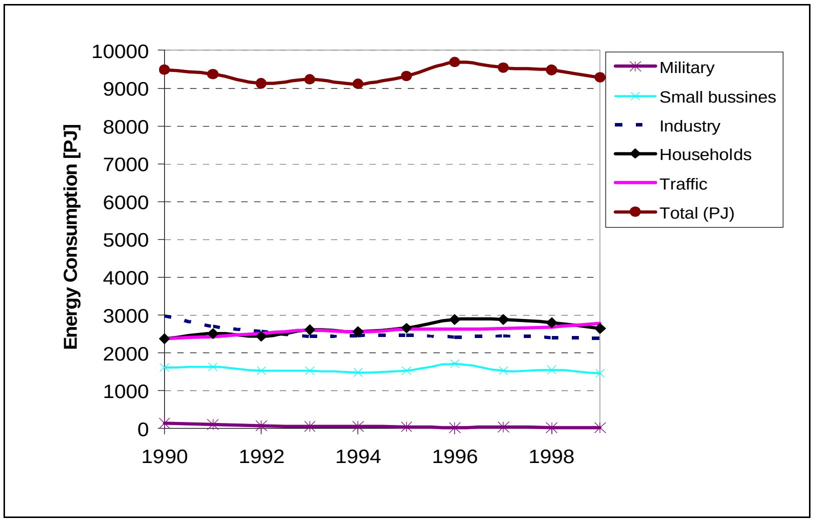


Fig. 2.16 Development of Final Energy Consumption of Germany [176, 120]

Considering the energy situation, the traffic and household sectors will play important roles in the future hydrogen based energy system in the country. Hydrogen as a sustainable and clean energy carrier offers the best solution for the energy problems faced by both sectors. Therefore, traffic and household sectors as realistic hydrogen use scenarios for the future hydrogen based energy system in Germany are considered in the study. This section discusses the scenarios in more detail.

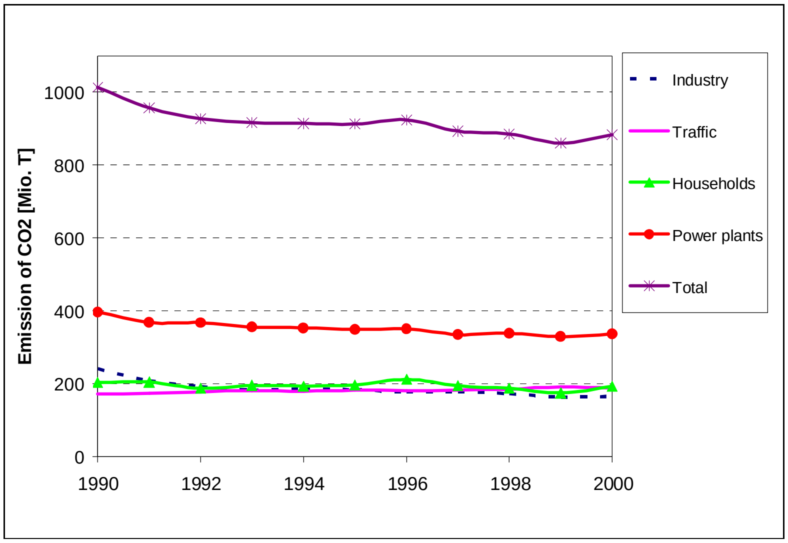


Fig. 2.17 Development of energy-related CO_2 emission in Germany[176, 120]

2.4.1 Traffic Scenarios

Traffic is one of the key factors of global economies and for the mobility of people. Within the traffic sector, land transport, and especially road transport, can contribute to a large extent to the reduction of vehicle emissions by the implementation of better fuels and engines. To fulfil the Kyoto reduction targets for CO_2 emissions, the traffic sector will have to contribute further. Therefore, the German government supports the search for future fuels (including hydrogen) that will be based on renewable energies with extremely low CO_2 emissions in the overall energy chain.

2.4.1.1 Road Traffic Population

Table 2-5 shows the development of the number of private cars and of all vehicles in Germany (1985-2003). The private cars account for over 80% of the road transport, followed by trucks (5%), motorcycles (6%), tractors (0.3%), and buses (0.2%). In general, road transport has shown a steady the growth since 1985.

Table 2-5. Road traffic populations in Germany [x 1000] [176]

Vehicle Type	**1985**	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**
Private cars (incl. Stationwagon)	25.845	30.685	40.404	42.840	44.307	44.605	44.916
Buses (incl. Trolleys)	69	70	86	86	87	85	86
Trucks	1.281	1.389	2.215	2.527	2.640	2.632	2.602
Tractor-traillers	64	78	124	162	177	179	180
Motor cycles (excl. small m’cycle)	993	1.233	2.067	2.767	2.905	2.985	3.051
Micscellaneous	2.366	2.293	2.590	2.983	3.074	3.114	3.147
Total	**30.618**	**35.748**	**47.486**	**51.365**	**53.190**	**53.600**	**53.982**

Total distances travelled by each vehicle types in Germany are presented in Table 2-6. For example, the private cars (Pkw) with the total population of about 45 millions have the total distance (in 2003) of 577.8 x 10^9 km. It means that one car travels about 13,000 km/yr. Meanwhile, buses and trucks have travelled about 42,000 km/yr and 22,000 km/yr, respectively.

Table 2-6. Distance travelled by vehicle types in Germany [in 10^9 veh. km] [BASt]

Vehicle Type	1985	1990	1995	2000	2001	2002	2003
Private cars (incl. stationwagon)	332.5	431.5	535.1	559.5	575.5	583.6	577.8
Buses (incl. Trolleys)	2.9	3.1	3.7	3.7	3.7	3.6	3.6
Trucks	29.9	33.1	52.8	58.7	60.2	58.3	57.7
Tractor-traillers	4.4	5.8	9.7	13.1	13.7	13.7	14.2
Motor cycles (incl. mofas)	10.8	8.6	13.6	16.8	17.8	16.0	16.4
Micscellaneous	3.8	6.2	9.6	11.5	11.8	12.1	12.5
Total	**384.3**	**488.3**	**624.5**	**663.3**	**682.7**	**687.3**	**682.2**

Table 2-7. Traffic Accidents in Germany (x 1000) [StBA, BASt, 176]

Accident Number	1985	1990	1995	2000	2001	2002	2003
Damage to people	328	340	388	383	375	362	355
- of which result in injuries	319	332	379	375	368	355	348
- of which result in fatalities	8	8	9	8	7	7	7
Not damage to people	1513	1671	1850	1967	1998	1927	1905
Total Accidents	**1840**	**2011**	**2238**	**2350**	**2374**	**2289**	**2260**

2.4.1.2 Road Traffic Accident

Table 2-7 shows that the total number of the road traffic accidents in Germany increased by 29% from 1,840,000 accidents (in 1985) to the maximum number of 2,374,000 accidents (in 2001). The accident decreased by 5% to 2,260,000 accidents (in 2003). Meanwhile, the accidents resulted to injuries and fatalities were remains constant. This number, however, is smaller compared to other countries in Europe (e.g. France, Italy, etc).

2.4.1.3 Hydrogen Vehicle Scenarios

Hydrogen as a new vehicle fuel provides the opportunity for both, the reduction or avoidance of polluting emissions and the drastic reduction of the noise level produced. Hydrogen operated in internal combustion engines has a low noise potential and significantly reduces pollutant levels but especially the fuel cell electric drive opens the chance for very low noise levels at zero emission capability. Hydrogen is a "clean burning" fuel, contributing to significantly reduce local emissions where it is used. If hydrogen is derived from renewable resources, if carbon is successfully sequestered, or if environmentally benign nuclear power sources can be developed, the total environmental impact of hydrogen as a fuel would be minimal. Disadvantage of hydrogen in principal, not representing a primary but only a secondary energy carrier, at long term can be transformed into its advantage. It can be derived from various sources. This diversity means that different geographic regions can obtain hydrogen from whatever feedstock is available which would tend to reduce concerns over regional energy security.

Hydrogen vehicles and the infrastructure scenarios have been studied by numerous companies and organizations. They include: (1) Transport Energy Strategy (TES) of German automobile and energy industry database for consensus process on alternative fuels in cooperation with the German Ministry of Transport; (2) European Integrated Hydrogen Project (EIHP), coordination of harmonized EU-wide regulations for hydrogen vehicles and their refueling infrastructure; (3) Hydrogen Network (HYNET) of European hydrogen industry (in preparation) secretariat for a European industry interest and eventually lobby group to foster hydrogen energy; (4) L-B- Systemtechnik (LBST) is the commercial sister company of the non-profit Ludwig-Bölkow-Systemtechnik GmbH, support industry, politics, and non-governmental organizations. A hydrogen fuelled vehicles scenario for Germany till the year of 2050 is shown in Figure 2.18.

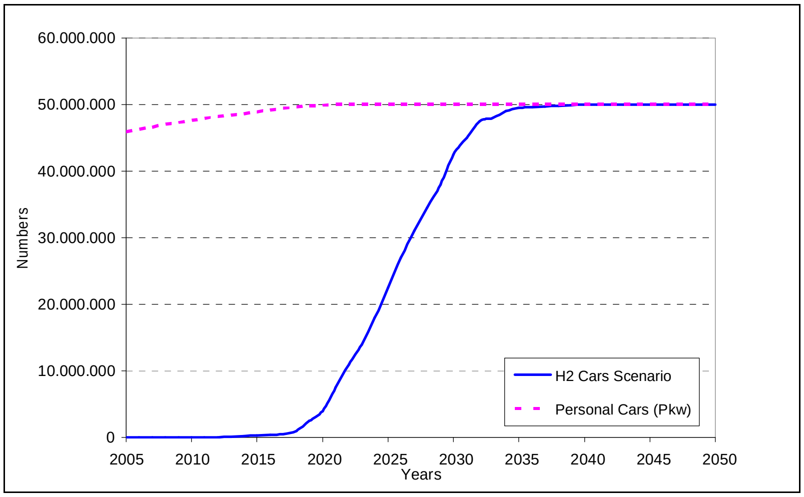


Fig. 2.18 Hydrogen private cars (Pkw) scenario for Germany [34]

2.4.1.3.1 *Fuelling Stations*

Hydrogen vehicle (fuel cell or ICE) is anticipated to expand rapidly. It may be prudent for fuelling station designs to accommodate future dispensing capacity growth. There are several approaches to the growth issue and some types of stations can be expanded to higher capacities more easily than others. One solution is to design the station for the expected growth instead of the near-term capacity requirement. This approach certainly increases initial cost, but it may result in lower life-cycle costs.

a. Fuelling Station Design

The number of vehicles that will refuel at a station, vehicle driving patterns, and vehicle fuel economies will determine the quantity of hydrogen to be dispensed. The station design must satisfy the demand. For fleet stations, the number of vehicles will generally be known or determinable. For stations serving vehicles that may refuel at a variety of sites, the number of vehicles refuelling per day may vary. The average number of vehicles refuelling at the station must then be estimated. The vehicle driving patterns determine how many kilometres vehicles drive per day. In some cases, the mileage may be well known (i.e., in transit bus fleets). In other cases, vehicle mileage may vary significantly from day to day. For this situation, the average vehicle mileage must be estimated for the vehicles refuelling at the station. In general, estimates should be conservative (overestimates); otherwise, the station design may not provide the necessary capacity.

Fuel usage for typical hydrogen vehicles is shown in Table 2-8. For example, light-duty fuel cell vehicles are assumed to have a fuel economy of roughly 0.012 kg/km for hydrogen. If the vehicle is driven 20,000 km per year, the average daily hydrogen fuel use will be 0.68 kg/day.

Table 2-8. Fuel usage of hydrogen fuel cell vehicles [39]

Vehicle Type	Fuel consumption		Mileage (km/yr)	Average Daily Usage (kg/day)
	kg/km	km/kg		
Light Duty	0.012	80.5	20,000	0.68
Transit Bus	0.087	11.5	65,000	15.5

b. Type and Size of the Station

In order to properly service hydrogen vehicles, the station design must ensure that the station components can dispense the expected daily hydrogen usage in the fuelling time available. In general there are two types of hydrogen fuelling station designs to be considered for the hydrogen economy. They include stations that receive and store hydrogen delivered as a compressed gas and cryogenic liquid; and the stations that produce hydrogen on-site by reforming natural gas (or some other hydrocarbon feedstock) or electrolysis.

Station designs using tube trailers or liquid hydrogen cryogenic tanks store quantities of hydrogen, which are periodically replenished when the tube trailers are replaced or the liquid tanks are refilled. The hydrogen is typically replenished on time scales longer than one day so the storage components must store significantly more than the daily hydrogen usage. Liquid hydrogen tanks can store very large quantities and do not limit the station throughput. Tube trailers store roughly 275 kg and mobile fuelling concepts store considerably less. The daily hydrogen usage should generally be less than this amount; otherwise, the trailer or mobile fueler would have to be replaced too often.

Station designs using electrolysers or on-site reformers produce hydrogen at a specified rate. If these components cannot produce hydrogen as quickly as the refuelling requires, there is a potential bottleneck. Buffer or cascade storage (which is discussed subsequently) can ease the production requirement over short time intervals, but the overall daily hydrogen production capacity must be greater than or equal to the average daily dispensing requirement.

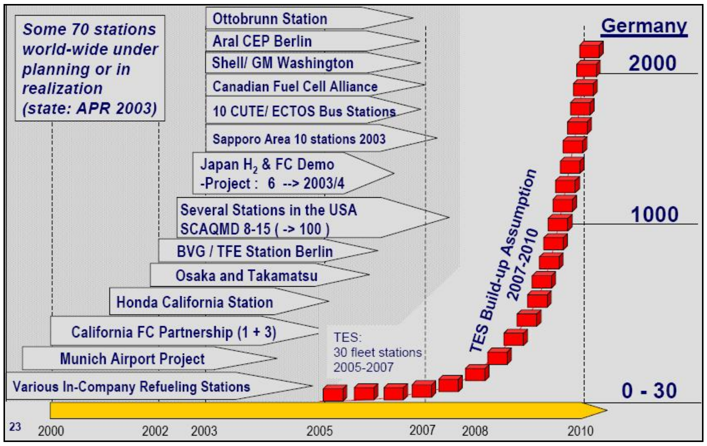


Fig. 2.19 Selected planned hydrogen filling stations in Germany and worldwide [210]

c. Development Scenarios

Currently, there are about 16 units of hydrogen fuelling stations installed in Germany (Table 2-9). They are located in several cities such as München, Hamburg, Berlin, and so on. The world first public hydrogen fuelling station was opened as part of the Aral station in Messedam-Berlin on November 12, 2004. In general, the hydrogen fuelling stations store and deliver hydrogen in two forms, i.e. liquid and compressed gas.

Table 2-9. Lists of hydrogen filling station by country and technology [214]

Country	Number	Company	Technology
US	25	Air Products and Chemical; Stuart	GH2 and LH2 facilities; H2 from NG
Germany	16	Linde, BMW, Total, BP, Aral	H2 from natural gas; electrolysis
Japan	11	Linde, Senju, Honda, Toyota	Electrolysis; oil, gas-reformation
Canada	6	Stuart energy, Hydrogenics	Electrolysis; H2 from natural gas
Sweden	2	BP, Stuart Energy	Hydro electrolysis
Spain	2	BP, IMET	Electrolysis, H2 from natural gas
Portugal	2	BP, Arliquido	LH2 from crude oil
Italy	2	AEM, SOL	Electrolysis, LH2
Belgium	2	Messer Griesheim, Nexben	LH2 from natural gas
Australia	2	BP	GH2 from oil, gas & solar
Norway	1	Norsk Hydro	Electrolysis
Iceland	1	Royal Dutch Shell	Geothermal & Hydro electrolysis
Denmark	1	Linde	LH2
Luxemburg	1	Shell; Air Liquide	GH2
Netherlands	1	IMET; Linde	RE-based electrolysis
UK	1	BP	H2 from crude oil
China	1	British Oxygen	H2 from natural gas
Taiwan	1	Ztek Corp.	H2 from natural gas
South Korea	1	Pressure Product Industries	GH2
Singapore	1	Air product	GH2
Total	80		

Regardless of all problems which might appear to exist today, hydrogen is expected to become one or even the leading energy source within the next 20-30 years [210]. After the initial learning phase (2005) there is a dramatic increase in the opening of hydrogen service stations. The first indicators of this learning phase are opening of H2 station in Berlin (2002), which is followed by another CUTE (Clean Urban Transport for Europe) project with opening the largest public hydrogen fuelling station in Berlin (2004). Altogether there are already about 80 fuelling stations around the world. Most facilities are in Germany, USA, and Japan. Fig. 2.19 shows hydrogen fuelling station scenario developed by [34, 210]. They estimated of 30 fleet fuelling stations will be available in the period 2005-2007, and 2000 stations in 2010.

d. Hydrogen Autobahn

Linde AG proposed to set up 40 hydrogen filling stations along the Autobahn on the “International Hydrogen Day, in Berlin on February 24, 2005. It makes it possible to drive pollution-free between all the major cities in Germany. The fuel stations will form a 1800-kilometre "hydrogen ring," connecting Berlin, Munich, Stuttgart and Cologne with fuel stations every 50 kilometres [220].

2.4.2 Households Scenarios

The Federal Republic of Germany is a densely populated country with approximately 83 million inhabitants (2003), which corresponds to a population density of 230 persons per square kilometres. The Federal Republic of Germany is characterized already today as an industrialized country with having a low number of young people. The population development shows that in a few years there will be more people aged 65 years than aged 15 years or less. Low numbers of births and a declining propensity to get married also affect the size of households, which have shown a tendency to decrease for years in the Federal Republic of Germany. Households with more than 5 persons have become very rare, while the number of one-person households is growing continually. There is an above-average number of one-person households especially in large cities.

Table 2-10. Numbers of the German households (x 1000) [176]

	1997	1998	1999
Households (in April)	37457	37532	37795
1-person households	13259	13297	13485
2-person households	12221	12389	12554
3-person households	5725	5643	5645
5-person households	4537	4527	4444
Households with 5 or more persons	1715	1676	1666

2.4.2.1 Households

Nearly 98% of the about 37 million dwelling units in Germany are located in residential buildings, the remaining 2% in residential homes, other buildings with housing space and inhabited provisional accommodations (Table 2-10). More than half of the inhabited dwelling units are located in buildings with 3 or more dwelling units, a good fourth in buildings with one dwelling unit, and just under one fifth in residential buildings with 2 dwelling units. A share of 86.9% of the about 33.8 million inhabited dwelling units in residential buildings was equipped with some form of centralized heating system. The remaining 13.1% have to be heated with single or multi-room stoves or did not give details on how their dwelling unit was heated. Among the type of energy indicated for heating, gas ranked first (43.3%), followed by oil heating (34%), and district heating (13.1%). The remaining 9.6% were distributed over energy types of electricity (4.6%), coal (3.8%), wood and other renewable energies (1.1%) or there was no information available 0.1% [176].

2.4.2.2 Household Final Energy Consumption

The share of household energy consumption (in 1999) was 28.5% or 2647 PJ (Table 2-11). Mineral oil and natural gas are the most important energy carriers of household energy consumption. Both have a share about one third. Since the middle of the 90s natural gas took the leadership. Electricity is about 1/6 of the total energy consumption. Coal and mainly brown coal are loosing importance in the German household energy mix. Only 0.7 % of household energy consumption was still from coal, 1.0 % from brown coal in 1999.

Table 2-11. Energy carrier of household energy consumption in % [176]

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Final energy consumption in PJ	9484	9367	9127	9232	9109	9323	9689	9543	9481	9288
Industry in %	31,4	28,8	28,1	26,4	27	26,5	25	25,7	25,4	25,6
Traffic in %	25	25,9	27,6	28,1	28	28,1	27,2	27,7	28,3	29,9
Households in %	25,1	26,8	26,7	28,3	28,1	28,5	29,8	30,2	29,6	28,5
Small bussines in %	17	17,4	16,8	16,6	16,3	16,4	17,7	16	16,4	15,7
Military in %	1,5	1,1	0,8	0,6	0,6	0,5	0,3	0,4	0,3	0,3
Households in PJ	2380	2510	2437	2613	2560	2657	2887	2882	2806	2647

Figure 2.20 shows that nearly 80 % of the household energy in Germany is used for heating purposes. Information or communication and lightning add only a little more than 3 % of the energy consumption. If private car use is taken into account heating and car driving need 86 % of household energy and information, communication and lightning fall back to 1 % each. Primary energy used for heating includes heating oil, natural gas, electricity, and renewable energies.

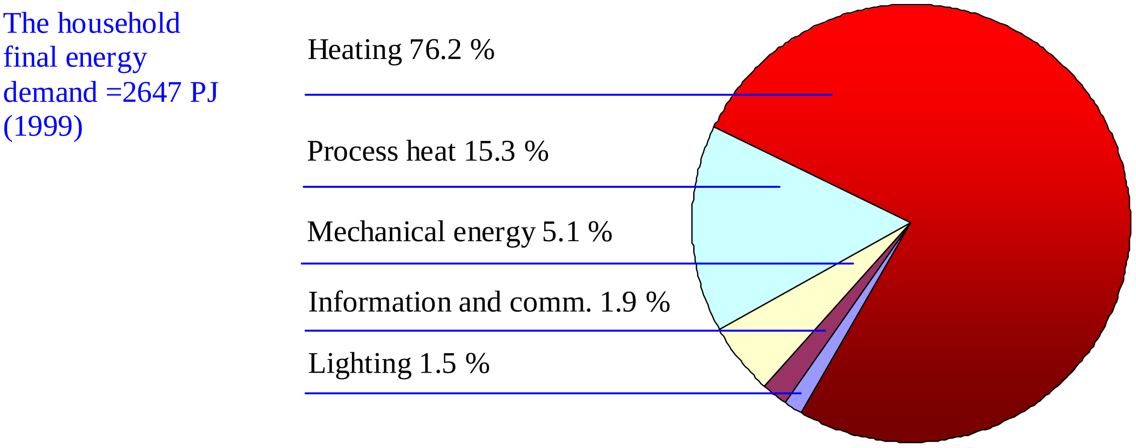


Fig. 2.20 Final energy consumption in households, Germany 1999 [176]

The market for heating oil decreased in size during the last years. The main reason is the shift in domestic heating from oil to natural gas. The share of natural gas as an energy carrier increased for the economy in general as well as for household purposes. Gas demand increased by 400 % since 1975. In 16.5 Mio households heating systems are based on natural gas [121]. These are 42% of all dwellings. Electricity market was open for household demand since 1998. According [26] renewable energies held a share of 4.5 % of electricity production and 1 % of warming.

2.4.2.3 Hydrogen Scenarios for Households

In general, hydrogen use in the households sector can replace all of today's uses covered by natural gas, town gas or by liquid petrol gas. Thus hydrogen can be used for boilers, for cooking stoves, for catalytic heater devices, for central heating furnaces as well as for efficient decentralized cogeneration applications for combined heat and electricity. But, the most efficient conversion concepts for households will be catalytic heat and hot water production, and fuel cell combined heat and power (FC-CHP) production. Both technologies, catalytic heaters and fuel cells, can be configured from very small initial power capacities to larger ones in modular form. Therefore, high flexibility and efficiency can be achieved from the very beginning. Catalytic heaters operating with hydrogen and air easily achieve 75% efficiency at the site of application. With hydrogen oxygen operation 99% are the present state of the art.

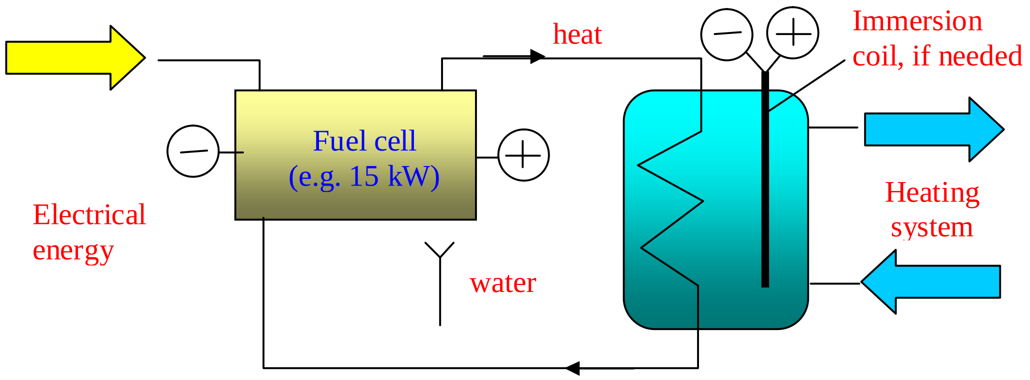


Fig. 2.21 Diagram of fuel cell – combined heat and power

2.4.2.3.1 Operational Principles of FC-CHP

The main component of FC-CHP is a fuel cell. In contrast to mobile applications, for this purpose phosphorus acid fuel cells are advantageous. They operate at temperatures between 160 and 220°C and thus supply enough thermal energy for heating rooms and water. Figure 2.21 show a simplified schematic diagram of FC-CHP. Heat is generally recovered in the form of hot water or low-pressure steam (< 0.2 MPa), but the quality of heat is dependent on the type of fuel cell and its operating temperature. The one exception to this is the PEM fuel cell, which operates at temperatures below 100°C, and therefore has only low quality heat. Generally, the heat recovered from FC-CHP systems is appropriate for low temperature process needs, space heating, and water heating. In the case of SOFC and MCFC technologies, medium pressure steam (up to about 1 MPa) can be generated from the fuel cell’s high temperature exhaust gas, but the primary use of this hot exhaust gas is in recuperative heat exchange with the inlet process gases.

2.4.2.3.2 Development Scenarios

In the first stage, fuel options required for the CHPs will be natural gas transformed to hydrogen in a separate reformer unit. Based on this, the Vaillant GmbH is currently developing systems for single households, which are supposed to be available within the next years. In these systems, hydrogen currently is produced from natural gas, which is already distributed over the existing infrastructure. Later on, it is conceivable to distribute pure hydrogen through the same pipelines. On other hand, the local power company, HEW in Hamburg, is now running one fuel cell plant supplying clean energy to the whole block of buildings working on pure hydrogen.

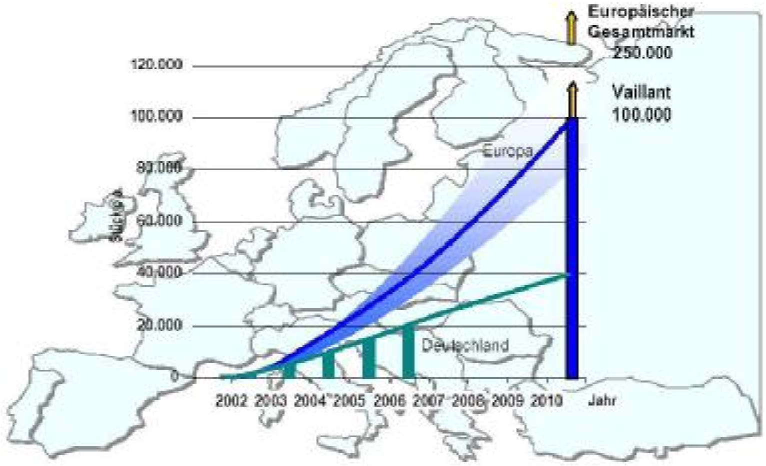


Fig. 2.22 Market growth prognosis of FC-CHP from the Vaillant [194]

As a starting point Vaillant together with the partners Ruhr gas, EON engineering, ELE Energy and EUS Society for Innovative Energy Conversion tested several low-temperature cells with protons of leading diaphragm (PEM) install in North Rhine-Westphalia in 2001. On the basis of the field test results Vaillant started to produce CHPs at a pilot scale in 2003. In 2004/2005 the series production and marketing were started. Vaillant proposed to continue the CHPs production, as shown in Figure 2.22.

Chapter 3

SCENARIO DESCRIPTION

3.1 INTRODUCTION

As described in the Chapter 2, hydrogen for traffic sectors and household applications has been considered as a realistic hydrogen use scenario for this study. To make hydrogen available for the scenario an infrastructure covering the following steps must be built up: production, storage, transportation, filling station, and end-use technology. This chapter describes the hydrogen objects for the selected scenarios and their related activities to hydrogen considered in the study. The choice was limited to the existing plants or demonstrations projects which are available in Germany. They include solar hydrogen production plant, hydrogen storage at depot, hydrogen filling station, hydrogen energetic applications (i.e. hydrogen private car and fuel cells – combined heat and power for households), and hydrogen transportation (i.e. LH_2 road tanker and GH_2 pipeline).

3.2 OUTLINE OF THE STUDY OBJECTS

A key of precondition for the realisation of a hydrogen economy is the development of a hydrogen infrastructure which, by definition, includes the systems needed to produce hydrogen, to store it, and to deliver it to users. As discussed in Section 2.3, in order to realize the hydrogen energy economy in Germany, the required "clean" hydrogen may be imported from other countries [200, 201,168]. For example, the Euro-Quebec Hydro-Hydrogen Pilot Project, 1989-2001 (EQHHPP) considered to import hydrogen from Canada, where the cheapest electricity is available. The hydrogen is produced from water in large-scale water electrolysis plants powered by renewable energies (e.g. hydro, wind, solar, etc). It is imported to Germany using a large LH_2 tanker ship, and/ or using a long distance GH_2 pipeline. The imported hydrogen is then stored in mass storage plants located near a harbour (called "terminals"). Furthermore, the hydrogen is then transported or distributed to the regional storages or to user centres via regional transport by road, rail, river, and pipeline [208].

Fig. 3.1 shows the simplified scheme of the hydrogen energy economy considered in the study. Similar to other energy carriers (such as LPG) the hydrogen economy may be represented by hydrogen storage and transport. Storage at terminal is mainly used to store a large bulk quantity of hydrogen arriving from abroad, where the hydrogen can be stored in the form of liquid hydrogen (LH_2) and compressed gaseous hydrogen (GH_2). In case of transhipment, the LH_2 storage is filled from an LH_2 tanker, while GH_2 storage from a long-distance pipeline. The hydrogen is distributed the regional distributors (e.g. depot) through regional transport, such as tanker truck, inland waterway, rail cars, or regional pipeline. To facilitate a regional distribution various hydrogen companies and traders should install depots for the intermediate storage of hydrogen. The hydrogen stored at depots is mainly used for the distribution in smaller tank trucks, for delivery by third parties, as buffer stocks, for reasons of economy (the storage of lots bought at low prices), and for operational reasons (the emptying, cleaning, and putting into operation of tank truck). Finally, the hydrogen can be distributed to hydrogen filling stations or directly to end-users through tanker truck or pipeline.

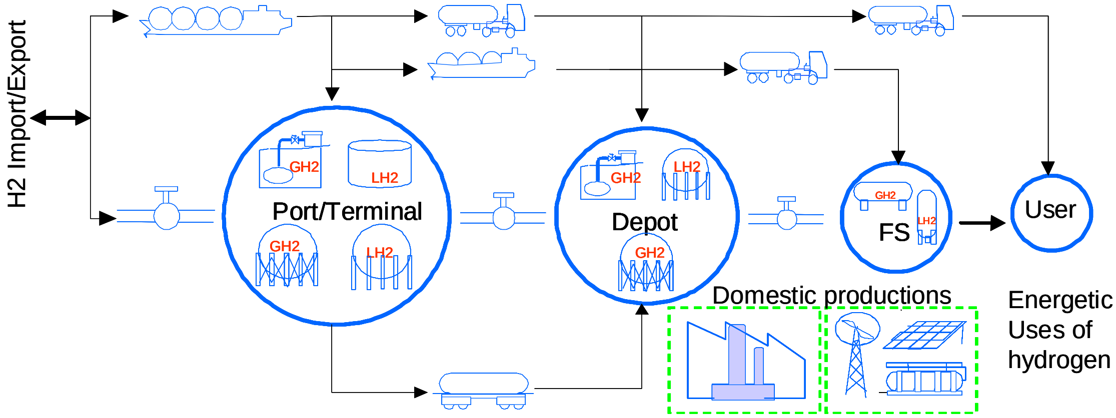


Figure 3.1 Hydrogen production, transport, storage and end-use pathways [187]

Small amounts of hydrogen may be produced domestically from reforming of hydrocarbons, refinery byproducts, and chemical by products as in the present production, or water electrolysis using electricity during peak power production or using renewable energies [168, 72, 197, 201].

Although some experts predicted that the hydrogen economy might be realized in the next 30-50 years (2030-2050) [30, 201], some of the infrastructures (such as hydrogen filling station) have been built worldwide. Besides, several industrial-scale hydrogen production plants (e.g. water electrolysis) as well as the end-use technologies (such as fuel cells) have also been successfully demonstrated. For example, a solar hydrogen plant has been successfully demonstrated in Germany for 13 years (1986-1999) [181, 182]. The study is focused on the following existing hydrogen plants information obtained through study visits, open literature, and contact or discussion with some German experts:

(1). Hydrogen production

The study considers a solar hydrogen plant (Solar-wasserstoff-Bayern, SWB) that was an industrial scale demonstration project (1986-1999) situated in Neunburg vom Wald, Germany. The system mainly consists of electricity generation, electrolyser, compressor, hydrogen storage, and so on. The hydrogen is produced from water through water electrolysis by using electricity generated from solar energy.

(2). Hydrogen storage

Since the large-scale hydrogen storages at terminals or depots as shown in Fig. 3.1 are not yet available the study considers the large-scale hydrogen storage situated in Ingolstadt, Germany. It stores a large amount of hydrogen in liquid phase (LH_2) currently used for the regional distribution. Therefore, it may be considered as storage depot. The tank is filled (loading) directly from a liquefaction plant at the flow rate of 180 kg/h. The LH_2 is distributed to costumers (e.g. hydrogen filling station) by a LH_2 tanker truck.

(3). Hydrogen filling station

Hydrogen filling stations are a key of the hydrogen economy. Currently the numbers increase dramatically. The study considers the first public filling station owned by BVG, Berlin. The station stores hydrogen in liquid form, and delivers it to public hydrogen vehicles both in liquid and gaseous form. The tank is filled from the nearest hydrogen depot through an LH_2 tanker truck.

(4). Hydrogen energetic applications

The study considers a hydrogen vehicle and a fuel cell - combined heat and power (FC-CHP) for household applications. The hydrogen private car (e.g. BMW 735i) stores hydrogen in liquid form, and delivers it to the internal combustion engine (ICE). For household application, the FC-CHP is regarded to provide electricity and heat for residential buildings situated in Hamburg.

(5). Hydrogen transportation

The study considers two types of hydrogen transport, i.e. a LH_2 tanker truck and GH_2 pipeline operated in Germany. The LH_2 truck (e.g. Linde) with a capacity of 53 m^3 is regularly used to deliver LH_2 from a storage depot to end-uses technology (e.g. hydrogen filling stations). The transport routes, numbers of filling station and the truck delivery times were modelled in the study. The considered GH_2 pipeline proposed to transport hydrogen from a hydrogen plant to user storage with the distance of about 53 km.

3.3 HYDROGEN PRODUCTION

The study considers a solar hydrogen plant situated at Neunburg vorm Wald, Germany. The plant was built by the Solar-Wassertoff-Bayern GmbH (SWB) founded in 1986, as a joint venture with 70% of the shares held by Bayernwerk AG and 10% each by BMW AG, Linde AG (both through wholly owned subsidiaries) and Siemens AG [181, 182]. Objective of the project was to improve the system components, test them in interaction with another and among other things reduce conversion losses, advance their suitability for practical implementation, and develop optimised overall concepts

Fig. 3.2 shows a layout of the overall facility from the aerial photograph which shows the operating and multi-purpose building (information center) and the plant subsystems installed outdoors. Prominent features are the South-oriented photovoltaic solar fields, the storage vessels for hydrogen and oxygen gas, liquid and gaseous nitrogen, and the liquid hydrogen filling station.

3.3.1 System Description

A solar hydrogen plant is a hydrogen production plant using solar energy to electrochemically decompose water in an electrolyser to obtain hydrogen and oxygen. In the electrolysis of water the electric current is passed through an electrolyte solution of water and potassium hydroxide or alkali, decomposing the water into its constituent elements hydrogen and oxygen. Hydrogen is formed in the cathode and oxygen in the anode. A diaphragm separates the two cells to keep the two gases from recombining into water. The produced hydrogen is then stored in a pressurized vessel. Energy input required to produce one cubic meter of hydrogen is about 5 KWh [181, 182].

The plant is an industrial-scale demonstration facility. It comprises major system components of a possible future energy supply based on (solar) hydrogen, such as photovoltaic solar generators, water electrolyzers, hydrogen and oxygen storage facilities, catalytic and advanced conventional heaters, a catalytically heated absorption refrigeration unit, fuel cells for stationary and mobile application, and a gaseous hydrogen filling station as shown in Fig. 3.3.

The larger solar generators (about 360 KW photovoltaics modules) convert the sunlight into direct current (DC) electricity, which is mainly used to power electrolysers. The feed power through maximum power point (MPP) –controlled DC/DC converters is connected to a common DC busbar interconnecting the solar generators, water electrolyzers and AC power grid. Two types of electrolyzers were installed to produce hydrogen (and oxygen) classified as low-pressure and high-pressure electrolyzers. Two advanced low-pressure water electrolyzers employing different technologies, rated at 111 KWe and 100 KWe capacity, total maximum hydrogen output 47 m /h. Addtionally, an advanced pressure-type electrolyzer of 100 KWe is characterized by operation at 32 bar pressure, provision for intermittent working mode and fast control response. No subsequent compression of the product gases to the SWB system pressure of approximately 3 MPa is necessary.

Figure 3.2 The solar-hydrogen plant in Neunburg vorm Wald [182].

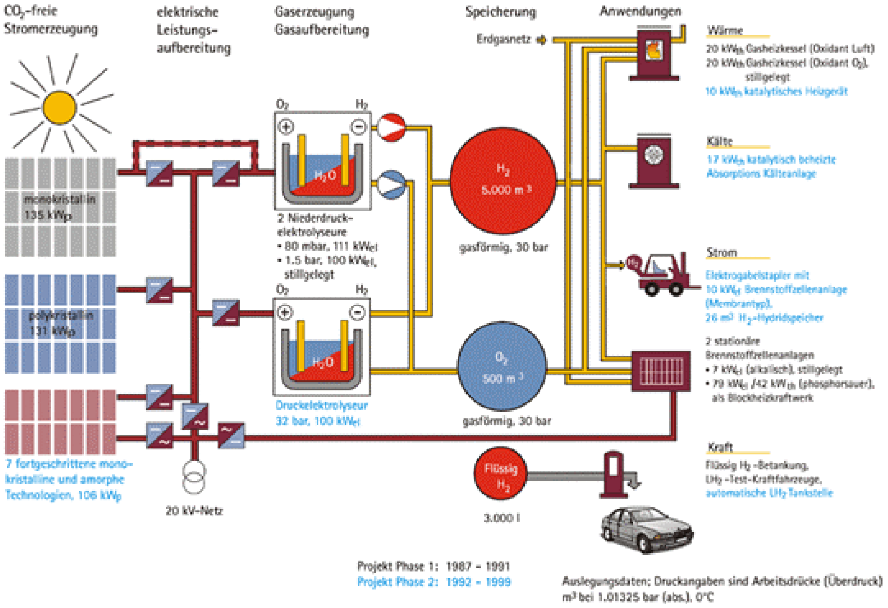


Figure 3.3 Diagram of the solar-hydrogen plant [181].

3.3.2 The GH_2 storage

The high-pressure hydrogen tank of the plant stores the largest hydrogen inventory of 5000 Nm^3 compared to other components. It may be the largest contributor to societal risk as assessed in this study. Therefore, the study is focused on the two horizontal cylindrical high-pressure hydrogen storages (Fig. 3.4) with an operating pressure of 3 MPa at ambient temperature. The tank is filled directly from the water electrolysis in the plant generated from the two low-pressure electrolyzers requiring subsequent compression of the product gases. The stored hydrogen in this plant is mainly used for energetic utilization, such as fuel cells and gas-fired heating boilers of calorific-value. Two types of fuel cell plants, i.e. alkaline and phosphoric acid were tested.

Figure 3.4 GH2 storage at the solar-hydrogen plant [215].

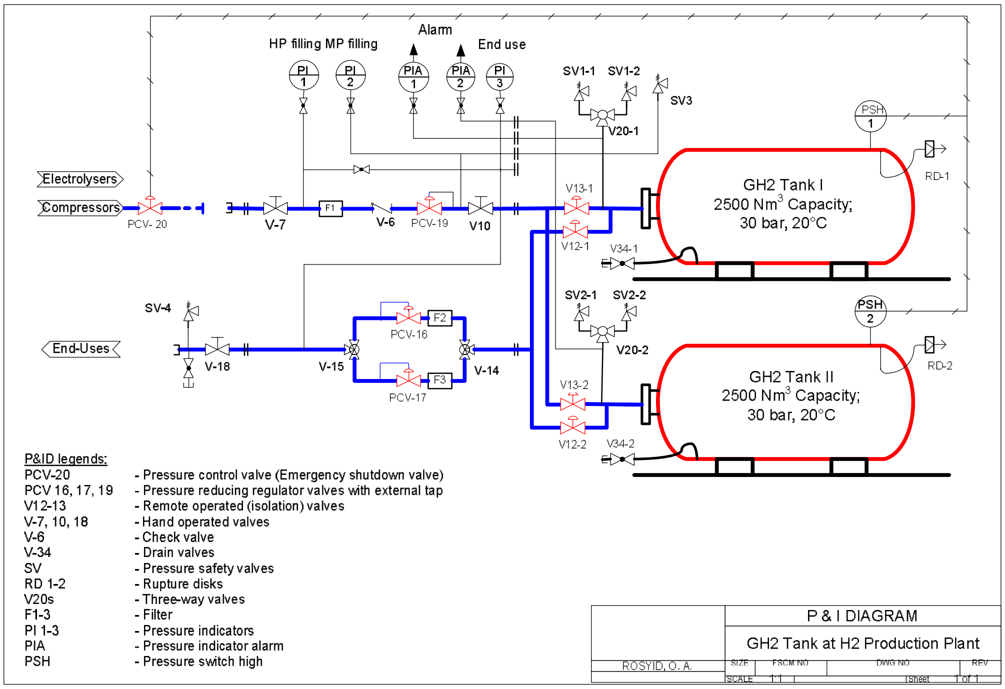


Figure 3.5 Simplified P&I Diagram of the GH2 storage [119, 102].

Table 3-1 Most important capacities and dimensions of the GH_2 storage

H2 Storage / lines	Dimension	Capacity
1. High-pressure vessel	L= 9.8 m, D= 2.8 m, V_{useful} =50m^3	2x2500 Nm^3 (*) 30 bar (400 kg)
2. Input line	50.8 mm (2 in)	30 Nm^3/h
3. Output line	50.8 mm (2 in)	30 Nm^3/h

Source: Messer Griesheim GmbH, Linde AG; (*) m^3 H_2 at 15°C, and 1 bar (NTP)

Fig. 3.5 shows a simplified piping and instrumentation diagram of the high-pressure storage. The tank is filled from electrolysers continuously during the day (e.g. 200 /year) through filling valve, V7 and V13. The filling process is stopped when the set point at the pressure control valve, PCV-19 is reached. Pressure indicator and alarms (PIA) are installed to measure and indicate pressure levels of the tank and its piping system. The tank PIAs are equipped with pressure switch or transmitter for remote controllers (e.g. alarm). If the operator fails to observe PIAs or to respond to the alarm the tank pressure increases rapidly and the tank is overfilled.

To protect against overpressure, each tank is equipped with two pressure safety valves (SVs) and a rupture disk (RD). One of the SVs is operated exchangeable at the relative pressure of 3.3 MPa. The SVs will automatically re-close if the tank pressure returns to the operating pressure. The rupture disks (RD-1 and RD-2) are provided in case the safety valves should fail. The ultimate overpressure protection of the tank is provided by stopping the filling line automatically. It is performed by a safety shut-off (PCV-20), which is actuated by PSH signal. The gas is withdrawn from the tank through withdrawal valve V12. The required output pressure is determined by setting pressure at the pressure control (i.e. high pressure=PCV-16, low pressure=PCV-17).

3.4 HYDROGEN STORAGE

The study focuses on liquid hydrogen (LH_2) storage situated in the Vonburg-Ingolstadt-Refinery (RVI), Germany, as a representative example. The LH_2 storage is used to store liquid hydrogen produced from the hydrogen liquefaction plant. The LH_2 is delivered to the consumers (e.g. hydrogen filling station) through a LH_2 tanker truck. The tank is directly filled from a liquefaction plant with daily capacity 4.4 ton LH_2 per day, and presently is the largest hydrogen liquefaction plant in Germany [78].

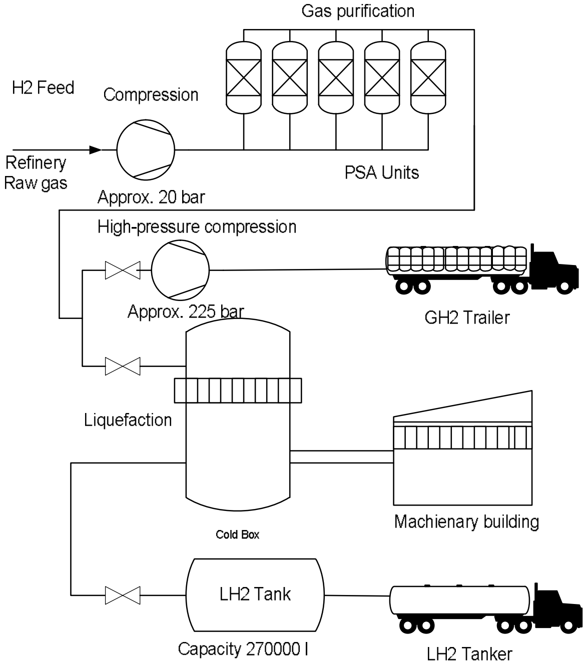


Figure 3.6 Process flow diagram of the liquefaction plant [78]

3.4.1 System description

The Linde liquefaction plant (Fig. 3.6) mainly consists of compressor units, Pressure Swing Adsorption (PSA) purification, liquefier, and LH_2 tank. The hydrogen rich raw gas supplied from the RVI refinery has pressures varying between 0.9-1.4 MPa. The gas is then compressed to about 2.1 MPa, and is cleaned in PSA purification units. The gas is further purified by low temperature and liquefied into para-hydrogen [78].

The liquefaction process which is designed for a flow rate of 180 kg/h based on the Claude cycle. The necessary refrigeration is provided at three temperature levels using: LN2 (from 300K to 80K), expansion turbine (80K to 30K), and Joule Thomson (JT) valve (30K to 20K). The cooling down process from ambient to LN2 temperature levels is operated manually for about 5 hours. Once the LN_2 temperature is reached the operating mode of 50% or 100% LH2 can be selected from the monitor screen, and the process control system starts automatically. The steady state liquefaction is achieved after a further 3 hours. Opening the JT valve and hence liquefaction capacity is controlled by the outlet temperature of the third turbine.

The liquid hydrogen is then stored in a horizontal vacuum insulated tank at -253°C having a capacity of 270,000 litres. The tank can store hydrogen for several weeks without significant vaporization [78]. The LH_2 is transported to consumers by using an LH2 tanker truck, which is loaded in the filling station. The whole plant is operated and controlled by a central process control system (PCS).

Figure 3.7 Hydrogen liquefaction plant in Germany [78]

3.4.2 The LH_2 Storage

The LH_2 storage mainly consists of a horizontal cylindrical cryogenic tank with a capacity of 270,000 litres (17,000 kg of LH2) at temperature of -253°C and pressure of 0.13 MPa, pressure building circuits, and piping system. Fig. 3.8 shows a simplified P&I diagram of the system developed in the study based on [216], study visit to a similar plant, and discussions with some experts. The LH2 tank is filled directly from a liquefaction plant. It is equipped with the level indicator LI, level switch (LSHL), and a trip switch (LSH) at successively higher levels. It has two independent shutoff valves V-1 and V-3, both of which are operator actuated. The LI is simply an indicator which has also transmitted to control room. The LSHL is connected to an audible/light alarm, and LSH to an automatic trip system and close main valve of the plant (PCV-40). The LH2 is withdrawn to an LH2 tanker truck through remotely controlled valve V-5.

The tank pressure is maintained by a pressure building circuit which mainly consists of a coil (ambient evaporator, D) and its pressure regulator (PCV-1). The circuit vaporizes liquid hydrogen from the bottom of the tank and sends hydrogen in the gas phase to the tank (top). Operation of the circuit is controlled by the PCV-1 triggered by PIC-1 based on the tank pressure (low) obtained and transmitted by pressure transmitter (PT). When the pressure in the tank is lower than the set point of the PCV-1, then the circuit is working.

In order to protect the tank against overpressure two pressure safety valves (SV-1, SV-2) are installed. One of the two safety valves is operated exchangeable at relative pressure of 0.143 MPa. Additionally, the PCV-2 is used as the secondary pressure relief devices. The operation of the PCV-2 is similar to the PCV-1, but it opens if the tank pressure is high.

Additionally, the tank is equipped with pressure switches (PIS and PSHL) used to protect the tank against excessive lower pressure. The PSHL activates the PCV-3 to close in case of the tank pressure is very low.

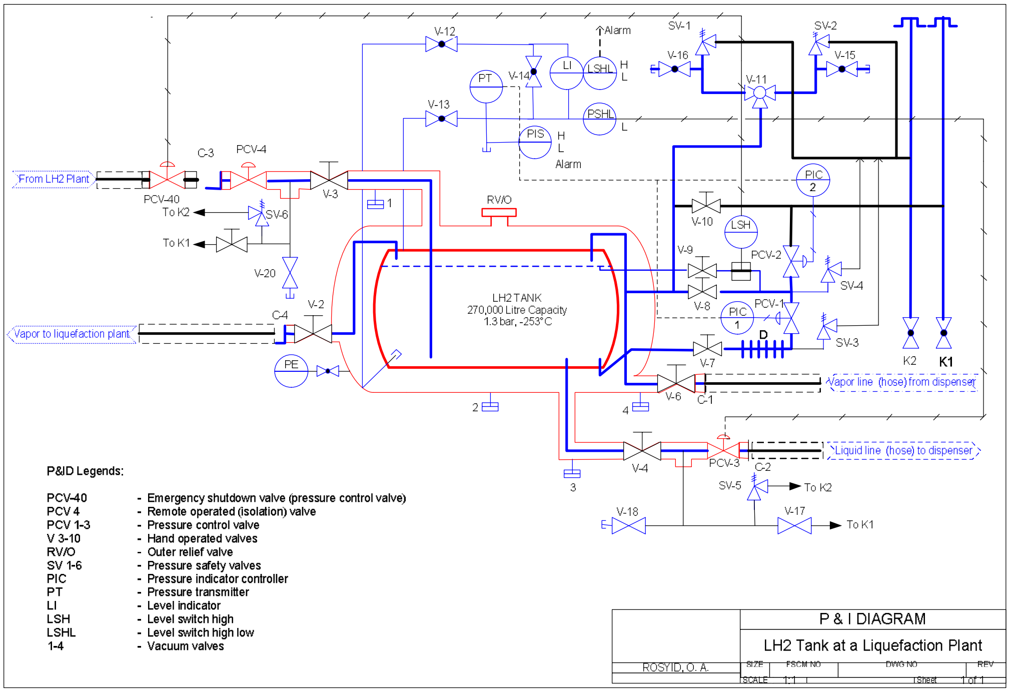


Figure 3.8 Simplified P&I diagram of the LH2 tank at depot [216, 223]

Table 3-2 The most important capacity and dimension of the LH2 storage at depot

Components	Dimension	Capacity
1. LH2 tank	Horizontal cryogenic tank	V=270,000 liter (17,000 kg).
2. Liquid lines	Diameter of 101.6 mm (4 in)*	180 kg/h
3. Vapor lines	Diameter of 101.6 mm (4 in)*	180 kg/h

Source. Linde AG; (*) estimated value

3.5 HYDROGEN FILLING STATION

The study considers a typical hydrogen filling station situated in the BVG's bus depot in Usedomerstrasse, Berlin. The station was built for BVG by TOTAL Deutschland GmbH, in co-operation with BVG, to gain experience with hydrogen used as a fuel for traffic. The research work was concentrated at the BVG'bus depot. Together with Linde AG as the project partner a hydrogen fueling station including a hydrogen competence center (Wasserstoff-Kompetenz-Zentrum) was opened on 23.10.2004. Currently the station is used to supply hydrogen fuel for the BVG's hydrogen buses operating daily on normal routes [197, 228].

3.5.1 System Description

The station is designed to provide hydrogen as fuel for transportation purposes both in liquid (LH_2) and compressed gaseous (CGH_2) form. The CGH_2 is required for a BVG city bus operated on a regular route in Berlin. On the study visit the station was not used to deliver LH_2 to any vehicle, and all the hydrogen was converted into CGH_2. The station stores hydrogen in liquid (LH_2) form (-253°C, 0.8 MPa), and delivers it in the form of CGH_2 to a hydrogen storage at vehicles at 25 MPa and 15 °C [228].

Figure 3.9 Hydrogen filling station BVG, Berlin [217, 228]

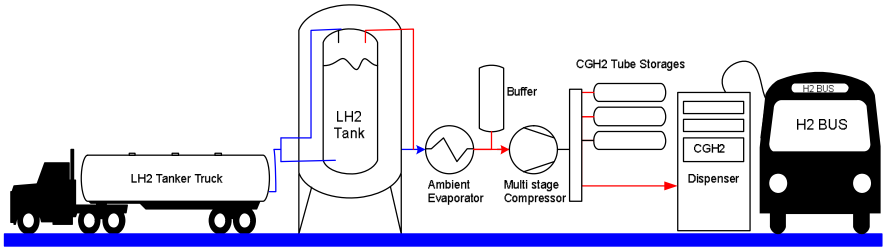


Figure 3.10 Process flow diagram of a LCGH2 filling station

Fig. 3.10 shows the process flow diagram of the hydrogen filling station including all the major components: (1) A double walled super-insulated (cryogenic) tank, to store LH2 with a capacity of 12,000 litres (800 kg of LH_2) at a temperature of –253°C and pressure of 0.8 MPa; (2) An ambient air evaporator, used to vaporize the liquid hydrogen to gaseous hydrogen by taking heat from the air; (3) A multi-stage diaphragm compressor, to raise the pressure of the gaseous hydrogen to three levels, i.e. 15 MPa, 20 MPa, and 35 MPa; (4) A tube trailer, used to store compressed gaseous hydrogen at three levels of pressure (15 MPa, 20 MPa, and 35 MPa), with a capacity of 60 kg; (5) A CGH_2 dispenser, to deliver compressed gaseous hydrogen to hydrogen vehicles (at 35 MPa).

The figure shows that the station filling process begins with the bulk delivery of LH_2. There is a dedicated lane around the station for LH_2 tanker operation. The tanker will pull in to the station, park under the storage and distribution system, and connect its hoses to the LH_2 double-walled vacuum storage tank (a Dewar vessel). The LH_2 is stored in the Dewar at a temperature of -253°C, and pressure of about 0.8 MPa. When hydrogen is needed, it is drawn from the Dewar by gravity and passed through an ambient evaporator where it temperature increased to about -30°C [197, 228]. The cold hydrogen gas is stored in a small buffer storage tank. A multi-stage compressor is then applied to increase the pressure to three levels of pressure (i.e.15 MPa, 20 MPa, and 35 MPa) and store it in tubes of a trailer with a capacity of about 60 kg (680 Nm^3) of hydrogen.

The LH2 storage has the largest hydrogen inventory compared to other equipment in the filling station. Therefore, the study focused on the LH2 storage where its risk may dominate the societal risk of the filling station.

3.5.2 The LH_2 Storage

The liquid hydrogen (LH_2) storage system is a cryogenic, double wall type, and vacuum super-insulated tank. It consists of an inner vessel of cryogenic chromium-nickel steel to hold liquid hydrogen at a temperature of –253°C and pressure of 0.8 MPa, and a supporting outer vessel of carbon steel. The space between the inner and the outer vessels is under vacuum and super-insulated with perlite. Fig. 3.11 shows a simplified piping and instrumentation diagram (P&ID) of the LH_2 tank installed at the station. The LH_2 tank mainly consists of following components: filling system, withdrawal parts, pressure building circuits, safety devices, instrumentation and control, and vacuum system.

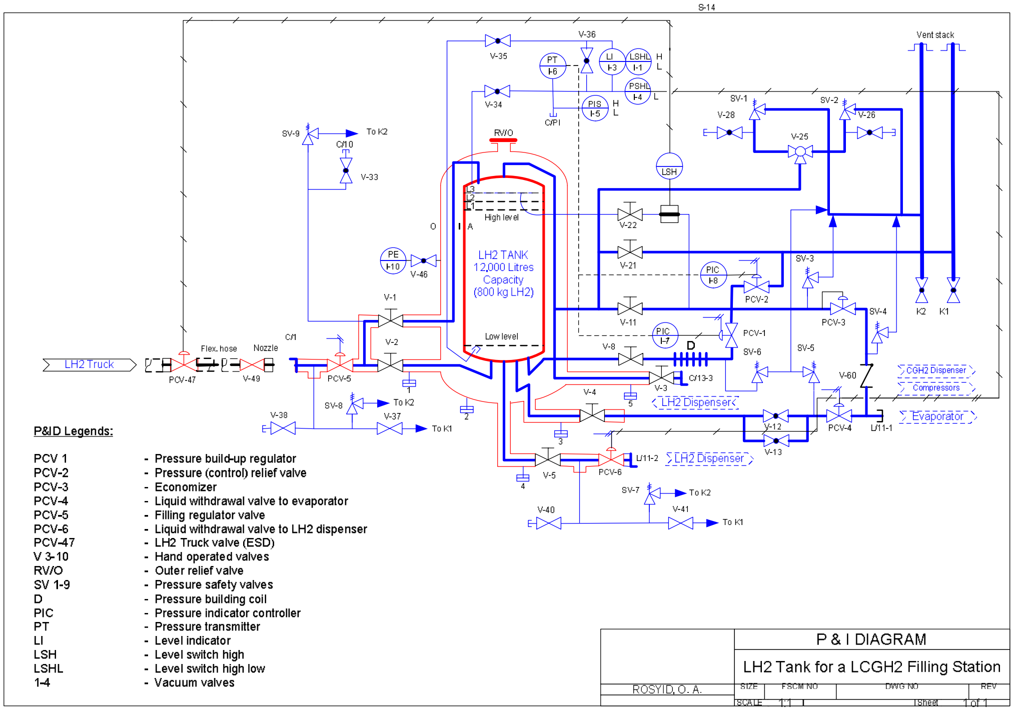


Figure 3.11 Simplified P&I diagram of the LH2 tank at filling station[216, 223]

Table 3-3 The capacity and dimension of the LH2 storage at filling station

Components	Dimension	Capacity
1. LH2 tank	Horizontal insulated vessel	V=12,000 liter (800 kg).
2. Liquid lines	Diameter of 50.8 mm (2 inch)*	
3. Vapor lines	Diameter of 50.8 mm (2 inch)*	

Source. Linde AG; (*)Estimated values

The tank is normally filled from a LH_2 tanker truck through the hose coupling C/1, pressure control valve PCV-5 and isolation valve V-2. Valve V-1 is used to inject the liquid hydrogen into the top of the tank in order to keep the tank pressure constant during filling. The filling is carried out by two operators who observe level indicators (LI). The filling is stopped manually if the level indicator (LI) reaches a high level. In case of operator fails to observe the LI, the level switch LSHL (which is connected to LI) will activate the alarm. The ultimate overfilling protection is provided by stopping the truck valve (PCV-47) automatically. It is actuated by the LSH signal. The signal is provided by overfill detector if the full trycock (V-22) is open.

The required tank pressure (operating pressure 0.7 MPa) is maintained by a pressure building circuit (PBC) which is regulated by the pressure controller PCV-1. The pressure is produced by converting the liquid hydrogen into gas by a pressure build-up evaporator D. The pressure controller PCV-2 ensures that the gas flows from the top of the tank into the vent lines when the tank pressure is too high.

To protect the tanks and piping system against overpressure, the system is equipped with two pressure safety devices (SV-1 and SV-2) with one of them in operation and the other one in standby. One of the two safety valves is operated exchangeable at a relative pressure of 0.77 MPa (10% of the operating pressure). Additionally, the PCV-2 is used as the secondary pressure relief device. The operation of the PCV-2 is controlled by the PIC using signal input given by tank pressure (PT). The valve is open if the tank pressure reaches the set point and it closes again if the tank pressure drops below the set point.

The liquid product is withdrawn from the tank through connector L/11-1 and L/11-2. The L/11-2 is connected to an LH_2 dispenser through a flexible vacuum insulated hose. The L/11-1 is connected to an evaporator to be converted into gaseous hydrogen, compressed, and then stored in the high-pressure tubes trailer (at a pressure of 25 MPa) which is connected to the CGH_2 dispenser.

The actual level and pressure inside the tank is measured and displayed by level and pressure indicators, respectively. The level indicator LI is a differential pressure gauge showing the tank contents in kg (or m^3 gas). The tank pressure gauge and level indicator are also equipped with limit-switch contacts or analog signals for remote transmission.

The tank vacuum jacket is protected against overpressure by an outer vessel relief device, RV/O. While the line relief valves are installed in the external tank and piping system at points where the liquid becomes trapped. Evacuation valves (1-9) are installed to draw vacuum within the tank and piping insulation space. The vacuum gauge tube, PE is a connection point for vacuum probe to measure vacuum in the tanks insulation space.

3.6 HYDROGEN ENERGETIC APPLICATIONS

3.6.1 Hydrogen Private Car

Size of little fuel cells technologies and internal combustion engines are today implemented. They showed excellent performance and safety in hydrogen city buses as well as in private cars. For example, BMW has successfully demonstrated hydrogen private cars (e.g. BMW 753i) for the past five or more years, since 1990 [51]. Hydrogen fuel in the vehicle can be stored in gaseous form (compressed gas), as a liquid (-253°C), or in solid media. A cryogenic hydrogen (LH_2) storage for vehicles offers great advantages compared with compressed gaseous storage, because it offers the highest density per volume. High-pressure hydrogen is stored in a thick-walled tank made of high strength material to ensure durability. Meanwhile, liquid hydrogen is stored in a double walled vessel with insulation, sandwiched between the walls. The study considers a hydrogen private car where hydrogen is stored in liquid form (LH_2).

3.6.1.1 System Description

Fig. 3.12 shows the arrangement of the main components of the BMW hydrogen private car. It is a private car driven by an internal combustion engine (ICE) modified from standard 6-cylinder gasoline engine, 2.5-5 litre, 80-140 kW, and with the driving range of 400 km [218]. The car stores hydrogen in liquid form (LH_2) in a cryo-tank at a temperature of -253°C, and a pressure of about 0.5 MPa. The LH_2 is transported to the engine compartment through a liquid line, and is heated in a central exchanger by engine water up to - 1°C. The GH_2 is then fed to a central, electrically operated supply valve with electronic control that injects the required fuel to each cylinder inlet port in sequence. The engine runs under lean conditions for all driving conditions, giving high efficiency and very low NOx emissions.

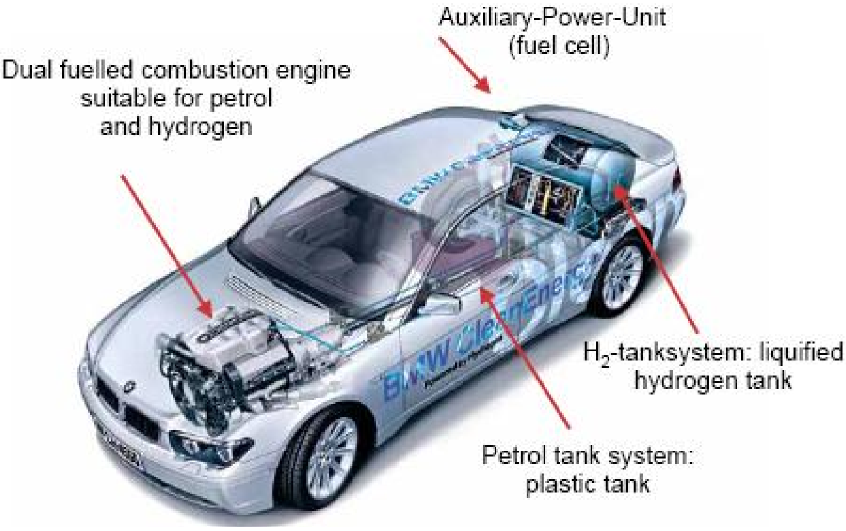


Figure 3.12 Arrangement of the main components of the BMW 735i with ICE [218]

3.6.1.2 The LH_2 storage

The study carried out by Directed Technology Inc (DTI) concluded that the most risk is contributed by the hydrogen tank. Therefore, the study is focused on the LH_2 tank.

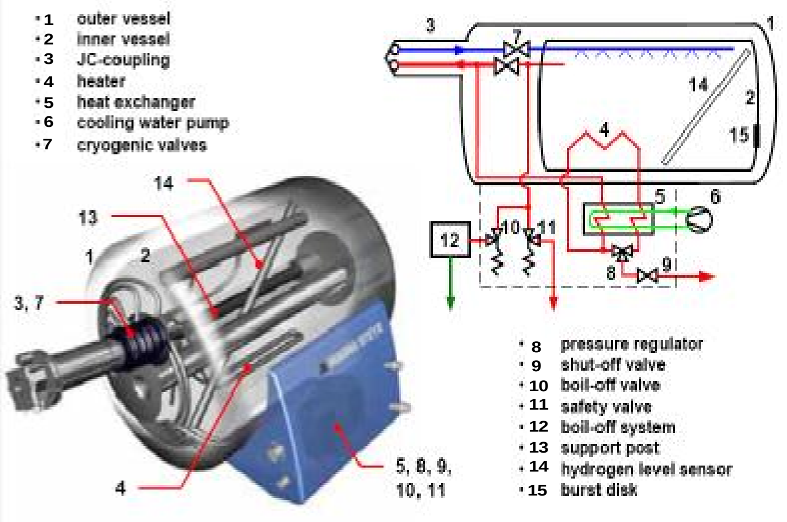


Figure 3.13 The LH_2 tank (Linde) installed in a BMW hydrogen car[219]

The LH_2 fuel tank (Fig. 3.13) is installed safely in the car trunk (back side of the passenger compartment) so that any release of gaseous hydrogen is directed away from the driver or passenger compartment of the vehicle. The fuel tank is mounted in a location to minimize damage from collision to the fuel tank itself and its accessories. The liquid hydrogen fuel tank is equipped with a hydrogen detection system that sounds an audible alarm if the level of gaseous hydrogen exceeds 20 % of the lower flammability limit.

Table 3-4 Most important capacities and dimensions of the LH_2 storage in a car

H_2 Storage/line	Dimension	Capacity
1. LH_2 tank	L=0.0m, D=0.4m, V=0.15m^3	150 l (6 kg of LH_2)
2. Liquid line	Diameter of 6.35 mm (0.25 in)*	
3. Vapour line	Diameter of 6.35 mm (0.25 in)*	

Source: Linde AG; (*) estimated value

3.6.2 Hydrogen for Household Applications

Hydrogen supplied to buildings (e.g. residential) can be used to provide energy in the form of heat and electricity by using fuel cells as combined heat and power (FC-CHP) generators. Two CHP options have been tested so far in Germany, i.e. CHP-based natural gas and CHP-based pure hydrogen (see Section 2.4.3). The fuel option required for the first CHP was natural gas to be transformed into hydrogen in a separate reformer unit. Based on this, the Vaillant GmbH is currently developing systems for individual households. Hydrogen is reformed from natural gas, which is already distributed over the existing infrastructure. Later on, it is conceivable to distribute pure hydrogen through the same pipelines. On the other hand, the local power company Hamburg (HEW) demonstrated a CHP supplying a clean energy to a whole block of buildings working on pure hydrogen for 3 years (1997-2000), as shown in Fig. 3.14. The last FC-CHP option was interesting to be considered in the study because of involving large amounts of hydrogen storage situated in a residential area. The plant is located in Lysersrasse, Hamburg-Bahrenfeld.

3.6.2.1 System Description

Two major German utilities based in Hamburg, “Hamburgische Electricitäts-Werke AG” (electricity and district heating), and “Hamburger Gaswerke GmbH” (gas), have founded a joint venture (ARGE) to build and operate two phosphoric-acid fuel cells (PAFC) in urban surroundings. One fuel cell is fueled by natural gas and the other by hydrogen. The performance of each cell was 200 KW_{el} and 220 KW_{th}. In combination with an existing heat pump system, the fuel cells provide electricity and low-temperature district heating to residential buildings [79]. A hydrogen-fed CHP (Fig. 3.14) was installed as a demonstration project funded as part of the EU’s EQHHPP (Euro-Québec Hydro-Hydrogen Pilot Project) in 1997. The objectives of EQHHPP were to demonstrate a hydrogen fueled energy system in urban surroundings. The focus was not only on the technical and operational aspects to meet public utility demands, but also on questions of public acceptance and legal aspects of transporting and storing hydrogen within a densely populated European city.

The fuel cell system designed for CHP applications primarily consists of a liquid hydrogen storage tank, ambient evaporator, fuel cell system, and heat & power station, as shown in Fig. 3.15. Each fuel cell system consists of two primary subsystems: the fuel cell stack that generates direct current electricity; and the power conditioner that processes the electric energy into alternating current or regulated direct current.

Figure 3.14 The FC-CHP plant at Lyserstrasse in Hamburg-Bahrenfeld[166]

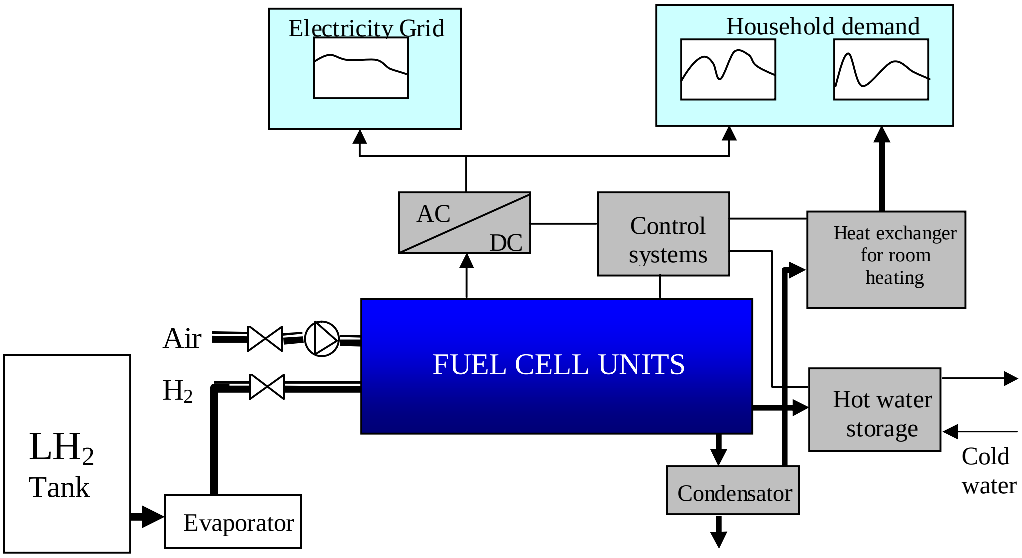


Figure 3.15 Block diagram of a hydrogen fuelled FC-CHP for household applications

For safety reasons, the hydrogen storage facility required the acceptance of the residents because it is located in an urban area. The fuel cell system was operated under the surveillance of the local safety authority (Amt für Arbeitsschutz, AfA). The safety check determined that the biggest safety hazard of the entire fuel cell unit was the pressure vessel containing water and steam at an operating pressure of approx. 1 MPa. Therefore the fuel cell unit had to be analyzed according to the pressure vessel ordinance [79]. Meanwhile, permission for the hydrogen tank was applied under the Federal Immision Act (Bundes-Immissionsschutzgesetz, BImSchG) through a full process with public participation. The Federal Institute for Materials Research and Testing (Bundesanstalt für Materialforschung und Pruefung, BAM, Berlin) provided a safety report for the preliminary testing of a tank and evaporator plant for liquefied hydrogen [79].

