

RISK ANALYSIS FOR THE INFRASTRUCTURE OF A HYDROGEN ECONOMY

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Abstract

Increasing scarcity of fossil fuels makes the deployment of hydrogen in combination with renewable energy sources or the utilization of electricity from full time operation of existing power stations an interesting alternative. A pre-requisite is, however, the safety of the required infrastructure is investigated and its design is evaluated with the associated risk to know, at least, the risks are not higher than that of existing supplies. Therefore, a risk analysis considering its most important objects such as storage tanks, filling stations, vehicles as well as heating and electricity supplies for residential buildings was carried out. The last is considered as representative of the entire infrastructure. The risk analysis is based on fault and event tree analyses, wherever required, and consequence calculations using the PHAST code. The procedure for evaluating the risk and corresponding results will be presented taking one of the objects as an example.

Keywords: hydrogen, risk, safety, fire, fault tree analyses, event tree analyses, explosion, PHAST.

Abstrak

Meningkatnya kelangkaan energi fosil membuat ide pemanfaatan hidrogen dalam kombinasi dengan sumber energi terbarukan atau pemakaian listrik dari suatu pusat pembangkitan yang beroperasi penuh menjadi alternatif yang amat menarik. Namun analisa awal adalah menyelidiki keamanan lingkungannya and disainnya dievaluasi terkait dengan risiko terkait untuk mengetahui, sedikitnya, risiko tidak lebih besar dari sistem yang telah ada. Karenanya analisa risiko mempertimbangkan objek terpenting seperti tanki penyimpanan, stasiun pengisian, kendaraan, dan juga fasilitas pensuplai panas dan listrik untuk bangunan hunian dilakukan. Yang tersebut terakhir dipertimbangkan sebagai perwakilan seluruh infrastruktur. Analisa risiko ini didasarkan pada analisa pohon kesalahan dan kejadian bila diinginkan dan perhitungan besarnya kecelakaan menggunakan perangkat lunak PHAST. Prosedur untuk mengevaluasi risiko dan hasilnya akan ditampilkan dengan mengambil salah satu objek sebagai contoh.

Kata kunci: hidrogen, risiko, keselamatan, kebakaran, fault tree analyses, event tree analyses ledakan, PHAST.

1. INTRODUCTION

Hydrogen is seen by many experts as a major energy carrier for the future [2;13]. An energy economy based on hydrogen (especially when produced from renewable energy sources), with fuel cells as a major energy conversion technology could then resolve the major concerns about security of energy supply, source of diversification and reduction of greenhouse gas emission. In recent years, European industry has realized several hydrogen vehicle prototypes and demonstration vehicles equipped with internal combustion engines (ICE) and fuel cell electric drives (PEMFC) combined with onboard storage systems using compressed gaseous hydrogen (CGH₂) or cryogenic liquid hydrogen (LH₂). More than 75

units of hydrogen fuelling stations in the worldwide are put into operation. Besides, hydrogen applications for residential equipped with fuel cell-combined heat and power (FC-CHP) are demonstrated worldwide to provide electricity and heat.

The significant increase of hydrogen used as an energy carrier the risks of an accident in production plants, during storage and transport, or while being applied rise as well. Currently, safety-relevant problems of handling hydrogen in industrial scale are well controlled, however in the future “untrained” personnel will deal with hydrogen. Technical equipments used could be failure. Beyond that the possibility of handling incidents and human error will be happened at many places.

The objective of the study is to determine promptly the safety-relevant boundary conditions for infrastructure of a hydrogen economy. A system-analytic method is used to evaluate of the system, in order the weak points of possible risks is proven and suggestions on the remedy are made. Beyond that the determined risks are to be compared with standards, and/or with the similar technologies.

2. HYDROGEN ECONOMY

The term, "hydrogen energy economy" refers to global economy hydrogen, using hydrogen for energy carrier [10]. It is a vision for future in which economic system is based on the use of hydrogen as an energy storage and transport medium. 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.

2.1 Hydrogen Cycle

A hydrogen energy economy mainly consists of three functional steps [10]:

- (1) production,
- (2) storage, transport, and distribution, and
- (3) end-uses.

A closed loop energy system shown in **Fig. 1** is envisage taking water from the water inventory of the earth, splitting it into hydrogen and oxygen, recombining them as they are turned into energy services, and giving water back to the inventory, quantitatively and qualitatively unaltered. With this vision energy sustainability is might nearly achieved.

