# A risk assessment approach for the underground storage of hydrogen, methane mixtures

Master Thesis

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submitted at

Chair of Economic- and Business Management
of the
Montanuniversitaet Leoben

Leoben, 04.03.2015

# Scope of Work

**Christoph Steiner** was requested to analyze in the master thesis at hand the topic:

## "A risk assessment approach for the underground storage of hydrogen, methane mixtures"

This master thesis deals with the underground storage of hydrogen and its accompanying risks. The main focus is set on storage of hydrogen-methane mixtures in porous media. The introduction of hydrogen in underground gas storage systems presents a significant change in the operating conditions of the facilities and the reservoir. Therefore the associated risks must be further examined.

The first part of the master thesis has to include a literature review on a wide range of topics related to the underground storage of hydrogen and the related risks as well as methodologies to assess risks. A system overview of the underground hydrogen storage system as well as an outline of similar projects must be provided. Safety and risk aspects arising due to the introduction of hydrogen in the system have to be examined and process safety risk management approaches have to be reviewed. Currently used risk assessment approaches in the oil and gas industry must be identified and compared.

Based on the literature review and the comparison of the risk assessment methods an appropriate method for the assessment of safety risks in case of hydrogen underground storage has to be selected. This method then must be exploited to create a conceptual structure for a certain case study.

Leoben, May 2014

o.Univ.Prof. Dr. Hubert Biedermann

Chair of Economic- and Business Management

# Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich diese Arbeit selbständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch sonst keiner unerlaubten Hilfsmittel bedient habe.

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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# Acknowledgment

First of all I want to thank DI Vassiliki Theodoridou for her valuable advice throughout the process of writing this thesis. I am thankful for her guidance and support and really enjoyed discussions with her, which were key for this thesis.

I also want to thank o.Univ.-Prof. Dipl.-Ing. Dr.mont. Hubert Biedermann for the opportunity to write this thesis at the Chair of Economics- and Business Management.

# Kurzfassung

Momentan stattfindende Forschungsprojekte befassen sich mit der Speicherung von Wasserstoff  Methan Gemische  in existierenden unterirdischen Gasspeichern. Das Hinzufügen von einem neuen Medium in das Gasspeichersystem könnte neue Risiken mit sich bringen, welche genau untersucht werden müssen. Das Ziel dieser Masterarbeit war die Auswahl einer Risikobeurteilungsmethode und die Erstellung einer konzeptionellen Struktur der vorgeschlagenen Methode für eine Fallstudie der Speicherung von Wasserstoff Methan Gemisch in porösen Speicher. Der erste Teil dieser Arbeit beinhaltet eine Literaturanalyse zu einer Vielzahl von Themen, die mit der Speicherung von Wasserstoff im Untergrund zusammenhängen. Ein Überblick über ein geplantes unterirdisches Wasserstoffspeichersystem und eine Kurzdarstellung von ähnlichen Projekten werden präsentiert. Zusätzlich werden Sicherheitsrisiken sowie weitere Gefahrenpotentiale für  Anlagen, Bohrungen und Lagerstätten vorgestellt. Im Anschluss daran wird ein Überblick über häufig verwendete Herangehensweisen der Risikobeurteilung gegeben. Weiters werden Risikobeurteilungsfallstudien für die CO2 Speicherung in Untergrundspeichern vorgestellt und Parallelitäten zur Wasserstoffspeicherung hervorgehoben. Der praktische Teil der Masterarbeit besteht aus der Erstellung einer konzeptionellen Struktur der Bow-Tie Risikoanalysemethode einschließlich der Identifikation von Gefahren, Konsequenzen und Barrieren. Unsicherheiten im System werden berücksichtigt durch den Einsatz von Fuzzy-Logik.

Am Ende der Arbeit werden vorläufige Ergebnisse von Forschungsarbeiten im Bereich der unterirdischen Speicherung von Wasserstoff dargelegt.

Schlagwörter: unterirische Wasserstoffspeicherung, Risikoanalyse , Bow-Tie, Wasserstoff, Kohlendioxid Abscheidung und Speicherung , unterirdische Gasspeicherung, Bedrohungen, Konsequenzen, Barrieren, Delphi-Studie, Fuzzy Logic

# Abstract

Currently ongoing research projects examine the storage of hydrogen methane mixtures in existing underground gas storage facilities. By adding a new medium in the gas storage system might cause new risks which need to be examined in detail. The aim of this thesis was to select a risk assessment method and to create a conceptual structure for the case of hydrogen methane mixture storage in porous reservoirs. The first part of this thesis includes a literature review of topics related to the underground hydrogen storage. An overview of a planned underground hydrogen storage system and a brief description of similar projects follow as next. In addition the thesis presents a list of security threats and other potential risks for facilities, wells and reservoir. Common approaches to risk assessment are also given. Furthermore, risk assessment case studies for CO2 underground storage are introduced and similarities for hydrogen storage high-lighted. The practical part of the thesis consists of creating a conceptual structure of a bow-tie analysis including the identification of hazards, consequences and barriers. Un-certainties in the system are taken into account through the use of fuzzy logic.

At the end of the thesis preliminary results of research projects in the field of hydrogen underground storage are presented.

Key Words: underground hydrogen storage, risk assessment, bow-tie, hydrogen, carbon capture and storage, underground gas storage, threats, consequences, barriers, Delphi-study, fuzzy logic

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# Abbreviations

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| ALARP | As Low As Reasonably Practical |
| Bel | Belief function |
| bpa | Basic probability assignment function |
| BSCAT | Barrier-based Systematic Cause Analysis Technique |
| CCPS | Center for Chemical Process Safety |
| CCS | Carbon Capture and Storage |
| CLT | Constant load testing |
| COG | Center of gravity |
| DGS | Dry Gas Seals |
| ESL | Evidence Support Logic |
| ETA | Event tree analysis |
| FBD | Failure Block Diagram |
| FEP | Features, Events and Processes |
| FMEA | Failure mode and effects analysis |
| FMECA | Failure mode and effects and criticality analysis |
| FPS | Fuzzy Possibility Score |
| FRB | fuzzy-rule-base |
| FTA | Fault tree analysis |
| HACCP | Hazard analysis and critical control points |
| HAZOP | Hazard and operability study |
| IEA | International Energy Agency |
| LOPA | Layer of protection analysis |
| m | Basic probability assignment function |
| MD | Measured Depth |
| MF | Microfine binder |
| MLD | Master logic diagram |
| P2G | Power to Gas |
| PC | Portland cement |
| PDCA | plan-do-check-act |
| Pl | Plausibility function |
| PSA | Petroleum Safety Authority |

| | |
|---|---|
| RCA | Root cause analysis |
| SCAT | Systematic Cause Analysis Technique |
| SF | Silica fume |
| SIL | Safety Integrity Level |
| SSRT | Slow strain rate testing |
| SSSV | Subsurface safety valve |
| SWIFT | Structured what if technique |
| TÜV | Technischer Überwachungsverein |
| UGS | Underground gas storage |
| WP | Work package |
| ZHA | Zurich hazard analysis |

# 1 Introduction

Currently there are ongoing efforts to decarbonize Europe's energy system. This leads to higher amounts of renewable energy amid the energy-mix. Increasing renewable energy generation brings challenges to the existing energy transport system. Those challenges arise because of the variability of the renewable energy sources like solar-sourced power or wind-power. To handle the variations in power generation huge amounts of storage will be necessary. Presently operating pumped hydro storages are able to stabilize the electric power grid during daytime-fluctuations but are expected to be far too small to stabilize the power grid for seasonal fluctuations.

Currently there are ongoing research projects examining the storage possibilities for renewable energy in existing underground gas storage systems. This method, often referred to as Power to Gas (P2G), would provide a storage capacity of 1500 to 3000 times the size of all pumped hydro storages that are currently operating[1] (Figure 1).

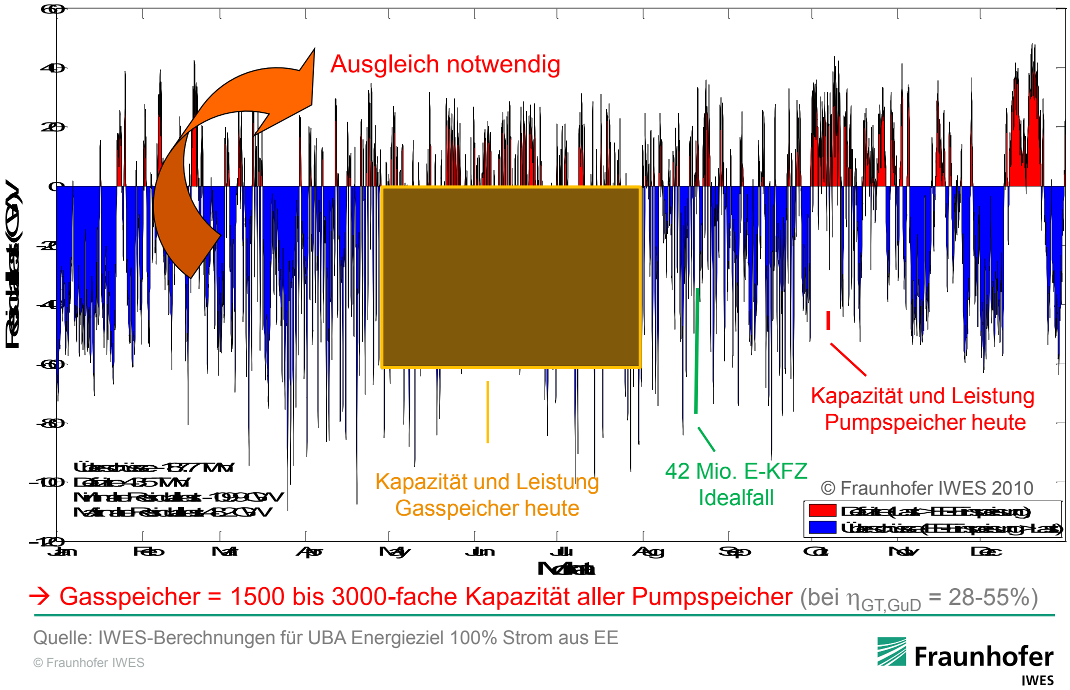


**Figure 1: Graph for an energy scenario of 100% renewables in 2050. Red indicates production deficits; blue shows a surplus in production. Also a comparison of storage capacity is shown in the graph as orange (gas storage facilities), green (42 million car batteries of electric cars) and red (capacity of pumped hydro storages)[1].**

Currently the project "Underground Sun Storage" focuses on the research and testing of methane / hydrogen mixtures in porous rocks with a share of up to 10 % hydrogen. The

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[1] Bard et al. (2012), p. 9, Access 22.02.2015

consortium consist of RAG Rohöl-Aufsuchungs Akitengesellschaft, VERBUND AG, axiom Angewandte Prozesstechnik Ges.m.b.H., Montanuniversitaet Leoben, IFA (Department for Agrobiotechnology)-Tulln BOKU (University of Natural Resources and Life Sciences, Vienna) and The Energy Institute at the Johannes Kepler University Linz, where RAG is the consortium manager and leading investor. Project partners are NAFTA a.s., DVGW (German Technical and Scientific Association for Gas and Water), ETOGAS G.m.b.H. and HYCHICO. The field test of the underground hydrogen storage will take place at the RAG gas field Lehen.

Figure 2 shows the work packages of the Underground Sun Storage project. Also indicated with their respective logo are the consortium members working on the work packages (WP).

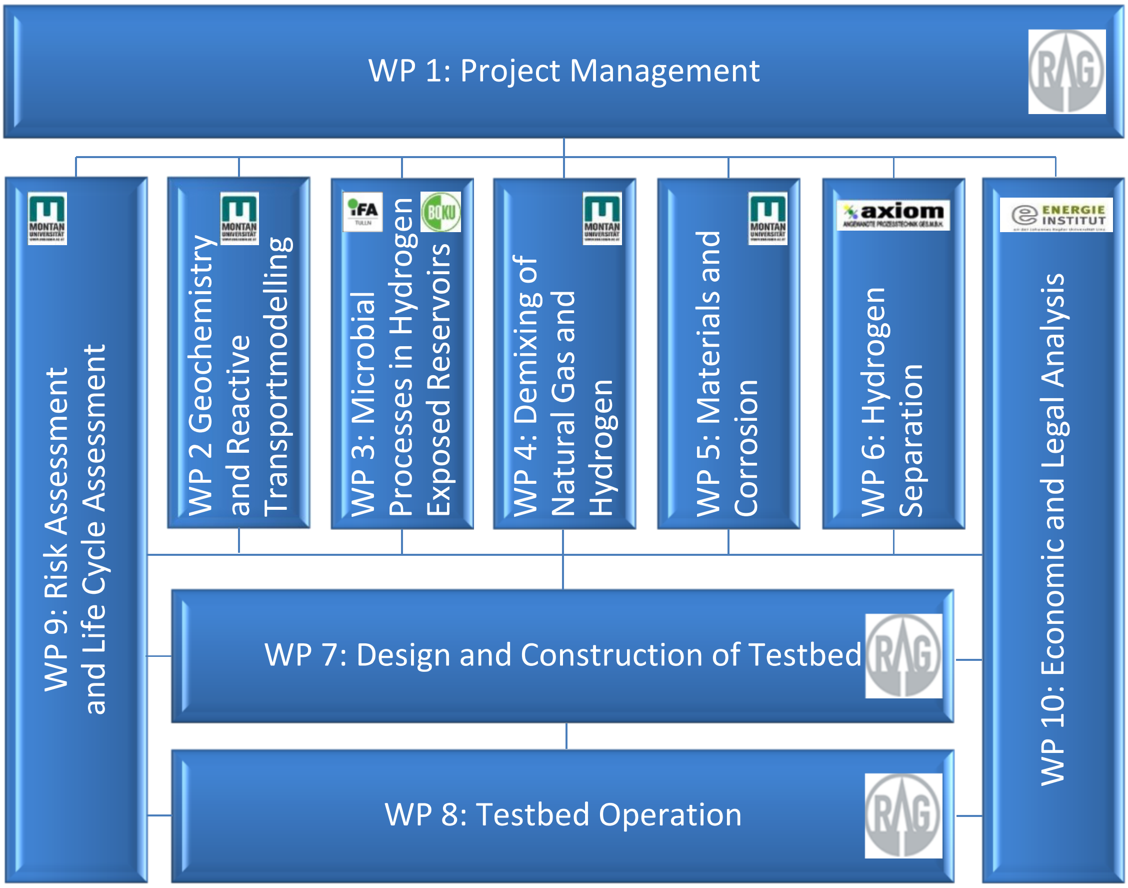


**Figure 2: Working Plan for the Underground Sun Storage project with the work packages and the consortium members working on the packages.**[2]

This thesis deals with parts of WP 9 (as seen in Figure 2), the Risk Assessment and Life Cycle Assessment. This work package is handled at the Montanuniversitaet Leoben, more specifically the Chair of Economic- and Business Management.

[2] Underground Sun Storage, Arbeitsplan (2014), Access 18.12.2014

# 2 $H_2$ Underground Storage: Overview

Much of the infrastructure needed for hydrogen underground gas storage (UGS) systems is already in place in form of underground gas storages. In these storage systems natural gas is stored to secure the gas supply for periods of high demand. $H_2$ UGS systems would use the same reservoirs, but with a partly different stored fluid mixture.

## 2.1 General Hydrogen properties and considerations

Hydrogen, discovered by Henry Cavendish in 1766, is the lightest gas. It has the atomic number 1 and is located in the s block of the periodic table of elements. It is colorless, odorless and has many applications, both historic and current. The use of hydrogen to fill airships for example has been halted since the Hindenburg disaster in 1937. Some of the current uses of hydrogen include the use in the Haber process and the reduction of metallic ores[3].

Table 1 shows a comparison of some properties of hydrogen, methane and carbon dioxide. Carbon dioxide has been included because in risk assessment case studies in 4.4 primarily carbon capture storage case studies are discussed. An important property for underground storage is the viscosity of the stored fluid, and as shown in Table 1 hydrogen has clearly the lowest viscosity of these three substances.

| **Property** | **$H_2$** | **$CH_4$** | **$CO_2$** |
|---|---|---|---|
| **Molecular Weight (g/mol)** | 2.0159 | 16.043 | 44.01 |
| **Melting point (°C) @1.013 bar** | -259.20 | -182.46 | -56.57 |
| **Boiling point (°C) @1.013 bar** | -252.78 | -161.48 | (Sublimation) -78.45 |
| **Critical temperature (°C)** | -240.01 | -82.59 | 30.98 |
| **Critical pressure (bar)** | 12.96 | 45.99 | 73.77 |
| **Critical density (kg/m$^3$)** | 31.263 | 162.7 | 467.6 |
| **Triple point temperature (°C)** | -259.19 | -182.46 | -56.56 |
| **Triple point pressure (bar)** | 0.077 | 0.117 | 5.187 |
| **Gas density (kg/m3) @1.013 bar at boiling point** | 1.3326 | 1.816 | 2.813 |
| **Gas density (kg/m3) @1.013 bar and 15 °C** | 0.0852 | 0.6797 | 1.8714 |
| **Compressibility Factor (Z) @1.013 bar and 15 °C** | 1.0006 | 0.99802 | 0.99435 |

3 Royal Society of Chemistry (2014), Access 05.08.2014

| | | | |
|---|---|---|---|
| **Viscosity (Poise) @1.013 bar and 15 °C** | 8.3969E-05 | 1.0245E-04 | 1.3711E-04 |
| **Solubility in water (vol/vol) @1.013 bar and 15 °C** | 0.0214 | 0.054 | 1.7163 |
| **Auto ignition temperature (°C)** | 560 | 595 | - |

**Table 1: Comparison of properties of $H_2$, $CH_4$ and $CO_2$[4]**

## 2.2 Underground gas storage systems

Currently operating underground gas storage systems consist of aboveground facilities (pipelines, metering station, compressor, cooling unit, wellhead, preheater, pressure reduction station, dryer, control room building) and underground system parts (well, reservoir), as shown in Figure 3.