3.6.2.2 The LH_2 Storage

The qualitative safety evaluation of the CHP-based pure hydrogen plant showed that the LH_2 storage was the largest contribution to the overall risk. Therefore the study was focused on the LH2 storage and its environments. The hydrogen infrastructure required for the system consists of a storage tank and refueling applications for liquid hydrogen (LH_2) and an evaporator for the fuel preparation.

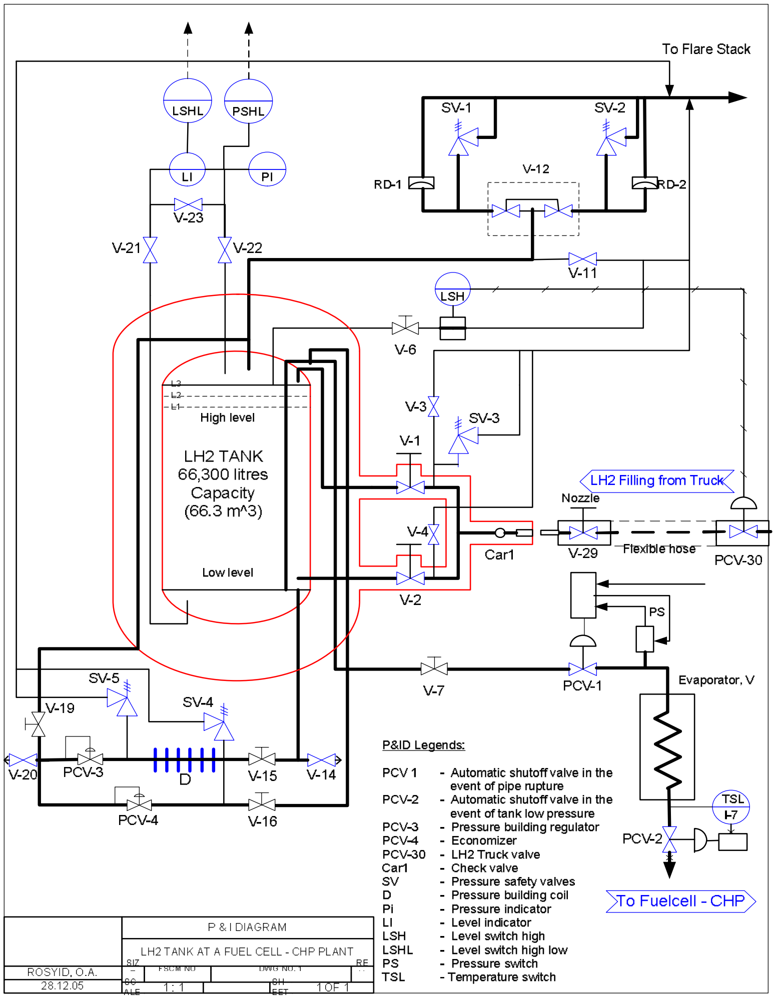


Figure 3.16 Simplified P&ID of the LH_2 tank at the CHP plant [223]

Fig. 3.16 shows the simplified P&I diagram of the LH2 tank that consists of two concentric walls (envelopes). It is used to store liquid hydrogen at low temperatures. The internal wall is made from stainless steel, and the external wall from carbon steel. These two envelopes are separated by super-insulation thermal (fire-resistant rock wool and aluminium) and the inter-space is under a guaranteed vacuum of 1.33×10^{-9} MPa. The tank has dimensions of 13.8 m of height, 3.1 m of external diameter, and internal volume (geometric) of 66.3 m^3. It has a capacity of 4282 kg of LH_2, consisting of 90% of liquid and 10% of vapour. The operating condition of the tank is at a pressure of 1.2 MPa, and a temperature of -253°C.

The tank contains liquid hydrogen with a gas phase on top of the liquid phase. The pressure of the gas phase is controlled by means of a pressure regulator (PCV-3), functioning like a pressure reducer, and a pressure build-up circuit. Withdrawal of hydrogen is made by opening the liquid hydrogen drain valve at the tank bottom directed towards the evaporator to be vaporized by the heat from ambient air. In case hydrogen is not used, the pressure goes up slowly in the tank because of the natural heat entries through the insulation and equipment of the tank. The increased tank pressure is monitored and manual degasifications are generally carried out by the operator, before the pressure reaches the pressure of opening of the valves. The economizer (PCV-4) valve remains closed if its set point pressure is higher than the tank pressure. It sends gaseous hydrogen to the utilization circuit when the tank pressure reaches its set point.

3.6.2.2.1 Filling Circuit

The tank is supplied periodically by trailer trucks of 53000 l of LH_2 supplied from the nearest production plant. Filling of the tank is carried out through a double wall flexible hose (like the tank). At the tank side, it is equipped with a non-return valve (Car1) protecting automatically from any leakage of liquid hydrogen. The filling can be done in the liquid phase through valve V-2 (to increase tank pressure) and/or gas phase through valve V-1 (to reduce tank pressure).

The tank filling is controlled by two operators, who observe the liquid level on the level indicator. The filling is stopped manually if the high level is reached. To protect the tank against overfilling, the high level is measured continuously and connected to an alarm via level switch, LSHL. If the high level is reached, firstly an alarm light signal and audible alarm are activated. Moreover, the tank is also equipped with an overfilling gauge (liquid hydrogen detection per bulb hydrogen). This makes it possible to avoid all overfilling of the tank, by automatically closing the pneumatic valve of the truck using its transmitted high level signal (LSH).

3.6.2.2.2 Pressure Building and Economizer Circuit

In order to maintain the tank pressure the tank is equipped with a pressure build-up circuit and economizer. The circuit vaporizes liquid hydrogen from the bottom of the tank and sends hydrogen in the gas phase to the tank (top). Operation of the circuit is controlled using the pressure regulator, PCV-3. If the pressure in the tank is low, the circuit is working. This circuit is protected against overpressure by a relief valve (SV-3). It is installed between the two isolating valves V-15 and PCV-3. In case hydrogen is not consumed, the pressure of the gas phase in the tank tends to increase. When this happens the pressure regulator PCV-4 (Economizer devices) sends the hydrogen gas from the tank to the circuit of utilization.

3.6.2.2.3 Pressure Relief Devices

Two sets of safety valves and rupture discs are installed in parallel to protect the tank against overpressure. One of two safety valves (SV-1, SV-2) is operated exchangeable at a relative pressure of 1.32 MPa. In case the safety valve does not provide relief, one of two rupture discs (RD-1, RD-2) will burs at a bursting pressure of 1.56 MPa. They are used to evacuate all the hydrogen in the event of loss of vacuum of the tank inter-space between two walls, or in case of fire on all the wall surface of 600°C. One set serve as backup, allows operation one or the other of the 2 sets.

3.6.2.2.4 Withdrawal Circuits

Hydrogen is withdrawn from the tank in the vapour phase and used to supply a fuel cell for household applications (FC-CHP). An automatic-close valve (PCV-1) is placed closely to the tank. It allows closing of the hydrogen supply to the utilization circuit in the event of abnormal pressure drop in this circuit. This valve is regulated by the pressure controller (PS) having a signal pressure of 0.1-0.2 MPa less than the operational pressure. Another automatic closing valve (PCV-2) is placed downstream of the evaporator allows closing of the utilization circuit in the event of very low pressure in the tank. The valve is regulated by a temperature detector (TSL), with the set point of -40°C.

3.6.2.2.5 Instrumentation and Control

A pressure indicator (PI) is installed to measure and to indicate the tank pressure. The tank level is measured using a level gauge (differential pressure) for indicating the liquid hydrogen level in the tank. A pressure switch (PSHL) is connected to the gas phase of the tank. It is used to actuate a high-pressure alarm and a low-pressure alarm. A level switch (LSHL) associated with measuring of the liquid level by differential pressure (LI). The LSHL is connected to a high-level alarm, when the high level is reached then the light and sound alarm are activated. In order to protect the tank against overfilling, an overfill detector (Mb) is installed. It makes possible to avoid overfilling of the tank. In the event of overfilling, the LSH actuates a visual/sound alarm, and an automatic stop of the transfer (closing of the pneumatic valve of the supply truck).

3.6.2.2.6 Stack for Evacuation of Hydrogen

The installation is equipped with a stack, which is constructed from stainless steel tube of diameter of 114 mm and a height of 20m. It is placed close to the tank. The stack is used to vent all hydrogen release from the two valves and the two rupture discs, the circuit of venting of the tank, and the purging of the filling terminal. A tube is located partly low to evacuate rain water which can be accumulated.

3.6.2.2.7 Evaporator (heat exchanger)

The evaporator vaporizes the liquid hydrogen into gaseous forms by heat from the air. It consists of tubes made of aluminium alloy coated internal and external fins. It has a capacity of 4282 kg, with the following characteristics: surface area of 72 m^2, flow rate of 24 kg/h, utilization maximum pressure of 3 MPa

Table 3-5 The most important capacity and dimension of the LH2 storage at CHP plant

Components	Dimension	Capacity
1. LH2 tank	Vertical cryogenic tank, H=13.8 m, D=3.1 m, V=68 m^3, V$_{useful}$=64.5 m^3	4200 kg of LH$_2$; P$_{max}$ =12 bar, T=-250°C
2. Liquid lines	Diameter of 3 inch (*)	
3. Vapor lines	Diameter of 3 inch (*)	

Source: TUHH, MVE, Air Liquide; (*) estimated value

3.7 HYDROGEN TRANSPORTATION

Long distances between the location of hydrogen production and consumers require methods of transportation to distribute hydrogen. Intercontinental transports are required to transport hydrogen from a large-scale hydrogen production located outside Germany to the storage at terminals. Meanwhile, local transport is required to transport hydrogen between storages at terminals, storage at depots, storage at filling stations, and storage at consumer premises. The study considered two means of transport, i.e. LH$_2$ tanker truck and GH$_2$ pipeline which are operated in Germany.

3.7.1 Road Tanker Truck

It seems likely that liquid hydrogen will be delivered to filling stations by LH_2 tanker trucks because LH_2 does not have to be transported under pressure. The volume of fuel that can be transported is much larger than what is possible with the compressed gas. Nevertheless, the density of liquid hydrogen is lower than that of other fuels (e.g. gasoline), and the tanker has to be well insulated. Therefore, only around 2,000 to 4,000 kg can be delivered by a single tanker, enough to fill 400 to 800 vehicles, or a two to four day supply for a filling station, yet only a 5 to 10 hour supply for a station on a busy motorway. The study considers hydrogen transportation by means of a LH_2 tanker truck to transport hydrogen from a depot to a filling station.

3.7.1.1 System Description

The study focuses on a hydrogen delivery by means of a LH_2 tanker truck from a hydrogen plant (depot) to hydrogen filling stations situated in a city. The truck delivery characteristics, such as numbers of filling stations, roundtrip distances, and number of deliveries per year were modelled using the spreadsheet model developed by [143] based on hydrogen demand for the city. Coverage of the hydrogen station was compared with the idealized numbers of gasoline stations. According to [143] numbers of the hydrogen stations are at least 10% (for a small market penetration) of the total gasoline stations

Table 3-6 Hydrogen truck delivery model for the study

Hydrogen Delivery Model	Values	Remarks
Population, N:	100,000	Number of population
Average pop. Density, D (1/km^2):	1,000	Ranges: 700-1202
Average number of per person, LDVP:	0,8	Ranges: 0,5-1,2
H2 filling station capacity, S (kg/day):	100	Selection: 100, 1500
H2 consumption, Q (kg/veh.day):	0.68	Based on H2LDV 20,000km/yr (Table 2-8)
Fraction of H2 LDVs, H2LDV:	0.01	Selections: 0.01; 0.1; 0.3; 0.7
Distance H2 plant to the city gate, X:	100	in km
Ideal numbers of gasoline station:	40	N*LDVP/2000; 2000 LDVs/station
Hydrogen demand of the city, C:	544	N*LDVP*Q*H2LDV; in kg/day
Number of hydrogen filling station, n:	8	C/(0.7*S); 0.7= 70% of output capacity
City area, A (km^2):	100	N/D
Hydrogen station area (km^2):	12.9	A/n
Average distance between stations (km):	3.6	SQRT(A)
Round trip distance per delivery (km):	215	2*X + 1.5*SQRT(A)
LH2 truck capacity (kg):	4000	Existing tank truck capacity
Truck delivery per station, T (days):	40	T/S, One truck every 40 days
Truck delivery for the city (days):	5	One truck every 5,1 days
Numbers of deliveries per year:	71	70,9 trips per year
Coverage of the H2 stations:	19.4%	H2 station/Gasoline station, min. 10%

The city was modelled as an ideal area assumed to be “circular” city, with a population density which is higher in the central core and lower in the outer regions. A city of 100,000 people is assumed to have an average population density of 1000 people/km^2 or an area of 100 km^2 (radius of 10 km). An average number of light duty vehicle (LDV) per person is assumed to be 0.8, so that the ideal number of gasoline stations for the city is 40. The hydrogen demand of the city for the 1% early fleet market penetration (assuming that the hydrogen consumption per vehicle is about 0.68 kg/day) (see Table 2-8) is 544 kg/day. Assuming that the capacity of a hydrogen station is 100 kg/day with the output capacity of 70%, the number of a hydrogen filling station is calculated to be about 8 units. The table also shows that the total roundtrip distance is 215 km with total deliveries of 71 trips per year. The detailed calculation is shown in Table 3-6.

In the QRA study it is also assumed that the city has a uniformly distributed group of equally sized hydrogen stations (Fig. 3.17). The LH_2 tank truck is supposed to transport LH_2 from a production plant (in city “A”) to the filling stations (in city “B”). It makes about 71 deliveries per year along a round trip distance of 215 km. The route is broken into two segments of uniform population density. The first segment is the round trip distance of 200 km (i.e.2x100 km) with the population density of 500 people/km^2. The second segment is around the city B of about 15 km with population density of 1000 people/km^2.

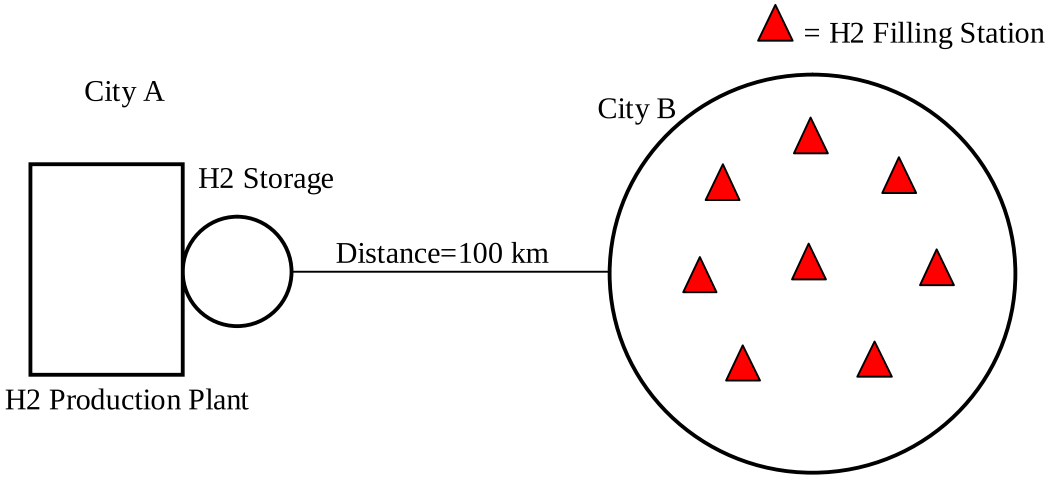


Figure 3.17 Hydrogen truck delivery for the city B

3.7.1.2 The LH2 Tanker Truck

The LH_2 tank truck has a capacity of 53m^3 or about 4000 kg of LH_2 (-253°C, 0.13 MPa). The tank has dimensions of 2.5m of diameter and 8.5m of length. The tank is typically a double-walled cylindrical tank consisting of an inner pressure vessel, enclosed in an outer casing or jacket. The inner pressure vessel is designed, manufactured and tested to meet the requirements of “Technische Regeln für Dampfkessel” (TRD), “Bundesimmissionsschutz-gesetz” (BImSchG), as well as Sec. VIII of the ASME Boiler and Pressure Vessel Code.

Fig. 3.19 shows a typical internal piping arrangement of a cryogenic tank truck. It has two liquid phase lines. The first liquid line is used to fill the truck at the production plant through connector C/1 and V-8, and to unload it using the off-loading pump through C/2 and V-14. The second liquid line is a pressure-building circuit (PBC) used to increase the inner tank pressure by vaporizing a small amount of liquid. The coil (D) with a large heat transfer area can readily vaporize liquid and return the warmed gas to the ullage (top) space of the tank. This pressure build-up is performed prior to and during the offloading process in order to maintain adequate suction pressure for the centrifugal transfer pump.

The gas-phase lines include a pressure-relief device, which directly communicates with the vapor or gas space near the midpoint of the top centerline. A spring loaded pressure relief valve (V-19) and a rupture disk device (RD) are normally provided on the tank truck. These relief devices are designed to maintain pressure at a safe level under emergency conditions, including exposure of the vessel to a fire. Pressure-relief devices are designed to the requirements of Section VIII of the ASME Boiler & Pressure Code as well as CGA pamphlet S1.2, “Pressure Relief Device Standards—Cargo and Portable Tanks for Compressed Gases.”

Another gas-phase circuit has multiple uses as a gas-phase outlet, pressure building coil return, and a transfer pump re-circulation line.

Figure 3.18 Schema of an LH_2 tank truck [Linde AG]

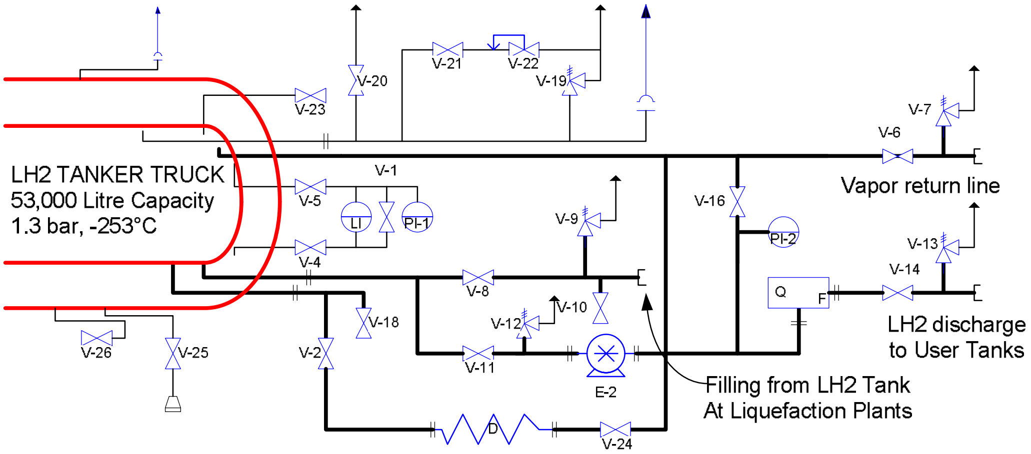


Figure 3.19 Simplified P&I diagram of an LH_2 tank truck [131].

Table 3-7 The most important capacities and dimensions of the LH_2 truck

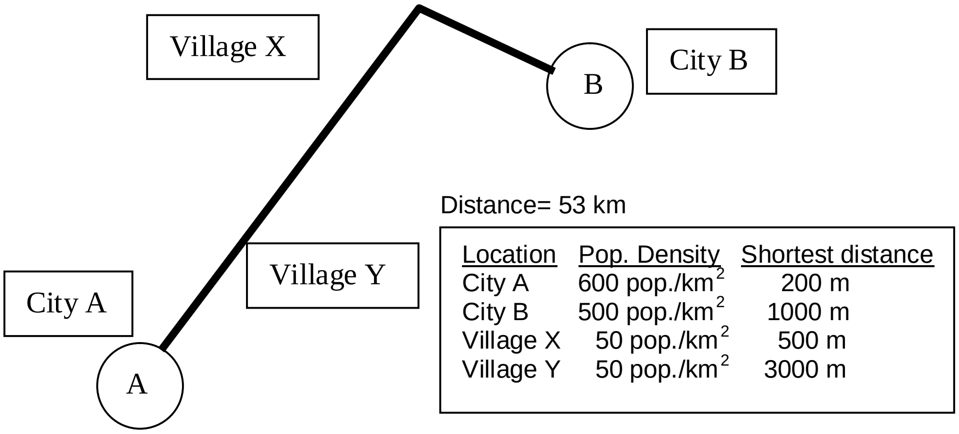
Components	Dimension	Capacity
1. LH2 tank	Length 13.6 m, diameter 2.5m	53,000 l (4000 kg)
2. Liquid line	Diameter of 76.2 mm (3 in)	
3. Vapour line	Diameter of 50.8 mm (2 in)	

Source: Linde AG; [131]

The inner vessel pressure, transfer pump discharge pressure, and liquid contents are monitored with trailer-mounted gauges. A differential pressure indicator is the most common device used for contents measurement. Sampling of product in the inner pressure vessel is necessary in order to determine the level of product purity. A liquid tap typically teed externally to a liquid line can be used for sampling. The vacuum level can be monitored using the trailer-equipped thermocouple gauge tube.

3.7.2 Hydrogen Pipeline

Hydrogen delivery by gas pipeline is currently the lowest cost delivery option at high volumes, and is likely to play a key role in distributing hydrogen in a future hydrogen economy. Currently, few dedicated hydrogen pipelines exist—those that are built to transmit hydrogen as a chemical feedstock for commercial uses, and they are not adequate to broadly distribute hydrogen to serve hydrogen vehicles or household applications. Transport of gaseous hydrogen in pipeline system is a technology, which has long been applied. More than 750 km of hydrogen pipelines (1990) have been put in place worldwide [96]. The German company Hüls AG has started as early as 1938 to operate a hydrogen distribution grid in the Rhine/Ruhr region. Long-distance pipeline transportation of hydrogen gas has not reached an international dimension up to now.



Location	Pop. Density	Shortest distance
City A	600 pop./km^2	200 m
City B	500 pop./km^2	1000 m
Village X	50 pop./km^2	500 m
Village Y	50 pop./km^2	3000 m

Figure 3.20 Description of hypothetical GH_2 pipeline routes [72, 119].

The distribution of hydrogen gas seems to be as straightforward as the distribution of natural gas, and therefore a pipeline similar to that used in natural gas could be employed. As it happens, hydrogen reacts with common seals and lubricants currently used in natural gas pipelines and it will be necessary to develop new materials that will not degrade, nor contaminate the gas on its journey. Furthermore, due to the much lower density of hydrogen, much more gas must be moved through a pipe to deliver a certain amount of energy than in use of natural gas. This means the gas must either be transported at a greater speed, or the pipe must be of greater diameter.

3.7.2.1 System Description

The study considers hydrogen transportation by means of a GH_2 pipeline from a hydrogen production plant to a user storage operated in Germany. The pipeline has a distance of 53 km, a diameter of 150mm, is located underground, and the operating conditions are a pressure of 2.4 MPa and a temperature of 15°C [72]. The gaseous hydrogen has regularly transported from facility A to facility B through the GH_2 pipeline. It is transported over a distance of 53 km through areas with varying population densities.

The pipeline was installed and constructed to meet requirements according to the “Bundesimmunschutzgessetz” (BImSchG) [72]. It constructed by using special steel materials (e.g. ultrafine grain steels) to meet the requirement of high strength and high ductility to enable a high system pressure and appropriate for welding. Besides, it is wrapped, cathodically protected, and hydro-tested before it is put into service. The pipeline crosses four towns, as shown in Fig. 3.20, with one of them closer than 200 m.

3.7.2.2 The GH_2 Pipeline

Fig. 3.21 shows a diagram of GH_2 pipeline and associated measuring and control devices. The pipeline is equipped with two compressors each with a capacity of 8000 N/m^3 (piston type) used to increase the hydrogen pressure to 2.4 MPa (24 bar) at rate of 4000 Nm^3/h. The pipeline is located three meters below the ground level. It is divided into seven stations (sections). In case of leakage or any problems in the pipeline each station is equipped with an automatic control to close valve. The valves are placed at specific points. For this purpose two types of valve are normally used, i.e. manually (hand wheel) remotely and operated valves. Besides, the pipeline system is also equipped with measuring and control devices linked to control room located in the "central control room", which constantly manned and from which the system is monitored, controlled and supervised. Table 3-8 shows the most important capacity and dimensions of the pipeline system studied.

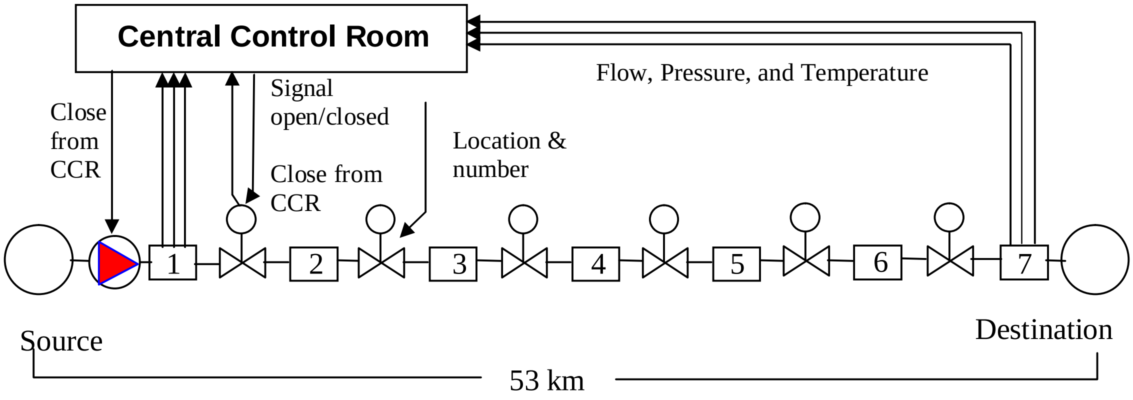


Figure 3.21 The transport of hydrogen by underground pipeline [187, 72]

Table 3-8 Description of the hypothetical GH_2 pipeline considered in the study [72]

Product:	Hydrogen
Length of pipeline:	53 km
Diameter:	150 mm (outer diameter)
Flow rate:	4000 Nm^3/h (0.1 kg/s)
Line type:	Underground (3 m)
Normal operating pressure:	24 bar, 15°C
Wall thickness:	10 mm
Valve stations:	7

Chapter 4

RISK ASSESSMENT METHODS

4.1 INTRODUCTION

Safe practices in the production, storage, distribution, and use of hydrogen are essential for the widespread acceptance of hydrogen technologies. A catastrophic failure in any hydrogen project could damage the public's perception of hydrogen and could also decrease the ability of hydrogen technologies to gain the approval of the insurance community, a necessity for commercialization. The study aims at establishing the safety technological boundary condition for the safe use of hydrogen cycle, determining the risk connected with hydrogen uses at large-scale, and classify these risks within the risk ranges of the similar technologies. In order to reach to above aims, a quantitative risk assessment (QRA) method was used to determine the risk connected with hydrogen for study objects described in Chapter 3. The chapter gives a brief description of the QRA method. Additional information about the models is presented in Appendix E (Consequence models) and Appendix F (Fault tree analysis method).

4.2 QUANTITATIVE RISK ASSESSMENT

Risk [107, 2, 242] may be defined as a combination of hazard and probability of hazard occurrence, where hazard is defined as the degree of harm to human beings, property, society or environment. In this sense the risk is defined as a quantitative measured of hazard. In order to estimate the risk a quantitative risk assessments (QRA) method may be applied.

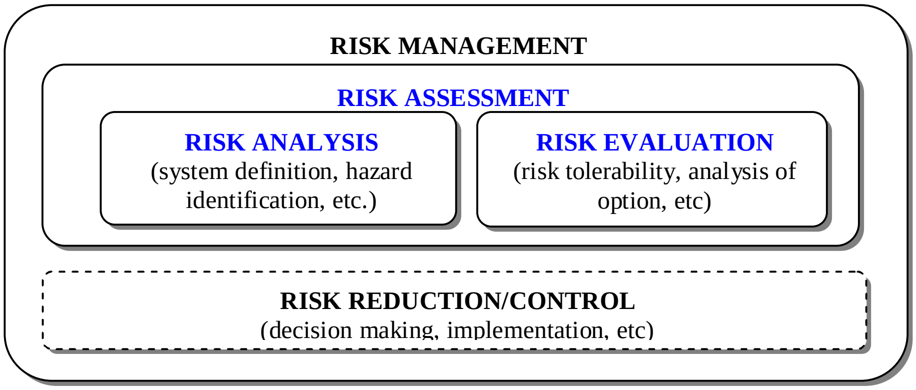


Fig. 4.1 The activities in the risk management process [71]

Risk assessment is a step in the risk management process. It is measuring two quantities of the risk, the magnitude of the potential hazard, and the probability that the hazard will occur. It may be the most important step in the risk management process, and may also be the most difficult and prone to error. Once risks have been identified and assessed, the steps to properly deal with them are much more programmatical. Fig. 4.1 shows the different processes in risk management procedure adopted from the International Electrotechnical Commission (IEC) [71, 2]. This figure shows relationships between the definitions of risk analysis, risk assessment and risk management. The study is focused on the risk assessment, which consists of two parts, i.e. risk analysis and risk evaluation.

4.2.1 Risk Analysis

A risk analysis is a systematic use of available information to identify hazards and to estimate the risk to individuals or populations, property or the environment. In a plant, it can be further separated in at least three levels [71], depending on how detailed the analysis is to be and the labour resources available, i.e. *qualitative methods*, *semi-quantitative methods*, and *quantitative methods*. During risk analysis, all three levels can be used in sequence. The first methods are used to determine which scenarios are relevant and to be analyzed further in the quantitative risk analysis, to identify the most hazardous events. It may be used as screening methods in the preliminary risk analysis. The methods include HAZOP, What-if, different check-lists, etc. Semi-quantitative methods are used to determine the relative hazards associated with undesired events. The methods are normally called index methods, point scheme methods, numerical grading, etc., where the hazards are ranked according to a scoring system. Both frequency and consequences can be considered, and different design strategies can be compared by comparing the resulting scores. The final level of analysis (i.e. quantitative methods) is the most extensive in terms of quantifying the risk. It is also the most labour intense.

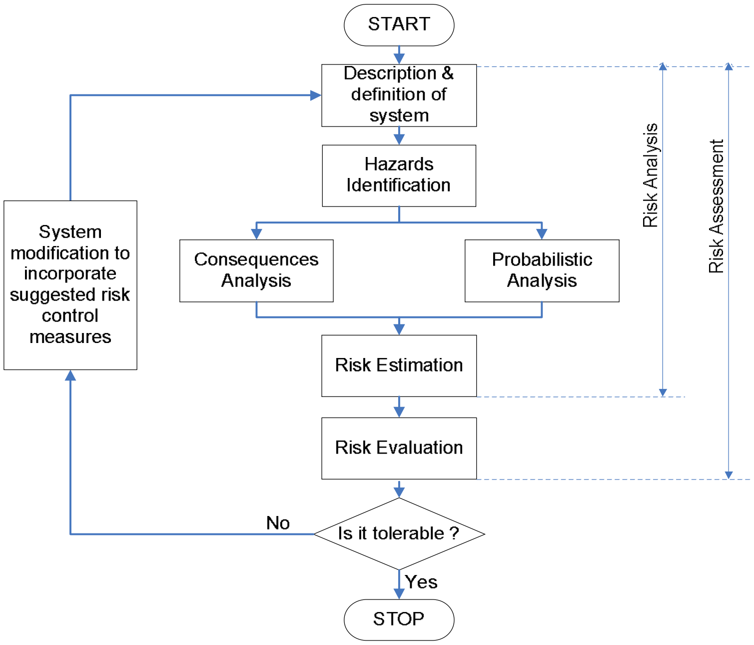


Fig. 4.2 Quantitative Risk Assessment (QRA) [71, 107].

At this level, a distinction can be made between a deterministic analysis and a probabilistic analysis [107]. The deterministic analysis focuses on describing the hazards in terms of the consequences. No consideration is taken of the frequency of the occurrence. A typical example is the determination of the worst case scenario expressed as a risk distance. The probabilistic approach determines the quantified risk based on both frequencies and consequences. The last approach was used in the study.

A quantitative risk analysis is focused on the combined effect of frequencies and consequences of a possible accident, as illustrated in Fig. 4.2. The first step, before starting to quantify the risk, is related to defining and describing the system. Detailed information of the system (such as process flow diagram, operating condition, etc) may be required. The next step is hazard identification. The step seeks an answer to the question: what can go wrong? This is the most important step because hazards that are not identified will not quantified, leading to an underestimation of risk [107]. The third step involves another question: how likely is the accident? Answering the question involves quantification of the probability of each accident scenario. Fault tree analysis may be used for this purpose. The next step is consequence analysis. It aims to quantify the negative impacts of the scenarios. The consequences can be measured in terms of the number of fatalities (that is used in the study), number of injuries, or value of the property lost. The last step of a QRA is to estimate the risk. The risk can be expressed as individual risk or as societal risk. These are the two most frequently used risk measures.

4.2.2 Risk Evaluation

Risk can be evaluated and risk criteria established using four different principles [140]. The principle of ***reasonableness*** says that an activity should not involve risks that by reasonable means could be avoided. Risks that by technically and economically reasonable means could be eliminated or reduced are always taken care of, irrespective of the actual risk level. The principle of *proportionality* means that the total risk that an activity involves should not be disproportionate to its benefits. By using the principle of *distribution*, risks should be legitimately distributed in society, related to the benefits of the activity involved. Single persons should not be exposed to disproportionate risk in comparison with the advantage that the activity affords them. The principle of *avoiding catastrophes* says that it is better that risks are realized in accidents with a lower number of fatalities. When discussing risk reduction, terms such as ALARP (As Low As Reasonably Practicable) are frequently used. Detailed description of the risk criteria will be given in section 4.6.4.

4.3 HAZARDS IDENTIFICATION

Hazard identification is the first step of risk analysis. It attempts to answer: What can go wrong? The objective of the hazard identification is to identify potential hazards (e.g., fire and explosion) which may cause a major accident before a substance (e.g. hydrogen) is used in systems. In which part(s) of the system are the hazards relevant (e.g., pressure vessels, storage). The next step in hazards identification is to develop scenario that will lead to system failure.

4.3.1 Hazard Identification Techniques

Depending on the extent of the consequences of the potential major hazards, the sources of hazard may be determined by simple means such as checklists, or by more complex methods such as HAZOP, FMEA, F&EI, and so on. The study uses the FMEA method to identify potential hazards related to the hydrogen system. The following section describes these methods.

4.3.1.1 HAZOP

The word of HAZOP is an abbreviation for “hazard and operability study”. HAZOP [107] is a simple yet structured methodology for hazard identification and assessment. The basic principle of HAZOP study is the normal and standard condition is safe, and hazard occurs when there is a deviation from normal conditions. The procedure allows the user to make intelligent prediction in the identification of hazard and operability problems.

In a typical HAZOP study, design and operation documents such as piping and instrument diagrams (PID), process flow diagram (PFD), and operating manuals are examined systematically by a group of experts. Abnormal causes and adverse consequences for all possible deviations from normal operation that could arise are identified for each unit of the plant. HAZOP is considered by a multi-disciplinary team of experts who have extensive knowledge of design, operation and maintenance of the process plant. To cover all possible malfunctions in the plant the imagination of the HAZOP team members is guided systematically with a set of guide words for generating the process variation deviations. The list of guide words along with their definition is given in Table 4-1.

Table 4-1 Guide words and their physical significance [107]

Guide words	Meaning	Parameter	Deviation
No	Negation intention	Flow Level	No flow Zero level
Less	Quantitative decrease	Flow Level Temperature	Low flow rate Low level Low temperature
More	Quantitative increase	Flow Level Temperature	High flow rate High level High temperature
Reverse	Logical opposite	Flow Pressure	Reverse flow Reverse pressure
Part of	Qualitative decrease	Concentration Flow Level	Concentration decrease Flow decrease Level decrease
As well as	Qualitative increase	Concentration of impurity Temperature of substance Level of impurity Pressure of substance	Concentration increase Temperature increase Level increase Pressure increase
Other than	Complete substitution	Concentration of desired substance Level of desired substance Flow of desired substance	Concentration zero Level zero Flow rate zero

4.3.1.2 Failure Modes Effect Analysis

A Failure Modes Effect Analysis (FMEA) is a systematic and structured method for identifying product ad process problems, assessing their significance, and identifying potential solutions that reduce their significance. The objective of a FMEA is a look for all the ways a process can fail (failure modes). Each failure mode has a cause and a potential effect. Some failure modes are more likely to occur than others, and each potential effect has a relative risk associated with it. FMEA is an inductive and efficient method for analyzing elements which can cause the failure of the whole, or of a large part of a system. It is good for generating the failure data and information at components level [107]. It has been recommended for use as a hazard identification technique mainly for systems dealing with low/moderately hazardous operations and the ones which cannot support the expensive and time-consuming HAZOP study [3].

The FMEA procedure involves the following steps: identification of each failure mode, of the consequence of the event (s) associated with it, its causes and effects; classification of each failure mode by relevant characteristics, including deductability, diagnosability, testability, item replaceability, and compensating and operating provisions.

4.3.1.3 Fire and Explosion Index (Dow Index)

The fire and explosion index [1] is a step-by-step objective evaluation of the realistic fire, explosion, and reactivity potential of process equipment and its contents. The quantitative measurements used in the analysis are based on historic loss data, the energy potential of the material under study, and the extent to which loss prevention practices are currently applied. It was developed by Dow Chemical Company for fire and explosion hazards. The overall structure of the methodology is sown in Fig. 4.3. The procedure is to calculate the fire and explosion index (F&EI) and to use this to determine fire protection measures and, in combination with a damage factors, to derive the base MPPD (the maximum probable property damage). This is then used, in combination with the loss control credits, to determine the actual MPPD, the maximum probable day outage (MPDO), and the business interruption (BI) loss [1]

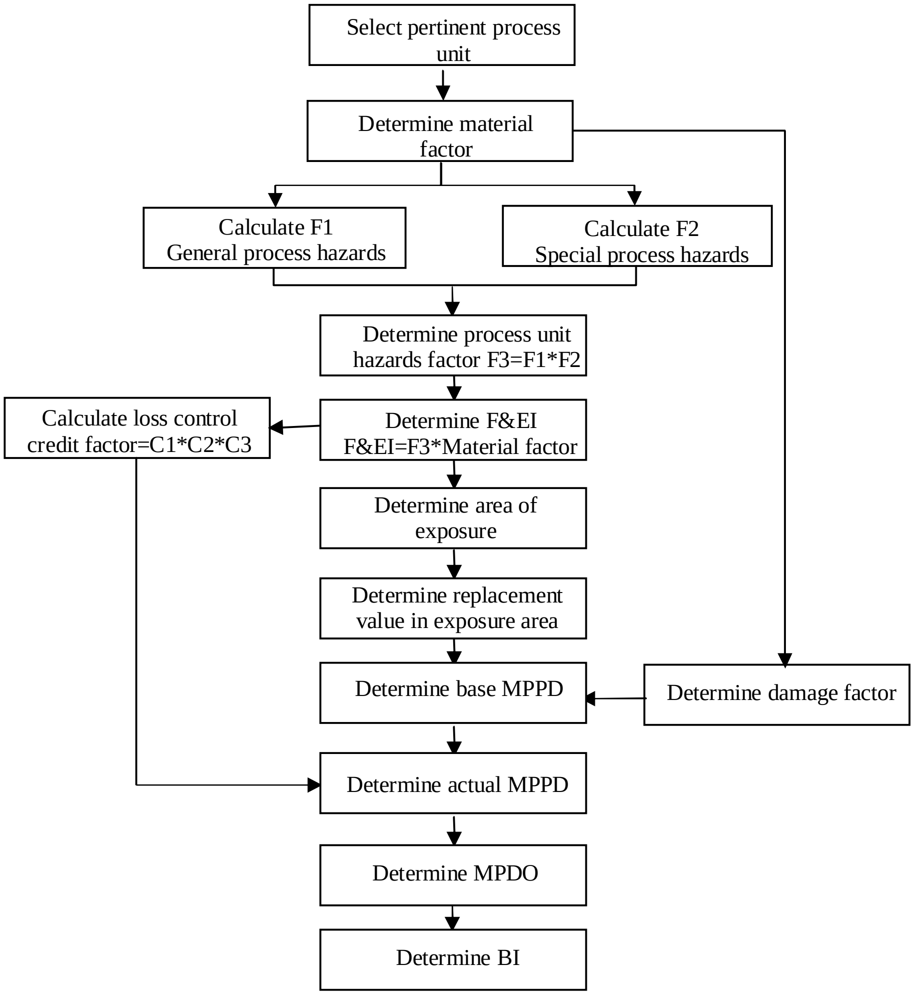


Fig. 4.3 Calculation procedures of F&E Index [1]

In the F&E Index calculation the material factor of hydrogen is twenty-one. Appropriate penalty of tank pressure is determined by consulting to Eq. 4-1 and using the operating pressure to determine an initial value.

$$Penalty = 0.16109 + 1.61503(p/6895) - 1.42879(p/6895)^2 + 0.5171(p/6895)^3 \qquad (4\text{-}1)$$

where, p = pressure (in kPa)

For liquid hydrogen (LH_2), the low temperature penalty is set to 0.30, hydrogen tanks use carbon steel and are operated at or below the ductile/brittle transition temperature. The penalty for the quantity of flammable/unstable material is calculated as follows: Flammable and combustible liquid or liquefied areas in storage outside the process area receive a lower penalty than those in the process, since there is no process involvement. The penalty is determined by using Fig. 4.4 with total kJ (i.e. quantity of material in storage times combustion heat factor, H_c) in any single storage vessel.

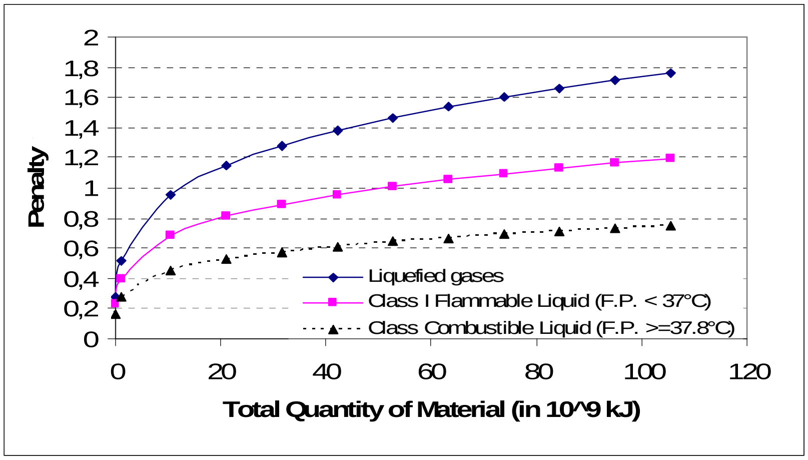


Fig. 4.4 Penalty of liquids or gases in storage [1]

The process unit hazards factor (F3) is the product of the general process hazards factor (F1) and the special process hazards factor (F2). The product is used rather than the sum because the contributing hazards included in F1 and F2 are known to have a compounding effect on each other. When penalties are properly applied to various process hazards, F3 is normally not in excess of 8.0. If a higher value is obtained, use a maximum of 8.0 [1]. The F&E index for several hydrogen systems calculated in the study has ranges between 147 to 170, or the degree of hydrogen hazards are classified as ”Heavy” to “Severe”.

4.3.2 Accident Scenarios of the Study Objects

4.3.2.1 Hydrogen Storages

The FMEA method has been used to define an initial list of incidents that consider all possible breaks or ruptures of items of equipment which would lead to a loss of containment (called accident scenarios). The considered systems mainly consist of a tank and piping system. Each of them, of course, may break or rupture in an infinite number of ways. For example, a pipe break may be any size from a pinhole to a full bore rupture and may be occurred any position between the pipe ends. This spectrum of failure needs to be reduced to a representative set of failures as defined in the depth of study. In this study, possible pipe failures are represented by either full bore ruptures or holes 20% of the diameter. Failure outcomes such as fires and explosions are considered since hydrogen is flammable. Releases caused by different failures may lead to similar outcomes and these can be combined to reduce the calculational burden. Therefore, the final choice of events to be modelled took into consideration the following factors: the size of the release; whether the release is instantaneous or continuous; and whether the release is liquid or vapour. Based on the above assumptions the following representative set of events was considered in the study:

1. Instantaneous release of the entire hydrogen inventory due to tank rupture, i.e. a catastrophic failure of the tank or vessel.
2. Continuous release of hydrogen due to: (i) Liquid or vapour release through a hole on the tank (may consider equal to the largest pipe diameter); (ii) Vapour release through relief

valves; (iii) Vapour release through rupture discs; (iv) Vapour release due to full-bore rupture of the vapour lines; (v) Liquid release due to full-bore rupture of the liquid lines

4.3.2.2 Hydrogen Transportation

4.32.2.1 Road tanker truck

Although a variety of mechanisms may cause a truck accident and cargo release, the greatest relevance with respect to risk analysis can be divided into two categories, i.e. accident-initiated releases and non-accident initiated releases. The accident-initiated releases with a truck represent a great potential for substantial damage and large releases of hydrogen. These include a collision between two vehicles, collisions with fixed objects, and overturn. Vehicular collision between two vehicles and with fixed objects presents the potential for substantial damage and can also represent relatively energetic impact accidents with the potential for significant damage and/or cargo release. Overturned vehicles are most likely during trucking operations where, for some truck designs and cargoes, the vehicle centre of gravity is high, especially on tight curves such as ramps. Meanwhile, the non-accident-initiated releases are characterized by equipment failures not associated with accidents such as leaks of pipes and fittings or failures of relief valves and rupture disks. These mechanisms result in relatively small quantities of cargo being released [3]. The CCPS [2] quoted that accident-initiated releases tend to dominate the risk of hydrogen in transportation. Therefore, the release frequency of hydrogen from the truck may be estimated from accident rates, and hence does not require a detailed fault tree analysis as in the case of other objects, e.g. tanks.

4.3.2.2.2 Pipeline

In Europe, the major gas companies of Belgium, Denmark, France, Germany, Italy, the Netherlands, the United Kingdom, and Spain have gathered their national statistics and published failure rate data under the European Gas Pipeline Incident Data Group. The European oil companies also publish annual failure rate data under the organization CONCAWE (the oil companies' study group for conservation of clean air and water—Europe) [3]. The databases published by these organizations include a large number of pipelines and incorporate many years of operating experience. Therefore, the general quality of data is good and it can be used with confidence in predicting the likelihood of pipeline failure in risk assessment. When considering all these databases together one broad conclusion comes out of the statistics, despite some variation caused by dissimilarity in the type of data collected—failures occur in roughly equal proportions in three broad categories: (1) Failures caused by external mechanical interference; (2) Failures caused by corrosion defects; (3) Failures caused by miscellaneous factors such as pipe material defects, natural hazards or operator error.

Failures caused by third party external mechanical interference include such causes as being damaged by excavators or other equipment in use by other utility or construction companies, damage during construction of land drainage, etc. The type of failure generally caused by third party mechanical interference is a puncture or split of the pipe or a gouge severely reducing the wall thickness of the pipe. Failure can be immediate or may occur some time later by fatigue. This type of incident is likely to have severe consequences and historically some of the most serious pipeline accidents resulting in ruptures have been caused by such incidents. Pipeline failures by corrosion can be due to internal corrosion or external corrosion. External corrosion failures are due to moisture in the ground and aggressive soils and can take two forms—small pinhole failures caused by pitting and more generalized corrosion leading to a reduction in pipe wall thickness over a plane area. External pitting corrosion leads to small leaks that are often difficult to detect but that gradually grow in size over a period of time. External area or plane defects cause a generalized reduction of wall thickness that can eventually fail catastrophically under pressure, leading to a large scale release. Pipelines can also fail for a variety of other causes. Typical causes are construction defects, pipe material defects, operator error, equipment failure, failure due to internal erosion and failure due to ground slip, flood ground erosion, earthquake, or mining. Failure modes of pipeline

4.4 ESTIMATING FREQUENCY

In general, probabilities of a hazardous event occurring during a given time interval can be derived from the probabilities (frequencies) of each of the contributory events whose occurrence, individually or in conjunction with other events, could lead to the occurrence of the hazardous event. A logical relationship between hazardous events and the corresponding contributory events are conveniently represented as a 'fault tree'. However, in some cases the tree is trivial due to the frequency being dominated by a single contributory cause, or due to the availability of statistical data on the frequency of the hazardous event itself, rather than only on the contributory events [158]. For example, onboard hydrogen storages in traffic systems or hydrogen transportation are more likely to occur because of traffic accidents than through the system malfunction. On the other hand, a large cryogenic storage vessel (e.g. LH_2 bulk storage) relies for integrity not only on the quality of its construction but also on the reliability of its pressure control system and protective devices. Therefore, a dual approach to the frequency estimation was used in the study. Firstly, fault tree analyses were carried out on a larger containment system where safety depends on the reliability of a large number of components. It includes stationary hydrogen storages (both liquid and gaseous). Secondly, failure rate data are used for certain discrete events for which adequate statistics exist, or for which system reliability considerations is not the main cause of failure. It includes hydrogen onboard storage and hydrogen transportation.

4.4.1 Fault Tree Analysis

Fault tree analysis (FTA) [86, 42, 107] is an analytical tool that uses deductive reasoning to determine the occurrence of an undesired event (called "Top" Event). The FTA, along with component failure data and human reliability data, can enable determination of the frequency of occurrence of an accidental event. It yields both qualitative as well as quantitative information.

A logical relationship between Top events and the corresponding contributory events are conveniently represented as a 'fault tree'. The Top event is taken as the root of a tree of logic. Then, each situation that could cause that effect is added to the tree as a series of logic expressions. Basic events at the bottom of the fault tree are linked via logic symbols (known as gates) to the Top events. The logical connections in the fault tree are generally represented by two types of gates, the "OR" and the "AND". If components from several barriers have to fail for the undesired event to occur, these are combined with the initiating event by an "AND" gate. If several of these combination exist, they are input into an "OR" gate, just as contributions from different initiating events to the undesired events.

Quantitative evaluation of a fault tree requires quantitative reliability data for equipments as well as human error. When fault trees are labelled with actual numbers about probabilities or frequencies, a computer program can be used to calculate failure probabilities from fault trees. Fault trees for complex system normally must be evaluated with the aid of computer program. There are three methods available for this purpose: (1) direct simulation of the fault tree, (2) minimal cut set calculation using a simulation procedure, and (3) minimal cut set calculation by analytical methods. The last procedure was used to calculate undesired events of the study objects. A brief description of the method is to be discussed in the following section, and the detailed description of the program is presented in the Appendix F.

4.4.1.1 Analytical Approach

As described before, the evaluation of a fault tree for a complex system requires the aid of computer programs. Some of the programs are readily available as commercials software, such as CARA Fault Tree Application from SINTEF, AvSim$^+$ from Isograph, and so on. The study used the fault tree analysis (FTA) program developed by Hauptmanns (1978). The FTA program basically consists of two following sub-programs, i.e. (1) determination of minimal cut set with an analytical approach, and (2) fault tree evaluation.

The first sub-program is used to determine minimal cut sets with an analytical method. The method is made up of Boolean algebra operations in order to transform the tree in such a way that it is expressed in term of its minimal cut sets. In contrast to other methods, this method does not require reliability data for obtaining the minimal cut sets of the tree [86]. These are only needed for calculating the probability of the undesired events. Basically two approaches may be used in the method, i.e. the "Top-down" approach, in which the algorithm starts with the undesired event represented by the Top gate working its way down to the basic events, and the "Bottom-up", where the calculation is initiated at the level of basic events, and ends with the undesired event. The latest is, however, not implemented in the program.

After finding the minimal cut sets the procedure may be continued with the evaluation of the fault tree, e.g. calculation of the expected frequency of the undesired event (Top event). This is calculated by forming the expectation of the structure function given in Eq. F-1 (Appendix F). With eliminating of the powers of binary variables in the Eq.F-1, which are equal to the binary variables themselves (law of idempotencies), the general relationship of the structure function can be described as [86]:

$$y\,(\overset{\mathbf{r}}{x}) = \sum_{i=1}^{L} k_i - \sum_{i=1}^{L-1}\sum_{j=i+1}^{L} k_i \cdot k_j + \sum_{i=1}^{L-2}\sum_{j=i+1}^{L-1}\sum_{k=j+1}^{L} k_i \cdot k_j \cdot k_k + \mathbf{K} + (-1)^{L-1}.k_1 \cdot \mathbf{K} \cdot k_L \qquad (4\text{-}2)$$

An upper bound of the occurrence probability of the system is equal to the expectation of the first term on the right side of the Eq.3, a lower to that of the first two terms, a close upper if the three terms are evaluated, etc. Since the used probabilities are usually small numbers, in most cases the evaluation of the upper bound is a satisfactory approximation to the true result. If initiating events are taken into account, the Eq. 3 is evaluated for each of them separately using unavailability for the basic events. The corresponding expected frequency of the undesired event is obtained by multiplying the unavailability with the frequency of the initiating event.

For a stand-by component subjected to maintenance, the unavailability of the component (basic event) is given Eq. F-11 (Appendix F). By integrating the Eq.F-11 over the time interval between two inspections, the average unavailability is given by:

$$\overline{u_i}(t) = 1 - \frac{T_i}{q_i}\left[\exp(-l_i q_i) - 1\right] \qquad (4\text{-}3)$$

Where, q_i is the time between inspections, T_i is the mean time to failure for components i. It is the inverse of the failure rate, l, i.e. $l = 1/T_i$. If the component is not an object of maintenance its reliability and unreliability coincide, i.e., $q_i(t)=u_i(t)$.

Uncertainties of the reliability data are propagated through the fault tree by a Monte Carlo calculation, where lognormal or rectangular distribution can be used. The corresponding probability density functions (pdf) for failure rate (λ) (and analogous for unavailability, u) is given in Eq. F-14 (Appendix F). Based on the Monte Carlo methods, the program calculates a failure rate (and analogous for an unavailability) using the following equation:

$$l_i = l_{50,i} \cdot \exp\left[\sqrt{-2 \cdot \ln z_p} \cdot \cos(2p \cdot v_p) \cdot s_i\right] \qquad (4\text{-}4)$$

Where z_p and v_p are random numbers uniformly distribute in the interval 0, 1. Several trials are carried out from which the mean value and standard deviation of the probability of occurrence of the undesired event are calculated, in Eq. F-7 and Eq. F-8 (Appendix F), respectively.

4.4.1.2 Equipment Reliability Data

Evaluation of a fault tree requires the input of reliability data such as failure frequencies and probabilities for technical components and human actions as well as frequencies of occurrence for initiating events including external events. Mathematical description behaviour of component, reliability data on process plant, human error, and its uncertainties are described in Appendix F. The reliability data used in FTA are mostly a mixture of plant-specific data, generic data, and estimates.

An ideal situation is to have valid historical data from identical equipment in the same application. But in most cases, plant-specific (e.g. hydrogen plants) data are unavailable, because of the limited historical database of equipment failures. Only a small number of hydrogen technologies, systems and components are currently in operation. To overcome these problems generic failure rate data as surrogates for or supplements to plant-specific data have been used in the study. Because of the uncertainties inherent in risk analysis methodology, generic failure rate data are frequently adequate to identify the major risk contributors in a process or plant [8].

However, selecting appropriate generic data requires understanding and judgment. In many cases, the analyst can find a number of generic data points that might be used for a QRA. Data points chosen for use must provide the level of confidence necessary without creating an unacceptable tolerance uncertainty [2]. The uncertainties of data selection can be reduced by learning as much as possible about data sets, including the taxonomy and equipment boundaries used; the type, design, and construction of the equipment; the process medium; plant operation and maintenance programs; and failure modes. After data have been selected and combined with other generic data or plant-specific data to a single data point, judgment must still be exercised in their use. The analyst may choose to use the generic data directly if the equipment description, process conditions, and failure mode of the data sources are similar to the equipment being studied [8].

4.4.2 Direct Use of Base Failure Data

The QRA study on onboard hydrogen storage (e.g. a hydrogen private car) and hydrogen road transports (e.g. LH_2 tanker truck) are focused on the loss of containment of the hydrogen due to either an accident breaching a transport container or a failure of associated equipment such as relief valves or fittings while in transit. The CCPS [3] quoted that accident-initiated releases tend to dominate the risk of hazardous material transportation. The incident release frequencies of hydrogen road transport and onboard hydrogen storage are more likely to occur due to the traffic accidents than through the system malfunctions. Therefore, the losses of containment frequencies for these systems were estimated directly from the accident rate data. Fault tree analyses were not performed for these systems. Similar to this, the loss of containment frequencies of a hydrogen pipeline may also be estimated by direct use of the base failure rate data. In the following section, these methods are described.

4.4.2.1 Estimation of accident frequency for the onboard hydrogen storage

The release chance of an onboard storage is generally a function of the distance travelled [126]. Thus, the frequency of an accident is often expressed as an accident rate per km. Accident rates of a road hydrogen transport for a given road length may be calculated from historical data records according to the equation:

$$Accident\ rate = \frac{Accidents\ number\ per\ year}{Vehicle - km\ per\ year} = \frac{Accidents}{vehicle - km} \qquad (4\text{-}5)$$

A typical value for the road accident rate is 3.0 x 10^{-6} accidents/vehicle-km [126]. The loss of containment (release) frequency for the onboard hydrogen storage can be estimated from the above accident rates, by using the following equation:

$$F = F_A \cdot L_a \cdot P_r \qquad (4\text{-}6)$$

where:

F = Expected frequency of hydrogen release from onboard storage(1/yr)
F_A = Accident rates (1/veh.km)
L_a = Annual distance for a given vehicle (km/yr)
P_r = conditional probability for release given an accident

4.4.2.2 Estimation of accident frequency for the road transportation

As described in Section 4.3.3.2.1, the release frequency of a truck transport is dominated by truck accident such as collisions and overturning. The non-accident-initiated release or railroad grades do not contribute substantially to the risk analysis. Therefore, the release frequency of the hydrogen road transport can be estimated from the accident rate, as given in the following equation [3]:

$$F = F_A \cdot L_s \cdot T \cdot P_r \qquad (4\text{-}7)$$

where

F = Expected frequency of hydrogen release from road transport(1/yr)
F_A = Accident rates (1/veh.km)
L_s = Length of the route segment (km)
T = Truck per year travelling on the route (1/yr)
P_r = Conditional probability for release given an accidents (-)

It is similar to the previous section, with exception that the annual distance of the truck is calculated for a certain route. The truck accident rates (F_A) can be obtained from the truck road accident data (see Table 5-16). As for comparison, truck accident rates (in accidents per veh-km) for California, Illinois, and Michigan is shown in Table 4-2. The table shows truck accident rates for different broad classes of route types (e.g., urban versus rural, divided versus undivided highway). It also shows that the conditional probability of release of an accident involving a truck carrying hazardous material is a function of vehicle characteristics and the nature of the accident. This conditional release probability has a significant influence on overall risk since it typically addresses the relative likelihoods of different sizes of releases having substantially different potential consequences. With respect to the nature of the incident, the most significant factor is the general accident type.

In the QRA, the transport routes may be divided into several segment routes crossing areas in different population densities (Pop./km^2) along the segment routes. For example, in the study two segment routes were considered for the LH_2 Tanker truck to deliver hydrogen from a production plant to a hydrogen fuelling station in a city.

Table 4-2 Truck accident rates for California, Illinois, and Michigan [3]

Highway Class		Truck Accident Rate ($1/10^6$ veh.km)	Conditional Probability
Area	**Roadway**		
Rural	Two-lane	1.36	0.09
Rural	Multilane, undivided	2.79	0.08
Rural	Multilane, divided	1.34	0.08
Rural	Freeway (limited access)	0.40	0.09
Urban	Two-lane	5.38	0.07
Urban	Multilane, undivided	8.65	0.06
Urban	Multilane, divided	7.75	0.06
Urban	Freeway (limited access)	1.35	0.06
Urban	One-way street	6.03	0.06

4.4.2.3 Estimation of failure frequency for a pipeline

Failure frequencies for hydrogen pipelines can be estimated from the existing historical failure rate data of general gas pipeline. For example, the failure rates for the USA compared with those for Europe as shown in Table 4-3. It shows that the pipelines with a diameter of 6 inches or less have an overall failure rate of 1.24 x 10^{-3}/km-year, which is higher than the overall rate for all diameter pipelines. Additional data for gas pipeline is shown in Table 4-4.

Table 4-3 Failure rates of gas pipeline for different causes (1/km-yr) [3]

Cause	USA		Europe
	All pipelines	**lines <=6 in**	**All pipelines**
External interference	4.2E-04	8.1E-04	4.2E-04
Corrosion	1.2E-04	9.3E-05	1.1E-04
Material/construction defects	1.6E-04	2.1E-04	1.3E-04
Others	6.2E-05	1.2E-04	5.0E-05
Total	**7.7E-04**	**1.2E-03**	**7.0E-04**

Table 4-4 Failure size in gas pipeline by causes (in %) [3]

Size	External Interference	Corrosion	Material failure/ construction defects	Others
Rupture	23.4	1.2	10.5	7.9
Hole	50.6	1.3	25.0	2.5
Pinhole	26,0	97.5	64.5	89.6
Total	100	100	100	100

Table 4-5 Failure rates of gas pipeline by cause and size (1/km-yr) for Europe

Size	External Interference	Corrosion	Material failure/ construction defects	Others	Total
Rupture	9.8E-05	1.3E-06	1.3E-05	4.0E-06	1.2E-04
Hole	2.1E-04	1.4E-06	3.1E-05	1.3E-06	2.5E-04
Pinhole	1.1E-04	1.0E-04	8.1E-05	4.5E-05	3.4E-04
Total	**4.2E-04**	**1.1E-04**	**1.3E-04**	**5.0E-05**	**7.0E-04**

The failure data from Table 4-3 (for Europe) can be combined with the data on failure size by cause from Table 4-4 to produce the failure rates by cause and size given in Table 4-5. For example, in the Table 4-3 gave a failure rate of 4.19x10^{-4} /km-year for external interference. Using the failure size distribution for external interference from Table 4-4 gives failure rates of 9.8 x 10^{-5}/km-year for rupture, 2.12 x 10^{-4}/km-year for hole, and 1.09 x 10^{-4}/km-year for pinhole. The similar calculation results are shown in Table 4-5.

The release frequency of hydrogen from a pipeline can be calculated using a simple model given by [183]:

$$F = F_p \cdot L_s \cdot E \qquad (4\text{-}8)$$

where,

F = Expected frequency of hydrogen release from GH_2 pipeline(1/yr)
F_p = Failure rate of gas pipeline (1/km.yr)
L_s = Length of the route segments (km)
E = Exposure factors for the route segments

4.4.3 Event Tree Analysis

Having identified a set of top events and estimated their initial frequencies as discussed at the previous section, it is necessary to consider the range of possible consequences that could occur after the original failure, and to estimate the probabilities of alternative outcomes. This can be done with using an "event tree analysis (ETA)". An event tree is a logic diagram in which all of possible outcomes of a single initiating event are described.

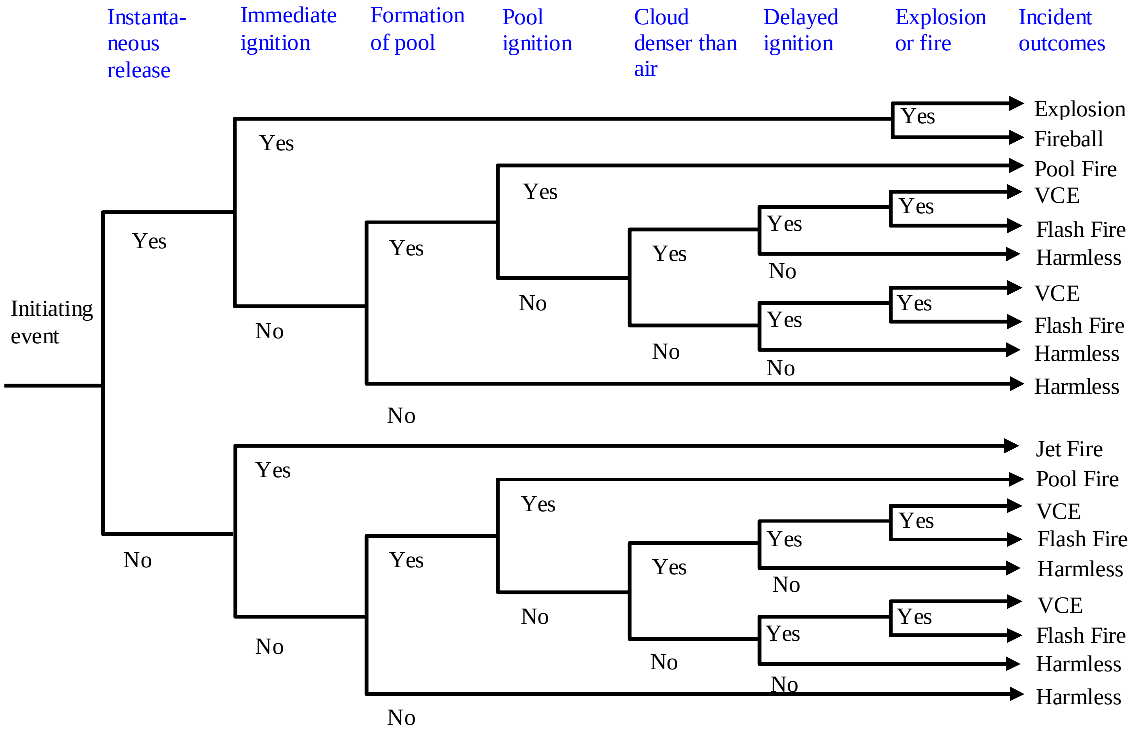


Fig. 4.5 Event tree diagram of LH_2 releases [17, 2]

4.4.3.1 Event Trees Diagram for Hydrogen Release

A hydrogen release may have many event outcomes, depending on the timing and type of ignition. For example, a released substance may be ignited immediately at the point of release, or it may be ignited after the cloud has been dispersing for a certain amount at time, or it may not ignite at all. Fig. 4.5 and 4.6 show event tree diagrams to develop incident outcomes from hydrogen releases (in liquid and gaseous forms). For a given release of hydrogen an early explosion, fireball, or jet fire outcomes will be occurred if it is followed by immediate ignition. Otherwise, a pool (pool fire may occurs if it ignites) may be formed or the substance may be evaporated and disperse away from the release centre following the wind direction. If concentration of the hydrogen clouds is within its flammability limits (4-75%/vol) and an ignition source exists around the clouds, then a delayed outcome (such as a vapour cloud explosion, or flash fire) may occur. Frequencies of the event outcomes (such as explosion, fireball, etc.) for a given scenarios are calculated by multiplying the initial frequency with the associated branch probabilities of the event tree diagram.

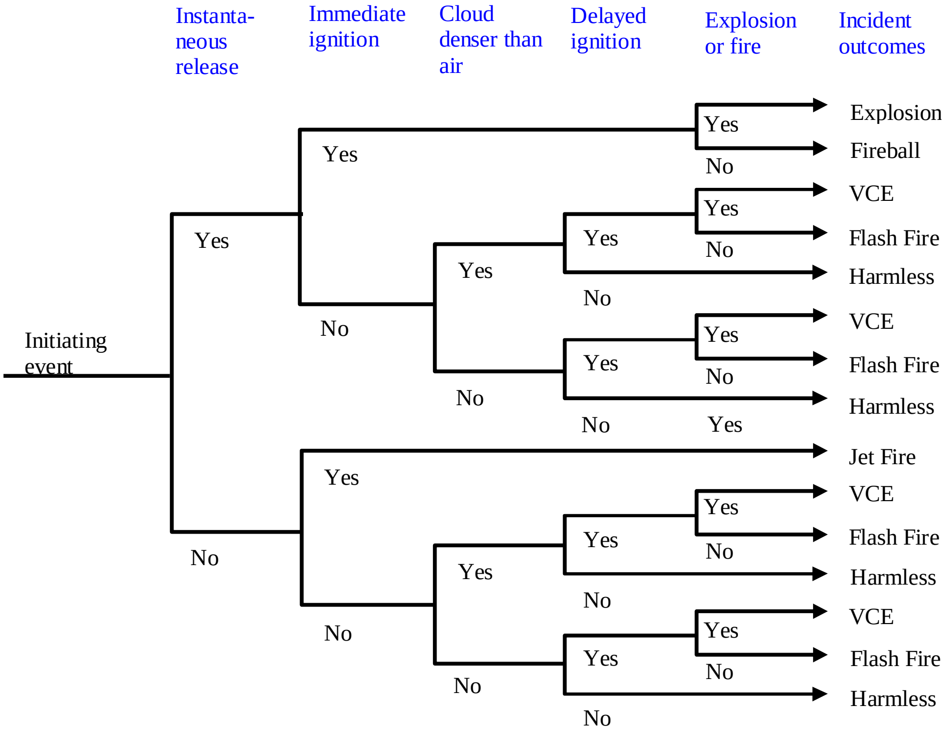


Fig. 4.6 Event tree diagram of GH_2 release [17, 2]

4.4.3.1 Conditional Probabilities

In order to calculate the frequencies of the event outcomes the probabilities for each of the branches of the event tree diagram have to be first determined. They can be estimated by using fault tree analysis or are developed based on numbers of accidents in the past. In the Canvey Study, for example, it is quoted that covering 59 incidents involving small spills of LPG and flammable liquids gave probability of ignition of 0.9 [36]. On the other hand, the LPG study carried out by [187] set the probability of ignition occurring for road transport as shown in Table 4-6.

Table 4-6 Ignition probability in the LPG Study of TNO for road transport [187]

Scenario	**Immediate ignition**	**Delayed ignition**	**No ignition**
Broken pipe hole	0.1	0.05	0.85
Instantaneous release of tank contents	0.4	0.5	0.1

Based on a limited number of hydrogen accidents, [36] gave some probabilities for hydrogen and other combustible materials released from road tankers that generally carry up to 30.3 m^3 inventories. These values are presented in Tables 4-7 and Table 4-8, and are generally applicable to tank truck and station releases. Table 4-8 shows that the immediate ignition of hydrogen release is a very likely event. It gives the probability is 0.9 for large spill, and 0.5 for small spill. The same ways for delayed ignition gives probability of 0.09 for a large release, and 0.45 for a small release. The small spills meant that it involves 10% of tank inventory, large spill involve 100% of tank inventory.

Table 4-7 Conditional probabilities of spill for a transport truck accident [36]

Fuel	Small spill	Large Spill	Total
Hydrogen	0.06	0.02	0.08
Propane	0.075	0.025	0.01
Gasoline	0.09	0.07	0.16
Ethyl alcohol	0.09	0.06	0.15

Table 4-8 Conditional probabilities of immediate ignition for given a spill [36]

Fuel	Immediate Ignition		Delayed Ignition	
	Small spill	Large Spill	Small spill	Large Spill
Hydrogen	0.50	0.90	0.45	0.09
Propane	0.25	0.75	0.68	0.23
Gasoline	0.15	0.50	0.04	0.05
Ethyl alcohol	0.20	0.60	0.04	0.04

Table 4-9 Conditional probability of hydrogen release used in the study

Event	Instantaneous	Continuous	Sources
Immediate ignition	0.90	0.50	Expert opinion
A pool is formed?	0.40	0.20	Relationship
Pool ignited	0.80	0.80	Relationship
Cloud denser than air?	0.20	0.20	Relationship
Delayed ignition	0.09	0.45	Expert opinion
Explosion rather than fire	0.20	0.20	Historical data

Several references [36, 17, 96] concluded that an unconfined space release explosion is a very unlikely event, because an explosion requires several circumstances, such as the presence of obstacles and a very strong source of ignition (>1000 Joule) (see Chapter 2). According to the evaluation given by several authors based on explosion accidents in the past, only a small portion of the energy of a hydrogen cloud is expected to be liberated in an open air explosion; it is estimated to be in the range of 0.1 – 10%, mostly < 1% [96]. Statistical evaluation to 25 selected hydrogen accidents recorded by UNEP, OECD, MHDAS, BARPI (see Chapter 2) give a fire contribution for about 60%, explosion 30%, and 10% for both fire and explosion. Based on the above information it can be estimated that the probability is 0.2 for explosion, and 0.8 for fire. Table 4-10 give a summary of the incident outcomes probabilities used in the study.