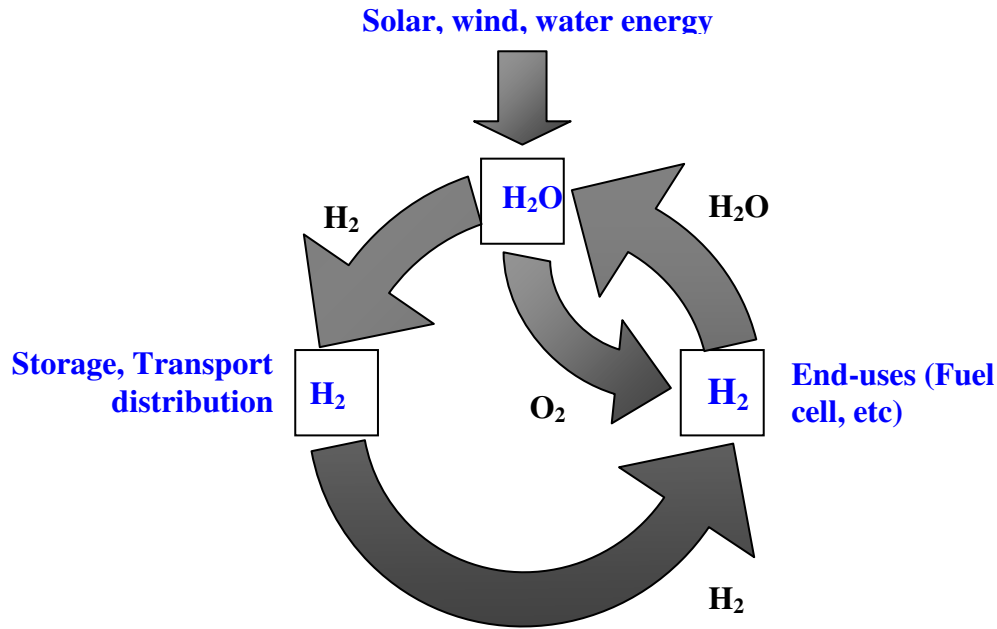


Fig.1. Hydrogen energy carrier a closed-loop energy cycle [10]

Presently hydrogen is mainly produced from fossil fuels via natural gas reforming as well as the partial oxidation of heavy fuel oil (or diesel) and coal. 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. For a large-scale storage, hydrogen can be stored underground in ex-mines, caverns and or aquifers. Hydrogen is then transported, by means of pipelines or super tankers, to energy consumption centres. It is then used in electricity, transportation, industrial, residential and commercial sectors as a fuel and or an energy carrier.

2.2. Hydrogen Safety

In principle, there is no absolute safety in engineering [6]. Every energy carrier has its specific safety risks. Hydrogen has a gross affinity to the air (oxygen), its flammable limit is wider and its energy ignition is very small. But the diffusion of hydrogen in air is quicker, so that the hydrogen leakage or hydrogen fire will quickly go up. In normal conditions hydrogen is an odourless and a colourless gas with molecular weight of 2.016 [13]. It is the lightest among all elements. Its density is 0.08376 kg/m^3 at standard temperature and pressure, it is about 14 times less than air. It is liquefied at -253°C , solidifies at -259.3°C , and having low critical point (-240°C , 13 bar). Compared with other fuels, hydrogen has the highest energy content per unit mass among all fuels. Hydrogen has a higher heating value of 141.9 MJ/kg , it almost three times higher than gasoline.

Under ambient condition hydrogen is flammable over a wide range concentration from 4-75%, and explosive in a range of 18.3% until 59% [10;13]. The minimum temperature required to initiate self-sustained combustion in a combustible fuel mixture in the absence of ignition source is 585°C, higher than other fuels. However, the minimum energy required to initiate combustion is 0.02 mJ (milli Joule), almost an order of magnitude lower than that conventional fuels. Therefore hydrogen can be combusted only by an ignition source such as a flame or a spark. Explosion of hydrogen is greater than methane at a much lower concentration. The diffusion coefficient for hydrogen is 0.61 cm³/sec, this is 4 times as high as that for methane. Hydrogen therefore mixes in air considerably faster than methane or petrol vapour, which is advantageous in the open air but represents a potential disadvantage in badly ventilated interiors. Since both hydrogen and natural gas are lighter than air they expand quickly.

The prospect of hydrogen energy economy often raises safety question. Part of the reason is associated with the Hindenburg case where the German airship exploded in 1937 and 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 airship [10]. In 1997, a NASA investigator Dr. Addison Bain, however, publicized his surprising finding that the highly combustible varnish that used to treat the fabric on the outside of the vessel most likely caused the tragedy.

3. A QUANTITATIVE RISK ASSESSMENT METHOD

A quantitative risk analysis is focused on the combined effect of frequencies and consequences of a possible accident, as illustrated in **Fig. 2** [10].

The first step, before starting to quantify the risk, is related to defining and describing the system. Detail information of the system such as process flow diagram, operating condition may be required.

The second 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 be quantified, leading to an underestimated risk. Based on this information the accident scenarios that will lead to system failure are determined.

The third step involves another question: how likely is the accident? Answering the question involves quantification of the probability of each scenario. Fault tree analysis (FTA) and event tree analysis (ETA) might be combined to be used for this purpose.

The fourth 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 fifth or the last step of the QRA is to estimate and evaluate the risk. The risk can be expressed as individual risk or as societal risk, as the most frequently used risk measures. Terms of “tolerable risk” is introduced in this step.