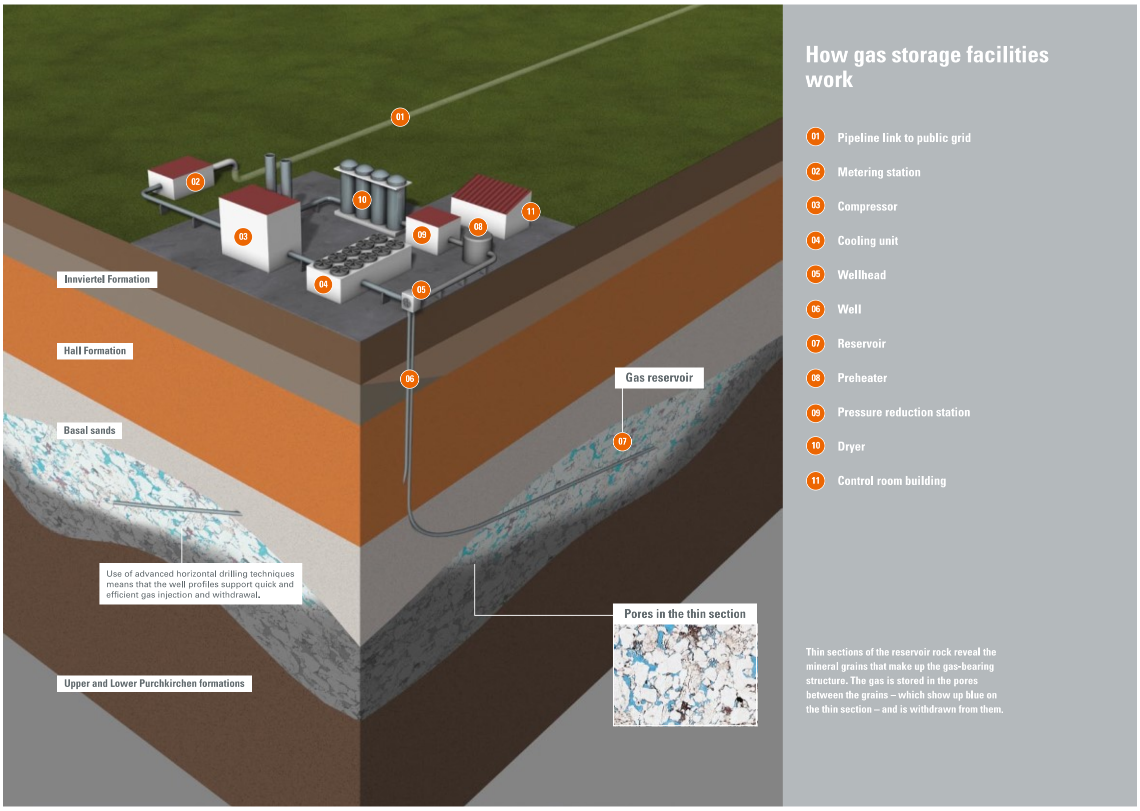


**Figure 3: Overview of an exemplary underground gas storage system[5]**

In Austria RAG and OMV both are operating underground gas storage systems and internationally many other companies do as well.

Different types of UGS are in use, specifically depleted gas or oil reservoirs, aquifers, salt caverns, limestone reservoirs and some alternative options.

[4] Air Liquide (2014), Access 22.02.2015

[5] RAG Austria (2011), p. 4, Access 24.05.2014

### 2.2.1 Surface facilities

Surface facilities have the task to condition the gas either for injection into the reservoir (compressing, cooling) or for injection into the pipeline system after producing it from the reservoir (preheating, pressure reduction, drying). In addition metering the gas flow is a task of the surface facilities.

**Metering Station**

Metering stations are installed to measure the amount of injected and produced gas. However, meter accuracy is an issue, and this causes differences in the readings of the measurement tools for injected and produced gas. Therefore the actual stored volume of the storage usually does not match the book quantity of inventory[6].

The use of ultrasonic-, turbine- and diaphragm-meters for a hydrogen-methane-mixture is considered to be unproblematic[7]. The report by DBI suggests that further testing regarding the accuracy of the gas-meters has to be done for different gas-hydrogen-mixtures[7].

**Compressor**

The higher the hydrogen content is in the gas-mixture, the higher is also the temperature of the gas-mixture at the desired higher pressure[8]. This increase in output temperature could necessitate additional cooling units.

Typically used Dry Gas Seals (DGS) to seal the atmosphere from the compressor shells show less than one percent increase of leakage, which is within the limits of tolerance[8].

DVGW experts suggest that research concerning the explosion-protection has to be conducted. In addition the influence of hydrogen on the condensation of the gas-mixture has to be clarified[9].

**Cooling Unit**

The compression of the gas mixture results in an increased fluid temperature compared to the uncompressed gas. Cooling units reduce the temperature of the fluid mixture before it is injected into the reservoir. As mentioned before, in case of a hydrogen-natural gas mixture additional cooling capacities could be required.

Typical cooling units use fin fan coolers[10], a dry cooler using cooling air, which is agitated by a fan, passing along finned tubes containing the hot fluid[11].

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[6] Cf. Flanigan, O. (1995), p. 118

[7] Cf. DBI (2012), p. 22

[8] Cf. DVGW (2013), p. 59

[9] Cf. DVGW (2013), p. 60

[10] Cf. Flanigan, O. (1995), p. 150

[11] Cf. AGA (2014), Access 30.6.2014

**Wellhead**

The wellhead sits on the surface and connects the tubing, casing and surface flow line using spools and valves to control the flow. The wellhead valves and connections therefore act as a barrier for fluid flow out of the reservoir. Seals and connections are long lasting under the influence of hydrogen, although further tests regarding the sealing ability and durability of the seals are suggested by DBI[12].

**Preheater**

Pressure reduction will cool the fluid mixture down; therefore before the pressure reduction station the preheater heats the gas.

**Pressure reduction station**

At the pressure reduction station the high-pressured fluid coming from the reservoir is decompressed to required output pressures. During this operation the temperature of the gas mixture decreases.

**Dryer**

After producing the fluid from the reservoir it is usually not dry enough to inject it directly into the pipeline. Therefore a dryer, or dehydration unit, dries the gas to fulfill the gas quality requirements.

### 2.2.2 Downhole equipment

Downhole equipment has to provide a seal from the wellbore to the surrounding rock formations and also has to allow a safe injection and production of the fluid mixture. Downhole equipment often also is called "well completion", which could be defined as an "*assembly of downhole tubulars and equipment required to enable safe and efficient production*"[13]. Below a short description for some of the most important parts of the downhole equipment is given.

**Packer**

Packers are used to seal the annulus from the tubing, which provides the conduit for production and injection. Various types of packers can be identified by different setting mechanisms, applications and retrievability.

Sealing elements of packers (elastomers) could potentially absorb hydrogen under application of high pressure. When the pressure is then released rapidly the hydrogen is released again and in this process fractures of the elastomers can originate[14].

**Tubing**

The tubing is a wellbore tubular through which the fluid is injected or produced.

[12] Cf. DBI (2012), p. 23

[13] Schlumberger Oilfield Glossary(2014), Access 18.12.2014

[14] Cf. DGMK (2014), p. 4

**Travel Joints**

The travel joint is part of the tubing string that allows the tubing to move in axial direction while maintaining a hydraulic seal between the tubing and the annulus.

**Cement**

Cement is placed between the casing and the borehole wall and acts as a sealing. The requirements for the cement are much higher for storing hydrogen - natural gas mixtures than for natural gas without hydrogen[15].

**Subsurface Safety Valve (SSSV)**

The SSSV is a fail-safe safety-valve system that in case of emergency is designed to seal off the wellbore, and is typically installed in the upper part of the wellbore.

### 2.2.3 Underground storage options

UGS systems can be classified into different UGS storage types depending on the geologic formation. The three most common types are "*depleted gas reservoirs, aquifers and mined salt caverns*"[16]. A brief description of the individual storage types is given below.

**Depleted oil and gas reservoirs**

Depleted gas and oil reservoirs are old reservoirs where most of the recoverable reserves have been produced.

They have proven ability in trapping gas. However, gas losses can occur through leaky wells, leaky caprocks, dissolution in water, diffusion into surrounding groundwater, viscous fingering and contamination with other hydrocarbons[17].

**Aquifers**

An aquifer is a porous rock containing filled with water.

To possibly use an aquifer as an UGS the permeable water bearing formation has to have an impermeable caprock[18]. The lack of existing infrastructure, the need for more cushion gas and the higher geologic uncertainty compared to depleted reservoirs make the development of aquifers to UGS more expensive than the development of UGS from depleted reservoirs[19].

**Salt caverns**

Salt caverns are artificially generated caverns in salt formations or salt domes.

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[15] Cf. DGMK (2013), p. 12

[16] Lord, A.S. (2009), p. 8

[17] Cf. Lord, A.S. (2009), p. 9

[18] Cf. EIA (2004), Access 30.6.2014

[19] Cf. Lord. A.S. (2009), p. 11

Salt cavern UGS systems can be operated with comparably small amounts or no cushion gas with high injection and production rates[18]. Generally, bedded salt structures are more challenging to develop than salt dome caverns, because they present more heterogeneities that can lead to differences in fracture pressure and bedding plane slip[20].

**Limestone reservoirs**

Limestone reservoir UGS systems are far less common than depleted reservoirs- aquifer- or salt cavern- UGS systems. UGSs have been developed in permeable reef structures and naturally fractured limestone reservoirs, and current research also focuses on the generation of caverns in limestone using hydrochloric acid[21].

**Alternative options**

In regions where all of the above options are not available for UGS, alternatives options are possible.

Abandoned coal mines are an alternative, if the coal seam is surrounded by impermeable layers[22]. Very important for these UGS is the role of adsorption of gas by coal, which increased the gas storage volume by a factor of ten for a decommissioned coal mine UGS in Belgium[23].

The water curtain technique deals with the problem that rock caverns are never completely sealing. Therefore a water curtain is created by multiple holes in the caverns that provide a continuous water flow, which should prevent gas flow into the rock fractures[24].

Another option is using lined hard rock caverns. In this technique the caverns are lined with steel or plastic and the rock should be self-supporting. Currently at least one UGS of this type is operational, using a cylindrical cavern that is lined with steel[25].

In refrigerated mined caverns the temperature of the stored fluid is reduced, also reducing the amount of cavern-volume needed for a certain amount of gas (in standard cubic meters).

## 2.3 Similar projects

Steffen Schmitz (2013) and Mikhail Panfilov (2010, 2006) presented an overview of $H_2$ underground storages and also discussed town gas experiences from Germany, Czechoslovakia and France.

[20] Cf. Bruno, M. & Dusseault, M. (2002), p. 24

[21] Cf. Lord. A.S. (2009, p. 15

[22] Cf. Lord, A.S. (2009), p. 16

[23] Cf. Raven Ridge Resources, Inc. (1998), p. 3

[24] Cf. Lord, A.S. (2009), p. 17

[25] Cf. Lord, A.S. (2009), p. 18

**$H_2$ UGS in Teesside, UK**

Near Teesside, UK, three salt caverns are used to store pure hydrogen. The caverns are at a depth of 400 m and can store 1 million $m^3$ of hydrogen at 50 bar, with the gas mixture consisting of 95 % hydrogen and 3-4 % $CO_2$[26]. The salt caverns have an elliptical shape and are located in the upper premium[27].

**$H_2$ UGS in the Gulf of Mexico region in the U.S.A.**

Three caverns in the Gulf of Mexico region in the U.S.A. are currently operating (see Figure 4).

The ConocoPhillips operated storage is used for hydrogen storage since 1986[28] and is working at pressures between 70 and 135 bar. The salt cavern is located at a depth of about 850 to 1150 meters and possesses a storage volume of 580 000 $m^3$ [29].

In 2007 Praxair's cavern storage became operational and is connected to Praxair's hydrogen pipeline network[30]. It is working at pressures between 76 and 134 bar, located at depth of about 820 to 1400 m with a diameter of roughly 60 m and has a storage volume of 570 000 $m^3$ [31].

The Air Liquide hydrogen storage project has a working gas volume of 85 $10^6$ $m^3$ with a 16 inch diameter well completed at 1646 m[32].

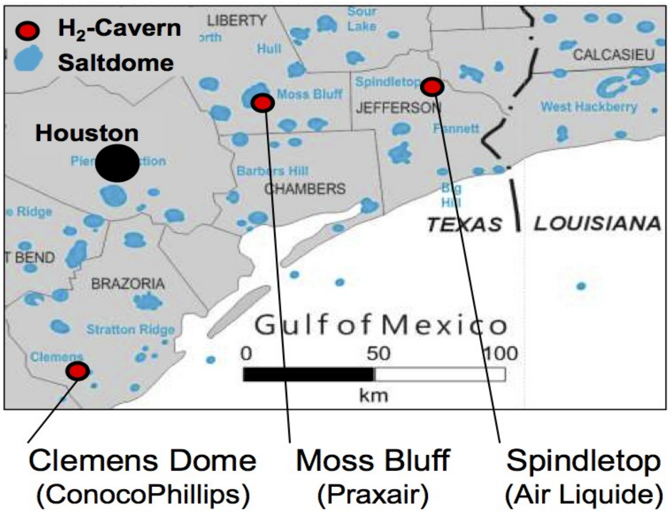


**Figure 4: Hydrogen UGS caverns at the U.S. Gulf of Mexico region[33]**

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[26] Cf. Panfilov, M. (2010), p. 842

[27] Cf. Schmitz, S. (2013), pp. 4, Access 29.05.2014

[28] Cf. Krause & Müller-Syring (2014), p. 14

[29] Cf. Schmitz, S. (2013), p. 9, Access 21.07.2014

[30] Cf. Praxair, Inc. (2007), Access 21.07.2014

[31] Cf. Schmitz, S. (2013), p. 13, Access 21.07.2014

[32] Cf. Parsons Brinckerhoff (2014), Access 21.07.2014

[33] Kruck, O. & Albes, D. (2012), p. 13, Access 21.07.2014

**$H_2$ UGS in Russia**

The Yakshunovskoe UGS stores mixtures of hydrogen and methane[34]. Also cavern storages for pure hydrogen, operating at 90 bar, are existent[35].

**Town gas**

Town gas, a hydrogen-carbonic gas mixture containing 50-60 % hydrogen, 15-20 % CO2 + CO, 10-20 % CH4 and small amounts of nitrogen, was stored in multiple underground storages in the past[36]. Also mentioned are that small amounts of oxygen were present in town gas[37].

Town gas storages were operating in Germany, France, Belgium, Czechoslovakia, Poland and the U.S.A.[38]. For three town gas UGS more detailed data have been found[39]:

- UGS Kiel: This UGS is located in Kiel in the north of Germany. It is a salt cavern UGS operating at 80-100 bar with a volume of 32 000 $m^3$ and a 62 % hydrogen concentration.
- UGS Lobodice: Located in today’s Czech Republic, approximately 220 km east of Prague and this aquifer UGS had a 50 % hydrogen content in the stored gas mixture.
- UGS Beynes: Located in France, roughly 20 km west of Versailles this aquifer UGS contained a 50 % hydrogen content gas mixture.

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34 Basniev, K.S. et al. (2010), p. 49

35 Cf. Schmitz, S. (2013), p. 17, Access 21.07.2014

36 Cf. Panfilov, M. (2010), p. 843

37 Cf. DVGW (2013), p. 51

38 Cf. DVGW (2013), p. 54

39 Cf. Panfilov et al. (2006), p. 2

## 2.4 Underground Storage for the Underground Sun Storage project

In the Underground Sun Storage project a depleted gas reservoir (porous medium) was chosen as the storage alternative. The depleted gas reservoir Lehen, which is near Vöcklabruck and operated by RAG, has the following properties:

- It is located at a depth of 1070 m subsurface (true vertical depth)
- The initial pressure of the reservoir was 107 bar
- The original gas in place was 5.5 million norm cubic meters and 4.4 million norm cubic meters have been produced leading to a present pressure of 32 bar.
- An average permeability of 600 mD is present in the reservoir with a reservoir thickness of 1.5 m.
- The average temperature in the reservoir is 39 °C

### 2.4.1 Planned surface facilities in the project Underground Sun Storage

The surface facilities planned for the Underground Sun Storage project can be seen in Figure 5. This plan was presented at the second stakeholder workshop on 21 November 2014 of the Underground Sun Storage project by Pichler, M.[40]. There are some differences to the regular UGS system. For underground hydrogen storage part of the gas conditioning is the separation of methane and hydrogen with membrane separators, a part of the project done by AXIOM within WP 6 (see Figure 2).

Also a well providing the needed water and solar panels for power generation are planned. The water and generated power is then used to generate hydrogen via electrolysis.

Additionally a test column will be constructed for testing different materials concerning their resistance and durability against hydrogen.

[40] Pichler, M. (2014), p. 9

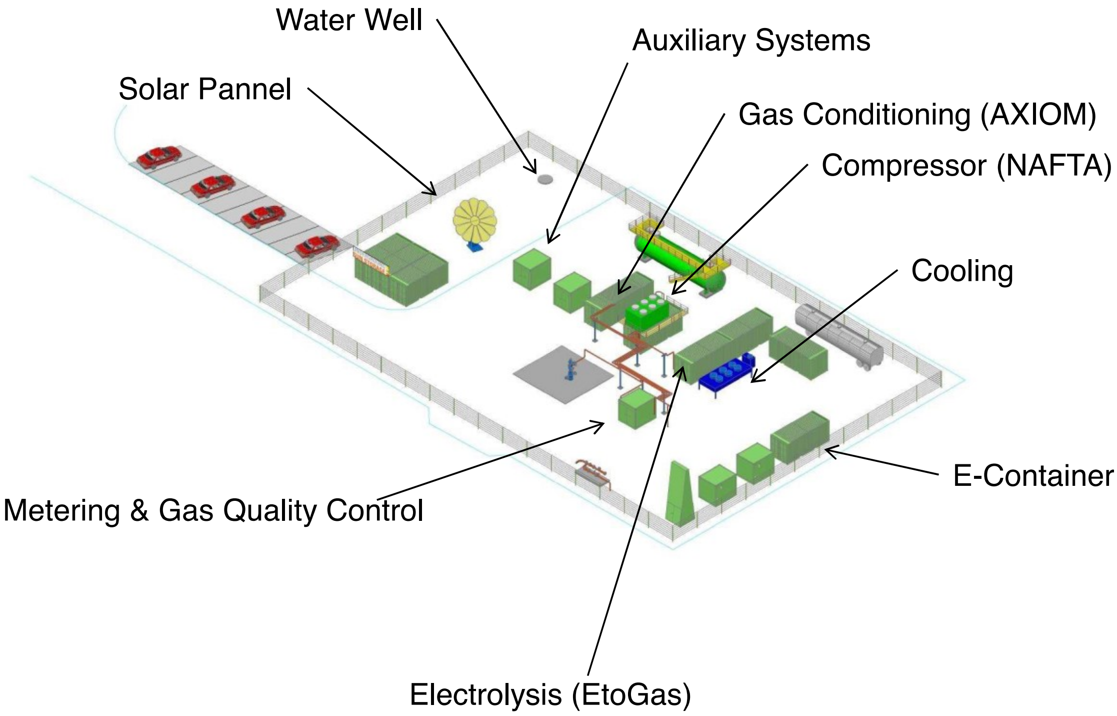


**Figure 5: Planned surface facilities for the project Underground Sun Storage[41]**

### 2.4.2 Planned completion for the Underground Sun Storage project

At the second stakeholder workshop on 21 November 2014 Pichler, M., presented the final planned completion for the Underground Sun Storage well Lehen (see Figure 6). It consists of a cemented casing, a tapered production string, starting with 3-½ inch and ending with 2-⅜ inch tubing. At 1150 m measured depth (MD) the casing and cement is perforated, thus allowing for injection and production of the reservoir through the perforations. Also a SSSV is installed and the hydraulic operation line for the SSSV is marked in Figure 6.