4.5 CONSEQUENCE MODELLING

Once the initiating event is defined, source models are selected to describe how materials are discharged from the process. The source model provides a description of the rate of discharge, the total quantity discharged (or total time of discharge), and the state of the discharge, that is, liquid, vapour or a combination. A dispersion model is subsequently used to describe how the material is transported downwind and dispersed to some concentration levels. If there is an immediate fire or explosion, there is no dispersion. Fire and explosion models convert the source model information on the release into energy hazard potentials such as thermal radiation and explosion overpressures. Finally, effect models convert these incident-specific results into effects on people (injury or death) and structures.

The consequence models employed in the study are those of the program package PHAST Professional (version 6.4), developed by DNV (UK). PHAST (Process Hazard Analysis Software Tool) [49] is a commercial consequence program package used for modelling: discharge, pool formation and evaporation, dense and buoyant gas dispersion, jet and pool fire, BLEVE and vapour cloud explosion, and so on. This section is to summarize the range of consequence models mostly used in PHAST. A detailed description of the models is presented in Appendix E.

4.5.1 Source Models

4.5.1.1 Discharge Models

Most of the incidents and hazards associated with escaping hydrogen such as fire, explosion, and even formation of a flammable vapour cloud usually involve the escape of liquid or gaseous hydrogen from the containment owing to either the failure of the containment or an abnormal discharge from an engineered outlet such as a relief valve, followed by vaporization and dispersion. In particular, a large quantity of liquid hydrogen and/or vapour may be released by failure of the tank, line or valve.

For hydrogen gas at low pressure, the flow through an orifice is governed initially by the equation of isentropic (constant entropy) flow, by solving the conservation of energy and mass Eq. E-1 (Appendix E). Meanwhile for liquid hydrogen, the release may be gas, liquid, or a two-phase mixture, depending on certain conditions. For example, if the release is from a container holding liquid under pressure, it will normally be liquid if the aperture is below the liquid level, and vapour or vapour-liquid mixture if it is above the liquid level. For a given pressure difference, the mass rate of release is much greater for a liquid or vapour-liquid mixture than for a gas. To calculate the rate of release given the size of the aperture using thermodynamic and physical properties of escaping liquid hydrogen the Bernoulli Eq.E-4 is used (Appendix E).

4.5.1.2 Pool Spreading and Evaporation

Immediately after release, the liquid hydrogen spreads out on the ground. It will spread until it meets an artificial boundary such as a dyke, until it reaches a minimum depth at which it no longer spreads, or until the evaporation rate is equal to the release rate so that the amount of liquid in the pool is no longer changing. Also immediately after release, the liquid hydrogen starts to boil off as it absorbs heat from the air, the ground and the sun. Mass is also lost from the pool when wind removes the evaporated material from the surface of the pool so that hydrogen evaporates in order to restore the partial vapour pressure. If hydrogen is released from containment as a liquid, vaporization must occur before a vapour cloud is formed. Immediately after release the heat for boil-off is taken from the ground. Equations used to calculate the pool radius, and evaporation rate are given in section E.1.2 (Appendix E).

4.5.2 Dispersion Models

The dispersion model implemented in the PHAST is called the "Unified Dispersion Model" (UDM) developed by [203]. The UDM calculates a dispersion in the downwind direction (all phases between near-field and far-field dispersion) including possible touchdown, rainout (and subsequent pool formation and re-evaporation). Fig. 4.7 shows the movement of the cloud in the downwind direction for the steady-state/continuous dispersion. The Cartesian coordinate x,y,z correspond to the downwind, cross wind and vertical directions, respectively. The point of release is given by $x=0$, plume centre line by $y=0$, and ground level by $z=0$. In addition to that, the cloud coordinate s as the arc length measured along the plume centre, and z is the distance from the plume centre-line. In case of continuous dispersion, the coordinate z indicates the direction perpendicular to the plume centre-line and perpendicular to the-y direction. The angle between the plume centre-line and the horizontal is denoted by q, and the vertical plume height above the ground by z_{cld}. Thus z and z are related to each other by $z=z_{cld} + z\cos(q)$.

For instantaneous dispersion, the coordinate ζ indicates the vertical distance above the plume centre-line and perpendicular to the-y direction. The angle between the plume centre-line and the horizontal is denoted by θ, and the vertical plume height above the ground by z_{cld}. Thus z and z are related to each other by $z = z_{cld} + z$. The concentration profiles c for continuous and instantaneous release are given in Appendix E (i.e. Eq. E-8 and E-9).

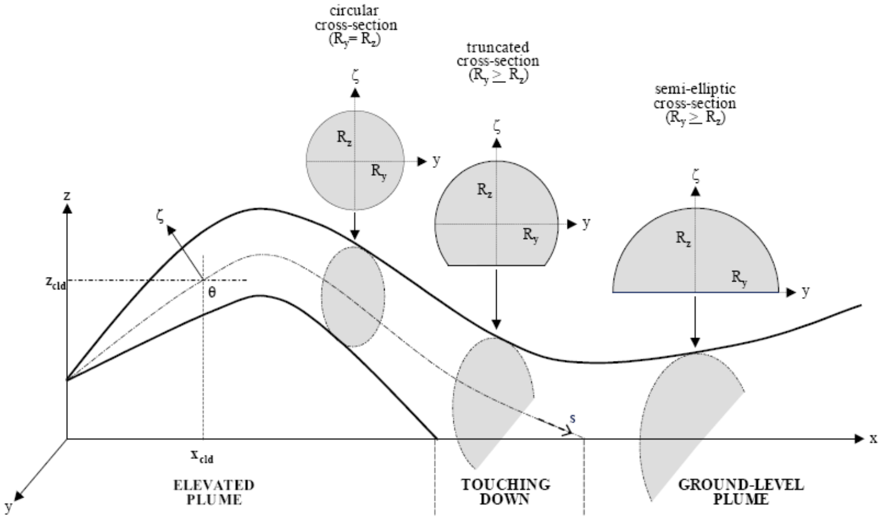


Fig. 4.7 UDM cloud geometry for continuous release [203]

4.5.3 Fire and Explosion Models

PHAST automatically generates the existing fire and explosion models (in section E.3, Appendix E) as long as the material is flammable. However, the right configuration of each model is required. For example, a pool fire only occurs if the flammable material is in liquid form and it is continuously released from a tank or a container in the direction of down-impinging to the ground. Output of the models is presented in the form of graphs and reports. There are several fire and explosion graphs, each of which shows a different type of the fire and explosion results. The following section is to review the types of models available for estimation of the consequences (effects) of accidental explosion and fire accident outcomes.

4.5.3.1 Explosion

When a large amount of hydrogen (liquid or gas) is rapidly released, a vapour cloud forms and disperses in the surrounding air. The release can occur from a storage tank, transport vessel, or pipeline. Event tree diagrams (Fig. 4.5 and 4.6) describe the various failure pathways under which this scenario can occur. If this cloud is ignited before the cloud is diluted below its lower flammability limit (LFL), a vapour cloud explosion (VCE) or flash fire will occur. The main consequence of a VCE is an overpressure that results while the main consequence of a flash fire is a flame contact accompanied by thermal radiation.

There are three methods available in PHAST for calculating the effects of explosions, and the one must be selected to generate an explosion model. The models include TNT, Multi-Energy, and Baker Strehlow. The study uses the *TNT* model (as the program default) to calculate explosion effects from the hydrogen system. A detailed description of the model is presented in section E-4 (Appendix E).

The explosion may occur either early or delayed (late) explosion (vapour cloud explosion, VCE). Both early explosion and VCE are modelled as two concentric circles with radius R1 and R2 (as shown in Fig. 4.8). However, they have different location of the explosion centre. Explosion centre of the early explosion is on the release point. Meanwhile, for the delayed VCE it is displaced from the release point [203], as shown in Fig. 4.8. The centre of the explosion is taken as the centre of the explosive cloud. The two effect zones correspond to two different explosion damage levels. The lethality is constant with one value inside the central zone and constant with another value in the annulus formed by the inner and outer circles. The lethality in each zone is set according to the vulnerability parameter settings for explosions. There is one outcome representing all weathers and directions. The analytic solution to the number of lethality (N) for this outcome is the sum of the products of the area of each zone, its lethality and the population density.

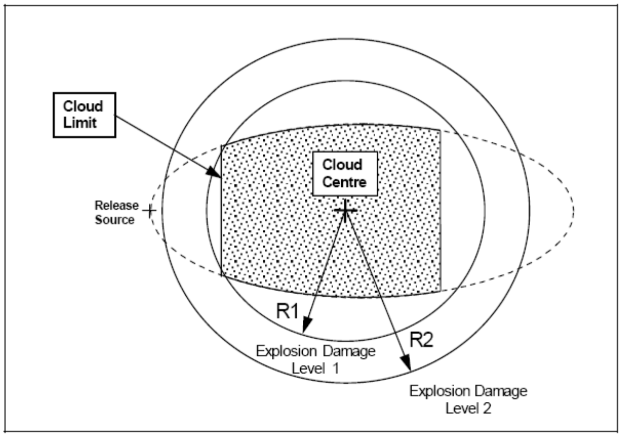


Fig. 4.8 The effect zone for a vapour cloud explosion [205]

Fatal effect zone of the explosion (A_{fatal}) is calculated as the sum of the inner effect zone area (A_1) multiplied by its vulnerability (f_1) and the outer effect zone area (A_2) multiplied by its vulnerability (f_2):

$$A_{fatal} = A_1 \cdot f_1 + A_2 \cdot f_2 \qquad (4\text{-}9)$$

Where

A_1 = circle area of inner (= $p^*(R_1)^2$) [m^2]
A_2 = circle area of outer (= $p^*(R_2-R_1)^2$) [m^2]
$f_{1,2}$ = vulnerability in inner and outer zone areas [%]

4.5.3.2 Flash Fire

Accidental releases of hydrogen (liquid or gaseous) often result in the formation of a cloud of vapour that is dense relative to ambient conditions. If the cloud encounters an ignition source then a vapour cloud flash fire may result. A flash fire is a non-explosive combustion of a vapour cloud resulting from a release of flammable material into the open air [1]. Major hazards from flash fires are thermal radiation and direct flame contact. Typically, the burning zone is estimated by first performing a dispersion calculation and defining the burning zone from the half-LFL limit back to the release point, even though the vapour concentration might be above the UFL. Turbulence induced combustion mixes this material with air and burns it. The flash fire envelope generated by the program shows the maximum area covered by the flash fire envelope, i.e. the area swept out by the flash fire footprint, through all wind directions.

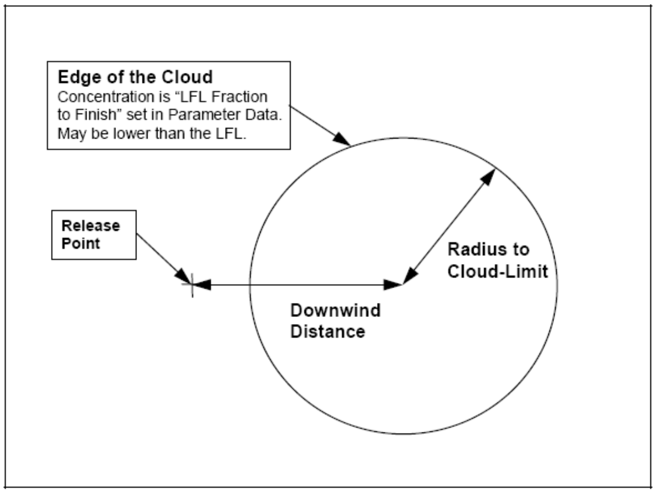


Fig. 4.9 The flammable zone of flash fire from instantaneous release [205]

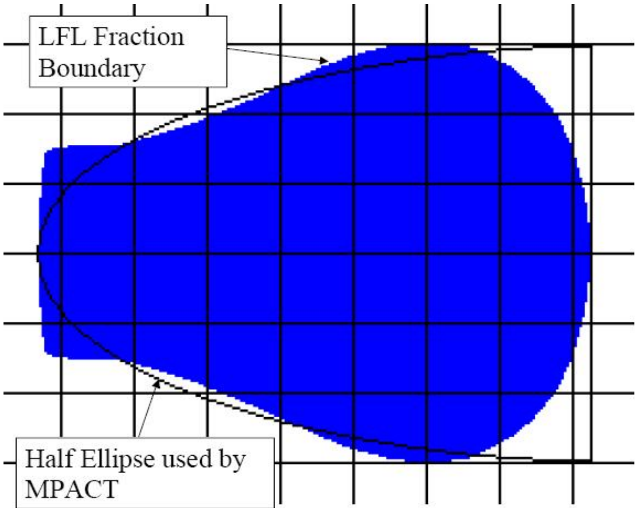


Fig. 4.10 Dispersion of cloud represented by a half-ellipse [205]

Flash fires are treated in different ways depending on the type of release. A flash fire resulting from instantaneous releases is presented as a circular cloud indicating the radius of the LFL fraction (2%) to finish. The circle starts centred at the release point and then proceeds to drift downwind as shown in Fig. 4.9. The flash fire description therefore gives the size and downwind position of the cloud at several time-steps during the time when it is developing to its fullest extent. The full description for each time-step includes: the distance the centre of the cloud has travelled downwind, the radius to the cloud-limit, and the flammable mass of the cloud.

For continuous releases the flash fire effect zone is taken to be the cloud boundary to the LFL fraction represented as an ellipse. There is also the possibility that the ellipse is defined as a ‘half-ellipse’ rather than the full shape. This approximation is made to economise on storage space and processor time. Fig. 4.10 shows an example where the LFL fraction boundary is described by a half-ellipse.

Two parameters are used to define the dispersion cloud shape; the downwind cloud length (L_{LFL}) and the cloud area (A_{LFL}) within the boundary defined by the LFL fraction. In a full approximate ‘semi-ellipse’ approximation is applied, where the horizontal and vertical ellipse semi-axis lengths A, B are set using: (i) same flammable length so that $A = L_{LFL}$ and (ii) same flammable area $A_{LFL} = 0.5*\pi*A*B$, again so that B is defined directly.

4.5.3.3 BLEVE and Fireball

A boiling liquid expanding vapor explosion (BLEVE) may occur when there is a sudden loss of containment containing liquid gas (e.g. LH_2). The primary cause is usually an external flame impinging on the shell of a vessel above the liquid level, weakening the container and leading to sudden shell rupture [2]. A pressure relief valve does not protect against this mode of failure, since the shell failure is likely to occur at a pressure below the set pressure of the relief system. It should be noted, however, that a BLEVE can occur due to any mechanism that results in the sudden failure of containment, including impact by an object, corrosion, manufacturing defects, internal overheating, etc. The sudden containment failure allows the superheated liquid to flash, typically increasing its volume over 200 times [2]. This is sufficient to generate a pressure wave and fragments.

Due to the fact that hydrogen is flammable, a fireball may result as well. According to [2], blast overpressure and fragment effects from BLEVEs are usually small compared to fireball effects, although they might be important in the near field. These effects are of interest primarily for the prediction of domino effects on adjacent vessels. The study, however, only considers fireball effects resulting from a BLEVE. The program models a fireball, calculating the shape of the flame, and a wide range of radiation results. Eq. E-14a (Appendix E) used by the program to calculate thermal radiation (kW/m^2) resulted from the fireball.

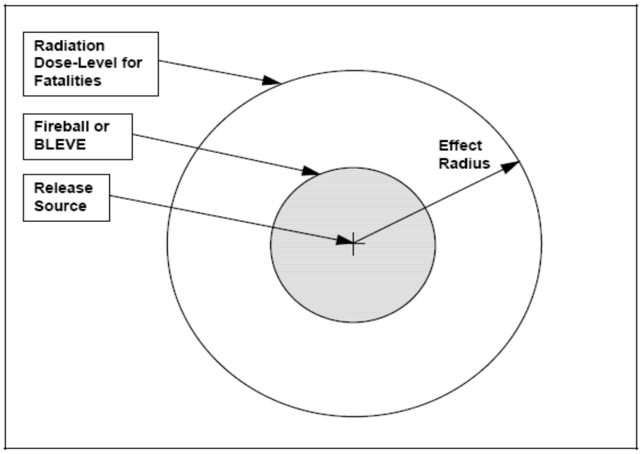


Fig. 4.11 The fatal effect zone for a fireball or BLEVE [205]

The dimension used to define a fireball/BLEVE is the radius to the radiation impact of concern. This is defined in terms of 'Thermal Dose Units' $((kW/m^2)^N s)$. The exponent, N, depends on the N constant defined for flammable probit calculations. This measure takes fireball duration into account in calculating the potential fatality effects. The duration calculated by the fireball/BLEVE model used in this calculation is limited to a maximum exposure time parameter. Additional fatality effects due to BLEVE overpressure or vessel fragments are not considered in the study. The zone is centred at the release point. Fig. 4.11 illustrates the approach. The effect distance (z) of the fireball is equal to its downwind radius (x). The fatal effect zone is calculated as the effect zone area $(=p*x^2)$ [in m^2] multiplied with its vulnerability level [*%*].

4.5.3.4 Jet Fire

A jet fire or spray fire is a turbulent diffusion flame resulting from the combustion of a flammable fuel continuously released with some significant momentum in a particular direction [94]. Jet fires can arise from releases of gaseous and liquid pressurized hydrogen. There are two jet fire models available, i.e. API 521 and Shell jet fire, and the model that is selected by the user. The shell method treats the flame as a tilted cone frustum, whereas the API model treats it as a banana-shape plume, i.e. tapered at the end, and bent by the wind. The study uses API model to calculate thermal impacts resulted from jet fires. A detailed description of the API model is presented in section E.4.3 (Appendix E).

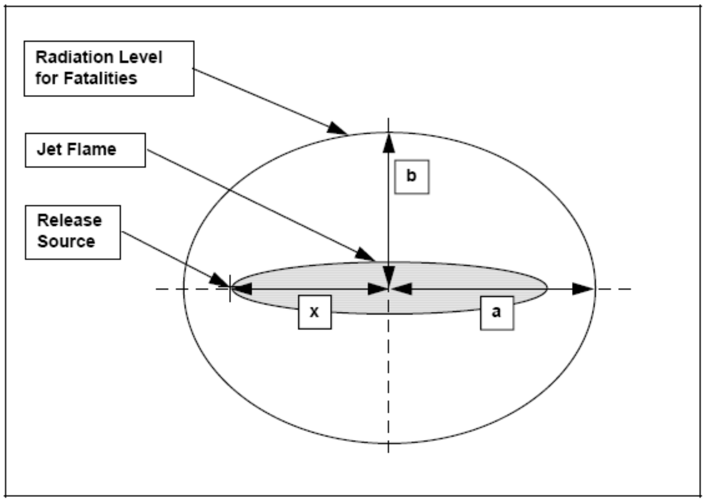


Fig. 4.12 The Fatal effect zone for a jet fire [205]

The fatal effect-zone of jet fire is modelled as an ellipse. Three dimensions describe the ellipse as illustrated in Fig. 4.12. Axes "a" and "b" are the major and minor axes of the ellipse, and "d" is relative offset of the ellipse centre from the release point defined as the ratio $d=x/a$ where "x" is the distance from the release point to the ellipse centre. Thus for an ellipse centred at the release point $d=0$. For an ellipse with the effect zone starting at the same point as the release $d=1$. Jet fires can be displaced from the release point according to the wind speed and the rainout position, because of the effect of wind speed and also elevation of the flame. "$d>1$" *if* the effect zone is displaced from the release point. The effect distance (z) is calculated as the sum of downwind radius (a) and the downwind distance (x) from the release location, or $z=a+x$, where $x=d*a$. The fatal effect zone area (A_{fatal}) is calculated as the effect zone area ($A_z = \pi*a*b$) [in m^2] multiplied with its vulnerability level [in %].

4.5.3.5 Pool Fire

Pool fire is a turbulent diffusion fire burning above a horizontal pool of vaporising flammable liquid where the liquid has zero or low initial momentum [93, 94]. The program models a pool fire, calculating the shape and intensity of the flame, and a wide range of radiation results. A detailed description of the pool fire model is presented in section E.3.2 (Appendix E). The primary effects of such fires are due to thermal radiation from the flame source. The pool fires, however, tend to be localized in effect and are mainly of concern in establishing the potential for domino effects and employee safety zones, rather than for community risk [2]. Therefore, the pool fire impact was not considered in the risk calculation.

Similar to the jet fire, the fatal effect-zone of pool fire is modelled as an ellipse. Three dimensions describe the ellipse as illustrated in Fig. 4.13. Axes *a* and *b* are the major and minor axes of the ellipse, and *d* is relative offset of the ellipse centre from the release point defined as the ratio *x/a* where *x* is the distance from the release point to the ellipse centre. The effect distance and the fatal effect zone of the pool fire are calculated similar to the jet fire (See Section 4.5.5.4)

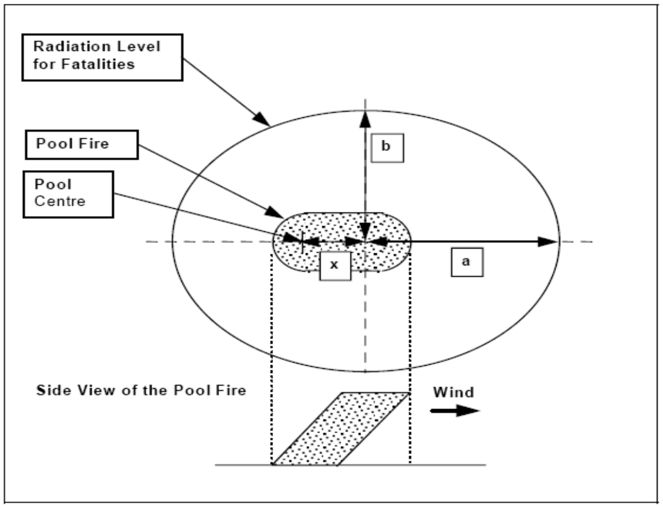


Fig. 4.13 The Fatal effect zone for a pool fire [203]

4.5.4 Impact Models

The source models generate a variety of outcomes that are caused by release of hazardous material or energy. The dispersion models estimate concentrations and/or doses of dispersed vapour. The explosion models estimate shock wave overpressures and fragment velocities, and fire models predict radiant flux generated from the outcomes. These models rely on the general principle that the severity of the outcome is a function of distance from the source of release. The next step in the QRA is to assess the consequences of these outcomes on human beings, expressed as deaths or injuries.

One method of assessing the consequence of an outcome is the direct effect model, which predicts effects on people or structures based on predetermined criteria (e.g., death is assumed to result if an individual is exposed to a certain thermal radiation level). In reality, the consequences may not take the form of discrete functions (i.e., a fixed input yields a singular output) but may instead conform to probability distribution functions. Therefore, a statistical method of assessing a consequence (called dose-response method) may be appropriate. This method is coupled with a probit equation to linearize the response. The probit (probability unit) method described by Finney (1971) reflects a generalized time-dependent relationship for any variable that has a probabilistic outcome that can be defined by a normal distribution. The probit variable Y is related to the probability P by [160]:

$$P = \frac{1}{\sqrt{2p}} \int_{-\infty}^{Y-5} \exp\left(-\frac{u^2}{2}\right) du \tag{4-10a}$$

where P is the probability or percentage, Y is the probit variable, and u is an integration variable. The probit variable is normally distributed and has a mean value of 5 and a standard deviation of 1. For spreadsheet computations, a more useful expression for performing the conversion from probit to percentage is given by

$$P = 50\left[1 + \frac{Y-5}{|Y-5|} erf\left(\frac{|Y-5|}{\sqrt{2}}\right)\right] \tag{4-10b}$$

where:

$$erf(x) = \frac{2}{\sqrt{p}} \int_{0}^{x} e^{-t^2} dt \tag{4-10c}$$

4.5.4.1 Thermal Impacts

The purpose of the thermal impact models is to estimate the likely injury or damage to people and objects from the thermal radiation of incidents. Thermal impacts of fire on humans depend on the rate at which heat is transferred from the fire to the person, and the time the person is exposed to the fire [43]. Even short-term exposure to high heat flux levels may be fatal. This situation could occur to persons wearing ordinary clothes who are inside a flammable vapour cloud (defined by the lower flammability limit) when it is ignited. In the study, it is assumed that all persons inside a flammable cloud at the time of ignition are killed and those outside the flammable zone are not.

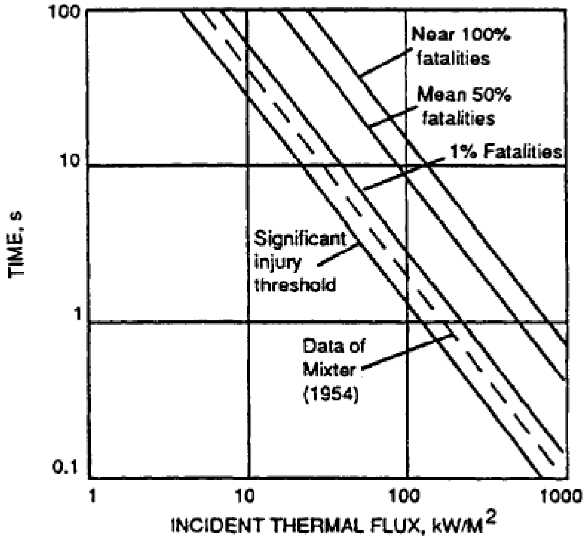


Fig. 4.14 Serious injury/fatality levels for thermal radiation [2]

API (1996a) RP 521 and World Bank (1985) [2] provides a short review of the effects of thermal radiation on people. The thermal radiation impacts suggested by World Bank (1985) are shown in Table 4-10. Furthermore, Mudan (1984) summarized the data of Eisenberg et al. (1975) for a range of burn injuries, including fatalities, and of Mixter (1954) for second-degree burns (Fig. 4.14).

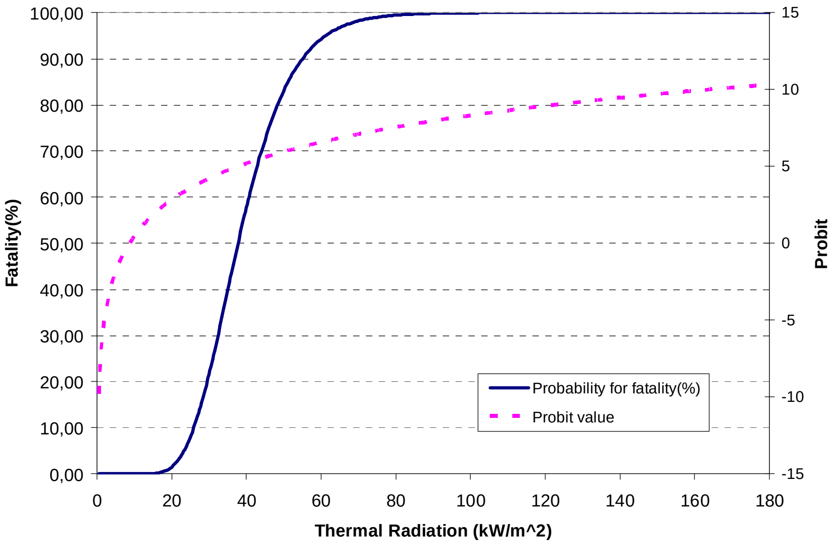


Fig. 4.15 Effect of thermal radiation on man

Eisenberg et al. (1975) develop a probit model to estimate fatality levels for a given thermal dose from pool and flash fires, based on nuclear explosion data [2], and shown in Fig. 4.15:

$$Y = -14.9 + 2.56 \ln\left(\frac{t \cdot I^{4/3}}{10^4}\right) \tag{4-11}$$

where Y is the probit, t is the duration of exposure (sec), and I is the thermal radiation intensity (W/m^2).

Lethality levels (%) of the thermal radiation impacts (such as pool fire, jet fire and fireball) to people can be calculated from the Eq.4-11. For example, thermal radiation impact from jet fires with exposure time of 20s (flammable) is shown in Table 4-10. It should be noted that the time exposure (t_s) in fireball is equal to the fireball duration, while in jet fire and pool fire is set to 18.7s (flammable).

Table 4-10 Thermal Radiation impact from Jet fires (duration 20s)

Intensity level (kW/m^2)	Time(s)	Probit value	Lethality level (%)
18.2	20	2.7	1
24.7	20	3.7	10
37.5	20	5.1	56
125.6	20	9.3	100

4.5.4.2 Overpressure Impacts

The purpose of the explosion impact models is to predict the impact of blast overpressure and projectiles on people and objects. Explosion effects have been studied for many years, primarily with respect to the layout and sitting of military munitions stockpiles. Explosion effects are classified according to effects on structures and people [2].

4.5.4.2.1 Effect Blast on Equipment and Structures

Explosion overpressure level and damage effect on structures are shown in Table 4-11. Overpressure duration is important for determining effects on structures. The positive pressure phase of the blast wave can last from 10 to 250 ms, or more, for typical VCEs. The same overpressure level can have markedly different effects depending on the duration [2]. Eisenberg et al. (1975) provide a simple probit model to describe the effects on structures.

$$Y = -23.8 + 2.92\ln(p) \qquad (4\text{-}12)$$

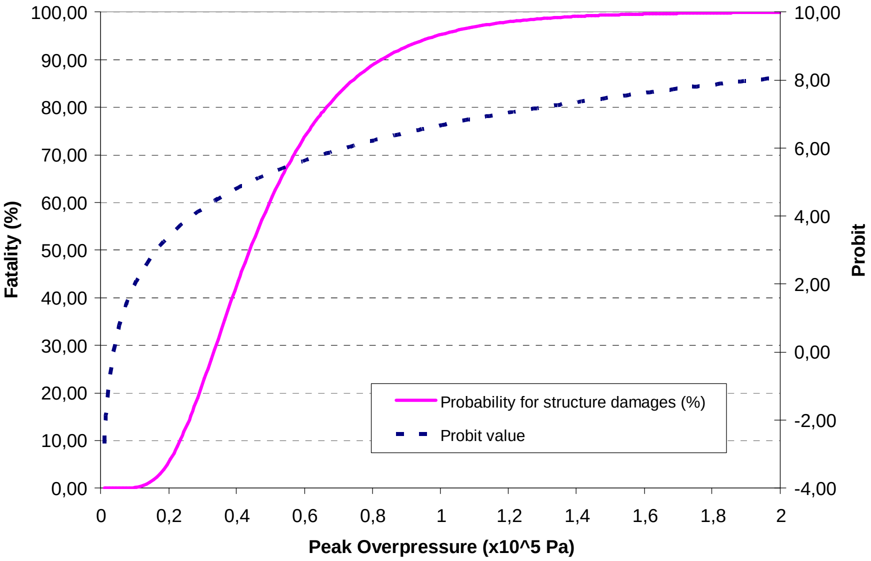


Fig. 4.16 Peak Overpressure impacts on structures

where *Y* is the probit and *p* is the peak overpressure (Pa). The probit, *Y*, can be converted to a percentage using Eq. (4-7), as shown in Fig.4.16. The percentage here represents the percent of structures damaged.

Table 4-11 Explosion overpressure level and damage effects on structure [2]

Overpressure (bar)	Damage produced by blast effect
0.0207	No considerable damage except shattering of few glass panes
0.1379	Partial collapse of buildings
0.2068	Steel framed building distorted and pulled away from the foundation

4.5.4.2.2 Blast Effects on People

The purpose of the model is to determine the fatality probability of the occupants of buildings subject to blast loading. This is dependent on the level of blast loading, the type and construction of the building. In general, three categories of blast induced injury are identified:

(1). Primary injury is due directly to blast wave overpressure and duration (Table 4-13). The location of most severe injuries is where the density differences between adjacent body tissues are greatest, i.e. the lungs, the ears, the abdominal cavity, the larynx and trachea.

(2). Secondary injury is due to building collapse and impact by missiles produced as results of the explosion. This give rise to laceration, penetration and blunt trauma.

(3). Tertiary injury is due to displacement of the entire body followed by high decelerative impact loading which is when broken or fractured limbs can occur.

A study performed by [101] shows that the secondary effects are the dominant cause of fatalities. Primary and tertiary are less important at the overpressure levels considered, although impairment of hearing or lung damage may effects the ability of people to escape from collapsed buildings.

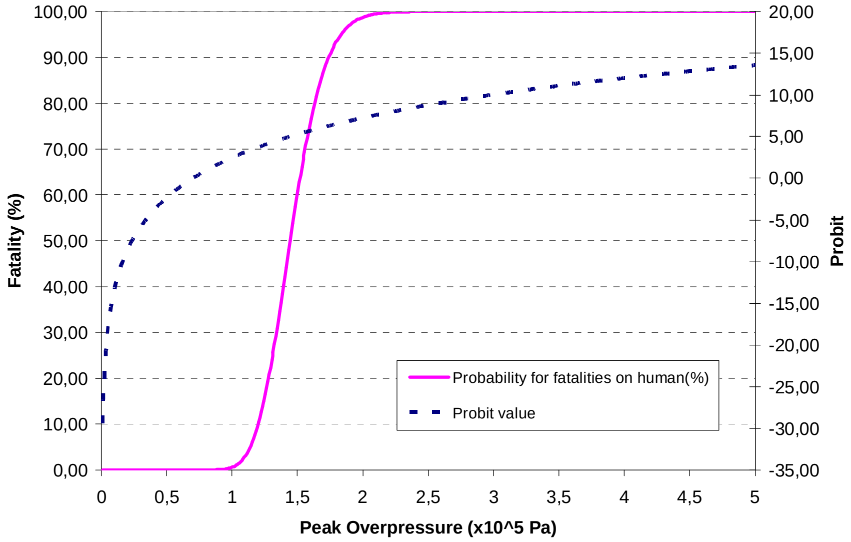


Fig. 4.17 Peak overpressure of hydrogen explosion on man

Eisenberg et al. (1975) provide a probit for fatalities as a result of lung hemorrhage due to the direct effect of overpressure,

$$Y = -77.1 + 6.91 \ln(p) \tag{4-13}$$

where Y is the probit and p is the peak overpressure (Pa), and is plotted in Fig. 4.17. The probit equation also shows that it requires relatively high blast overpressures (>1 hPa) to produce fatality (primarily due to lung hemorrhage). Another probit equation was developed by the HSE [92], based on peak overpressure:

$$Y = 1.47 + 1.37 \ln(p) \tag{4-14}$$

Quest [93] used the explosion/lethality relationship for the Canvey study as shown in Table 4-12.

Table 4-12 Hazardous explosion overpressure level [93]

HSE Probit	Peak Overpressure (bar)	Fatality (%)
1	0.2	1
5	0.9	50
7	3.0	95

Table 4-13 Summary historical data on damage to humans from air blast effects [101]

Effects on people	**Peak overpressure (mbar)**
Annoying noise of continuous type at 10-15 Hz and 137 dB	1.4
Loud noise at 143 dB	2.8
Sound 'note' as an unusual event – an explosion	0.34
Threshold for temporary loss of hearing	13.8
Threshold for eardrum rupture	138
50% eardrum rupture threshold	331
Threshold of skin laceration by missiles	69 - 138
Personnel knocked down or thrown to the ground	103-200
Possible death by persons being projected against obstacles	138
Low personnel risk when inside a resistant structure	69
50% probability of eardrum rupture	345-483
90% probability of eardrum rupture	689-1034
Threshold of internal injuries by blast	483
Serious missile wounds giving about 50% fatality	276 - 345
Serious missile wounds giving near 100% fatality	483 - 689
Threshold of lung haermorrhage	827-1034
50% fatality from lung haemorrhage	1379 - 1724
99% fatality from lung haemorrhage	2068 -2413
People standing up will be thrown a distance	552 - 1103
People lying up on the ground are picked up and hurled about	827 - 1655
Immediate blast fatalities	4826 – 13,790

Analysis of the blast effects on people are highly uncertain as they are based on injury models developed from condensed phase explosions. The probit approach could not be used due to the small distances involved. Therefore the study took a conservative approach, as shown in Table 4-14, considering that all or a proportion of personnel in the vicinity of an explosion will be fatalities.

Table 4-14 Fatality probability for explosion used in the study

Overpressure (bar)	**Damage produced by Blast Effect**	**Fatality (%)**
0.0207	No considerable damage except shattering of few glass panes	0.01
0.1379	Partial collapse of Buildings	1
0.2068	Steel framed building distorted and pulled away from the foundation	10

4.6 RISK ESTIMATION

Risk can be defined as a function of accident consequence and likelihood (Section 4.2). After discussing how to *estimate* accident consequences (section 4.4), and how to estimate incident likelihood (Section 4.5) this section combines the consequence and likelihood to estimate, to measure, and to present the risk. The following presentation is based on procedure described in [2, 159, 205].

4.1.1. Risk Measures and Presentation

In general, risk is a measure of economic loss, human injury or environmental damage in terms of both the likelihood and the magnitude of the loss, injury or damage [2]. The study describes risk measures which estimate risk of human fatality caused by the immediate impact of hydrogen accidents—fire and explosion. Two common ways used of combining incident frequency and consequence data to produce risk estimates, i.e. individual risk and societal risk.

Individual risk (IR) measures are single numbers or a set of risk estimates for various individuals or geographic locations. In general, they consider the risk to an individual who may be in the effect zone of an accident or set of accidents. The size of the accident, in terms of the number of people impacted by a single event, does not affect the individual risk.

Societal risk (SR) measures are single number measures, tabular sets of numbers, or graphical summaries which estimate risk to a group of people located in the effect zone of an accident or set of accidents. Societal risk estimates include a measure of accident size (for example, in terms of the number of people impacted by the accident or set of accidents considered). Some societal risk measures are designed to reflect the observation that people tend to be more concerned about the risk of large accidents than small accidents, and may place a greater weight on large incidents.

The large quantity of frequency and consequence information generated by a QRA must be integrated into a presentation that is relatively easy to understand and use. The form of presentation will vary depending on the goal of the QRA and the measure of risk selected. The presentation may be on a relative basis (e.g., comparison of risk reduction benefits from various remedial measures) or an absolute basis (e.g., comparison with a risk target). Published risk studies have used a variety of presentation formats, including both individual and societal risk measures.

4.1.1.1. Individual Risk (IR)

Common forms of presentation of individual risk are risk contour plots and individual risk profiles, also known as risk transects. The risk contour ("isorisk" lines) plot shows individual risk estimates at specific points on a map. It connects points of equal risk around the facility. The individual risk profile (risk transect) is a plot of individual risk as a function of distance from the risk source. This plot is two-dimensional (risk vs distance) and is a simplification of the individual risk contour plot (Fig. 4.18). In order to use this format, two conditions must be met: the risk source should be compact (i.e., well approximated by a point source) and the distribution of risk should be equal in all directions. A candidate for this presentation format is a generic risk assessment for a common hazardous item [2].

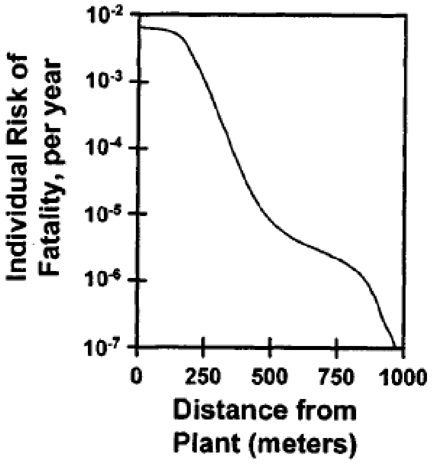


Fig. 4.18 Example of an individual risk, i.e. risk profile [2]

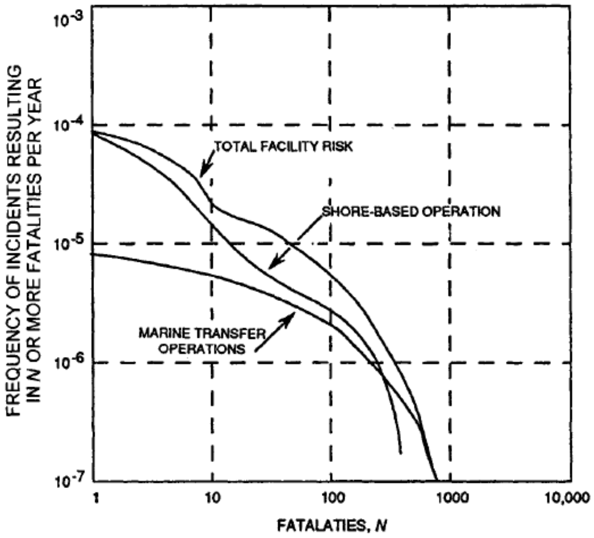


Fig. 4.19 An example F-N curve for a single liquefied flammable gas facility [2].

4.1.1.2. Societal Risk (SR)

A common form of societal risk (SR) is known as an F-N (frequency-number) curve. An F-N curve is a plot of cumulative frequency versus consequences (expressed as number of fatalities). A logarithmic plot is usually used because the frequency and number of fatalities range over several orders of magnitude. It is also common to show contributions of selected incidents to the total F-N curve as this is helpful for identification of major risk contributors. Fig. 4.19 is a sample F-N curve for a single liquefied flammable gas facility [2]. The facility contains two major parts—a shore-based operation and a marine transfer operation. The F-N curves for these two components of the installation are plotted in Fig. 4.19, along with the F-N curve for the total facility. The societal risk F-N curve for the total facility is equal to the sum of the F-N curves for the two facility components.

4.1.2. Risk Calculations

4.1.2.1. Analytical Approach

The model is an analytical model used to calculate the risks associated with hydrogen hazards developed following QRA procedure given by several authors. One of the procedures was given by [205]. They developed a model called MPACT (population impact of toxic and flammable effects) model implemented in the SAFETI DNV software. The MPACT is a mathematical model that calculates a number of results relating to the impact on the land and population potentially affected by the various toxic and/or flammable events that are defined as inputs by the user. It employs the assumption that each event can be treated independently from other events. This assumption can be made because the frequency of accidental releases in the chemical industry is very low in comparison with the duration of the hazardous effects themselves. The integration of the risk from all possible events can, therefore, be built up event by event and this is one of the principles underlying the MPACT algorithm.

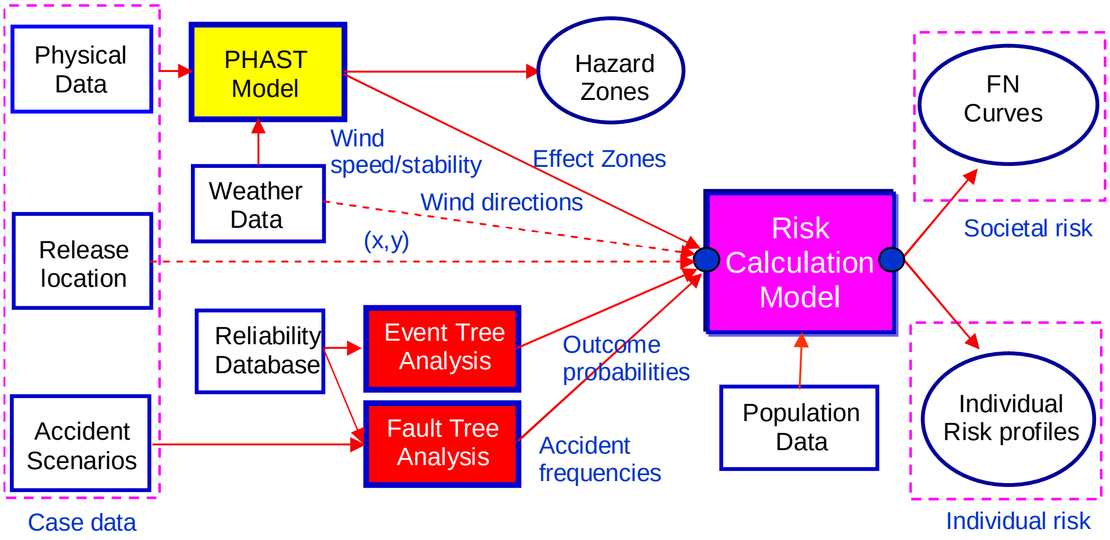


Fig. 4.20 The risk calculation model environment modified from [205]

Based on this algorithm the model combines the consequences of hydrogen related accidents to the population and their frequencies. The accident consequences of hydrogen (i.e. fire and explosion outcomes) in terms of their effect zones (distances), as one of the model inputs were calculated using PHAST (section 4.5), and the result is presented in Section 5.4. Since the model is concerned with risk it also needs frequencies for each possible event and outcome. Within the model the frequency of each outcome is calculated from the frequency of the event itself and the probabilities defined on each branch of the event tree. The event frequencies of the system were simulated using the Fault Tree Analysis program developed by [86], as well as by using historical statistical data (section 4.4). The estimated frequencies are presented in section 5.3. Finally, superimposes them on the population to calculate the risk for fatalities in the surrounding area. The results are presented as F-N curve for societal risk and individual risk profiles. Fig. 4.20 shows the relationship between the risk calculation model and its input and output.

The number of people (N) affected by each accident outcome is given by

$$N_i = \sum_{x,y} (A \cdot D)_{x,y} \cdot p_{f,i} \qquad (4\text{-}15)$$

where, A is fatal effect area [m2] of the outcomes (see section 4.5.5), D is the population density [Pop./m2], and $p_{f,i}$ is probability that incident outcome case i will result in a fatality at location x, y (fatality level). Additionally, the program also calculates rate of death (1/yr), which is the weighted number of fatalities per year, given by:

$$R_d = \sum_{All\,model} \sum_{o} F_{M|o} \cdot N_{M|o} \qquad (4\text{-}16)$$

and the “Okrent” number given by:

$$O_k = \sum_{All\,model} \sum_{o} F_{M|o} \cdot N_{M|o}^2 \qquad (4\text{-}17)$$

The “Okrent” number is a risk measure that reflects the greater impact on society of accidents that cause high numbers of fatalities. The factor of 2 is known as the aversion index.

4.1.2.2. Drawing Risk Profile

Once risks have been calculated, the risks can be defined in terms of the complete set of triplet of numbers (s_i,f_i,c_i) [125, 242]:

$$R_i \cong (s_i,\, f_i, c_i), \qquad i = 1, \ldots\ldots, n \tag{4-18}$$

In eq. (4-18) s_i describes an accident scenario, f_i is its expected frequency of occurrence, and c_i represents the consequences, i.e. category and magnitude of damage. “*n*” is the number of scenarios taken into account in determining the risk. Theoretically, *n* would be arbitrarily large, since many scenarios are conceivable. In practice, however, the scenarios are not taken into account if they are unlikely.

Table 4-15 Triplet sorted in order of increasing consequence

s_i	f_i	c_i	**Cumulative f_i**
s_1	f_1	c_1	$\sum_1^n f_i - f_1$
s_2	f_2	c_2	$\sum_1^n f_i - \sum_1^2 f_2$
…	…	…	…
s_{n-1}	f_{n-1}	c_{n-1}	$\sum_1^n f_i - \sum_1^{n-1} f_i$
s_n	f_n	c_n	0

In order to presents the estimated risks as individual and societal risk (F-N curve), the triplet can be transformed into the risk profiles by means of so-called “complementary cumulative distribution function (CCDF)”. To create a risk profile, the triplets must be ordered in increasing order of consequence, i.e. so that $ci < ci+1$, as described in the Table 4-15. The risk profile can be plotted as a step function as in Fig. 4. 21.

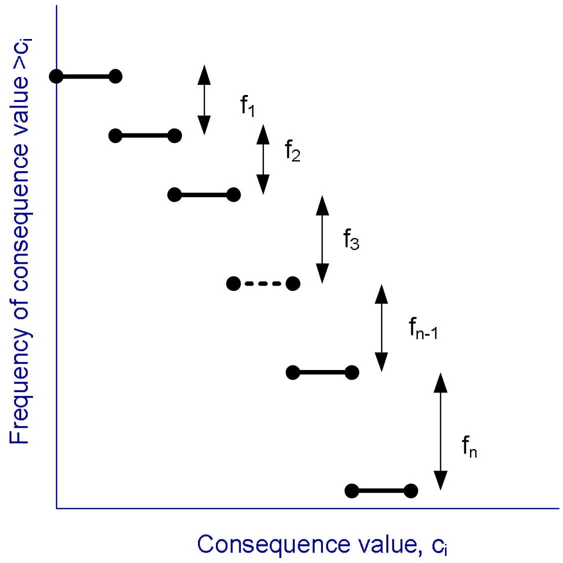


Fig. 4.21 F-N or F-C curve complementary probability distribution [125]

The individual risk (IR) profile is a two-dimensional (risk vs distance) graph, and is plot of IR as a function of distance from the risk source (i.e. effect distance, z). The *IR* is plotted as a logarithmic plot ("semilogy"). Meanwhile, the societal risk (SR) is known as an F-N curve. The F-N curve is a plot of cumulative frequency vs consequences (expressed as number of fatalities). A logarithmic plot ("log-log") is used because the frequency and number of fatalities range over several orders of magnitude.

4.1.3. Risk Acceptance Criteria

There is no zero risk situations. All actions, decisions or situations involve some level of risk, though in most cases the risk is very low. Very low or reasonable risk is considered to be acceptable. Many regulatory frameworks require the management of risk to a level that is reasonable but fall short of defining the specific criteria for major unwanted events. In many risk assessments it may be necessary to determine the level of acceptable risk during the Scoping process. The criteria must be established prior to performing quantitative risk assessment to enable comparison against the desired safety level [83]. The study uses the risk acceptance criteria called "ALARP" (as shown in Fig. 4.22) proposed by the European Integrated Hydrogen project phase 2 (EIHP2) [83, 243], as well as described by the German accident commission for risk management [172].

The ALARP (**A**s **L**ow **A**s **R**easonably **P**racticable) principle was developed by the UK authority. It is based on general risk for society. This choice also satisfies the general criteria of assuring that the risk level associated with hydrogen applications should be similar to or smaller than the risk associated with comparable non hydrogen systems. The ALARP principle is that *the residual risk shall be as low as reasonably practicable*. It means that a risk is low enough that attempting to make it lower would actually be more costly than any cost likely to come from the risk itself. This is called a *tolerable risk*.

The upper line of this figure represents the risk acceptance curve. The region between this line and the lower line denotes the ALARP area. For scenarios with risk level (that lie) between these lines the risk should be reduced if practical, typically subject to cost benefit analysis. For scenarios with risk levels above the upper curve, measures to reduce the risk must be implemented.

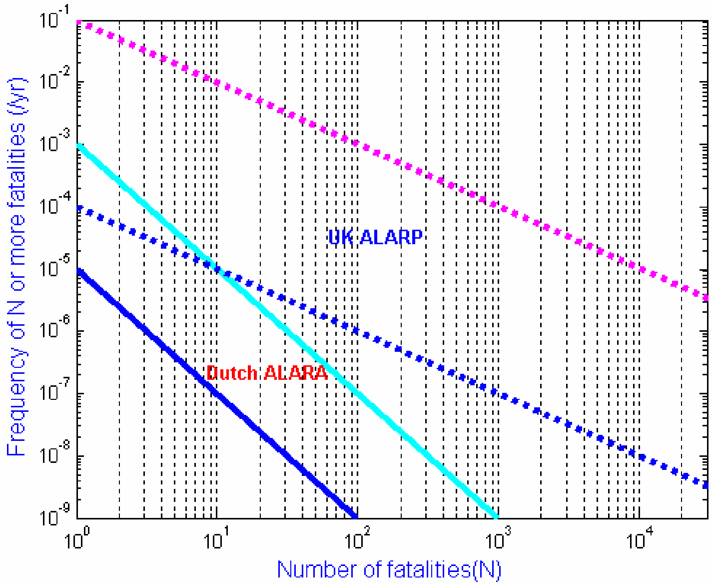


Fig. 4.22 Societal risk curve, FN curve with ALARP region [83, 172, 243]

The risk acceptance criteria are in general developed based on the mathematical expression:

$$F \cdot N^{a} = k \tag{4-19}$$

where, “F” is likelihood of N or more fatalities, “N” is number of fatalities, “a” is the aversion factor (>1, often 2), and “k” is constant. The slope of the societal risk (as plotted as a log-log basis) is simply “a”. It is designed to reflect the society’s aversion to a single accident with multiple fatalities as opposed to several accidents with few fatalities. The Netherlands used a value of 2. This is usually interpreted to mean that the Dutch authorities have built in degree of “risk aversion” to a lager accident. Meanwhile, the UK set the value of “a” as one, which is termed as “risk neutral”, i.e. no aversion. The Dutch slope and more severe than the U.K. ones

The Dutch approach [246] to the development of the criteria may be summarised as follow: (1) Start from the premise that “the risk from a hazardous activity to a member of the public should be significant when compared with the risk of “everyday life”; (2) Identify age group of lowest risk (10-14 years old) and the “everyday” risk level for this group is 1 x 10^{-4} /year (3) Based individual criterion on 1% of lowest everyday risk – i.e. 1 x 10^{-6} /year; (4) Translate into a societal risk anchor of 10^{-5} /year for 10 or more fatalities; (5) Apply an aversion slope of -2, as a heavier weight must be assigned to a larger consequences; (6) Apply a factor of 100 to both individual and societal risk criteria to generate a “negligible” risk value. The resultant F-N curves are illustrated in Fig. 4.22 (solid lines), and may be characterised as follows:

- Application:	Those existing hazards facilities, Netherlands
- Zones:	3 – Unacceptable, Reduction desired, Acceptable
- Anchor points:	1x10^{-5}/yr for 10 or more fatalities (upper limit of “unacceptable”); 1x10^{-7}/yr for 10 or more fatalities (lower limit of “acceptable”)
- Consequence cut-off:	1000 (efficiently)
- Frequency cut off:	1 x 10^{-9}/yr

For the UK approach [246], the development of risk criteria can be summarized as follows: (1) Start from the premise that “risk of death of one in a thousand per year is about the most that is ordinarily accepted under modern conditions in the UK; (2) suggest that 1/10 of this should be tolerable for risk associated with 3rd party activities (i.e. 1 x 10^{-4} /yr). (3) for societal risk, use the Canvey study risk to provide an “anchor” for the lower limit intolerable (2 x 10^{-4} /yr for 500 or more fatalities); (4) apply an aversion slope of -1 which is “risk neutral”; (5) insert a corresponding “negligible” line 1000 times lower. The resultant F-N curves are illustrated in Fig. 4.22 (dotted lines), and may be characterised as follows:

- Application:	Identifiable community, UK
- Zones:	3 – Intolerable, ALARP, Negligible
- Anchor points:	2x10^{-4}/yr for 500 or more fatalities (lower limit of “intolerable”); Upper limit of “negligible” 1000 times lower
- Consequence cut-off:	none
- Frequency cut off:	1 x 10^{-8}/yr

Chapter 5

THE QRA RESULTS AND EVALUATIONS

5.1 INTRODUCTION

This chapter presents the quantitative risk assessment (QRA) results for the study objects described in the Chapter 3. They were obtained using the methods described in the Chapter 4. Firstly, accident scenarios for the study objects were identified using the FMEA method. The frequencies of the undesired events were estimated using a combination of fault tree and event tree analysis. Frequencies for the hydrogen road transport and on-board storages were estimated from the accident rate data (see section 4.4.3) combined with event tree analyses. Consequences of the undesired events were simulated with the PHAST professional version 6.4 developed by DNV Software (UK). The consequence and frequency analysis results were then combined to estimate the risk to the environment. The estimated risks were then compared with the risk acceptance criteria given by [83, 172, 243, 221]. The results are presented in the form of tables and graphs.

5.2 THE ACCIDENT SCENARIOS

This section describes the possible accident scenarios of the hydrogen objects included in the study. The FMEA method was mainly used to define a list of undesired events that consider all possible breaks or ruptures of items of equipment which would lead to a loss of containment from the hydrogen study objects. The QRA study on hydrogen systems are concerned with flammable properties of liquid, of gas, and the systems have therefore been examined to identify the events which could lead to the release of hydrogen to the atmosphere. The hydrogen can only be released to the atmosphere either as a result of as a result of loss of containment from the storage tanks, through the rupture of pipelines, or handling of failure.

The total number of equipments in a study object where a safety evaluation has to be made can be very large. Since not all equipments contribute significantly to the risk, it is not worthwhile to include all installations in the QRA. According to the European Council Directive (EC Directive) [159], the QRA may be carried out if the hydrogen (as a dangerous substance) is thought to be present at a location (e.g. industrial sites and transportation routes) in amounts that can endanger the environment. The threshold quantity for hydrogen and other dangerous substances are given in the EC Directive “96/82/EC on the control of major-accident hazards involving dangerous substance” (“Seveso-II directive”). It regulates the production, handling and storing of hydrogen as well as other relevant fuels (such as LPG, Ammonia, etc.). It also recommends that the installation that has a larger quantity than the threshold quantity are required to implement a major-accident prevention plan, which includes maintaining risk analysis and implementing a safety management system as well as preparing emergency action plan. For hydrogen, the threshold level amount is 5 tons, for LPG 50 tons, for methanol 500 tons, and for gasoline 2500 tons [236, 159].

Based on the above guidelines the accident scenarios of the hydrogen objects were focused on hydrogen storage and transport, as they have the greatest potential for large releases of hydrogen and consequential damage. Furthermore, the study only considered the societal risk evaluation of the hydrogen objects. Therefore, the QRA study was done only on equipments that contribute most to the societal risk in each installation.

Hydrogen storage and transport mainly consists of tank container and its piping system linking the various pieces of equipments. Each of them, of course, may break or rupture in an infinite number of ways. The final choice of incidents to be modelled took into consideration the following factors: the size of the release, whether the release is instantaneous or continuous, and liquid or vapour phase. The lists of accident scenarios of the study objects are described in the following sections.

5.2.1 Hydrogen Production

The QRA study was focused on the hydrogen storage as the largest hydrogen inventory in the plant. The hydrogen storage (compressed gaseous hydrogen, CGH_2) has a total capacity of 5000 Nm^3 (±420 kg of H_2) at a pressure of 3 MPa and ambient temperature. It mainly consists of two large cylindrical CGH_2 tank installed outdoors and its piping system. The piping systems used to connect the tank to other equipments such as electrolysers, pressure relief devices, instrumentations, end-use technologies, and other outlines. Each of them, of course, may break or rupture in an infinite number of ways. By considering the factors above (section 5.1), the following scenarios have been assessed: (1) Instantaneous release of the complete hydrogen inventory caused by tank rupture; (2) Continuous release of hydrogen in liquid or vapour phase through a hole in the tank; (3) Continuous release of hydrogen in vapour phase due to relief valves fail open; (4) Continuous release of hydrogen in vapour phase due to rupture discs ruptures prematurely; (5) Continuous release of hydrogen due to a full-bore rupture of the vapour lines.

The summary of the scenarios considered for the hydrogen plant is given in Table 5-1. The table shows the five accident scenarios A-E, including with following information: undesired events, inner diameter (tank, pipe, and hole), release direction, and discharge data (i.e. flow rate or mass, and release duration. Due to inadequate information the diameter of pipes and holes were estimated from a similar study (e.g. LPG).

Table 5-1 List of accident scenarios for the GH_2 storage at production plant

Scenarios	Undesired events		Inner diameter (mm)			Release Direction	Type of Bund Surface	Discharge Data	
	Type	Phase	Tank	Pipe	Hole			Flowrate (kg/s) or mass (kg)	Duration (s, or inst)
A	Tank rupture	Vapor	N/A	-	-	-	N/A	445	inst.
B	Tank leak	Vapor	N/A	-	50.8	Down	N/A	3.3	135.9
C	Relief valve	Vapor	N/A	50.8	12.7	Vertical	N/A	0.3	17550.3
D	Rupture disc	vapor	N/A	50.8	50.8	Vertical	N/A	2.3	194.9
E	Line rupture	Vapor	N/A	50.8	50.8	Vertical	N/A	2.3	194.9

5.2.2 Hydrogen Storage at Depot

The study considered the large-scale liquid hydrogen storage (as depot), having a capacity of 270 m^3 (270,000 litres), and situated in Ingolstadt. It is used to store hydrogen in the liquid phase (± 16,000 kg of LH_2) at temperature of -253°C and pressure of 1.3 bar (Section 3.4). The hydrogen plant is subjected to the accident regulation of German “Storfallverordnung” [78]. The hydrogen storage has a maximum liquid inventory of 16 tons, which is more than the quantity thresholds (Section 5.1). Therefore it is required to implement a major-accident prevention plan, which includes performing risk analysis and implementing a safety management system. A systematic safety study was performed based on the HAZOP method by the German technical inspection agency (TÜV) [78]. The essential hazards assumed were:

(1) Incorrect coupling of the liquid hydrogen connection during filling of trailers; (2) Loss of the insulation vacuum of the LH_2 tank followed by blow-out of the safety valve via vent line and the 22 m high stack, which is designed for low temperature.

The LH_2 storage plant mainly consists of a cryogenic, double-walled, and vacuum super-insulated tank and its piping system. The piping system consists of lines linking the different pieces of equipment, filling lines, withdrawal lines, and so on. Each of them, of course, may break or rupture in an infinite number of ways. By considering the factors above (section 5.1), the following accident scenarios were assessed: (1) Instantaneous release of the complete hydrogen inventory caused by tank rupture; (2) Continuous release of hydrogen in liquid or vapour phase through a hole in the tank; (3) Continuous release of hydrogen in vapour phase through relief valves; (4) Continuous release of hydrogen in vapour phase through rupture discs; (5) Continuous release of hydrogen release in vapour phase due to a full-bore rupture of the vapour lines; (6) Continuous release of hydrogen in the liquid phase due to a full-bore rupture of the liquid lines.

The summary of the scenarios considered for the hydrogen plant is given in Table 5-2. The table gave similar information given in Table 5-1. The LH_2 storage has an additional scenario because it includes liquid and vapour phases.

Table 5-2 List of accident scenarios considered for the LH_2 storage at depot

Scenarios	Undesired events		Inner diameter (mm)			Release Direction	Type of Bund	Discharge Data	
	Type	Phase	Tank	Pipe	Hole			Flowrate (kg/s) or mass (kg)	Duration (s, or inst)
A	Tank rupture	Liquid	N/A	-	-	-	N/A	16248	inst.
B	Tank leak	Liquid	N/A	-	127	Down	N/A	84.4	192.6
C	Relief valve	Vapor	N/A	50.8	50.8	Vertical	N/A	3.5	3600
D	Rupture disc	Vapor	N/A	50.8	50.8	Vertical	N/A	3.6	3600
E	Line rupture	Vapor	N/A	50.8	50.8	Vertical	N/A	4.2	3600
F	Line rupture	Liquid	N/A	127	127	Vertical	N/A	30.5	532.7

Table 5-3 List of accident scenarios considered for the LH_2 storage at filling station

Scenarios	Undesired events		Inner diameter (mm)			Release Direction	Type of Bund Surface	Discharge Data	
	Type	Phase	Tank	Pipe	Hole			Flowrate (kg/s) or mass (kg)	Duration (s, or inst)
A	Tank rupture	Liquid	2500	-	-	-	N/A	800	inst.
B	Tank leak	Liquid	2500	-	76.2	Down	N/A	30.4	26.3
C	Relieve valve	Vapor	2500	50.8	12.7	Vertical	N/A	0.5	1566
D	rupture disc	vapor	2500	50.8	50.8	Vertical	N/A	3.6	223.4
E	Line rupture	Vapor	2500	50.8	50.8	Vertical	N/A	4.2	192.0
F	Line rupture	Liquid	2500	76.2	76.2	Vertical	N/A	9.4	85.4

5.2.3 Hydrogen Filling Station

Similar to previous plant, the QRA study is focused on the LH_2 storage that is available in the plant. The hydrogen filling station considered in the study consists of the following major components: a double wall super-insulated cryogenic (LH_2) tank, an ambient air evaporator, a multi-stage diaphragm compressor, a tubes trailer, and hydrogen dispensers. The LH_2 tank is used to store liquid hydrogen with capacity of 12,000 litres (±800 kg of LH_2) at a temperature of –253°C and pressure of 0.8 MPa. It is the largest hydrogen inventory in the plant, and may dominate the societal risk of the fuelling station. The complete list of the accidents scenarios for the plant is given in Table 5-3.

5.2.4 Energetic Uses of Hydrogen

5.2.4.1 Hydrogen in Private Cars

We now consider specific safety risks in the hydrogen-powered vehicle (e.g. private car), by examining onboard hydrogen systems failures that might lead to hazardous conditions, in both normal operation and during a collision. In general the hydrogen vehicle has relatively few potential hazards compared to other vehicle systems. There are no toxic chemicals, acids, and so on that could harm the environment. A study carried out by [185, DTI (2003)] concluded that the only potential hazard to hydrogen-fuelled vehicle is due to the hydrogen itself. Most of the time a large amounts of hydrogen is available in the storage tank. The study therefore was limited to one issue, i.e. the failure modes which could lead to a release of hydrogen from the hydrogen tank and the piping system.

The study considered a hydrogen private car (e.g. BMW 735i) where hydrogen is stored in liquid form (LH_2) in a cryo-tank at a temperature of -253°C, and at a pressure of about 0.5 MPa. Similar to the previous plant, the scenarios for the hydrogen car are given in Table 5-4.

Table 5-4 List of accident scenarios for the onboard LH_2 storage in private car

Scenarios	Undesired events		Inner diameter (mm)			Release Direction	Type of Bund Surface	Discharge Data	
	Type	Phase	Tank	Pipe	Hole			Flowrate (kg/s) or mass (kg)	Duration (s, or inst)
A	Tank rupture		400	-	-	-	N/A	6	Inst.
B	Tank leak	Liquid	400	-	12.7	Down	N/A	3.4	1.8
C	Relieve valve	Vapor	400	12.7	5.08	Vertical	N/A	0.1	79.5
D	rupture disc	Vapor	400	12.7	12.7	Vertical	N/A	0.2	40.4
E	Line rupture	Vapor	400	12.7	12.7	Vertical	N/A	0.2	33.9
F	Line rupture	Liquid	400	12.7	12.7	Vertical	N/A	0.2	29.9

Table 5-5 List of accident scenarios considered for the LH_2 storage at the CHP plant

Scenarios	Undesired events		Inner diameter (mm)			Release Direction	Type of Bund Surface	Discharge Data	
	Type	Phase	Tank	Pipe	Hole			Flowrate (kg/s) or mass (kg)	Duration (s or inst)
A	Tank rupture	Liquid	3100	-	-	-	N/A	4200	inst.
B	Tank leak	Liquid	3100	-	76.2	Down	N/A	30.4	138.3
C	Relief valve	Vapor	3100	50.8	50.8	Vertical	N/A	3.5	1211.9
D	Rupture disc	Vapor	3100	50.8	50.8	Vertical	N/A	3.6	1173
E	Line rupture	Vapor	3100	50.8	50.8	Vertical	N/A	4.2	1010.6
F	Line rupture	Liquid	3100	76.2	76.2	Vertical	N/A	10.9	387.2

5.2.4.2 Hydrogen for Household Applications

As described in section 3.7, the safety evaluation of hydrogen for household applications, i.e. fuel cells-combined heat and power (FC-CHP) plant was focused on the LH2 storage and its environment. The LH2 storage marks the largest contribution to the overall risk. The LH2 tank has a capacity of 66.3 m3 (about 4200 kg of LH2). The list of accident scenarios considered for the LH2 storages at the CHP plant is given in Table 5-5.

5.2.5 Hydrogen Transportation

5.2.5.1 Road Tanker Truck

As discussed in Section 4.3.3.3.1, the various mechanisms of the LH_2 tanker truck failures may be caused by accident-initiated release and non-accident-initiated release. The study addresses only the accident-initiated releases, as these are expected to have the greatest potential damage and large hydrogen releases. Release from the safety valve is not considered to be an accident. Some typical truck accident scenarios include collisions with other vehicles, road debris, buildings, or animals; collisions with trains; and overturns. The release sizes range from the full loss of contents to small drips. Small drips usually result from valve and fitting leaks that are not associated with accidents. Thus, they are not considered in the study, which focuses on accident-initiated releases. The release sizes studied were catastrophic failure (i.e. the instantaneous release of the entire contents of the tank) and continuous release (resulting from tank leak or pipe rupture). Therefore, the accident scenarios considered for the LH_2 tanker truck is shown in Table 5-6. Purple book [159] suggested that the effective hole diameter is about 50 mm (2 inches).

Table 5-6 List of accident scenarios considered for the LH_2 tanker truck

Scenarios	Undesired events		Inner diameter (mm)			Release Direction	Type of Bund Surface	Discharge Data	
	Type	Phase	Tank	Pipe	Hole			Flowrate (kg/s) or mass (kg)	Duration (s or inst.)
A	Tank rupture	Liquid	2500	-	-	---	N/A	4000	inst.
B	Tank leak	Liquid	2500	-	76.2	Down	N/A	30.4	131.7
C	Line rupture	Vapor	2500	50.8	50.8	Vertical	N/A	4.2	962.5
D	Line rupture	Liquid	2500	76.2	76.2	Horizontal	N/A	10.9	367

5.2.5.1 GH_2 Pipeline

As discussed in Section 4.3.3.3.2, several types of pipeline failure incidents are considered. The generic pipeline failure modes are based on historical incident data and include the loss of containment events resulting from corrosion leaks, external mechanical interference (third party damage); construction defects, material defects, and other causes. The release sizes are generally categorized by hole sizes, such as pinholes (about 0.1 inches in diameter), holes (1-1.5 inches in diameter), and rupture (line size). Due to the fact that the pipe is underground and the material transported (i.e. hydrogen) is non-toxic, the pinholes were not considered in the study. The accident scenarios considered for the GH2 pipeline is shown in Table 5-7. The holes were taken to be 20% of the pipe diameter, and ruptures taken as the pipe cross-sectional area. Each of the selected release sizes will be analyzed for different failure causes.

Table 5-7 List of accident scenarios considered for the GH_2 pipeline

Scenarios	Undesired events		Inner diameter (mm)			Release Direction	Type of Bund Surface	Discharge Data	
	Type	Phase	Tank	Pipe	Hole			Flowrate (kg/s)	Duration (s)
A	Rupture	Vapor	-	150	150	Vertical	N/A	1.9	158
B	Hole (20%)	Vapor	-	150	30	Vertical	N/A	1.8	168

5.3 FREQUENCY ESTIMATION RESULTS

This section describes the estimated frequency results of the accident scenarios considered for the study objects. Two approaches were carried out to estimate expected frequencies of the study objects (section 4.4.1), i.e. using fault-tree approach and direct use of the base failure data. The first approach (fault tree analysis) was performed to the four hydrogen objects, namely the GH_2 storage at production, the LH_2 storage at the depot, the LH_2 storage at the filling station and the LH_2 storage at the FC-CHP plant. Fault tree analysis for the plants ("Top events") is fully reproduced in Appendix G. It includes fault tree diagrams, reliability data, and summary of the results. Assuming a lognormal distribution for the basic event failure rate data, the expected frequencies of the Top events have been computed using the FTA-based analytical approach (described in section 4.4.2). The results are presented as the mean value as well as the 5th percentiles, 50th percentiles, 95th percentiles, and the 95% uncertainty factor (K-95).

The second approach was performed using equations and historical data described in the Section 4.4.3. The expected frequency for the onboard LH_2 storage in vehicle and LH_2 truck were estimated from German traffic accident rates. Meanwhile, the frequency for the GH_2 pipeline was estimated from the base failure data of gas pipeline for Europe.

Frequencies of the accident outcomes may occur following the accident scenarios are calculated by using event tree analysis (ETA). It performed by assigning conditional probabilities to all of the branches of the event trees of Fig. 4.5 (for LH_2) and Fig. 4.6 (for GH_2) and multiplying them by the expected frequency of each initiating events (top event). The probabilities for both event trees are given in Table 4-9.

5.3.1 Production Plant (GH_2)

Expected frequencies of the accident scenarios for the GH_2 tank at the production plant were synthesised from the component failure rate data associated with each of the identified failure mode, using the FTA approach (described in section 4.4.2). The accident scenarios of the GH_2 storage can be classified into two Top events, i.e. instantaneous and continuous. Therefore two fault tree diagram were developed for the Top events.