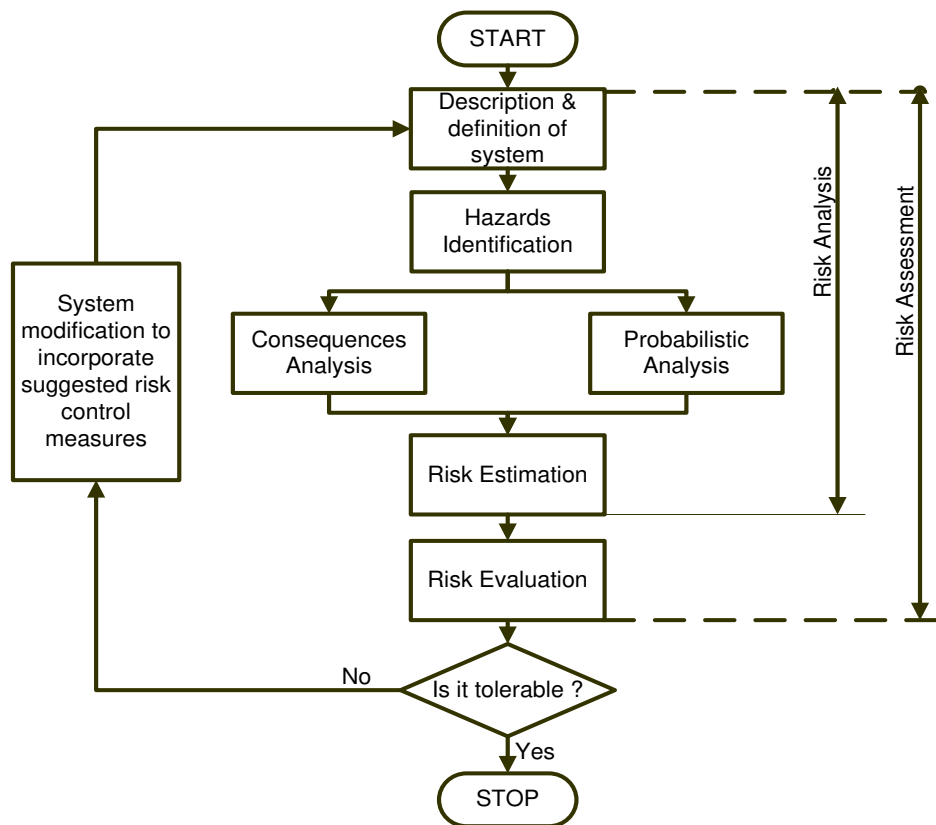


Fig.2 Procedure for the application of risk assessment [10]

3.1. Probabilistic Analysis

It involves estimating the likelihood of each of the scenarios that were identified in the hazard identification step. Two basic forms of which likelihood can be expressed: frequency and probability. Frequency is the expected number of occurrences of the event per unit time. While, probability is the measure of how likely it is the same event will occur. The likelihood of the above hydrogen scenarios occurring during a given interval can be derived from the probabilities of each of the contributory events whose occurrence, separately or contemporaneously as appropriate, could lead to the occurrence of the event. Therefore, a dual approach to likelihood estimation was attempted. Firstly, fault tree analyses are carried out on the larger containment systems were safety depend on the reliability of a large number components. Secondly, failure rate data are used for certain discrete events for which adequate statistics exist, or for which system reliability considerations are not the main causes of the failure. In order to calculate frequency of the possible outcomes for the scenarios an event tree analysis was performed, i.e. by multiplying the initiating event frequency and their outcome probabilities.

3.1.1. Fault tree analysis (FTA)

Fault tree analysis is an analytical tool that uses deductive reasoning and a graphical depiction of the reasoning process to determine the various combinations that, if they occur, lead to the occurrence of an undesired event [4;7]. This is the second QRA steps which answer to the question, “How is likely of the accident?” It is a structured, systematic approach that can be used to evaluate a single system or multiple systems and account for system interactions. It may be used in such way as to link the top event of a fault tree with an event tree. To evaluate the fault trees the study used an analytical approach based-computer program developed by Hauptmanns (1988).

3.1.2. Event tree analysis (ETA)

Event tree analysis uses inductive logic and a graphical depiction to represent the various events (outcomes) that may follow from an initiating event. It uses branches to show the various possibilities that may arise at each step. It is often used to relate a failure event to various consequence models. Each branch is conditional on the previous answer in the tree. The frequency of each outcome is obtained by multiplying the outcome probabilities by initiating event frequency. A hydrogen release may have many event outcomes, depending on the timing and type of ignition. A release may ignite immediately at the point of release (e.g. fireball, jet fire, pool fire, or early explosion), or it may ignite after the cloud has been dispersing for several minutes (e.g. cloud flash fire, vapour cloud explosion, etc) or it may not ignite at all which means harmless.

3.2. Consequence Analysis

In parallel with frequency analysis, consequence analysis evaluates the resulting impact on the public and the environment of accidents or incidents occur [10]. Most of hydrogen plant accidents involve release of liquid, gas or both. The size of the accident will generally depend on the length of the release period and the rate of the release. This is in turn depends on the size of the hole, form of the hole, its position, and pressure. The consequence evaluation is performed by mathematical or computational modelling, which is used to predict the size, shape and orientation of hazard zones that could result from hydrogen events. The study used software named PHAST 6.4 to calculate consequence impacting from the hydrogen scenarios [1].

3.3. Risks Estimation and Evaluation

A risk as a quantitative measure of hazard can be expressed as the combination of consequence and likelihood [6]. The study used an analytical model to calculate a number of results relating to the impacts on population potentially affected by various hydrogen events. 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 mathematically very low in comparison with the duration of the hazardous effects themselves. Hydrogen risk assessment model developed in the study. The integration of the risk from all possible events can, therefore, be built up event by event, this is the principles underlying the model algorithm. While each event can be treated separately, this does not necessarily mean a discrete outcome. A given release event can give rise to different outcomes. Releases of flammable materials in particular can give rise to a range of hazardous phenomena depending on a number of factors.