[41] Pichler, M. (2013), p. 9

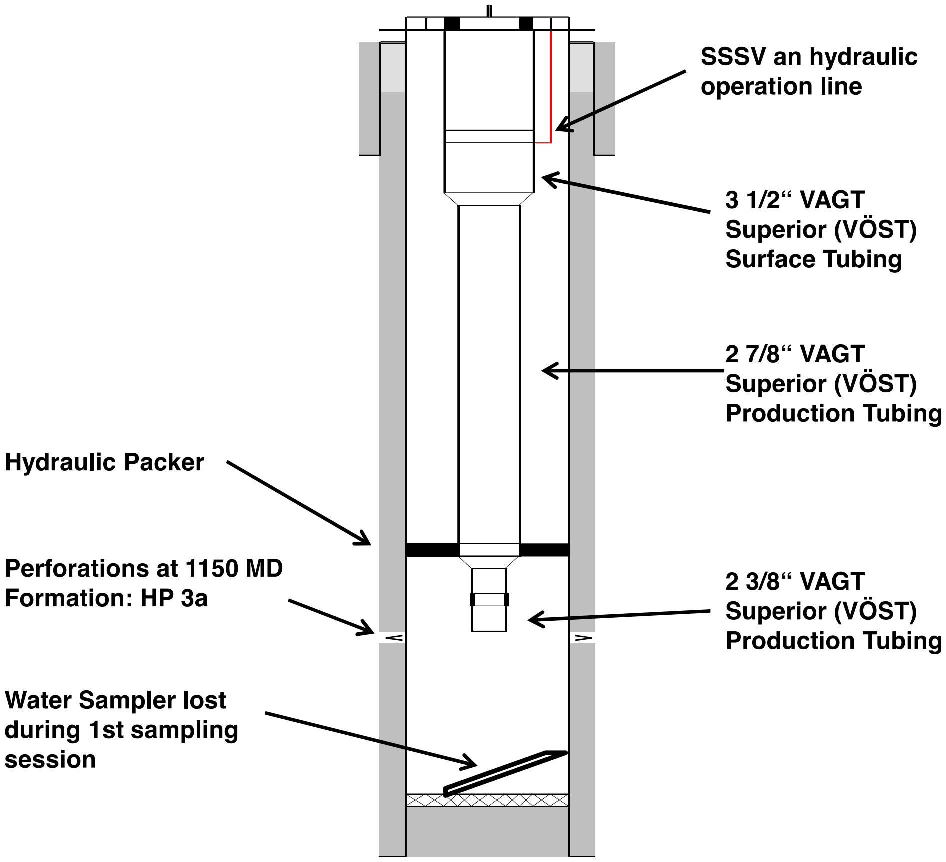


**Figure 6: Planned completion for the Underground Sun Storage well Lehen II[42]**

# 3 Safety and risk aspects

In this section safety and risk aspects are addressed. Because the project is so unique and limited experience exists for the storage of hydrogen-methane mixtures in the subsurface, only general safety and risk aspects concerning hydrogen can be addressed. A look into different industries is included (e.g. handling of hydrogen by NASA regarding valves) to mitigate the lack of knowledge of the safety and risk properties of hydrogen in underground gas storage systems. The aspects have been split into aboveground and underground and are discussed separately.

[42] Pichler, M. (2014), p. 12

## 3.1 Aboveground

### 3.1.1 Ignition and flame properties of $H_2$ mixtures

Within the project NATURALHY[43] safety aspects of the pipeline network have been evaluated depending on the hydrogen content of the fluid mixture. The safety risks associated with the fire behavior of a fluid leaking out of a high-pressure pipeline are rated lower for the hydrogen-natural gas mixture than for the pure natural gas. The reasons for this are the reduced energy content of the hydrogen-natural gas mixture and the therefore shorter flame length[44].

Safety risks regarding the power of explosions and the flame velocities have also been investigated within the NATURALHY project. It was found that in general the addition of hydrogen to the fluid increases the power of the explosion. Below 10 vol.-% this effect is very weak, but above 40 vol.-% the impact of the explosion increases strongly and also the risk for a detonation is rising with higher hydrogen concentrations. Tests with bottlenecks and obstacles for the fluid flow showed that they could increase flame velocities[45].

Another important effect is the difference in the upper explosive limit for hydrogen and natural gas. Hydrogen shows a much higher upper explosive limit with 77 mol-% than methane with 16.5 vol.-%[46]. This creates a wider ignition range for hydrogen-natural gas mixtures and for pure natural gas.

Table 2 shows the safety rankings for methane and hydrogen for specific characteristics. The ignition limit for hydrogen is ranked as less safe than the ignition limits for methane because of the wider ignition range for hydrogen. Hydrogen also has a very low ignition energy compared to methane and also the flame temperature is slightly higher with 585°C compared to 540°C for methane[47].

[43] Cf. DBI (2014), Access 1.7.2014

[44] Cf. DVGW (2013), p. 87

[45] Cf. DVGW (2013), p. 86

[46] Cf. Hattwig, E. & Stehen, H. (2004), p. 281

[47] Cf. Science Applications International Corporation (2003), p. 9

| Characteristic | Fuel ranking | |
|---|---|---|
| | Methane | Hydrogen |
| **Specific Heat** | 2 | 1 |
| **Ignition Limit** | 2 | 3 |
| **Ignition Energy** | 1 | 3 |
| **Ignition Temperature** | 2 | 1 |
| **Flame Temperature** | 1 | 2 |
| **Explosion Energy** | 2 | 1 |
| **Flame Emissivity** | 2 | 1 |

**Table 2: Safety ranking of methane and hydrogen (adjusted)[48]. (1 – safest, 2 – less safe, 3 – least safe)**

### 3.1.2 Surface equipment considerations

Surface equipment like pipelines, valves, seals, compressors or gas detection systems are subject to exposure to hydrogen when they are used in hydrogen UGS systems.

Safety relevant gas detection systems are still usable as long as the main component of the fluid mixture is still natural gas[68]. For many pieces of surface equipment investigations have already been conducted. All of these parts (to my knowledge) are listed:

**Valves**

Concerning the connection of high-pressure systems and low-pressure systems (e.g. the pressure reduction station) NASA states that "*pressure-regulating valves, shutoff valves and check valves do not adequately protect low-pressure systems connected to high-pressure systems*"[49]. NASA then also claims in this report that the hydrogen supply has to be disconnected if pressure differences are too high. It is not clear whether or not such a design feature is already implemented in pressure reduction stations in underground gas storage systems. In the context of valves Altfeld[50] stated that the comparably low density of hydrogen causes a decreased mass flow rate through a small opening compared to pure methane. However, although the energetic losses are smaller for hydrogen leaks, volumetric losses of hydrogen are larger compared to methane[51].

As far as the valve-material sensitivity to hydrogen is concerned, only ball valve seals made from X20 Cr13 can be problematic, but no negative effects are expected for hydrogen concentrations of 10 % or lower[52].

[48] Science Applications International Corporation (2003), p. 13

[49] NASA (1997), p. 5-37

[50] Cf. Altfeld, K. (2013), p. 6

[51] Cf.  Haeseldonckx & D'haeseleer (2006), p. 1383

[52] Cf. Altfeld, K. (2013), p. 5

**Compressors**

Altfeld[52] investigated the materials used in compressors and stated that they are not sensitive to hydrogen.

**Filters**

Regarding filters NASA[53] stated that they should not be made of sintered metal and recommends using filters made of non-calendered woven wire meshes.

**Seals**

Seals and connections did prove to be chemically stable when they were used in town gas operations. Nevertheless, further research is recommended by DBI on hydrogen concentration limits for components like valves or seals[54].

Altfeld[52] concludes that the increased permeation rate through seals due to hydrogen is not troubling and that a 10 % hydrogen concentration in natural gas is tolerable.

Because not all of the possible surface equipment has been covered so far a closer look at elastomers and metals (especially steels) is warranted, because these materials are often the used in surface and subsurface equipment:

**Metals**

Hydrogen embrittlement is a major issue aboveground and underground. Hydrogen embrittlement describes "*a variety of effects of hydrogen on the physical and mechanical properties of metals*"[55]. Foh et al. [56] and DGMK 752[57] both mention that the terms describing the failure mode due to hydrogen are not used consistently in all studies. Foh[56] also goes on to describe failures due to hydrogen like blistering and hydrogen stress cracking as effects of hydrogen embrittlement, whereas DGMK 752[57] describes these kind of failures as separate effects and mentions effects caused by hydrogen embrittlement additionally. In DGMK 752[57] hydrogen embrittlement is described as a failure mode existing in three different forms: lagged failure, reduced plasticity and brittleness[56,58]. Therefore care has to be taken when only the term "hydrogen embrittlement" is mentioned without description of what the author exactly means with this expression.

Regardless of the source of information, it is clear that the presence of hydrogen can possibly lead to various types of failure in steels and are a function of multiple parameters[59]:

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[53] Cf. NASA (1997), p. 5-37

[54] Cf. DBI (2013), p. 23

[55] Foh, S. et al. (1979), p. 69

[56] Cf. Foh, S. et al. (1979), p. 70

[57] Cf. DGMK (2014), p. 23

[58] Cf. DGMK (2014), p. 24

[59] DGMK (2014), p. 23

- Pressure: Higher hydrogen pressures lead to higher brittleness of the material. Starting at a pressure of 50 bar major losses of ductility occur[60].
- Temperature
- Hydrogen concentration
- Stress state
- Metal composition
- Tensile strength
- Grain size
- Micro-structure
- Type of impurities in the structure
- Heat treatment

DGMK 752 states that steels are especially prone to hydrogen induced cracking (HIC), stress oriented hydrogen induced cracking (SOHIC), blistering and fractures induced from absorption of atomic hydrogen. But with the exception of high-strength steels all currently operating equipment should be able to handle hydrogen concentrations below 10 vol.-%[61].

They also noted that whereas hydrogen embrittlement occurs at lower temperatures, blistering and fracturing occurs at higher temperatures and pressures (>200°C, >100 bar)[62]. It is important to indicate here again that DGMK 752[63] mentions hydrogen embrittlement as a separate failure mode, whereas Foh et al.[64] describe hydrogen embrittlement as the cause for the other failures modes. As far as carbon steels go, DGMK 752[65] states that carbon steels with strength below 800 MPa show more resistance to hydrogen embrittlement than high-grade steels with more than 0.3 % carbon.

In API RP 941 operating limits for steels under hydrogen influence at elevated temperatures can be found. Carbon steels show a much smaller operating window than CrMo steels, as can be seen in Figure A 1[66] in Appendix A: Supplementary Tables and Figures.

Within the NATURALHY project it was found that the steel-pipelines already in place are capable of dealing with mixtures containing up to 30 vol.-% of hydrogen[67]. Also ductile

[60] Cf. Batisse, R. (2013), p. 12

[61] Cf. DGMK (2014), p. 34 & 35

[62] Cf. DGMK (2014), p. 27

[63] DGMK (2014)

[64] Foh et al. (1979)

[65] Cf. DGMK (2014), p. 31

[66] API (2008), API RP 941, p Figures-3

[67] Cf. DVGW (2013), p. 44

cast iron pipelines that were used for town gas did not appear to have problems with hydrogen, although they reached hydrogen contents of more than 50 vol.-%[68].

Batisse[69] investigated the influence of hydrogen on pipeline steels and summarized that there is a decrease in toughness, a loss of ductility and accelerated crack growth in pipeline steels[70]. Batisse recommends limiting the hydrogen pressure to 20 bars in pipelines operating at a maximum pressure of 85 bars with a factor loading of 0.73. This results in a 17 % - 21 % hydrogen concentration[70].

**Elastomers**

Elastomers, e.g. used in seals or packers, are extensively used in UGS systems. Tests with pure hydrogen under pressure and temperature conditions similar to UGS conditions have been conducted. It was found that also in elastomers blister-fractures could appear, when hydrogen under high pressure is absorbed into the elastomer and released under an abruptly decreasing pressure[71]. The occurrence of damages in the elastomers is depending on the hydrogen concentration in the fluid mixture and for low concentrations of hydrogen no material failures on the elastomers are to be expected[72]. These results are in line with the analysis of Altfeld[73] who investigated the $H_2$ sensitivity of seals, valves and compressors within the GERG project[74].

[68] Cf. DBI (2012), p. 19

[69] Batisse, R. (2013)

[70] Cf. Batisse, R. (2013), p. 30

[71] Cf. DGMK (2014), p. 37

[72] Cf. DGMK (2014), p. 40 & 41

[73] Altfeld, K. (2013)

[74] Cf. Altfeld, K. (2013), p. 3

## 3.2 Underground

### 3.2.1 Geochemical reactions

The loss of hydrogen due to geochemical reactions and the potential for the generation of toxic gas is a concern. Foh et al.[75] studied these reactions at assumed reservoir conditions of 298 K (24.85 °C) and 2000 psi (137.9 bar) and concluded that only oxygen, $Fe_2O_3$ and sulfur could react with hydrogen. Foh et al.[76] found following three possible chemical reactions:

- $H_2 + O2 \rightarrow H_2O$
- $H_2 + S \rightarrow H_2S$
- $H_2 + 3\ Fe_2O_3 \rightarrow 2\ Fe_3O_4 + H_2O$

However, temperatures above the assumed reservoir temperature or catalysts are necessary for the reaction[76].

Nagy[77] and Pichler[78] stated additional possible reactions of injected hydrogen or oxygen with pyrite ($FeS_2$), which is a common mineral in UGS reservoirs[79,80]:

- $FeS_2 + 3.5\ O_2 + H_2O \rightarrow Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+$
- $FeS_2 + 3.75\ O_2 + 3.5\ H_2O \rightarrow Fe(OH)_3 + 2\ SO_4^{2-} + 4\ H^+$
- $FeS_2 + H_2SO_4 + H_2 \rightarrow FeSO_4 + 2\ H_2S$

The first two chemical equations require oxidizing conditions in the reservoir, which are not present as long as no oxygen is injected. Also the third chemical reaction does not represent a major threat of $H_2S$ generation, because even at temperatures above 90 °C the reaction is very slow[81].

The introduction of hydrogen into the reservoir fluid very likely results in a decrease in the pH-values. These reduced pH-conditions induce dissolution of e.g. calcite but other minerals like illite will be precipitated[82]. However, Pichler[78] concluded that hydrogen changes the pH-conditions into the alkaline direction, which leads to dissolution of dolomite and precipitation of calcite. As mentioned later in this thesis also the preliminary results of WP 2 show that the pH-value is increasing due to the presence of hydrogen (see 5.7.1 WP 2 Geochemistry and Reactive Transportmodelling).

[75] Foh et al. (1979)

[76] Cf. Foh et al. (1979), p. 79

[77] Nagy, A. (2008)

[78] Pichler, M. (2013)

[79] Pichler, M. (2013), p. 48

[80] Nagy, A. (2008), p. 6 & 16

[81] Cf. Pichler, M (2013), p. 89 & 49

[82] Cf. Pudlo, et al (2013), p. 398

### 3.2.2 Microbial considerations

Bacteria in the subsurface, either already in there before the storage activities or introduced by storage activities, have multiple effects. A table of potential respiration processes due to bacteria can be seen in Table 3. Bacterial effects represent major problems and are considered to be the main concern for hydrogen underground storage, because bacterial effects "are very difficult to identify and to number in situ"[83].

There is a possibility that $H_2S$ is formed using the injected hydrogen and sulfates in the formation water. $H_2S$ is highly toxic and facilitates corrosion of steel. The DGMK 752[84] report also mentions plugging of the near wellbore area or gravel packs can occur by the accumulation of bacteria or bacterial induced precipitation of iron sulfides.

Bacteria also can form acetic acid ($CH_3COOH$) from hydrogen and carbon dioxide by homoacetogenes.

Another possibility is the generation of methane by bacteria from carbon monoxide, carbon dioxide and hydrogen. This generation of methane by bacteria was observed in town gas operations[85]. In Lobodice and Beynes the composition of the gas mixture changed from initially 55 % hydrogen, 20 % $CO+CO_2$ and 20 % $CH_4$ to 37 % $H_2$, 12 % $CO+CO_2$ and 40 % $CH_4$[86]. This reaction is made possible by methanogenic bacteria, which are anaerobic bacteria and highly active at typical UGS conditions (100 bar, 35°C). The process of methane generation results in a reduced reservoir pressure due to the decrease in number of moles during the reaction and the conversion of gas phase into liquid phase[87].

In DGMK 756[88] also mentioned are the consumption of the hydrogen, energetic losses in the process, the accumulation of biomass, reductions in permeability and resulting changes in flow paths and dissolution and precipitation (e.g. illite) of rocks.

Increasing temperatures due to microbiological processes have been observed in town gas operations[88].

Another effect of bacteria in hydrogen UGS has been investigated by Panfilov[89,90]. Numerical analysis regarding temporal and spatial variations of methane and $CO_2$ content in the underground hydrogen storage has been conducted. Oscillations of the population size of the methanogenic bacteria in the time domain have been found. These temporal

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[83] Nadau, L. (2013), p. 24

[84] Cf. DVGW (2014), p. 49

[85] Cf. DGMK (2014), p. 60

[86] Cf. Panfilov. et al. (2006), p. 3

[87] Cf. Panfilov, M. (2010), p. 845

[88] Cf. DGMK (2013), p. 60 & 61

[89] Panfilov et al. (2006)

[90] Panfilov, M. (2010)

variations are caused by a cycle of nutrient abundance resulting in bacterial growth followed by nutrient shortage resulting in a declining bacterial population, at which point nutrient abundance emerges again. Also in the spatial domain oscillations occur due to the different diffusivities of bacteria and nutrient. This causes instabilities that eventually stabilize (stationary wave) and results in regions of the reservoir that are rich in $CO_2$ or $CH_4$[91].

To reduce the impact of bacteria in the underground hydrogen storage disinfectant experiments have been conducted from 1970 to 1973 but did not show promising results and can therefore not be considered as suitable[92]. Another possible solution to the bacterial problem could be the separation of hydrogen from the natural gas before injection into the UGS and to store it separately. Before re-injection into the pipeline network these two gases are then mixed again. This approach has been investigated in the NATURALHY project, but was regarded as problematic and costly[93].

Detailed studies regarding the microbiological phenomena can be found in DGMK 756[94].

| Reaction | | Free Energy (kJ/mol H2) | Microbial group and representatives |
|---|---|---|---|
| $2\ H_2 + O_2$ | $2\ H_2O$ | -238 | Aerobe H2-usage |
| $5\ H_2 + 2\ NO_3^- + 2\ H^+$ | $N_2 + 6\ H_20$ | -224 | Nitrate reducers<br>Paracoccus denitrificans |
| $H_2 + MnO_2$ | $Mn(OH)_2$ | -163 | Manganese reducers |
| $4\ H_2 + NO_3^- + 2\ H^+$ | $NH_4^+ + 3\ H_2O$ | -150 | Nitrate reducers |
| $H_2$ + Fumarate | Succinate | -86 | Fumarate-reducer |
| $H_2$ + Caffeate | Hydrocaffeate | -85 | Acetobacterium woodii |
| $H_2 + 2\ Fe(OH)_3$ | $2\ Fe(OH)_2 + 2\ H_2O$ | -50 | Iron reducers<br>Alteromonas putrefaciens |
| $4\ H_2 + SO_4^{2-} + 2\ H^+$ | $H_2S + 4\ H_2O$ | -38 | Sulphate reducing prokaryotes<br>Desulfovibrio vulgaris |
| $4\ H_2 + HCO_3^-$ | $CH_4 + 3H_2O$ | -34 | Methanogens<br>Methanosarcina barkeri |
| $H_2 + S^0$ | $HS^- + H^+$ | -28 | Sulphur reducers |

[91] Cf. Panfilov, M. (2010), p. 861

[92] Cf. Nadau, L. (2013), p. 21

[93] Cf. Altfeld & Pinchbeck (2013), p. 10

[94] DGMK (2013)

| | | | |
|---|---|---|---|
| | | | Desulfuromonas |
| $4\ H_2 + 2\ HCO_3^- + H^+$ | $CH_3COO^- + 4\ H_2O$ | +26 | Homoacetogenes<br>Acetobacterium woodii |
| $H_2 + SeO_4^{2-}$ | $SeO_3^{2-} + H_2O$ | -172 | Selenate reducers<br>Sulfurospirillum barnesii |
| $H_2 + AsO_4^{3-}$ | $AsO_3^{3-} + H_2O$ | -108 | Arsenate reducers<br>Sulfurospirillum barnesii |
| $4\ H_2 + S_2O_3^{2-} + 2\ H^+$ | $2\ H_2S^- + 3\ H_2O$ | -44 | Thiosuphate reducers<br>Sulfurospirillum deleyianum |
| $N_2 + 16\ ATP + 8\ H^+ + 8\ e^-$ | $2\ NH_3 + H_2 + 16\ ADP + 16\ P_i$ | | Nitrogen fixation in sulphate reducing prokaryotes / Archaea |

**Table 3 Potential types of respiration in underground $H_2$-storages[95]**

### 3.2.3 Reservoir seal integrity

Reservoir seal integrity is a very important issue when considering underground hydrogen storage. The capillary entry pressure for gas to enter the water-saturated caprock hinders the gas to leave the reservoir through the top reservoir seal.