Fig. G1.1 (Appendix G) shows the fault tree diagram for the instantaneous release (e.g. tank rupture) of GH_2 storage at the production plant. The undesired events which may contribute to this Top events include: (1) tank excessive over pressure while all the pressure relief devices fail closed; (2) an external events (e.g. Earthquake, mechanical impacts, etc); and (3) spontaneous events (e.g. H_2 embrittlement, fatigue failure, etc). The tank overpressure may be caused by tank overfilling or an external heat source (e.g. fire around the installation). Due to inadequate information on the basic events the last two undesired events are presented as undeveloped events. The reliability data for these events have been estimated from similar studies, and they require judgment from the experts. The expected frequency of the scenario is estimated by assigning the failure data (Table G1.1.1) to each basic events of the FTA (Fig. G1.1). Summary of the FTA result is shown in the Appendix G. It includes lists of minimal cut sets, expected frequencies of the initiating events considered, and the top event frequency and its uncertainties for 10,000 trial numbers.

The fault tree related to the second Top event was a continuous release of hydrogen from the tank and its piping system. The fault tree diagram was fully reproduced, and is shown in Fig. G1.2 (Appendix G). The events may contribute to this Top events includes: (1) hydrogen release at venting circuits, (2) release from piping system, (3) release from holes of the tank or vessel, or drain valve fails open. A continuous release through venting system may be occurred due to the PRDs (i.e. rupture disk or pressure safety valve) fail open prematurely. Pipe rupture was considered as the continuous release of hydrogen. It may result in great damage to environment. This may occur if the associated emergency (remotely operated) shutoff valves fail to close. Hydrogen release due to tank leak or drain valve failure was represented as an undeveloped event, because information about it is insufficient. By assigning the failure rate data (Table G1.2.1) to each basic events of the fault tree the Top event frequency is estimated with the same procedure as above. The summary of the FTA result is presented in the Appendix G.

Table 5-8 Expected frequencies of the GH_2 storage at production plant(1/yr)

Release Type	Distribution parameters				K-95	Percentage
	5%	50%	Mean	95%		
Instantaneous	4.8E-09	1.7E-07	1.8E-06	6.2E-06	35.8	5.0%
Continuous	1.9E-06	1.5E-05	3.4E-05	1.2E-04	14.2	95.0%
Overall	**1.8E-06**	**1.5E-05**	**3.6E-05**	**1.3E-04**	**8.6**	**100.0%**

Table 5-9 Accident outcome frequencies of the GH_2 Storage at production plant(1/yr)

Release Scenarios	Accident Outcomes	Conditional Probability	5%	50%	Mean	95%
Instantaneous	Early explosion	0.008	1.4E-08	1.1E-07	2.7E-07	9.8E-07
	Fireball	0.030	5.4E-08	4.5E-07	1.1E-06	3.9E-06
	Late Explosion	0.000	4.1E-10	3.4E-09	8.1E-09	2.9E-08
	Flash Fire	0.001	1.6E-09	1.4E-08	3.2E-08	1.2E-07
Continuous	Jet Fire	0.475	8.5E-07	7.1E-06	1.7E-05	6.2E-05
	Late Explosion	0.043	7.7E-08	6.4E-07	1.5E-06	5.6E-06
	Flash Fire	0.171	3.1E-07	2.6E-06	6.1E-06	2.2E-05
No effect		0.273	4.9E-07	4.1E-06	9.8E-06	3.5E-05
Overall		**1.000**	**8.6E-06**	**2.8E-05**	**3.6E-05**	**9.0E-05**

The summary of the fault tree analyses results for the GH_2 storage plant with the trial number of 10,000 is shown in Table 5-8. The table shows that the expected frequency of the overall system is 3.6 x 10^{-5}/year (once per 27,777 years), with the contribution of instantaneous and continuous release of hydrogen from the GH_2 tank is 1.8 x 10^{-6} /year (once per 555,556 years) and 3.4 x 10^{-5} /year (once per 29,412 years), respectively. The table also shows that only 5% of the hydrogen release from the GH_2 storage occurs instantaneously.

The accident outcome frequencies of the two initial frequencies above were calculated by multiplying the expected frequencies with the outcome probabilities calculated from the event tree diagram for GH_2 release (Fig. 4.6). The result is shown in Table 5-9. The table shows that fire outcomes (with account for about 67%) are more dominant than explosion. Only about 7% of the accident outcome may result in an explosion, and the rest (26%) may have no effect on the population.

5.3.2 Storage at Depot (LH_2)

Similar to the previous object (5.3.1) the expected frequency of the accident scenarios considered for the LH_2 storage at the hydrogen filling station was synthesised from the component failure data associated with each of the identified failure modes, using the FTA approach. The accident scenarios considered for the study objects can be classified into two TOP events, i.e. instantaneous and continuous. Additionally, the continuous release scenario includes hydrogen release both in the liquid and vapour phase. Therefore three fault tree diagrams were developed related to the three Top events: (1) instantaneous release of hydrogen, (2) continuous release of hydrogen in the liquid phase, and (3) continuous release of hydrogen in the vapour phase. A detailed description of the FTAs for the plant is presented in Appendix G2.

Fig. G2.1 shows the first fault tree diagram for the instantaneous release of hydrogen. The fault tree was divided into four branches to be considered as the main contributor to the Top event (e.g. tank rupture). These include: (1) tank overpressure and all PRDs fail closed (blockage); (2) tank excessive under-pressure (low pressure) and the underpressure protection failure; (3) external events (e.g. Earthquake, mechanical impacts, etc.); and (4) spontaneous events (such as low temperature embrittlement, fatigue failure, etc.). Similar to previous system that the two last events (i.e. external and spontaneous events) are presented as undeveloped events. The tank overpressure was mainly caused by tank overfilling or tank loss of vacuum. Human error and instruments failure may great potential leading to overfilling. The expected frequency of the To event is estimated by assigning the failure data (Table G2.1.1) to each basic events of the FTA. The result is shown in Appendix G2.

The second and third fault trees related to the Top events of continuous release of hydrogen for both the liquid and vapour phase are shown in Fig. G2.2 and G2.3, respectively. The main contributors to the top events are piping rupture, connections failure, tank leak, or release through venting circuits. Release during unloading of the tanker truck involving human error, may contribute to the continuous release of hydrogen in the liquid stage. Besides, pipe rupture in various liquid lines may occur if the emergency (remotely operated) shutoff valve fails to close. Similar to the previous plant hydrogen release through the venting system may occur due to pressure relief devices (PRD) failing open prematurely.

The summary of the FTA results for the LH_2 storage at depot is presented in Table 5-10. The table shows that the overall expected frequency of the loss of containment of hydrogen from the LH2 tank at the depot is 1.2 x 10^{-4} /year (once per 10,905 years), with the instantaneous and continuous release are 2.8 x 10^{-6} /year (once per 357,143 years) and 8.9 x 10^{-5} /year (once per 11,249 years), respectively. It also shows that only 3.1% of the hydrogen release from the LH2 storage occurs instantaneously.

Table 5-10 Expected frequencies of the LH_2 storage at depot

Failure modes	**5%**	**50%**	**Mean**	**95%**	**K-95**	**Percentage**
Instantaneous release	2.3E-08	6.4E-07	4.9E-06	1.8E-05	27.5	4.0%
Liquid continuous release	9.1E-07	1.7E-05	8.3E-05	3.2E-04	18.8	67.5%
Vapour continuous release	1.8E-07	4.8E-06	3.5E-05	1.3E-04	26.2	28.5%
Overall	**5.0E-06**	**4.8E-05**	**1.2E-04**	**4.6E-04**	**9.6**	**100.0%**

Table 5-11 Accident outcome frequencies of the LH_2 storage at depot

Release Scenarios	**Accident Outcomes**	**Conditional Probability on Release**	**5%**	**50%**	**Mean**	**95%**
Instantaneous	Early explosion	0.0072	3.6E-08	3.4E-07	8.8E-07	3,3E-06
	Fireball	0.0287	1.4E-07	1.4E-06	3.5E-06	1,3E-05
	Pool fire	0.0005	2.5E-09	2.4E-08	6.3E-08	2,3E-07
	Late explosion	0.0000	1.1E-11	1.1E-10	2.8E-10	1,1E-09
	Flash fire	0.0000	4.6E-11	4.4E-10	1.1E-09	4,2E-09
Continuous	Jet Fire	0.4801	2.4E-06	2.3E-05	5.9E-05	2,2E-04
	Pool fire	0.0768	3.8E-07	3.7E-06	9.4E-06	3,5E-05
	Late Explosion	0.0017	8.6E-09	8.3E-08	2.1E-07	7,9E-07
	Flash Fire	0.0069	3.5E-08	3.3E-07	8.5E-07	3,2E-06
No effect		0,3957	2.0E-06	1.9E-05	4.9E-05	1.8E-04
Overall		**0,9976**	**2.3E-05**	**8.8E-05**	**1.2E-04**	**3.4E-04**

The accident outcome frequencies of the above initial frequencies were calculated by multiplying the expected frequencies with the outcome probabilities resulting from the event tree diagram for LH_2 release (Fig. 4.5), and the result is shown in Table 5-11. The table shows that most of the accident outcomes (which account for 59%) are dominated by fire, and only 1% of this may result in explosion. The rest (about 40%) of the accident may have no effect to the population.

5.3.3 Hydrogen Filling Station (LH_2)

Similar to the previous object (5.3.2) the expected frequency of the accident scenarios considered for the LH_2 storage at the hydrogen filling station was synthesised from the component failure data associated with each of the identified failure modes, using the FTA approach. Three fault tree diagrams were fully reproduced, and are shown in Appendix G3. They include: (1) instantaneous release of the hydrogen due to tank rupture (Fig. G3.1); (2) continuous release of hydrogen in the liquid phase (Fig. G3.2); and (3) continuous release of hydrogen in the vapour phase (Fig. G3.3).

In general, the fault trees developed for the filling station are similar to those for LH_2 at the depot. The storage operations, however, involve more human activities than the one of storage at depot, especially, during loading and unloading activities. Therefore, human error in the filling station may highly contribute to the Top events.

Table 5-12 Expected frequencies of the LH_2 storage at filling station (/yr)

Failure modes	**5%**	**50%**	**Mean**	**95%**	**K-95**	**Percentage**
Instantaneous release	6,0E-09	2,8E-07	4,3E-06	1,3E-05	46,7	0,6%
Liquid continuous release	1,5E-05	1,9E-04	6,2E-04	2,4E-03	12,7	86,8%
vapour continuous release	8,9E-07	1,7E-07	9,0E-05	3,4E-04	26,2	12,6%
Overall frequency (/yr)	**4,7E-05**	**3,4E-04**	**7,1E-04**	**2,5E-03**	**7,3**	**100,0%**

Table 5-13 Accident outcome frequencies of the LH_2 storage at filling station (/yr)

Release Scenarios	**Accident Outcomes**	**Conditional Probability on Release**	**5%**	**50%**	**Mean**	**95%**
Instantaneous	Early explosion	0,0011	5,1E-08	3,7E-07	7,7E-07	2,7E-06
	Fireball	0,0043	2,0E-07	1,5E-06	3,1E-06	1,1E-05
	Pool fire	0,0000	5,5E-10	3,9E-09	8,3E-09	2,9E-08
	Late explosion	0,0000	2,5E-12	1,8E-11	3,7E-11	1,3E-10
	Flash fire	0,0000	9,8E-12	7,1E-11	1,5E-10	5,2E-10
Continuous	Jet Fire	0,4970	2,3E-05	1,7E-04	3,6E-04	1,2E-03
	Pool fire	0,0795	3,7E-06	2,7E-05	5,7E-05	2,0E-04
	Late Explosion	0,0018	8,4E-08	6,1E-07	1,3E-06	4,5E-06
	Flash Fire	0,0072	3,4E-07	2,4E-06	5,1E-06	1,8E-05
No effect		0,4086	1,9E-05	1,4E-04	2,9E-04	1,0E-03
Overall frequency (/yr)		**0,9994**	**1,7E-04**	**5,5E-04**	**7,1E-04**	**1,8E-03**

The frequencies were estimated by assigning to each basic event of the fault trees the associated equipment failure rates or probabilities given in Table G3 (Appendix G). The summary result of the top event frequencies is presented in the Appendix G3, and is also shown in Table 5-12. The table shows that the overall expected frequency of the loss of containment of hydrogen from the LH2 tank at the fuelling station is 4.7 x 10-4 /year (once per 2,146 years), with the instantaneous and continuous release are 7.7 x 10-6 /year (once per 129,870 years) and 4.6 x 10-5 /year (once per 2,182 years), respectively.

The accident outcome frequencies of the above frequencies calculated by multiplying the expected frequencies with the outcome probabilities resulted from the event tree diagram for LH_2 release (Fig. 4.5). The result (Table 5-13) shows that most of the accident may result in fire outcomes (about 59%), and only about 1% may result in explosion. The rest (about 40%) may have no effect to the population.

5.3.4 CHP Plant (LH_2)

Similar to the previous plant (5.3.2) the expected frequency of the accident scenarios considered for the LH_2 storage at the CHP plant was synthesised from the component failure data associated with each of the identified failure modes, using the FTA approach. Three fault tree diagrams were fully reproduced, and are presented in Appendix G4. They include: (1) instantaneous release of hydrogen (Fig. G4.1); (2) continuous release of hydrogen in the liquid phase (Fig. G4.2); and (3) continuous release of hydrogen in the vapour phase (Fig. G4.3).

In general, the fault trees are similar to those for previous object (as described for the LH_2 storage plants). They are different as to component types and their arrangements. In order to protect it against overpressure the tank is equipped with two set of safety valves and rupture disks are installed in parallel. Therefore, the fault tree introduces common cause failure (CCF) events. Besides, to protect the tank from underpressure rupture (implosion), the tank is equipped with pressure control PCV-2 that closes the outlet lines automatically (i.e. it is triggered by TSL) in case the tank pressure is low.

The expected frequencies for the LH_2 at CHP plant were estimated by assigning to each basic event of the fault trees the associated equipment failure rates or probabilities given in Table G4 (Appendix G). Summary of the expected frequency results is presented in the Appendix G4, and is also shown in Table 5-14.

Table 5-14 Expected frequencies of the LH_2 storage at CHP plant(/yr)

Failure modes	5%	50%	Mean	95%	K-95	Percentage
Instantaneous release	3,9E-07	3,1E-06	6,9E-06	2,5E-05	8,0	4,8%
Liquid continuous release	8,3E-07	1,6E-05	8,4E-05	3,2E-04	19,7	58,8%
vapour continuous release	2,3E-07	6,6E-06	5,2E-05	1,9E-04	28,3	36,4%
Overall frequency (/yr)	**5,1E-06**	**5,2E-05**	**1,4E-04**	**5,4E-04**	**10,3**	**100,0%**

Table 5-15 Accident outcome frequencies of the LH_2 Storage at CHP plant (/yr)

Release Scenarios	Accident Outcomes	Conditional Probability on Release	5%	50%	Mean	95%
Instantaneous	Early explosion	0,0087	4,4E-08	4,5E-07	1,2E-06	4,7E-06
	Fireball	0,0348	1,8E-07	1,8E-06	5,0E-06	1,9E-05
	Pool fire	0,0007	3,8E-09	3,9E-08	1,1E-07	4,0E-07
	Late explosion	0,0000	1,7E-11	1,7E-10	4,8E-10	1,8E-09
	Flash fire	0,0000	6,8E-11	7,0E-10	1,9E-09	7,3E-09
Continuous	Jet Fire	0,4759	2,4E-06	2,5E-05	6,8E-05	2,6E-04
	Pool fire	0,0761	3,9E-07	4,0E-06	1,1E-05	4,1E-05
	Late Explosion	0,0017	8,7E-09	8,9E-08	2,4E-07	9,3E-07
	Flash Fire	0,0069	3,5E-08	3,6E-07	9,8E-07	3,7E-06
No effect		0,3927	2,0E-06	2,0E-05	5,6E-05	2,1E-04
Overall frequency (/yr)		**0,9975**	**2,4E-05**	**9,9E-05**	**1,4E-04**	**4,0E-04**

Table 5-14 shows that the overall expected frequency of the loss of containment of hydrogen from the LH_2 tank at the CHP plant is 4.3 x 10^{-5} /year (once per 23,148 years), with the instantaneous and continuous release are 6.2 x 10^{-6} /year (once per 161,290 years) and 5.7 x 10^{-5} /year (once per 27,027 years), respectively. The table also shows that only 14.4% of the release from the LH2 tank may occur instantaneously, and the rest (85.6%) may release continuously.

The accident outcome frequencies of the above hydrogen release incident were calculated by multiplying the expected frequencies (Table 5-14) with the outcome probabilities resulted from the event tree diagram for LH_2 release (Fig. 4.5). The result is shown in Table 5-15. The table shows that the fire mostly dominate of the accidents outcomes with account for about 61%, and only about 3% of the accident may result in explosion. The rest (about 36%) of the accidents may result no effect to the population.

5.3.5 Hydrogen Private Car (LH_2)

The second approach (i.e. using historical failure rate data) has been used to estimate the overall failure frequencies of the on-board storage tank in the private car. The reason is that according to experience of the past [2], a flammable release resulting from a road accident can be more significant than from normal operation. Therefore, the release frequency of the onboard hydrogen storage used in the study was extracted from the vehicle road accident data.

The road traffic accident rates for Germany can be calculated from the road accident data (Chapter 2) by using of Eq. 4-5. The results (Table 5-16) show that the overall road traffic accident rate for Germany (2003) is 3.31 x 10^{-6} accidents/vehicle-km. the results is comparable with a typical value given in reference (see 4.4.3.1).The annual distance for a given vehicle was calculated from Table 2-5 and Table 2-6. The results (Table 5-17) show that the annual distance travelled by a private car in Germany (2003) is 12,900 km/veh.yr.

The expected frequency of hydrogen release from the onboard storage in a private car can be calculated by using Eq. 4-6, and the private car data in Table 5-16 and Table 5-17. Assuming that the overall chance of hydrogen release from the storage is 0.02 (one accident in 50 results in a release), the calculated release frequency of the onboard hydrogen storage is about 7.1 x 10^{-4} per year (once in 1408 years). Assuming that 20% of the release may lead to a catastrophic failure (instantaneous release), the incident frequencies of the continuous and instantaneous scenarios are shown in Table 5-18.

Furthermore, by multiplying the above initial frequencies with the outcome probabilities resulting from the event tree analysis (Fig.4.5), the associated outcome frequencies are shown in Table 5-19. The table also shows that the fire outcomes may dominate the accidents from the onboard hydrogen storage, which accounted for about 62%. Only about 4% of the accidents may lead to an explosion and the rest (about 35%) has no effect on the population.

Table 5-16 Road traffic accident rate (accidents/10^6 veh.km) for Germany

Vehicle Type	1990	1995	2000	2001	2002	2003
Private cars (incl. Stationwagons)	3.53	3.05	3.00	2.90	2.77	2.76
Buses (incl. Trolleys)	0.01	0.01	0.01	0.01	0.01	0.01
Trucks	0.16	0.17	0.17	0.17	0.16	0.16
Tractor-trailers	0.01	0.01	0.01	0.01	0.01	0.01
Motor cycles (incl. Mofas, mopeds)	0.14	0.16	0.19	0.19	0.19	0.19
Micscellaneous	0.26	0.20	0.21	0.20	0.19	0.19
Total	**4.12**	**3.58**	**3.54**	**3.48**	**3.33**	**3.31**

Table 5-17 Annual distance each type of vehicles (x1000 km/veh.yr) for Germany

Total Distance	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**
Private cars (incl. Stationwagons)	14.1	13.2	13.060	13.0	13.1	12.9
Buses (incl. Trolleys)	44.1	42.9	43.237	42.7	42.2	42.0
Trucks	23.8	23.8	23.230	22.8	22.1	22.2
Tractor-traillers	74.2	78.2	80.661	77.5	76.5	79.1
Motor cycles (incl. Mofas, mopeds)	7.0	6.6	6.072	6.1	5.4	5.4
Micscellaneous	2.7	3.7	3.855	3.8	3.9	4.0
Total	**165.8**	**168.4**	**170.1**	**166.0**	**163.2**	**165.4**

Table 5-18 Expected frequencies of the onboard LH_2 storage in private car

Release Type	**Frequency (/yr)**	**Percentage**	**Source**
Instantaneous	1,4E-04	19,7%	Estimated based on the accident rate data
Continuous	5,7E-04	80,3%	
Overall	**7,1E-04**	**100,0%**	

Table 5-19 Accident outcome frequencies of the onboard LH_2 storage in private car

Release Type	**Conditional Probability on Release**	**Outcome Probability**	**Outcome Frequency (/yr)**
Instantaneous	Early Explosion	0,0360	2,6E-05
	Fireball	0,1440	1,0E-04
	Pool fire	0,0064	4,5E-06
	Late explosion	0,0000	2,0E-08
	Flash fire	0,0001	8,2E-08
Continuous	Jet fire	0,4000	2,8E-04
	Pool fire	0,0640	4,5E-05
	Late explosion	0,0014	1,0E-06
	Flash fire	0,0058	4,1E-06
No effect		0,3423	2,4E-04
Overall		**1,0000**	**7,1E-04**

5.3.6 Road Tanker Truck (LH_2)

Similar to the onboard storage in the passenger car, the overall failure frequencies of the LH_2 tanker truck was derived from the traffic accident data. Table 5-16 shows that the accident rate of a road transport by truck in Germany is about 1.6 x 10^{-7}/veh.km. As for comparison the truck accident rates (average values) for California, Illinois, and Michigan are 1.5 x 10^{-6} /veh.km for rural area and 5.8 x 10^{-6} /veh.km for urban area (see Table 4-2).

As described in the section 3.4.2, the study considered an LH_2 truck delivery from a hydrogen plant to the eleven hydrogen filling stations situated in a small city with the roundtrip distance of about 215 km. The route is broken into two segments, i.e. 200 km of the route along rural population and 15 km inside the city. Based on the above information the initiating frequencies of the accident scenarios for the two route segments can be calculated by applying Eq. 4-7. The results (Table 5-20) shows that the initiating frequencies of hydrogen release from the LH_2 tanker truck along the distance of 215 km is 1.6 x 10^{-7}/yr. Assuming that the conditional release probability for given accident is 0.02, the estimated associated release frequencies of the two segments (i.e. 200 km and 15 km) are 6.4 x 10^{5}/yr (once per 15,625 years), and 4.8 x 10^{-6}/yr (once per 208,333 years), respectively.

Table 5-20 Expected release frequencies of the LH_2 truck for given routes

Route Segment	Truck Accident Rate (/veh.km)	Release Probability	Segment Distance (km)	Trip Number(/yr)	Initiating Frequency (/yr)
1	1,60E-07	0,02	200	100	6,4E-05
2			15	100	4,8E-06

Table 5-21 Accident outcome frequencies of the LH_2 Truck for given routes

Segment Route	Release Type	Outcome Types	Outcome Probabilities	Frequencies (/yr)
Segment1	Instantaneous	Early Explosion	0,0360	2,3E-06
		Fireball	0,1440	9,2E-06
		Pool fire	0,0064	4,1E-07
		Late Explosion	0,0000	1,8E-09
		Flash Fire	0,0001	7,4E-09
	Continuous	Jet Fire	0,4000	2,6E-05
		Pool fire	0,0640	4,1E-06
		Late Explosion	0,0014	9,2E-08
		Flash Fire	0,0058	3,7E-07
No effect segment 1			0,3423	2,2E-05
Overall segment 1			**1,0000**	**6,4E-05**
Segment 2	Instantaneous	Early Explosion	0,0360	1,7E-07
		Fireball	0,1440	6,9E-07
		Pool fire	0,0064	3,1E-08
		Late Explosion	0,0000	1,4E-10
		Flash Fire	0,0001	5,5E-10
	Continuous	Jet Fire	0,4000	1,9E-06
		Pool fire	0,0640	3,1E-07
		Late Explosion	0,0014	6,9E-09
		Flash Fire	0,0058	2,8E-08
No effect segment 2			0,3423	1,6E-06
Overall segment 2			**1,0000**	**4,8E-06**

Outcome frequencies are calculated by multiplying the expected initiating frequency (Table 5-20) with the outcome probabilities resulting from the event tree diagram (Fig. 4.5). Table 5-21 shows the outcome frequencies of the two above initiating frequencies assuming that 20% of the release may result in a catastrophic rupture (instantaneous release). This table also shows that the hydrogen release for a given truck accident may lead mostly to fires (which accounted for about 62%), and only about 4% may lead to explosions. The remaining (about 34%) of the releases may has no effect on the population.

5.3.7 Hydrogen Pipeline (GH_2)

The expected frequency of the GH_2 pipeline is estimated from the base failure rate for the pipelines given in Table 4-5. It allows one to focus on the likelihood of holes and ruptures. These rates now need to be adjusted to the increased wall thickness used for this pipeline as compared to the typical wall thickness for this diameter. Table 5-22 shows reduction factors of the failure rates for pipe rupture and holes recommended by [3]. The factors were judged based on the benefits of increased wall thickness and surveillance. The likelihood of a rupture or hole was judged to decrease by a factor of roughly 0.7 overall. Looking at individual causes, external interference and material failure/construction defects were also found to decrease by a factor of roughly 0.7. The likelihood of a corrosion-induced failure doubled while other causes were considered only half as likely. Given that a special surveillance system is to be put into place, whereby the pipeline right-of-way will be visually checked once a day, the likelihood of an external interference event is expected to be reduced. Since it is possible that a repair or construction crew could get set up between line surveys, and because some external interference events are due to natural causes that are not affected by the line surveillance, only a 50 percent credit is given. For example, rupture and hole by external interference (in Table 4-5) have been corrected as: ruptures is equal to 3.3 x 10^{-5} /km-year (i.e. 9.8 x 10^{-5} /km-year x 0.35); and holes is equal to 7.4 x 10^{-5} /km-year (i.e. 2.1 x 10^{-4} /km-year x 0.35). With the same procedure, the result is shown in Table 5-23.

Table 5-22 Reduction factors for failure rates for rupture and hole [3]

Causes of the Pipe failure	Wall Thickness	Surveillance	Total reduction factor
External interference	0.7	0.5	0.35
Corrosion	1.0	1.0	1.0
Material failure/construction defect	0.7	1.0	0.7
Other	1.0	0.5	0.5

Table 5-23 Estimated failure rates of GH_2 pipeline for rupture and hole [/km-yr]

Size	External Interference	Corrosion	Material failure/ construction defects	Others	Total
Rupture	3.4E-05	1.3E-06	9.2E-06	2.0E-06	4.7E-05
Hole	7.4E-05	1.4E-06	2.2E-05	1.2E-04	2.2E-04
Total	**1.1E-04**	**2.7E-06**	**3.1E-05**	**1.3E-04**	**2.7E-04**

Table 5-24 Expected release frequency of the GH_2 pipeline [/yr]

Release size	External Interference	Corrosion	Material fail/ const. defects	Others	Total	Percentage
Pipe rupture	3.6E-05	1.3E-06	9.6E-06	2.1E-06	4.9E-05	32.9%
Hole in the pipe	7.7E-05	1.4E-06	2.3E-05	6.5E-07	1.0E-04	67.1%
Total	**1.1E-04**	**2.7E-06**	**3.3E-05**	**2.8E-06**	**1.5E-04**	**100.0%**

Table 5-25 Accident outcome frequencies of the GH_2 pipeline

Release Size	Incident Outcomes	Conditional Probabilities on Release	Outcome Frequencies (/yr)
Pipe rupture	Jet Fire	0.164	2.5E-05
	Late Explosion	0.015	2.2E-06
	Flash Fire	0.059	8.8E-06
Hole in the pipe	Jet Fire	0.336	5.0E-05
	Late Explosion	0.030	4.5E-06
	Flash Fire	0.121	1.8E-05
No effect		0.275	4.1E-05
Overall		**1.000**	**1.5E-04**

The general calculation procedure for pipelines involves multiplying a pipeline failure rate per km-year (Table 5-23) by the pipeline length and by a release probability, which might be the chance of a significant release. Thus, the overall frequency of a release is calculated using Eq. 4-8. Assumed that the conditional probability for release is 0.02, the release frequency of the GH_2 pipeline with a length of 53 km is given in Table 5-24. This table shows that the total failure rate of the pipeline is 1.5 x 10^{4} /yr (once per 6,666 years). This table also shows that the probability of the pipe rupture (32.9%) is less than that for leak in the pipe (67.1%).

The accident outcome frequencies were calculated by multiplying the expected initiating frequency (Table 5-24) with the outcome probabilities resulting from the event tree diagram (Fig. 4.6) for the continuous release. Table 5-25 shows that the fire mostly dominates the accident outcomes (accounting for 68%). Only 4.5% of the accident outcome may lead to an explosion and the remaining (27.5%) of the accidents have no effect on the population.

5.4 CONSEQUENCES MODELLING RESULTS

The consequence analyses that are passed to the impact calculations give the shapes and sizes of the different effect zones. For some impacts the results may be independent of weather conditions. For other impact there is a separate result for each weather condition. For example, the effect zone shape of BLEVE/fireball is a circle and is weather independent. Therefore, the effect zone is centred at the release point. This section presents the consequence modelling results for the hydrogen study objects by using PHAST Professional 6.4 (DNV). The procedure employed in the consequence computations is summarized in Section 4.5. The study considered three weather conditions that are available in PHAST model and recommended by the TNO [159] i.e. weather category of 1.5/F, 1.5/D, and 5.0/D. These weather categories represent wind speed and Pasquill stability, respectively.

This section presents a variety of results for accident outcomes of the hydrogen release (loss of containment, LOC) from the study objects described in chapter 3. These include results of dispersion and fire and explosion models. Dispersion models are presented as various graphs of dispersed hydrogen vapour cloud concentrations. Meanwhile, fire and explosion models are presented as thermal radiation flux and shock wave overpressure impacts, respectively. These models rely on the general principle that severity of the outcome is a function of distance from the source of release, called effect distance (*z*). The assessment of the effects on humans is presented in the risk calculation section (5.5).

The effect distances from the fire and explosion models are presented for different fatality levels (e.g. 1%, 10%, or 100%). These fatality levels are set based on the probit equation for thermal impact given in Eq. 4-11 (fire models), and Table 4-14 for overpressure impacts (explosion models). The maximum effect distance (*z*) of the outcomes is calculated as the sum of the downwind radius (*a*) and downwind distance (i.e. distance of the circle centre from the release centre, *x*) or $z= a+x$. The downwind distance (*x*) is equal to downwind radius (*a*) multiplied with the offset ratio (*d*), or $x=a*d$. The effect zone centred at the release point ($d=0$), the *x* is equal to zero. Therefore the maximum effect distance is equal to its downwind radius, $z=a$.

Due to a problem which may arise in distinguishing many curves in one graph, most of the consequence graphs show curves for two study objects only. They include GH_2 storage at production plant (object 1) and LH_2 storage at the CHP plant (object 5). All consequence calculation results, however, are presented in the associated tables.

5.4.1 Dispersion

Accidental release of gaseous hydrogen or spillage of liquid hydrogen lead to evolution and dispersion of a gas could whose shape is influenced by the type and rate of release and by atmospheric conditions as well as by topography. There are several concentration graphs generated by PHAST, each of which shows a different aspect of the concentration profile for the cloud. These graphs are generated from the source models, and the dispersion report shows the details of the values plotted in the graphs. These include maximum concentration on footprint, side view, and centreline concentration.

Fig. 5.1 shows the movement of the cloud in the downwind direction both for continuous (steady state) and instantaneous dispersion. It presents different shapes of the contours inside the cloud, seen from the side through the centreline of the cloud for two example study objects (i.e. object 1 and object 5), and weather 1.5/F. Hydrogen is the lightest of all gases and tends to rise. For liquid hydrogen, however, the density of the saturated hydrogen vapour at the boiling point is higher than air density. It is therefore negatively buoyant when it first evaporates. The heat capacity of saturated hydrogen vapour is very small and the temperature is raised quickly and the buoyancy changes to neutral and positive.

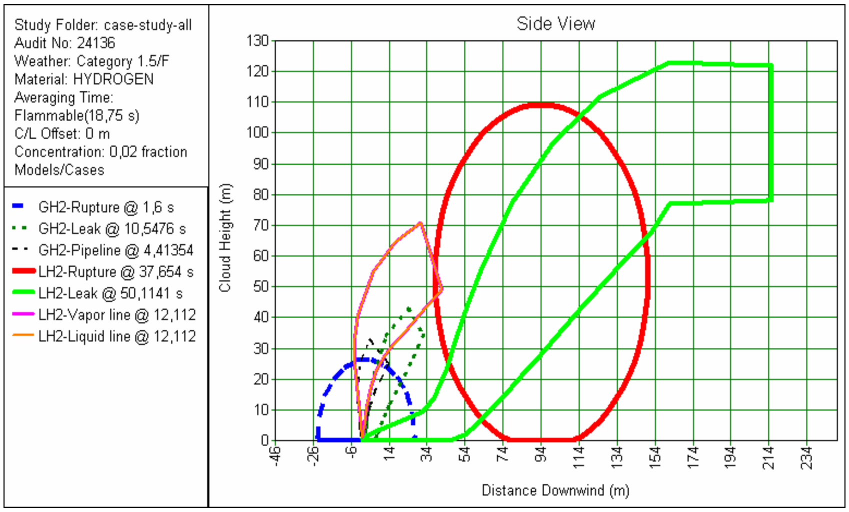


Figure 5.1 Side view of the hydrogen release for the two study objects (1 & 5)

The concentration through the centre line of the cloud at a given time, as a function of distance downwind is shown in Fig. 5.2. All of the concentration graphs show the concentration at a given time, since the shape of the contours will change over the course of the dispersion, as the cloud moves with the wind and air is entrained.

Fig. 5.3 shows the maximum concentration footprint of the hydrogen release inside the cloud. It shows the calculated distributions of hydrogen concentration. The outer boundary indicates the LFL fraction of the lower flammability limit concentration (2%). Similar to the previous graph it is plotted for two study objects and weather 1.5/F only. Two different concentration profiles of the cloud from different release scenarios (i.e. continuous and instantaneous) can also be seen in this picture.

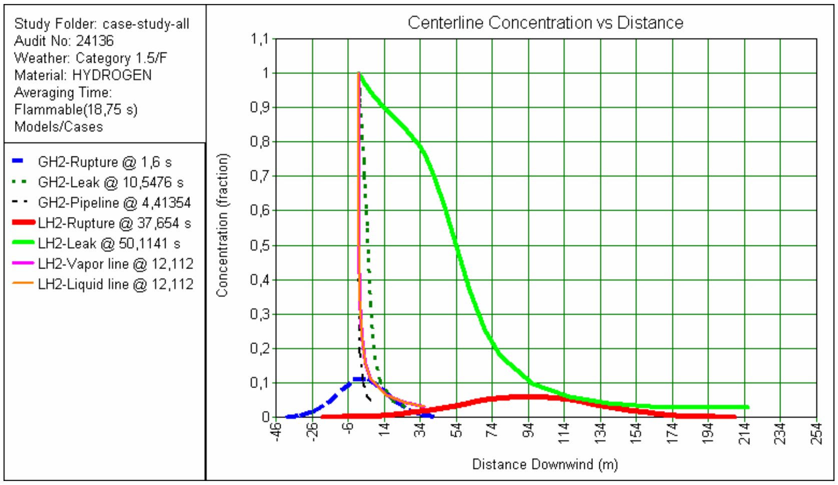


Figure 5.2 Centre line concentration for the two study objects (1 & 5)

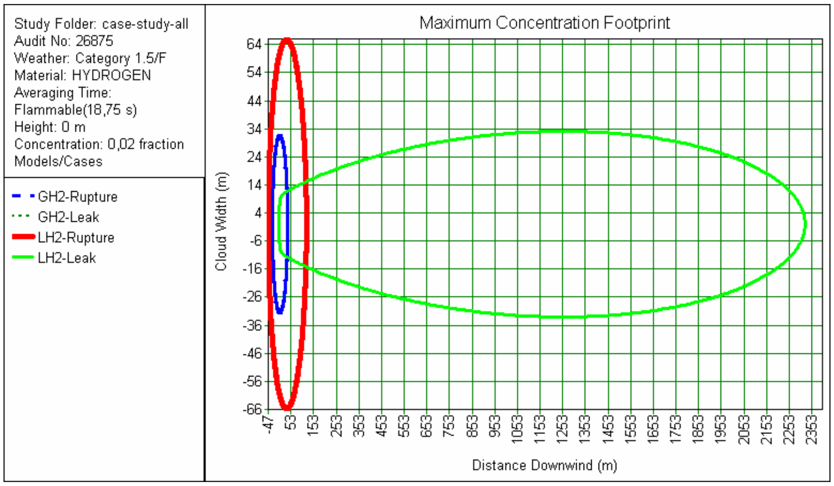


Figure 5.3 Footprint of the hydrogen release for a concentration of 2% and different event

A minimum concentration of the dispersion results for a flammable material would normally specify some fraction of the lower flammability limit (LFL fraction). The LFL fraction to finish means the concentration (as a fraction of the LFL) that determines the maximum distance at which a flammable cloud can be ignited. Typical values are full (100%) and a half (50%) of the LFL (i.e. 0.04 fraction). The 50% will give more conservative results, and can be used to include the effects of imperfect mixing, which may give local concentration higher than those predicted by the dispersion modelling. Therefore, the hydrogen release with its LFL of 4% the concentration interest may be set to 0.02 fractions (2%). Alternatively, for flammable release, PHAST will automatically continue dispersion until it reaches the LFL fraction to finish set in the flammable parameter. Additionally, it can be used in setting the location for delayed explosions and the area covered by a flash fire [49].

5.4.2 Fire and Explosions

PHAST automatically generates the existing fires and explosions models as long as the material is flammable. This section presents a summary of the consequence calculation results for the study objects presented both in the form of tables and graphs. Each of the models is presented by two graphs and a table, each of which shows thermal or overpressure impacts from different study objects. The first graph shows thermal radiation or peak overpressure levels vs downwind distances, and the second graph presents their lethality radii.

4.4.2.1 Jet Fire

Jet fires are mainly generated by any flammable containments leading to continuous releases (e.g. tank leak, pipe rupture, etc). PHAST will automatically calculate the jet fire impacts for given continuous models set by the user. The jet fire impact is thermal radiation (kW/m^2) presented as table and graph such as a distance graph and fatality radii. Figure 5.4 shows the radiation levels (in kW/m^2) for the jet fire as a function of distance downwind (in m) for two study objects and the weather category of 1.5/F. The radiation level is measured at the height of the release point used for the calculation of effects. Assuming that the orifice area in the tank (hole) is equal to the largest pipe diameter, the graph shows that the undesired events of tank leak dominate all of the system hazards. Furthermore, a larger inventory of hydrogen may results in a larger jet fire impact. The radiation levels remain constant for some downwind distance, and immediately drop to the lowest level.

Figure 5.5 shows the 1% lethality radii for the jet fire radiation impacts resulting from the tank leak events of the two hydrogen study objects. The graph shows that the fatal effect zone of a jet fire is presented as an ellipse centred on the release point. The fatality levels are calculated using the probit equation for thermal radiation impact from jet fires. The 1% fatality is equal to thermal radiation of 18.2 kW/m^2 or probit level of 2.7 (see Table 4-10).

Table 5-26 shows the effect zones of the jet fire impacts for the seven hydrogen study objects for different fatality levels (of 1%, 10%, and 56%), and for the weather category of 1.5/F. The risk calculation, however, includes the jet fire impacts for all weather categories. The fatal effect-zone of a jet fire is modelled as an ellipse (4.5.5.4) centred at the release point (*d*=0). Axes *a* and *b* are the major and minor axes of the ellipse, and *d* is the relative offset of the ellipse centre from the release point defined as the ratio *x/a* where *x* is the distance from the release point to the ellipse centre. The effect distance (z) is calculated as the sum of downwind radius (*a*) and the downwind distance (*x*) from the release location. The table also shows that the study objects of GH_2 pipeline did not reach the minimum fatality level (i.e. 1%).

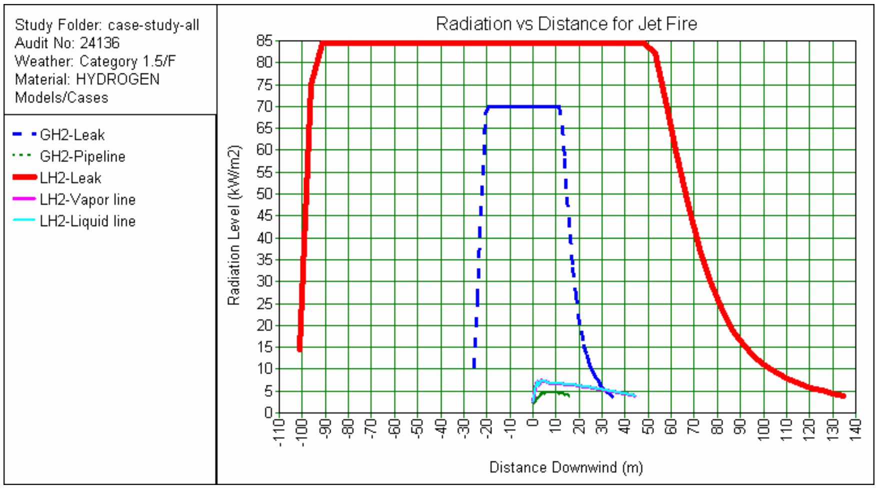


Figure 5.4 Radiation vs distance for jet fire for different release events

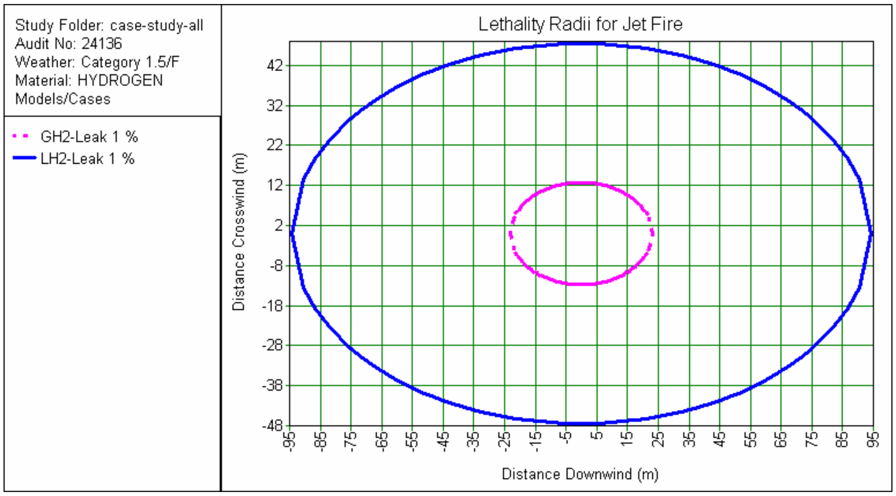


Figure 5.5 Effect zones (1% fatality) of the jet fires for GH_2 (solar) and LH_2 (CHP)

4.4.2.2 Fireball

Fireball is mainly generated from any flammable (e.g. hydrogen) containment leading to instantaneous releases (e.g. tank rupture). PHAST calculates a wide range of thermal radiation impacts (kW/m^2) resulted from a fireball. The fireball impacts are presented both in tables and graphs such as a distance graph, fatality radii, and so on. The distance graph shows the radiation level for the fireball as a function of the downwind distance. The radiation level is measured at the height of the release point used for the effect calculations. Figure 5.6 shows the radiation levels versus distance for fireballs for two study objects only and for all weathers. The fifth object (LH$_2$ storage at CHP) gives greater fireball impact than the first object (GH$_2$ storage at production plant). The radiation levels dramatically decrease with an increase of the distance from the release location.

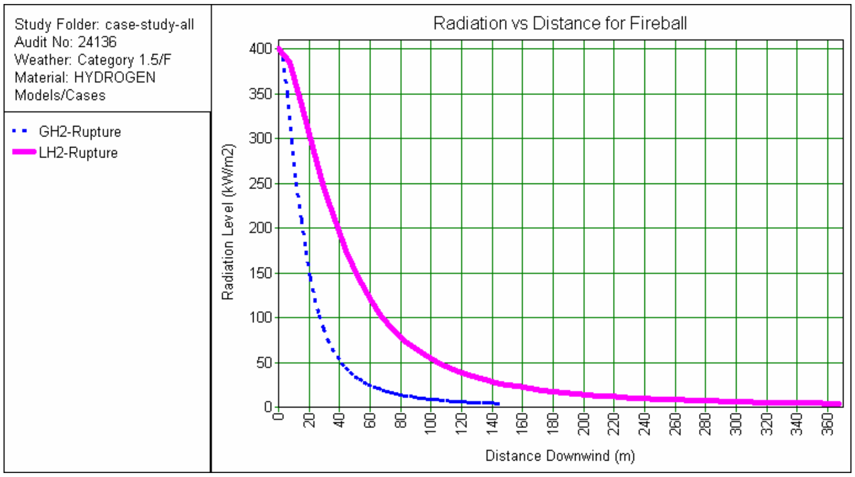


Figure 5.6 Radiation vs distance of the fireball for the two hydrogen study objects

Effect zones of the fireball are presented as a circle or ellipse centred at the release point, and weather independence. Figure 5.7 shows the radii or ellipses for 1% fatalities resulting from fireball radiation. It plots the fatality levels resulting from fireball calculated using the probit equation 4-8. This measure takes fireball duration (t) into account in calculating the potential fatality effects. Therefore, fatality level (%) from the fireball is proportional to different values of thermal radiation (kW/m^2), and depends on the fireball duration. For example, in Table 5-27 it shows that 1% fatality (probit value of 2.7) proportional to different intensity levels.

Table 5-27 presents the fireball impacts for the all study objects, for different fatality levels (of 1%, 10%, and 56%), and for all weather categories. The effect distance (z) of fireball is equal to its downwind radius, because the fireball centre is in the release point and weather independent. The seventh object (GH$_2$ pipeline) is not assumed to produce a fireball, because the release from the object is classified as continuous.

Table 5-26 Thermal impacts of jet fires for the hydrogen plants (Weather 1.5/F)

Study Objects	Consequence	Units	Fatality level (probit)		
			1%(2.7)	10%(3.7)	56%(5.1)
Intensity level (I)		kW/m^2	18.2	24.7	37.5
Exposure time (t)		s	20	20	20
1 (Solar)	Downwind semi-axis (a)	m	22.6	21.4	19.6
	Crosswind semi-axis (b)	m	12.5	9.5	6.4
	Offset ratio (d)	-	0.0	0.0	0.0
	Effect distance (z)	m	22.6	21.4	19.6
2 (Depot)	Downwind semi-axis (a)	m	114.9	110.6	105.1
	Crosswind semi-axis (b)	m	59.2	44.9	30.6
	Offset Ratio (d)	-	0.0	0.0	0.0
	Effect Distance (z)	m	114.9	110.6	105.1
3 (FS)	Downwind semi-axis (a)	m	73.1	70.2	66.3
	Crosswind semi-axis (b)	m	34.8	26.1	17.4
	Offset Ratio (d)	-	0.0	0.0	0.0
	Effect Distance (z)	m	73.1	70.2	66.3
4 (Car)	Downwind semi-axis (a)	m	26.7	25.3	23.2
	Crosswind semi-axis (b)	m	11.0	8.2	5.5
	Offset Ratio (d)	-	0.0	0.0	0.0
	Effect Distance (z)	m	26.7	25.3	23.2
5 (CHP)	Downwind semi-axis (a)	m	94.3	70.1	66.2
	Crosswind semi-axis (b)	m	47.4	26.1	17.4
	Offset Ratio (d)	-	0.0	0.0	0.0
	Effect Distance (z)	m	94.3	70.1	66.2
6 (Truck)	Downwind semi-axis (a)	m	73.0	70.2	66.2
	Crosswind semi-axis (b)	m	34.7	26.1	17.4
	Offset Ratio (d)	-	0.0	0.0	0.0
	Effect Distance (z)	m	73.0	70.2	66.2
7 (Pipeline)	Downwind semi-axis (a)	m	n.r.	n.r.	n.r.
	Crosswind semi-axis (b)	m	n.r.	n.r.	n.r.
	Offset Ratio (d)	-	n.r.	n.r.	n.r.
	Effect Distance (z)	m	n.r.	n.r.	n.r.

Notes: n.r. = not reached; probit uses exposure time (t) = 20 s (for flammable materials)

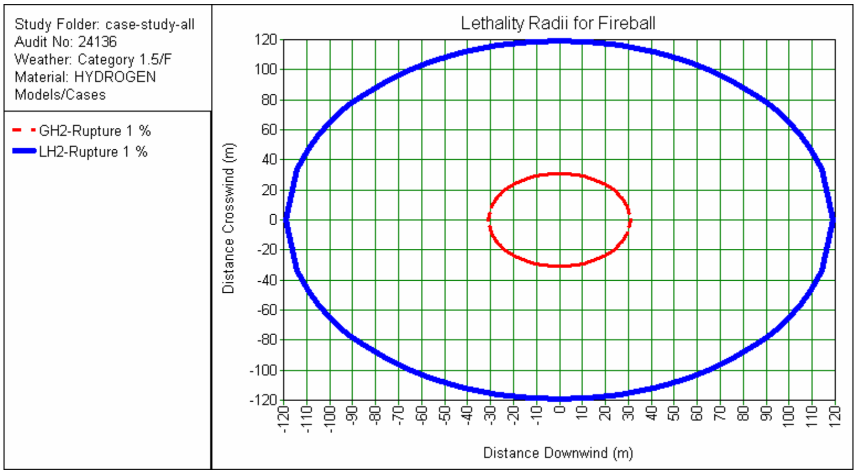


Figure 5.7 Effect zones (1% fatality) of the fireball for the two hydrogen study objects

4.4.2.3 Flash Fire

Flash fires are treated in different ways depending on the types of release. Flash fires resulting from instantaneous releases (e.g. tank rupture) are represented as circular cloud indicating the radius of the LFL fraction (2%) to finish (see section 4.5.5.2). The circle starts centred at the release point and then proceeds to drift downwind. For continuous releases the flash fire effect zone is taken to be the cloud boundary to the LFL fraction represented as an ellipse. There is also the possibility that the ellipse is defined as a ‘half-ellipse’ rather than the full shape. Figure 5.8 shows the maximum area covered by the flash fire envelope, i.e. the area swept out by the flash fire footprint, through all wind directions. The envelope is given for LFL (4%) and half the LFL (2%), and is at the height for calculation of effects.

Table 5-27 Thermal impact levels of the fireball for the hydrogen plants (all weathers)

Study Objects	**Consequence parameters**	**Units**	**Fatality levels (probit)**		
			1%(2.7)	**10%(3.7)**	**56%(5.1)**
1 (Solar)	Fireball duration (t)	s	3.4	3.4	3.4
	Intensity level (I)	kW/m^2	68.5	92.8	140.8
	Effect Distance (z)	m	42.9	35.4	26.3
2 (Depot)	Fireball duration (t)	s	11.4	11.4	11.4
	Intensity level (I)	kW/m^2	27.8	37.8	57.3
	Effect Distance (z)	m	217.6	185.3	61.1
3 (FS)	Fireball duration (t)	s	4.2	4.2	4.2
	Intensity level (I)	kW/m^2	59	80.2	121.6
	Effect Distance (z)	m	56.3	46.7	35.4
4 (Car)	Fireball duration (t)	s	0.8	0.8	0.8
	Intensity level (I)	kW/m^2	200.4	272.2	412.7
	Effect Distance (z)	m	4.9	3.4	n.r.
5 (CHP)	Fireball duration (t)	s	7.2	7.2	7.2
	Intensity level (I)	kW/m^2	39.0	53.0	80.4
	Effect Distance (z)	m	119.1	101.0	78.7
6 (Truck)	Fireball duration (t)	s	7.1	7.1	7.1
	Intensity level (I)	kW/m^2	39.5	53.6	81.4
	Effect Distance (z)	m	116.5	98.8	76.9

Notes: n.r. = not reached; effect distance (z)=downwind distance; exposure time (t)=fireball duration

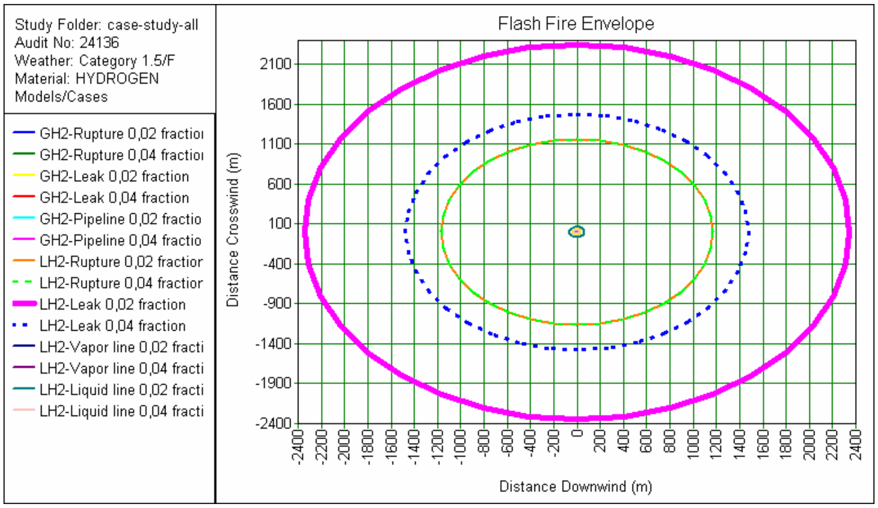


Figure 5.8 Effect zones of the flash fires for the two study objects

Table 5-28 shows effect distances resulting from flash fires for the all hydrogen study objects. They are calculated for the LFL fraction (2%), for different loss of containment events (A-F) and weather 1.5/F. Loss of containment A (except for the object no.7) presents a flash fire resulting from an instantaneous release. While the rests (B-F) presents flash fires resulting from continuous releases. The flash fire description therefore gives the size and downwind distance of the cloud at several time-steps during the time when it is developing to its fullest extent.

Table 5-28 Thermal impact of flash fire (0.02 fraction) for the hydrogen plants

Study objects	Consequence	Unit	Loss of containment events					
			A	B	C	D	E	F
1 (Solar)	LFL fraction radius	m	27.7	46.2	2.7	8.2	8.2	-
	Downwind distance	m	10.2	0.0	0.0	0.0	0.0	-
	Effect distance	m	37.9	46.2	2.7	8.2	8.2	-
2 (Depot)	LFL fraction radius	m	2483.1	279.3	15.9	15.5	17.6	48.4
	Downwind distance	m	435.2	0.0	0.0	0.0	0.0	0.0
	Effect Distance	m	2918.3	279.3	15.9	15.5	17.6	48.4
3 (FS)	LFL fraction radius	m	136.0	184.4	6.0	15.5	18.0	26.0
	Downwind distance	m	71.0	0.0	0.0	0.0	0.0	0.0
	Effect Distance	m	207.0	184.4	6.0	15.5	18.0	26.0
4 (Car)	LFL fraction radius	m	24.4	84.8	2.3	3.0	3.1	3.6
	Downwind distance	m	11.5	0.0	0.0	0.0	0.0	0.0
	Effect Distance	m	35.9	84.8	2.3	3.0	3.1	3.6
5 (CHP)	LFL fraction radius	m	1167.1	2347.0	15.9	15.5	17.6	27.9
	Downwind distance	m	358.0	0.0	0.0	0.0	0.0	0.0
	Effect Distance	m	1525.1	2347.0	15.9	15.5	17.6	27.9
6. (Truck)	LFL fraction radius	m	2739.3	184.4	13.0	15.5	17.6	120.3
	Downwind distance	m	130.0	0.0	0.0	0.0	0.0	0.0
	Effect Distance	m	2869.5	184.4	13.0	15.5	17.6	120.3
7 (Pipeline)	LFL fraction radius	m	7.9	7.3	-	-	-	-
	Downwind distance	m	0.0	0.0	-	-	-	-
	Effect Distance	m	7.9	7.3	-	-	-	-

Notes: For 1-6: A=tank rupture; B=tank leak; C=relief valve; D=rupture disc; E=vapour line, F=liquid line
For 7: A =pipeline rupture; B=Hole in the pipeline

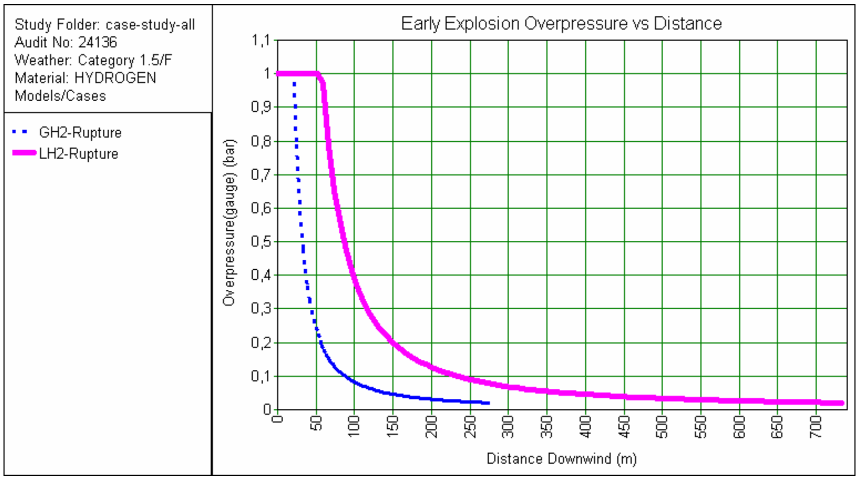


Figure 5.9 Early explosion overpressure vs distance of the two hydrogen objects

4.4.2.4 Early Explosion

An early explosion may be generated from any instantaneous release. It occurs at the beginning of the release, before the cloud has started to disperse. The main consequence of the explosion is overpressure (bar). Fig. 5.9 shows the early explosion overpressure vs distance for two study objects. The fifth object (LH_2 at CHP) shows greater impacts that than of the first object (GH_2 at production plant). Effect zones of the explosion are presented as a circle or ellipse centred at the release point, and independent of the weather conditions. Fig. 5.10 shows the effect zones in terms of overpressures radii of the early explosion for 0.021 bar (about 0.01% fatality). The fatality levels correspond to different explosion damage levels is shown in Table 4-14. For example, 1% fatality corresponds to peak overpressure of 0.14 bar, and 10% fatality correspond to 0.21 bar. Table 5-30 shows the early explosion impacts calculated by using the TNT model (in PHAST) for different fatality levels, and for the all study objects.

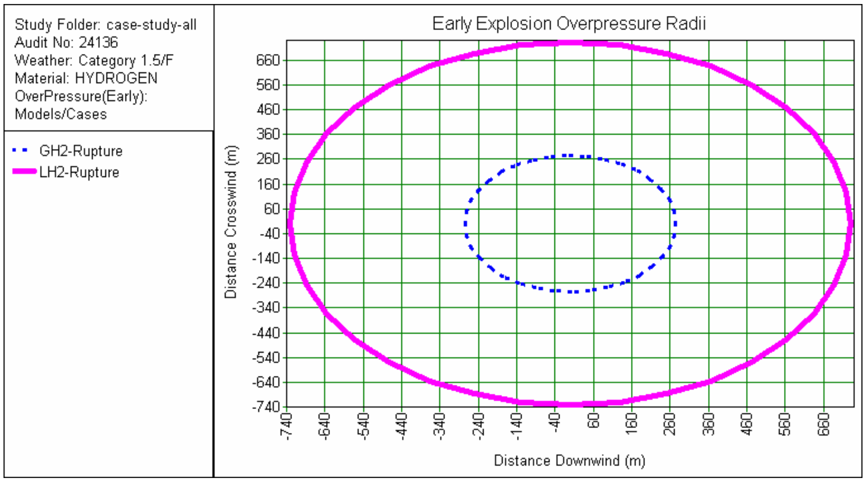


Figure 5.10 Effect zone (0.01% fatality) of the early explosion for the two study objects

Table 5-29 Early explosion impacts of the hydrogen objects

Study Objects	Consequence parameters	Units	Fatality levels (%)		
			0.01	1	10
1 (Solar)	Effect Distance (z)	m	334.4	86.7	67.0
2 (Depot)	Effect Distance (z)	m	1149.3	297.6	230.3
3 (FS)	Effect Distance (z)	m	421.3	109	84.4
4 (Car)	Effect Distance (z)	m	82.5	21.4	16.5
5 (CHP)	Effect Distance (z)	m	732.1	189.6	146.7
6 (Truck)	Effect Distance (z)	m	720.0	186.5	144.3
7 (Pipeline)	Effect Distance (z)	m	-	-	-

Notes: 0.01%=0.02 bar; 1% = 0.1379 bar; 10% = 0.2068 bar (See Section 4.5.6.2.2)

4.4.2.5 Late Explosion (VCE)

Late explosion or vapour cloud explosion (VCE) may occur if the vapour cloud is ignited before it is diluted bellow its LFL (4%). The centre of the explosion of the VCE is the cloud centre at the point downwind from the release centre at the moment of ignition. Fig. 5.11 shows the overpressure (bar) as a function of distance downwind (m) of the late explosion (VCE) resulting from different loss of containments events (LOCs) of the two objects. There is a separate overpressure curve for each release event with different profiles and explosion centre location. Overpressure resulting from the tank ruptures (both GH_2 and LH_2) increase instantaneously to the maximum peak overpressure and then decrease with the increase of distance. On other hand, the continuous releases (e.g. leak) require a certain time before peak overpressure reached, after that it begins to decrease again to zero.

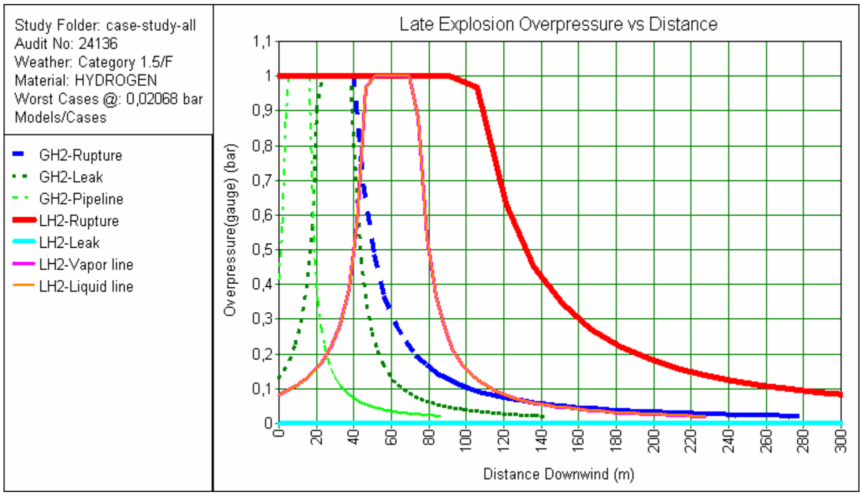


Figure 5.11 Peak overpressure vs distance of the late explosion

Effect zones of the late explosion (VCE) are calculated similar to the early explosion, except that the explosion centre is not at the centre of the release point (see 4.5.5.1). It is modelled as two concentric circles displaced from the release point. The overpressure radii of the late explosion for the time when the leading edge (for a continuous release) or the cloud centre (for an instantaneous release) reaches a given distance downwind is given in Fig. 5.12. This figure shows that the effect zones for the study objects GH_2 (solar) and LH_2 (CHP) at 0.01% fatality (0.02 bar) are 341.2 m and 741 m, respectively. Meanwhile, the explosion centre of the LH_2 leak events is located far away from the release centre, but it results in a small zone.

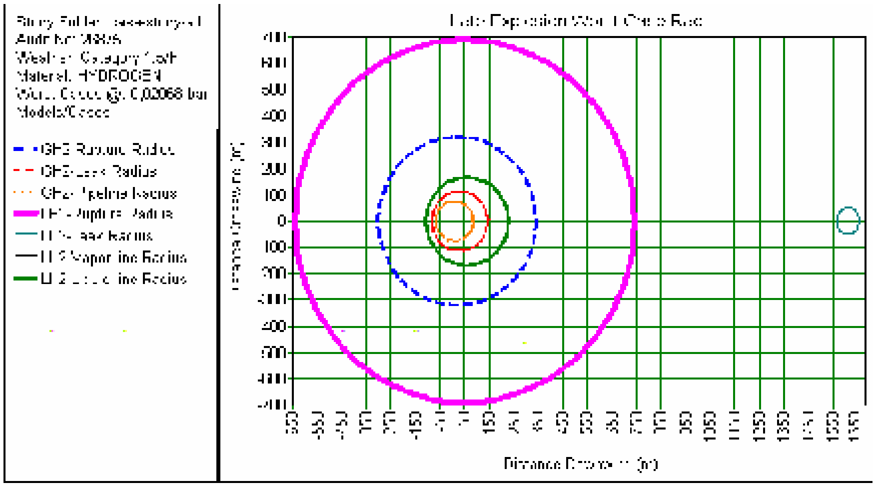


Figure 5.12 Effect zones (0.01% fatality) of late explosion for the two study objects

The effect distances for 1% and 10% fatality resulting from late explosion for different loss of containment events (A-F) of the all study objects, and for the weather category 1.5/F are presented in the Table 5-30. Assume that the fatality is constant with one value inside the central zone and constant with another value in the annulus formed by the inner and outer circles.

Table 5-30 Late explosion impacts for the hydrogen objects (Weather 1.5/F)

Study object	Late explosion	Unit	A		B		E		F	
			1%	10%	1%	10%	1%	10%	1%	10%
1. Solar	Overpressure radius	m	80.2	62.1	28.1	21.8	19.6	15.1	-	-
	Downwind distance	m	30.0	30.0	60.0	60.0	10.0	10.0	-	-
	Effect distance	m	110.2	92.1	88.1	81.8	29.6	25.1	-	-
2. Depot	Overpressure radius	m	26.3	20.3	146.1	113.1	28.6	22.1	68.9	53.3
	Downwind distance	m	560.0	560.0	450.0	450.0	40.0	40.0	110.0	110.0
	Effect Distance	m	586.3	580.3	596.1	563.1	68.6	62.1	178.9	163.3
3. FS	Overpressure radius	m	78.3	60.6	54.1	42.0	28.6	22.1	40.6	31.4
	Downwind distance	m	70.0	70.0	180.0	180.0	40.0	40.0	60.0	60.0
	Effect Distance	m	148.3	130.6	234.1	222.0	68.6	62.1	100.6	91.4
4. Car	Overpressure radius	m	17.0	13.2	7.9	6.1	-	-	-	-
	Downwind distance	m	10.0	10.0	70.0	70.0	-	-	-	-
	Effect Distance	m	27.0	23.2	77.9	76.1	-	-	-	-
5. CHP	Overpressure radius	m	134.9	104.4	94.0	72.8	28.6	22.1	43.4	33.6
	Downwind distance	m	130.0	130.0	250.0	250.0	40.0	40.0	60.0	60.0
	Effect Distance	m	164.9	134.4	344.0	322.8	68.6	62.1	103.4	93.6
6. Truck	Overpressure radius	m	60.5	46.6	21.3	16.5	130.0	100.0	28.6	22.0
	Downwind distance	m	160.0	160.0	20.0	20.0	130.0	130.0	40.0	40.0
	Effect Distance	m	220.5	206.6	41.3	36.5	260.0	230.0	68.6	62.0
7. Pipe	Overpressure radius	m	18.5	14.3	17.5	13.6	-	-	-	-
	Downwind distance	m	10.0	10.0	10.0	20.0	-	-	-	-
	Effect Distance	m	28.5	24.3	27.5	33.6	-	-	-	-

Notes: For 1-6: A=tank rupture; B=tank leak; C=relief valve; D=rupture disc; E=vapour line, F=liquid line
For 7: A =pipeline rupture; B=Hole in the pipeline

5.5 RISK ESTIMATION RESULTS

In order to calculate the risk associated with the hydrogen study objects the consequence results (Section 5.4) and their respective frequencies (Section 5.3) have to be combined. Together with additional data (e.g. population density) they are superimposed on the population to calculate the fatality risk in the surrounding area. In calculating the distribution of the risk effects on the local area, the method uses a grid superimposed on the area, as a structure for the calculations of the risk at different locations, and of the number of people affected by a given flammable effect zone. All the flammable impacts are modelled by superimposing the appropriate effect zones for the release onto the risk grid. In addition to that, particularly in the hydrogen transportation (i.e. LH_2 tanker truck and GH_2 pipeline) the risk is calculated for different route segments along the transportation route. This section presents the risk estimation results for the hydrogen study objects. The risks are mainly presented in the forms of individual and societal risk (F-N curve). Summary of the risk calculation results are presented in Appendix H.

5.5.1 Risk Calculation

The risk associated with the hydrogen study objects was calculated by combining the consequence and frequency analysis results, using the risk calculation model, described in Section 4.6.2. The model assumed that risk of each event can be treated independently from other events. Integration of the risk from all possible events can, therefore, be built up event by event and this is one of the principles of the model.

Table 5-31 illustrates an example to calculate the fireball risks impacted on the population with the model described in section 4.6.2 (analytical approach). Inputs of the model mainly consist of consequence and frequency analysis results. Firstly, effect zone area of the outcome is calculated based on the fire and explosion models described in section 4.5.5. Each accident outcome has a different effect zone area which is calculated as the area of the respective shapes of the outcome. For example, a fireball is modelled as a circle with radius (*r*), where r is equal to downwind (a) or crosswind (b), and centred at the release centre. So that the factored area (A_f) is equal to the effect zone area ($A=p*r^2$) multiplied with the associated fatality level (%). Number of fatality for given outcome, rate of death, and "Okrent number" are calculated using eq. 4-15, 4-16, and 4-17 respectively. The array sum can be calculated as factored area (A_f) multiplied with frequency (*F*) and divided by the defined grid area. The average value of the Germany population density (i.e. 0.00023 people per square meter) was used in the study. It is approximately 231 inhabitants per square kilometre of land [176]. The table shows that the fatality number (N values) may be impacted by the fireball are 0, 0, 1 people, for the fatality level of 1%, 10%, and 56%, respectively.

In order to obtain the overall risks of a hydrogen study object, the risks resulting from other considered accident outcomes (such as jet fire, flash fire, early explosion, late explosion) have been calculated in a similar manner. Furthermore, the calculations were repeated for different weather categories (i.e. 1.5/F, 1.5/D. 5.0/D), and for all scenarios (undesired events) considered. Table 5-32 shows the overall risk of the hydrogen fuelling station. The risk calculation included six different release event types (i.e. tank rupture, tank leak, relief valve open, rupture disk break, liquid line rupture, and vapour line rupture). The same outcomes (i.e. continuous flash fire, jet fire, late explosion) were considered for each of the release events. Additional incident outcomes such as fireball and early explosion were considered for the tank rupture event. The mean value of the overall risk for death of the hydrogen fuelling station is 9.6 x 10^{-5} per year. These procedures were repeated for all the study objects, the results are presented in Appendix H.