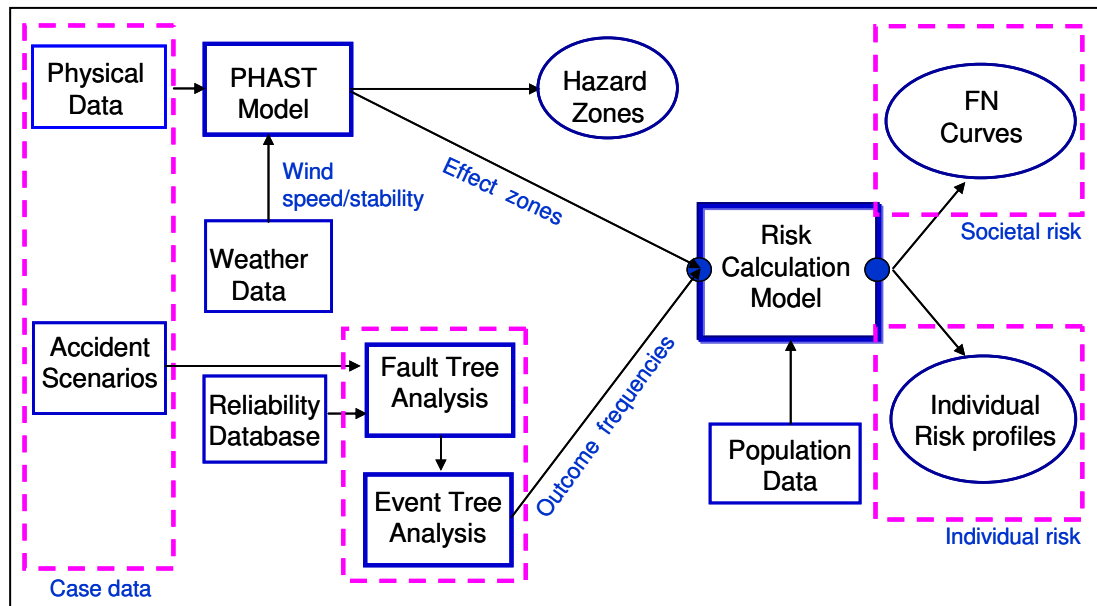


Fig.3 A risk estimation model (analytical approach) used in the study [10]

Fig. 3 shows relationship between the risk calculation model and its input and output, developed in study. The input of the model includes: relevant consequences effects for a given scenario resulted from the PHAST, frequencies for each possible event and outcome, ignition source, and wind direction probability. The wind directional probability needs to be taken into account so that the risk is correctly distributed within the region at risk from the collection of events. The calculated risks are then presented in the form of individual and societal risks. Individual risk (IR) expresses the likelihood of experiencing fatal effects at a given location, and is presented as cumulative curve of accident frequencies versus distance effects of the hydrogen incident outcomes. In other hand, the societal risk (SR) is expressed in terms of the likelihood of event outcomes that affect a given number of people in a single incident. 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.

In many risk assessments it may be necessary to determining 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. The study uses the risk acceptance criteria called “ALARP” (As Low As Reasonably Practicable) or “ALARA” (As Low As Reasonably Achievable). They are proposed by the European Integrated Hydrogen project phase 2 (EIHP2), as well as by the German accident commission for risk management [3;11].

4. CASE STUDY

4.1. System description

The study considers a solar hydrogen plant situated in Germany. The plant was built in 1986, as a joint venture Bayernwerk AG, BMW AG, Linde AG, Siemens AG [10]. 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, and so on as shown in **Fig. 4**.