During storage operations the pressure inside the reservoir is varying, which can lead to changes in the subsurface stress-field. Resulting from these changes the reservoir caprock become more permeable and fractures could form. Storage-induced gas leakage (from newly created fractures and increased permeabilities of the caprock), storage-activated gas leakage (reactivation of pre-existing leakage paths) and tectonic failure gas leakage paths are identified[96,97] (see Figure 7). Also salt properties are subject to change when the stress-field is changing and the once-sealing salt structure could become more permeable[98].

A distinct characteristic of introducing hydrogen into the system is the high chemical reactivity of hydrogen, which could result in chemical reactions with minerals of the caprock, but the effects on reservoir seal integrity are not fully known yet[99]. However, a

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[95] DGMK (2013), p. 58

[96] Cf. DGMK (2014), p. 43

[97] Jimenez, J. & Chalaturnyk, R. (2002), p. 9

[98] Cf. Lord, A.S. (2009), p. 21

[99] Cf. DGMK (2013), p. 44

chemical reaction is considered to be unlikely because reservoir temperatures are too low[98].

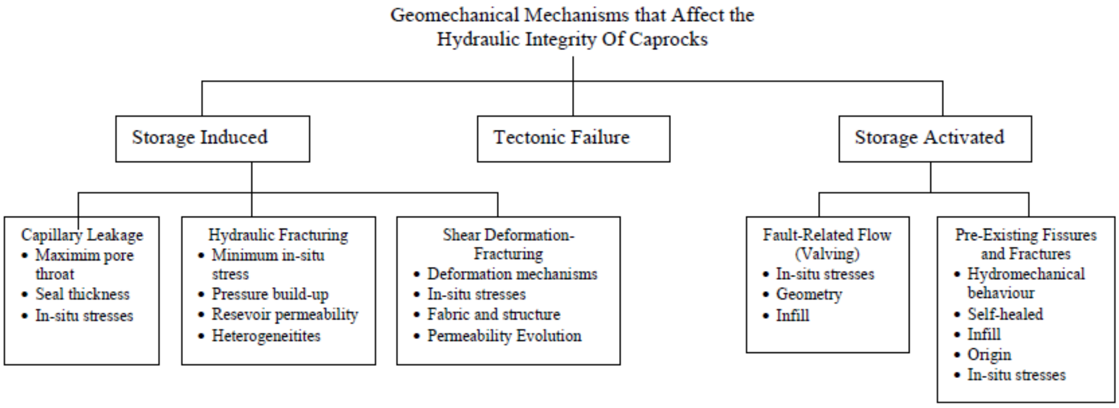


**Figure 7: Geomechanical Mechanisms affecting the hydraulic integrity of caprocks[97]**

In case a path for gas leakage is present, the existence of hydrogen in the reservoir increases the risk that gas is leaking because it has a much higher mobility than natural gas[100].

In case of depleted reservoir and aquifer type UGS systems diffusion of hydrogen through the caprock could also lead to significant losses of hydrogen. However, because of the steadily reducing concentration gradient of hydrogen in the caprock this reaction will slow down over the course of the operation of a hydrogen UGS[101].

### 3.2.4 Cement integrity

Cement integrity is essential because the cement presents a seal of the wellbore against the surrounding formation. Figure 9 shows possible leakage paths in a wellbore. This figure is taken from a study regarding $CO_2$ storage. However, the leakage paths, except for (b), are valid for hydrogen UGS in existing natural gas UGSs. The cement plug for leakage path (b) is in operational UGS wells not present, and therefore this is not a valid leakage path[102].

Generally, the two mechanisms responsible for flow in a porous medium are a) viscous flow and b) diffusion.

- **a) Viscous flow**: The viscous flow of a fluid is dependent on the pressure gradient and the viscosity of the fluid. The dynamic viscosity of hydrogen at 20 MPa and 50 °C is with 0.00935 mPa*s roughly half the dynamic viscosity of methane[103]. If the viscous flow is described by Darcy's law, a constitutive equation

[100] Cf. Lord, A.S. (2009), p. 22

[101] Cf. DGMK (2013), p. 45 & 46

[102] Cf. DGMK (2013), p. 13

[103] Cf. DGMK (2014), p. 18

describing flow of a fluid through a porous medium, the determined flow rate for a 50 % decreased viscosity is increased by 50 %. A 10 vol.-% hydrogen concentration in methane would reduce the dynamic viscosity and increase the potential leakage rate only by about 5 %, which is not critical. For hydrogen concentrations much higher than 10 % also much higher gas leakage rates have to be expected, which could potentially be critical[103].

- **b) Diffusion:** The diffusion of a fluid (e.g. described by Fick's law) is dependent on concentration gradients and the diffusivity of the fluid. Gluth et al.[104] published experimental results of multicomponent gas diffusion in hardened cements. They determined diffusivity coefficients for various cements and different temperatures. The resulting diffusion coefficients versus temperature can be seen in Figure 8a and 8b. (A) is Portland cement (PC) 2 plus Silica fume (SF) with a water to binding material ratio of 0.25. (B) is Microfine binder (MF) with a water to binding material ratio of 0.3[105]. It can be clearly seen that the diffusion is strongly temperature dependent and increases with increasing temperatures and that the diffusivity of hydrogen is generally higher than the diffusivity of $CO_2$ or $N_2$.

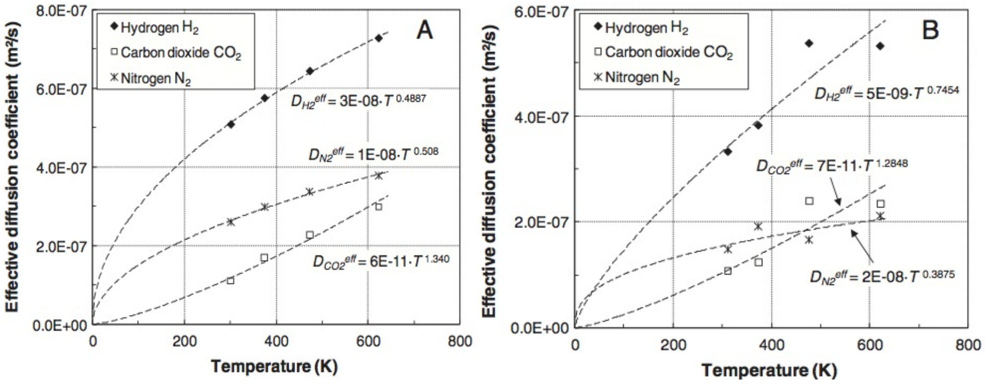


**Figure 8a and 8b: Plot of effective diffusion coefficients versus temperature for (A) membrane PC2 + SF (0.25), and (B) membrane MF (0.30)[106].**

Other possible risks include the possible biochemical (see 3.2.2) and geochemical reactions (see 3.2.1) involving hydrogen that could possibly alter the sealing properties of the cement in a negative way. Experiences with direct influence of hydrogen on cements have been gained during research for permanent disposal sites of nuclear waste. The metal corrosion generated hydrogen can be viewed as an inert gas and therefore the influence of hydrogen on the cement was found to be minor[107]. Care has to be taken with

[104] Gluth et al. (2012)

[105] Gluth et al. (2012), p. 658

[106] Gluth et al. (2012), p. 662

[107] Cf. DGMK (2014), p. 19 & 20

these findings, because the pressure and temperature conditions for permanent disposal sites of nuclear waste and hydrogen UGSs cannot automatically assumed to be similar.

To alleviate the problem of gas leakage through micro-cracks in the cement of UGS wells, the use of the right amount of synthetic rubber, depending on temperature and confining pressure, could be beneficial. This could make a completely tight annulus feasible as the synthetic rubber dampens pressure changes during the setting of the cement and thereby prohibits micro-cracks[108].

Additionally DGMK 752[109] suggests using cement with low $SiO_2$ concentration, low fractions of water and fine-grained cement.

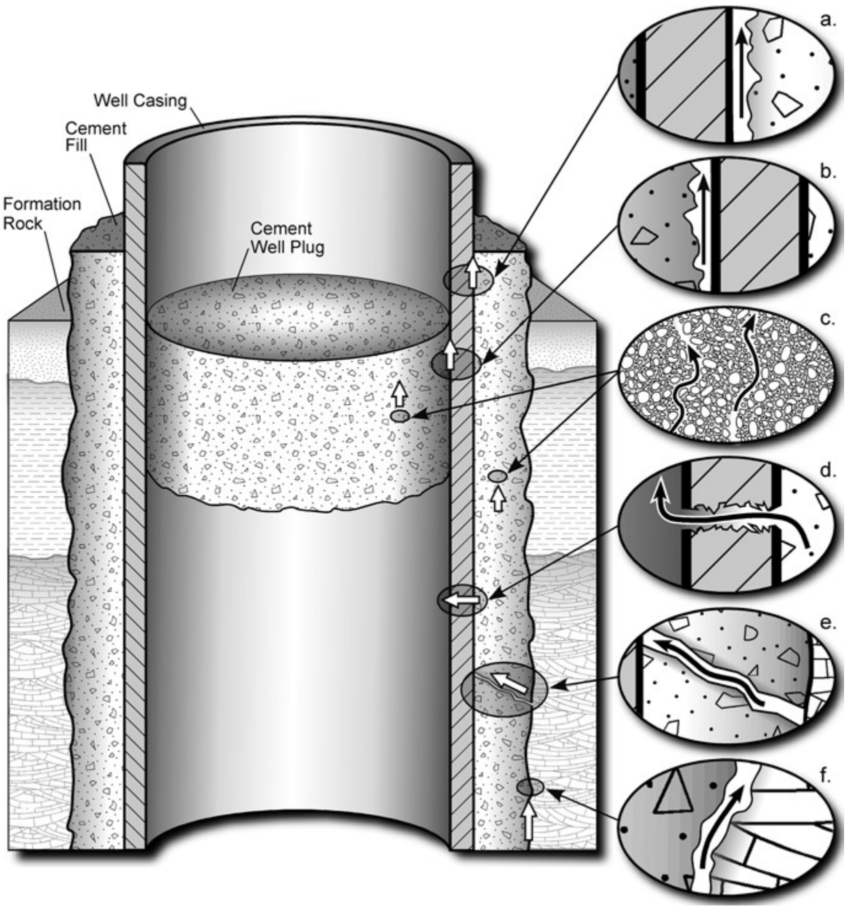


**Figure 9: Possible leakage paths in a wellbore. (a) between casing and cement, (b) between the cement plug and casing (not present in UGS wells), (c) leakage through the cement, (d) through the casing (corrosion), (e) through cement fractures, (f) through conduits between cement and rock[110]**

[108] Talabani, S. & Hareland, G. (1995), p. 280

[109] Cf. DGMK (2014), p. 71

[110] Gasda, S et al (2004), p. 709

### 3.2.5 $H_2$ influence on downhole equipment

Downhole equipment like packers, tubing and travel joints would also be exposed to the hydrogen – natural gas mixture. Many of the components are made of steel and elastomers. The aspects discussed in 3.1.2 are also valid for the downhole equipment and therefore not discussed again at this point. Of special importance for downhole equipment steels is the use of high strength steels used in the subsurface equipment of UGS wells, because high strength steels are more sensitive to hydrogen embrittlement than other used steels in the UGS system[111].

Concerning valves, like a SSSV, it should be noted that also hear a potential gas leakage can be expected to have a higher flow-rate compared to methane because of the increased diffusion and reduced viscosity.

Generally sealing tests for hydrogen-methane gas mixtures for all used cements, metals and seals are still necessary and leakage threshold values could potentially have to be adapted[112].

### 3.2.6 Solubility of hydrogen in water

The solubility of hydrogen in water could potentially also be an important factor. The solubility of hydrogen in water is mostly an economic problem, but it is not clear whether the solubility of hydrogen in water can also lead to hydrogen leaving the storage system, which would then also be a safety risk. According to experimental data the solubility of hydrogen is a linear function of pressure. The experiments have been conducted in in the range of -51.6 °C – 343.3 °C[113] (125 °F – 650 °F) (Figure 10). These results match the expectations about solubility according to Henry's law, which makes it reasonable to use Henry's law constants for solubility calculations within this temperature range. It can be seen that at higher temperatures the slope of the solubility is generally higher than at lower temperatures.

[111] Cf. DGMK (2014), p. 23

[112] Cf. DGMK (2014), p. 11

[113] Cf. Pray et al. (1950), p. 7

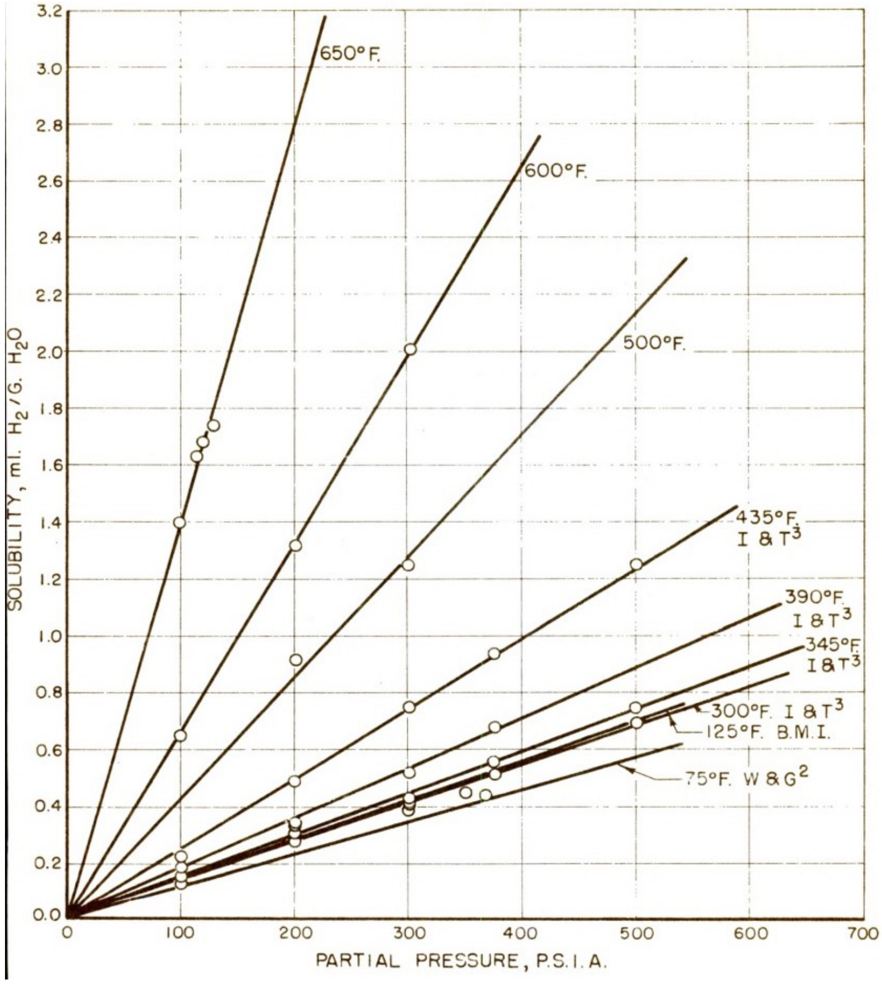


**Figure 10: Solubility of hydrogen in water vs partial pressure of hydrogen[114]**

[114] Pray et al. (1950), p. 20

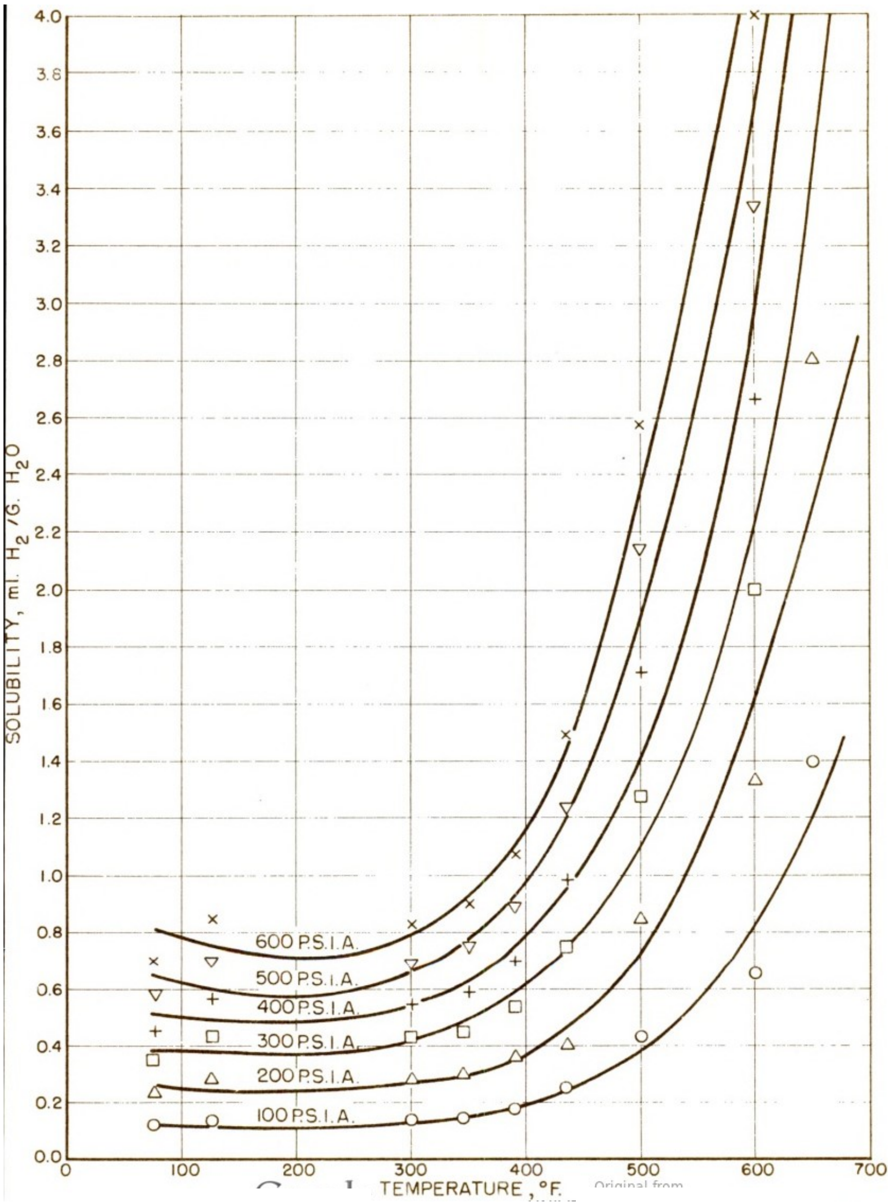


**Figure 11: Solubility of hydrogen in water vs temperature[115]**

The results of the experiments of Pray et al. (1950) show that for the range of -6.7 °C to 93 °C (20 °F – 200 F) the solubility of hydrogen decreases with increasing temperature (Figure 11). However, according to Kaye & Laby[116] the solubility of methane is 0.0023 g/100 g water compared to 0.0016 g/100 g water for hydrogen, when the total pressure of the solution is at 1 atm. Pichler[117] mentioned that the losses are expected to be minor, but repeated contact of the storage gas with non-saturated fluids (e.g. active aquifer) could lead to increased losses through this process of solubility.