Table 5-31 Analytical risk calculations of the fireball impacts on population

Parameters	**Units**	**Lethality Level**		
		1%	**10%**	**56%**
Intensity Level	kW/m^2	59.0	80.2	121.6
View Factor		0.15	0.2	0.3
Probit Level	-	2.7	3.7	5.1
Downwind semi-axis (a)	m	56.3	46.7	35.4
Crosswind semi-axis (b)	m	56.3	46.7	35.4
Offset Ratio (d)	-	0.0	0.0	0.0
Effect Distance (z)	m	56.3	46.7	35.4
Frequency (F)	per year	1.1E-08	1.1E-08	1.1E-08
Grid cell size (g)	m	10.0	10.0	10.0
Population density (N/m^2)	Pop./m^2	0.00023	0.00023	0.00023
Effect zone area (A)	m^2	9950.2	6854.0	3933.0
Factored area(A_f)	m^2	99.5	685.4	2202.5
Number of fatality (N)	people	0	0	1
Array sum(/yr)	per year	1.1E-08	7.4E-08	2.4E-07
Rate of death(/yr)	per year	4.0E-09	2.7E-08	8.8E-08
Okrent(/yr)	per year	1.0E-10	7.0E-10	2.3E-09

Table 5-32 The overall risk of the hydrogen filling station

LOCs	Accident outcome	Weather	Fatality Level	Frequency(/yr)				Effect Distance (m)	Fatality (N)
				5%	50%	Mean	95%		
Liquid line rupture	Late Explosion	1.5/F	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	100.6	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	91.4	0
		1.5/D	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	103.0	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	93.2	0
		5.0/D	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	93.0	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	85.6	0
	Flash Fire	1.5/F	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	60.5	1
		1.5/D	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	48.0	1
		5.0/D	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	64.0	1
Relief valve	Late Explosion	1.5/F	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	54.4	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	21.5	0
		1.5/D	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	54.0	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	21.3	0
		5.0/D	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	43.2	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	19.0	0
	Flash Fire	1.5/F	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	14.4	0
		1.5/D	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	14.0	0
		5.0/D	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	16.0	0
Rupture disk	Late Explosion	1.5/F	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	56.4	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	50.4	0
		1.5/D	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	57.8	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	51.5	0
		5.0/D	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	51.0	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	46.3	0
	Flash Fire	1.5/F	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	37.6	1
		1.5/D	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	32.3	0
		5.0/D	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	39.4	1
Tank leak	Late Explosion	1.5/F	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	234.1	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	222.0	1
		1.5/D	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	320.0	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	304.0	1
		5.0/D	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	331.5	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	313.0	1
	Jet Fire	1.5/F	1%	2.3E-05	1.7E-04	3.6E-04	1.2E-03	148.4	0
			10%	2.3E-05	1.7E-04	3.6E-04	1.2E-03	143.2	0
			56%	2.3E-05	1.7E-04	3.6E-04	1.2E-03	136.5	1
		1.5/D	1%	2.3E-05	1.7E-04	3.6E-04	1.2E-03	148.4	0
			10%	2.3E-05	1.7E-04	3.6E-04	1.2E-03	143.2	0
			56%	2.3E-05	1.7E-04	3.6E-04	1.2E-03	136.5	1
		5.0/D	1%	2.3E-05	1.7E-04	3.6E-04	1.2E-03	118.3	0
			10%	2.3E-05	1.7E-04	3.6E-04	1.2E-03	113.3	0
			56%	2.3E-05	1.7E-04	3.6E-04	1.2E-03	107.2	1
	Flash Fire	1.5/F	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	253.4	22
		1.5/D	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	263.0	24
		5.0/D	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	238.0	20
Vapour line rupture	Late Explosion	1.5/F	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	68.6	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	62.1	0
		1.5/D	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	69.3	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	62.7	0
		5.0/D	1%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	62.5	0
			10%	8.4E-08	6.1E-07	1.3E-06	4.5E-06	57.4	0

	Flash Fire	1.5/F	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	42.0	1
		1.5/D	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	55.0	2
		5.0/D	60%	3.4E-07	2.4E-06	5.1E-06	1.8E-05	26.0	1
Tank Rupture	Late Explosion	1.5/F	1%	2.5E-12	1.8E-11	3.7E-11	1.3E-10	148.3	0
			10%	2.5E-12	1.8E-11	3.7E-11	1.3E-10	130.6	1
		1.5/D	1%	2.5E-12	1.8E-11	3.7E-11	1.3E-10	144.0	0
			10%	2.5E-12	1.8E-11	3.7E-11	1.3E-10	125.4	1
		5.0/D	1%	2.5E-12	1.8E-11	3.7E-11	1.3E-10	224.5	0
			10%	2.5E-12	1.8E-11	3.7E-11	1.3E-10	212.2	1
	Early Explosion	-	1%	5.1E-08	3.7E-07	7.7E-07	2.7E-06	109.0	0
			10%	5.1E-08	3.7E-07	7.7E-07	2.7E-06	84.4	0
	Fireball	-	1%	2.0E-07	1.5E-06	3.1E-06	1.1E-05	56.3	0
			10%	2.0E-07	1.5E-06	3.1E-06	1.1E-05	46.7	0
			60%	2.0E-07	1.5E-06	3.1E-06	1.1E-05	35.4	1
	Flash Fire	1.5/F	60%	9.8E-12	7.1E-11	1.5E-10	5.2E-10	263.0	6
		1.5/D	60%	9.8E-12	7.1E-11	1.5E-10	5.2E-10	218.0	5
		5.0/D	60%	9.8E-12	7.1E-11	1.5E-10	5.2E-10	543.0	32
Overall risk						**3.3E-03**			

5.5.2 Risk Presentation

Two risk measures were considered to present the risk associated with the hydrogen study objects, i.e. individual and societal risk (F-N curve), as described in section 4.6.1.

5.5.2.1 Individual Risk (IR)

The *IR* of the hydrogen study objects are presented as risk profiles. To create a risk profile, the triplets of the overall risk in Table 5-32 must be transformed into risk profiles and plotted by means of the CCDF, as described in section 4.6.2.2. The risk is expressed as individual risk depending on distance from the objects.

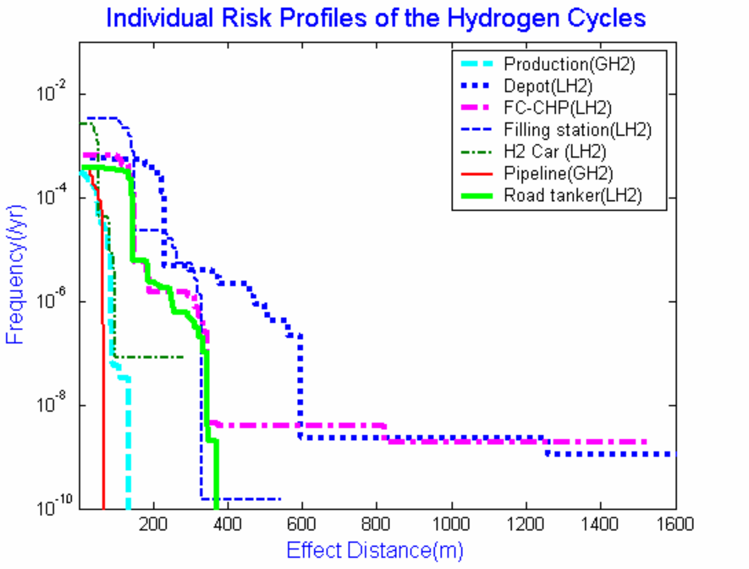


Figure 5.13 Individual risk profiles of the hydrogen cycle

Fig. 5.13 shows an individual risk profile for the hydrogen study objects, with the capacity of 6 – 16250 kg of hydrogen. Failure of such objects leads to fatal consequences from a distance of 35 m (e.g. pipeline) up to a distance of 4374 m (e.g. depot). It seems that the effect distance is proportional to the hydrogen capacity. The consequence calculation result, however, shows that the risks of the GH_2 (e.g. production plant) have smaller distance compared with the one of LH_2 (e.g. depot). The figure also shows that the hydrogen objects have a higher risk at a shorter distance than that at the larger distance from the object. The overall ***IR*** of the hydrogen objects is in the ranges of 10^{-2} and 10^{-4} per year. The production plant (GH_2) has the lowest risks levels (2.3 x 10^{-4} /year). The risks are sharply decreasing with the increase of the distance. For example, risk of the LH_2 at fuelling station decreased from 3.6 x 10^{-3} /year to about 10^{-10} at a distance of 322 m.

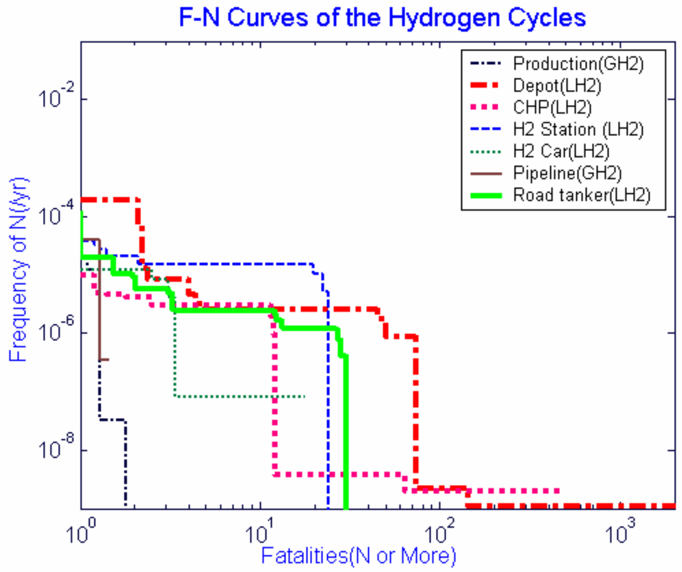


Figure 5.14 Societal risks (FN-Curves) of the hydrogen study objects

5.5.2.2 Societal Risk (SR)

All of the information required for individual risk calculation, as well as information on the population surrounding the facility or along the transportation routes are required for the societal risk calculation. By using the procedure described in section 4.6.2.2, the societal risks (F-N curves) for the hydrogen study objects are presented in Fig. 5.14. It is connected to the hydrogen plants, with the capacity of 6 – 16250 kg of hydrogen. Failure of such plants leads to maximum fatality number of about 2 people (for GH2 pipeline) up to 2100 people (for LH_2 at depot). These fatalities are connected to the risk of 10^{-9} /year. The GH_2 plants (e.g. production plant and pipeline) give the lowest risk compared to the one of LH_2 plants.

The figure also shows that the hydrogen objects have a lower societal risk than that of individual risk. For example, the individual risk (risk to 1 person) of the road tanker is about 10^{-4}/yr, and the societal risk drops to 10^{-6} with correspond to the fatality number of about 20 people. The overall risk of the hydrogen study objects are in the ranges of 10^{-3} and 10^{-5} /year.

5.6 RISK EVALUATION

5.6.1 Summary of the Numerical Results

5.6.1.1 The Frequency

Table 5-33 shows that the overall average of the hydrogen release frequencies of the study objects is about 1.9 x 10-3 per year (once per 517 years). Based on frequency calculation results of the study objects, GH2 storage has a lower accident frequency compared with the

LH2 storage. The reason is that the LH2 storage introduces more potential hazards than the one in GH2 (i.e. cryogenic liquid hazards). All these may contribute to modes of potential failure and result in great contributions to the overall release frequency.

Table 5-33 Overall release frequencies of the hydrogen study objects

No	Plant	Storage types	5%	50%	Mean	95%	K-95	Source
3	Solar H_2 plant	GH_2	1.8E-06	1.5E-05	3.6E-05	1.3E-04	8.6	FTA
4	H_2 Fuelling Station	LH_2	4.7E-05	3.4E-04	7.1E-04	2.5E-03	7.3	FTA
5	H_2 Fuel Cell - CHP	LH_2	5.1E-06	5.2E-05	1.4E-04	5.4E-04	7.3	FTA
6	H_2 Depot	LH_2	5.6E-06	4.8E-05	1.2E-04	4.6E-04	9.6	FTA
7	H_2 Private Cars	LH_2	-	-	7.1E-04	-	-	Data
8	H_2 Road Tanker	LH_2	-	-	6.9E-05	-	-	Data
9	H_2 Pipeline	GH_2	-	-	1.5E-04	-	-	Data
Overall			**7.5E-04**	**1.7E-03**	**1.9E-03**	**3.9E-03**	**2.3**	

The loss of containment events (LOCs) of hydrogen storages and transportations considered in the QRA study include: continuous and instantaneous release. Frequency analysis showed that the overall average contributions of the continuous dominated to about 94% of the scenario and only 6% for the instantaneous. It means that the probability of occurrence per year of the instantaneous release is very low. The instantaneous release of hydrogen mainly results from a catastrophic failure of tank storage (e.g. tank rupture), and release the all inventory contents. Tank rupture is mainly caused by tank overpressure (with the contribution of more than 50%), it is followed by external events, and spontaneous events. In case of LH_2, there is an additional incident that may contribute to the tank rupture, i.e. tank under-pressure with the contribution of about 30%. All hydrogen storages are equipped with redundant safety protections against tank overpressure, such as pressure relief valves and rupture discs. The tank overpressure may lead to tank rupture, if all pressure relief devices fail close. The tank overpressure is mainly caused by tank overfilling, loss of vacuum (in case of LH_2 only), external fire, internal explosion, overheating of the pressure building circuits (in case of LH_2 only), and so on.

The continuous release gave the greatest contribution to the loss of containment event in the hydrogen study objects. It is mainly caused by pipelines rupture and tank leakage. Although the tank leakage event may be considered as a rare event but it may result severe damage to environment. In case of LH_2 storage, an additional release may be resulted from pressure building circuit (PBC) failure.

Fires and explosions are the two incident outcomes which may result from a hydrogen release when ignition sources exist. The frequency analysis showed that the fire outcomes are mostly dominant. They account for about 60%, only about 5% result in explosion, and the rest (35%) has no effect (harmless) on the environment. It can be understood that an explosion requires certain conditions such as confined area. high ignition energy, and so on.

Several errors may exist during the frequency analysis include: (1) incorrect estimation of probability or frequencies of the basic events, (2) erroneous assumption of independence of bottom events, and so on.

5.6.1.2 The Consequence

The loss of containment event of the study objects results in different types of consequences, such as jet fires, fireballs, explosions, and so on. Each of the outcomes was modelled for different shapes and sizes that is required for the impact calculations. Circle and ellipse are the shapes considered to calculate impact zones resulting from fires and explosions.

The major hazards associated with hydrogen are fires and explosions, and in the event of contact with the liquid or cold boil off vapour, frostbite and burns. The study considers fire and explosion hazards because they may result in fatalities in the population around the installation. In general, the fire and explosion consequences are proportional to their inventory capacity. A larger hydrogen inventory (in kg) may result in larger impacts.

In general, human fatalities of the hydrogen consequence may be estimated by using of probit equations. Fatality level (%) of fire outcomes is proportional to thermal radiation (kW/m^2), while the peak overpressure (bar) for the explosion. The existing the probit equations for explosion could not be used directly to estimate the human fatalities, because they showed small impacts. A conservative approach has been taken to estimate fatalities for given explosion, instead of the probit equations.

Errors which may arise in consequences analyses include: (1) imperfections and over-simplifications in the physical models as representations of real behaviour, (2) error in the parameters of the physical models, (3) error due to simplification in the computing, and so on.

5.6.1.3 The Overall Risk

The societal risk results as a measure of the risk that the events pose to the local population expressed by frequency *F* as a function of fatalities *N*, which is then plotted to give the ***F-N*** curve. The frequencies for given values of *N* can be summed for all outcomes and events to give the overall societal risk. The overall risk of the hydrogen study objects is 8.5 x 10-3/ year (once in 118 years) shown in Table 5-36. The most contributor to the overall risk is LH2 storage at fuelling station (accounted for 39%), followed by LH2 storage in private car (accounted for 35%), LH2 at CHP plant (7.7%), LH2 at depot (6.5%), GH2 pipeline (5%), LH2 tanker truck (4.4%), and GH2 at production plant (2.7%). Figure 5.17 shows the overall risk for the hydrogen cycles.

Table 5-34 The overall individual risk of the hydrogen study objects

Study Objects	5%	50%	Mean	95%
GH2 at production plant	1.1E-05	9.5E-05	2.3E-04	8.5E-04
LH2 at depot	2.3E-05	2.2E-04	5.5E-04	2.1E-03
LH2 at fuelling station	2.2E-04	1.6E-03	3.3E-03	1.1E-02
LH2 at CHP plant	2.3E-05	2.4E-04	6.5E-04	2.5E-03
LH2 in private car	-	-	3.0E-03	-
LH2 tanker truck	-	-	3.7E-04	-
GH2 pipeline	-	-	4.1E-04	-
Overall risk	**9.5E-4**	**3.5E-03**	**8.5E-03**	**1.3E-02**

5.6.2 Evaluation Against the Risk Criteria

As described in section 4.6.3, the study uses the ALARP risk acceptance criteria proposed by the EIHP2 (European Integrated Hydrogen Projects). Figure 5.15 shows that, according to the Dutch regulations (Dutch National Environmental Policy Plan, 1989), as well as U.K. standards (Health and Safety Commission, 1991), the individual risk for the hydrogen objects (both hydrogen storages and transportations) run almost entirely in the unacceptability zone, being higher than 1 x 10^{-6} /year (for the Dutch regulations) or 1 x 10^{-4} /year (for the U.K standards) or where the measures to reduce the risk must be implemented.

The figure also shows that the societal risk level appears globally lower than the individual one. In fact, also the curves relevant to the hydrogen objects, fall well in the acceptable of the UK ALARP zone (dotted lines). However, assuming the limits proposed by Dutch regulations (solid lines), different in slope and more severe than the U.K. ones, most of the curves fall within the ALARA zone. These mean that the hydrogen storages and transports may be accepted for the public. Should the plants be implemented for the public, the risk must be reduced as far as reasonable and practicable, typically subject to cost benefit analysis. Meanwhile, hydrogen production plant (GH_2) and pipeline (GH_2) fall well in the acceptable zones of the ALARP as well as the ALARA.

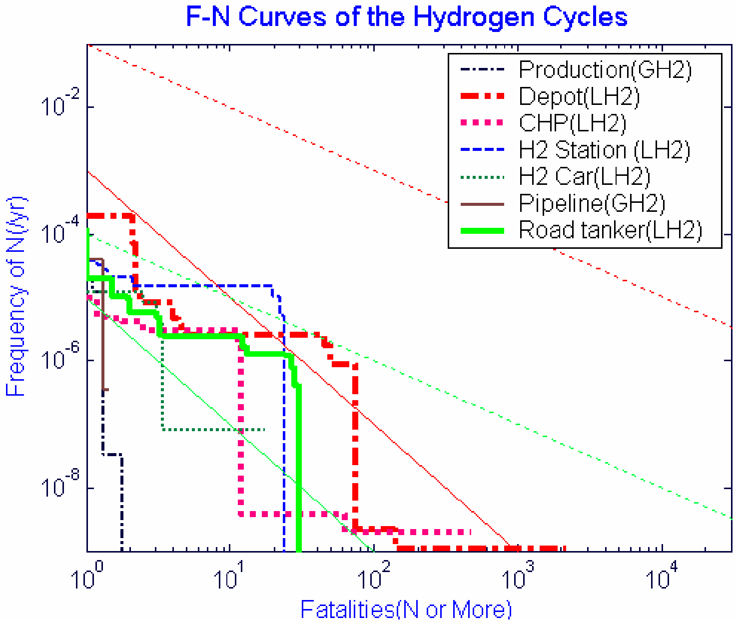


Figure 5.15 F-N curve of the hydrogen cycles with the ALARP criteria

5.6.3 Comparisons with the LPG study

5.6.3.1 LPG Study Objects

Propane (C_3H_8) is a very common fuel, particularly in rural areas where it is used for crop drying, cooking, heating, and as a motor vehicle fuel. Propane is also the main constituent of "bottle gas" or LPG- Liquified Petroleum Gas. LPG may also contain butane, propylene, or butylene. These are gases at standard conditions, but become liquids at room temperature at moderate pressures. At 38°C, propane liquifies at about 13.8 bar, while butane remains a liquid at pressures above 4.14 bar at this temperature. LPG can therefore be handled as a liquid at room temperature with moderate pressure cylinders. LPG is primarily a domestic fuel, produced as a by-product from natural gas processing and crude oil refining.

Table 5-35 Dimension and capacities of the LPG study objects [187]

Specifications	Storage		Transport	
	Depot	Fuelling Station	Road Tanker	Pipeline
Capacity (m^3) or (m^3/h)	165	20	45	225
Capacity (kg)	86576	10494	22300	-
Tank type	Cylindrical	Cylindrical	Cylindrical	
Length (m)	21	7	11	n.a.
diameter (m)	3.2	2.1	2.3	0.3
liquid line (m)	0.1	0.08	0.08	-
Vapour line (m)	0.1	0.05	0.05	-

The risks of the hydrogen study objects were compared with the LPG study objects given in the LPG study [187]. The LPG study describes the present and future activities relating to LPG in the Netherlands, which include of storage and transport systems. The study took four LPG objects that have similar size and function to the hydrogen study. Assuming that the LPG truck and LPG pipeline operate on the similar routes as the one of the LH_2 truck and GH_2 pipeline, respectively. It also assumed that LPG is pure Propane with the liquid density of 575 kg/m^3 (see Appendix A). They include LPG storage at depot, LPG filling station, LPG road tanker, and LPG pipeline, as shown in Table 5-35.

5.6.3.2 The Frequency Comparison

Frequencies of the LPG objects were estimated using the same procedure given for the hydrogen study (i.e. given in section 4.4). Most of the expected frequency, however, was taken from the TNO study [187], as shown in Table 5-36. Expected frequency of the LPG truck and LPG pipeline were estimated from the truck accident rate and pipeline failure data given in [187]. Assuming that the LPG truck and pipeline operate on similar routes as the one for the LH2 truck and pipeline, the expected frequency is calculated using eq. 4-7 and 4-8, respectively. The result is shown in Table 5-36. A brief comparison between the LPG and hydrogen study objects show that the overall incident frequency of the hydrogen study objects is bit higher lower than of the LPG. The hydrogen objects frequency is 1.0 x 10-3 /year (once per 991 years), while the LPG is 9.3 x 10-4 /year (once per 1077 years).

Table 5-37 shows accident outcome frequencies of the LPG study objects. It can be seen that the fire mostly dominates the accident outcomes (accounting for 23%). Only 2% of the accident outcome may lead to explosions and the remaining (75%) of the accidents have no effect on the population

Table 5-36 Expected Frequency of the LPG study objects considered

No	**LPG Objects**	**Frequency (/yr)**	**Source of Justification**
1	LPG depot	2.2E-04	TNO (1983)
2	LPG filling station	5.4E-04	TNO (1983)
3	LPG Truck	6.9E-05	1.6E-7/veh-km (TNO), take similar route as for the LH_2 truck
4	LPG pipeline	1.1E-04	1.0E-4/km-yr (TNO), take similar route as for the GH_2 pipeline
Total		**9.3E-04**	

5.6.3.3 The Consequence Comparison

The consequences of the LPG study objects have been assessed using the same procedure given for the hydrogen study (i.e. given in section 4.5). This assessment includes the impacts of fireball, flash fire, explosions, etc to human. A brief consequence comparison between hydrogen and LPG study is presented in Fig. 5.16 and Fig. 5.17. The consequences of the LH2 filling station were compared with the LPG filling station. Due to the fact that LPG has higher density per volume the LPG objects are simulated for different sizes. The LH2 fuelling station (tank capacity of 12m3) was compared with the various capacities of LPG fuelling station (i.e. 20m3, 12m3, and 2m3). The LPG fuelling station with the tank capacity of 20m3 is a modern above-ground installation in the Netherlands [187]. Two other capacities were considered for the same tank geometric volume (12m3) and the same tank inventory in kg (2m3) with the LH2 fuelling station.

Table 5-37 Accident outcome frequency of the LPG study objects

LOCs	**Accident Outcomes**	**Frequency (/yr)**				
		Depot	**Filling station**	**Truck Route 1**	**Truck Route 2**	**Pipeline**
Instantaneous.	Early explosion	9.6E-08	2.3E-06	4.6E-06	3.5E-07	-
	Fireball	6.4E-08	1.5E-06	3.1E-06	2.3E-07	-
	Pool fire	7.7E-08	1.8E-06	3.7E-06	2.8E-07	-
	VCE	5.8E-09	1.4E-07	2.8E-07	2.1E-08	-
	Flash fire	3.8E-09	9.2E-08	1.8E-07	1.4E-08	-
Continuous	Jet fire	2.2E-05	5.1E-05	4.5E-06	3.4E-07	6,8E-05
	Pool fire	3.1E-05	7.3E-05	6.5E-06	4.8E-07	-
	VCE	2.3E-07	5.5E-07	4.8E-08	3.6E-09	8.3E-06
	Flash fire	1.6E-07	3.6E-07	3.2E-08	2.4E-09	2.2E-05
Harmless		1,6E-04	3.8E-04	4.1E-05	3.1E-06	7.5E-06
Total		**2.2E-04**	**5.2E-04**	**6.4E-05**	**4.8E-06**	**1.1E-04**

Table 5-38 Qualitative assessment of the hydrogen and LPG consequences

	LH2 12m^3	**LPG 20m^3**	**LPG 12m^3**	**LPG 2m^3**
Early explosion	3	1	2	4
Late explosion	3	1	2	4
Flash fire	1	2	3	4
Fireball	3	1	2	4
Average	**2.5**	**1.25**	**2.25**	**4**

Note: 1=highest. 2=high. 3=moderate. 4=low

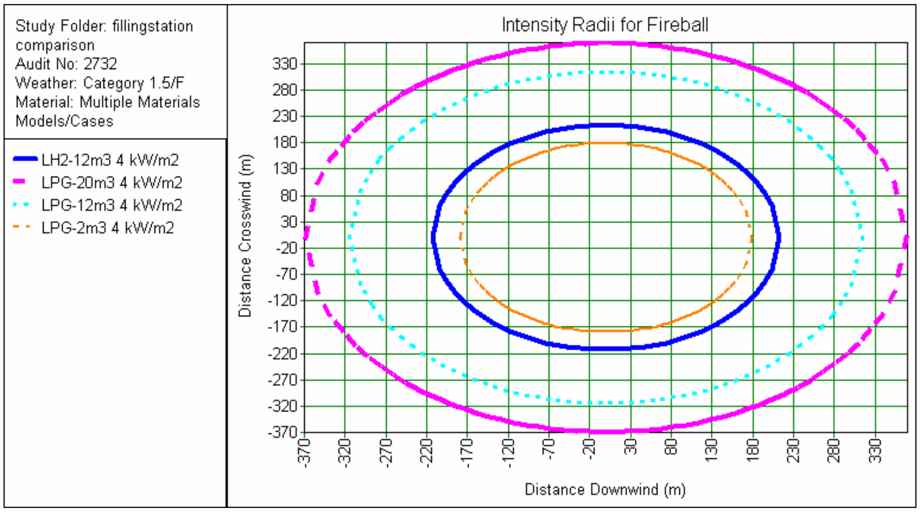


Figure 5.16 Intensity radii for LH2 and various capacity of LPG

The results show that hydrogen poses less risk than LPG. The large effect distances for hydrogen especially flash fire (Fig. 5.17) are caused by the large energy density of the released gas and wider ranges of the flammability limit. A simple qualitative assessment (in Table 5-38) also shows that hydrogen poses lower consequences than of LPG. In this table, accident outcomes resulted from catastrophic rupture of the hydrogen tank (12 m^3) and LPG tank (20 m^3) were compared qualitatively.

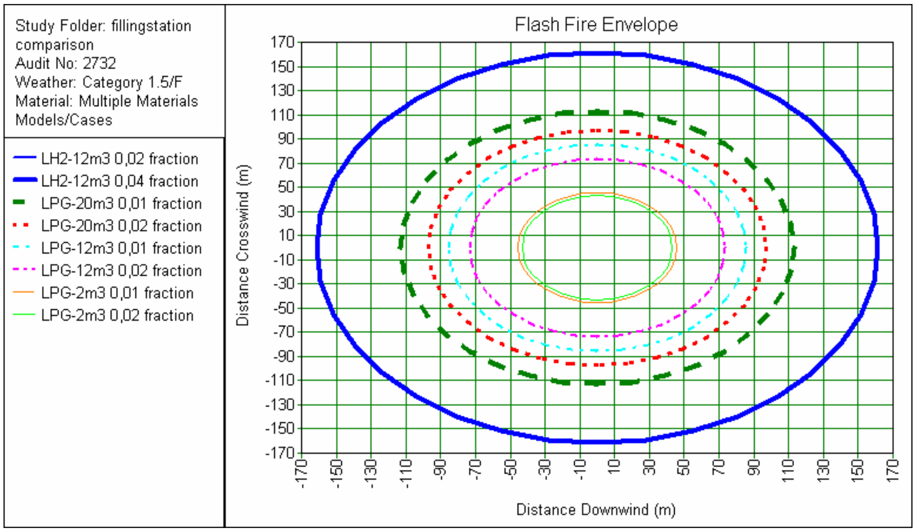


Figure 5.17 Flash fire impacts of LH2 and various capacity of LPG

5.6.3.4 The Risk Comparisons

5.6.3.4.1 Individual Risk

Individual risk of the two hydrogen study objects (i.e. LH_2 at depot and filling station) were compared with the one of the LPG study. Figure 5.18 shows that the total individual risk of hydrogen storage objects are higher than that of LPG, but the maximum effect distances of the hydrogen objects are lower than that of LPG. For example, failure of hydrogen objects lead to fatal consequences from a distance of less than 350 m, while for the LPG is about 1200 m from the storage. Safety distances to an individual risk level of 1 x 10^{-6}/yr of the hydrogen storages are about 330 m and 450 m (for LH_2 at filling station and depot, respectively). Meanwhile, for the LPG objects are about 580 m and 1600 m (for LPG filling station and depot). This is due to the fact that hydrogen poses lower consequences than that of LPG (see previous section).

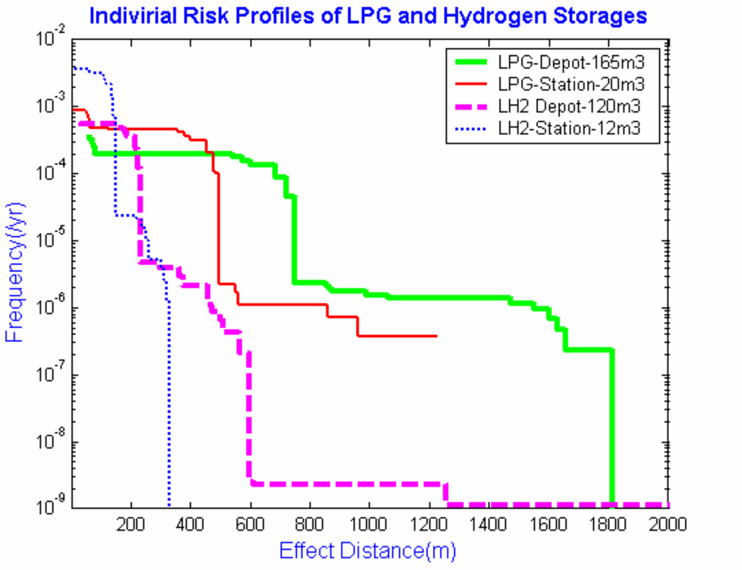


Figure 5.18 Individual risk comparison between hydrogen and LPG storages

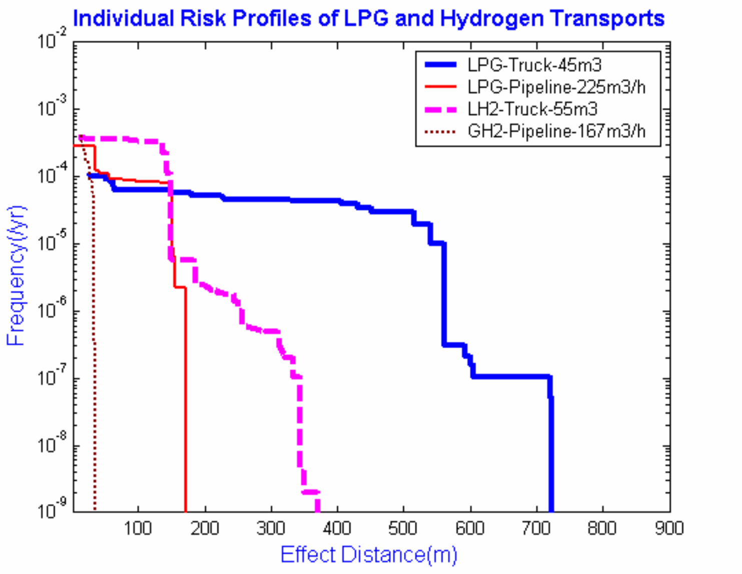


Figure 5.19 Individual risk comparisons between of hydrogen and LPG transports

Figure 5.19 shows that the individual risk of the hydrogen transports at short distance is comparable to that for LPG, but their effect distances are smaller. Especially, the hydrogen pipeline shows the lowest effect distance of the all means of transportations. Failure of hydrogen transports lead to fatal consequences from a distance of less than 50 m up to 344 m (for GH_2 pipeline and LH_2 truck, respectively), while for the LPG is about 170 m up to 720 m (for LPG pipeline and truck, respectively). Safety distances to an individual risk level of 1 x 10^{-6}/yr of the hydrogen transports are about 40 m up to 250 m (for GH_2 pipeline and LH_2 truck, respectively). Meanwhile, for the LPG objects are about 170 m up to 560 m (for LPG pipeline and truck). Based on the fact above it can be concluded that the hydrogen study objects have a lower individual risk than those of the LPG.

5.6.3.4.1 Societal Risk

Societal risks of the hydrogen study objects were also compared with the LPG objects. Fig. 5.20 shows the societal risk (F-N curves) for the hydrogen and LPG storages. The individual risks of the hydrogen storages are a bit higher than that of LPG, but their maximum fatality number is smaller. For example, failure of the LH_2 station lead to maximum fatality number of about 230 people, while for the LPG station is more than 1000 people. The societal risks (F-N curves) of the hydrogen storages are comparable to those of LPG. The curves for both storages fall well in the acceptable of the UK ALARP zone (dotted lines), and fall above the acceptable risk criteria of the Dutch ALARA zone (solid lines). According to the UK ALARP, it means that the storages may be accepted for the public. Should the plants be implemented for the public, the risk must be reduced as far as reasonable and practicable, typically subject to cost benefit analysis. For the Dutch ALARA, however, the measures to reduce the risk must be implemented.

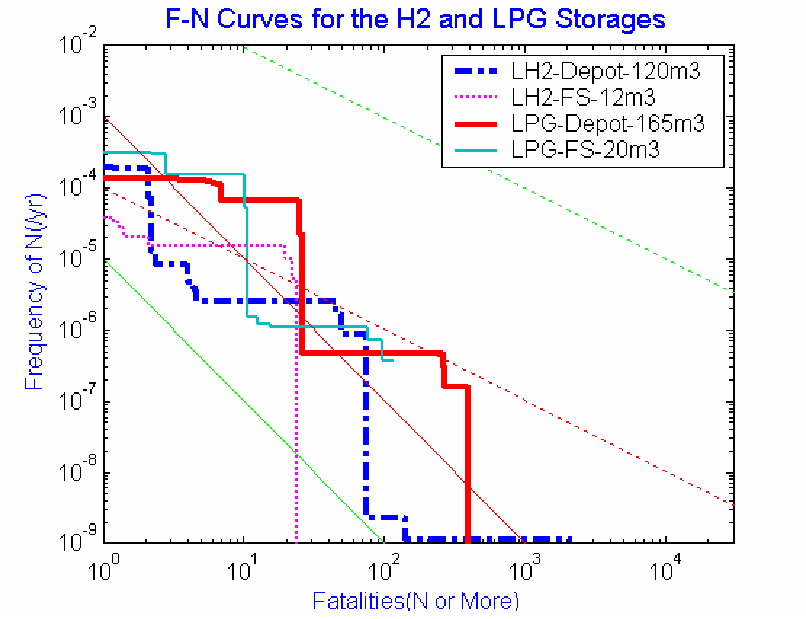


Figure 5.20 F-N curves comparison of the hydrogen and LPG storages

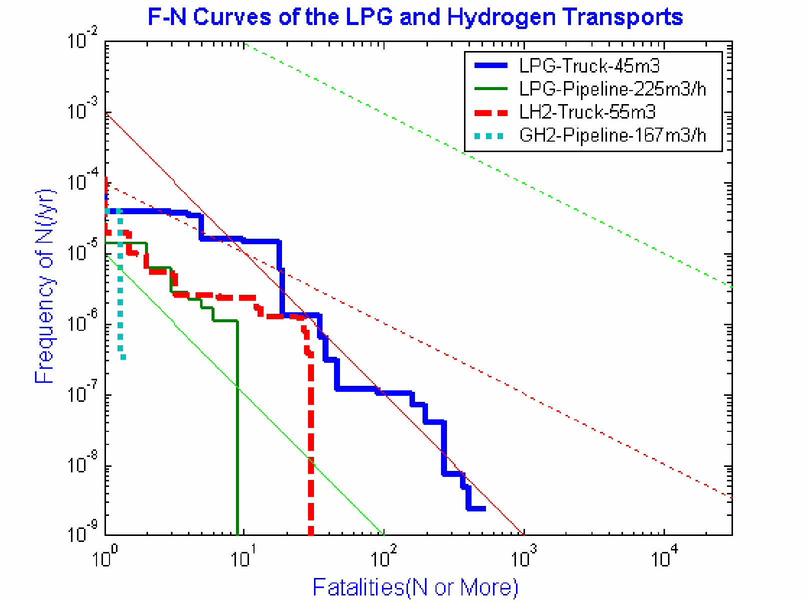


Figure 5.21 F-N curves comparison of the hydrogen and LPG transports

Fig. 5.21 shows that the societal risks as well as the maximum fatality number of the hydrogen transports are lower than that of the LPG. For example, the maximum fatality number for LH_2 truck is about 30 people, while for LPG truck is more than 500 people. The figure also shows that the hydrogen pipeline showed the lowest risk compared with the LPG. In fact, the F–N curve obtained for hydrogen transports (GH_2 pipeline and LH_2 truck) are still below those of LPG transports. Both the hydrogen and LPG transports, however, fall within the Dutch ALARA (solid lines), and in the acceptable zone of the UK ALARP (dot lines).

Chapter 6

SUMMARY AND OUTLOOK

Hydrogen was considered as a candidate energy carrier for the delivery of energy to the public and industry. As a storage medium for energy, hydrogen fulfils several requirements concurrently, proving to be the most environmentally friendly energy carrier. Moreover, hydrogen's special characteristics render it the ideal storage medium for electricity generated from renewable energy sources, making it the most important link in a sustainable energy value chain, which is completely emission free from beginning to end. Unfortunately, the public's first response to the proliferation hydrogen fuel is not associated with the hydrogen's environmental benefits but instead focuses on the safety issues and hydrogen's dubious association with the Hindenburg disaster. Before regulations and the market drive hydrogen to the fuel of chose, the safety issues must be systematically addressed and interdisciplinary techniques defined for application.

Hydrogen has a long history of safe use in the chemical, manufacturing, and utility industries, which are predominantly operated by highly trained people. However, as a large-scale energy carrier in the hands of the general public, where untrained people will deal with hydrogen, it may create safety issues in the society. To make hydrogen available at a large-scale as an energy carrier, an infrastructure covering the following steps must be built up: production, transportation, storage, filling station, and end-use. The technical installations used could fail, and the possibility of handling incidents may occur in many places. Therefore it is reasonable to determine the safety technological conditions and associated operating procedures for the realization of the hydrogen infrastructure at an early stage. This is the goal of the present work in which system-analytic methods, called "quantitative risk assessment (QRA)", are used to evaluate the risks, to identify possible weak points, and to make suggestions for improvement quantitatively. The QRA mainly consists of probabilistic safety analysis, consequences analysis, and risk estimation. Results of the study are presented in the form of individual risk and societal risk.

The QRA study was carried out for seven hydrogen study objects which may represent the hydrogen energy cycle. Total numbers of installation in a study object where a safety evaluation has to be made can be very large. Since not all installations contribute significantly to the risk, it is not worthwhile to include all installations in the QRA study. The QRA may be carried out if the hydrogen is thought to be present at a location (e.g. stationary establishment and transportation routes) in amount that can endanger the environment. The study was focused on hydrogen storages and transports of the objects where the largest hydrogen inventory is available most of the time. The hydrogen study storages include hydrogen storage at production plant, depot (liquefaction plant), filling station, vehicle, and CHP for households. The hydrogen transports include a road tanker truck and hydrogen pipeline.

Accident scenario of the hydrogen cycle is mainly initiated with release events, called "loss of containments events (LOCs)". It includes continuous and instantaneous release. The results showed that a continuous release mostly dominates the accident which is accounted for about 94% and instantaneous (accounted for 6%). The instantaneous release mainly results from a catastrophic failure of tank storage (e.g. tank rupture), and releases all the inventory. The main contributor to the tank rupture is tank overpressure (which accounted for about 50%), it is followed by external events, and spontaneous events. In case of LH_2, an additional incident may contribute to the tank rupture, i.e. tank under-pressure (excessively low pressure) with a contribution of about 30%.

Fires and explosions are the two accident outcomes resulting from a hydrogen release in the present of ignition sources. The results showed that the fires mostly dominate the accidents which account for about 60%, explosion of 5%, and the rest (35%) has no effect (harmless) to the environment.

According to the existing standards (e.g. ALARP criteria) the individual risk for both hydrogen storages and transportations run almost entirely in the unacceptability zone. The societal risk level, however, appears globally lower than the individual one. In fact, also the curves relevant to hydrogen transportations and GH_2 storage fall well in the acceptable of the UK ALARP zone. However, assuming the limits proposed by Dutch regulations, different in slope and more severe than the U.K. ones, the curves fall within the ALARA zone. Meanwhile, the F-N curves for the LH_2 storages fall well within UK ALARP zone and upper the risk acceptance curve of the Dutch ALARA. According to the ALARP principles, for scenarios with risk levels below the acceptable curve no measures to reduce the risk are required. For scenarios with risk level (that lie) between these lines the risk should be reduced if practical. Should the plants be implemented for the public, the risk must be reduced as far as reasonable and practicable, typically subject to cost benefit analysis. For scenarios with risk levels above the upper curve, measures to reduce the risk must be implemented.

Aside from which risk criteria selected the hydrogen objects are comparable to those of LPG objects. Although, the individual risks of hydrogen storage objects seems to be higher than those of LPG, but the maximum effect distances of the hydrogen objects are smaller. In fact, hydrogen poses less consequence than LPG. The large effect distance for hydrogen, especially flash fires are caused by the large energy density and wider ranges of the flammability limit of hydrogen. The societal risks (F-N curves) of all hydrogen objects are lower than that those of LPG. The fire and explosion risks for hydrogen objects are at short distances comparable with those for LPG, but the effect distances for the worst events are smaller. One should remember that equally sized hydrogen and LPG tanks are considered: the latter has much higher energy content per volume.

In order to avoid the greatest potential impacts to the nearby population some failure modes leading to the tank rupture should be avoided. These include tank overpressure, under-pressure (for LH_2 case only), and spontaneous events (e.g. hydrogen embrittlement, fatigue, ect). Tank overfilling involving human error may greatly contribution to the tank overpressure. An adequate operating procedure and operator training shall be established for the hydrogen public facilities. In case of LH_2, loss of vacuum may also contribute to the tank overpressure. Additional safeguards against this event (i.e. vacuum breaker connected to Nitrogen supply) may be considered. Some events like a significant volume of sub-cooled LH_2 added and excess withdrawal rates may be considered as initiating event of tank underpressure. Safeguards against these events (such as withdrawal protection, pressure building circuits) shall be high reliability. The best material selection and adequate design of the hydrogen tank should be considered in development of the hydrogen infrastructure, to avoid any spontaneous events such as hydrogen embrittlement, cold embrittlement (LH_2 case only), fatigue, etc, that may lead to tank rupture.

Tank leak or piping rupture may result in a continuous release or spillage of the hydrogen content. Protective measures against this scenario should be considered. In case of piping rupture, an emergency shutoff device (ESD) may be remotely or automatically operated should be considered to stop flow of the release. Hand operated valves may not possible to protect this event.

The hydrogen economy has enormous societal and technical appeal as a potential solution to the fundamental energy concerns of abundant supply and minimal environmental impact. The ultimate success of a hydrogen economy depends on how the market reacts. Although the market will ultimately drive the hydrogen economy, government plays a key role in the move from fossil fuel to hydrogen technology. The investments in R&D are large, the outcome for specific, promising approaches is uncertain, and the payoff is often beyond the market's time horizon. Thus, early government investments in establishing goals, providing research support, and sharing risk are necessary to prime the emergence of a vibrant, market driven hydrogen economy.

The public acceptance of hydrogen depends not only on its practical and commercial appeal, but also on its record of safety in widespread use. The special flammability, buoyancy, and permeability of hydrogen present challenges to its safe use that is different from, those of other energy carriers. Another key to public acceptance of hydrogen is the development of safety standards and practices that are widely known and routinely used like those for self service gasoline stations or plug-in electrical appliances. The technical and educational components of this aspect of the hydrogen economy need careful attention.

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Appendix A

HYDROGEN SAFETY PROPERTIES

A.1 INTRODUCTION

Hydrogen is the first element in the periodic table. The isotope of mass one is the lightest and simplest atom, consisting of one proton and one electron. It forms the simplest diatomic molecule. Hydrogen is found in traces in gaseous form in the troposphere (less than 10^{-3} vol. %) [46]. Higher up in the atmosphere, in the region called exosphere, it is the dominating element. On the earth it is found chemically bound in water, crude oil, coal, and some minerals and organisms. This appendix gives a review of quantities and properties of hydrogen which are relevant in safety aspects. This review is intended as a basis for the study, as a guide for detailed investigations.

A.2 PHYSICAL PROPERTIES

Table A-1 shows the physical properties of hydrogen in comparison to methane, gasoline, and propane in order to assist in establishing the relative hazards.

A.2.1 State

In general, a gas can be changed into a liquid by reducing its temperature, and a liquid to a solid by reducing its temperature further. To some extent, an increase in pressure will cause a substance to liquefy and solidify at higher temperature than would otherwise be required. The transition from liquid to gas is known as boiling and the transition from liquid to solid as freezing. Accordingly, each substance has a characteristic boiling temperature and freezing temperature (at a given pressure). The opposite transitions, from gas to liquid and solid to liquid, are known as condensation and melting respectively. The condensation temperature is the same as the boiling temperature and the melting temperature is the same as the freezing temperature. The process of condensation is also known as liquefaction and the process of freezing is also known as solidification. Boiling and freezing temperatures are most meaningfully compared relative to "absolute zero". Absolute zero (–273.15 ºC) is the lowest temperature in the universe at which all molecular motion stops [46].

Hydrogen has the second lowest boiling point and melting points of all substances, second only to helium. Hydrogen is a liquid below its boiling point of 20K (–253 ºC) and a solid below its melting point of 14K (–259 ºC) and atmospheric pressure. Obviously, these temperatures are extremely low. Temperatures below 200K (–73 ºC) are collectively known as cryogenic temperatures, and liquids at these temperatures are known as cryogenic liquids. The boiling point of a fuel is a critical parameter since it defines the temperature to which it must be cooled in order to store and use it as a liquid. Liquid fuels take up less storage space than gaseous fuels, and are generally easier to transport and to handle. For this reason, fuels that are liquid at atmospheric conditions (such as gasoline, diesel, methanol and ethanol) are particularly convenient. Conversely, fuels that are gases at atmospheric conditions (such as hydrogen and natural gas) are less convenient as they must be stored as a pressurized gas or as a cryogenic liquid.

The boiling point of a pure substance increases with applied pressure up to a point. Propane with a boiling point of –42 ºC, can be stored as a liquid under moderate pressure, although it is a gas at atmospheric pressure. Unfortunately, hydrogen's boiling point can only be increased to a maximum of -240 ºC through the application of approximately 1.3 MPa, beyond which additional pressure has no beneficial effect.

Table A-1 Physical Properties of H_2, methane, gasoline, and propane [12, 36, 46]

Property	**Hydrogen**	**Methane**	**Gasoline**	**Propane**	**Units**
Molecular weight	2.016	16.043	107	44.097	amu
Triple point pressure	0.007042	0.01174	-	-	MPa
Triple point temperature	13.803	90.68	180 - 220	85.5	K
Normal boiling point (NBP) temp.	20.268	11.632	310-478	231.1	K
Critical pressure	1.293	4.5988	2.48 – 2.7	4.3	MPa
Critical temperature	32.976	190.56	540-569	369.8	K
Density at triple point	31.4	160.4	230		kg/m^3
Density of liquid at triple point	77	451.6	-		kg/m^3
Density of solid at triple point	68.65	487.2	-		kg/m^3
Density of liquid at NBP	70.8	422.6	700	575	kg/m^3
Density of vapour at NBP	1.34	1.82	4.5	2.40	kg/m^3
Density of gas at NTP	0.083764	0.65119	4.4	1.69	kg/m^3
Density ratio: NBP liquid to NTP gas	845.2	649	159	340	-
Heat of fusion	58230	58470	161000		J/kg
Heat of vaporization	445590	509880	309000		J/kg
Heat of sublimation	507390	602440	-		J/kg
Heat of combustion (low)	119.9	50.0	44.5	46.3	MJ/kg
Heat of combustion (high)	141.9	55.5	48.0	50.4	MJ/kg
Energy density	8.49	21.14	31.15	23.1	MJ/liter
Specific heat (Cp) of NTP gas	14890	2220	1620		J/kg-K
Specific heat (Cp) of NBP liquid	9690	3500	2200		J/kg-K
Specific heat ratio (Cp/Cv) of NTP gas	1.383	1.308	1.05	1.14	-
Specific heat ratio (Cp/Cv) of NBP liquid	1.7	1.7	-		-
Viscosity of NTP gas	0.8	1.1	0.52	8.0	10^{-5} kg/m-s
Viscosity of NBP liquid	0.000013	0.000113	0.0002		kg/m-s
Thermal conductivity of NTP gas	0.1897	0.033	0.0112		W/m-K
Thermal conductivity of NBP liquid	0.1	0.186	0.131		W/m-K
Surface Tension	0.00193	0.01294	0.0122		N/m
Dielectric constant of NTP gas	1.00026	1.00079	1.0035		-
Dielectric constant of NBP liquid	1.233	1.6227	1.93		
Index of refraction of NTP gas	1.00012	1.0004	1.0017		
Index of refraction of NBP liquid	1.11	1.2739	1.39		
Adiabatic sound velocity in NTP gas	1294	448	154		m/s
Adiabatic sound velocity in NBP liquid	1093	1331	1155		m/s
Compressibility factor (Z) of NTP gas	1.0006	1.0243	1.0069		-
Compressibility factor (Z) of NBP liquid	0.01712	0.004145	0.00643		-
Gas constant (R)	4.123	518.27	78.02		m^3-Pa-/kg-K
Isothermal bulk modulus of NBP liquid	50.13	456.16	763		MN/m^2
Volume expansivity (b) of NBP liquid	0.01658	0.00346	0.0012		/K
percentage of thermal energy radiated from diffusion flame to surroundings	17-25	23-32	30-42		percent

NTP= 1 atm and 20°C (293.15K) Normal temperature and Pressure; NBP= Normal Boiling Point

A.2.2 Odour, Colour and Taste

Pure hydrogen is odourless, colourless and tasteless. A stream of hydrogen from a leak is almost invisible in daylight. Hydrogen that derives from reforming other fossil fuels is typically accompanied by nitrogen, carbon dioxide, carbon monoxide and other trace gases. In general, all of these gases are also odourless, colourless and tasteless.

A.2.3 Toxicity

Hydrogen is non-toxic but can act as a simple asphyxiant by displacing the oxygen in the air. Oxygen levels below 19.5% are biologically inactive for humans. Effects of oxygen deficiency may include rapid breathing, diminished mental alertness, impaired muscular coordination, faulty judgement, depression of all sensations, emotional instability and fatigue. As asphyxiation progresses, dizziness, nausea, vomiting, prostration and loss of consciousness may result, eventually leading to convulsions, coma and death. At concentrations below 12%, immediate unconsciousness may occur with no prior warning symptoms. In an enclosed area, small leaks pose little danger of asphyxiation whereas large leaks can be a serious problem since the hydrogen diffuses quickly to fill the volume. The potential for asphyxiation in unconfined areas is almost negligible due to the high buoyancy and diffusivity of hydrogen.

A.2.4 Density and Related Measures

A.2.4.1 Density

Hydrogen has the lowest atomic weight of any substance and therefore has very low density both as a gas and a liquid. Density is measured as the amount of mass contained per unit volume. Density values only have a meaning at a specified temperature and pressure since both of these parameters affect the compactness of the molecular arrangement, especially in a gas. The density of a gas is called its vapour density, and the density of a liquid is called its liquid density.

A.2.4.2 Specific volume

Specific volume is the inverse of density and expresses the amount of volume per unit mass. Thus, the specific volume of hydrogen gas is 11.9 m^3/kg at 20 ºC and 0.1 MPa , and the specific volume of liquid hydrogen is 0.014 m^3 /kg at –253 ºC and 0.1 MPa.

A.2.4.3 Specific Gravity

A common way of expressing ***relative*** density is as specific gravity. Specific gravity is the ratio of the density of one substance to that of a reference substance, both at the same temperature and pressure. For vapour, air (with a density of 1.203 kg/m^3) is used as the reference substance and therefore has a specific gravity of 1.0 relative to itself. The density of other vapours is then expressed as a number greater or less than 1.0 in proportion to its density relative to air. Gases with a specific gravity greater than 1.0 are heavier than air; those with a specific gravity less than 1.0 are lighter than air. Gaseous hydrogen, of a density of 0.0837 kg/m3, has a specific gravity of 0.0696 and thus has approximately 7% the density of air. For liquids, water (with a density of 1000 kg/m^3) is used as the reference substance: it has a specific gravity of 1.0 relative to itself. As with gases, liquids with a specific gravity greater than 1.0 are heavier than water; those with a specific gravity less than 1.0 are lighter than water. Liquid hydrogen, with a density of 70.8 kg/m^3, has a specific gravity of 0.0708 and has thus approximately (and coincidentally) 7% of the density of water.

A.2.4.4 Expansion Ratio

The difference in volume between liquid and gaseous hydrogen can easily be appreciated by considering its expansion ratio. The expansion ratio is the ratio of the volume at which a gas or liquid is stored compared to the volume of the gas or liquid at atmospheric pressure and temperature. When hydrogen is stored as a liquid, it is vaporizes upon expansion to atmospheric conditions with a corresponding increase in volume. Hydrogen's expansion ratio of 1:848 means that hydrogen in its gaseous state at atmospheric conditions occupies 848 times more volume than it does in its liquid state. When hydrogen is stored as a high-pressure gas at 250 bar and atmospheric temperature, its expansion ratio to atmospheric pressure is 1:240. While a higher storage pressure increases the expansion ratio somewhat, gaseous hydrogen under any conditions cannot approach the expansion ratio of liquid hydrogen.

A.2.4.5 Hydrogen Content

Even as a liquid, hydrogen is not very dense. Ironically, every cubic meter of water (made up of hydrogen and oxygen) contains 111 kg of hydrogen whereas a cubic meter of liquid hydrogen contains only 71 kg of hydrogen. Thus, water packs more mass of hydrogen per unit volume, because of its tight molecular structure, than hydrogen itself. This is true of most other liquid hydrogen-containing compounds as well; a cubic meter of methanol contains 100 kg of hydrogen and a cubic meter of heptane contains 113 kg. Hydrocarbons are compact hydrogen carriers with the added advantage of having a higher energy density than pure hydrogen. When used as vehicle fuel, the low density of hydrogen necessitates that a large volume of hydrogen be carried to provide an adequate driving range.

A.2.4.6 Leakage

The molecules of hydrogen gas are smaller than those of tall other gases, and hydrogen can diffuse through many materials considered airtight or impermeable for other gases. This property makes hydrogen more difficult to contain than other gases. Leaks of liquid hydrogen evaporate very quickly since the boiling point of liquid hydrogen is so extremely low. Hydrogen leaks are dangerous in that they pose a risk of fire where they mix with air. However, the small molecular size that increases the likelihood of a leak also results in very high buoyancy and diffusivity, so leaked hydrogen rises and becomes diluted quickly, especially outdoors. This results in a localized region of flammability that disperses quickly. As the hydrogen dilutes with distance from the leakage site, the buoyancy decreases and the tendency for the hydrogen to continue to rise decreases. Very cold hydrogen, resulting from a liquid hydrogen leak, becomes buoyant after is evaporates.

A.3 CHEMICAL PROPERTIES

A.3.1 Energy

A.3.1.1 Energy Content

Every fuel can liberate a fixed amount of energy when it reacts completely with oxygen. This energy content is measured experimentally and is quantified by a fuel's higher heating value (HHV) and lower heating value (LHV). The difference between the HHV and the LHV is the "heat of vaporization" and represents the amount of energy required to vaporize a liquid fuel into a gaseous fuel, as well as the energy used to convert water to steam. The higher and lower heating values of comparative fuels (at 25°C and 0.1 MPa) are indicated in Table A-2. Gaseous fuels are already vaporized so no energy is required to convert them to a gas. The water that results from both a combustive reaction and the electrochemical reaction within a fuel cell occurs as steam therefore the lower heating value represents the amount of energy available to do external work.

Both the higher and lower heating values denote the amount of energy (in Joules) for a given weight of fuel (in kilograms). Hydrogen has the highest energy-to-weight ratio of any fuel since hydrogen is the lightest element and has no heavy carbon atoms. It is for this reason that hydrogen has been used extensively in the space program where weight is crucial. Specifically, the amount of energy liberated during the reaction of hydrogen, on a mass basis, is about 2.5 times the heat of combustion of common hydrocarbon fuels (gasoline, diesel, methane, propane, etc.). Therefore, for a given load duty, the mass of hydrogen required is only about a third of the mass of hydrocarbon fuel needed.

The high energy content of hydrogen also implies that the energy of a hydrogen gas explosion is about 2.5 times of that of common hydrocarbon fuels [46]. Thus, on an equal mass basis, hydrogen gas explosions are more destructive and carry further. However, the duration of a deflagration tends to be inversely proportional to the combustive energy, so that hydrogen fires subside much more quickly than hydrocarbon fires.

Table A-2 Energy densities of comparative fuels [46, 227]

Fuel	Energy Density (LHV, in kJ/m^3)	Remarks
Hydrogen	10,050	Gas at 0.1 MPa and 15°C
	1,825,000	Gas at 20 MPa and 15°C
	4,500,000	Gas at 69 MPa and 15°C
	8,491,000	Liquid
Methane	32,560	Gas at 0.1 MPa and 15°C
	6,860,300	Gas at 20 MPa and 15°C
	20,920,400	Liquid
Propane	86,670	Gas at 0.1 MPa and 15°C
	23,488,800	Liquid
Gasoline	31,150,000	Liquid

A.3.1.2 Energy Density

Whereas the energy content denotes the amount of energy for a given weight of fuel, the energy density denotes the amount of energy (in Joules) for a given volume (in m^3) of fuel. Thus, the energy density is the product of the energy content (LHV) and the density of a given fuel. The energy density is really a measure of how compactly hydrogen atoms are packed in a fuel. It follows that hydro-carbons of increasing complexity (with more and more hydrogen atoms per molecule) have an increasing energy density. At the same time, hydrocarbons of increasing complexity have more and more carbon atoms in each molecule so that these fuels are heavier and heavier in absolute terms. On this basis, hydrogen's energy density is poor (since it has such low density) although its energy to weight ratio is the best of all fuels (because it is so light). The energy density of comparative fuels, based on the LHV, is indicated in Table A-2.

A.3.2 Flammability

Three things are needed for a fire or explosion to occur: a fuel, oxygen (mixed with the fuel in appropriate quantities) and a source of ignition. Hydrogen, as a flammable fuel, mixes with oxygen whenever air is allowed to enter a hydrogen vessel, or when hydrogen leaks from any vessel into the air. Ignition sources take the form of sparks, flames, or high heat.

A.3.2.1 Flashpoint

All fuels burn only in a gaseous or vapour state. Fuels like hydrogen and methane are already gases at atmospheric conditions, whereas other fuels like gasoline or diesel that are liquids must be converted to vapour before they burn. The characteristic that describes how easily these fuels can be converted to vapour is the flashpoint. The flashpoint is defined as the temperature at which the fuel produces enough vapour to form an ignitable mixture with air at its surface. If the temperature of the fuel is below its flashpoint, it can not produce enough vapour to burn since its evaporation rate is too slow. Whenever a fuel is at or above its flashpoint, vapour is present. The flashpoint is not the temperature at which the fuel bursts into flames; that is the autoignition temperature.

Table A-3 Chemical properties of Hydrogen and comparative Fuels [36, 46, 17, 227]

Properties	**Hydrogen**	**Methane**	**Propane**	**Gasoline**
Higher Heating Value (kJ/g)	141.86	55.53	50.36	47.5
Lower Heating Value (kJ/g)	119.93	50.02	45.6	44.5
Flammability limit (vol%)	4 - 75	5.3 – 15	2.1 – 9.5	1-7.6
Detonability limit (vol%)	18.3 – 59	6.3 – 13.5	2.6 – 7.4	1.1-3.3
Ignition energy (mJ)	0.02	0.29	0.26	0.305
Autoignition Temperature (°C)	585	540	490	230 - 480
Flame temperature (°C)	2045	1875	1925	2197
Burning speed (m/s)	2.65 – 3.25	0.37 – 0.45	0.43 – 0.52	0.37 – 0.43
Quenching gap (mm)	0.64	2.03	1.78	2.0
Flash point (°C)	-253	-188	-104	-43

A.3.2.2 Flammability Range

The flammability range of a gas is defined in terms of its lower flammability limit (LFL) and its upper flammability limit (UFL). The LFL of a gas is the lowest gas concentration that will support a self-propagating flame when mixed with air and ignited. Below the LFL, there is not enough fuel present to support combustion; the fuel/air mixture is too lean. The UFL of a gas is the highest gas concentration that will support a self-propagating flame when mixed with air and ignited. Above the UFL, there is not enough oxygen present to support combustion; the fuel/air mixture is too rich. Between the two limits is the flammable range in which the gas and air are in the right proportions to burn when ignited.

A stoichiometric mixture occurs when oxygen and hydrogen molecules are present in the exact ratio needed to complete the combustion reaction. If more hydrogen is available than oxygen, the mixture is rich so that some of the fuel will remain un-reacted although all of the oxygen will be consumed. If less hydrogen is available than oxygen, the mixture is lean so that all the fuel will be consumed but some oxygen will remain. Practical internal combustion and fuel cell systems typically operate lean since this situation promotes the complete reaction of all available fuel. One consequence of the UFL is that stored hydrogen (whether gaseous or liquid) is not flammable while stored due to the absence of oxygen in the cylinders. The fuel only becomes flammable in the peripheral areas of a leak where the fuel mixes with the air in sufficient proportions.

Hydrogen is flammable over a very wide range of concentrations in air (4 – 75%) and it is explosive (detonate) over a wide range of concentrations (15 – 59%) at standard atmospheric temperature. The flammability limits increase with temperature as illustrated in Figure A.2. As a result, even small leaks of hydrogen have the potential to burn or explode. Leaked hydrogen can concentrate in an enclosed environment, thereby increasing the risk of combustion and explosion. The flammability limits of comparative fuels are shown in Table A-3.

A.3.2.3 Autoignition Temperature

The autoignition temperature is the minimum temperature required to initiate self-sustained combustion in a combustible fuel mixture in the absence of a source of ignition. In other words, the fuel is heated until it bursts into flame. Each fuel has a unique ignition temperature. For hydrogen, the autoignition temperature is relatively high at 585 ºC. This makes it difficult to ignite a hydrogen/air mixture on the basis of heat alone without some additional ignition source. The autoignition temperatures of comparative fuels are indicated in Table A-3.

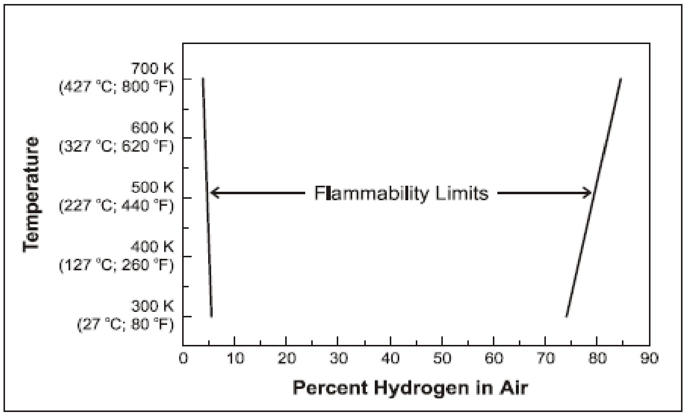

Figure A.1. Variation of Hydrogen Flammability Limits with Temperature [46]

A.3.2.4 Ignition Energy

Ignition energy is the amount of external energy that must be applied in order to ignite a combustible fuel mixture. Energy from an external source must be higher than the autoignition temperature and be of sufficient duration to heat the fuel vapour to its ignition temperature. Common ignition sources are flames and sparks.

Although hydrogen has a higher autoignition temperature than methane, propane or gasoline, its ignition energy at 0.02 mJ (Table A-3) is about an order of magnitude lower and it is therefore more easily ignitable. Even an invisible spark or static electricity discharge from a human body (in dry conditions) may have enough energy to cause ignition. Nonetheless, it is important to realize that the ignition energy for all of these fuels is very low so that conditions that will ignite one fuel will generally ignite any of the others.

Hydrogen has the added property of low electro-conductivity so that the flow or agitation of hydrogen gas or liquid may generate electrostatic charges that result in sparks. For this reason, all hydrogen conveying equipment must be thoroughly grounded.

A.3.2.5 Burning Speed

Burning speed is the speed at which a flame travels through a combustible gas mixture. It is different from flame speed. The burning speed indicates the severity of an explosion since high burning velocities have a greater tendency to support the transition from deflagration to detonation in long tunnels or pipes. Flame speed is the sum of burning speed and displacement velocity of the unburned gas mixture. Burning speed varies with gas concentration and drops off at both ends of the flammability range. Below the LFL and above the UFL the burning speed is zero. The burning speed of hydrogen at 2.65–3.25 m/s (Table A-3) is nearly an order of magnitude higher than that of methane or gasoline (at stoichiometric conditions). Thus hydrogen fires burn quickly and, as a result, tends to be relatively short-lived.

A.3.2.6 Quenching Gap

The quenching gap (or quenching distance) describes the flame extinguishing properties of a fuel when used in an internal combustion engine. Specifically, the quenching gap relates to the distance from the cylinder wall that the flame extinguishes due to heat losses. The quenching gap has no specific relevance for use with fuel cells. The quenching gap of hydrogen (at 0.064 cm) is approximately 3 times less than that of other fuels, such as gasoline (Table A-3). Thus, hydrogen flames travel closer to the cylinder wall before they are extinguished making them more difficult to quench than gasoline flames. This smaller quenching distance can also increase the tendency for backfiring since the flame from a hydrogen-air mixture can more readily get past a nearly closed intake valve than the flame from a hydrocarbon-air mixture.

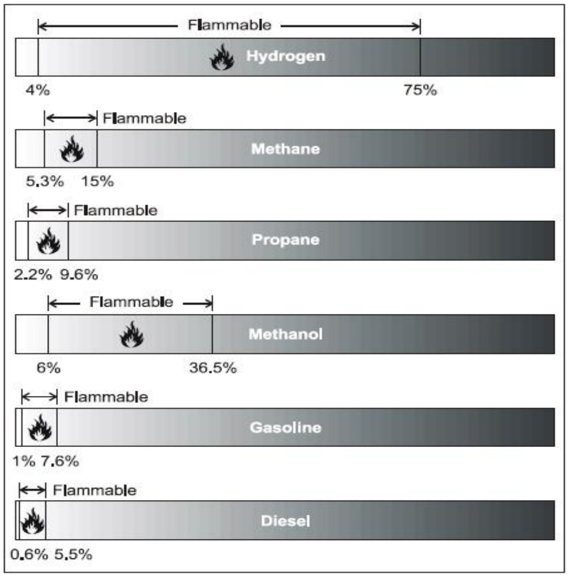

Figure A.2. Flammability Ranges of Comparative Fuels at Atmospheric Temperature [46]

Table A-4 Combustion properties of hydrogen in air at 1 Atm and 25°C[36]

Combustion properties	**Deflagration**	**Detonation**	**Units**
Heat of reaction (high)	142.5	142.5	MJ/kg
Lower lammability limit in air	4.1	18.3	Volume%
	0,0036	0,0183	kg/m^3 of air
Upper flammability limit in air	74	59	Volume%
	0.067	0.0518	kg/m3 of air
Optimum detonation mixture ratio in air	-	29.5	Volume%
Detonation maximum overpressure in air	-	1.5	Mpa
Auto-ignition temperature	574	574	°C
Minimum ignition	0.02	$^{3}10^{7}$	mJ
Maximum flame temperature in air	2591.2	2044.9	°C
Explosion energy	-	2,02	kg TNT/m^3 of NTP gas
laminar burning velocity in air	1.0-3.3	-	m/s
Detonation velocity in air	-	1480-2150	m/s
maximum overpressure ratio	8:1	14.5:1	

A.3.3 Hydrogen Embrittlement

Constant exposure to hydrogen causes a phenomenon known as hydrogen embrittlement [HE] in many materials. The HE can lead to leakage or catastrophic failures in metal and nonmetallic components. The mechanisms that cause HE effects are not well defined [36]. Factors known to influence the rate and severity of HE include hydrogen concentration, hydrogen pressure, temperature, hydrogen purity, type of impurity, stress level, stress rate, metal composition, metal tensile strength, grain size, microstructure and heat treatment history. Moisture content in the hydrogen gas may lead to metal embrittlement through the acceleration of the formation of fatigue cracks. According to [56, 96], HE can be classified into three categories:

(1.) Hydrogen reaction embrittlement
It is a phenomenon in which the hydrogen chemically reacts with a constituent of the metal to form a new microstructural element or phase such as a hydride or gas bubble, e.g. methane gas if combined with carbon, or steam if combined with oxygen. These reactions usually occur at higher temperatures. They result in the formation of blisters or expansions from which cracks may originate to weaken the metal.

(2.) Internal hydrogen embrittlement
It means that hydrogen is introduced into the metal during its processing, e.g. chemical reactions with water to form metal oxide and liberate hydrogen. It is a phenomenon that may lead to the structural failure of material that never has been exposed to hydrogen before. Internal cracks are initiated showing a discontinuous growth. Not more than 0.1 – 10 ppm hydrogen on the average is involved. The effect is observed in the temperature range between -100 and +100°C and is most severe near room temperature.

(3.) Environmental hydrogen embrittlement
It means that the material was subjected to a hydrogen atmosphere, e.g. storage tanks. Absorbed and/or adsorbed hydrogen modifies the mechanical response of the material without necessarily forming a second phase. The effect occurs when the amount hydrogen that is present, is more than the amount of metal that is present, is more than the amount that is dissolved in the metal. The effect strongly depends on the stress imposed on the metal. It also maximizes at around room temperature.

A.3.4 Cold Embrittlement

Hydrogen in liquid phase (LH2) is classified as a cryogenic liquid. The cryogenic temperature can affect structural materials. With decreasing temperature, ultimate stress and yield stress increase for most metals, generally connected with a corresponding drop in fracture toughness which is a measure of the material's ability to resist crack propagation. The lower the toughness, the smaller is the tolerable crack length. A material can change from ductile to brittle behaviour as soon as the temperature falls below its "nil-ductility-temperature", which is sometimes considerably higher than the cryogenic temperature. It is a particular problem in cryogenic equipment exposed to periodic temperature of the cryogen. Several accidents with failure of a cryogenic storage tank have been traced to originate from cold embrittlement, for example the severe accident with the rupture of a 4250 m^3 LNG tank in Cleveland, 1944 [56].

A.3.5 Material Questions [96]

Materials for hydrogen containing components have to meet the requirements of high strength and high ductility to permit a high system pressure and to be appropriate for welding. Respective materials are ultrafine grain steels and thermochemically treated steels. Usually applied dense coatings on the surface of the ferritic steels containing gaseous hydrogen prevent the adsorption of hydrogen unless they are damaged by plastic deformation. An additional requirement for material containing LH2 is a sufficient fracture viscosity. Adequate materials are aluminium alloys, austenitic steels and steels with a high Ni fraction.

Appendix B

HYDROGEN PRODUCTION TECHNOLOGIES

B.1 INTRODUCTION

Although hydrogen is the most abundant element in the Universe, it does not exist in free state in any significant amount on the Earth. It is found almost always chemically bound to other elements such as water, biomass, or fossil fuels. Molecular hydrogen, therefore, must thus be extracted from compounds such as water or organic molecules. This appendix discusses several methods of hydrogen production from fossil fuels, water, or as a chemical by product.