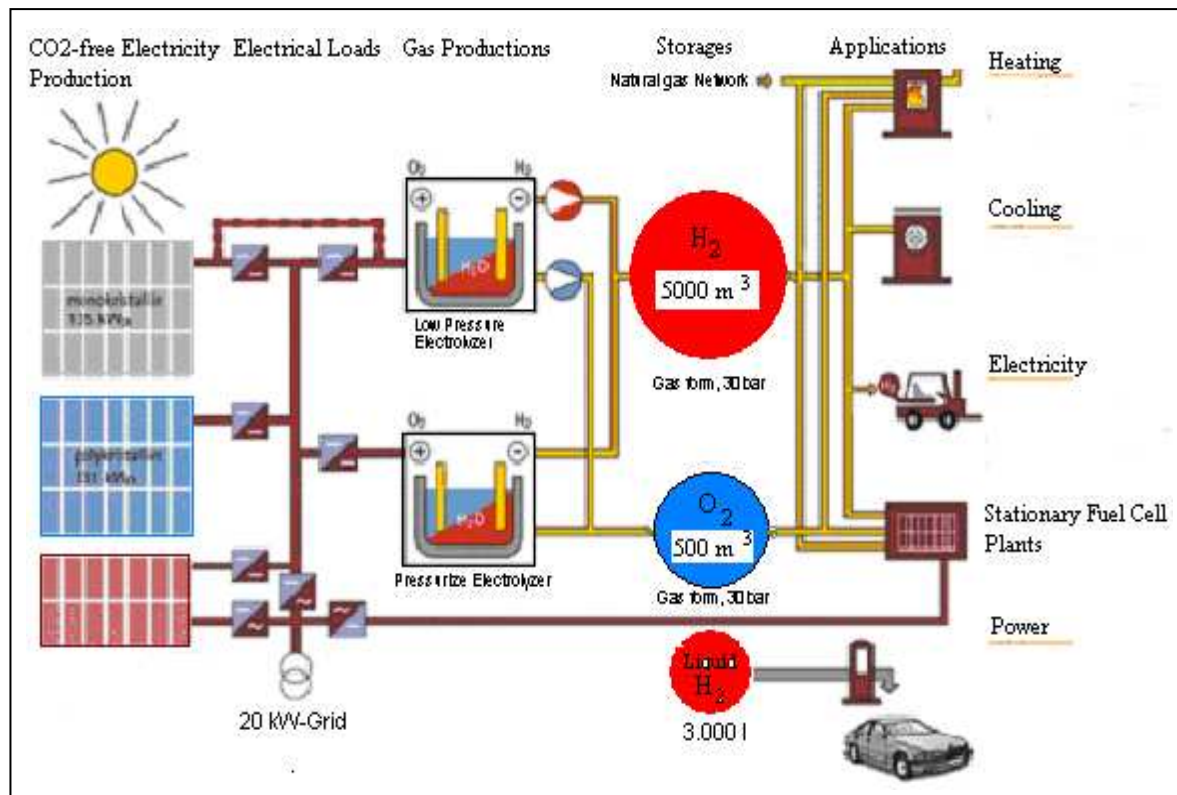


Fig. 4 Diagram of the solar-hydrogen plant [10].

The solar hydrogen plant produces hydrogen and oxygen by electrochemically decomposing of water in an electrolyser. In the electrolysis process of water the electric current is passed through an electrolyte solution (potassium hydroxide or alkali) and decompose 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.

4.2 Description of the Hydrogen Storage

The high-pressure hydrogen tank of the plant stores the largest hydrogen inventory of 5000 Nm³ compared to other components, see **Fig. 5**. It consists of two horizontal cylindrical high-pressure hydrogen storages 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 electrolyzes 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.

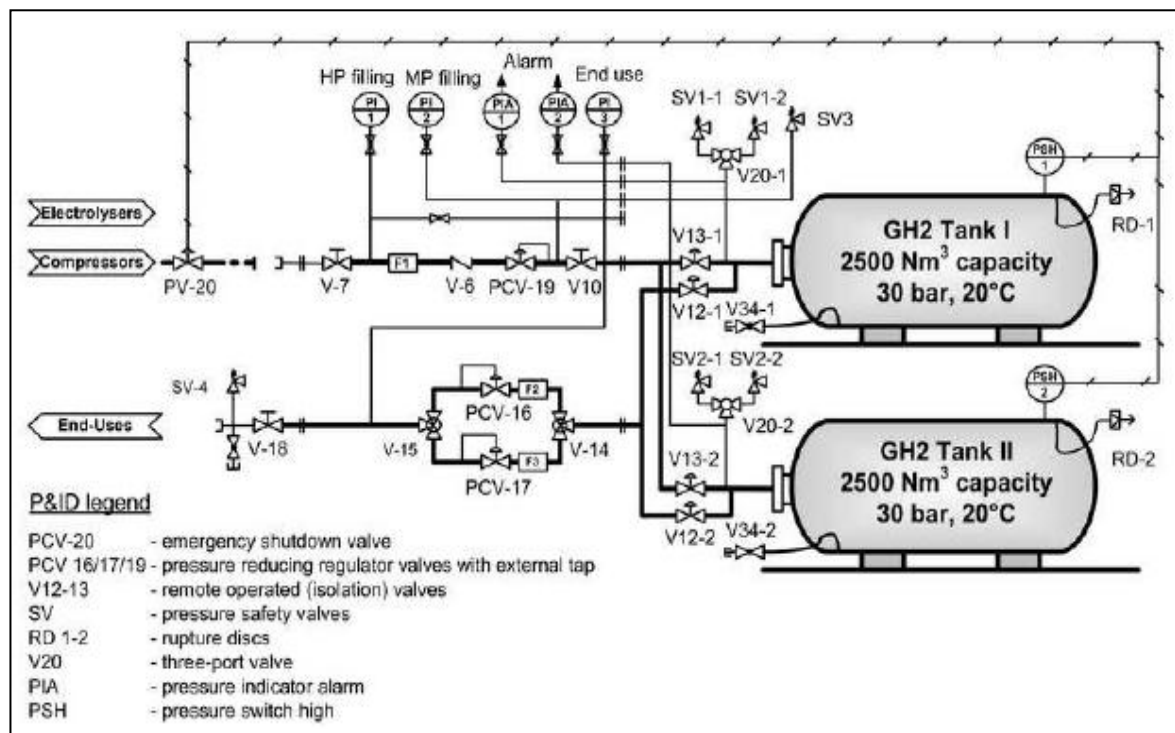


Fig. 5 Simplified P&ID Diagram of the GH2 storage [10].

5. THE RESULTS

The study considers a hydrogen production plant. Total number of installations in the 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. 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. For hydrogen, the threshold level amount is 5 tons [12]. Based on the above guidelines the study was focused on the hydrogen storages, as they have the greatest potential damage and large release of hydrogen and consequential damage.