[115] Pray et al. (1950), p. 22

[116] Cf. Kaye, G.W.C. & Laby, T.H. (1986), p. 219

[117] Pichler, M. (2013), p. 23

# 4 Risk assessment approaches

Risk assessment is "*that part of risk management which provides a structured process that identifies how objects may be affected, and analyses the risk (…) before deciding on whether further treatment is required*"[118]. To analyze risks it is necessary to determine probability and impact of a certain event.

Figure 12 shows a typical risk management workflow. The three parts of the risk assessment are:

- Risk identification
- Risk analysis
- Risk evaluation

It is crucial that the first part of risk assessment, risk identification, is as complete as possible, because not identified risks will not be part of the further steps and could potentially be significant.

Many different risk assessment methods exist and e.g. can be found in ISO 31010[119] or Preiss[120].

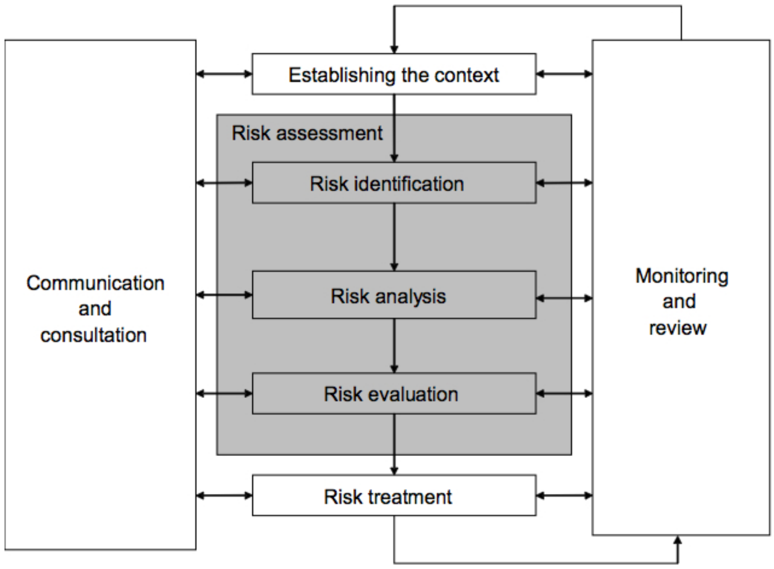


**Figure 12: Typical risk management workflow. In the grey area the risk assessment component can be identified[121]**

[118] IEC (2009), ISO 31010, p. 6

[119] IEC (2009); ISO 31010

[120] Preiss, R. (2009)

[121] IEC (2009), ISO 31010, p. 12

## 4.1 Risk assessment methods

To provide an overview of risk assessment methods, approaches from different sources are listed below, before a specific look at risk assessment methods in the oil and gas industry will be taken.

### 4.1.1 Risk assessment methods from ISO 31010

ISO 31010[122] provides a list of risk assessment methods, which are classified into categories:

- Look-up methods
  - Check-lists
  - Preliminary hazard analysis (PHA)
- Supporting Methods
  - Structured interview and brainstorming
  - Delphi technique
  - Structured what if technique (SWIFT)
  - Human reliability analysis (HRA)
- Scenario Analysis
  - Root cause analysis (single loss analysis) (RCA)
  - Scenario analysis
  - Toxicological risk assessment
  - Business impact analysis
  - Fault tree analysis (FTA)
  - Event tree analysis (ETA)
  - Cause / consequence analysis
  - Cause-and-effect analysis
- Function analysis
  - Failure mode and effect analysis (FMEA)
  - Reliability-centered maintenance
  - Sneak analysis (Sneak circuit analysis)
  - Hazard operability study (HAZOP)
  - Hazard analysis and critical control points (HACCP)
- Controls assessment
  - Layers of protection analysis (LOPA)
  - Bow-tie analysis
- Statistical methods
  - Markov analysis
  - Monte-Carlo analysis
  - Bayesian analysis

[122] IEC (2009), ISO 31010 p. 23-26

### 4.1.2 Other risk assessment methods

Risk assessment methods not included in the ISO 31010 have also been found in Preiss[123], Kröger[124] and IVSS[125]:

- 3-F method
- Functional Safety
- Relative risk ranking
- Wacker approach
- Zurich hazard analysis (ZHA)
- Master logic diagram (MLD)
- Fishbone diagrams
- DOW Fire & Explosion index
- TÜV NORD-method

## 4.2 Usage in the oil and gas industry

To get an overview over the presently used risk assessment approaches a look at the publications in onepetro.org regarding certain keywords has been taken.

Table 4 shows the keywords and found number of publications on onepetro.org for each keyword. Care has to be taken with certain keywords like "monte carlo analysis", because Monte Carlo simulations are used for various purposes and not exclusively risk assessment. The search options were modified to include only publications from 01.01.2009 to 01.07.2014.

The most used risk assessment methods will further be discussed in the next paragraphs. Additionally the Wacker analysis will be discussed, because this too is an important method used in Austria, although no publications on onepetro.org have been found.

| Keyword for onepetro.org search | Publications in onepetro.org since 2009 |
|---|---|
| Look-up methods | |
| Check-lists | 34 |
| Preliminary hazard analysis (PHA) | 17 |
| Supporting Methods | |
| Structured interview and brainstorming | 19 |
| Delphi technique | 69 |

123 Preiss, R. (2009)

124 Kröger, W. (2010)

125 IVSS (2012)

| | |
|---|---|
| Structured what if technique (SWIFT) | 2 |
| Human reliability analysis (HRA) | 12 |
| Scenario Analysis | |
| Root cause analysis (single loss analysis) (RCA) | 271 |
| Scenario analysis | 88 |
| Toxicological risk assessment | 0 |
| Business impact analysis | 4 |
| Fault tree analysis (FTA) | 80 |
| Event tree analysis (ETA) | 32 |
| Cause / consequence analysis | 7 |
| Cause-and-effect analysis | 12 |
| Function analysis | |
| Failure mode and effect analysis (FMEA) | 106 |
| Reliability-centered maintenance | 33 |
| Sneak analysis (Sneak circuit analysis) | 0 |
| Hazard operability study (HAZOP) | 263 |
| Hazard analysis and critical control points (HACCP) | 5 |
| Controls assessment | |
| Layers of protection analysis (LOPA) | 23 |
| Bow-tie analysis | 83 |
| Statistical methods | |
| Markov analysis | 2 |
| Monte-Carlo analysis | 1401 |
| Bayesian analysis | 31 |
| Other methods | |
| 3-F method | 1 |
| Functional Safety | 34 |
| Relative risk ranking | 7 |
| Wacker approach | 0 |
| Zurich hazard analysis (ZHA) | 0 |
| Master logic diagram (MLD) | 0 |
| Fishbone diagrams | 15 |
| DOW Fire & Explosion index | 1 |
| TÜV NORD-method | 0 |

**Table 4: onepetro.org search hits for risk assessment method-keywords.**

### 4.2.1 Root cause analysis (RCA)

The RCA is a method to analyze incidences, problems or major losses to minimize the risk of a reoccurrence. To achieve this the root causes of the problem are identified and corrective action against these original causes can be taken. It can be viewed as a tool of continuous improvement, because corrective measures usually only minimize the causes for the problem and cannot eliminate them entirely[126,127]. Typically the RCA is a reactive process, but it is also possible to use it in a proactive way to not only find corrective actions but also preventive actions[128].

The basic process for a RCA is as follows[126,127]:

- Forming a team of experts, depending on the type of failure
- Definition of scope and objectives
- Data acquisition
- Analyzing the failure and identification of the root causes
- Find and implement solutions
- Checking the effectiveness of the found solution

Strengths of this approach are the structured analysis, documentation (acquired data, hypotheses, conclusions and solutions to the problem). However, this method also has shortcomings because the availability of the needed experts could be problematic, needed data could be missing and the resources of the team may be limited[129].

### 4.2.2 Scenario analysis

Scenario analysis describes a method that creates representations of the future by extrapolation of trends or imagination. Scenario analyses are extensively used for the purpose of decision-making by e.g. creating scenarios for oil initially in place of a hydrocarbon reservoir. Certain scenarios or sets of scenarios can then be chosen to representing a “best case”, “worst case” or “best estimate case”.

In the context of technical risk analysis a scenario can be defined as “one event, multiple events or a combination of events, leading to an undesired extent of damage”[130].

The process of a scenario analysis is described in ISO 31010[131] as follows:

- Creating a team of experts that understand and are able to predict possible changes in the future
- Definition of the problem

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[126] Cf. IEC (2009), ISO 31010, p. 44

[127] Cf. Garg & Gokavarapu (2012), p. 1

[128] Cf. Perkinson, L. (2012), p. 1

[129] Cf. IEC (2009), ISO 31010, p. 45

[130] Preiss, R. (2009), p. 10

[131] Cf. IEC (2009), ISO 31010, p. 41

- Identification of possible changes in the future (nature of the changes and timing of the changes)
- Ranking of the predicted changes by importance and uncertainty
- Creation of reasonable scenarios, including a story of how the state of the system changes from the current to the future state
- Evaluation of the initial subject regarding the plausible scenarios and modification of the subject to the scenarios to make it less risky

Strengths of a scenario analysis are that it presents a wide range of possible futures, which is very useful for the prediction of future states where very high uncertainties exist. However, the drawback that comes along with it is the creation of unrealistic scenarios. Care has to be taken when decisions are to be made based on scenario analysis, because the availability of data is often problematic, which can lead to unrealistic results of the scenario analysis[131].

### 4.2.3 Fault tree analysis (FTA)

The fault tree analysis is a method to find and analyze the faults / causes for a specific event. Also the sensitivity of a system to the failure of certain parts of the system can be evaluated[132].

The FTA can be used for qualitative (identification of causes and logic connections) and quantitative evaluation (calculation of probability of a top-event) of risks and it is based on reliability theory, Boolean algebra and probability theory[133].

[132] Cf. Preiss, R. (2009), p. 78

[133] Cf. Ericson, C. (1999), p. 1

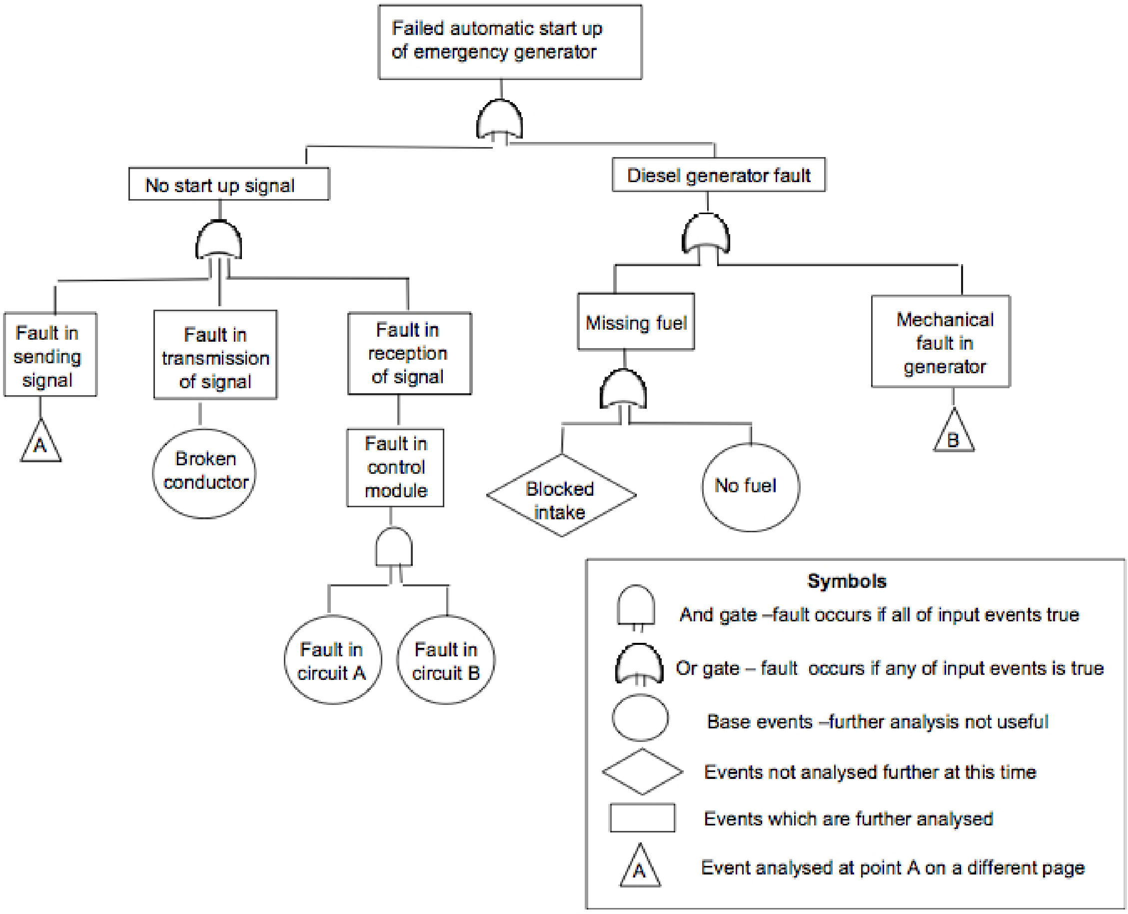


**Figure 13: Example of a FTA**[134]

Figure 13 shows an example of a fault tree. Different event types and connections are used to build a fault tree.

The process of creating a fault tree is described in ISO 31010[135] as follows:

- A top event has to be defined, which describes the event that is going to be analyzed regarding its causes or faults.
- Direct causes for a defined top event are then identified.
- The next step is to analyze the already found causes by finding the causes for these top faults. This mechanism of going into detail is continued until it is no longer reasonable.
- A quantitative analysis can be performed in case all the necessary inputs for the calculation are known.

Additionally so-called minimal cut sets can be found. Minimal cut sets are sets of simultaneously transpiring single events that are necessary for a top event to occur[136].

[134] IEC (2009), ISO 31010, p. 49

[135] Cf. IEC (2009), ISO 31010, p. 50

[136] Cf. Preiss, R. (2009), p. 83

Strengths of the FTA include the clear representation of the system and its possible failures and the identification of minimal cut sets to optimize corrective actions. Disadvantages of this method are the lack of time dependencies, high range of uncertainties in quantitative analyses where input probabilities are not known exactly and that the failure mode of a component in the FTA only knows the states "failed" or "not failed" and nothing in between[137,138].

### 4.2.4 Failure mode and effects analysis (FMEA) and Failure mode and effects and criticality analysis (FMECA)

FMEA is a systematic approach to identify failure modes, causes and consequences and it gives recommendations on how to mitigate the consequences or avoid the failures.[139] An important aspect of the FMEA is that it is designed to prevent failures already in the planning stage to avoid costly failure corrections in later stages.

The FMECA is an expansion to the FMEA with more detailed analysis of the criticality of the failure to prioritize corrective actions[140,141].

The FMEA/FMECA objectives are[142],[139],[143]:

- Support for decision making in the design process
- Provide criteria for a test phase
- Taking into account all failure modes, systems and processes
- Create input for other analyzing techniques and safety models
- Shorten the development phase
- Saving of costs
- Improving the functionality of products and processes

To process for conducting a FMECA is described by NASA, which used this method for the Apollo-project, as a combination of FMEA and a Criticality Analysis (CA)[144]. The process is described as follows[145],[146]:

- Defining the system, creation of a team and acquisition of data

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137 Cf. IEC (2009), ISO 31010, p. 51

138 Cf. Preiss, R. (2009), p. 91

139 Cf. IEC (2009), ISO 31010, p. 46

140 Cf. Preiss, R. (2009), p. 30

141 Cf. Vesely, W. E. et al. (1981), p. II-4

142 Cf. Preiss, R. (2009), p. 32

143 Cf. NASA (1966), p. 1-2

144 Cf. NASA (1966), p. 1-3

145 Cf. IEC (2009), ISO 31010, p. 47

146 Cf. Preiss, R. (2009), p. 35

- Understanding and breakdown of the system into its base elements in a hierarchical manner
- Analyzing the elements on the lowest hierarchical level and working upwards to higher levels.
- Identification of requirements for the design regarding the found failures
- Carrying out the CA. Several possible methods exist for this part (mode criticality index, level of risk, risk priority number, …)

Strengths of this method include the wide range of applicability, the cost saving potential and it provides input to other methods. However, it is necessary to use e.g. FTA to analyze combinations of failure modes[147].

### 4.2.5 Hazard operability study (HAZOP)

The HAZOP is a method that evaluates processes or facilities regarding potential hazards and operability problems. The HAZOP is a qualitative technique, but it is also possible to use risk matrices for a semi-quantified assessment[148]. It has similarities to the FMEA; both methods identify possible mode, causes and consequences of failures. However, the FMEA starts by identifying failure modes of single system elements and works its way up to the consequences, whereas the HAZOP also considers unwanted consequences and works back to the causes[149,150].

HAZOP is extensively used also in the oil and gas industry to identify errors in the design of processes or facilities. It can be described as "*the last and best line of defense we have for catching design errors and omissions*"[151].

The process of a HAZOP is described as follows[152]:

- Appointment of a HAZOP leader and a HAZOP team
- Definition of objectives, scope and guidewords. Guidewords are words describing the deviation of a system component from the desired value.
- Data acquisition
- Breakdown of the system into its components and agreeing on the purpose of all components
- Identification of unfavorable consequence through application of the defined guidewords on the system components
- Finding of causes and consequences of each found unfavorable consequence and development of recommendations

[147] Cf. Preiss, R. (2009), p. 50

[148] Cf. Herbert, I. L. (2011), p. 2

[149] Cf. IEC (2009), ISO 31010, p. 32

[150] Cf. Preiss, R. (2009), p. 53

[151] Duhon, H. J. (2009), p. 1

[152] Cf. IEC (2009), ISO 31010, p. 33

- Documentation of the workshops (e.g. through online documentation using templates)

Strengths of the HAZOP method include the wide range of applicability, the especially good applicability for continuous processes and the excellent documentation. Limitations of the technique are that it assumes processes to operate in a safe manner under nominal conditions and that the quality of the results is heavily dependent on the quality of the data and the expertise of the team[153].