B.2 PRODUCTION FROM FOSSIL FUELS

B.2.1 Steam Reforming of Natural Gas

Steam reforming refers to the endothermic, catalytic conversion of light hydrocarbons (Methane to Gasoline) with water vapour. A simplified basic flow diagram of the conventional steam reforming process is shown in Figure B.1. Industrial scale processes of this kind are normally carried out at temperatures of 850°C and pressures in the order of 25 bar, according to:

$$C_nH_m + n\ H_2O \rightarrow n\ CO + (n + m/2)\ H_2.$$

Exothermic catalytic conversion (shift reaction) of the resulting carbon monoxide produces pure hydrogen according to:

$$CO + H_2O \rightarrow CO_2 + H_2.$$

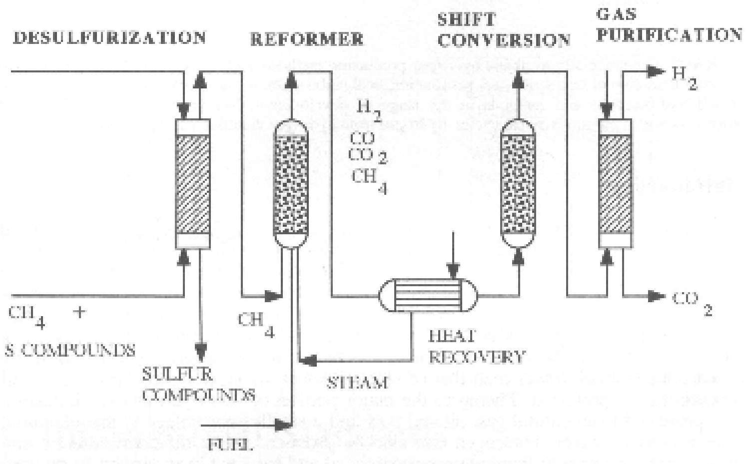

Figure B.1 A simplified basic flow diagram of the conventional steam reforming [211]

The energy released from this reaction can however not be directly used for the reformation. Using absorption or membrane separation, the carbon dioxide is removed from the gas mixture, which is further cleaned to remove other unwanted components. The leftover gas consisting of approx. 60% combustible parts (H_2, CH_4, CO) is, along with a portion of the primary gas itself, used to fuel the reformer. Steam reforming is not apt to convert hydrocarbons heavier than naphtha to hydrogen, thus partial oxidation of heavier feedstock is used to produce hydrogen. Heavy residues from petrochemical processes are the preferred feedstock for the production of hydrogen and carbon monoxide-rich gases.

B.2.2 Partial Oxidation of Heavy Oil

As steam reforming is not applicable to convert hydrocarbons heavier than naphtha to hydrogen, partial oxidation of heavier feedstock is used to produce hydrogen. A simplified flow diagram of the process is shown in Figure B.2. The process basically proceeds at moderately high pressure with or without a catalyst, depending on the raw material and process selected. The catalytic partial oxidation which occurs at 600°C, uses feedstock ranging from methane to naphtha. The non-catalytic partial oxidation operates at 1150-1315°C and can use hydrocarbons ranging from methane, heavy oil to coal. There are three main steps, i.e. synthesis gas generation, water-gas shift reaction, and gas purification. The shift reaction and gas purification either by the conventional wet scrubbing or by the pressure swing adsorption operation are similar to those used in steam reforming. In the synthesis gas generation step, the hydrocarbon feedstock is partially oxidized with oxygen and the carbon monoxide produced is shifted with steam to CO_2 and H_2. Pure oxygen is used in the process because of the difficulties of separating nitrogen to produce pure hydrogen. The partial oxidation reactions are as follow:

$$
\begin{array}{lcl}
C_n\,H_m + n/2\ O_2 & \longleftrightarrow & n\,CO + m/2\ H_2 + \text{heat} \\
C_n\,H_m + n\,H_2O + \text{heat} & \longleftrightarrow & n\,CO + (n+m/2)\ H_2 \\
CO + H_2O & \longleftrightarrow & CO_2 + H_2 + \text{heat}
\end{array}
$$

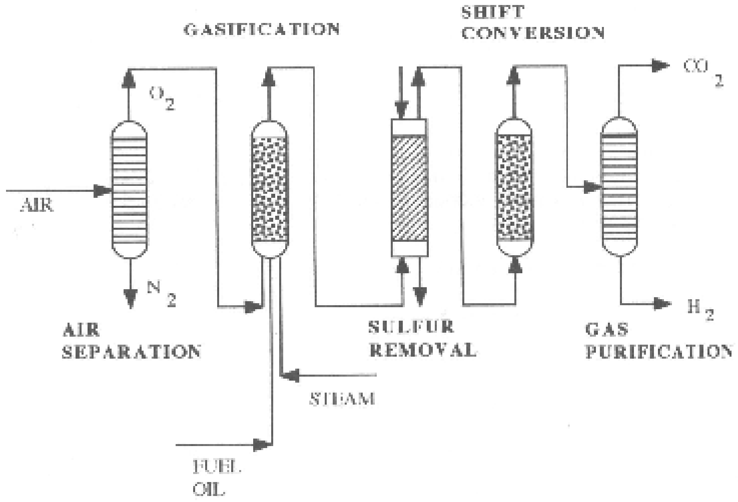

Figure B.2 Process flow sheet for H_2 production from partial oxidation of heavy oil [211].

The hydrocarbon-oxygen reaction is exothermic, the additional energy required for the endothermic hydrocarbon-steam reaction, similar to steam reforming, is supplied by burning additional fuel. The reactions occur mainly in the flame and in an empty brick-lined reactor. The shift reaction occurs along with the oxidation-gasification reactions at temperatures above

1200°C without the presence of catalysts. The product is a very hot mixture of H_2 (46%, by vol.), CO (46%, by vol.), CO_2 (6%, by vol.), CH_4 (1%, by vol.), N_2 (1%, by vol).

B.2.3 Coal Gasification

Coal gasification is defined as a process, in which coal is converted to gaseous products. When coal is fed into a gasification reactor and heated up, it mainly undergoes pyrolysis reactions in which gases, volatile tar components and char are formed (see Fig. B.3). Coal gasification is generally done with oxygen of 95% purity, at high temperatures and elevated pressures. It is used for the production of hydrogen or hydrogen-rich gas products. Gasification reactions are:

$$2\,C + O_2 \leftrightarrow 2\,CO + \text{heat}$$
$$C + H_2O + \text{heat} \leftrightarrow CO + H_2$$

Basically, all types of coal can be gasified to produce hydrogen, although certain limitations associated with the gasification process or the characteristics of the coal have to be respected. The coal gasification process is complicated because of the need of handling solids including transport, size reduction and removing large amounts of ash. The handling operations for solids significantly affect the cost of hydrogen production.

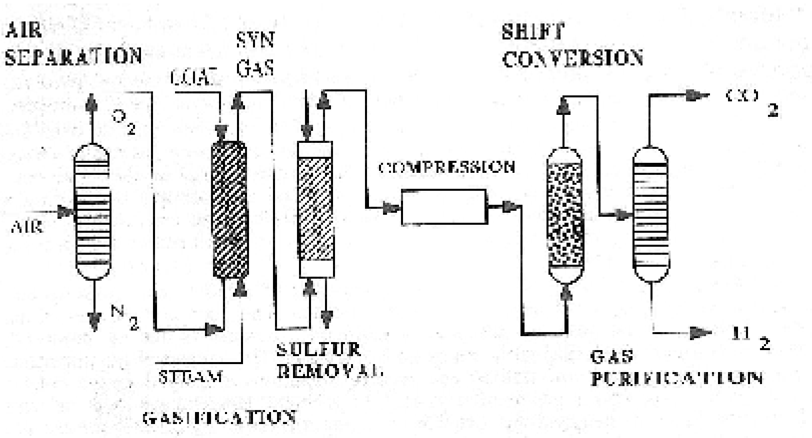

Figure B.3 Process flow sheet for hydrogen production from coal gasification [211]

B.3 CHEMICAL BY-PRODUCT (CHLORINE-ALKALI ELECTROLYSIS)

A solution of salt in water is electrolytically decomposed into hydrogen and soda lye (cathode) and chlorine (anode) for the mercury process (as shown in Fig. B.4). Chlorine and caustic soda are the main products made from the chlorine-alkali electrolysis technology. Mercury is used as a negative electrode or cathode that works with a titanium anode to keep the highly reactive products involved apart when electricity is passed through brine. As mercury is extremely toxic, 100% needs to be recycled within the plant to ensure there are no dangers to the environment. The chlorine-alkali electrolysis process results in the manufacture of Cl_2, H_2, and NaOH caustic solution. Of these three, the primary product is Cl_2. The overall process reaction is:

$$2NaCl + 2H_2O \rightarrow Cl_2 + H_2 + 2NaOH$$

The plant produces NaOH, H_2, and Cl_2 as described above plus HCl and liquid sodium hydrosulfite. The Olin facility (USA) has a total rated output of 340 tonnes/day of Cl_2, 348

383 tonnes/day of NaOH, and 9 tonnes/day of H_2 produced by the 60 cells in the building [96].

The chlorine-alkali water electrolysis is the only large-scale technological method to be commercialized, where the hydrogen is actually a by-product of the chlorine production and mostly used as a thermal energy source and substitute of natural gas.

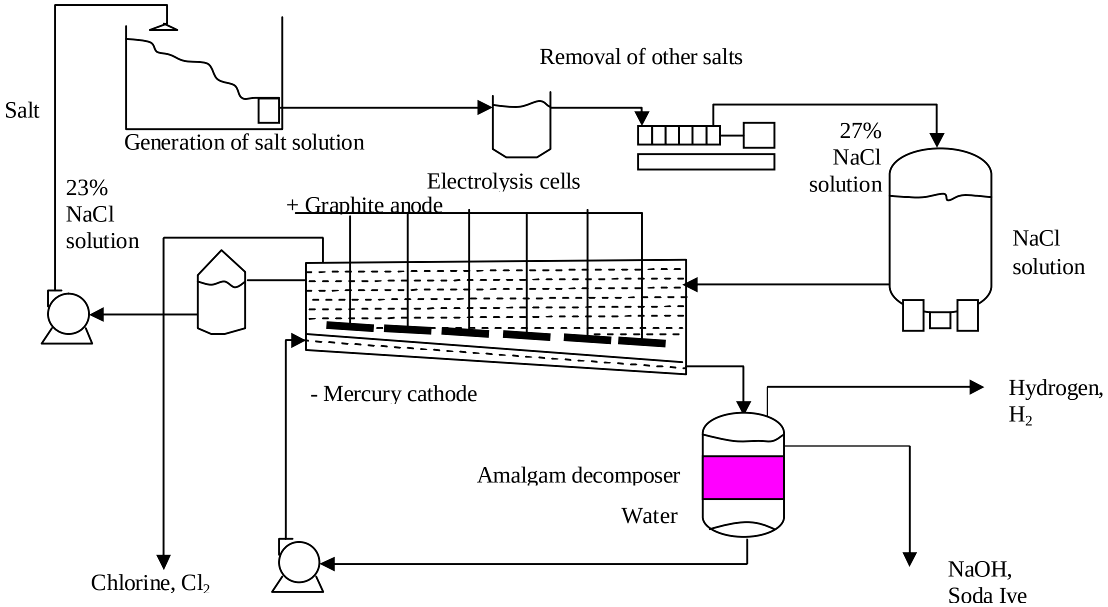

Figure B.4 Electrolyte chlorine (and hydrogen) production using mercury process [96]

B.4 REFINERY BY-PRODUCT (CATALYTIC REFORMING)

Catalytic reforming is a conversion process in which a catalytically promoted chemical reaction converting low octane feed components into high octane products. The use of a catalyst results in much higher octane levels and yields than can be obtained in thermal reforming. In addition, significant amounts of valuable hydrogen are produced as a by-product (Figure B.5).

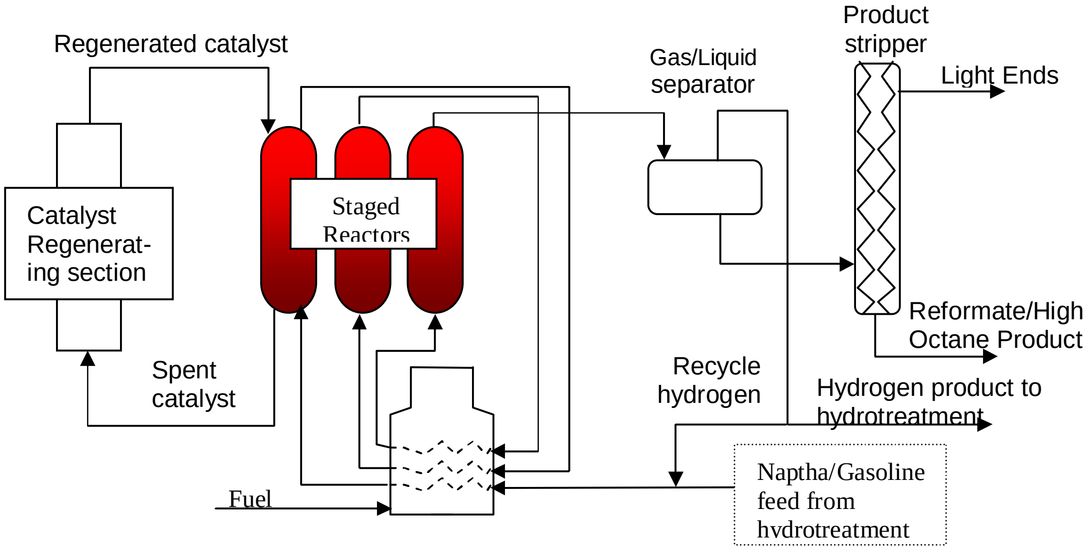

Figure B.5 Catalytic reforming flow diagram (continuous) [214]

Feed to the reformer (naptha, a light petroleum fraction) is mixed with recycled hydrogen gas, raised to the reaction temperature (482 – 548°C) by heat exchange and a fired heater, and is then charged to the reactor section. After proceeding through the series of reactors, effluent is cooled by air or water cooling. Gas and liquid products are then separated. Some of the gas from the separator is recycled back to the reactor section; net hydrogen produced is used elsewhere in the refinery complex (e.g., hydrocracking). The liquid effluent is then pumped to a stabilizer system where light, volatile hydrocarbons (methane, ethane, propane and butane) are fractionated off. Aromatic components are left in the stabilizer bottoms as reformate. The primary product stream (80-90%) is a high-quality gasoline blending component.

B.5 PRODUCTION FROM BIOMASS

B.5.1 Steam Gasification of Biomass

Along with the commercial methods of biomass utilization, this can be used to produce hydrogen via pyrolysis and gasification. Coke, methanol and primary gases are obtained in the first stage. In the second, the reaction with (air) oxygen and/or steam results in a mixture of 20% H_2, 20% CO, 10% CO_2, almost 5% CH_4 and 45% N_2. Using pure oxygen or steam only eliminates the nitrogen component. The transformation of this gas mix into hydrogen rich gas is named, depending on the feedstock, gasification (solids) or reforming (gas). Endothermic reactions of hydrocarbons with steam create synthetic gases with high hydrogen content, whereby the so called shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$) can be used to alter the molar CO/H_2 ratio. The hydrogen content of the gas is determined by the process parameters “pressure and temperature”.

B.5.2 Biomass Fermentation

From high moisture content biomass a liquid manure biogas can be produced via methane fermentation. This gas contains high CO and CH_4. Although it contains hardly any hydrogen, this gas can be used as a fuel for advanced high temperature fuel cells (MCFC), whereby methane reformation takes place directly at the electrode due to the high temperatures (~ 650°C). The fermentation process of biomass is commercially tested and available. The combination of the process for the production of hydrogen has not, as far as is known, been carried out so far. Only in connection with the molten carbonate fuel cell would such an option appear to be of interest, as this process offers high electricity generation efficiency with reduced plant complexity [96].

B.5.3 Biological Hydrogen Production

There are various biological processes by which hydrogen is released or appears as an intermediate product. One can basically separate these into two process types: photosynthesis, for which light is required and fermentation, which occurs in darkness. As there is still no sign of a market in this area, a detailed description will not be given. The use of biological processes for hydrogen production is presently at the point of technical system development, whereby there also still remain many unresolved fundamental biochemical questions. At the moment an algae-bacteria-system seems to be the best candidate for the first technical application. Investigations carried out so far indicate that hydrogen production costs of 25 cent/kWh H_2 or less are achievable [96].

B.6 WATER ELECTROLYSIS

The most common way of splitting water is by electrolysis, though it can also be done using a thermochemical reaction or simply by heating. Electrolysis at a small scale can be carried out almost anywhere - passing a current through water is sufficient to generate a few bubbles of hydrogen at the cathode and oxygen at the anode. In order to make it efficient an electrolyte is required - an alkali such as potassium hydroxide is often used - and efficiencies of about 90% are standard [96]. Research into high temperature and polymer electrolyte electrolysers is progressing with the hope that these may be cheaper or more efficient than the current technology. Table B-1 shows the present development of electrolyzers.

B.6.1 Conventional Water Electrolysis

Conventional alkaline electrolysis works with an aqueous alkaline electrolyte. The cathode and anode areas are separated by a micro-porous diaphragm to prevent mixing of the product gases. Presently in Germany, conventional unpressurised electrolysis utilizes new materials that replace the previously used asbestos diaphragm. With output pressures of 2 - 5 bar these processes can reach efficiencies, related to the lower heating value of hydrogen, of around 65%. Newly developed diaphragms and membranes from other materials demonstrate, through their good turn off characteristics, relatively good reliability when subject to fluctuating operating conditions. They are therefore applicable in conjunction with renewable energy technologies.

Conventional water electrolysers have been in use commercially for many decades. Units with capacities from 1 kWe to 125 MWe are available. The Electrolyser Corporation Ltd. (Canada) and Norsk Hydro Electrolysers AS (Norway) are well established manufacturers of conventional elctrolysers, offering units with very high capacity. Several manufacturers have also established themselves in the 1 - 100 kW range in Europe (e.g. Ammonia Casale, ELWATEC, Hidroenergia VCST (up to 1 MPa), vHS (von-Hoerner-System; up to 30 bar but also unpressurised).

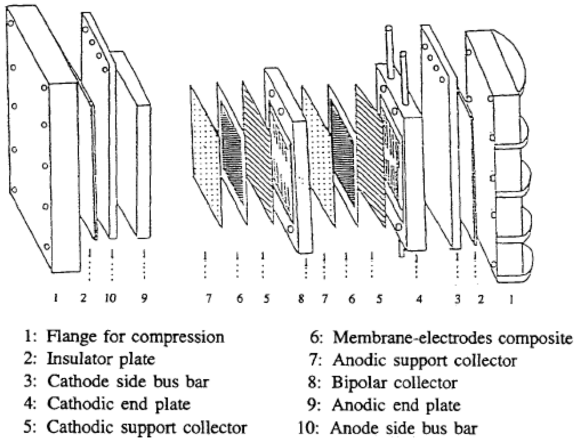

Figure B.6 Schematic of SPEWE module consisting of 5 cells with a total electrode of 500 cm^2, production capacity of 2 Nm^3/h, from [96]

B.6.2 High Pressure Water Electrolysis

Through a special material choice and optimization, high pressure water electrolysis allows the generation of hydrogen at pressures of up to 5 MPa. The processes under development attempt to find an appropriate capacity optimization that will also allow a problem free connection of the electrolyser with a fluctuating current supply (e.g. Wind or PV connection for isolated plants). A development work to mention is that being carried out by GHW (Gesellschaft für Hochleistungswasserelektrolyse) for the commercialization of a high performance electrolyser with output pressures up to the 5 MPa level. The goal of these efforts is to reach, along with the high output pressure, an appropriately optimized operating efficiency applicable to strongly varying loads. In the field of small capacity units (under 100kW), vHS has the appropriate equipment to offer.

Table B-1 Present electrolyzer development [96]

Electrolyser Type	Anode (A) Cathode (C)	Operating Condition	Cell Efficiency (%)	Cel Voltage (V)	Current Density (kA/m^2)	Energy Cons. (kWh/Nm^3 H_2)	Remarks
Alkaline (20-30% KOH)	(A):Ni; (C):Ni, Steel	70 - 90°C, Ambient pressure	77-80	1.84 - 2.25	1.3-2.5	4.3-4.9	Com. large-scale prov. tech., simple, low eff., corrosive electrolyte
		80°C, ambient pressure	83	1.8	3	4.3	Norsk Hydro, >400 kW, capacity 100-400 Nm3/h
		90°C, 3.2 MPa	79	1.7	4	4.2	Lurgi, 25 MW, capacity 5100 Nm3/h
		30-85°C, 0.3 - 0.9 MPa	69		3.5	5.0	Hysolar 350 kW
		100°C; 0.11 MPa	87	1.7	5	4.0	Research center Jülich, Hysolar 10 kW
		110°C, 0.5 MPa	90	1.7	5	3.9	Hydrogen system, <100 kW, commercial 5-10 kW
Advanced alkaline (25-40 % KOH)	(A): Ni (C): Ni	90-145°C, < 4 MPa	80-90	1.5 - 3.0	-	3.8 - 4.3	Lab scale, prototype, com. potential, severe cor. at higher temp.
		120°C		1.5	2.5	3.8	Research center Jülich, 10 kW
Inorganic Membrane alkaline (14-15% NaOH)	(A):spinel oxide (C):NiS	90-120°C < 4 MPa	82-91	1.6-1.9	1.6 -1.9	3.6-4.0	Lab scale, prototype, non-noble metal cat., membrane perf. needs to be demonstrated
Solid polymer (Nafion)	(A): Ti, (C): carbon with Pt	80-150°C, < 4 MPa	85-90	1.4 - 2.0	2.5-20		100 kW, compact, non-cor. elect., noble metal cat, exp. membrane
		100-130°C, < 4 MPa	88	1.7	10		GIRI, Osaka, production rate 1.3 Nm3/h
Intermediate temp Molten Carbonate (KOH/NaOH)	(A): Ni (C): Ni	300-600°C	82-91	1.3-1.4	>2		simple double cell configuration
High-temperature (solid Y_2O_3 stab. ZrO_2)	(A): Ni-NiO, (C):Ni	800-1000°C, < 3MPa	90-100	0.95-1.3	10	3.5	Very small lab scale, non-cor. Electr., severe material & fabrication problem

B.6.3 Solid Polymer Electrolyte Water Electrolysis

Solid Polymer Electrolyte Water Electrolysis (SPEWE) is considered to be a promising method because it can operate at high current densities due to the extreme volume reduction compared with the KOH electrolyte, and low cell alloys. It is based on the use of a proton conducting membrame of the sulfonic acid type, Nafion, with a tenth of a millimetre thickness, which acts both as an acid and as a separating wall. In these membrane electrolyzers, only clean water is used. SPEWE has the advantages of cell compactness, simpliyity in design and operation, lack of corrosion. A considerable handicap, however, is represented by the high cost of the membrane production and the need of noble metal primary electrodes.

B.7 SUMMARY OF HYDROGEN PRODUCTION METHODS [96]

If hydrogen production processes are compared, the interdependence of efficiency, capital investment and value of the byproduct has to be taken into account. From the reaction equations, it can be derived that an essential part of the hydrogen is gained from water, e.g. 50% in the case of steam reforming of natural gas plus CO conversion. On the other hand, all carbon in the raw materials is finally converted to CO_2 and released into the atmosphere. The least unfavourable process is steam reforming with a CO_2 to H_2 ratio of 0.25, and the worst in coal gasification with a respective ratio of 1. The use of heavier raw materials is connected with a loss of efficiency since a larger mass of C-carriers and water need to be heated up to reaction temperature.

Table B-2 Characteristics of splitting process for hydrogen production from [46]

Splitting process	Energy required [kWh/Nm^3 of H_2]		Status	Efficiency (%)	Cost relative to SMR	Fraction of production [%]
	in theory	in practice				
Steam methan reforming (SMR)	0,78	2-2.5	mature	70 - 80	1	48
Partial oxidation of heavy oil	0,94	4,9	mature	70	1,8	30
Naphta reforming			mature			
Coal gasification	1,01	8,6	mature	60	1.4 - 2.6	18
Partial oxidation of coal			mature	55		
Chloralkali electrolysis			mature		byproduct	4
Water electrolysis	3,54	4,9	R&D - mature	27	5-10	
Thermochemical cycles			R&D	35-45	6	
Biomass conversion			R&D		2-2.4	-
Photolysis			R&D	< 10		

Reforming of natural gas and partial oxidation of heavy oils are presently the least expensive and most frequently applied methods of hydrogen production (see Table B-2). Meanwhile, electrolysis is the most expensive process unless cheap electricity is available. Production of hydrogen from coal gasification is not an ideal alternative in term of the necessary reduction of CO_2 emissions in the future, because the reduction is no higher than 20-30% compared with the coal feed. In this respect, gasification of CO_2-neutral biomass would be better alternative, although non-CO_2 gases with a global warning potential are emitted with its combustion [96].

Appendix C

HYDROGEN ACCIDENTS

C.1 INTRODUCTION

Although the history of hydrogen technology demonstrates an excellent safety record, accidents have occurred. As noted by [36] there is an extremely negative public reaction to the use of hydrogen, particularly centering on memories of the airship Hindenburg event. The goal of the appendix is to summarize several accidents related to hydrogen (including Germany).

C.2 HYDROGEN ACCIDENTS

The following description of accidents does not represent a complete list of all accident involving hydrogen. Rather, it consists of examples of accidents about which the authors have more than just a casual knowledge of the conditions or causes. Table C-1 shows a list of accidents related to hydrogen collected from some accident databases, such as UNEP, OECD, MHDAS, BARPI, etc.

Table C-1 Summary of accidents related to hydrogen [UNEP, OECD, MHDAS, BARPI, 117]

Year	Date	Location	Origin of Acidents	Death	Injury	Evacuated
2001	01.05	Oklahoma (trailer), USA	Fire	1	1	15
2001	18.04	Labadie, Missouri	Fire	NA	NA	NA
2000	14.09	Pardies	Fire & Explosion	NA	NA	NA
2000	03.09	Gonfreville-LOrcher	Explosion		12	
1999	07.05	Panipat, India	Fire	5		
1999	08.04	Hillsborough, USA	Fire & explosion	3	50	38
1998	15.9	Torch, Canada	Fire	--	--	--
1998	08.06	Auzouer, Touraine	Explosion & fire	__	1	200
1998	25.04	France	Fire	NA	NA	NA
1992	22.04	Jarrie	Fire	1	2	
1992	18.01	Pennsylvania, USA	Fire	1	3	--
1992	16.01	Sodegaura, Japan	explosion	10	7	---
1992	08.01	Wilmington, USA	Leakage	---	16	---
1991	09.06	Pardies	Fire	NA	NA	NA
1991	14.02	Daesan, Korea	Explosion	---	2	---
1991	-.10	Hanau-Frankfurt, Germany	Explosion	NA	NA	NA
1990	25.07	Birmingham, UK	Fire, gas cloud	---	> 60	70050
1990	29.04	Ottmarsheim	Fire	NA	NA	NA
1988	15.06	Genoa, Italy	Explosion	3	2	15000
1986	28.01	Challenger, USA	Explosion	7	--	--
1984	13.10	Waziers, France	Fire	NA	NA	NA
1978	12.06	USA	Fire		9	
1975	NA	Ilford, Esses	Explosion	1		
1937	06.05	Hindenburg, Lakehurst, USA	Fire	36	NA	NA
1894	25.05	Tempelhof-feld, Germany	Explosion	NA	NA	NA
1980	NA	EU chemical industries	Fire and explosion	NA	NA	NA
1992	NA	US nuclear power plant	Fire and explosion	NA	NA	NA

C.2.1 The Hindenburg

On May 6, 1937 at 19:25, the German Zeppelin LZ 129 Hindenburg caught fire and was totally destroyed within a minute while attempting to dock with its mooring mast at Lakehurst Naval Air Station in New Jersey. Of the 97 people on board, 13 passengers and 22 crew-members were killed. One member of the ground crew also died, bringing the death toll to 36. The cause of the disaster is still uncertain. At the time, many thought the ship had been hit by lightning. Many still believe that the highly flammable hydrogen was the cause. Some German even cried foul play, suspecting sabotage intended to sully the reputation of the Nazi regime. Recently, NASA investigator Dr. Addison Bain, however, has shown that the highly combustible varnish treating the fabric on the outside of the vessel most likely caused the tragedy [16, 231, 233].

C.2.2 The Challenger

An important event in the history of the US space program is the space shuttle Challenger accident on January 28, 1986. Liquid hydrogen propellant played an important role in that event. The three main engines on the shuttle are fueled by 383,000 gallons of liquid hydrogen and 143,000 gallons of liquid oxygen. The Challenger shuttle was engulfed in the hydrogen fire. The hydrogen fire destroyed the remains of the external hydrogen tank and caused the shuttle to experience even more severe aerodynamic loads than the increased thrust had caused. Seven people were killed in the accident [17, 231, 232].

C.2.3 Hanau Accidents

In October 1991, the Heraeus Quarzglas company, an optical fiber production firm in Hanau, Germany, suffered a hydrogen vapor cloud explosion. A 100 m^3 storage tank containing 370 kg of hydrogen gas burst about 35 minutes after being refilled. The following vapor cloud explosion caused property damage and (fortunately) only a few personnel injuries. The tank had suffered a structural failure. Investigation revealed that the tank had been modified to position it vertically. Tank welds experienced increased tension because of the modification. Other reasons that reduced the tank lifetime, thus helped cause the tank to fail, were material fatigue, and hydrogen-induced aging [231].

C.2.4 Tempelhof Field

The soldiers of the Royal Prussian Air Ship Division stored large amounts of hydrogen gas. They kept some 1000 cylinders in a shed. On 25 May 1894 about 400 of them burst without apparent reason. Damage was considerable [231]. The famous Professor Adolf Martens was appointed scientific head of the consequent investigation. He is seen as the father of materials research and testing in Germany. He founded metal and lattice microscopy and constructed many test machines. Result: The cylinders were made from unsuitable material. Martens made numerous proposals for the prevention of such accidents. The quality assurance program he devised became the basis of the German pressure vessel code.

C.2.5 European Chemical Industry

Drogaris (1993) [36] lists accident case histories from the 1980's for the European chemical industry. Nine of the 121 event descriptions discussed in the compilation included hydrogen as a combustible material. Three of those nine reports dealt with hydrogen as the primary (largest quantity or initial) substance involved in the accident. Briefly, these events were:

- 1985, sulfuric acid corrosion generated hydrogen gas in a tank at a fertilizer plant; the gas was ignited by an oxy-acetylene weld cutter flame (2 fatalities).
- 1988, an ammonia synthesis reactor had a hydrogen explosion during low pressure testing. The reactor had been leaking from some flanges and was undergoing a retest (1 fatality).
- 1989, a hydrogenated alcohol plant had a relief valve on a tank under inspection, hydrogen leaked from the valve under inspection. The hydrogen ignited in a jet fire (4 fatalities).

C.2.6 LH2 Accidents in Three Hydrogen Plants

Edeskuty [56] summarizes three hydrogen accidents related to liquid hydrogen (LH2), i.e.: (1) minor explosions in a hydrogen vent system, (2) combustion of hydrogen in the open atmosphere, (3) liquid hydrogen dewar storage explosion.

In the first accident, several explosions occurred in a liquid hydrogen facility consisting of 15,000 kg of LH2. All of the hydrogen vents were manifolded into a common vent system terminating in a flare stack. During no operation of the system the liquid hydrogen was venting the normal boil-off through the lighted flare stack. The accident was initiated a few minutes after a technician removed one of the check valves leading into the vent system from a source other than the two dewar. Fortunately, there were no injuries. Edeskuty [56] concluded that it is the best not to join separate components of a system to a common vent line when there is any possibility of interaction.

The combustion accident occurred in an experimental facility while the sound level of a rapid flow of hydrogen was measured. The hydrogen was obtained as liquid hydrogen and converted to high-pressure. The hydrogen entered the piping system connecting the hydrogen supply tanks to the discharge nozzle at 23 MPa, and at ambient temperature. The unplanned ignition occurred after the hydrogen flow was reduced to 16 kg/s (from 55 kg/s). It was estimated that about 90 kg (10% of the total hydrogen vented) participated in the combustion. The closest observers, located 600 m away did not detect a pressure wave, however, windows were rattled in a building about 3200 m. Away from the extent of damage, it was estimated that the buildings had experienced an overpressure of 1.2-2.4 kPa. Edeskuty [56] concluded that it is very difficult to eliminate all ignition source from rapidly venting hydrogen.

The explosion occurred in a LH2 storage dewar used to supply gaseous hydrogen (GH2) to a semiconductor building. It caused property damage and injury to five persons in the vicinity of the dewar. The dewar has a capacity of 34 m^3 (2000 kg) and a working pressure of 1.03 MPa. The accident occurred about 2 days after the dewar was filled from the LH2 supplier. Some possible causes of the accidents were attributed to an H2-O2 reaction, breaking of the vacuum. What happened exactly is uncertain, but it was speculated that a partial blockage in the vent line prevented adequate venting of the high boil-off rate after insulation vacuum was broken. Te resulting pressure buildup in the tank caused its rupture. Five persons were injured. They had skin burns (some third degree), shrapnel wounds, and blast effect wounds. Conclusions drawn in [56] include: (1) redundant instrumentation is recommended to provide an adequate, and believable, indication of actual operating conditions; (2) more than one vent point should be provided because the failure of a single vent could result in damage to the equipment and injury to personnel; (3) advance emergency planning should address appropriate actions to be taken in the event of possible emergency conditions; and (4) no action should be taken until the total consequences of that action have been thoroughly evaluated.

C.2.7 US Chemical Industry

On August 3, 1987, a hydrogen explosion occurred at an ammonia production plant, where a welder was making maintenance repairs to defective piping. The welder was injured, but recovered from burns at a hospital. There was no damage to other personnel or the plant. Another explosion occurred at a styrene production plant on April 20, 1984. The explosion killed two employees, and injured two more seriously. The cause of the accident was that the seal on the man-head tank entry for a knock-out drum of a hydrogen compressor had failed, and about 30 kg of hydrogen leaked at high pressure.

C.2.8 US Nuclear Power Plants

About 41 undesired events involving hydrogen (Table C-2) have occurred in US nuclear power plants until 1992. Most of the hydrogen was used in the cooling system of the electrical generators.

Table C-2 Undesired events involving hydrogen in the US nuclear power plant [36]

Event Location	**Explosion events**	**Fire events**	**Leakage**	**Other events**	**Total Events**
Turbine building, generator cooling system	2	7	7	0	16
hydrogen storage system for turbine coolant	2	1	0	0	3
Vapor collection tank cover system	0	0	11	0	11
Radioactive waste gas, radiolytic hydrogen	1	0	1	8	10
lead acid batteries	1	0	0	0	1
Total hydrogen events	**6**	**8**	**19**	**8**	**41**

C.2.9 NASA Operations

An important report discussing incidents with hydrogen in aerospace operations is [148]. The report lists 96 incidents of releases of hydrogen, both gaseous and cryogenic. This study was performed on National Aeronautic and Space Administration (NASA) facilities. Twenty-six percent of the accidents were caused by work area deficiencies, such as inadequate work conditions during installation or maintenance, or lack of training. Procedure deficiencies accounted for 25% of the mishaps. Design deficiencies accounted for 22% of the events. Planning deficiencies, such as test plans and hazard studies, resulted in 14% of the events. Component malfunctions (accountable to the component) resulted in 8% of the events. Material incompatibility and material failures accounted for 3% of the events. These events were not catastrophic failure, and few events resulted in fires.

C.2.10 Tractor-Trailer Collision

The NASA truck pulling a hydrogen trailer has an accident where a passenger car collided with the tractor-trailer. The trailer turned. The hydrogen vented and was ignited by nearby burning diesel fuel from the tractor-trailer. Both drivers were injured, but the hydrogen burned off rapidly and did not contribute very much to the human injury or vehicle damage.

C.2.11 Redstone Complex, Alabama

On October 31, 1980, a hydrogen explosion occurred in an auxiliary building at a test stand complex at the NASA Redstone complex in Alabama. The explosion destroyed two support buildings and severely damaged a large amount of equipment. Fortunately, no one was injured. Gaseous hydrogen leaked into one of the auxiliary buildings from a high pressure hydrogen gas system. The system piping was 88.9 mm (3.5 inch) outer diameter, carbon steel of 15.2 mm (0.6 inch) wall thickness meant to handle high pressures. The pipe had been attacked by galvanic corrosion on the outer wall for some time, thinning the wall to only 0.41 mm (0.016 inch) thickness.

C.2.12 LH2 Truck, Ohio

The Linde division of Union Carbide had a truck accident on August 25, 1987 near Columbus, Ohio. The truck was toppled and lost the vacuum insulation. The hydrogen boiled and vented, but there was no ignition. The possibility of ignition caused emergency response personnel to close the interstate highway and to evacuate nearby homes and businesses.

C.3 CAUSES OF THE ACCIDENTS

Seven generic cause categories of hydrogen accidents have been defined by Balthasar and Schödel [21] prepared for the hydrogen safety manual for the Commission of the European Communities, as shown in Table C-3. The accident categories were defined based on the hydrogen accident report for the US DOE. Additionally, the causes of the 96 NASA incidents (as described in section C.1.9) are presented in Table C-4.

Table C-3 Cause of hydrogen accidents [21]

Categories	**Incident (%)**
Undetected leaks	22
Hydrogen-oxygen off gas explosion	17
Piping and pressure vessel rupture	14
Inadequate inert gas purging	8
Vents and exhaust systems incidents	7
Hydrogen-chlorine incidents	7
Other incidents	25
Total	**100**

Table C-4 NASA operation incidents [148]

Categories	**Incident (%)**
Work area deficiencies	26
Procedure deficiencies	25
Design deficiencies	22
Planning deficiencies	14
Components malfunction	8
Material incompatibility	3
Total	**100**

Appendix D

HYDROGEN STANDARDS, CODES, AND REGULATIONS

D.1 INTRODUCTION

All fuels inherently possess a degree of danger due to their high energy content [227]. Safe use of hydrogen fuel requires preventing volatile combinations of the three combustion factors–ignition source (spark or heat), oxidant (air), and fuel. Safety is also achieved through testing, certification, and establishment of comprehensive safety assessments based on hydrogen site plans. Ensuring the safe use of hydrogen as a common fuel is of paramount importance for a successful transition to a hydrogen economy. Therefore, a set of rules (legislations, regulations, codes and standards) is needed connected to production, storage, transport, and use of hydrogen. This section summarizes existing codes, standards, and regulations about the safety aspects of hydrogen handling and usage as an energy carrier. It includes international and national standards, codes and regulations.

D.2 INTERNATIONAL CODES, STANDARDS, AND REGULATIONS

Table D-1 Published International Hydrogen Standards [17, 225]

Standards	**Regulated Aspects**	**Converter (Country)**
ISO TC 197	Hydrogen technology	
- ISO 13984	LH_2 – Land vehicle fueling system interfaces	SCC (Canada)
- ISO 14687	Hydrogen fuel – Product specifications	ANSI(USA)
- ISO 15594	Airport hydrogen fueling facilities	DIN (Germany)
- ISO 15866	GH_2 & hydrogen blends - Vehicular fuel systems	ANSI(USA)
- ISO 15869	GH_2 – Vehicle fuel tanks	ANSI(USA)
- ISO 15916	Basic requirements for safety of H2 systems	DIN (Germany)
- ISO 13985	LH_2- Land vehicle tanks	SCC (Canada)
- ISO 13986	LH_2 tank for multimodal transport	SCC (Canada)
- ISO/DIS 17268	GH_2 – Land vehicle filling connectors	
- ISO/ DIS 21009-1	Liquid hydrogen storages	
- ISO/WD 22734	H_2 generators using water electrolysis process	
- ISO/ CD 22734	Electrolysers	
- ISO/CD 24490	Cryogenics pumps	
- ISO/AWI 16110	H_2 generators using fuel processing technologies	
- NWIP N 253	Dispensing units	
- ISO/NP 20012	GH_2 and hydrogen blends - Filling stations	
ISO TC 22	Road vehicles	
ISO TC 58	Gas cylinder	
IEC TC 105	Fuel cells technologies	
IEC TC 69	Electrical system	

DIS - Draft International Standards; WG – Working Group

D3 THE EU REGULATIONS

Table D-2 EU Directives for hydrogen filling station and other infrastructures [225, 226]

Directive	Regulated Aspects (descriptions)
97/23/EC	PED (Pressure Equipment Directive)
94/9/EC (ATEX)	ATEX directive - Concerning equipment and protective systems intended for use in potentially explosive atmospheres (relevant for manufacturers of hydrogen equipment and applications)
1999/92/EC (ATEX)	ATEX directive - Minimum requirements for improving EU: Protection of Workers in Explosive Atmospheres (relevant for operators of hydrogen applications)
89/336/EEC (EMC)	Electromagnetic Compatibility Council directive - the approximation of the laws of the Member States relating to electromagnetic compatibility.
98/37/EC	The Machinery Safety Directive (relating to machinery)
96/82/EC	The SEVESO II directive - the control of major-accident hazards involving dangerous substances (relevant for larger amounts1 of hazardous substances)
70/156/EEC	Type-approval of motor vehicles and their trailers (not well adapted to hydrogen vehicles)
94/55/EC	The approximation of the laws of the Member States with regard to the transport of dangerous goods by road

Table D-3 List of directives/ regulations to be amended for road vehicles [225, 226]

EEC-Directive/ECE-Regulation	Regulated Aspects
70/220/EEC incl. latest amendment & ECE R83	Emissions
70/221/EEC incl. latest amendment & ECE R34/58	Fuel tanks/rear protective devices
78/316/EEC incl. latest amendment	Identification of controls
80/1268/EEC incl. latest amendment & ECE R 101	Fuel consumption
80/1269/EEC incl. latest amendment & ECE R84	Engine Power
96/27/EC & ECE R95	Side impacts
96/79/EC & ECE R94	Frontal impact
96/96/EC & PTI	Road worthiness tests
99/94/EC	CO2 labelling
70/156/EEC incl. latest amendment	Base directive
NEW EC Directive & ECE R100	Electric Vehicles
78/317/EWG (under progress)	Defrost/Demist

D.4 GERMAN STANDARDS AND REGULATIONS

Table D-4 German standards, guidelines, and regulations related to hydrogen [21, 171]

Standard, Code, Regulation	Regulated Aspects	Remarks
TRG 730	Hydrogen filling stations	Richtlinie für das Verfahren der Erlaubnis zum Errichten und zum Betreiben von Füllanlagen
BImSchG	Construction and installations	Bundesimmissionsschutzgesetz
TRD	Pressure vessel and pipeline	Technische Regeln für Dampfkessel

GefstoffV	Dangerous materials	Gefahrstoffverordnung
ElexV	Plants in explosion endangered rooms	Verordnung über elektrische Anlagen in explosionsgefährdeten Bereichen
VDI	Plants electric process engineering in connection with the establishment	VDI-Richtlinien
StVG	Road vehicles regulations	Straßenverkehrgesetz
StVZO	Equipment in vehicles: all systems to store hydrogen in vehicle and to supply the motor or fuel cell	Straßenverkehr-Zulassungs-Ordnung
DIN 2403	Colour code for hydrogen pipeline (yellow)	Kennzeichnung von Rohrleitungen nach dem Durchflußstoff.
VdTÜV	VdTÜV-Richtlinien (Guidelines)	Verband der Technischen Überwachungs–Vereine e.V.
BG	Accident prevention rules	Berufgenossenschaft
EX-RL	Explosion protections	BGR 104 Explosionsschutz-Regeln
VDE	Determination of explosion hazards for the establishment of electric plants	Verband der Elektrotechnik Elektronik Informationstechnik e.V.

Table D-5 The most important legislation for operation of hydrogen vehicles [229]

Regulated aspects	National Regulations	Regulations of the Trade Corporative Association (Berufsgenossenschaftliche)	Others Regulation
H2 vehicles	StVZO BetrSchV/ DruckbehV - TRG - TRB - TRR GefStoffV BetrSichV/ ElexV	BG-Vorschrift “Fahrzeuge” (BGV D29) BG-Vorschrift „Arbeiten an gasleitungen“ (BGV D2) Explosionsschutz- Richtlilien EX-RL (BGR 104) BG-Information „Wasserstoff“ (BGI 612)	EIHP 2: CGH2 regulation Rev. 8 (Draft) LH2 Regulation Rev. 11 (Draft) DIN 2403
H2 Filling Station	BetrSichV/ DruckbehV - TRG (TRG 406) - TRB - TRR ExV (11. GSGV) BetrSichV/ElexV GefStofV ArbstättV	BG-Vorschrift “Gase” (BGV B6) BG-Vorschrift „Arbeiten an Gasleitungen“ (BGV D2) Explosionsschutz- Richlinien EX-RL (BGR 104) BG-Information „Wasserstoff“	EIHP 2: CGH2 regulation Rev. 8 (Draft) LH2 Regulation Rev. 11 (Draft) DIN 2403
Worshop for H2 vehicles	BetrSichV/ DruckbehV - TRG - TRB - TRR ExV (11. GSGV)	BG-Vorschrift “Gase” (BGV B6) BG-Vorschrift „Arbeiten an Gasleitungen“ (BGV D2) Explosionsschutz- Richlinien EX-RL (BGR 104) BG-Information „Wasserstoff“	EIHP 2: CGH2 regulation Rev. 8 (Draft) LH2 Regulation Rev. 11 (Draft)

	BetrSichV/ ElexV GefStofV ArbstättV		
Storage for H2 Vehicle	ExV (11. GSGV) BetrSichV/ ElexV GefStofV ArbstättV	Explosionsschutz- Richlinien EX-RL (BGR 104) BG-Information „Wasserstoff“	VDI 2053

D.5 THE US CODES, STANDARDS AND REGULATIONS

Table D-6 Status of the US codes, standards, and regulations for hydrogen [17]

Regulated Aspects	**Codes, Standards, Regulations**	**Status**
Hydrogen production	NFPA 70/NEC/CEC ASME Boiler and Pressure Vessel Code (BPVC 1995) section VIII	Mature Mature
Hydrogen transportation	DOT 49 CFR	Mature Mature
Hydrogen pipeline	NEC/CEC ANSI/ASME B31.1, B31.8	Mature Mature
Hydrogen storage	NFPA 50 A: Gaseous hydrogen NFPA 50 B: Liquid hydrogen	Mature (1994) Mature (1994)
Hydrogen filling station	HV-3: Hydrogen vehicle fuel HV-1: Hydrogen vehicle connector NFPA 52. CNG vehicle fuel NGV1: NGV connector	Under development Under development Base for HV-3 Base for HV-1
Hydrogen vehicle	HV-3: Hydrogen vehicle fuel NFPA 52: CNG vehicle fuel HV-2: Gaseous hydrogen tanks NGV2: CNG storage tanks	Under development Base for HV-3 Under development Base for HV2

Table D-7 The US codes federal regulations (CFR) for hydrogen [17]

CFR	**Descriptions**
29CFR1910.103 40CFR68 - 40CFR86.25 - 40CFR68.130	Gaseous and cryogenic hydrogen handling and storage Chemical accident prevention provisions. - Worst-case release scenario analysis. - Threshold mass for accidental release prevention is given for H2.
49CFR - 49CFR 173.115 - 49CFR 172.101	Shipping and handling hydrogen gas and cryogenic hydrogen - GH2, LH2, and CH4 classified as hazard class 2 (flammable gas) - Quantity of GH2, LH2, or CH4 allowed in passenger aircraft or rail cars

Appendix E

CONSEQUENCE MODELS USED IN THE STUDY

E.1 INTRODUCTION

The objective of this section is to review the range of consequence models used for the study. Some material on these models is readily available, either in the general literature or as part of the AICHE/CCPS publication series, especially, the PHAST Professional v6.4 [49] developed by DNV (UK).

E.2 SOURCE MODELS

E.2.1 Discharge Models

Most of incident and hazards associated with escaping hydrogen such as fire, explosion, and even formation of a flammable vapour cloud usually involve the escape of liquid or gaseous hydrogen from the containment owing to failure followed vaporization and dispersion. In particular, a large quantity of liquid hydrogen and/or vapour may be released by failure of the tank, line or valve.

For hydrogen gas at low pressure, the flow through an orifice is governed initially by the equation of isentropic (constant entropy) flow, by solving the conservation of energy and mass equation. When the ratio of upstream pressure is lower than so-called critical pressure, the mass flow through the orifice is given by [183]:

$$Q = CAP_0 \sqrt{\frac{2gM_w}{RT_0}\frac{g}{g-1}\left[\left(\frac{P_2}{P_0}\right)^{2/g} - \left(\frac{P_2}{P_0}\right)^{\frac{g+1}{g}}\right]} \qquad \text{(E-1)}$$

where,

P_0	Stagnation pressure upstream (N/m^2)	γ	Ratio specific heat for H_2 (=1.42)
P_2	Downstream stagnation pressure (=101325 N/m^2)	C	Discharge coefficient (=0.86, GH_2, generated by PHAST)
M_w	Molecular weight (=2.016)	A	Aperture area (m^2)
R	Universal gas constant (=8310 J/kmol/K)	g	Acceleration of gravitation (=9.80 m/s^2).
T_0	Upstream stagnation temperature (K)		

The velocity of the gas is given by

$$u = 2C\frac{g}{g-1}\frac{P_0}{r_0}\left[1-\left(\frac{P_2}{P_0}\right)^{\frac{g+1}{g}}\right] \qquad \text{(E-2)}$$

In most situation, the pressure outside the throat of the orifice is atmospheric, so that for upstream pressures greater than about 2 bar absolute, the flow will be critical, or supersonic. For these conditions, the mass flow is given by:

$$Q = CA\sqrt{g\,P_0\,r_0\left(\frac{2}{g+1}\right)^{\frac{g+1}{g-1}}} \qquad \text{(E-3)}$$

$$u_{throat} = \sqrt{g\,RT_{throat}}$$

To calculate the rate of release given the size of the aperture using thermodynamic and physical properties of escaping liquid hydrogen (LH2) we can use the Bernoulli equation [17]:

$$Q = CAr\sqrt{\frac{2(P_1 - P_a)}{r} + 2gh} \qquad \text{(E-4)}$$

where,

Q	Release rate (kg/s)	h	Height of liquid tank (m)
C	Discharge coefficient (=0.6, LH_2, generated by PHAST)	P_a	Ambient pressure (=101325 N/m^2)
P_1	Vapor pressure of LH2 (N/m^2)	r	LH2 density (=71 kg/m^3)

The fluid release may be gas, liquid, or a two-phase mixture, depending on certain conditions. For example, if the release is from a container holding liquid under pressure, it will normally be liquid if the aperture is below the liquid level, and vapour or vapour-liquid mixture if it is above the liquid level. For given pressure difference, the mass rate of release is usually much greater for a liquid or vapour-liquid mixture than for a gas.

Two-phase flows are classified as either reactive or non-reactive [2]. The reactive case is typical of emergency relief of exothermic chemical reactions, while the non-reactive case involves the flashing of liquids as they are discharged from containment. Two special considerations are required. If the liquid is sub-cooled, the discharge flow will choke at its saturation vapor pressure at ambient temperature. If the liquid is stored under its own vapor pressure, a more detailed analysis is required. Both of these situations are accounted for by the following expression:

$$\dot{m} = A\sqrt{G_{SUB}^2 + \frac{G_{ERM}^2}{N}} \qquad \text{(E-5)}$$

where,

$\dot{m}$	is two-phase mass discharge rate (kg/s)
A	is area of the discharge (m^2)
G_{SUB}	is sub-cooled mass flux (kg/m^2s)
G_{ERM}	is equilibrium mass flux (kg/m^2s)
N	is a non-equilibrium parameter (-)

Mass flux for the sub-cooled and equilibrium is given by

$$G_{SUB} = C_D\sqrt{2\cdot r_f\cdot g_c(P - P^{sat})} \qquad \text{(E-6a)}$$

$$G_{ERM} = \frac{h_{fg}}{h_{fg}}\sqrt{\frac{g_c}{TC_p}} \qquad \text{(E-6b)}$$

where,

C_D	is the discharge coefficient (-)
r_f	is the density of the liquid (kg/m^3)
g_c	is the gravitational constant (m/s^2)
P	is the storage pressure (Pa)
P^{sat}	is the saturation vapor pressure of the liquid at ambient temperature (Pa)
h_{fg}	is the enthalpy change on vaporization(J/kg)
v_{fg}	is the change in specific volume between liquid and vapour (m^3/kg)
T	is the storage temperature (K)
C	is the liquid heat capacity (J/kg.K)

E.2.2 Pool Spreading and Vaporization Models

Immediately after release, the liquid hydrogen spreads out on the ground. It will spread until it meets an artificial boundary such as a dyke, until it reaches a minimum depth at which no longer spreads, or until the evaporation rate is equal to the release rate so that the amount of liquid in the pool is no longer increasing. Also immediately after release, the liquid hydrogen starts to boil off as it absorbs heat from the atmosphere, the ground and possibly from the sun. Mass is also lost from the pool when wind removes the evaporated material from the surface of the pool so that hydrogen evaporates in order to restore the partial vapour pressure. The Fay equations for instantaneous radial spill are given below [17]:

$$r_m = \left\{ 8 \frac{\sqrt{2g}}{3v_e} \left(\frac{Vo}{3.14} \right)^{3/2} \right\}^{0.25} \qquad \text{(E-7a)}$$

$$t_m = 0.7 \left[\frac{4r_m^2}{3gv_e} \right]^{0.33} \qquad \text{(E-7b)}$$

$$\dot{m} = 3.14 v_e\, r\, r_m^2 \qquad \text{(E-7c)}$$

where

r_m - max radius of the spread/pool radius (in m)
t_m - time to max radius spread (s)
$\dot{m}$ - max rate of vaporization of liquid spread (kg/s)
Vo - total volume of liquid spilled (m^3)
v_e - rate of liquid pool without burning (=0.00194 m/s)
g - gravitation constant (9.8 m/s^2)

For a continuous radial spill at a fixed location used the equation

$$r_m = \sqrt{\frac{dV/dt}{3.14 v_e}} \qquad \text{(E-8)}$$

If hydrogen is released from its containment as a liquid, vaporization must occur before a vapor cloud is formed. The rate at which vaporization takes place determines the formation of a vapor cloud. Immediately after release the heat boil-off is taken from the ground. The model given by TNO(1979) [17] gives the evaporation rate as:

$$m_g = \frac{I_s(T_a - T_b)}{H_v\sqrt{p\,a_s t}} \qquad \text{(E-9)}$$

where,

m_g	is evaporation rate from the ground (kg/s);
T	is time(s)
I_s	is surface coefficient of heat conduction (W/mK)
T_a	is ambient temperature (K) ;
H_v	is heat of evaporation of LH2 (J/kg);
T_b	is saturation temperature of LH2 (K)
a_s	is surface thermal diffusity (m^2/s)

Both I_s and a_s are properties of the surface and typical values as shown in the Table E-1:

Values for soil heat conductivity and thermal diffusity [183]

Substance	**I_s**	**a_s**	**m_g**
Average ground	0.9	4.3e-7	0.464
Dry sand	0.3	2.3	6.68e-5
Sandy ground (dry)	0.3	2	7.16e-5
Sandy ground(damp)	0.6	3.3	1.12e-4
Gravel	2.5	11	2.54e-4
Carbon steel	45	127	1.35e-3
Concrete	0.42	13e-7	0.124

E.3 DISPERSION MODELS

E.3.1 Continuous Release

The continuous release profile extends from the source downwind (Fig. E.1). An elevated, heavy vapour/aerosol release starts out with a circular cross section. Upon touching down, the cross section becomes a truncated ellipse, and the cloud levels off as the vertical component of momentum is converted into downwind and cross-wind momentum. Aerosol droplets may rain out shortly after touchdown. Rain-out produces a pool which spreads and vaporises. If spilled onto water, part of the material may also dissolve. The vapour from the pool is added back to the plume, as a function of time. The plume can become buoyant after evaporating all aerosol droplets and picking up heat by ground conduction, or by condensing water picked up over a wet surface. A buoyant plume lifts off and rises until constrained by the mixing layer.

The Cartesian co-ordinates x, y, z correspond to the downwind, cross-wind (lateral horizontal) and vertical directions, respectively; x=0 corresponds to the point of release, y = 0 to the plume centre-line and z = 0 to ground-level. In addition to these cartesian co-ordinates use is made of the 'cloud' coordinates s and ζ. Here s is the arclength measured along the plume centre, with s=0 corresponding to the point of release. The concentration profile for continuous release (Plume) is given by [203; 9]:

$$c(x,y,z) = c_0(x).F_v(z).F_h(y) \qquad \text{(E-10)}$$

where

$$c_0(x) = \frac{Q}{p\,u s_y s_z}; \quad F_h(y) = \exp\left\{-\left|\frac{(y)}{\sqrt{2}s_y}\right|^m\right\}; \quad F_v(z) = \exp\left\{-\left|\frac{z}{\sqrt{2}s_z}\right|^n\right\}, \text{ and}$$

Q = mass emission rate (kg/s)

u = wind speed (m/s)

$s_{y,}$ = standard deviation of horizontal profile of cloud concentration (m)
$s_{z,}$ = standard deviation of vertical profile of cloud concentration (m)
y = the crosswind distance from the cloud axis (m)
z = distance from Plume center-line (m)

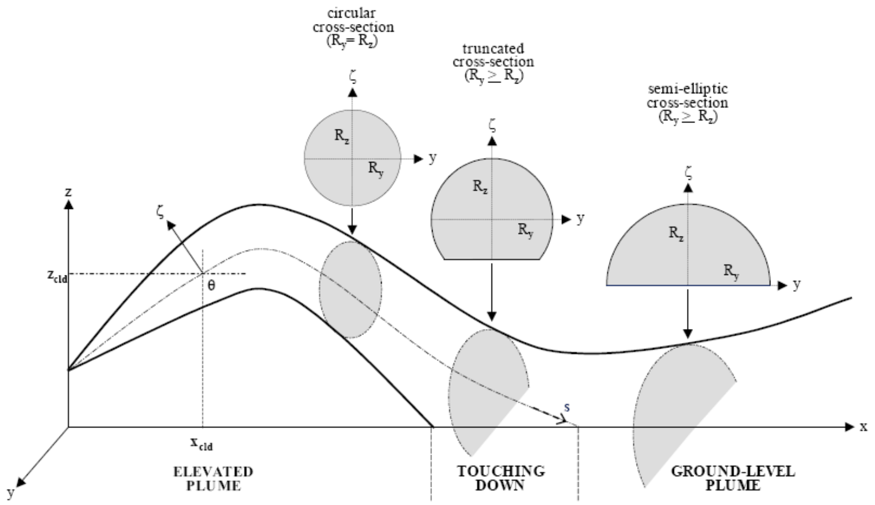

Fig. E.1 UDM cloud geometry for continuous release [203]

The co-ordinate ζ indicates the direction perpendicular to the plume centre-line and perpendicular to the y-direction. The angle between the plume centre-line and the horizontal is denoted by $\theta = \theta(s)$, and the vertical plume height above the ground by $z_0 = z_{cld}(s)$. Thus z and ζ are related to each other by $z = z_{cld} + \zeta \cos(\theta)$.

E.3.2 Instantaneous Release

The concentration profile $c = c(x,y,\zeta,t)$ for instantaneous release (Fig. E.2) is given in Eq.E-9, with exponential decay in x,y,ζ described by means of ('passive') dispersion coefficients $\sigma_x = \sigma_y$, σ_z, and with near field top-hat profile (e.g. sharp-edge jet) developing into a Gaussian profile in the far field.

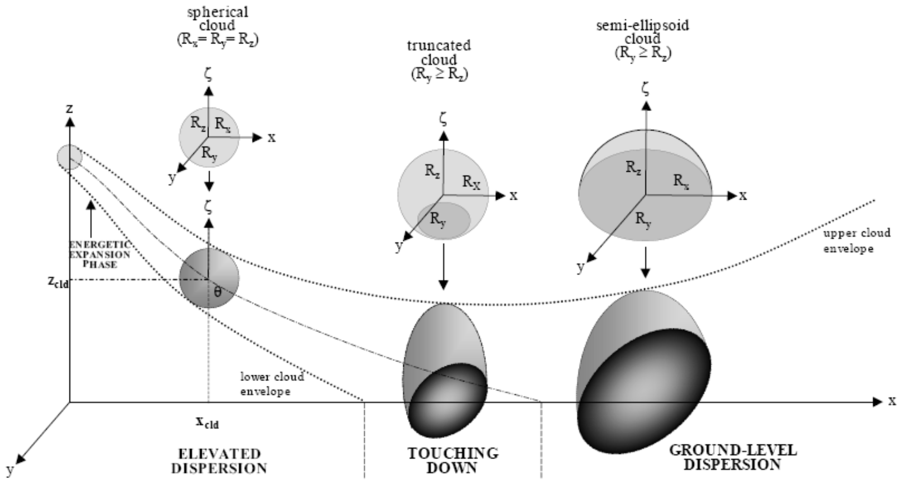

Fig. E.2 UDM geometry for instantaneous release [203]

$$c(x,y,z\,;t) = c_0(t).F_v(z\,).F_h(x,y) \tag{E-11}$$

where

$$c_0(t) = \frac{Q_i(t)}{p^{3/2}\sqrt{2}s_x s_y s_z}; \qquad F_v(z\,) = \exp\left\{-\left|\frac{z}{\sqrt{2}s_z}\right|^n\right\}; \text{ and}$$

$$F_h(x,y) = \exp\left\{-\left[\left(\frac{x - x_{cld}(t)}{\sqrt{2}s_x}\right) + \left(\frac{y}{\sqrt{2}s_y}\right)\right]^m\right\};$$

The co-ordinate ζ indicates the vertical distance above the Plume centre-line and perpendicular to the y-direction. The angle between the plume centreline and the horizontal is denoted by θ, and the vertical plume height above the ground by z_{cld}. Thus z and ζ are related to each other by $z = z_{cld} + \zeta$. Furthermore, $x_{cld}(t)$ is the downwind distance of the centre of the cloud at time t, and Q_i is the mass (kg) in the initial instantaneous at time t. At the core averaging time the along wind dispersion is assumed to be identical to the cross-wind dispersion, i.e. $\sqrt{2}s_x = R_x = R_y$. When m = n = 2, Equations (Eq. E-9) reduce to the Gaussian form.

E.4 FIRE AND EXPLOSION MODELS

The surface emissive power (SEP) is the heat flux due to heat radiation at surface area. It can be calculated with the Stefan-Bolzmann-equation [230]:

$$SEP = et\,(T_f^4 - T_a^4) \tag{E-12}$$

Where,

SEP	is surface emissive power, in W/m^2 ;
e	is emittance factor (emissivity)
t	is constant of Stefan-Bolzmann (=5.6703.10^{-8} W/m^{2}K^4)
T_f	is radiator surface temp of the flame (K);
T_a	is ambient temperature (K).

The heat flux q at certain distance from the fire, which is experienced by the receiver per unit area, can be calculated by:

$$q = SEP \cdot F_{view} \cdot t_a \tag{E-13}$$

where,

q	is heat flux at a certain distance, W/m^2;
F_{view}	is view factor
t_a	is atmospheric transmissivity

E.4.1 Fireball

In reality the radiative emission from fireball varies over its surface, but in most literature a uniform heat radiation is assumed. In PHAST, the flame is modelled as spheres (circles) (Fig. E.3). Each circle is defined by the downwind co-ordinate *x* and elevation *z* of the center of the circle, by the radius *r*, and by the inclination of the circle from the horizontal, as shown in the illustration below [49]. The flame radius, r_{flame}, and flame duration, t_{Flame}, are calculated from as:

$$r_{flame} = 2.9 M_{bleve}^{1/3} \tag{E-14}$$

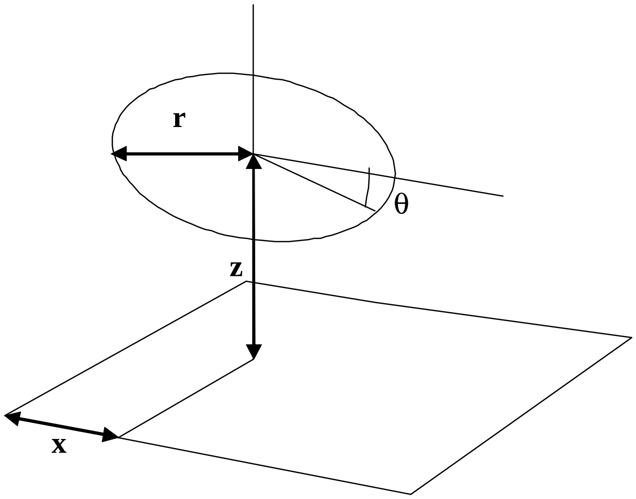

Fig. E.3 Shape of fireball [49]

$$t_{flame} = \begin{cases} 0.45 M_{bleve}^{1/3} & M_{bleve} < 3700 \\ 2.59 M_{bleve}^{1/6} & 3700 \le M_{bleve} \end{cases} \tag{E-15}$$

Where, M_{bleve} is flammable mass involved in the fireball. The emissive power, E is calculated as:

$$E = \frac{f_s \cdot M_{bleve} \cdot H_{comb}}{4p \cdot r_{flame}^2 \cdot t_{flame}} \tag{E-16a}$$

Where f_s is the fraction of heat radiated from the surface, given by:

$$f_s = 0.27 \left(\frac{P_{sat}}{10 P_{Atm}} \right)^{0.32} \tag{E-16b}$$

$$P_{sat} = \begin{cases} P_{atm} & -> \quad P_{atm} > P_{svp} \\ P_{svp} & -> \quad P_{atm} < P_{svp} \end{cases} \tag{E-16c}$$

and P_{svp} is the saturation vapour pressure of the substance, and calculated using the substance properties.

E.4.2 Pool Fire

The flame shape of the pool fire can be modelled as a cylinder sheared (Fig.E.4) in the direction of the wind with diameter *D*, height *H* and tilt angle θ (measured from the vertical). The flame is described by three circles (c_1, c_2, c_3) arranged along the centerline of the flame, each defined by the downwind co-ordinate *x* and elevation *z* of the center of the circle, and by the radius *r*. These flame-circle co-ordinates are the main input to the radiation calculations.

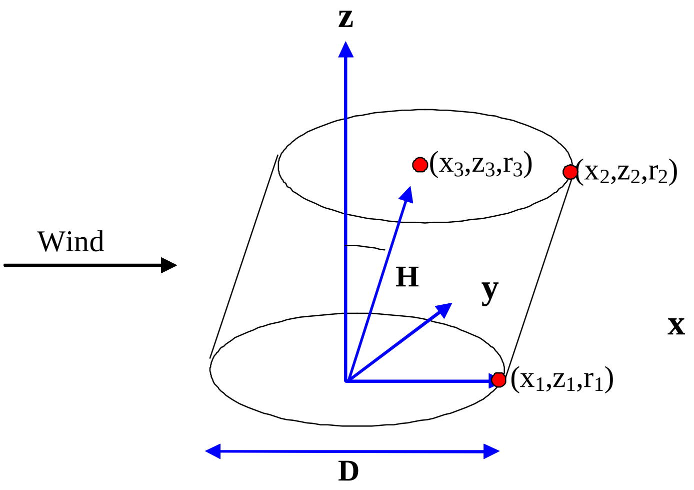

Fig. E.4 Shape of pool fire flame [49]

If the release is bunded, the diameter D is given by size of the bund. Otherwise, if it release volume and the thickness of the pool can be determined, the circular pool diameter can be calculated with:

$$D = \sqrt{\frac{4V}{pd}} \qquad \text{(E-17)}$$

Where,

V = volume of the released liquid [m^3]; δ = thickness of the pool [m]

The maximum burn rate, m_{max} (in kg/s/m^2), is taken from [49]:

$$m_{\max} = 10^{-3}\frac{\Delta H_c}{\Delta H_v^*} \qquad \text{(E-18)}$$

where, ΔH_v* is the modified heat of combustion:

$$\Delta H_v^* = \begin{cases} \Delta H_v + C_{pL}(T_b - T_a) & T_b > T_a \\ \Delta H_v & T_a > T_b \end{cases} \qquad \text{(E-19)}$$

and C_{pL} is the liquid specific heat, T_b is the boiling point temperature, and T_a is the atmospheric temperature. The actual pool fire burn rate, m is then given by [49]:

$$m = m_{\max}\left[1 - e^{-\frac{D}{L_b}}\right] \qquad \text{(E-20)}$$

Where, L_b is the burn rate characteristic scale length which is taken from the material property data. The flame length, H is given by [49] as:

$$H = 42D\left[\frac{m}{r_a\sqrt{gD}}\right]^{0.61} \qquad \text{(E-21)}$$

Where ρ_a is the density of air and g is the acceleration due to gravity. The tilt angle θ can be approximated with the standard quadratic formula, taking only the positive root:

$$q = \arcsin\left(\frac{-1+\sqrt{1+4A^2}}{2A}\right) \qquad \text{(E-22)}$$

Where, $A = 0.7Re^{0.109}.Fr^{0.428}$, *Re* is a Reynolds number ($=U_wD/v_a$), *Fr* is a Froude number ($=U_w^2/gD$), U_w is the wind velocity, v_a is the kinetic viscosity of the air, and *g* is the acceleration due to gravity.

If the flame dimension have been determined as well as the heat generated in the flame due to combustion, the surface emissive power can be calculated. The maximum surface emissive power, E (in W/m^2) for a tilted cylindrical flame according to approach of the Yellowbook [230]:

$$E = \frac{F_s \cdot m \cdot \Delta H_c}{(1+4H/D)}\left[1-e^{-\frac{D}{Ls}}\right] \qquad \text{(E-23)}$$

Where, F_s is fraction of the generated heat radiated from flame surface, m is burning rate (in kg/m^2.s), ΔH_c is heat o, and Ls is the emissive power characteristic scale length.

E.4.3 Jet fire

There are two jet fire models available in the PHAST, i.e. API and Shell models. The *Shell* method treats the flame as a tilted cone frustum, whereas the *API* model treats it as a banana-shaped plume—i.e. tapered at the ends, and bent by the wind. The study uses API model to calculate thermal impacts resulted from jet fires. Therefore, only the API model to be discussed in the appendix.

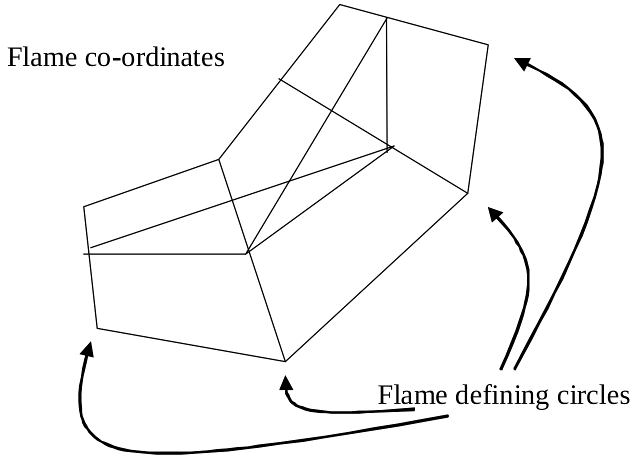

Fig. E.5 Shape of API RP521 Jet fire [49]

The flame is a jet that may be bent by the wind or by the effects of gravity, and it is described by ten circles (c_1 to c_{10}) equally spaced along the flame length. Each circle is defined by the downwind co-ordinate x and elevation z of the center of the circle, by the radius r, and by the inclination of the circle from the horizontal; the illustration below shows a portion of the middle of a flame, with four circles:

The flame length, L, is calculated as:

$$L = 0.003271918(Q \cdot \Delta H_{comb})^{0.478} \tag{E-24}$$

Where, Q is the mass discharge rate (kg/s) and DH_{comb} is the heat of combustion (=119.9 MJ/kg, for H_2). The maximum radius of the flame is given by:

$$R_{\max} = \frac{0.1244L}{2} \tag{E-25}$$

where L is the flame length (m). If the flame is horizontal, then it is assumed not to be deflected by the wind. For a vertical flame, the program first calculates the velocity ratio, U_{ratio}, as a measure of the power of the wind to deflect the jet:

$$U_{ratio} = \frac{U_w}{U_0} \tag{E-26}$$

where U_w is the wind speed (m/s) and U_0 is the jet velocity. The jet velocity, U_0, is calculated as:

$$U_0 = \frac{Q}{r_{vapor} p R_{\exp}^2} \tag{E-27}$$

where Q is the mass discharge rate, r_{vapor} is the vapor density at one atmosphere and R_{exp} is the expanded radius. The expanded radius is calculated as:

$$R_{\exp} = \sqrt{\frac{Q}{r_{vapor} p U_0}} \tag{E-28}$$

If the velocity ratio is less than 0.0001, then the flame is treated as being perfectly vertical [49]. For larger values of the velocity ratio, the program calculates the increase in x and z between each circle. For each circle, the gradient dz/dx is

$$\frac{dz}{dx} = 3.2p \frac{R_{\exp}}{U_{ratio}} \left(\frac{1}{s} - \frac{1}{L} \right) \tag{E-29}$$

where R_{exp} is the expanded radius, U_{ratio} is the velocity ratio, s is the distance of the circle along the centerline of the flame, and L is the flame length. The radius of the flame as a function of distance along the length is set according to [49]. The radius of the first circle, r_1, is set equal to the expanded radius of the jet. For the other circles, the radius, r_i, is given by:

$$r_i = \frac{0.29 s_i}{2} \sqrt{\ln\left(\frac{L}{s_i} \right)} \tag{E-30a}$$

where:

$$s_i = \frac{(i-1)}{(N-1)} L \tag{E-31b}$$

and L is the flame length. If the emissive power was not specified in the input data, the program calculates it as described below. The calculations involve several stages. The fraction, F_s, is

$$F_s = \{0.21\exp(-0.00323U_0) + 0.11\} f_{MW} \tag{E-32a}$$

where:

$$f_{MW} = \begin{cases} 1 & M_w < 21 \\ \sqrt{\dfrac{M_w}{21}} & 21 \le M_w \le 60 \\ 1.69 & 60 < M_w \end{cases} \tag{E-32b}$$

U_0 is the jet velocity and M_W is the molecular weight of the substance released. If the value calculated is greater than the maximum allowed (set as 0.5), then F_s is set to 0.5. The surface emissive power of the flame, E_m, is calculated from [49] as:

$$E_m = \frac{F_s \cdot Q \cdot H_{comb}}{A_{total}} \tag{E-33}$$

Where, F_s the fraction of heat radiated, Q is the mass discharge rate, H_{comb} is the heat of combustion, and A_{Total} is the total surface area of the flame. If the calculated value of E_m is greater than the maximum surface emissive power set in the Jet Fire Parameters, then the maximum value from the parameters is used instead. The program calculates either the jet velocity or the expanded radius, depending on which items are supplied in the input data:

E.4.4 TNT Model

The program has three methods for calculating the effects of explosions, i.e. TNT, Multi-Energy, and Baker Strehlow. The study uses *TNT* method (as the program default) to calculate explosion impacts from the hydrogen system. Therefore, the appendix discuses this model only.