5.1. Frequency Analysis Results

Expected frequencies of the accident scenarios for the H₂ storages at the production plant were synthesised from the component failure rate data associated with each of the identified failure mode, using the FTA approach. Two accident scenarios (top events) are considered, i.e. instantaneous and continuous. The summary of the fault tree analyses results for the plant with the trial number of 10,000 is shown in **Table 1**.

Table 1. Expected frequencies of the GH₂ storage at production plant

Release Scenario	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 1 shows that the expected mean frequency of the overall system is 3.6×10^{-5} /year, in other words once per 27,777 years. The contribution of instantaneous release of hydrogen from the GH₂ tank is 1.8×10^{-6} /year (once per 555,556 years), while continuous release is 3.4×10^{-5} /year (once per 29,412 years).

Instantaneous release is only 5% of the overall hydrogen release from the GH₂ storage.

The accident outcome frequencies of the GH₂ Storage at production plant is shown in **Table 2**. The mean value is obtained by multiplying the mean instantaneous frequencies or continuous frequencies (that is given in **Table 1**) with the conditional probabilities of the accident outcomes that has been calculated from the event tree diagram for GH₂ release.

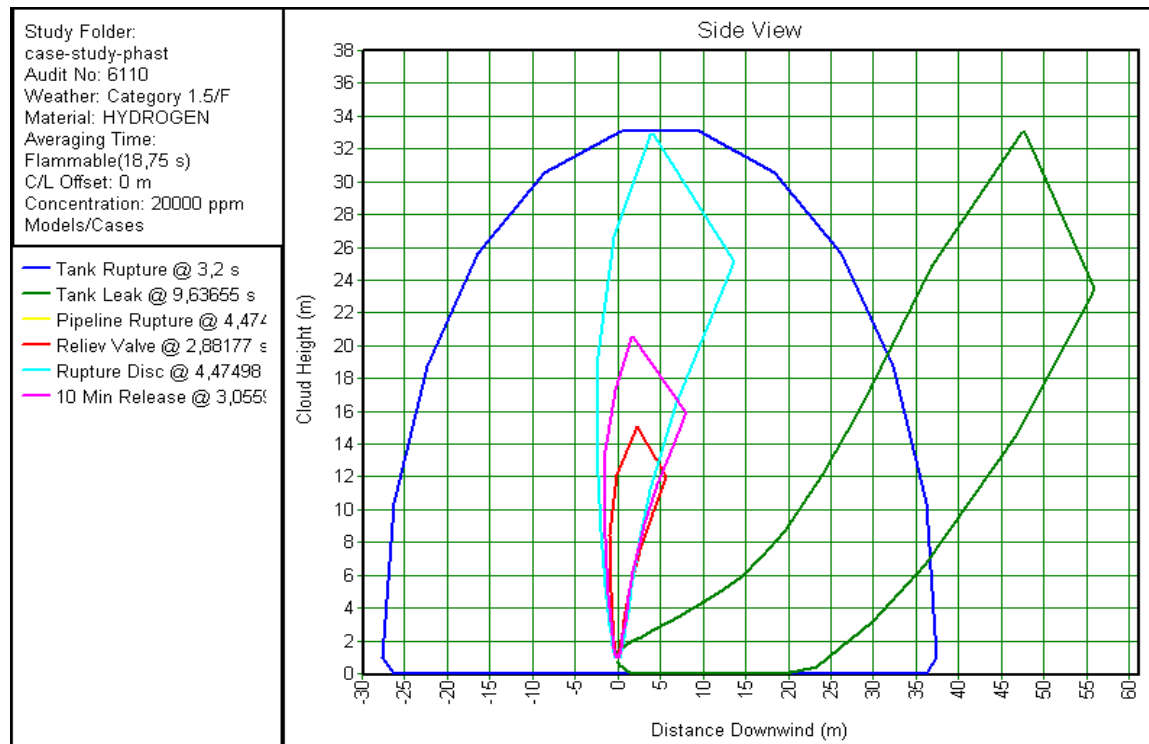
Table 2 implies that fire outcomes (bold) account for about 67%, more dominant than explosion. The accident outcome resulting explosion is about 7%, and 26% may have no effect on the human population.

Table2. Accident outcome frequencies of the GH₂ Storage at production plant

Release Scenario	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 on human population		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

5.2. Consequence Modelling Results

The hydrogen release may result in different types of consequences, such as jet fire, fireball, explosions and so on. Each of the outcomes was modelled for different shapes and sizes that are required for impact calculations. Circle and ellipse are the most shapes considered to calculate impact zones resulted from fires and explosions. The study considers fire and explosion hazards because they may result fatality to the population around the installation.