### 4.2.6 Bow-tie analysis

The bow-tie analysis provides an easy to understand way of a certain event with its causes and consequences. Also barriers for both the cause- and consequence-side of the diagram are visualized. This method can also be seen as a combination of FTA and ETA, with the FTA concentrating on the causes of an event and the ETA concentrating on the consequences of the event[154,155].

The first major company to implement this method as a risk assessment method was Royal Dutch/Shell Group in the 1990s[156]. Since then, many other industries (including healthcare, military, transport, aviation, banking and the nuclear industry) and regulators have incorporated this approach[157,158].

[153] Cf. Preiss, R. (2009), p. 69

[154] Cf. IEC (2009), ISO 31010, p. 64

[155] Cf. Preiss, R. (2009), p. 102

[156] Cf. Jones, F. (2012), p. 2

[157] Cf. Book, G. (2012), p. 1

[158] Cf. Jones. F. (2012), p. 3

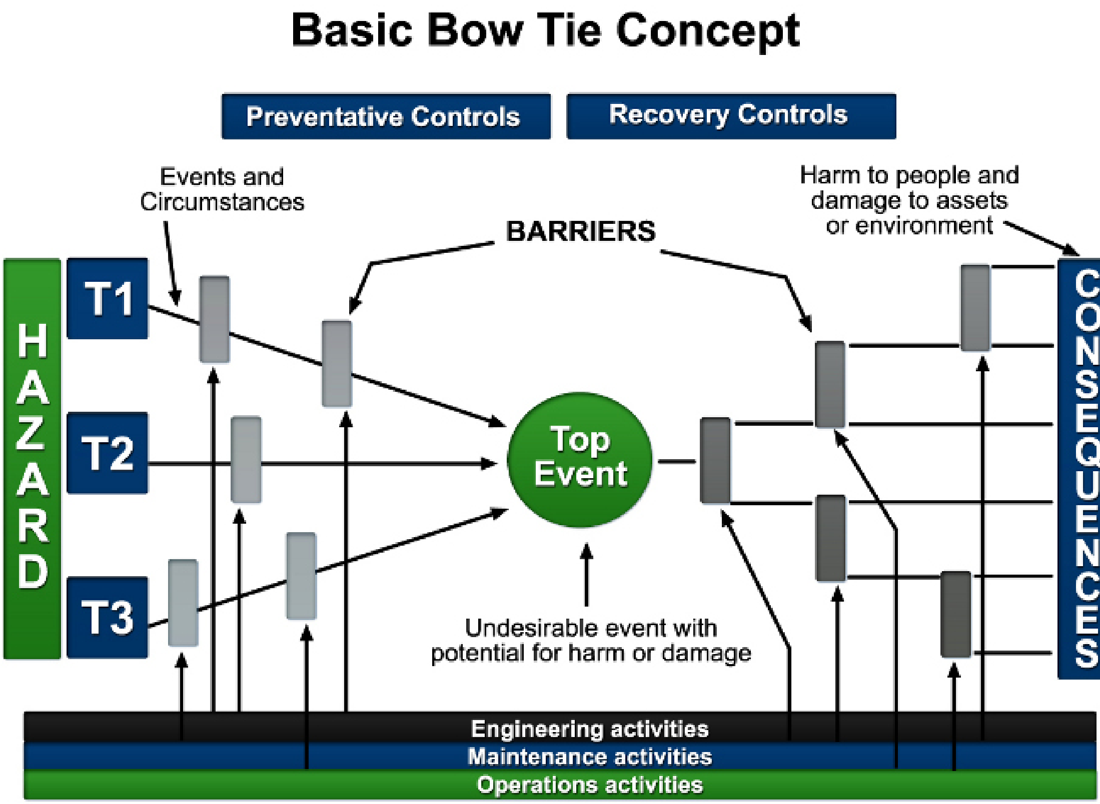


**Figure 14: Example of a bow-tie diagram[159]**

Figure 14 shows an example of a bow-tie diagram. The process of the bow-tie diagram construction is described in ISO 31010[160] as follows:

- To construct a bow-tie diagram, an event (risk) has to be identified and is placed in the middle of the diagram. This event is also called top event and describes the moment at which control over the hazards are lost[161].
- The causes (or threats), the incidence that makes a certain hazard operant, should be identified and listed considering hazards. Ideally a hazard register is already in place and can be used for this task[161]. Additionally escalation factors can be introduced to describe certain factors that might cause escalation and are often described as factors having a negative influence on barriers[162].
- The next step is to place barriers (prevention controls, escalation controls) as vertical bars across the drawn lines. Prevention controls have the task to prevent the top-event from happening when threats are operant. This can be done by detecting threats in an early stage where counteractive action is possible, or by

[159] saacosh (2014), Access 7.7.2014

[160] Cf. IEC (2009), ISO 31010, p. 65

[161] Cf. Preiss, R. (2009), p. 103

[162] Cf. Preiss, R. (2009), p. 104

acting against the threat[163]. Escalation controls serve the purpose of controlling the factors that have a negative influence on the barriers.

- The right hand side of diagram is to be drawn next. Consequences have to be identified and connected to the risk.
- Like on the left hand side also on the right hand side barriers can be drawn. These barriers are called mitigation and recovery controls. The purpose of these barriers is to mitigate the consequences of the event and can be of technical or organizational character[162].
- Below the diagram activities can be shown which support the controls.

Strengths of the bow-tie analysis are the easy to understand illustration of the problem, the focus on barriers and the low required level of expertise to use this method. Also a greater ownership of process safety can be achieved by assigning responsibilities for controls to personnel. Additionally efficiency gains by the reduced workload compared to other methods or by the reduction of unnecessary barriers can be achieved[164,165].

However, this method also has limitations. It cannot handle multiple simultaneously taking place causes triggering a consequence and problems of quantification with very complex systems can arise[165].

Book[166] has listed various types of applications of the bow-tie method:

- Logical structured approach
- Complete risk management
- Demonstration
- Communication
- Identification of critical systems
- Organizational improvements
- Analysis of specific risks
- Define procedures and competences for each task
- Layer of protection analysis (LOPA)

### 4.2.7 Monte Carlo analysis

The Monte Carlo simulation is a statistical method calculating many possible outcomes on the basis of statistically distributed input parameters. This is a simple technique used e.g. to calculate original oil in place for a hydrocarbon reservoir. The output of a Monte Carlo simulation for multiplicative models will always be approximately lognormal distributed according to the central limit theorem.

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[163] Cf. Jones, F. (2012), p. 5

[164] Cf. Book, G. (2012), p. 8

[165] Cf. IEC (200), ISO 31010, p. 66

[166] Cf. Book, G. (2012), p. 4-7

As a byproduct to Monte Carlo simulation a sensitivity analysis can be conducted, measuring the significance of an input variable for a certain output variable[167].

The process for conducting a Monte Carlo simulation is as follows:

- Development of a mathematical model for a system
- Conducting many calculations using random numbers for each model parameter according to their distribution (triangular, normal, log-normal, …)
- Analyzing the results of the Monte Carlo simulation

Strengths of a Monte Carlo analysis are that it is relatively simple to conduct, sensitivity analysis can be done and that any kind of distribution can be chosen for the input variables. However, using such a probabilistic model also has drawbacks like the lack of a physical case, like a scenario analysis is providing, for a certain calculated value. In terms of risk analysis also high-consequence/low probability events may not be represented strong enough[168].

### 4.2.8 Wacker approach

The Wacker approach is also discussed here because it is used in an Austrian oil and gas company operating UGSs in Austria. The Wacker method consists of two parts, a Wacker-plausibility-check for screening and the Wacker-analysis for risk identification.

**Wacker-plausibility-check**

The Wacker-plausibility-check is a screening method, which means that it is used to provide the first steps for a more detailed analysis of process safety[169].

Therefore it is used at a very early stage in the planning process to evaluate the plausibility of the safety concepts regarding the handled energy potentials through systematically conducted scenario development. The focus is set on abrupt failure of tanks and pipes caused by pressure and temperature, released by human or technical fault, in the system. The energy (pressure or temperature) that is resulting in failure of tanks and pipes can be brought into the system from the outside, accumulate inside the system or can be activated potential energy[170].

**Wacker-analysis**

The Wacker-analysis is a method for risk identification and therefore provides the first step in a risk assessment process.

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[167] Cf. Murtha, J. A. (1997), p. 361

[168] Cf. IEC (2009), ISO 31010, p. 75

[169] Cf. IVSS (2012), p. 15

[170] Cf. IVSS (2012), p. 15

Wacker-analysis can be applied in the planning stage as well as for already running processes. Consequences of an assumed failure in the system are investigated and resulting risks are deduced. Like in other methods, a complete identification of hazards is essential to the success of the method[171].

To support the completeness of the analysis a list of questions, designed specifically for the chemistry-industry, exists. Also an interdisciplinary team of experts should be used to increase the quality and completeness of the analysis[171].

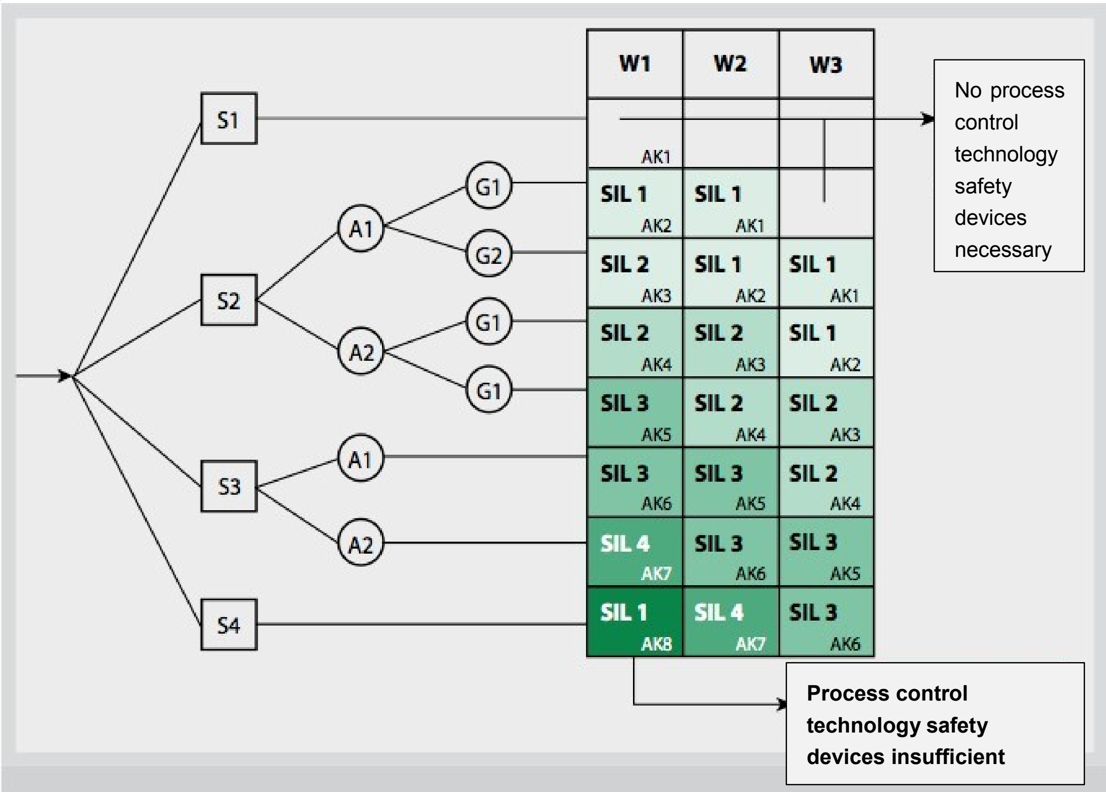


**Figure 15: Translated risk-graph after VDI 2180 sheet 1[172]**

To find appropriate safety mechanisms the results of the Wacker-analysis can be combined in a risk-graph (e.g. VDI 2180). The risk graph (Figure 15) uses the parameters[172]:

- S1 to S4: damage parameter; ranging from S1 = minor injuries to S4 = many fatalities
- A1 and A2: duration and frequency of persons in the hazardous area; A1 = seldom or sometimes and A2 = frequently or permanent
- G1 and G2: possibility of a corrective action against the hazard by the affected person; G1 = possible and G2 = barely possible

[171] Cf. IVSS (2012), p. 27

[172] Wolfanger, H. (2008), p. 40 cited from VDI (2007), VDI 2180-1

- W1 to W3: probability of the event; ranging from W1 = low probability to W3 = high probability

The combination of the parameters results in a required SIL (Safety Integrity Level) that describes the requirements for a specific safety measure.

## 4.3 Identification of boundaries for the underground hydrogen storage system

A system can be defined as "*a deterministic entity comprising an interacting collection of discrete elements*"[173]. The UGS system for storage of a hydrogen-methane mixture is defined to consist of the following underground elements:

- Wellbore
  - Casing
  - Packer
  - Cement
  - SSSV
  - Tubing hanger
  - And other downhole equipment
- Groundwater horizons
- Rock formations surrounding the wellbore
- Neighboring reservoirs
- Reservoir
  - Caprock
  - Pore space
  - Microorganisms
  - Reservoir water
  - Rock formation beneath the reservoir / aquifer

## 4.4 Risk assessment case studies

Recent developments in Carbon Capture and Storage (CCS) warrant a closer look at a risk assessment case studies, e.g. by Tucker et al[174]. Similarly to planned hydrogen UGSs, a depleted gas field is the subject of investigation and the stored gas mixture is of different composition than the original gas in place.

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[173] Vesely, W. E. et al. (1981), p. I-3

[174] Tucker et al. (2013)

### 4.4.1 Containment risk management for $CO_2$ storage in a depleted gas field, UK North Sea[175]

Tucker et al. describe a risk assessment case study for a potential $CO_2$ offshore storage site. The reservoir is a depleted gas reservoir located in the Central North Sea and is called "Goldeneye". This field is part of a Shell CCS and is described as having a good permeability and tank like behavior. This along with other motives like the relatively new facilities (installed in 2004), were the reasons why this field was chosen as a candidate[176].

To evaluate the storage candidate a method called ESL (Evidence Support Logic), which is implemented in the TESLA software, was used. The risk assessment was then conducted using a bow-tie risk assessment[177].

**TESLA assessment**

TESLA is a software product from Quintessa and is based on ESL. ESL is a tool to "*break a decision down into a hierarchical structure, simplifying the problem and presenting it in such a way that information can be easily gathered and categorized and enabling the optimization of data gathering (…)*"[178]. One important feature of ESL is that it not only includes probabilities for the hypothesis to be either true or false, but a third element describing the uncertainty is added. Tucker et al. call this a three-value logic compared to other two-value logic methods[177] (see Figure 16).

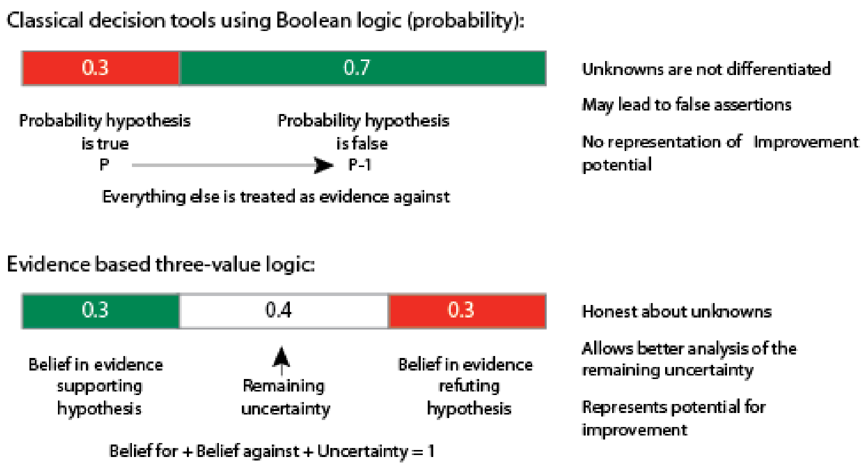


**Figure 16: Two-value logic (Boolean logic) compared to three-value logic[179]**

[175] Tucker et al. (2013)

[176] Cf. Tucker et al. (2013), p. 4805

[177] Cf. Tucker et al. (2013), p. 4806

[178] Quintessa (2014), Access 24.07.2014

[179] Tucker et al. (2013), p. 4807

The first part of the risk assessment is the identification of the risks. To be able to come up with a complete list they collated their identified risk with a FEP (Features, Events and Processes) database for $CO_2$ storages. Such a database can be found on the webpage of Quintessa[180]. In addition to the FEP also links and references to the listed FEPs can be found there.

To evaluate all the gathered data from FEP and past experiences of Shell the quality and the interpretation of the data was analyzed using ESL. An ESL tool implemented in the TESLA software from Quintessa was used for this purpose. For all sub-hypothesis the results can then be aggregated using weighting factors for supporting and opposing hypothesis to be able to make a top-level assessment for the entire project. When this is done repeatedly during the project, an evaluation of whether the global risk is increasing or decreasing can be carried out[181].

Also used was a so called “ratio plot”, which can be used to visualize a hypothesis with its sub-hypothesis in terms of ratio of evidence for and against the hypothesis and the corresponding uncertainty. An example of a ratio plot can be seen in Figure 17. In the best case all hypothesis move vertically towards higher evidence ratios and horizontally towards lower uncertainty values during a project.

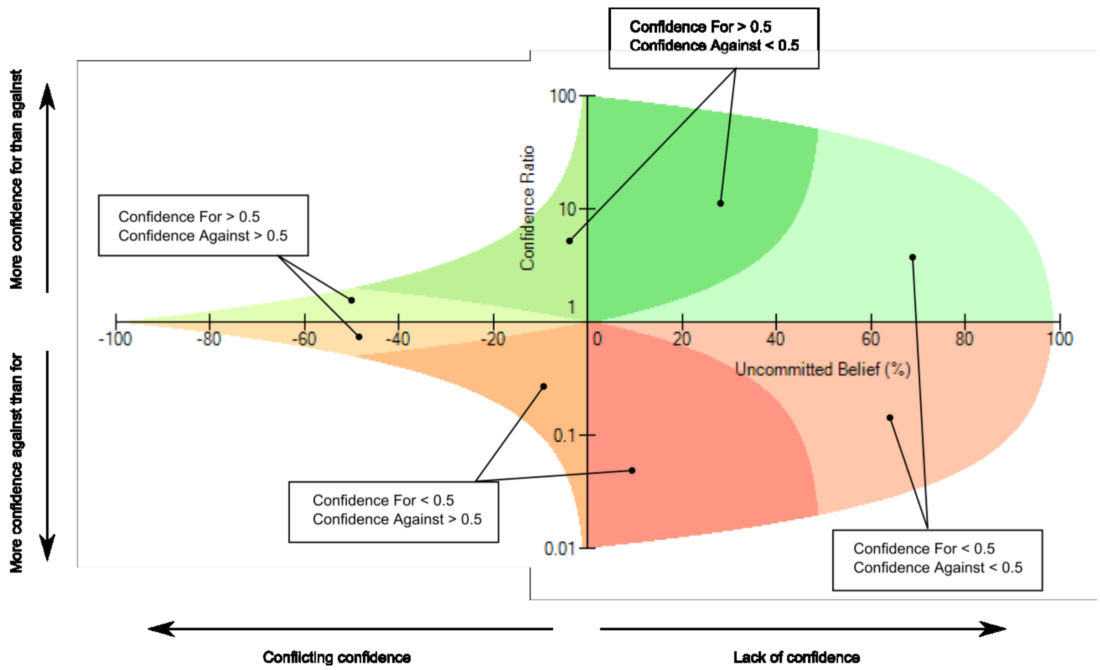


**Figure 17: Ratio plot used in TESLA[182]**

[180] Quintessa (2014), $CO_2$ FEP Database, Access 17.02.2015

[181] Cf. Tucker et al. (2013), p. 4806 & 4807

[182] TESLA (2014), p. 35, Access 25.07.2014

**Bow-tie**

The construction of the bow tie has been done during multiple workshops with multidisciplinary participants over a timespan of several months and under instruction by an independent bow tie expert.