The program calculates the mass of TNT that is equivalent to the effective flammable mass in the cloud [49]:

$$m_{TNT} = \left(\frac{H_{comb}}{H_{TNT}}\right) m_{eff} \tag{E-34a}$$

$$m_{eff} = mX' f_e \tag{E-34b}$$

where H_{TNT} = 4.7 x 10^6 J kg^{-1} is the heat of combustion of TNT using up its own oxygen, i.e. without additional oxygen from the atmosphere, H_{comb}= 191.93 MJ/kg (for hydrogen), m is the mass in the cloud at the time of the explosion, X' is the explosion efficiency (taken from the PHAST Library), and f_e is the ground reflection factor, set to 1 for an air burst, and 2 for a ground burst.

The explosion radius, R', is the distance from the explosion center to the distance of interest:

$$R' = d_i^{Input} - d_{explosion} \tag{E-35}$$

If mX'$H_{combustion}$ is less than 10^3 J then the overpressure is set to zero. Otherwise, the overpressure P_o is calculated using an approximation of the Kingery and Bulmash curves as published in [115]:

$$\log_{10} P_0 = a(\log_{10} z)^2 + b\log_{10} z + c \tag{E-36a}$$

where: a = 0.2518, b = -2.20225, c = 5.8095, and

$$z = \frac{R'}{m_{TNT}^{1/3}} \tag{E-36b}$$

The explosion radius R' is calculated from:

$$R' = z m_{TNT}^{1/3} \tag{E-37a}$$

where:

$$\log_{10} z = \left(\frac{-b - \sqrt{b^2 - 4a(c - \log_{10} P_0)}}{2a} \right) \tag{E-37b}$$

and a = 0.2518, b = -2.20225 and c = 5.8095.

Appendix F

FAULT TREE ANALYSIS METHODS USED IN THE STUDY

F.1 INTRODUCTION

Fault tree analysis (FTA) [86, 42, 107] is a deductive method which is normally used in a quantitative way, although it requires as an initial step a qualitative study of the system under consideration. After defining the undesired events, its logical connection with the basic events of the system are searched for and the result of this search is represented graphically by means of a fault tree. The logical connections in the fault tree are generally represented by two types of gates, the "OR" and the "AND". Quantitative evaluation of a fault tree requires quantitative reliability data for equipments as well as human error. This appendix describes a FTA method which is used in the study. The FTA uses analytical approach, and developed by Hauptmanns [86].

F.2 FAULT TREE ANALYSIS

F.2.1 Fault Tree Basics [86]

Any accident starts with an initiating event, often the failure of an operational component. In order to counter-act this, a technical system usually disposes of a protective & safety systems made up of stand-by components. These are normally capable of coping with the major part of initiating events and may be considered as barriers between those and the undesired events. The undesired events only occur if these barriers fail. If components from several barriers have to fail for the undesired event to occur, these are combined with the initiating event by an "AND" gate. If several of these combination exist, they are input into an "OR" gate, just as contributions from different initiating events to the undesired events. Any system represented by a fault tree has basic events which act in series (OR gates) or in parallel (AND gates), with a combination of the two being most frequent. The basic event may be described by a binary variable.

$$x_i = \begin{cases} 1, & \text{if basic event } i \text{ is true, e.g. component } i \text{ has failed.} \\ 0, & \text{if basic event } i \text{ is not true, e.g. component } i \text{ is working.} \end{cases} \tag{F-1}$$

Analogous description may be used for the state of the system:

$$y = \begin{cases} 1, & \text{if the undesired event has occured.} \\ 0, & \text{if the undesired event has not occured.} \end{cases} \tag{F-2}$$

Where ψ is the structure function of a system. A group of basic events which, in case they are true, are just sufficient to cause the undesired event is called a minimal cut set. A fault tree may have several minimal cut sets, each of which represents one way of bringing about the undesired event. Representation of the fault tree in terms of its minimal cut sets gives insight into the structure of the system under investigation. The structure function of the system as function of the minimal cut sets described as:

$$y(\vec{x}) = 1 - \prod_{l=1}^{L} [1 - k_l(\vec{x})] \tag{F-3a}$$

$$k_i(\vec{x}) = \prod_{i=k} x_i \tag{F-3b}$$

The κ_i represent the L minimal cut sets of the system, which the value of L depending on its complexity, and k_i are the binary functions associated with them.

Fault trees for complex systems normally must be evaluated with the aid of a computer program. There are mainly three methods available for this purpose: (1) direct simulation of the fault tree, (2) minimal cut set calculation using a simulation procedure, and (3) minimal cut set calculation by analytical methods. The last procedure was used to calculate undesired events of the study objects, and to be discussed in more details in the following section.

F.2.2 Determination of Minimal Cut Sets by Analytical Methods

The analytical method uses Boolean algebra operations in order to transform a fault tree into minimal cut sets. In contrast to the simulation methods, it does not require information on component failure behaviour [242]. This is only needed for calculating the failure probability of the system. It finds all minimal cut sets of a system. In order to avoid difficulties with computer capacity, a cut-off criterion must be applied [242].

Basically two approaches may be used in the method, i.e. the "Top-down" approach, in which the algorithm starts with the undesired event represented by the Top gate working its way down to the basic events, and the "Bottom-up", where the calculation is initiated at the level of basic events, and ends with the undesired event. In order to understand the method the "Top-down" approach to be discussed in this section, and is described in [86]. In this method the tree is presented by a matrix in which the entry of a "1" indicates a connection and a "0" means that there is none. For example, matrix $\bar{A}_0$ (in Fig. F.2) is the representation of a fault tree (Fig. F.1). Rows of matrix represent the "OR" gates (upper part) and "AND" gates (lower part). The columns are divided into three blocks, i.e.: basic events, OR-gates, and AND-gates.

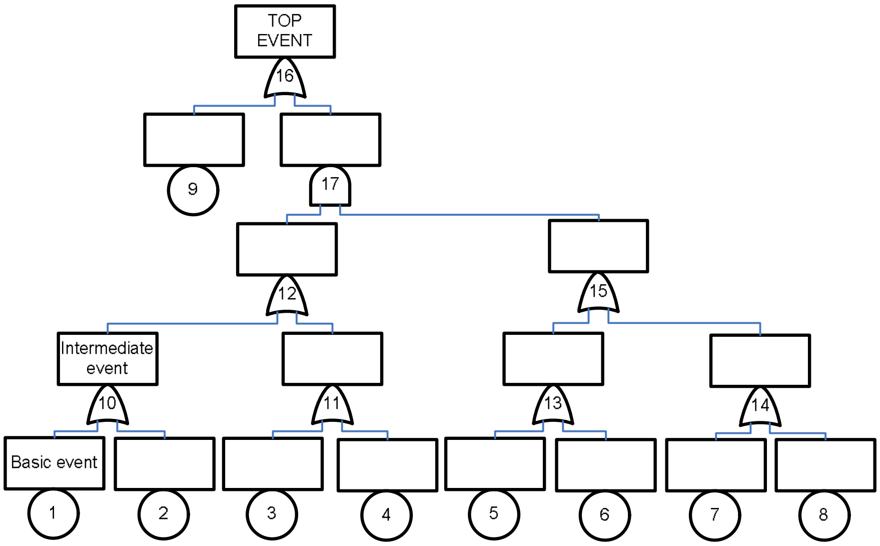

Figure F.1 The fault tree is presented by a matrix

$$
\begin{array}{lc}
 & \begin{array}{ccccccccc:ccccccc:c} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 \end{array} \\
\textit{Gate no.} & \begin{array}{ccccccccc:ccccccc:c} \multicolumn{9}{c}{\textit{Basic events}} & \multicolumn{7}{c}{\textit{OR}-\textit{gates}} & \textit{AND}-\textit{gates} \end{array} \\
\begin{array}{l} 10 \\ 11 \\ 12 \\ 13 \\ 14 \\ 15 \\ 16 \\ 17 \end{array} &
\bar{A}_0 = \left[\begin{array}{ccccccccc:ccccccc:c}
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0
\end{array}\right]
\end{array}
$$

Figure F.2 The fault tree is presented by a matrix

The minimal cut sets of the fault tree can be determined by transformation of the matrix $\bar{A}_0$ into a form which only contains “0” in the two blocks on the right side, which represent the gates. This is achieved by replacing the gates systematically by their entries. In the case of an “AND” gate, all entries figure in original row, where the replacement is made. If a gate is of the “OR” type, for each entries a new row opened [86]. The algorithm starts with the top gate. In this example, replacing gate “16” in the matrix $\bar{A}_0$ by entries, which lead to:

$$
\begin{array}{c}
\begin{array}{cc} \textit{Basic events} & \qquad\qquad\qquad \textit{Gates} \end{array} \\
\bar{A}_1 = \left[\begin{array}{ccccccccc|cccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{array}\right]
\end{array}
$$

The first row of the matrix $\bar{A}_1$ already contains a representation in terms of components (only component “9”). Therefore, it is retained unchanged in further step. Replacement of gate “17” in the second row, which represent an “AND” gate, lead to:

$$
\begin{array}{c}
\begin{array}{cc} \textit{Basic events} & \qquad\qquad\qquad \textit{Gates} \end{array} \\
\bar{A}_2 = \left[\begin{array}{ccccccccc|cccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0
\end{array}\right]
\end{array}
$$

In the next step gate “12” in the second row of $\bar{A}_2$ is replaced. It is “OR” gate, which implies that for each its entries a new row is opened. This lead to:

$$
\begin{array}{c}
\begin{array}{cc} \textit{Basic events} & \qquad\qquad\qquad \textit{Gates} \end{array} \\
\bar{A}_3 = \left[\begin{array}{ccccccccc|cccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0
\end{array}\right]
\end{array}
$$

These procedures are repeated until all the gates side contains only “0”. The final result is shown in the matrix $\bar{A}_4$.

$$\begin{array}{cc}
 & \begin{array}{ccccccccc|cccccccc}
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 \\
\multicolumn{9}{c}{\textit{Basic events}} & \multicolumn{8}{c}{\textit{Gates}}
\end{array} \\
\bar{A}_4 = & \left[\begin{array}{ccccccccc|cccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}\right]
\end{array}$$

It can be seen that $\bar{A}_4$ only has entries different from “0” in the block which corresponds to the components of the tree. Each row represents a minimal cut set. The procedure above gives all the cut sets of the tree. These do not necessarily have to be minimal [86]. Therefore non-minimal cut sets have to be eliminated after the cut sets have been obtained. This applies also if a minimal cut set appears several times, then it is retained only once. Both elimination steps are realized using Boolean operations [86].

F.2.3 Calculation of Probability and Expected Frequency of the Undesired Events from Minimal Cut Sets.

After finding the minimal cut sets the procedure may be continued with fault tree evaluation, e.g. calculation of the expected frequency of the undesired event (Top event). This is calculated by forming the expectation of the structure function given in Eq. F-1. With eliminating of the powers of binary variables in the Eq.F-1, which are equal to the binary variables themselves (law of idempotencies):

$$x_i^m = x_i \qquad (m \neq 0) \tag{F-4}$$

The general relationship of the structure function can be described as:

$$y(\vec{x}) = \sum_{i=1}^{L} k_i - \sum_{i=1}^{L-1} \sum_{j=i+1}^{L} k_i.k_j + \sum_{i=1}^{L-2} \sum_{j=i+1}^{L-1} \sum_{k=j+1}^{L} k_i.k_j.k_k + \mathbf{K} + (-1)^{L-1}.k_1.,\mathbf{K},.k_L \tag{F-5}$$

An upper bound of the occurrence probability of the system is equal to the expectation of the first term on the right side of the Eq.3. Since the used probabilities are usually small numbers, in most cases the evaluation of the upper bound is a satisfactory approximation to the true result. If initiating events are taken into account, the Eq. F-3 is evaluated for each of them separately using unavailabilities for the basic events [86]. The corresponding expected frequency of the undesired event is obtained by multiplying the unavailability with the frequency of the initiating event.

Uncertainties of the reliability data are propagated through the fault tree. This is performed by a Monte Carlo calculation, with the used of a lognormal distribution, described in the following section. Based on the Monte Carlo simulation, the program calculates a failure rate (and analogous to unavailability) using the following equation [86]:

$$l_i = l_{50}.\exp\left[\sqrt{-2.\ln z_p}.\cos(2p.v_p).s_i\right] \tag{F-6}$$

Where z_p and v_p are random numbers uniformly distributed in the interval [0, 1]. Several trials are carried out from which the mean value and standard deviation of the probability of occurrence of the undesired event are calculated, e.g. for the unreliability according to:

$$\bar{q}_s = \frac{1}{P}.\sum_{p=1}^{P} q_{s,p} \tag{F-7}$$

With the standard deviation:

$$s_{q_s} = \sqrt{\frac{\frac{1}{P}.\sum^{P} q_{s,p}{}^2 - \bar{q}_s{}^2}{P}} \tag{F-8}$$

Where, P is the total number of trials and $q_{s,p}$ is the unreliability of the system calculated in trial p.

F.3 FAILURE PROBABILITIES OF TECHNICAL COMPONENTS AND HUMAN ERROR

F.3.1 Mathematical description of component behaviour [86].

Behaviour of a component may be described as a constant probability or is described by an exponential distribution. The behaviours of a component described by a constant probability are indicated either its unavailability, u, i.e. the probability of its being in failed state, or its complementary value, the availability, p= 1-u. If a component behaviour, i, is described as an exponential distribution, the corresponding probability density function (pdf) is given by:

$$f_i(t) = \frac{1}{T_i}\exp\left(-\frac{t}{T_i}\right) \qquad (t > 0) \quad (T_i > 0) \tag{F-9}$$

Integration of the Eq.10 over time t yields the unreliability, q_i, i.e. the probability that component i experiences its first failure until time t, is stated as.

$$q_i(t) = 1 - \exp\left(-\frac{t}{T_i}\right) \qquad (t > 0) \quad (T_i > 0) \tag{F-10}$$

Where T_i is the mean time to failure for components *i*. It is the inverse of the failure rate, λ, i.e. $\lambda=1/T_i$. If the component is not an object of maintenance its reliability and unreliability coincide, i.e., $q_i(t)=u_i(t)$.

For the component subjected to maintenance, the unavailability of the component is given by:

$$u_i(t) = 1 - \exp[1 - l_i(t - nq_i)] \qquad (t > 0) \tag{F-11}$$

Where, θ_i is the time between inspections, and n is integer parts of the quotient t/θ_i.

An average unavailability can be obtained by integrating Eq.F-11 over the time interval between two inspections is given by:

$$\overline{u}_i(t) = 1 - \frac{T_i}{q_i}[\exp(-l_i q_i) - 1] \tag{F-12}$$

Due to $\lambda_i \ \theta_i \leq 1$, the exponential function of the Eq.F-12 may be approximated by the first three term of its Taylor Series. This procedure leads to the well-known results:

$$\overline{u}_i(t) \cong \frac{l_i q_i}{2} \tag{F-13}$$

F.3.2 Reliability Data for the Process Plant Analysis

An ideal situation is to have valid historical data from the identical equipment in the same application. But in most cases, the plant-specific (e.g. hydrogen) data are unavailable, because of the expense of testing and limited historical database on equipment failure. Only a small number of hydrogen technologies, systems and components are currently in operation. To overcome this problem generic failure rate data as surrogates for or supplements to plant-specific data have been used in the study. Because of the uncertainties inherent in the risk analysis methodology, generic failure rate data are frequently adequate to identify the major risk contributors in a process or plant [8].

F.3.3 Common Mode Failure

Apart from the independent failure treated previously, the possibility of common mode failures in technical system has to be contemplated [86]. This type of failure leads to the simultaneous unavailability of several components, and it especially grave if it affects a redundant structure, i.e. several components instead of one arranged in such a way that one of them is capable of performing the mission of the principal components. According to [86] the common modes may be distinguished as follow:

1. Failures of two or more redundant components or partial systems which are of similar or identical design owing to an outside cause, for example a corrosive environment which leads to rapid component degradation.
2. Failure of two or more redundant components or partial systems which occur as a consequence of a single failure; this type of common mode failure is called causal failure.
3. Failure of two or more redundant components or partial systems which occur as a consequence of functional dependences as for example, the dependence on a common auxiliary system.

F.3.4 Human Error

So far only the failures of technical components have been considered. The technical systems, however advanced their automation, still rely on human intervention in some respects. A fault tree analysis would be incomplete if this aspect were neglected. In modern process plants direct operator control is unusual. Automatic controllers generally ensure that process parameters are maintained close to nominal levels, except perhaps for start-up and shut-down, when an increase degree of human intervention is normally required.

In fault tree analysis, human error should be introduced as basic events to be quantified. A quantification is at present, only possible for the failure of an operator to carry out a planned intervention, e.g. opening or closing a valve. Meanwhile, an unplanned act (e.g. playing around with buttons or changing positions of valves because of absent-mindedness or with the intention of causing harm) cannot be quantified [157]. The human error quantification still remains less exact than the quantification of the failure of technical components.

Human error is defined as an act outside tolerance limits. It is evident that the permissible interval of tolerance depends on the type of human act in question and on the circumstances under which it is carried out. Hauptmanns [157] distinguished human error as follow:

a. Error or omission: failure to perform a task or part of a task
b. Error of commission: performing a task or step incorrectly
c. Extraneous act: introducing some task or step which should not have been performed
d. Sequential error: performing some task or step out of sequence
e. Timing error: failure to perform a task or step within the allowed time oer performing them too early or too late.

F.3.5 Uncertainties

Uncertainties exist in the estimation of reliability data. In case of technical components these may be due to differences in the performance of components of the same class and grouping of similar but not identical components working under similar but not identical operating conditions. If data from the literature is used this leads to the necessity to select values from different sources without knowing whether component designs and operating conditions are comparable and it is very probable that they are not. For this reason use of a statistical distribution for unavailabilities and failure rates is indicated instead of a single point value. A lognormal distribution is usually chosen for this purpose because it fits observed data reasonable well [86]. The corresponding probability density function (pdf) for failure rate (λ) (and analogous for unavailability, u) is given by [86]:

$$f(l) = \frac{1}{\sqrt{2p}\, l\, s} \exp\left[-\frac{(\ln l - m)^2}{2s^2}\right] \qquad (l, s > 0) \qquad \text{(F-14)}$$

The mean value, μ, and, variance, s^2, of the natural logarithms are calculated as follow:

$$m = \frac{1}{N}\sum_{n=1}^{N} \ln l_n = l_{50} \qquad \text{(F-15)}$$

and,

$$s^2 = \frac{1}{N-1}\sum_{n=1}^{N} (\ln l_n - m)^2 \qquad \text{(F-16)}$$

Where N is the total number of measured values or data taken from the literature and λ_{50} is corresponding to median. The mean value of the distribution is given by

$$l = l_{50} \exp\left(\frac{s^2}{2}\right) \qquad \text{(F-17)}$$

And the dispersion of the data is characterized by K-95 factor:

$$K_{95} = \exp(1.6449s) \qquad \text{(F-18)}$$

Where 1.6449 is a constant value of the exponential function made the probability of encountering value of λ in the interval $\lambda_{05} = \lambda_{50}/K < \lambda < \lambda_{50}.K = \lambda_{95}$ equal to 90%, with the probability of λ lying below of above these limits being 5% each [86]. Therefore, they represent the 5% and 95% centiles of the distribution, respectively. If insufficient data are available for calculating the dispersion factor K, an estimate is frequently made which reflect the analyst's subjective judgement as to the uncertainties. Uncertainties of human error probabilities and other basic event are treated in the same way in the context of the analysis.

Appendix G

FAULT TREE ANALYSIS OF THE STUDY OBJECTS

G.1 INTRODUCTION

This appendix contains the derivation of fault trees in order to estimate frequency of the study objects. It is presented only for four study objects, i.e. production plant, storage at depot, filling station and households applications. The fault trees were developed for all of the major containment systems (i.e. tank or vessel) in the study. The data on each study object is given in the following order:

1. Logic diagram of the fault tree
2. A table giving the estimates of probabilities or frequencies of the basic events in the fault trees, and the sources of those estimates
3. Summary of the results of the computation of the Top event frequency in the fault tree.

G.2 FAULT TREES

The analytical method for constructions and evaluations of the fault trees is given in Appendix F. The fault trees include two or three sub-fault trees representing the instantaneous and continuous (both in liquid and vapour phases) release of hydrogen from the containment systems. The sub-fault trees are as follows:

1. Instantaneous release of hydrogen from GH2 tank in the production plant (G1.1)
2. Continuous release of hydrogen from GH2 tank in the production plant (G1.2)
3. Instantaneous release of hydrogen from LH2 tank at depot (G2.1)
4. Continuous release of hydrogen in liquid phase from LH2 tank at depot (G2.2)
5. Continuous release of hydrogen in vapour phase from LH2 tank at depot (G2.3)
6. Instantaneous release of hydrogen from LH2 tank at filling station (G3.1)
7. Continuous release of hydrogen in liquid phase from LH2 tank at filling station (G3.2)
8. Continuous release of hydrogen in vapour phase from LH2 tank at filling station (G3.3)
9. Instantaneous release of hydrogen from LH2 tank at CHP plant (G3.1)
10. Continuous release of hydrogen in liquid phase from LH2 tank at CHP plant (G3.2)
11. Continuous release of hydrogen in vapour phase from LH2 tank at CHP plant (G3.3)

Summary of the computation results consists of the following:

(a) A list of the more significant minimal cut sets
(b) Expected frequencies of several initiating events considered in the study
(c) The top event expected frequency including with its uncertainties (i.e. median, the upper and lower 95% confidence limits, and uncertainty factor K-95).

Due to the study is focused on the societal risk, the minimal cut sets that may not result in fatality on the publics (e.g. release from relief valve, rupture disk, etc.) are not considered in the calculation of the expected frequencies, especially, in the case of continuous release of hydrogen both in liquid and gaseous phase.

Fig. G1.1. GH2 Tank at Production Plant

FAULT TREE DIAGRAM

Instantaneous Release of Hydrogen (Tank Rupture)

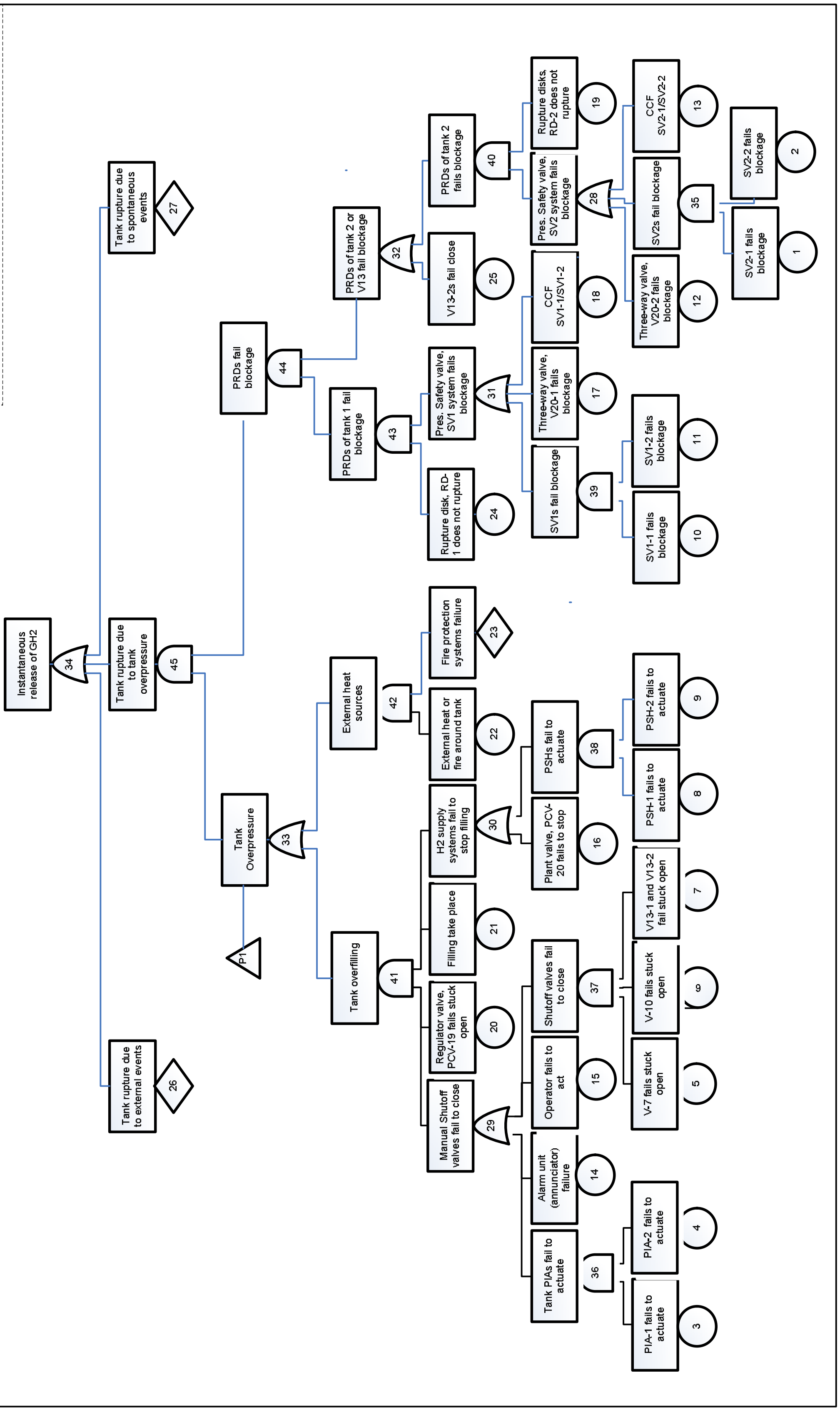

Table G1.1.1. Estimates of basic event probabilities and frequencies for the G1.1 fault tree

Basic Event No.	Component symbol	Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1	SV2-1	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
2	SV2-2	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
3	PIA-3	Pressure indicator and alarm fails to actuate (low)	F	5,9E-07	2,4	[240], Pressure transmitter
4	PIA-4	Pressure indicator and alarm fails to actuate (low)	F	5,9E-07	2,4	[240], Pressure transmitter
5	V-7	Hand operated (isolation) valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
6	V-10	Hand operated (isolation) valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
7	V-13s	Remote operated (isolation) valve fails stuck open (2 units)	F	3,5E-05	2,2	[88], pneu. shutoff valve
8	PSH-1	Very high pressure switch fails to actuate (low)	F	5,6E-07	5,4	[8], p. 171
9	PSH-2	Very high pressure switch fails to actuate (low)	F	5,6E-07	5,4	[8], p. 171
10	SV1-1	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
11	SV1-2	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
12	V20-2	Three-way valve fails blockage	F	3,3E-06	4,7	[241]
13	CCF SV2	Common cause failure of SV2-1 and SV2-2	F	1,1E-07	8,4	0.1 x SV
14	-	Alarm unit (annunciator) fails to sound	F	2,8E-07	10,3	[8], annunciators
15	-	Operator fails to act	P	1,0E-03	2,0	[88,137]
16	-	Plant valve fails stuck open (emergency shutdown valve)	F	4,4E-06	2,8	[224], ESD valve
17	V20-1	Three-way valve fails blockage	F	3,3E-06	4,7	[241]
18	CCF SV1	Common cause failure of SV1-1 and SV1-2	F	1,1E-07	8,4	0.1 x SV
19	RD-2	Rupture disk does not rupture	F	2,0E-05	10,0	[158]
20	PCV-19	Self-pressure operated control valve (fails to change position)	F	9,3E-06	5,0	[184]
21	-	Filling take place	F	2,3E-02	3,0	200/years
22	-	External heat or major fire around the tank	F	1,1E-09	10,0	[116]
23	-	Fire protection system, fire suppression system (water)	F	2,5E-06	14,9	[8], p. 207
24	RD-1	Rupture disk does not rupture	F	2,0E-05	10,0	[158]
25	V-13s	Remote operated (isolation) valves fails stuck close (2 units)	F	3,5E-05	2,2	[88], pneu. shutoff valve
26	-	External events (e.g. Earthquake)	F	1,1E-12	10,0	[116], Table A8.3
27	-	Spontaneous events (e.g. H2 embrittlement)	F	1,0E-11	10,0	[116]

F= Frequency [/h], P=Probability [-]

Table G1.1.2 List of minimal cut sets of the G1.1 fault tree

Cut set No.	Order	Basic Events
1	1	26
2	1	27
3	5	17 22 23 24 25
4	5	18 22 23 24 25
5	6	12 17 19 22 23 24
6	6	10 11 22 23 24 25
7	6	13 17 19 22 23 24
8	6	12 18 19 22 23 24
9	6	13 18 19 22 23 24
10	7	14 16 17 20 21 24 25
11	7	15 16 17 20 21 24 25
12	7	14 16 18 20 21 24 25
13	7	15 16 18 20 21 24 25
14	7	1 2 17 19 22 23 24
15	7	10 11 12 19 22 23 24
16	7	10 11 13 19 22 23 24
17	7	1 2 18 19 22 23 24
18	8	3 4 16 17 20 21 24 25
19	8	8 9 14 17 20 21 24 25
20	8	12 14 16 17 19 20 21 24
21	8	8 9 15 17 20 21 24 25
22	8	12 15 16 17 19 20 21 24
.	.	
.	.	
.	.	
110	13	1 2 5 6 7 8 9 10 11 19 20 21 24

The total results for 10,000 trials:

Table G1.1.3 Expected frequencies of the considered initiating events

Initiating Event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
21	Tank overfilling	2.5E+02	6.3E-09	1.6E-06
22	External heat or fire around the tank	2.6E-05	2.2E-05	5.7E-10
26	External events	2.3E-08	1	2.3E-08
27	Spontaneous events	2.3E-07	1	2.3E-07

The top event expected frequency and its uncertainties:

Expected frequency [/yr]:	1.8E-06
Median [/yr]:	1.7E-07
5% confidence limit [/yr]:	4.8E-09
95% confidence limit [/yr]:	6.2E-06
K-95	35.8

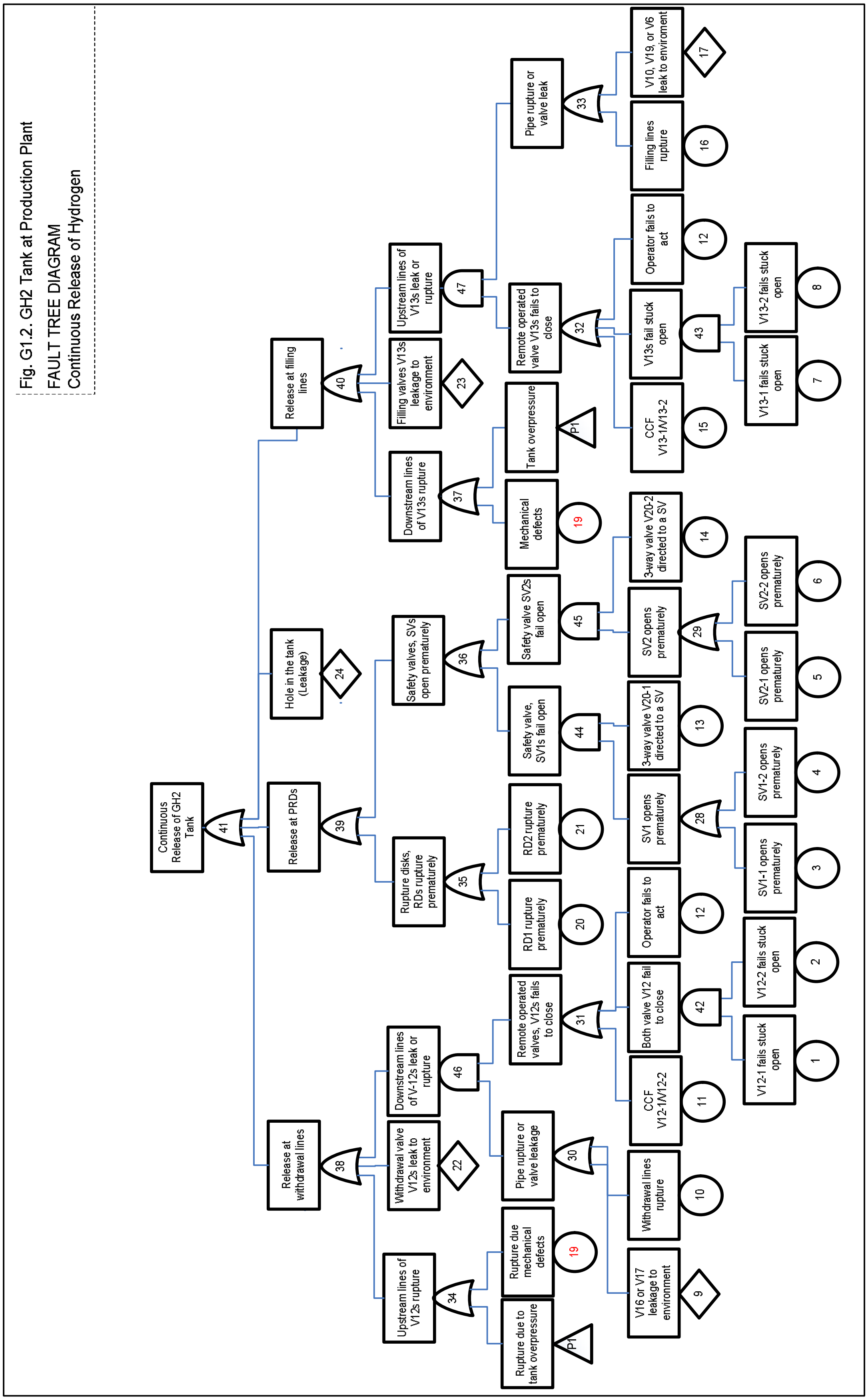

Fig. G1.2. GH2 Tank at Production Plant

FAULT TREE DIAGRAM

Continuous Release of Hydrogen

Table G1.2.1. Estimates of basic event probabilities and frequencies for the G1.2 fault tree

Basic Event No.	Component symbol	Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1	V12-1	Remote operated (isolation) valve fails stuck open	F	1,8E-05	2,2	[88], pneu. shutoff valve
2	V12-2	Remote operated (isolation) valve fails stuck open	F	1,8E-05	2,2	[88], pneu. shutoff valve
3	SV1-1	Pressure safety valve fails open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
4	SV1-2	Pressure safety valve fails open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
5	SV2-1	Pressure safety valve fails open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
6	SV2-2	Pressure safety valve fails open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
7	V13-1	Remote operated (isolation) valve fails stuck open	F	1,8E-05	2,2	[88], pneu. shutoff valve
8	V13-2	Remote operated (isolation) valve fails stuck open	F	1,8E-05	2,2	[88], pneu. shutoff valve
9	PCV-16, 17	Pressure control valves leak to environments (2 units)	F	8,8E-07	5,5	[224], process control valve
10	-	Withdrawal line rupture	F	2,7E-08	10,0	[8], straight section
11	CCF V12	Common cause failures of V12-1 and V12-2	F	1,8E-06	6,7	0.1 x Basic no.1
12	-	Operator fails to act (fails to change valve position)	P	1,0E-03	2,0	[88,137]
13	V20-1	Three-way valve is directed to one safety valve	P	5,0E-01	2,0	Guess estimate, 50%
14	V20-2	Three-way valve is directed to one safety valve	P	5,0E-01	2,0	Guess estimate, 50%
15	CCF V13	Common cause failures of V13-1 and V13-2	F	1,8E-06	6,7	0.1 x Basic no.7
16	-	Upstream line of V13s rupture	F	2,7E-08	10,0	[8], straight section
17	V10	Hand operated (isolation) valves leak to environment	F	1,1E-06	13,8	[184]
18		Pipe rupture due to tank overpressure	F	1,6E-11	35,0	fault tree analysis
19	-	Pipe rupture due to mechanical defect	F	3,6E-10	10,0	[8, 158]
20	RD1	Rupture disk fails break prematurely	F	1,0E-06	10,0	[183]
21	RD2	Rupture disk fails break prematurely	F	1,0E-06	10,0	[183]
22	V12s	Remote operated (isolation) valve leaks to environment	F	3,8E-07	5,5	[224], ESD valve
23	V13s	Remote operated (isolation) valve leaks to environment	F	3,8E-07	5,5	[224], ESD valve
24	-	Hole in the tank	F	2,1E-10	20,8	[8, 116, 159], pressure vessel

F= Frequency [/h], P=Probability [-]

Table G1.2.2 List of minimal cut sets of the G1.2 fault tree

Cut set No.	Order	Basic Events
1	1	24
2	1	22
3	1	20
4	1	23
5	1	18
6	1	19
7	1	21
8	2	9 11
9	2	3 13
10	2	12 16
11	2	5 14
12	2	10 11
13	2	9 12
14	2	4 13
15	2	15 16
16	2	12 17
17	2	6 14
18	2	10 12
19	2	15 17
20	3	1 2 9
21	3	7 8 16
22	3	1 2 10
23	3	7 8 17

The total results for 10,000 trials:

Table G1.2.3 Expected frequencies of the considered initiating events

Initiating event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
10	Withdrawal lines rupture	6.3E-04	1.1E-02	6.8E-06
16	Filling lines rupture	6.3E-04	1.1E-02	6.8E-06
18	Pipe rupture due to tank overpressure	1.4E-06	1	1.4E-06
19	pipe rupture due to mechanical impacts	8.4E-06	1	8.4E-06
24	Serious leakage in the tank	1.0E-05	1	1.0E-05

The top event expected frequency and its uncertainties:

Expected frequency [/yr]:	3.4E-05
Median [/yr]:	1.5E-05
5% confidence limit [/yr]:	1.6E-06
95% confidence limit [/yr]:	1.2E-04
K-95:	8.0

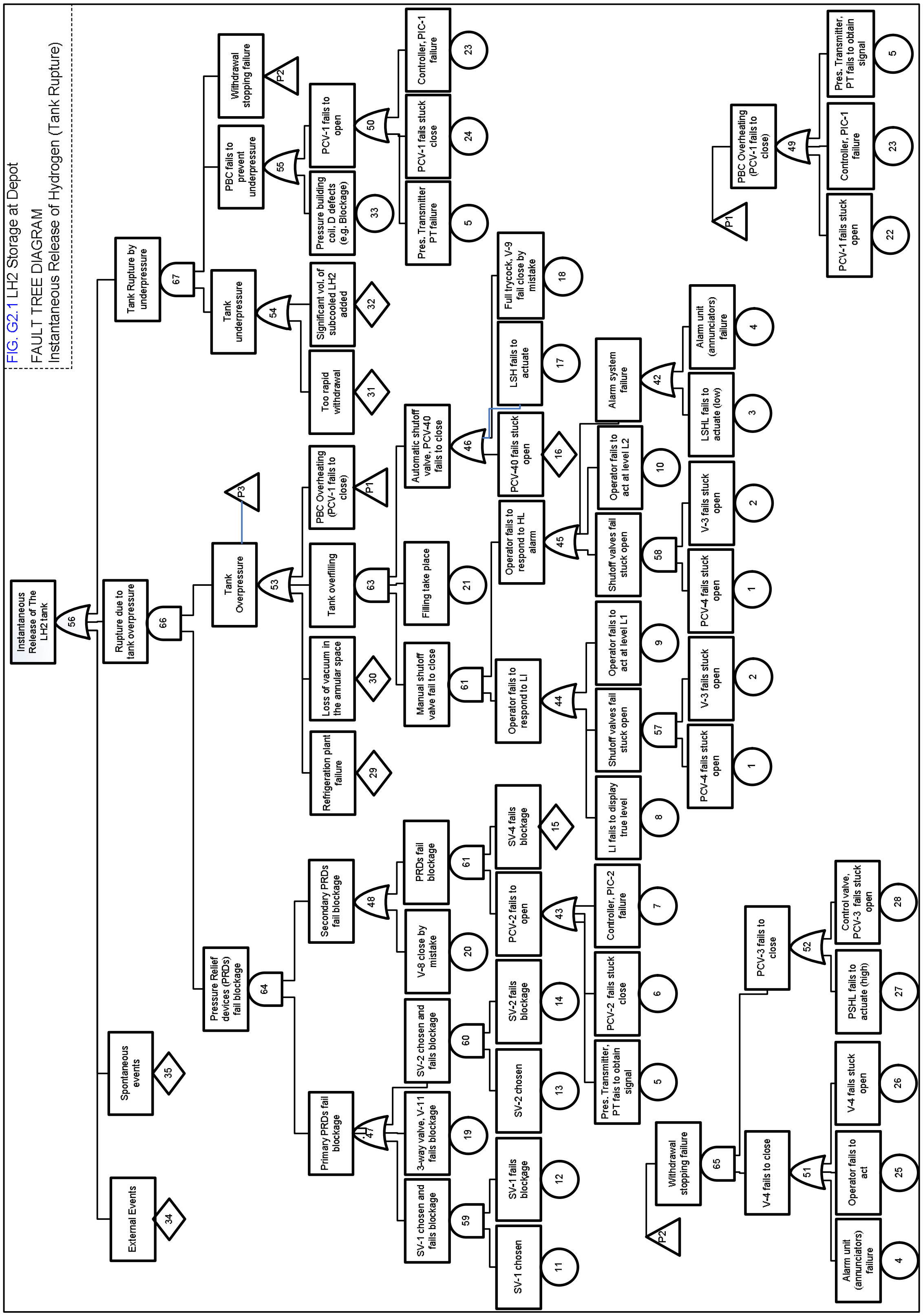

FIG. G2.1 LH2 Storage at Depot
FAULT TREE DIAGRAM
Instantaneous Release of Hydrogen (Tank Rupture)

Table G2.1.1. Estimates of basic event probabilities and frequencies for the G2.1 fault tree

Basic Event No.	Component symbol	Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1	PCV-4	Remote operated (isolation) valve fails stuck open	F	1,8E-05	2,2	[88], pneu. shutoff valve
2	V-3	Hand operated (isolation) valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
3	LSHL	Level switch of high level fails to actuate (low)	F	2,8E-05	13,8	[8]
4		Alarm unit (annunciator) fails to sound	F	2,8E-07	10,3	[8], annunciators
5	PT	Pressure transmitter fails to obtain signal	F	5,8E-07	32,0	[224]
6	PCV-2	Control valve fails stuck close	F	6,1E-07	8,4	[224]
7	PIC-2	Pressure controller fails to operate	F	1,1E-05	14,9	[8]
8	LI	Level indicator fails to display true level	F	7,7E-07	5,6	[184]
9	-	Operator fails to act at level L1	P	1,0E-03	2,0	[88,137]
10	-	Operator fails to act at level L2	P	1,0E-03	2,0	[88,137]
11	SV-1 ch	Pressure safety is chosen to operate	P	5,0E-01	2,0	Guess estimate, 50%
12	SV-1	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
13	SV2 ch	Pressure safety is chosen to operate	P	5,0E-01	2,0	Guess estimate, 50%
14	SV-2	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
15	SV-4	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
16	PCV-40	Plant valve fails to close (emergency shutdown valve)	F	4,4E-06	2,8	[184], ESD valve
17	LSH	Very high level switch fails to actuate (low)	F	2,8E-05	15,1	[8]
18	V-9	Full trycock fails close by mistake	P	1,0E-03	2,0	[88,137]
19	V-11	Three-way valve fails blockage	F	3,3E-06	4,7	[241]
20	V-8	Hand operated valve close by mistake	P	1,0E-03	2,0	[88,137]
21	-	Filling take place	F	8,7E-03	5	76 times/yr, operat. data
22	PCV-1	Control valve fails stuck open	F	2,5E-07	27,7	[224]
23	PIC-1	Pressure controller fails to operate	F	1,1E-05	14,9	[8]
24	PCV-1	Control valve fails stuck close	F	6,1E-07	8,4	[224]
25	-	Operator fails to act	P	1,0E-03	2,0	[88,137]
26	V-4	Hand operated (isolation) valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
27	PSHL	Very low pressure switch fails to actuate (high)	F	5,6E-06	49,0	[8], p.160
28	PCV-3	Control (isolation) valve fails stuck open	F	2,5E-07	27,7	[224], process control valve
29	-	Refrigeration plant failure (e.g. resulting GH2)	F	2,0E-07	3,3	[88], Guess estimate
30	-	Loss of vacuum in the annular space	F	1,4E-08	2,9	Guess estimate
31	-	Withdrawal too rapid (excess withdrawal rates)	F	2,3E-08	10	Guess estimate
32	-	Significant volume of subcooled LH2 added	F	8,7E-08	5	Guess estimate
33	D	Pressure building coil fails to operate	F	6,7E-11	30	[240]
34	-	External events (e.g. Earthquake)	F	1,1E-12	10,0	[116], Table A8.3
35	-	Spontaneous events (e.g. H2 embrittlement)	F	1,0E-11	10,0	[116]

F= Frequency [/h], P=Probability [-]

Table G2.1.2 List of minimal cut sets of the G2.1 fault tree

Cut set No.	Order	Basic Events
1	1	34
2	1	35
3	3	19 20 29
4	3	19 20 30
5	3	5 19 20
6	3	19 20 22
7	3	19 20 23
8	3	5 15 19
9	4	4 27 31 33
10	4	4 27 32 33
11	4	4 5 27 31
12	4	4 5 27 32
13	4	4 23 27 31
14	4	4 24 27 31
15	4	4 23 27 32
16	4	4 24 27 32
17	4	11 12 20 29
18	4	13 14 20 29
19	4	25 27 31 33
20	4	26 27 31 33
21	4	4 28 31 33
22	4	11 12 20 30
23	4	13 14 20 30
24	4	5 11 12 20
25	4	5 13 14 20
29	4	5 25 27 31
30	4	5 26 27 31
.	.	.
281	8	4 7 9 13 14 15 18 21

The total results for 10,000 trials:

Table G2.1.3 Expected frequencies of the considered initiating events

Initiating event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
21	Tank overfilling	1.2E+02	2.5E-08	3.0E-06
22	Pressure building circuit overheating	1.7E-02	6.9E-05	1.2E-06
29	Refrigeration plant failure	2.3E-03	6.9E-05	1.6E-07
30	Loss of vacuum in the annular space	1.5E-04	6.9E-05	1.0E-08
31	Excess withdrawal rates	5.4E-04	1.1E-04	5.9E-08
32	Significant volume of subcooled LH2 added	1.2E-03	1.1E-04	1.3E-07
34	External events	2.6E-08	1	2.6E-08
35	Spontaneous events	2.6E-07	1	2.6E-07

The top event expected frequency and its uncertainties:

Expected frequency [/yr]	4.9E-06
Median [/yr]:	6.4E-07
5% confidence limit [/yr]:	2.3E-08
95% confidence limit [/yr]:	1.8E-05
K-95.	27.5

FIG. G2.2 LH2 Storage at Depot

FAULT TREE DIAGRAM

Continuous Release of Hydrogen in Liquid Phase

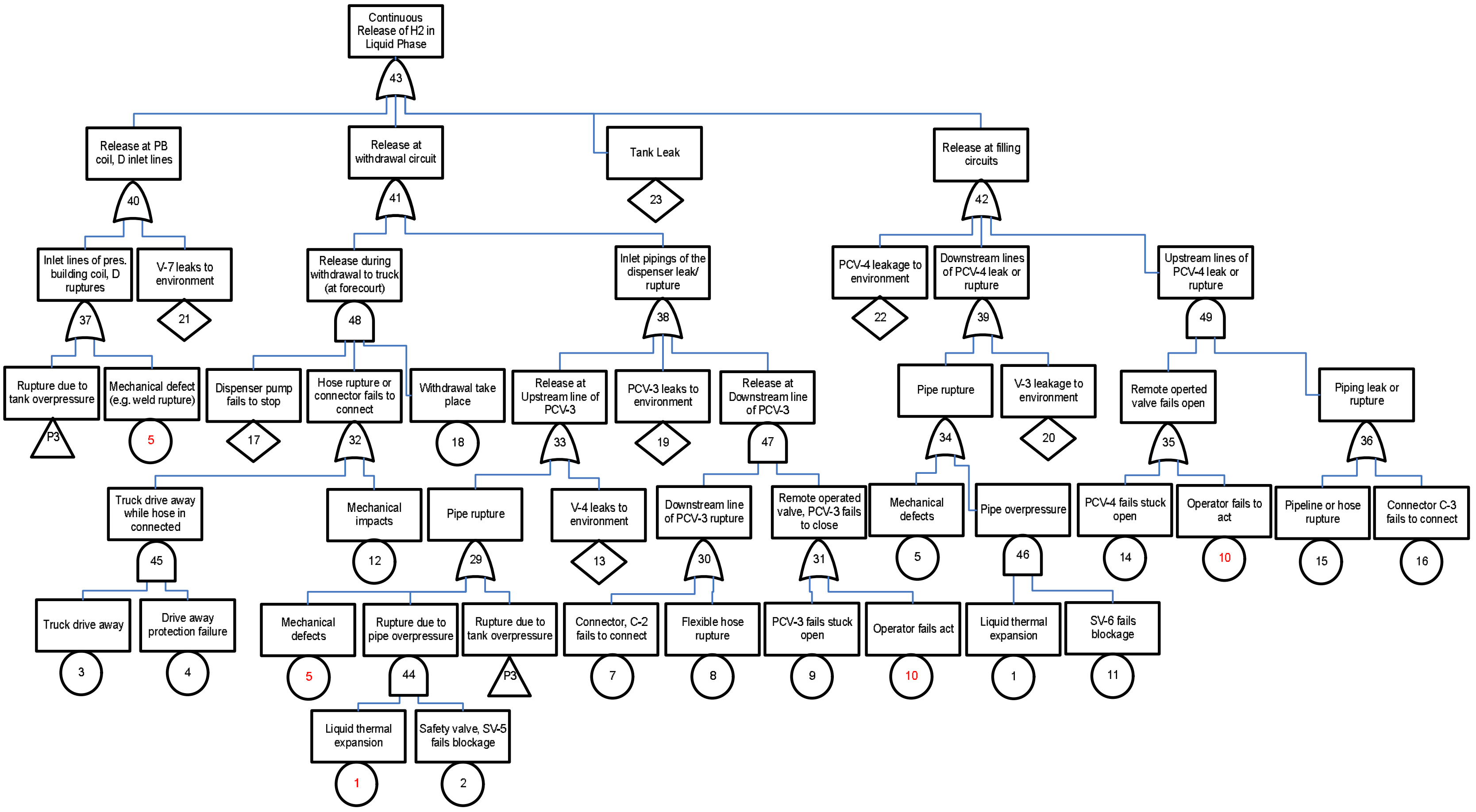

Table G2.2.1 Estimates of basic event probabilities and frequencies for the G2.2 fault tree

Basic Event No.	Component symbol	Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1	-	Liquid thermal expansion	F	1,1E-07	10	Guess estimate, likely incident
2	SV-5	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
3	-	Truck drives away	F	1,1E-06	10	Guess estimate, 1 per 100 years
4	-	Drive away protection failure	F	1,1E-08	10	Guess estimate, unlikely incident
5		Weld rupture	F	3,0E-10	31,6	[116], Table A14.4
6		Pipe rupture due to tank overpressure	F	2,1E-10	38,2	FTA
7	C-2	Connector fails to connect	F	1,5E-07	14,9	[8], page. 184
8	-	Flexible hose to dispenser ruptures	F	1,5E-07	14,9	[8], hoses
9	PCV-3	Remote operated (isolation) valve fails stuck open	F	1,8E-05	2,2	[88], pneu. shutoff valve
10	-	Operator fails to act	P	1,0E-03	2,0	[88,137]
11	SV-6	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
12	-	Mechanical impact (e.g. cranes etc)	F	1,1E-11	10,0	[116], Table IX.2
13	V-4	Hand operated (isolation) valves leak to environment	F	1,1E-06	13,8	[224]
14	PCV-4	Remote operated (isolation) valve fails stuck open	F	1,8E-05	2,2	[88], pneu. shutoff valve
15	-	Filling lines from the plant ruptures	F	6,9E-10	15,0	[8], p. 183, metal pipe
16	C-3	Connector fails to connect	F	1,5E-07	14,9	[8], page. 184
17		Dispenser valve fails stuck open or LH2 pump fails to stop	P	3,8E-05	10,0	[116], Table A8.2
18		Withdrawal takes place	F	2,3E-02	10,0	200/year
19	PCV-3	Remote operated (isolation) valve leaks to environment	F	1,0E-07	10,0	[183]
20	V-3	Hand operated valve leaks to environment (rupture)	F	1,1E-06	13,8	[224]
21	V-7	Hand operated valve leaks to environment (rupture)	F	1,1E-06	13,8	[224]
22	PCV-4	Remote (control) operated valve leaks to environment	F	3,8E-07	5,5	[224]
23		Serious leakage from inner tank (refrigerated, double wall)	F	2,3E-09	10,0	[116], Table A8.2

F= Frequency [/h], P=Probability [-]

Table G2.2.2 Lists of minimal cut sets of the G2.2 fault tree

Cut set No.	Order	Basic Events
1	1	23
2	1	21
3	1	19
4	1	22
5	1	5
6	1	20
7	1	6
8	1	13
9	2	10 15
10	2	1 11
11	2	7 9
12	2	14 15
13	2	10 16
14	2	14 16
15	2	1 2
16	2	8 9
17	2	7 10
18	2	8 10
19	3	12 17 18
20	4	3 4 17 18

The total results for 10,000 trials:

Table G2.2.3 Expected frequencies of the considered initiating events

Initiating event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
1	Pipe rupture due to liquid thermal expansion	2.6E-04	2.1E-02	5.5E-06
5	Pipe rupture due to mechanical impacts	2.4E-05	1.0E+00	2.4E-05
6	Pipe rupture due to tank overpressure	2.1E-05	1.0E+00	2.1E-05
8	Flexible hose to dispenser failure	5.1E-03	6.0E-03	3.1E-05
15	Filling lines rupture	2.3E-05	8.3E-02	1.9E-06
18	Release during unloading to a LH2 truck	5.4E+02	2.10E-10	1.1E-07

The top event expected frequency and its uncertainties:

Expected frequency [/yr]	8.3E-05
Median [/yr]:	1.7E-05
5% confidence limit [/yr]:	9.1E-07
95% confidence limit [/yr]:	3.2E-04
K-95:	18.8

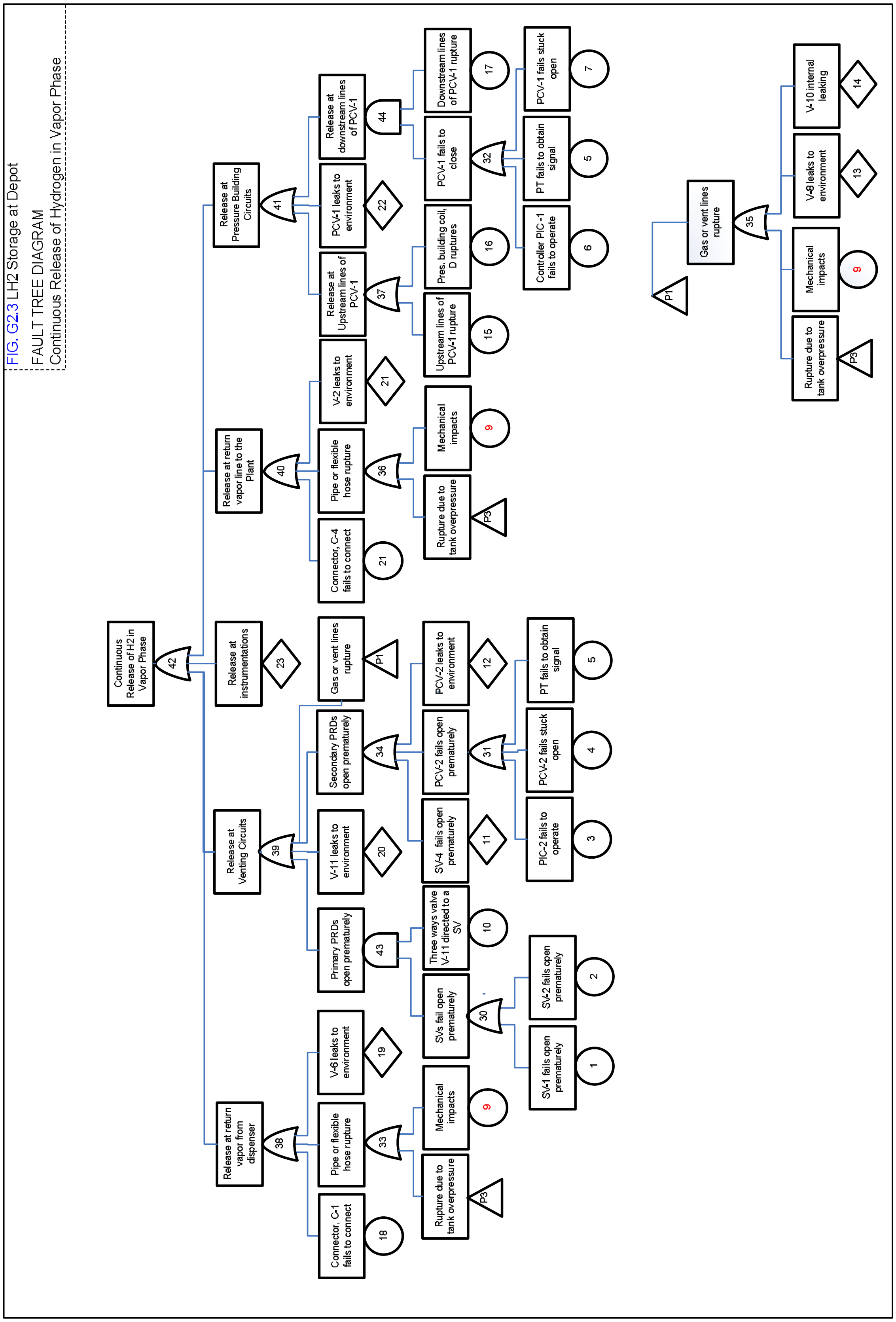

FIG. G2.3 LH2 Storage at Depot
FAULT TREE DIAGRAM
Continuous Release of Hydrogen in Vapor Phase

Table G2.3.1 Estimates of basic events probabilities and frequencies for the G2.3 fault tree

Basic Event No.	Component symbol	Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1	SV-1	Pressure safety valve fails open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
2	SV-2	Pressure safety valve fails open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
3	PIC-2	Pressure controller fails to operate	F	1,1E-05	14,9	[8]
4	PCV-2	Control valve fails stuck open	F	2,5E-07	27,7	[224], process control valve
5	PT	Pressure transmitter fails to obtain signal	F	5,9E-07	2,4	[240]
6	PIC-1	Pressure controller fails to operate	F	1,1E-05	14,9	[8]
7	PCV-1	Control valve fails stuck open	F	2,5E-07	27,7	[224], process control valve
8		Pipe rupture due to tank overpressure	F	2,1E-10	38,2	FTA
9		Mechanical impact (e.g. cranes etc)	F	1,1E-11	10,0	[116], Table IX.2
10	V-11	Three-way valve is directd to one safety valve	P	5,0E-01	2,0	
11	SV-4	Pressure safety valve fails open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
12	PCV-2	Control valve leaks to environment	F	4,4E-07	5,5	[224], process control valve
13	V-8	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
14	V-10	Hand valve leaks in close position (internal leakage)	F	7,3E-08	11,5	[224], p. 608
15		Upstream line of the PCV-1 (pipe) ruptures	F	6,9E-09	15,0	[8]
16	D	Pressure building coil ruptures	F	9,7E-10	2,5	[116] Table A14.6, [159] Table 3.11
17		Downstream line of the PCV-1 ruptures	F	6,9E-09	15,0	[8]
18	C-1	Connector fails to connect	F	1,5E-07	14,9	[8], page. 184
19	V-6	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
20	V-11	Three-way valve leaks to environment	F	1,1E-06	13,8	[224]
21	C-4	Connector fails to connect	F	1,5E-07	14,9	[8], page. 184
22	V-2	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
23	PCV-1	Control valve leaks to environment	F	4,4E-07	5,5	[224], process control valve
24		Release at instrumentation system	F	1,0E-09	10,0	Guess estimate

F= Frequency [/h], P=Probability [-]

Table G2.3.2 Lists of minimal cut sets of the G2.3 fault tree

Cut set No.	Order	Basic Events
1	1	24
2	1	18
3	1	20
4	1	21
5	1	23
6	1	19
7	1	8
8	1	11
9	1	22
10	1	15
11	1	9
12	1	12
13	1	3
14	1	13
15	1	14
16	1	16
17	1	4
18	1	5
19	2	1 10
20	2	2 10
21	2	6 17
22	2	7 17

The total results for 10,000 trials:

Table G2.3.3 Expected frequencies of the considered initiating events

Initiating event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
8	Vapour lines rupture due to tank overpressure	2.1E-05	1.0E+00	2.1E-05
9	Vapour lines rupture due to mechanical impacts	2.6E-07	1.0E+00	2.6E-07
16	Pressure building coil ruptures	9.9E-06	1.0E+00	9.9E-06
17	PBC outlet lines rupture	2.3E-05	1.3E-01	3.0E-06

The top event expected frequency and its uncertainties:

Expected frequency [/yr]:	3.5E-05
Median [/yr]:	4.8E-06
5% confidence limit [/yr]:	1.8E-07
95% confidence limit [/yr]:	1.3E-04
K-95	26.2

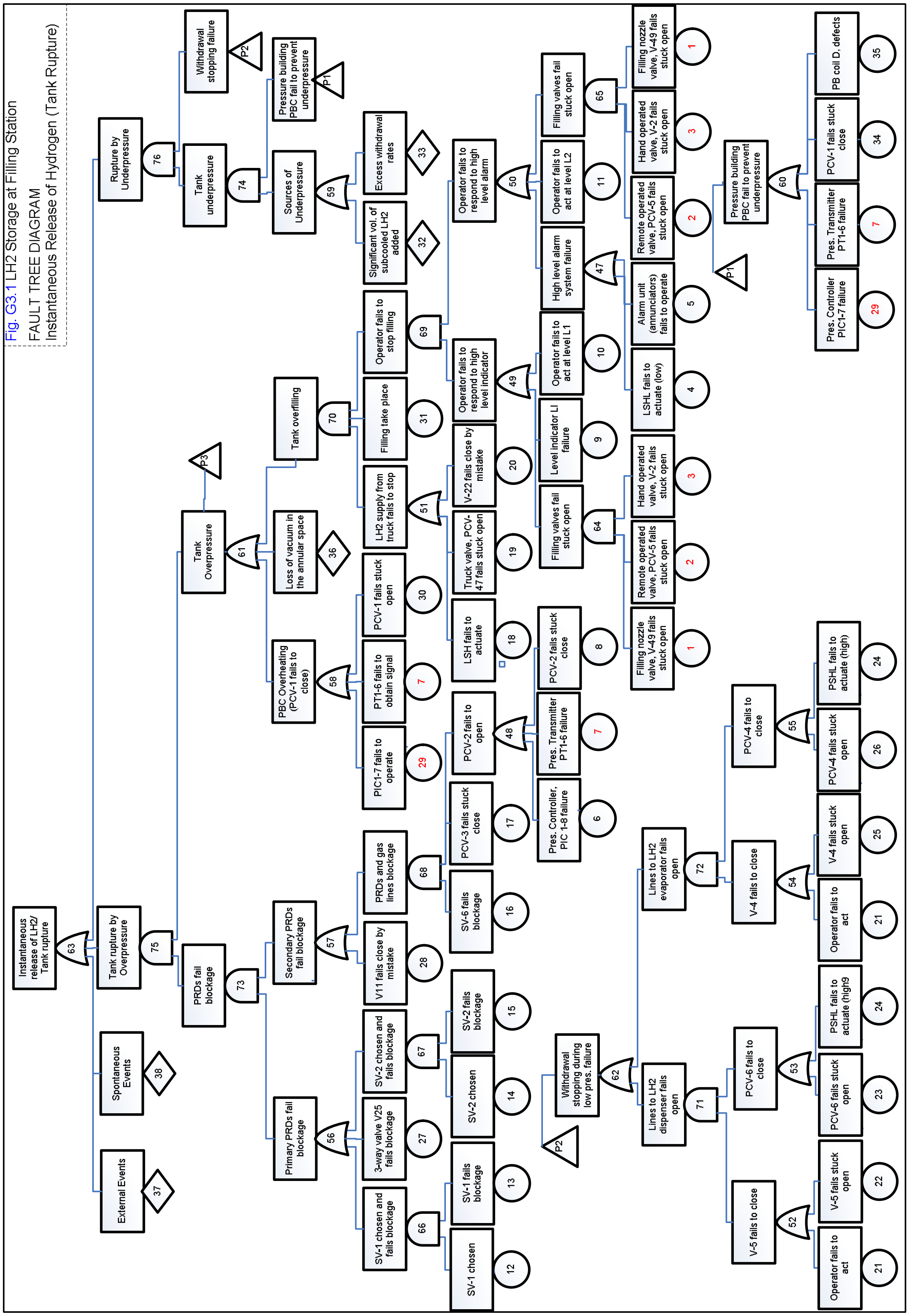

Fig. G3.1 LH2 Storage at Filling Station
FAULT TREE DIAGRAM
Instantaneous Release of Hydrogen (Tank Rupture)

Table G3.1.1. Estimates of basic event probabilities and frequencies for the G3.1 fault tree

Basic Event No.	Component symbol	Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1	V-49	Truck filling valve (nozzle) fails stuck open	F	8,4E-08	6,0	[8], manual valve
2	PCV-5	Remote operated (isolation) valve fails stuck open	F	1,8E-05	2,2	[88], pneu. shutoff valve
3	V-2	Hand operated (isolation) valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
4	LSHL	Level switch of high level fails to actuate (low)	F	2,8E-05	13,8	[8]
5		Alarm unit (annunciator) fails to sound	F	2,8E-07	10,3	[8], annunciators
6	PIC 1-8	Pressure controller fails to operate	F	1,1E-05	14,9	[8]
7	PT 1-6	Pressure transmitter fails to obtain signal	F	5,8E-07	32,0	[224]
8	PCV-2	Control valve fails stuck open	F	2,5E-07	27,7	OREDA[224]
9	LI	Level indicator fails to display true level	F	7,7E-07	5,6	[224]
10		Operator fails to act at level L1 (respond to indicators)	P	1,0E-03	2,0	[88,137]
11		Operator fails to act at level L2 (respond to alarm)	P	1,0E-03	2,0	[88,137]
12	SV1 ch	Pressure safety is chosen to operate	P	5,0E-01	2,0	Guess estimate, 50%
13	SV1	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
14	SV2 ch	Pressure safety is chosen to operate	P	5,0E-01	2,0	Guess estimate, 50%
15	SV2	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
16	SV3	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
17	PCV-3	Self-pressure operated control valve (fails to change position)	F	9,3E-06	5,0	T-Book [184]
18	LSH	Very high level switch fails to actuate (low)	F	2,8E-05	15,1	[8]
19	PCV-47	Truck valve fails stuck open (emergency shutdown valve)	F	4,4E-06	2,8	[224], ESD valve
20	V-22	Trycock (hand operated) valve close by mistake	P	1,0E-03	2,0	[88,137]
21	V-5	Operator fails to act	P	1,0E-03	2,0	[88,137]
22	V-5	Hand operated (isolation) valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
23	PCV-6	Control valve fails stuck open	F	2,5E-07	27,7	OREDA[224]
24	PSHL	Very low pressure switch fails to actuate (high)	F	5,6E-06	49,0	[8], p.160
25	V-49	Hand operated (isolation) valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
26	PCV-4	Control valve fails stuck open	F	2,5E-07	27,7	OREDA[224]
27	V-25	Three-ways valve fails blockage	F	3,3E-06	4,7	GRS [241]
28	V-11	Manual operated valve close by mistake	P	1,0E-03	2,0	[88,137]
29	PIC 1-7	Pressure controller fails to operate	F	1,1E-05	14,9	[8]
30	PCV-1	Control valve fails stuck open	F	2,5E-07	27,7	[224]
31		Filling takes place	F	2,7E-03	5	24 times/yr, operat. data
32	LH2	Significant volume of subcooled LH2 added	F	8,7E-08	5	Guess estimate
33		Withdrawal too rapid (excess withdrawal)	F	2,3E-08	10	Guess estimate
34	PCV-1	Control valve fails stuck close	F	6,1E-07	8,4	OREDA [224]
35	D	Pressure building coil fails to operate	F	6,7E-11	30	CPR12E [240]
36		Loss of vacuum in the annular space	F	1,4E-08	2,9	fault tree, guess estimate
37		External events (e.g. earthquake)	F	1,1E-12	10,0	[116], Table A8.3
38		Spontaneous events (e.g. H2 embrittlement)	F	1,0E-11	10,0	[116]

F= Frequency [/h], P=Probability [-]

Table G3.1.2. List of minimal cut sets of the G3.1 fault tree

Cut set No.	Order	Basic Events
1	1	37
2	1	38
3	3	27 28 36
4	3	7 27 28
5	3	27 28 29
6	3	27 28 30
7	4	7 21 23 32
8	4	7 21 24 32
9	4	12 13 28 36
10	4	14 15 28 36
11	4	7 22 23 32
12	4	7 21 23 33
13	4	21 23 29 32
14	4	21 23 32 34
15	4	21 23 32 35
16	4	7 12 13 28
17	4	7 14 15 28
18	4	7 24 25 32
19	4	7 21 26 32
20	4	7 21 24 33
21	4	21 24 29 32
22	4	21 24 32 34
23	4	21 24 32 35
24	4	12 13 28 29
25	4	14 15 28 29
26	4	12 13 28 30
27	4	14 15 28 30
...	...	...
217	10	1 2 3 8 14 15 16 17 20 31

The total results for 10,000 trials:

Table G3.1.3 Expected frequencies of the considered initiating events

Initiating event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
30	PBC overheating	1.7E-02	2.0E-04	3.4E-06
31	Tank overfilling	3.8E+00	1.6E-08	6.1E-08
32	Significant volume of sub-cooled LH2 added	1.2E-03	3.0E-04	3.6E-07
33	Excess withdrawal rates	5.4E-04	3.0E-04	1.6E-07
36	Loss of vacuum in the annular space	1.5E-04	2.0E-04	3.0E-08
37	External events	2.6E-08	1.0E+00	2.6E-08
38	Spontaneous events	2.6E-07	1.0E+00	2.6E-07

The top event expected frequency and its uncertainties:

Expected frequency [/yr]:	4.3E-06
Median [/yr]:	2.8E-07
5% confidence limit [/yr]:	6.0E-09
95% confidence limit [/yr]:	1.3E-05
K-95:	46.7

Fig. G3.2 LH2 Storage at Filling Station
FAULT TREE DIAGRAM
Continuous Release of Hydrogen in Liquid Phase

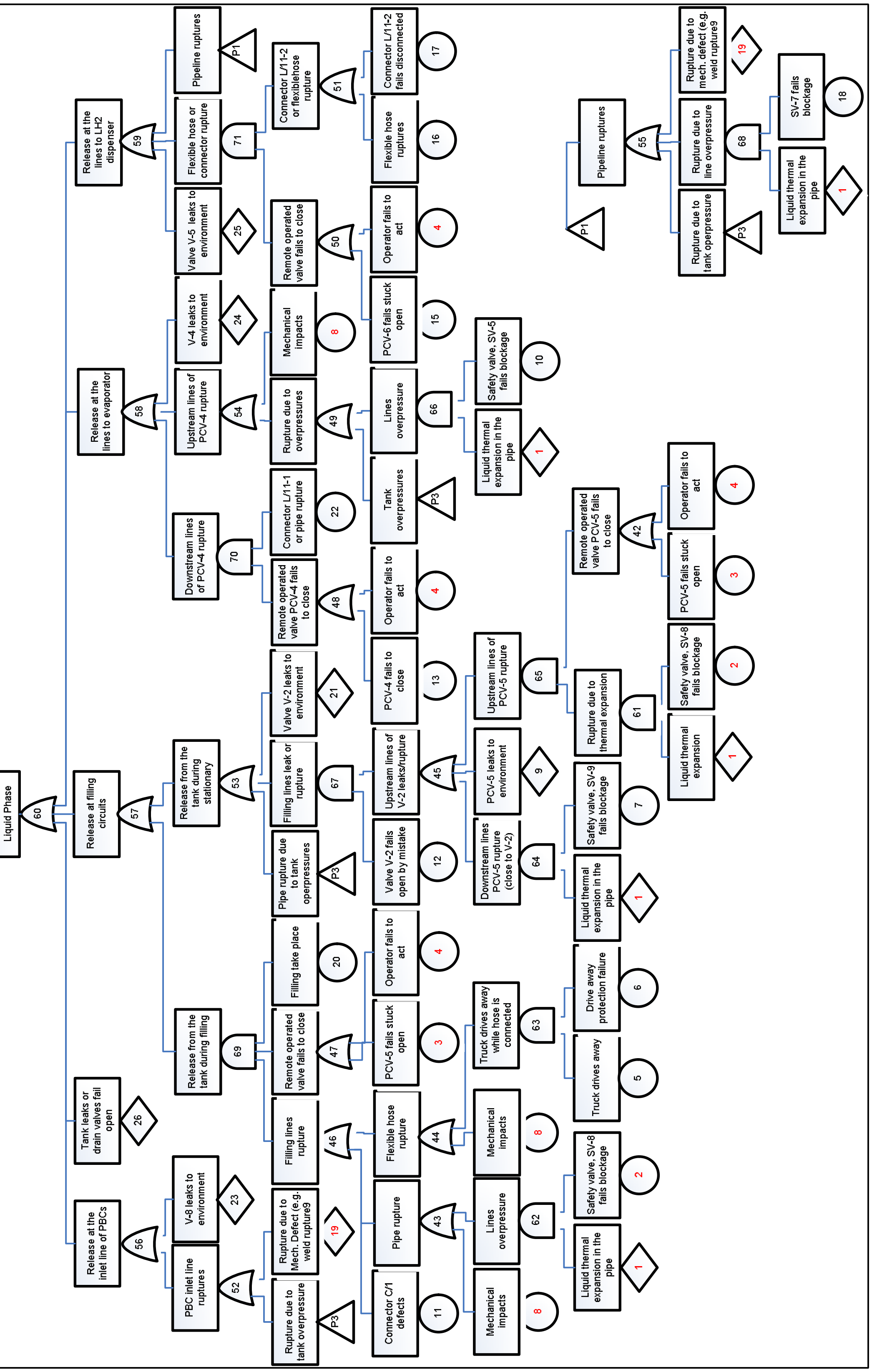

Table G3.2.1. Estimates of basic event probabilities and frequencies for the G3.2 fault tree diagram

		Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1		Liquid thermal expansion in the pipe	F	1,1E-07	10	Guess estimate, likely incident
2	SV-8	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
3	PCV-5	Remote operated (isolation) valve fails stuck open	F	1,8E-05	2,2	[88], pneu. shutoff valve
4		Operator fails to act	P	1,0E-03	2,0	[88,137]
5		Truck drives away	F	1,1E-06	10	Guess estimate, 1 per 100 years
6		Drive away protection failure	F	1,1E-08	10	Guess estimate, unlikely incident
7	SV-9	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
8		Mechanical impact (e.g. cranes etc)	F	1,1E-11	10,0	[116], Table IX.2
9	PCV-5	Remote (control) operated valve leaks to environment	F	3,8E-07	5,5	[224]
10	SV-5	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
11	C/1	Filling connector fails to connect	F	1,5E-07	14,9	[8], page. 184
12	V-2	Hand operated valve open by mistake	P	1,0E-03	2,0	[88,137]
13	PCV-4	Remote operated (isolation) valve fails stuck open	F	2,5E-07	27,7	OREDA[224]
14		Pipe rupture due to tank overpressure	F	1,3E-10	42,0	FTA
15	PCV-6	Remote operated (isolation) valve fails stuck open	F	1,8E-05	2,2	[88], pneu. shutoff valve
16		Flexible hose to dispenser ruptures	F	1,5E-07	14,9	[8]
17	L/11-2	Liquid withdrawal connector fails to connect	F	1,5E-08	14,9	[8], metal connector
18	SV-7	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
19		Weld rupture	F	3,0E-10	31,6	[116], Table A14.4
20		Filling takes place	F	2,7E-03	5	24 times/yr, operat. data
21	V-2	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
22	L/11-1	Connector fails to connect	F	1,5E-07	14,9	[8], page. 184
23	V-8	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
24	V-4	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
25	V-5	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
26		Serious leakage from inner tank (refrigerated, double wall)	F	2,3E-09	10,0	[116], Table A8.2

F= Frequency [/h], P=Probability [-]

Table G3.2.2. List of the minimal cut sets of the G3.2 fault tree

Cut set No.	Order	Basic Events
1	1	26
2	1	23
3	1	14
4	1	24
5	1	25
6	1	8
7	1	19
8	1	21
9	2	4 22
10	2	4 16
11	2	1 18
12	2	1 10
13	2	13 22
14	2	15 16
15	2	4 17
16	2	15 17
17	3	3 11 20
18	3	9 12 13
19	3	4 11 20
20	4	1 2 3 20
21	4	3 5 6 20
22	4	1 2 4 20
23	4	4 5 6 20
24	4	1 7 12 13
25	5	1 2 3 12 13
26	5	1 2 4 12 13

The total results for 10,000 trials:

Table G3.2.3. Expected frequencies of the considered initiating events

Initiating event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
1	Lines rupture due to liquid thermal expansion	2.6E-04	2.1E-02	5.5E-06
14	Line rupture due to tank overpressure	2.1E-05	1.0E+00	2.1E-05
16	flexible hose to LH2 dispenser rupture	5.1E-03	8.8E-02	4.5E-04
19	Line rupture due to mechanical defects	2.4E-05	1.0E+00	2.4E-05
20	Release from tank during filling from truck	3.8E+00	1.7E-05	6.5E-05
8	Lines rupture due to mechanical impacts	2.6E-07	1.00E+00	2.6E-07
26	Serious leakage of the tank	5.4E-05	1	5.4E-05

The top event expected frequency and its uncertainties:

Expected frequency [/yr]:	6.2E-04
Median [/yr]:	1.9E-04
5% confidence limit [/yr]:	1.5E-05
95% confidence limit [/yr]:	2.4E-03
K-95:	12.7

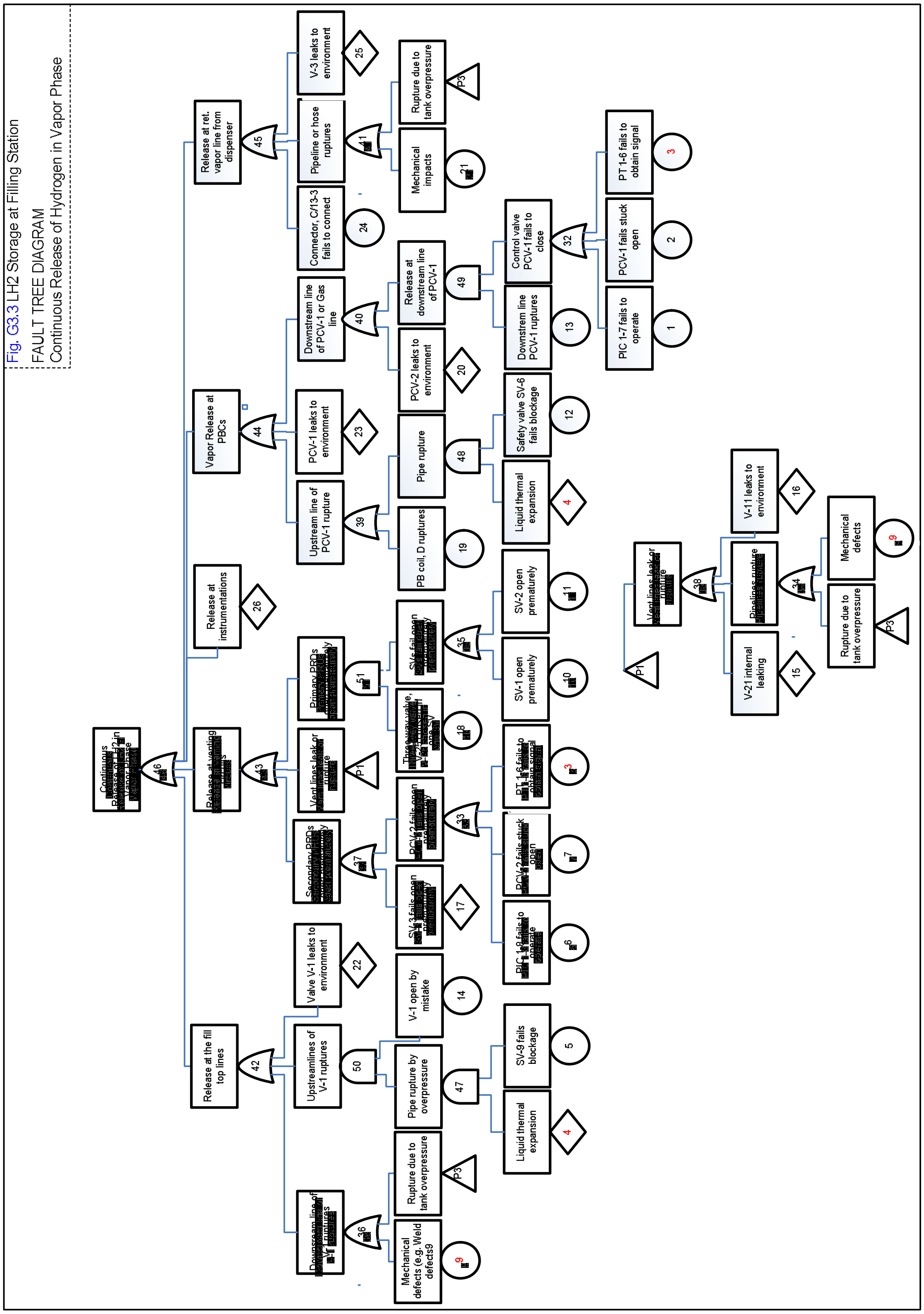

Fig. G3.3 LH2 Storage at Filling Station
FAULT TREE DIAGRAM
Continuous Release of Hydrogen in Vapor Phase

Table G3.3.1. Estimates of basic event probabilities and frequencies for the G3.3 fault tree

Basic Event No.	Component symbol	Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1	PIC 1-7	Pressure controller fails to operate	F	1,1E-05	14,9	[8]
2	PCV-1	Control operated valve fails stuck open	F	2,5E-07	27,7	[224]
3	PT 1-6	Pressure transmitter fails to obtain signal	F	5,8E-07	32,0	[224]
4		Liquid thermal expansion	F	1,1E-07	10	Guess estimate, likely incident
5	SV-9	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
6	PIC 1-8	Pressure controller fails to operate	F	1,1E-05	14,9	[8]
7	PCV-2	Control operated valve fails stuck open	F	2,5E-07	27,7	[224]
8		Pipe rupture due to tank overpressure	F	1,3E-10	42,0	FTA
9		Pipe rupture due to weld rupture	F	3,0E-09	31,6	[116], Table A14.4
10	SV-1	Pressure safety valve fails open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
11	SV-2	Pressure safety valve fails open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
12	SV-6	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
13		Downstream line PCV-1 rupture	F	6,9E-09	15,0	[8]
14	V-1	Hand operated valve fails open by mistake	P	1,0E-03	2,0	[88,137]
15	SV-3	Pressure safety valve fails open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
16	V-21	Hand valve leaks in close position (internal leakage)	F	7,3E-08	11,5	[224], p. 608
17	V-11	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
18	V-25	Three-ways valve chosen to one safety valve	P	5,0E-01	2,0	
19	D	Pressure building coil ruptures	F	9,7E-10	2,5	[116] Table A14.6, [159] Table 3.11
20	PCV-2	Control valve leaks to environment	F	4,4E-07	5,5	224], process control valve
21		Mechanical impact (e.g. cranes etc)	F	1,1E-11	10,0	[116], Table IX.2
22	V-1	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
23	PCV-1	Control operated valve leaks to environment	F	4,4E-07	5,5	[224], process control valve
24	C/13-3	Connector fails to connect	F	1,5E-07	14,9	[8], page. 184
25	V-3	Hand operated valve leaks to environment	F	1,1E-06	13,8	224]
26		Release at instrumentation	F	1,0E-09	10,0	Guess estimate

F= Frequency [/h], P=Probability [-]

Table G3.3.2. List of the minimal cut sets of the G3.3 fault tree

Cut set No.	Order	Basic Events
1	1	26
2	1	22
3	1	15
4	1	23
5	1	24
6	1	8
7	1	16
8	1	19
9	1	20
10	1	25
11	1	9
12	1	17
13	1	21
14	1	3
15	1	6
16	1	7
17	2	10 18
18	2	4 12
19	2	1 13
20	2	11 18
21	2	2 13
22	3	4 5 14

The total results for 10,000 trials:

Table G3.3.3. Expected frequencies of the considered initiating events

Initiating event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
4	Lines rupture due to liquid thermal expansion	2.6E-04	1.1E-02	2.9E-06
8	Lines rupture due to tank overpressure	2.1E-05	1.0E+00	2.1E-05
9	Lines rupture due to mechanical defects	2.4E-05	1.0E+00	2.4E-05
13	Outlet lines of the PBC rupture	2.3E-04	1.3E-01	3.0E-05
19	Pressure building coil ruptures	9.9E-06	1.0E+00	9.9E-06
21	Vapour lines rupture due to mechanical impacts	2.6E-07	1.0E+00	2.6E-07

The top event expected frequency and its uncertainties:

Expected frequency [/yr]:	9.0E-05
Median [/yr]:	1.7E-05
5% confidence limit [/yr]:	8.9E-07
95% confidence limit [/yr]:	3.4E-04
K-95:	19.6

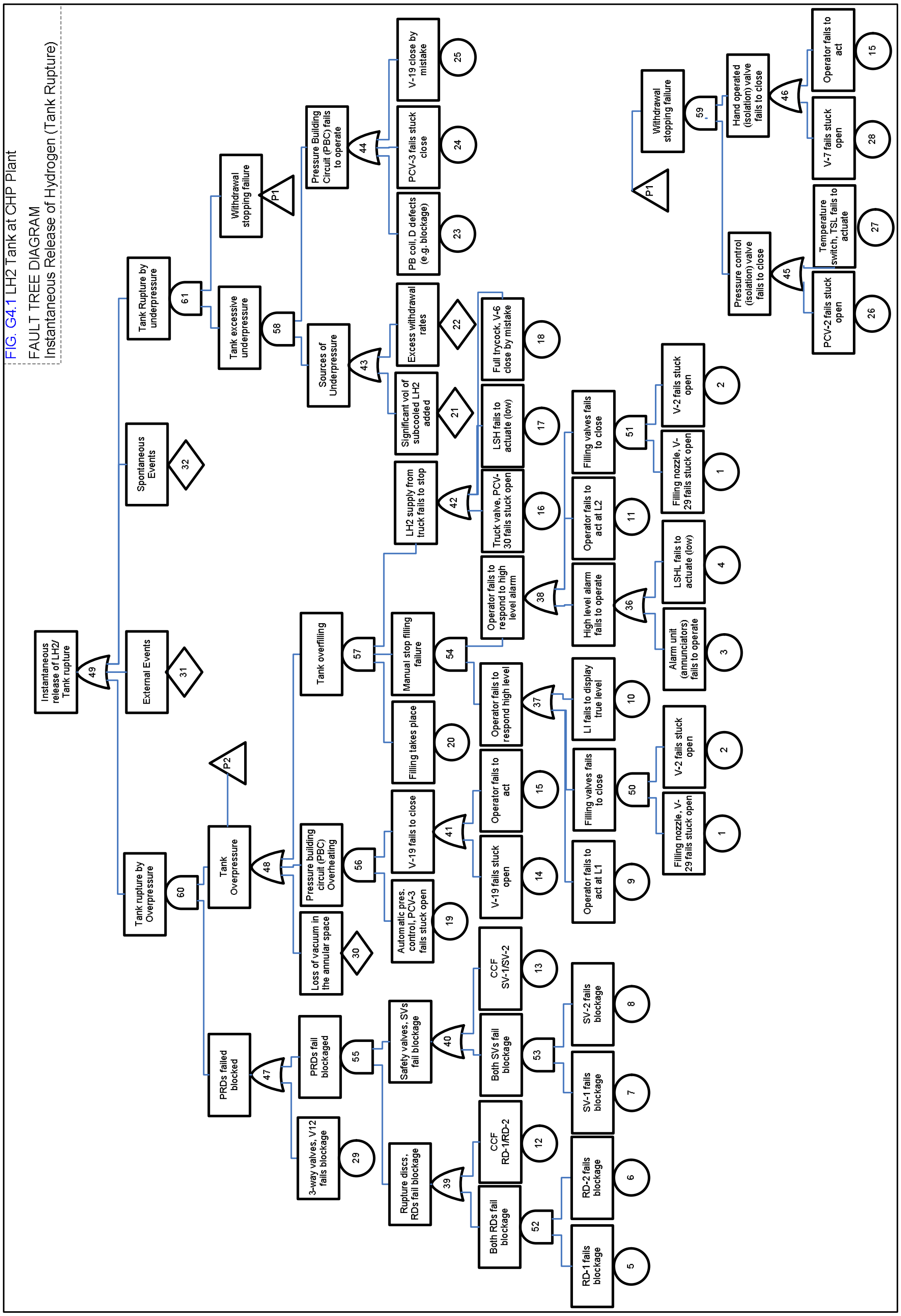

FIG. G4.1 LH2 Tank at CHP Plant

FAULT TREE DIAGRAM
Instantaneous Release of Hydrogen (Tank Rupture)

Table G4.1.1. Estimates of basic event probabilities and frequencies for the G4.1 fault tree

Basic Event No.	Component symbol	Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1	V-29	Truck nozzle valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
2	V-2	Hand operated (isolation) valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
3		Alarm unit (annunciator) fails to sound	F	2,8E-07	10,3	[8], annunciators
4	LSHL	Level switch of high level fails to actuate (low)	F	2,8E-05	13,8	[8]
5	RD-1	Rupture disk does not rupture (fails blockage)	F	2,0E-05	10,0	[158]
6	RD-2	Rupture disk does not rupture (fails blockage)	F	2,0E-05	10,0	[158]
7	SV-1	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
8	SV-2	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
9		Operator fails to act at level L1 (erespond to indicators)	P	1,0E-03	2,0	[88,137]
10	LI	Level indicator fails to display true level	F	7,7E-07	5,6	[224]
11		Operator fails to act at level L2 (respond to alarm)	P	1,0E-03	2,0	[88,137]
12		Common cause failure of RD-1 and RD-2	F	2,0E-06	10,0	0.1*RD
13		Common cause failure of SV-1 and SV-2	F	1,1E-07	8,4	0.1*SV
14	V-19	Hand operated (isolation) valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
15		Operator fails to act	P	1,0E-03	2,0	[88,137]
16	PCV-30	Truck valve fails stuck open (emergency shutdown valve)	F	4,4E-06	2,8	[224], ESD valve
17	LSH	Very high level switch fails to actuate (low)	F	7,8E-07	2,1	[8], switch-electric- flow
18	V-6	Trycock (hand operated) valve close by mistake	P	1,0E-03	2,0	[88,137]
19	PCV-3	Self-pressure operated control valve (fails to change position)	F	9,3E-06	5,0	T-Book [184]
20		Filling takes place	F	2,7E-03	5	24/yr,
21		Significant volume of subcooled LH2 added	F	8,7E-08	5	Guess estimate
22		Withdrawal is too rapid (excessive withdrawal rates)	F	2,3E-08	10	Guess estimate
23	D	Pressure building coil defects	F	6,7E-11	30	CPR12E [240]
24	PCV-3	Self-pressure operated control valve (fails to change position)	F	9,3E-06	5,0	T-Book [184]
25	V-19	Hand operated valve close by mistake	P	3,0E-03	7,1	NUREG/CR-1278
26	PCV-2	Control valve fails stuck open	F	2,5E-07	27,7	OREDA[224]
27	TSL	Temperature switch low fails to actuate (high)	F	2,5E-05	14,9	OREDA[224]
28	V-7	Hand operated (isolation) valve fails stuck open	F	8,4E-08	6,0	[8], manual valve
29	V-12	Three-way valve fails blockage	F	3,3E-07	4,7	GRS [241]
30		Loss of vacuum in the annular space	F	1,4E-08	2,9	fault tree, guess estimate
31		External events	F	1,1E-12	10,0	[116], Table A8.3
32		Spontaneous events	F	1,0E-11	10,0	[116]

F= Frequency [/h], P=Probability [-]

Table G4.1.2. List of the minimal cut sets of the G4.1 fault tree

Cut set No.	Order	Basic Events
1	1	31
2	1	32
3	2	29 30
4	3	12 13 30
5	3	14 19 29
6	3	15 19 29
7	4	15 21 23 26
8	4	12 13 14 19
9	4	15 22 23 26
10	4	15 21 24 26
11	4	15 21 25 26
12	4	15 21 23 27
13	4	21 23 26 28
14	4	5 6 13 30
15	4	7 8 12 30
16	4	12 13 15 19
17	4	15 22 24 26
18	4	15 22 25 26
19	4	15 22 23 27
20	4	22 23 26 28
21	4	15 21 24 27
22	4	21 24 26 28
23	4	15 21 25 27
24	4	21 25 26 28
25	4	21 23 27 28
…	…	…
146	8	4 5 6 7 8 10 18 20

The total results for 10,000 trials:

Table G4.1.3. Expected frequencies of the considered initiating events

Initiating event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
19	Pressure building circuit overheating	1.3E-01	4.4E-05	5.7E-06
20	Tank overfilling	3.8E+00	1.1E-07	4.2E-07
21	Significant volume os subcooled LH2 added	1.2E-02	1.3E-05	1.6E-07
22	Excess withdrawal rates	2.6E-03	1.3E-05	3.4E-08
30	Loss of vacuum in the annular space	1.5E-04	2.3E-03	3.5E-07
31	External events	2.6E-08	1.0E+00	2.6E-08
32	Spontaneous events	2.6E-07	1.0E+00	2.6E-07

The top event expected frequency and its uncertainties:

Expected frequency [/yr]:	6.9E-06
Median [/yr]:	3.1E-06
5% confidence limit [/yr]:	3.9E-07
95% confidence limit [/yr]:	2.5E-05
K-95:	8.0

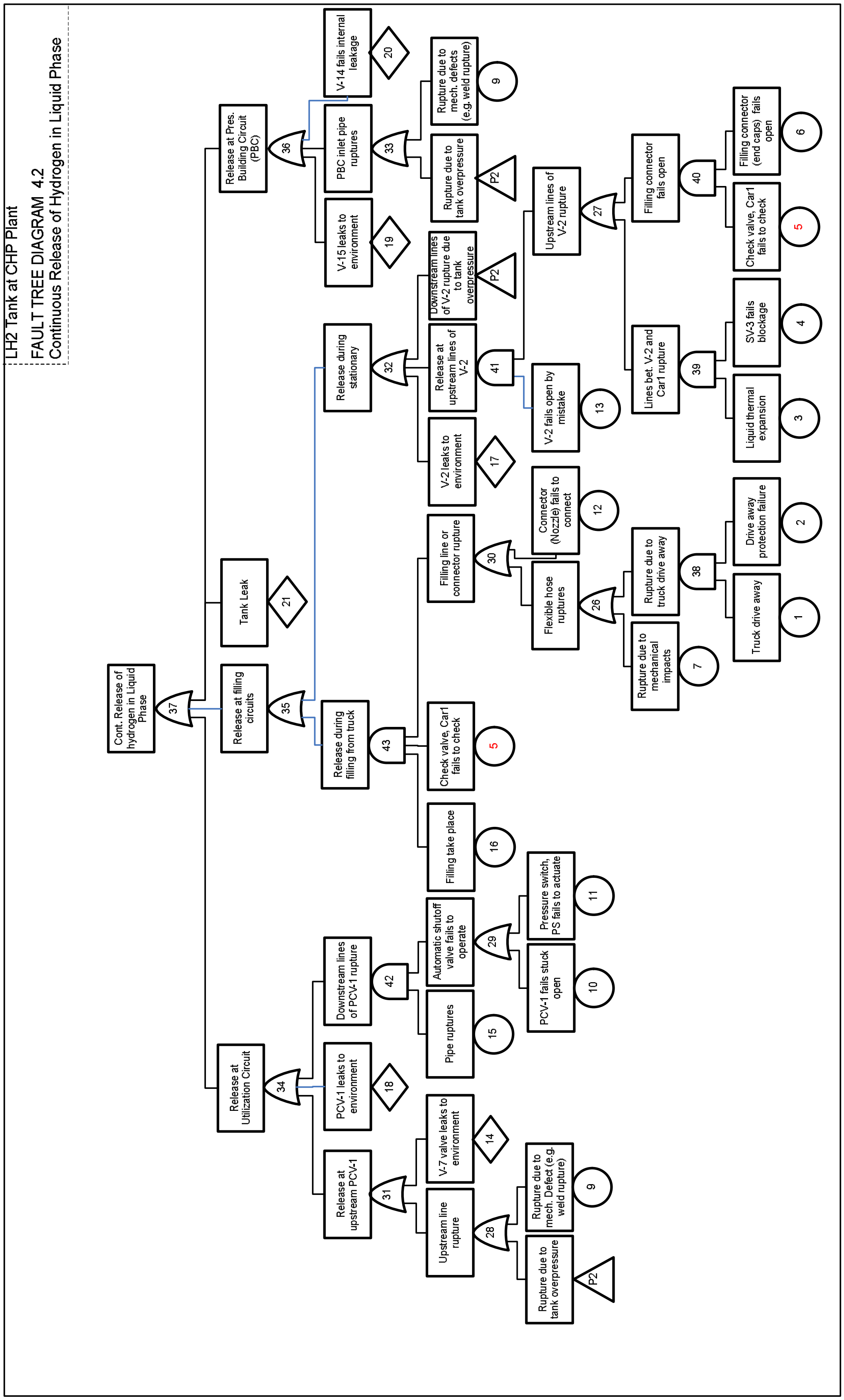
LH2 Tank at CHP Plant
FAULT TREE DIAGRAM 4.2
Continuous Release of Hydrogen in Liquid Phase
Cont. Release of hydrogen in Liquid Phase
37
Release at Pres. Building Circuit (PBC)
36
Tank Leak
21
Release at filling circuits
35
Release at Utilization Circuit
34
V-14 fails internal leakage
20
PBC inlet pipe ruptures
33
V-15 leaks to environment
19
Rupture due to mech. defects (e.g. weld rupture)
9
Rupture due to tank overpressure
P2
Release during stationary
32
Downstream lines of V-2 rupture due to tank overpressure
P2
Release at upstream lines of V-2
41
V-2 leaks to environment
17
Upstream lines of V-2 rupture
27
V-2 fails open by mistake
13
Filling connector fails open
40
Filling connector (end caps) fails open
6
Check valve, Car1 fails to check
5
Lines bet. V-2 and Car1 rupture
39
SV-3 fails blockage
4
Liquid thermal expansion
3
Release during filling from truck
43
Filling line or connector rupture
30
Connector (Nozzle) fails to connect
12
Flexible hose ruptures
26
Rupture due to truck drive away
38
Drive away protection failure
2
Truck drive away
1
Rupture due to mechanical impacts
7
Check valve, Car1 fails to check
5
Filling take place
16
Downstream lines of PCV-1 rupture
42
Automatic shutoff valve fails to operate
29
Pressure switch, PS fails to actuate
11
PCV-1 fails stuck open
10
Pipe ruptures
15
PCV-1 leaks to environment
18
Release at upstream PCV-1
31
V-7 valve leaks to environment
14
Upstream line rupture
28
Rupture due to mech. Defect (e.g. weld rupture)
9
Rupture due to tank overpressure
P2

Table G4.2.1. Estimates of basic event probabilities and frequencies for the LH2 tank at the G4.2 fault tree

Basic Event No.	Component symbol	Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1		Truck drive away	F	1,1E-06	10	Guess estimate, 1 per 100 years
2		Drive away protection failure	F	1,1E-08	10	Guess estimate, unlikely incident
3		Liquid thermal expansion	F	1,1E-07	10	Guess estimate, likely incident
4	SV-3	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
5	Car1	Non-return valve fails to check	F	8,3E-06	2,5	[88], check valve
6		Filling connector (end caps) fails open	F	1,5E-07	14,9	[8], page. 184
7		Mechanical impact (e.g. cranes etc)	F	1,1E-11	10,0	[116], Table IX.2
8		Pipe rupture due to tank overpressure	F	7,1E-10	28,9	FTA
9		Pipe rupture due to weld rupture	F	3,0E-09	31,6	[116], Table A14.4
10	PCV-1	Control valve fails stuck open	F	2,5E-07	27,7	[184]
11	PS	Pressure switch low fails to actuate	F	2,8E-07	5,4	[8], p. 171
12		Filling connector (Nozzle) fails to connect	F	1,5E-07	14,9	[8], page. 184
13	V-2	Hand operated valve fails open by mistake	P	1,0E-03	2,0	[88,137]
14	V-7	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
15		Downstream line of PCV-1 ruptures	F	1,1E-09	5,8	[116], Table A8.2, 2 meters
16		Filling take place	F	2,7E-03	5	24/yr,
17	V-2	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
18	PCV-1	Control valve leaks to environment	F	4,4E-07	5,5	[224], process control valve
19	V-15	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
20	V-14	Hand operated valve leaks in close position (internal leakage)	F	7,3E-08	11,5	[224], p. 608
21	Tank	Serious leakage from inner tank (refrigerated, double wall)	F	2,3E-09	20,8	[116], Table A8.2

F= Frequency [/h], P=Probability [-]

Table G4.2.3. Lists of initiating event of the G4.2 fault tree

Cut set No.	Order	Basic Events
1	1	2
2	1	18
3	1	8
4	1	19
5	1	14
6	1	20
7	1	9
8	1	17
9	2	10 15
10	2	11 15
11	3	5 12 16
12	3	3 4 13
13	3	5 7 16
14	3	5 6 13
15	4	1 2 5 16

The total results for 10,000 trials:

Table G4.2.3. Expected frequencies of the considered initiating events

Initiating event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
3	Filling lines rupture due to liquid thermal expansion	2.6E-04	1.3E-05	3.4E-09
6	Filling connector failure	3.7E-03	4.8E-06	1.8E-08
8	Filling lines rupture due to tank overpressure	5.0E-05	1.0E+00	5.0E-05
15	Liquid lines to evaporator (utilization lines) rupture	1.7E-05	7.3E-03	1.2E-07
16	Release from tank during truck filling	3.8E+00	8.9E-06	3.4E-05

The top event expected frequency and its uncertainties:

Expected frequency [/yr]:	8.4E-05
Median [/yr]:	1.6E-05
5% confidence limit [/yr]:	8.3E-07
95% confidence limit [/yr]:	3.2E-04
K-95:	19.7

FIG. G4.3 LH2 Tank at CHP Plant

FAULT TREE DIAGRAM
Continuous Release of Hydrogen in Vapor Phase

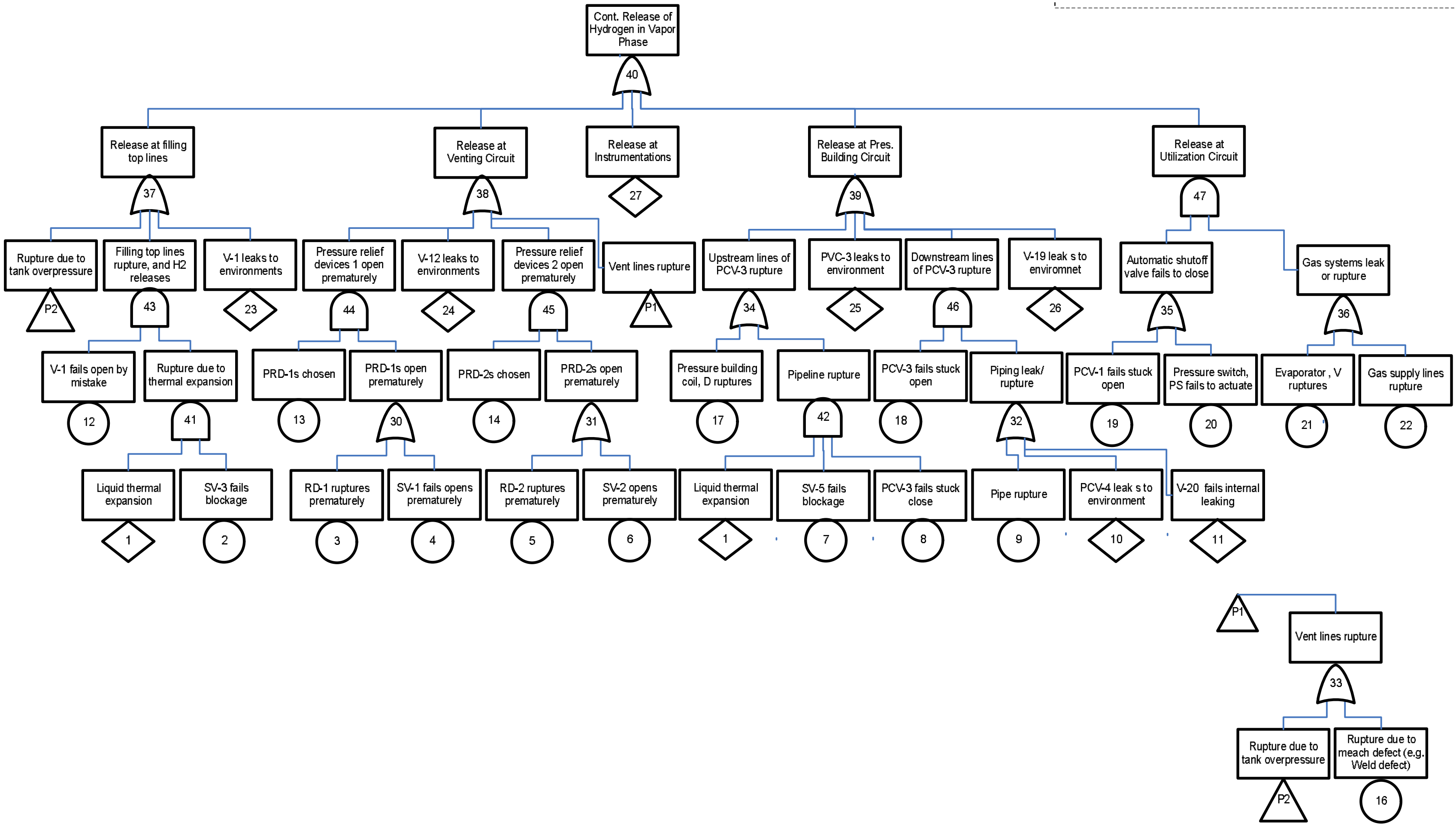

Table G4.3.1. Estimates of basic events probabilities and frequencies for the LH2 tank at the G4.3 fault tree

Basic Event No.	Component symbol	Descriptions of the Event/failure mode	F/P	Median	Uncertainty factor, K-95	Source of Justification
1		Liquid thermal expansion	F	1,1E-07	10	Guess estimate, likely incident
2	SV-3	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
3	RD-1	Rupture disk rupture prematurely	F	1,1E-08	31,6	Taylor [183]
4	SV-1	Pressure safety valve open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
5	RD-2	Rupture disk rupture prematurely	F	1,1E-08	31,6	Taylor [183]
6	SV-2	Pressure safety valve open prematurely	F	4,0E-07	3,9	[224], PSV-conventional
7	SV-5	Spring loaded pressure safety valve fails blockage	F	1,1E-06	8,4	[88]
8	PCV-3	Self-pressure operated control valve (fails to change position)	F	9,3E-06	5,0	T-Book [184]
9		Downstream lines of PCV-3 rupture	F	7,1E-07	2,5	[116], Table A14.6
10	PCV-4	Control valve leaks to environment	F	4,4E-07	5,5	[224], PSV-conventional
11	V-20	Hand operated valve fails open (internal leaking)	F	7,3E-08	11,5	[224], p. 608
12	V-1	Hand operated valve fails open by mistake	P	1,0E-03	2,0	[88,137]
13	V-12	Three-way valve is directed to PRD1s	P	5,0E-01	2,0	Guess estimate, 50%
14	V-12	Three-way valve is directed to PRD2s	P	5,0E-01	2,0	Guess estimate, 50%
15		Pipe rupture due to tank overpressure	F	7,1E-10	28,9	FTA
16		Pipe rupture due to mechanical defects (e.g. Weld rupture)	F	3,0E-09	31,6	[116], Table A14.4
17	D	Pressure building coil ruptures	F	7,1E-07	2,5	[116], Table A14.6
18	PCV-3	Self-pressure operated control valve (fails to change position)	F	9,3E-06	5,0	T-Book [184]
19	PCV-1	Control valve fails stuck open	F	2,5E-07	27,7	[224]
20	PS	Pressure switch low fails to actuate (high)	F	2,8E-07	5,4	[8], p. 171
21	V	Evaporator ruptures	F	9,7E-10	2,5	[116] Table A14.6, [159] Table 3.11
22		Gas consumption lines rupture	F	7,1E-07	2,5	[116], Table A14.6
23	V-1	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
24	V-12	Three-way valve leaks to environment	F	1,1E-06	13,8	[224]
25	PCV-3	Control valve leaks to environment	F	4,4E-07	5,5	[224], PSV-conventional
26	V-19	Hand operated valve leaks to environment	F	1,1E-06	13,8	[224]
27		Release at instrumentation	F	1,0E-09	10,0	Guess estimate

F= Frequency [/h], P=Probability [-]

Table G4.3.2. List of initiating event of theG4.3 fault tree

Cut set No.	Order	Basic Events
1	1	27
2	1	15
3	1	24
4	1	25
5	1	23
6	1	17
7	1	16
8	2	19 21
9	2	3 13
10	2	5 14
11	2	9 18
12	2	20 21
13	2	19 22
14	2	4 13
15	2	6 14
16	2	10 18
17	2	11 18
18	2	20 22
19	3	1 2 12
20	3	1 7 8

The total results for 10,000 trials:

Table G4.3.3. Expected frequencies of the considered initiating events

Initiating Event No.	Description	Frequency [/yr]	Unavailability	Frequency of the undesired event [/yr]
1	Filling top lines rupture	2.6E-04	6.2E-04	1.6E-07
9	Outlet lines of the PBC rupture	1.7E-05	6.1E-02	1.0E-06
15	Lines rupture due to tank overpressure	5.0E-05	1.0E+00	5.0E-05
21	Evaporator ruptures	9.9E-06	7.6E-03	7.5E-08
22	Gas lines connected to the fuel cells rupture	1.7E-05	7.6E-03	1.3E-07

The top event expected frequency and its uncertainties:

Expected frequency [/yr]:	5.2E-05
Median [/yr]:	6.6E-06
5% confidence limit [/yr]:	2.3E-07
95% confidence limit [/yr]:	1.9E-04
K-95:	28.3

Appendix H

SUMMARY OF THE RISK CALCULATION RESULTS

H.1 INTRODUCTION

This appendix presents summary risk calculation results of for the study objects. The risks are presented in the tables representing the formalized risk definition [242], i.e. based on the triplet numbers. These tables are plotted as individual risk and societal risk (F-N curve) by means of so-called complementary cumulative distribution function (CCDF), which is described in section 4.6.4. The risks are presented in the section 5.5.3. Therefore, these tables consists the following information:

(1) Accident scenarios including with release scenario (LOC) such as tank rupture, leakage, etc. and their associated accident outcomes (e.g. fireball, jet fires, etc.)
(2) Expected frequencies of the accident outcomes, including with their uncertainties (i.e. lower and upper limits of 95% confidence interval.
(3) Magnitude of damage (consequence) of the accident outcomes, including with effect distances and numbers of fatality (N) for different fatality level (1%, 10%, etc) and different weather conditions (1.5/F, 1.5/D, and 5/D).

H.2 THE OVERALL RISK

The overall risks presented in the appendix include seven study objects (described in chapter III). They includes

(1.) Production plant (GH_2)
(2.) Storage at depot (LH_2)
(3.) Filling station (LH_2)
(4.) FC-CHP plant (LH_2)
(5.) Hydrogen car (LH_2)
(6.) Road tanker (LH_2)
(7.) Pipeline (GH_2)

Table H-1 Overall risk of the GH$_2$ storage at the production plant

Release event	Accident outcome	Wea-ther	Fatality Level (%)	Frequency(/yr)				Effect Distance (m)	Fatality (N)
				5%	50%	Mean	95%		
Line rupture	Late Explosion (VCE)	1.5/F	1%	7,69E-08	6,41E-07	1,53E-06	5,56E-06	29,6	0
			10%	7,69E-08	6,41E-07	1,53E-06	5,56E-06	25,1	0
		1.5/D	1%	7,69E-08	6,41E-07	1,53E-06	5,56E-06	29,6	0
			10%	7,69E-08	6,41E-07	1,53E-06	5,56E-06	25,1	0
		5.0/D	1%	7,69E-08	6,41E-07	1,53E-06	5,56E-06	35,8	0
			10%	7,69E-08	6,41E-07	1,53E-06	5,56E-06	32,2	0
	Flash Fire	1.5/F	60%	3,08E-07	2,56E-06	6,12E-06	2,22E-05	17,9	0
		1.5/D	60%	3,08E-07	2,56E-06	6,12E-06	2,22E-05	16,0	0
		5.0/D	60%	3,08E-07	2,56E-06	6,12E-06	2,22E-05	23,6	0
Tank leak	Late Explosion	1.5/F	1%	7,69E-08	1,71E-06	4,95E-06	1,81E-05	88,1	0
			10%	7,69E-08	1,71E-06	4,95E-06	1,81E-05	81,8	0
		1.5/D	1%	7,69E-08	1,71E-06	4,95E-06	1,81E-05	87,0	0
			10%	7,69E-08	1,71E-06	4,95E-06	1,81E-05	80,9	0
		5.0/D	1%	7,69E-08	1,71E-06	4,95E-06	1,81E-05	72,8	0
			10%	7,69E-08	1,71E-06	4,95E-06	1,81E-05	67,6	0
	Jet Fire	1.5/F	1%	8,55E-07	7,12E-06	1,70E-05	6,17E-05	54,3	0
			10%	8,55E-07	7,12E-06	1,70E-05	6,17E-05	52,4	0
			56%	8,55E-07	7,12E-06	1,70E-05	6,17E-05	49,9	0
		1.5/D	1%	8,55E-07	7,12E-06	1,70E-05	6,17E-05	54,3	0
			10%	8,55E-07	7,12E-06	1,70E-05	6,17E-05	52,4	0
			56%	8,55E-07	7,12E-06	1,70E-05	6,17E-05	49,9	0
		5.0/D	1%	8,55E-07	7,12E-06	1,70E-05	6,17E-05	43,0	0
			10%	8,55E-07	7,12E-06	1,70E-05	6,17E-05	41,2	0
			56%	8,55E-07	7,12E-06	1,70E-05	6,17E-05	39,0	0
	Flash Fire	1.5/F	60%	3,08E-07	2,56E-06	6,12E-06	2,22E-05	60,8	1
		1.5/D	60%	3,08E-07	2,56E-06	6,12E-06	2,22E-05	60,7	1
		5.0/D	60%	3,08E-07	2,56E-06	6,12E-06	2,22E-05	55,1	1
Tank rupture	Late Explosion	1.5/F	1%	4,07E-10	3,39E-09	8,10E-09	2,94E-08	110,2	0
			10%	4,07E-10	3,39E-09	8,10E-09	2,94E-08	92,1	1
		1.5/D	1%	4,07E-10	3,39E-09	8,10E-09	2,94E-08	110,0	0
			10%	4,07E-10	3,39E-09	8,10E-09	2,94E-08	91,9	1
		5.0/D	1%	4,07E-10	3,39E-09	8,10E-09	2,94E-08	112,1	0
			10%	4,07E-10	3,39E-09	8,10E-09	2,94E-08	95,6	1
	Early Explosion	-	1%	1,36E-08	1,13E-07	2,70E-07	9,80E-07	89,7	0
			10%	1,36E-08	1,13E-07	2,70E-07	9,80E-07	69,4	1
	Fireball	-	1%	5,43E-08	4,53E-07	1,08E-06	3,92E-06	42,9	0
			10%	5,43E-08	4,53E-07	1,08E-06	3,92E-06	35,4	0
			60%	5,43E-08	4,53E-07	1,08E-06	3,92E-06	26,3	1
	Flash Fire	1.5/F	60%	1,63E-09	1,36E-08	3,24E-08	1,18E-07	60,5	1
		1.5/D	60%	1,63E-09	1,36E-08	3,24E-08	1,18E-07	56,7	1
		5.0/D	60%	1,63E-09	1,36E-08	3,24E-08	1,18E-07	135,2	2
Total risk						**2,33E-04**			

Table H-2 Overall risk of the LH2 storage at depot

Release event	Accident outcome	Weather	Fatality Level (%)	Frequency(/yr)				Effect Distance (m)	Fatality (N)
				5%	50%	Mean	95%		
Liquid line rupture	Late Explosion	1.5/F	1%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	178,9	0
			10%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	163,3	1
		1.5/D	1%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	154,2	0
			10%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	137,4	1
		5.0/D	1%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	168,1	0
			10%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	155,0	1
	Flash Fire	1.5/F	60%	3,5E-08	3,3E-07	8,5E-07	3,2E-06	112,0	4
		1.5/D	60%	3,5E-08	3,3E-07	8,5E-07	3,2E-06	83,4	2
		5.0/D	60%	3,5E-08	3,3E-07	8,5E-07	3,2E-06	114,8	5
Tank leak	Late Explosion	1.5/F	1%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	596,1	0
			10%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	563,0	5
		1.5/D	1%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	507,9	0
			10%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	474,4	5
		5.0/D	1%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	498,9	0
			10%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	469,8	4
	Jet Fire	1.5/F	1%	2,4E-06	2,3E-05	5,9E-05	2,2E-04	232,6	0
			10%	2,4E-06	2,3E-05	5,9E-05	2,2E-04	224,3	1
			56%	2,4E-06	2,3E-05	5,9E-05	2,2E-04	213,9	2
		1.5/D	1%	2,4E-06	2,3E-05	5,9E-05	2,2E-04	232,6	0
			10%	2,4E-06	2,3E-05	5,9E-05	2,2E-04	224,3	1
			56%	2,4E-06	2,3E-05	5,9E-05	2,2E-04	213,9	2
		5.0/D	1%	2,4E-06	2,3E-05	5,9E-05	2,2E-04	186,0	0
			10%	2,4E-06	2,3E-05	5,9E-05	2,2E-04	177,9	1
			56%	2,4E-06	2,3E-05	5,9E-05	2,2E-04	168,2	2
	Flash Fire	1.5/F	60%	3,5E-08	3,3E-07	8,5E-07	3,2E-06	460,0	74
		1.5/D	60%	3,5E-08	3,3E-07	8,5E-07	3,2E-06	360,8	45
		5.0/D	60%	3,5E-08	3,3E-07	8,5E-07	3,2E-06	378,1	49
Vapour line rupture	Late Explosion	1.5/F	1%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	68,6	0
			10%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	62,1	0
		1.5/D	1%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	59,3	0
			10%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	52,7	0
		5.0/D	1%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	62,5	0
			10%	8,6E-09	8,3E-08	2,1E-07	7,9E-07	57,4	0
	Flash Fire	1.5/F	60%	3,5E-08	3,3E-07	8,5E-07	3,2E-06	41,9	1
		1.5/D	60%	3,5E-08	3,3E-07	8,5E-07	3,2E-06	33,2	1
		5.0/D	60%	3,5E-08	3,3E-07	8,5E-07	3,2E-06	41,5	1
Tank rupture	Late Explosion	1.5/F	1%	1,1E-11	1,1E-10	2,8E-10	1,1E-09	586,3	0
			10%	1,1E-11	1,1E-10	2,8E-10	1,1E-09	580,3	0
		1.5/D	1%	1,1E-11	1,1E-10	2,8E-10	1,1E-09	390,2	0
			10%	1,1E-11	1,1E-10	2,8E-10	1,1E-09	340,7	9
		5.0/D	1%	1,1E-11	1,1E-10	2,8E-10	1,1E-09	609,6	0
			10%	1,1E-11	1,1E-10	2,8E-10	1,1E-09	573,9	3
	Early Explosion	-	1%	3,6E-08	3,4E-07	8,8E-07	3,3E-06	297,6	0
			10%	3,5E-08	2,5E-07	5,0E-07	1,8E-06	230,3	2
	Fireball	-	1%	1,4E-07	1,4E-06	3,5E-06	1,3E-05	217,6	1
			10%	1,4E-07	1,4E-06	3,5E-06	1,3E-05	185,3	4
			60%	1,4E-07	1,4E-06	3,5E-06	1,3E-05	61,1	2
	Flash Fire	1.5/F	60%	4,6E-11	4,4E-10	1,1E-09	4,2E-09	4374,1	2150
		1.5/D	60%	4,6E-11	4,4E-10	1,1E-09	4,2E-09	487,5	22
		5.0/D	60%	4,6E-11	4,4E-10	1,1E-09	4,2E-09	1258,3	143
Total risk						**5,5E-04**			

Table H-3 Overall risk of LH2 Storage at Fuelling Station

Release event	Accident outcome	Weather	Fatality Level (%)	Frequency(/yr)				Effect Distance (m)	Fatality (N)
				5%	50%	Mean	95%		
Liquid line rupture	Late Explosion	1.5/F	1%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	100,6	0
			10%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	91,4	0
		1.5/D	1%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	103,0	0
			10%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	93,2	0
		5.0/D	1%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	93,0	0
			10%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	85,6	0
	Flash Fire	1.5/F	60%	3,4E-07	2,4E-06	5,1E-06	1,8E-05	60,5	1
		1.5/D	60%	3,4E-07	2,4E-06	5,1E-06	1,8E-05	48,0	1
		5.0/D	60%	3,4E-07	2,4E-06	5,1E-06	1,8E-05	64,0	1
Tank leak	Late Explosion	1.5/F	1%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	234,1	0
			10%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	222,0	1
		1.5/D	1%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	320,0	0
			10%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	304,0	1
		5.0/D	1%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	331,5	0
			10%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	313,0	1
	Jet Fire	1.5/F	1%	2,3E-05	1,7E-04	3,6E-04	1,2E-03	148,4	0
			10%	2,3E-05	1,7E-04	3,6E-04	1,2E-03	143,2	0
			56%	2,3E-05	1,7E-04	3,6E-04	1,2E-03	136,5	1
		1.5/D	1%	2,3E-05	1,7E-04	3,6E-04	1,2E-03	148,4	0
			10%	2,3E-05	1,7E-04	3,6E-04	1,2E-03	143,2	0
			56%	2,3E-05	1,7E-04	3,6E-04	1,2E-03	136,5	1
		5.0/D	1%	2,3E-05	1,7E-04	3,6E-04	1,2E-03	118,3	0
			10%	2,3E-05	1,7E-04	3,6E-04	1,2E-03	113,3	0
			56%	2,3E-05	1,7E-04	3,6E-04	1,2E-03	107,2	1
	Flash Fire	1.5/F	60%	3,4E-07	2,4E-06	5,1E-06	1,8E-05	253,4	22
		1.5/D	60%	3,4E-07	2,4E-06	5,1E-06	1,8E-05	263,0	24
		5.0/D	60%	3,4E-07	2,4E-06	5,1E-06	1,8E-05	238,0	20
Vapor line rupture	Late Explosion	1.5/F	1%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	68,6	0
			10%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	62,1	0
		1.5/D	1%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	69,3	0
			10%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	62,7	0
		5.0/D	1%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	62,5	0
			10%	8,4E-08	6,1E-07	1,3E-06	4,5E-06	57,4	0
	Flash Fire	1.5/F	60%	3,4E-07	2,4E-06	5,1E-06	1,8E-05	42,0	1
		1.5/D	60%	3,4E-07	2,4E-06	5,1E-06	1,8E-05	55,0	2
		5.0/D	60%	3,4E-07	2,4E-06	5,1E-06	1,8E-05	26,0	1
Tank rupture	Late Explosion	1.5/F	1%	2,5E-12	1,8E-11	3,7E-11	1,3E-10	148,3	0
			10%	2,5E-12	1,8E-11	3,7E-11	1,3E-10	130,6	1
		1.5/D	1%	2,5E-12	1,8E-11	3,7E-11	1,3E-10	144,0	0
			10%	2,5E-12	1,8E-11	3,7E-11	1,3E-10	125,4	1
		5.0/D	1%	2,5E-12	1,8E-11	3,7E-11	1,3E-10	224,5	0
			10%	2,5E-12	1,8E-11	3,7E-11	1,3E-10	212,2	1
	Early Explosion	-	1%	5,1E-08	3,7E-07	7,7E-07	2,7E-06	109,0	0
			10%	5,1E-08	3,7E-07	7,7E-07	2,7E-06	84,4	0
	Fireball	-	1%	2,0E-07	1,5E-06	3,1E-06	1,1E-05	56,3	0
			10%	2,0E-07	1,5E-06	3,1E-06	1,1E-05	46,7	0
			60%	2,0E-07	1,5E-06	3,1E-06	1,1E-05	35,4	1
	Flash Fire	1.5/F	60%	9,8E-12	7,1E-11	1,5E-10	5,2E-10	263,0	6
		1.5/D	60%	9,8E-12	7,1E-11	1,5E-10	5,2E-10	218,0	5
		5.0/D	60%	9,8E-12	7,1E-11	1,5E-10	5,2E-10	543,0	32
Total risk						**3,3E-03**			

Table H-4 Overall risks of LH2 storage at an FC-CHP plant

Release event	Accident outcome	Weather	Fatality Level (%)	Frequency(/yr)				Effect Distance (m)	Fatality (N)
				5%	50%	Mean	95%		
Liquid line rupture	Late Explosion	1.5/F	1%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	103,4	0
			10%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	93,6	0
		1.5/D	1%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	85,4	0
			10%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	75,1	0
		5.0/D	1%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	95,4	0
			10%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	87,4	0
	Flash Fire	1.5/F	60%	3,5E-08	3,6E-07	9,8E-07	3,7E-06	27,9	0
		1.5/D	60%	3,5E-08	3,6E-07	9,8E-07	3,7E-06	23,3	0
		5.0/D	60%	3,5E-08	3,6E-07	9,8E-07	3,7E-06	32,1	0
Tank leak	Late Explosion	1.5/F	1%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	344,0	0
			10%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	322,8	2
		1.5/D	1%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	333,0	0
			10%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	312,0	2
		5.0/D	1%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	311,5	0
			10%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	293,0	1
	Jet Fire	1.5/F	1%	2,4E-06	2,5E-05	6,8E-05	2,6E-04	148,4	0
			10%	2,4E-06	2,5E-05	6,8E-05	2,6E-04	143,1	0
			56%	2,4E-06	2,5E-05	6,8E-05	2,6E-04	136,4	1
		1.5/D	1%	2,4E-06	2,5E-05	6,8E-05	2,6E-04	148,4	0
			10%	2,4E-06	2,5E-05	6,8E-05	2,6E-04	143,1	0
			56%	2,4E-06	2,5E-05	6,8E-05	2,6E-04	136,4	1
		5.0/D	1%	2,4E-06	2,5E-05	6,8E-05	2,6E-04	118,3	0
			10%	2,4E-06	2,5E-05	6,8E-05	2,6E-04	113,3	0
			56%	2,4E-06	2,5E-05	6,8E-05	2,6E-04	107,2	1
	Flash Fire	1.5/F	60%	3,5E-08	3,6E-07	9,8E-07	3,7E-06	184,5	12
		1.5/D	60%	3,5E-08	3,6E-07	9,8E-07	3,7E-06	186,2	12
		5.0/D	60%	3,5E-08	3,6E-07	9,8E-07	3,7E-06	182,0	12
Vapour line rupture	Late Explosion	1.5/F	1%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	68,6	0
			10%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	62,1	0
		1.5/D	1%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	59,3	0
			10%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	52,7	0
		5.0/D	1%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	62,4	0
			10%	8,7E-09	8,9E-08	2,4E-07	9,3E-07	57,4	0
	Flash Fire	1.5/F	60%	3,5E-08	3,6E-07	9,8E-07	3,7E-06	17,6	0
		1.5/D	60%	3,5E-08	3,6E-07	9,8E-07	3,7E-06	15,1	0
		5.0/D	60%	3,5E-08	3,6E-07	9,8E-07	3,7E-06	19,7	0
Tank rupture	Late Explosion	1.5/F	1%	1,7E-11	1,7E-10	4,8E-10	1,8E-09	264,9	0
			10%	1,7E-11	1,7E-10	4,8E-10	1,8E-09	234,4	4
		1.5/D	1%	1,7E-11	1,7E-10	4,8E-10	1,8E-09	249,0	0
			10%	1,7E-11	1,7E-10	4,8E-10	1,8E-09	217,5	4
		5.0/D	1%	1,7E-11	1,7E-10	4,8E-10	1,8E-09	376,5	0
			10%	1,7E-11	1,7E-10	4,8E-10	1,8E-09	353,8	2
	Early Explosion	-	1%	4,4E-08	4,5E-07	1,2E-06	4,7E-06	189,6	0
			10%	4,4E-08	4,5E-07	1,2E-06	4,7E-06	146,7	3
	Fireball	-	1%	1,8E-07	1,8E-06	5,0E-06	1,9E-05	119,1	0
			10%	1,8E-07	1,8E-06	5,0E-06	1,9E-05	101,0	1
			60%	1,8E-07	1,8E-06	5,0E-06	1,9E-05	25,8	1
	Flash Fire	1.5/F	60%	6,8E-11	7,0E-10	1,9E-09	7,3E-09	1525,7	475
		1.5/D	60%	6,8E-11	7,0E-10	1,9E-09	7,3E-09	333,6	11
		5.0/D	60%	6,8E-11	7,0E-10	1,9E-09	7,3E-09	819,7	64
Total risk						**6,4E-04**			

Table H-5 Overall risk of LH_2 storage in a private car

Release event	Accident outcome	Weather	Fatality Level (%)	Frequency (/yr)	Effect Distance (m)	Fatality (N)
Tank rupture	Late Explosion		1%	2,0E-08	27	0
		1.5/F	10%	2,0E-08	23,2	1
			1%	2,0E-08	26,7	0
		1.5/D	10%	2,0E-08	22,9	1
			1%	2,0E-08	51,1	0
		5.0/D	10%	2,0E-08	48,6	0
	Early Explosion		1%	2,6E-05	21,4	0
		-	10%	2,6E-05	82,5	0
	Fireball		1%	1,0E-04	5	0
			10%	1,0E-04	3,4	0
		-	60%	1,0E-04	-	-
	Flash Fire	1.5/F	60%	8,2E-08	45,8	2
		1.5/D	60%	8,2E-08	54,6	3
		5.0/D	60%	8,2E-08	283,8	177
Tank leak	Late Explosion		1%	1,0E-06	77,9	0
		1.5/F	10%	1,0E-06	76,1	0
			1%	1,0E-06	79,6	0
		1.5/D	10%	1,0E-06	77,4	0
			1%	1,0E-06	86,1	0
		5.0/D	10%	1,0E-06	84,7	0
	Jet Fire		1%	2,8E-04	56	0
			10%	2,8E-04	54	0
		1.5/F	56%	2,8E-04	51,4	1
			1%	2,8E-04	56	0
			10%	2,8E-04	54	0
		1.5/D	56%	2,8E-04	51,4	1
			1%	2,8E-04	44,4	0
			10%	2,8E-04	42,5	0
		5.0/D	56%	2,8E-04	40,3	1
	Flash Fire	1.5/F	60%	4,1E-06	84,8	25
		1.5/D	60%	4,1E-06	93,7	31
		5.0/D	60%	4,1E-06	98,6	34
		5.0/D	60%	4,1E-06	8,3	0
Vapour line rupture	Flash Fire	1.5/F	60%	4,1E-06	7,3	0
		1.5/D	60%	4,1E-06	7,6	0
		5.0/D	60%	4,1E-06	8,4	0
Liquid line rupture	Flash Fire	1.5/F	60%	4,1E-06	8,1	0
		1.5/D	60%	4,1E-06	8,3	0
		5.0/D	60%	4,1E-06	9,4	0
Overall risk				2,9E-03		

Table H-6 Overall risks of the LH_2 tanker truck at segment route I

Release event	Accident outcome	Weather	Fatality Level (%)	Frequency (/yr)	Effect Distance (m)	Fatality (N)
Tank rupture	Late Explosion	1.5/F	1%	1,8E-09	260,0	0
			10%	1,8E-09	230,0	2
		1.5/D	1%	1,8E-09	244,5	0
			10%	1,8E-09	214,0	2
		5.0/D	1%	1,8E-09	371,7	0
			10%	1,8E-09	349,7	1
	Early Explosion	-	1%	2,3E-06	186,5	0
			10%	2,3E-06	144,3	3
	Fireball	-	1%	9,2E-06	116,5	0
			10%	9,2E-06	98,8	2
			60%	9,2E-06	24,9	1
	Flash Fire (In)	1.5/D	60%	7,4E-09	263,1	27
Tank leak	Late Explosion	1.5/F	1%	9,2E-08	344,0	0
			10%	9,2E-08	322,0	1
		1.5/D	1%	9,2E-08	333,0	0
			10%	9,2E-08	312,0	1
		5.0/D	1%	9,2E-08	311,5	0
			10%	9,2E-08	293,0	1
	Flash Fire	1.5/F	60%	3,7E-07	184,4	30
		1.5/D	60%	3,7E-07	186,0	28
		5.0/D	60%	3,7E-07	182,0	27
Vapour line rupture	Jet Fire	1.5/F	1%	2,6E-05	148,4	0
			10%	2,6E-05	143,1	0
		1.5/D	1%	2,6E-05	136,5	1
			10%	2,6E-05	148,4	0
		5.0/D	1%	2,6E-05	143,1	0
			10%	2,6E-05	136,5	1
	Flash Fire	1.5/F	60%	3,7E-07	257,6	1
		1.5/D	60%	3,7E-07	245,1	1
		5.0/D	60%	3,7E-07	249,7	1
	Late Explosion	1.5/F	1%	9,2E-08	68,6	0
			10%	9,2E-08	62,0	0
		1.5/D	1%	9,2E-08	59,0	0
			10%	9,2E-08	53,0	0
		5.0/D	1%	9,2E-08	62,0	0
			10%	9,2E-08	57,0	0
Liquid line rupture	Late Explosion	1.5/F	1%	9,2E-08	220,5	0
			10%	9,2E-08	206,6	0
		1.5/D	1%	9,2E-08	219,0	0
			10%	9,2E-08	206,0	0
		5.0/D	1%	9,2E-08	212,0	0
			10%	9,2E-08	200,0	0
	Jet Fire	1.5/F	1%	2,6E-05	148,4	0
			10%	2,6E-05	143,1	0
		1.5/D	1%	2,6E-05	136,5	1
			10%	2,6E-05	148,4	0
		5.0/D	1%	2,6E-05	143,1	0
			10%	2,6E-05	136,5	1
	Flash Fire	1.5/F	60%	3,7E-07	120,3	13
		1.5/D	60%	3,7E-07	122,4	12
		5.0/D	60%	3,7E-07	119,0	12
Overall risk				**3,5E-04**		

Table H-7 Overall risks of the LH_2 tanker truck at segment route II

Release event	Accident outcome	Weather	Fatality Level (%)	Frequency (/yr)	Effect Distance (m)	Fatality (N)
Tank rupture	Late Explosion	1.5/F	1%	1,4E-10	260,0	0
			10%	1,4E-10	230,0	3
		1.5/D	1%	1,4E-10	244,5	0
			10%	1,4E-10	214,0	3
		5.0/D	1%	1,4E-10	371,7	0
			10%	1,4E-10	349,7	2
	Early Explosion	-	1%	1,7E-07	186,5	0
			10%	1,7E-07	144,3	7
	Fireball	-	1%	6,9E-07	116,5	0
			10%	6,9E-07	98,8	3
			60%	6,9E-07	24,9	2
	Flash Fire (in)	1.5/D	60%	5,5E-10	263,1	27
Tank leak	Late Explosion	1.5/F	1%	6,9E-09	344,0	0
			10%	6,9E-09	322,0	2
		1.5/D	1%	6,9E-09	333,0	0
			10%	6,9E-09	312,0	2
		5.0/D	1%	6,9E-09	311,5	0
			10%	6,9E-09	293,0	1
	Flash Fire	1.5/F	60%	2,8E-08	184,4	30
		1.5/D	60%	2,8E-08	186,0	28
		5.0/D	60%	2,8E-08	182,0	27
Vapour line rupture	Jet Fire	1.5/F	1%	1,9E-06	148,4	0
			10%	1,9E-06	143,1	1
		1.5/D	1%	1,9E-06	136,5	2
			10%	1,9E-06	148,4	0
		5.0/D	1%	1,9E-06	143,1	1
			10%	1,9E-06	136,5	2
	Flash Fire	1.5/F	60%	2,8E-08	257,6	1
		1.5/D	60%	2,8E-08	245,1	1
		5.0/D	60%	2,8E-08	249,7	1
	Late Explosion	1.5/F	1%	6,9E-09	68,6	0
			10%	6,9E-09	62,0	0
		1.5/D	1%	6,9E-09	59,0	0
			10%	6,9E-09	53,0	0
		5.0/D	1%	6,9E-09	62,0	0
			10%	6,9E-09	57,0	0
Liquid line rupture	Late Explosion	1.5/F	1%	6,9E-09	220,5	0
			10%	6,9E-09	206,6	1
		1.5/D	1%	6,9E-09	219,0	0
			10%	6,9E-09	206,0	1
		5.0/D	1%	6,9E-09	212,0	0
			10%	6,9E-09	200,0	1
	Jet Fire	1.5/F	1%	1,9E-06	95,2	0
			10%	1,9E-06	91,9	0
		1.5/D	1%	1,9E-06	87,5	1
			10%	1,9E-06	95,2	0
		5.0/D	1%	1,9E-06	91,9	0
			10%	1,9E-06	87,5	1
	Flash Fire	1.5/F	60%	2,8E-08	120,3	27
		1.5/D	60%	2,8E-08	122,4	24
		5.0/D	60%	2,8E-08	119,0	25
Overall risk				**2,6E-05**		

Table H-8 Overall risks of the GH_2 pipeline

Route	Scenario	Outcome	Weather	Fatality Level (%)	Frequency (/yr)	Effect Distance (m)	Fatality (N)
City A	Rupture	Late Explosion	1.5/F	1%	8,4E-08	28,5	0
				10%	8,4E-08	24,3	0
			1.5/D	1%	8,4E-08	28,5	0
				10%	8,4E-08	24,3	0
			5.0/D	1%	8,4E-08	34,5	0
				10%	8,4E-08	31,1	0
		Flash Fire	1.5/F	60%	3,4E-07	17,4	1
			1.5/D	60%	3,4E-07	15,0	0
			5.0/D	60%	3,4E-07	21,5	1
	Leak	Late Explosion	1.5/F	1%	9,9E-06	27,5	0
				10%	9,9E-06	33,6	0
			1.5/D	1%	9,9E-06	27,5	0
				10%	9,9E-06	33,6	0
			5.0/D	1%	9,9E-06	24,0	0
				10%	9,9E-06	30,6	0
		Flash Fire	1.5/F	60%	4,0E-05	16,6	1
			1.5/D	60%	4,0E-05	14,3	0
			5.0/D	60%	4,0E-05	20,3	1
City B	Rupture	Late Explosion	1.5/F	1%	8,4E-08	28,5	0
				10%	8,4E-08	24,3	0
			1.5/D	1%	8,4E-08	28,5	0
				10%	8,4E-08	24,3	0
			5.0/D	1%	8,4E-08	34,5	0
				10%	8,4E-08	31,1	0
		Flash Fire	1.5/F	60%	3,4E-07	17,4	1
			1.5/D	60%	3,4E-07	15,0	1
			5.0/D	60%	3,4E-07	21,5	1
	Leak	Late Explosion	1.5/F	1%	9,9E-06	27,5	0
				10%	9,9E-06	33,6	0
			1.5/D	1%	9,9E-06	27,5	0
				10%	9,9E-06	33,6	0
			5.0/D	1%	9,9E-06	24,0	0
				10%	9,9E-06	30,6	0
		Flash Fire	1.5/F	60%	4,0E-05	16,6	1
			1.5/D	60%	4,0E-05	14,3	1
			5.0/D	60%	4,0E-05	20,3	1
Village X	Rupture	Late Explosion	1.5/F	1%	8,4E-08	28,5	0
				10%	8,4E-08	24,3	0
			1.5/D	1%	8,4E-08	28,5	0
				10%	8,4E-08	24,3	0
			5.0/D	1%	8,4E-08	34,5	0
				10%	8,4E-08	31,1	0
		Flash Fire	1.5/F	60%	3,4E-07	17,4	0
			1.5/D	60%	3,4E-07	15,0	0
			5.0/D	60%	3,4E-07	21,5	0
	Leak	Late Explosion	1.5/F	1%	1,9E-06	27,5	0
				10%	1,9E-06	33,6	0
			1.5/D	1%	1,9E-06	27,5	0
				10%	1,9E-06	33,6	0
			5.0/D	1%	1,9E-06	24,0	0
				10%	1,9E-06	30,6	0

		Flash Fire	1.5/F	60%	3,4E-07	16,6	0
			1.5/D	60%	3,4E-07	14,3	0
			5.0/D	60%	3,4E-07	20,3	0
Village Y	Rupture	Late Explosion	1.5/F	1%	8,4E-08	28,5	0
				10%	8,4E-08	24,3	0
			1.5/D	1%	8,4E-08	28,5	0
				10%	8,4E-08	24,3	0
			5.0/D	1%	8,4E-08	34,5	0
				10%	8,4E-08	31,1	0
		Flash Fire	1.5/F	60%	3,4E-07	17,4	0
			1.5/D	60%	3,4E-07	15,0	0
			5.0/D	60%	3,4E-07	21,5	0
	Leak	Late Explosion	1.5/F	1%	6,2E-06	27,5	0
				10%	6,2E-06	33,6	0
			1.5/D	1%	6,2E-06	27,5	0
				10%	6,2E-06	33,6	0
			5.0/D	1%	6,2E-06	24,0	0
				10%	6,2E-06	30,6	0
		Flash Fire	1.5/F	60%	3,4E-07	16,6	0
			1.5/D	60%	3,4E-07	14,3	0
			5.0/D	60%	3,4E-07	20,3	0
Total risk					**4,1E-04**		

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1973 – 1979	Grundschule in Ciamis, Indonesien
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