**Fig. 6 Side view of the consequence analysis resulted from the hydrogen plant.**

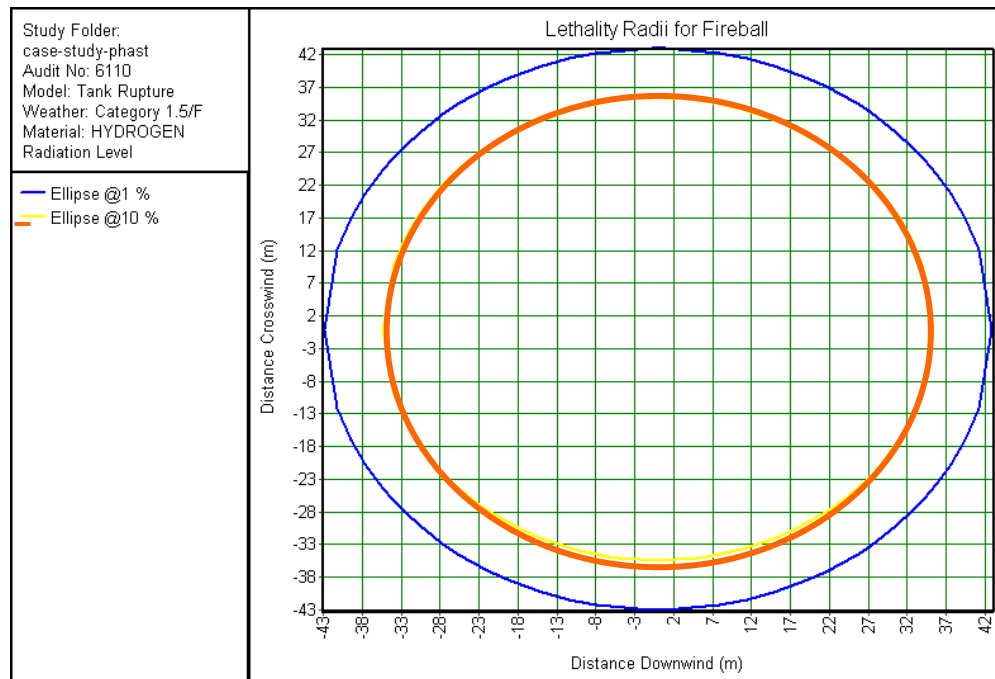


Fig. 7 Lethality radii for fireball may be resulted from the hydrogen plant

Table 3 below shows a summary of the effect distances resulting in fatalities to the nearby populations for given fatalities level: 1%, 10% and 60%. Different shapes of the consequence results (e.g. impact zones) calculated by PHAST software is shown in **Fig. 6** and **Fig. 7**.

Table 3. Effect distances (stated in meter) of the consequence impacts for the plant.

No	Event outcomes	Fatality level		
		1 %	10 %	60 %
1	Fireball	42.9	35.4	26.3
2	Jet fires	22.6	21.4	19.6
3	Early explosion	334.4	86.7	67.0
4	Late explosion (VCE), rupture	110.2	92.1	---
5	Flash fires	---	----	37.9

5.3. The Risk

Recommended individual risk regulation according to the Dutch National Environmental Policy Plan 1989 is 1×10^{-6} /year. The individual risk of the hydrogen storages as shown in **Fig. 8** runs in the unacceptability zone ($>1 \times 10^{-6}$ /year) for effect distance of 0 – 90m.