As a top-event for the created bow tie the loss of containment of $CO_2$ has been chosen. This means that in this case the hazard is $CO_2$ and a loss of $CO_2$ means that it is getting out of control. As next steps they introduced causes, consequences, barriers and escalation factors to the bow tie. An important part of the bow tie analysis is then to assess the effectiveness of each control / barrier. It is mentioned that the best way is to eliminate the hazard, which is in this case not possible ($CO_2$ cannot be substituted)[183]. This is another similarity to the underground hydrogen storage, where analogous to this case also the hydrogen cannot be substituted.

To complete the process of finding and assessing barriers the following set of questions was asked[184]:

- "Do we comply with company and industry standards?"
- "Can we improve the effectiveness of the existing controls?"
- "Are there any more controls that can be implemented?"
- "Is it reasonably practicable so to do?"

This set of questions ensures that the risk is "As Low As Reasonably Practicable" (ALARP).

The next step was to evaluate the found threats and consequences in terms of likelihood by a team of experts (see Figure 18). For each threat (cause) of the loss of containment of $CO_2$ an evaluation based on criteria of frequency of occurrence has been performed. It can be seen that no threat had more than a low risk to trigger the top event. The numbers next to the causes indicate the possible result of this specific threat.

The resulting bow tie can be seen in Figure 19. It can be assumed that certain threats like lateral migration or gas leakage accompanying injection wells could be similar to those faced in underground hydrogen storages.

A further assessment of the threats and consequences present in the bow tie diagram has been undertaken using a risk matrix, in this case the Shell risk assessment matrix. This step is performed to rank the threats and consequences in terms of importance and urgency.

After the evaluation of each threat by the technical team 13 new and unique risk barriers have been suggested by, from which 8 have been investigated further, 3 have been conditionally rejected and 2 have been rejected unconditionally[185].

[183] Cf. Tucker et al. (2013), p. 4810

[184] Tucker et al. (2013), p. 4810

[185] Cf. Tucker et al. (2013), p. 4814

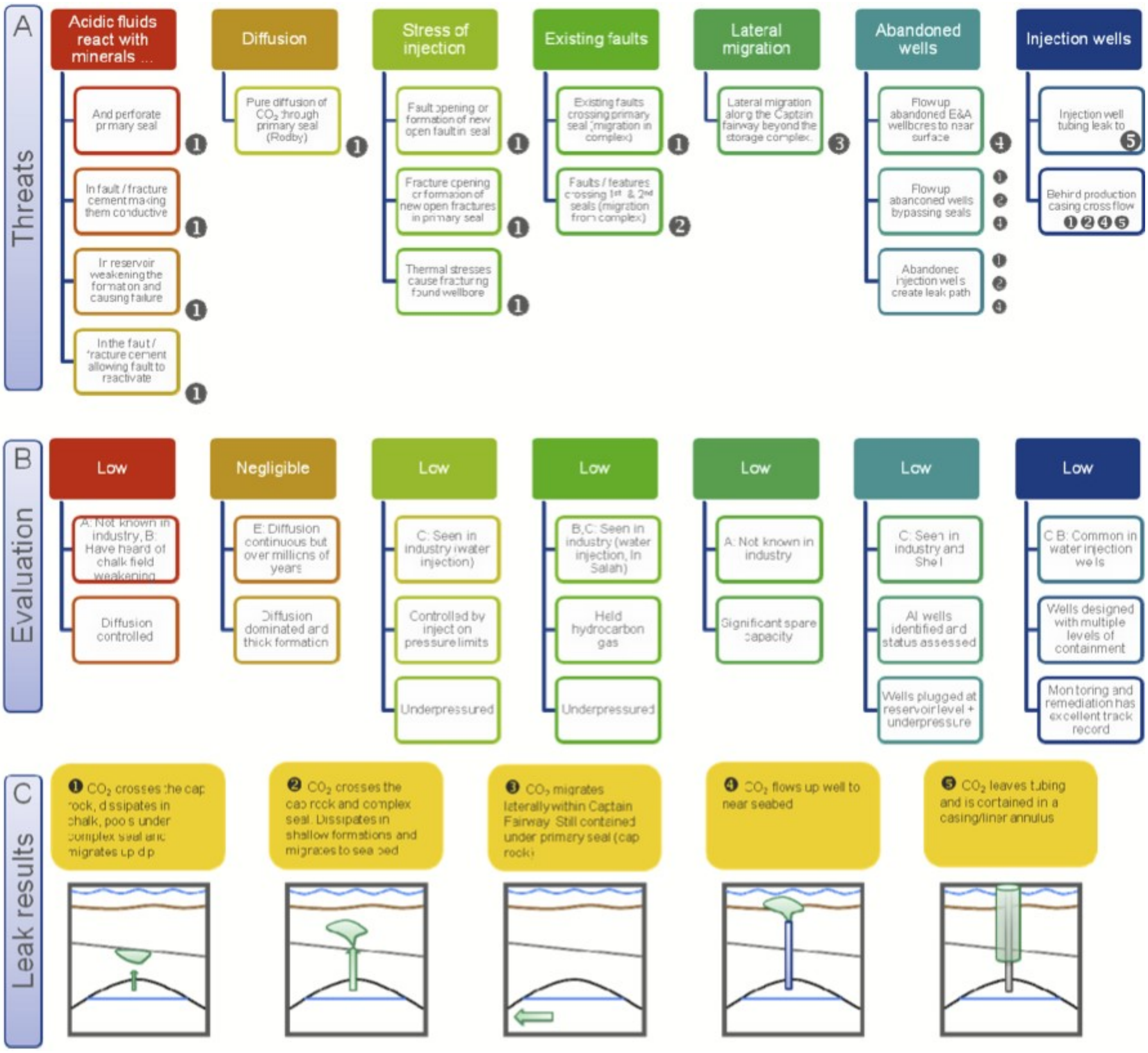


**Figure 18: Threats, evaluation and possible results / consequences for the Goldeneye bow tie.**[186]

[186] Tucker et al. (2013), p. 4811

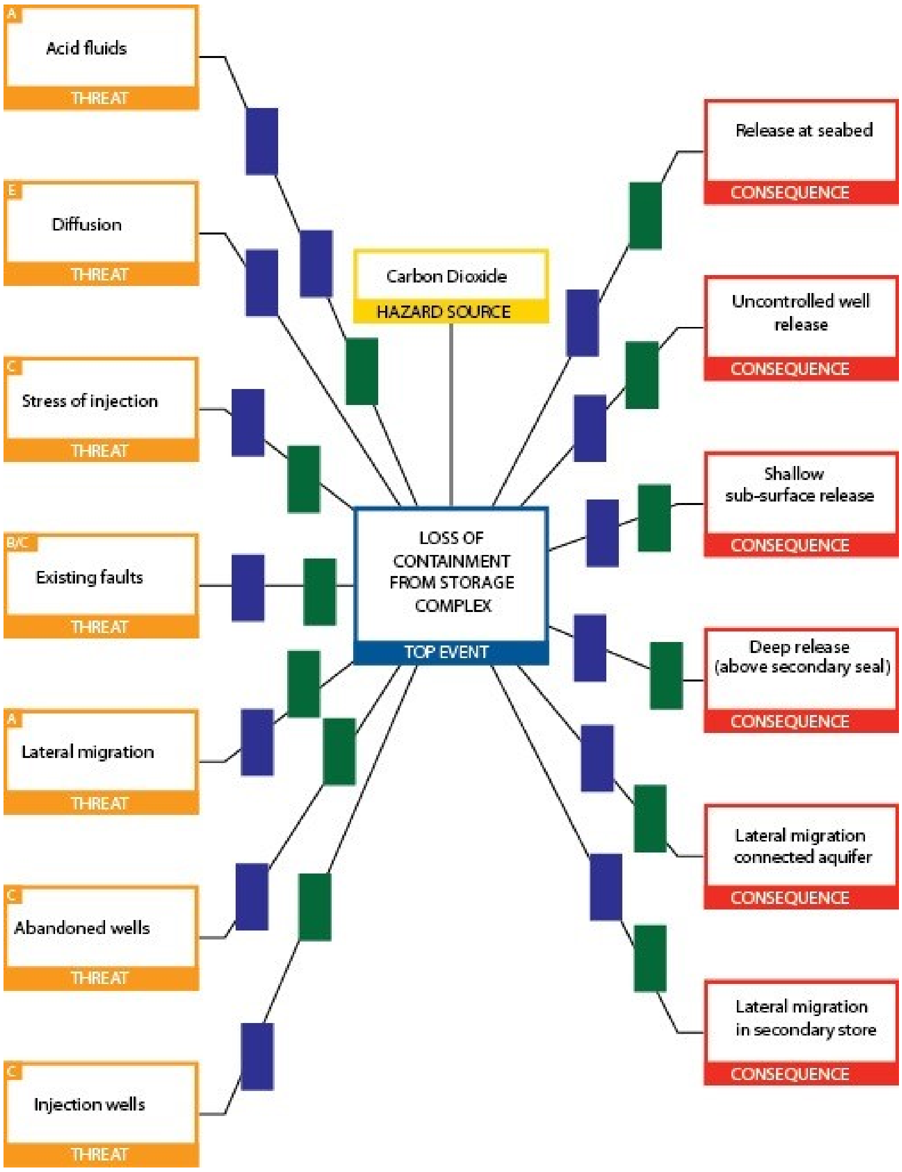


**Figure 19: Bow tie for the top event "Loss of containment from the storage complex" for the Goldeneye candidate.**[187]

This study can be related to the risk assessment of underground hydrogen storage insofar as that also a loss of containment of the stored fluid represents a hazard. Also the assessment of barriers using a set of questions provides a structured approach that can be very useful. A further assessment of the risks of the bow tie diagram using a risk matrix could be easily implemented in a risk assessment of underground hydrogen storage. This step may also be done using e.g. the VDI 2180 risk graph, like it is used in the Wacker analysis.

[187] Tucker et al. (2013), p. 4812

### 4.4.2 Development and Application of BowTie Risk Assessment Methodology for Carbon Geological Storage Projects[188]

Irani[188] developed a framework for risk assessment for carbon geological storage projects using a bow tie approach, fuzzy logic and Dempster-Shafer theory for evaluating the knowledge of the interviewed experts. The method is then applied to the Weyburn project, a CCS project. Brief discussions of the Dempster-Shafer theory and fuzzy logic are attached at the end 4.4.2. Liu et al. [189] stated that a combination of fuzzy logic and Dempster-Shafer theory could be advantageous when the information (or evidence) is not very strong and a so-called “lack of specificity” is present.

Irani[188] implemented fuzzy logic and the Dempster-Shafer theory in a fault tree. Interviews with experts to get their judgment on risks have been conducted. The different opinions of the experts have been captured using the Dempster-Shafter theory and these opinions are also implemented in the fault tree. The level of risk that was estimated by the experts is also implemented into the fault tree using fuzzy logic[190]. Because of the type of available data the risk evaluation is qualitative.

Also the public risk perception was evaluated regarding the geologic storage of $CO_2$. This was done on the basis of perceived risk and perceived benefit, both of which are subject to change over time due to multiple reasons. E.g. a catastrophic event will change the risk perception drastically. Irani[188] investigated the phenomena of risk perception, the impact of media coverage, race and gender effects and the trust effect. A survey has been conducted to evaluate the effects of media coverage and the trust effect on the public view.

To assess the potential for wellbore leakage an interaction matrix has been created. The interaction matrix is a means of addressing cause-effect relationships between different parameters. The highest weighting factors in the matrix were found to be cement top, casing centralization, well cleaning, cement placement, production and injection well history and cement volume reduction. With the exception of cement top the other effects are characterized as sustained casing pressures (SCP). SCP related problems have been observed in roughly 45 % of all wells operational in the Gulf of Mexico[191]. To assess the wells a so-called wellbore index is proposed that considers early time effects (including the effects of SCP), long-term effects and the cement top effect[192].

The last part of the work of Irani[188] was the construction of the complete bow tie and the thereby developed semi-quantitative risk assessment of geologic $CO_2$ storage with its

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188 Irani, M. (2012)

189 Cf. Liu et al. (2002), p. 12

190 Cf. Irani, M. (2012), p. 7

191 Cf. Irani, M. (2012), p. 88

192 Cf. Irani, M. (2012), p. 79

application on the Weyburn Project[193]. The left side of the bow tie diagram, in this thesis called "Failure Block Diagram" (FBD) can be seen in Figure 20. Over the brackets above the FBD the used methods for creating the particular part of the bow tie are listed. The used methods are the cause-effect method, the Analytic Hierarchy Process (AHP), the mitigation barriers approach and the consequence evaluation[194]. AHP is a process used for weighting branches on both sides of the bow tie, but will not be discussed here in detail. Blocks of the FBD connected to one gate in parallel are viewed as "OR" functions and directly connected blocks can be interpreted as "AND" functions with regard to fuzzy logic. The Bridge structure shown on the left hand side of Figure 20, which includes both "First Block" and "Second Block" and is connected by "Aquifer Exchange", is evaluated using Guth theory[195]. The used risk matrix used to combine consequence, which can be found on the right hand side of the bow tie, and probability, which is calculated on the left hand side of the bow tie, can be seen in Figure 21.

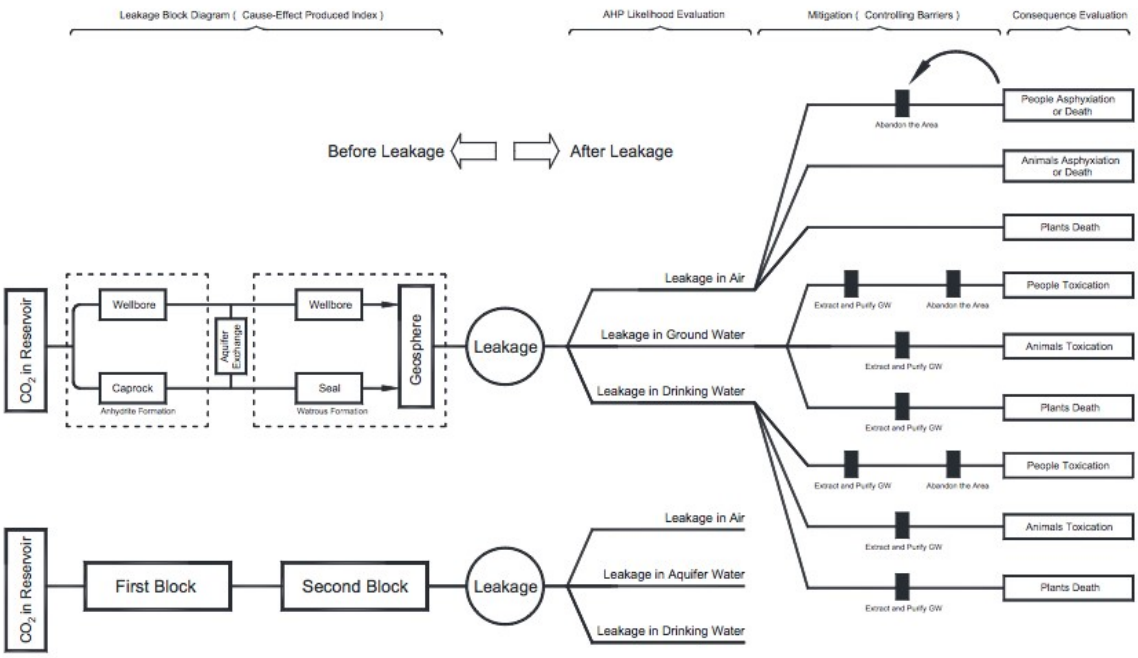


**Figure 20: FBD, the left side of the bow tie, as created by Irani[196]**

[193] Cf. Irani, M. (2012), p. 8

[194] Cf. Irani, M. (2012), p. 111

[195] Guth, M.A. (1991)

[196] Irani, M. (2012), p. 126

| Consequence Linguistic Value | | | | | | |
|---|---|---|---|---|---|---|
| | VH | M | M | H | VH | VH |
| | H | L | M | M | H | VH |
| | M | L | L | M | M | H |
| | L | VL | L | L | M | M |
| | VL | VL | VL | L | L | M |
| Risk Evaluation | | VL | L | M | H | VH |
| | | Likelihood Linguistic Value | | | | |

**Figure 21: Risk matrix used by Irani[197]. VL = very low, L = low, M = medium, H = high, VH = very high**

### Dempster-Shafer theory

The Dempster-Shafer theory, also called evidence theory, is a mathematical theory that allows the characterization of the level of knowledge using a *belief function*. It also contains a method to combine information from different sources[198]. It has been developed by Dempster[199] (1967) and Shafer[200]. In contrast to the traditional probability theory probabilities are assigned to sets and not to single events. Once the information about the events is good enough to allow for an assignment of probabilities to single events, the Dempster-Shafter theory simplifies to the traditional probability theory[201].

Sentz & Ferson[202] list three important functions in the Dempster-Shafer theory:

- "Basic probability assignment function (bpa or m)"
- "Belief function (Bel)"
- "Plausibility function (Pl)"

The *basic probability assignment function* assigns a value between 0 and 1 for a power set (1). A value of 0 represents a null set (a set of measure 0) (2), and the value of 1 describes the summation of all bpa's of the subsets of the power set (3)[201]. This means that the value of a bpa of a power set expresses the evidence that a certain element X belongs to a particular set A (4). Mathematically this can be described as follows[202]:

- $m: P(X) \rightarrow [0,1]$ (1)
- $m(\emptyset) = 0$ (2)

[197] Irani, M. (2012)

[198] Beierle & Kern-Isberner (2008), p. 419

[199] Dempster, A.P. (1967)

[200] Shafer, G. (1976)

[201] Cf. Sentz & Ferson (2002), p. 13

[202] Sentz & Ferson (2002), p. 13

- $\sum_{Y \in P} m(A) = 1$ (3)

The *belief function* and the *plausibility function* then give the upper and lower bounds for an interval that defines the probability of an event. In the case when Pl(A) and Bel(A) are the same value, the probability of an event P(A) can only be one single value. Once one of the functions m(a), Bel(A) or Pl(A) is known, it is possible to calculate the values of the other two functions[203].