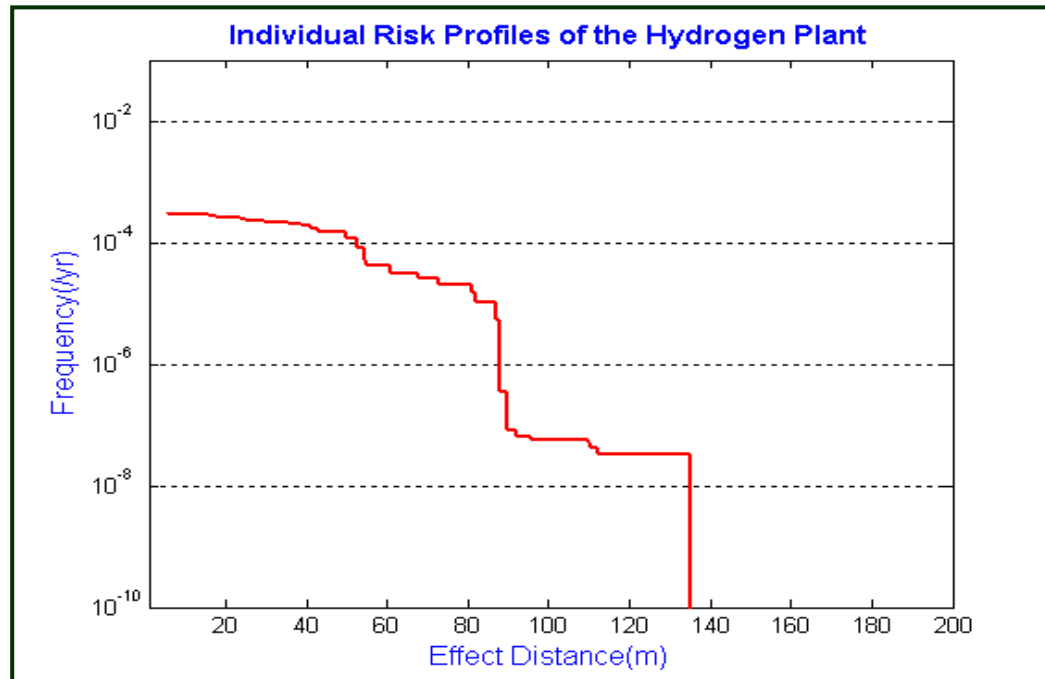


Fig.8 The individual risk (IR) of the study object

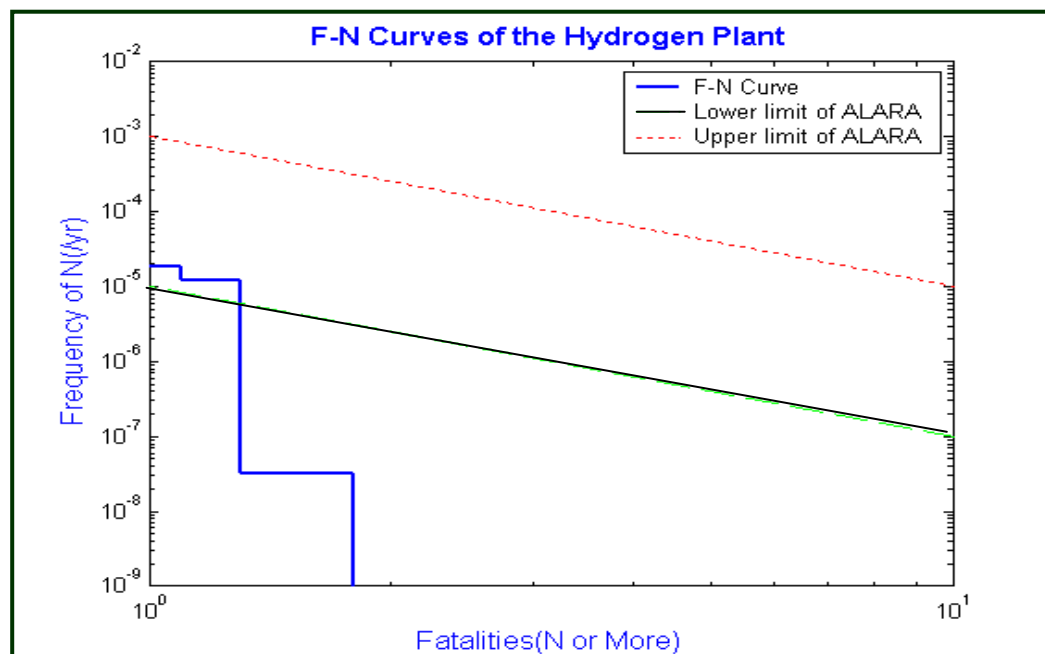


Fig.9 The societal risk (F-N curve) of the study object

The societal risk (F-N curve) of the study objects in **Fig.9** appear globally lower than the individual risk shown in Fig.8. Also the curves (relevant to the hydrogen storage) fall within the ‘acceptable’ risk mentioned in ‘ALARA’ (As Low As Reasonable Achievable) zones. ALARA is the standard of societal risk developed in the Netherlands. This means that the hydrogen plant can be accepted for public.

6. CONCLUSION

The individual risk for the hydrogen plant run almost entirely in the unacceptability zone. The societal risk, however, appears globally lower than the individual risk. In fact, the curves fall within the acceptable zone. Should the plants be implemented for the public, yes but the risk must be reduced as far as reasonable and practicable, typically subject to cost benefit analysis.

REFERENCES:

- [1] DNV (2002): PHAST Technical Manual. Det Norske Veritas (DNV) Software, UK.
- [2] DWV (2003): H2-Roadmap AP1 “Prinzipielle Anforderungen an die Infrastruktur”. Studie des DWV, Berlin, Germany.
- [3] EIHP (2003): Risk acceptance criteria for Hydrogen Refuelling Stations. European Integrated Hydrogen Project [EIHP2], By Norsk Hydro ASA and DNV for WP5.2.
- [4] Hauptmanns, U. (1988): Fault tree analysis for process plants. Engineering Risk and Hazards Assessment, vol. 1, pp 21-58, CRC Press.
- [5] Hauptmanns, U. (2002): Analytical Propagation of Uncertainties through Fault Tree. Reliability Engineering and System Safety, 76, p.327-329.
- [6] Hauptmanns, U., W. Werner (1991): Engineering risks – Evaluation and valuation. Springer-Verlag Berlin, Heidelberg, Germany.
- [7] Hauptmanns, U., P. Hömke, J. Huber, G. Reichart: Ermittlung der Kriterien für die Anwendung systemanalytischer Methoden zur Durchführung von Sicherheitsanalysen für Chemieanlagen. Gesellschaft für Reaktorsicherheit (GRS)mbH, Köln, Deutschland
- [8] IAEA (1999): Hydrogen as an Energy Carrier and its Production by Nuclear Power. Austria.
- [9] Roos, A.J. (1999): Guidelines for quantitative risk assessment. CPR 18E (“Purple book”), Voorburg, the Netherlands.
- [10] Rosyid, O.A. (2006): System-analytic Safety Evaluation of Hydrogen Cycle for Energetic Utilization, Dissertation, Otto-von-Guericke-University of Magdeburg, Germany.
- [11] SFK (2004): Risikomanagement im Rahmen der Störfall-Verordnung, Technische Systeme, Risiko Und Verständigungsprozesse. SFK-GS-41, Bonn.
- [12] Seveso II (1997): COUNCIL DIRECTIVE 96/82/EC on the control of major-accident hazards involving dangerous substances. Official Journal of the European Communities, No L 10/13, EN.
- [13] Tzimas E., C. Filiou, and J.-B. Veyret (2003): Hydrogen Storage- State-of-the- Art and Future Perspective. Institute of Energy, DG JRC, Petten, The Netherlands.
- [14] Winter, C.J. & J. Nitsch (1989): Wasserstoff als Energieträger. Spring-verlag Berlin Heidelberg, Germany.