To combine the information from different sources combination rules have to be used. There are different rules of combinations that can be applied, e.g. Dempster rule. This is a rule that ignores conflicting information and can therefore be seen as a strict AND-operation of information. Alternatives to the original Dempster rule include Yager's rule, Inagaki's unified combination rule or Zhang's center combination rule. These rules have been created to address the problem of strongly conflicting information[204]. Dempster-Shafer theory also provides a way to handle ignorance. This gives the Dempster-Shafter theory the benefit of treating randomness and ignorance differently by not assigning equal probabilities to all events in case of ignorance[205].

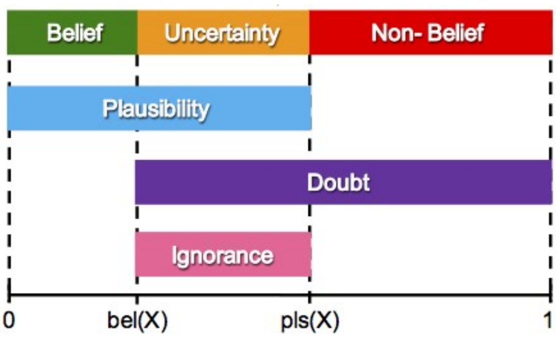


**Figure 22: Definition of different concepts in Dempster-Shafer theory[206]**

### Fuzzy logic

Vliém et al.[207] describe fuzzy logic as "*the many-valued logic with special properties aiming at modeling of the vagueness phenomenon and some parts of the meaning of natural language via graded approach*"[208].

In this context vagueness is defined as a phenomenon that occurs by grouping together objects with the same properties. A vagueness can arise when groupings like "all small numbers" are formed, where the property is very vague[209].

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[203] Cf. Sentz & Ferson (2002), p. 15

[204] Cf. Sentz & Ferson (2002), p. 16

[205] Cf. Liu et al. (2002), p. 4

[206] Irani, M. (2012), p. 32

[207] Vliem et al. (1999)

[208] Vliem et al. (1999), p. 9

[209] Cf. Vliém et al. (1999), p. 3

Vliém et al.[210] give examples of where fuzzy logic can provide a solution to a paradox where classical two-valued logic cannot and one of them is:

"One grain of wheat does not make a heap. Neither make it two grains, three, etc. Hence, there are no heaps."

This paradox cannot be solved as long as the in this example selected property "to be a heap" is not viewed as vague. Fuzzy logic resolves the problem by a smooth transition between the states of "no heap" to "heap".

### 4.4.3 Safety in Carbon Dioxide Capture, Transport and Storage[211]

The IEA (International Energy Agency) Hazard Reduction Group did research on a standard CCS system regarding safety in $CO_2$ capture, transport and storage. Although they did not consider subsurface safety risks in their study, the risk assessment approach could be relevant for underground hydrogen storages.

The identification of the risks was performed in four HAZID (hazard identification) meetings. Prior to the meetings all available information about the topic of the HAZID meeting was distributed among all team members. The team consisted of experts from the oil and gas industry, the Imperial College, the IEA and other institutions. A complete list of the participants is listed in the IEA report[211] p. 2. It is noted that the information about CCS was scarce and that this may require a repeated HAZID at later stages of the project[212]. This is another similarity to the underground hydrogen storage, because it too is a project, where a low level of experience is existent.

The four meetings where organized in a way that the first three sessions provided the input for session four, in which draft bow tie diagrams, including prevention controls, were generated.

Meeting 1 concentrated on analyzing non-CCS facilities and operations that are needed for a CCS process. Then the required modifications of the facilities due to the introduction of new substances, equipment and activities have been listed. This has been done using flow schemes of the processes[213].

In meeting 2 the information from meeting 1 was used and a structured HAZID has been conducted to find top-events and hazards for each top-event in a bow tie. For the brainstorming session keywords like "fire", "explosion" or "mechanical" have been chosen. It is noted that a bottom-up HAZID approach like HAZOP is not applicable in this situation, where the information about the process is so scarce[214].

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210 Vliém et al. (1999), p. 10

211 IEA (2009)

212 Cf. IEA (2009), p. 10

213 Cf. IEA (2009), p. 19

214 Cf. IEA (2009), p. 27

The focus of session 3 was set on changes to the system caused by CCS. Each segment of the CCS chain has been brainstormed to find hazards. The found hazards have then been added to bow ties constructed in meeting 2 or new bow ties have been created. Also barriers have been brainstormed[215].

Meeting 4 consisted of the bow tie construction including all barriers and initiating events. The found top-events are[216]:

- "Loss of containment of $CO_2$"
- "Loss of containment of oxygen"
- "Loss of containment of toxics"
- "Explosion"; and
- "Fire"

The resulting bow tie for "Loss of containment of $CO_2$" can be seen in Figure A 2 (Appendix A: Supplementary Tables and Figures).

What can be learned for the risk assessment of underground hydrogen storage is that for systems with scarce information a repeated HAZID could be required. Like Tucker et al.[217] the HAZID and the bow tie construction has been conducted in multiple team meetings.

[215] Cf. IEA (2009), p. 28

[216] IEA (2009), p. 28

[217] Tucker et al. (2013)

# 5 Safety Risk Assessment Concept for Underground Hydrogen Storage

The bow-tie method was chosen for the safety risk assessment for underground hydrogen storage. This method provides an easy to understand way of presenting risks. Additionally it was also shown by Irani[218], Li[219], Shahriar et al.[220] and others that a quantitative analysis using fuzzy logic could be applied to this method.

For the underground hydrogen storage in a porous medium the top-event relating the hazard hydrogen to safety was chosen to be “Loss of containment of $H_2$”. This is a similarity to the CCS case studies that are described in the previous chapters

Generally the proposed workflow after declaration of the top-event can be seen in Figure 23.

[218] Irani, M. (2012)

[219] Li, H. (2007)

[220] Sharhriar et al. (2012)

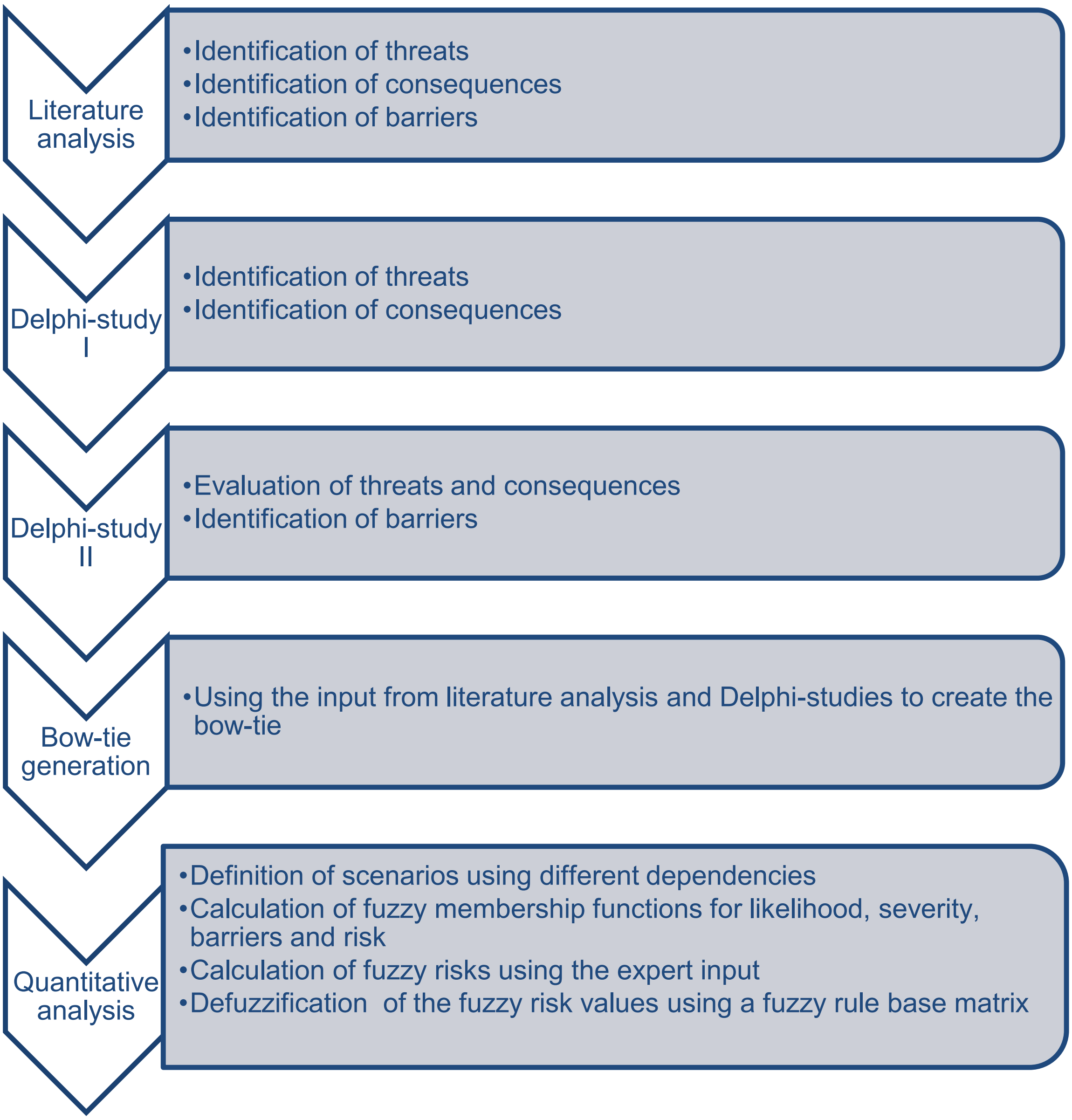


**Figure 23: Proposed workflow for the creation of the bow-tie and the analysis of the bow-tie**

## 5.1 Identification of threats

The identification of threats is the first step for conducting a bow-tie analysis. The available literature regarding threats associated with underground hydrogen storage has been screened for this purpose. Additionally some purely hydrogen related investigations have been included as well. The found threats regarding the loss of hydrogen can be categorized into the categories:

- Safety related
- Other (including business risks)

The threats have also been assigned to the previously defined system elements. The scope of this thesis is to assess safety risks only and therefore the other threats are mentioned, but disregarded for the purpose of the safety risk analysis.

The influences and threats of hydrogen found can be seen in Table 5. Safety related threats are assigned to the Top-Event loss of containment of hydrogen and for other threats the column "Top-Event" is filled with "other" or in some cases "loss of hydrogen". In case of abandoned wells the first category "well" also includes abandoned wells or pressure monitoring wells, as they can also be a possible threat for the containment of hydrogen.

| | **Well** | **Threat** | **Top Event** | **Source** |
|---|---|---|---|---|
| 1 | Casing / Tubing | $H_2$ embrittlement | Loss of containment of hydrogen | Foh et al. (1979), DBI (2013), DGMK (2014), Batisse (2013) |
| | | Corrosion due to H2S | Loss of containment of hydrogen | DGMK (2014) |
| 2 | Cement | Fractures | Loss of containment of hydrogen | DGMK (2013), Talabani & Hareland (1995) |
| | | Diffusion | Loss of containment of hydrogen | Gluth et al. (2012) |
| | | Viscous Flow | Loss of containment of hydrogen | DGMK (2014) |
| | | Biochemical and geochemical reactions | Loss of containment of hydrogen | Pichler (2013), Nagy (2008); not specifically for cement |
| 3 | Valves | Diffusion | Loss of containment of hydrogen | Altfeld (2013) |
| | | Blistering of elastomers | Loss of containment of hydrogen | DGMK (2014) |
| 4 | Packers | $H_2$ embrittlement | Loss of containment of hydrogen | Foh et al. (1979), DBI (2013), DGMK (2014), Batisse (2013) |
| | | Blistering of elastomers | Loss of containment of hydrogen | DGMK (2014) |
| | **Reservoir** | **Threat** | **Top Event** | **Source** |
| 1 | Caprock | *Leakage due to changes in the stress field* | Loss of containment of hydrogen | Lord (2009) |
| | | → Storage induced (Capillary leakage, hydraulic fracturing, shear-deformation fracturing) | Loss of containment of hydrogen | DGMK (2014), Jimenez & Chalaturnyik (2002) |

| | | | | |
|---|---|---|---|---|
| | | → Storage activated (Fault-Related Flow, Pre-existing fissures and fractures) | Loss of containment of hydrogen | DGMK (2014), Jimenez & Chalaturnyik (2002) |
| | | → Tectonic | Loss of containment of hydrogen | DGMK (2014), Jimenez & Chalaturnyik (2002) |
| | | Diffusion through caprock | Loss of containment of hydrogen | DGMK (2013) |
| | | Microbiological and geochemical reactions | Loss of containment of hydrogen | DGMK (2013) |
| 2 | Storage space | *Microbiological* | | |
| | | → In-situ self-organization ($CH_4$ / $CO_2$ ratio) | other | Panfilov (2006, 2010) |
| | | → Generation of $H_2S$ | Loss of containment of $H_2S$ | DGMK (2014) |
| | | → Generation of $CH_4$ | other | DGMK (2014), Panfilov (2006) |
| | | → Accumulation of biomass (loss of k) | other | DGMK (2013) |
| | | → Temperature increase (influence on other reactions) | Loss of containment of hydrogen / other | DGMK (2013) |
| | | → Dissolution of rock matrix | other | DGMK (2013) |
| | | → Precipitation (e.g. illite) | other | DGMK (2013) |
| | | *Geochemical* | | |
| | | → $H_2 + O_2 \rightarrow H_2O$ | Loss of hydrogen | Foh et al. (1979) |
| | | → $H_2 + S \rightarrow H_2S$ | Loss of hydrogen | Foh et al. (1979) |
| | | → $H_2 + 3\,Fe_2O_3 \rightarrow 2\,Fe_3O_4 + H_2O$ | Loss of hydrogen | Foh et al. (1979) |
| | | → $FeS_2 + 2\,H_2SO_4 + H_2 \rightarrow FeSO_4 + 2\,H_2S$ | Loss of hydrogen | Nagy (2008), Pichler (2013) |
| | | → Change of pH (influence on other reactions) | Loss of containment of hydrogen | Pichler (2013), Pudlo (2013) |
| 3 | Formation water | Solubility of hydrogen in water | Loss of containment of hydrogen | Pray et al. (1950) |
| | | pH change | Loss of containment of hydrogen | Pichler (2013), Pudlo (2013) |

**Table 5: Identified threats for the hazard hydrogen in the underground hydrogen storage system with the defined system elements and the assigned top-event.**

It should be noted that this list of threats is not necessarily comprehensive and also other causes could be present. Therefore it is suggested that for a specific project a Delphi-study is conducted. A proposed questionnaire for this study can be found in Appendix B.1: Questionnaire for the identification of threats and consequences. In the questionnaire all threats are listed, regardless of their assignment to the top-event "Loss of containment of hydrogen" in Table 5. This is done to present a maximum amount of information to the questioned expert without predetermining his response on whether the specific threat should be considered a safety related threat or not.

On the other hand not all of these listed threats will necessarily be present when the threats of a specific project are investigated.

## 5.2 Identification of consequences

To identify consequences case studies for CCS have been used. Most of the possible consequences have been taken from Tukker et al.[221] and Irani[222]. The consequences included in the draft structure of the bow-tie can be seen in Table 6. Additional threats were added based on the safety and risk aspects discussed in Chapter 2.4. Changes have been made because this case study deals with offshore subsurface storage of carbon dioxide and in our case the focus lies on the onshore subsurface storage. Also for the identification of the consequences a Delphi-study is used with an initial questionnaire proposed in Appendix B.1: Questionnaire for the identification of threats and consequences.

A further development of this side and categorization of consequences could be conducted once consequences have been found using a questionnaire. Grouping of consequences and increasing the complexity of the event tree side of the bow tie can enhance the quality of a possible quantitative analysis because more factors could be taken into account. This means e.g. the consequence "hydrogen enters ground water via fractures" could be linked to the presence of fractures. After defining a probability of the presence of fractures the probability of this consequence could be then calculated using the probability of the top-event and the probability of the fracture presence.

| Consequences | Source |
|---|---|
| Hydrogen leaves tubing and is contained in annulus /casing | Tucker (2013) |
| Hydrogen flows up in the tubing and is released to the surface | Tucker (2013) |
| Hydrogen enters ground water via fractures | Irani (2012), Chapter 3 |
| Hydrogen enters drinking water via fractures | Irani (2012), Chapter 3 |
| Hydrogen enters ground water via cement leakage | Irani (2012), Chapter 3 |

[221] Tucker et al. (2013)

[222] Irani, M. (2012)

| | |
|---|---|
| Hydrogen enters drinking water via cement leakage | Irani (2012), Chapter 3 |
| Deep release (above secondary seal) | Tucker (2013) |
| Lateral migration connected to aquifer | Tucker (2013) |
| Lateral migration in secondary store | Tucker (2013) |

**Table 6: Identified consequences for the top event "loss of containment of hydrogen"**

## 5.3 Identification of barriers

The identification of barriers is closely linked to the found threats and consequences. Prevention controls, barriers on the left side of the bow tie diagram, are intended to prevent the top event if a specific threat is active. On the right hand side of the bow tie the barriers are called mitigation or recovery controls and should mitigate the consequences in case of an occurring top-event.

Additionally escalation factors could exist; these are factors having a negative influence on the effectiveness of a barrier.

A list of preventive controls for the identified threats can be found in Table 7. For some threats multiple controls could be found, for other threats no barriers have been identified. To complete this list a questionnaire is prepared for usage in a Delphi-study. In Appendix B.3: Questionnaire for the identification of barriers the proposed questionnaire for the identification of preventive controls and recovery controls for the found causes and consequences can be found. This questionnaire can be used in a second round of Delphi-studies. At the same time the questionnaire in Appendix B.2: Questionnaire for the evaluation of the identified threats and consequences should be presented to experts to identify critical threats and consequences and to acquire data for a quantitative analysis.

In Table 6 very often "Well design, construction & completion" is mentioned. This very general formulation, which was used by Schultz et al.[223], contains specific parameters that can vary depending on the specific project. E.g. within this preventive control for $H_2$ embrittlement all the controlling parameters mentioned in 3.1.2 and 3.2.5 (pressure, temperature, hydrogen concentration, stress state, metal composition, tensile strength, grain size, micro-structure, type of impurities in the structure, heat treatment) have to be considered and the well designed accordingly. A refinement of barriers like this should be achieved with the Delphi-studies.

[223] Schultz et al. (2014)

| Well | Threat | Preventive control / Monitoring | Source |
|---|---|---|---|
| Casing / Tubing | $H_2$ embrittlement | • Well design construction & completion<br>• Pore Pressure Prediction and Monitoring<br>• Well Tests | Schultz et al. (2014) |
| | Corrosion due to H2S | • Well design, construction & completion<br>• Pore Pressure Prediction and Monitoring<br>• Well Tests | Schultz et al. (2014) |
| Cement | Fractures | • Small grain size<br>• Low water content<br>• Low $SiO_2$ concentration<br>• Use of synthetic rubber<br>• Pore Pressure Prediction and Monitoring<br>• Well Tests | Schultz et al. (2014), DGMK (2014), Talabani & Hareland (1995) |
| | Diffusion | • Small grain size<br>• Low water content<br>• Low $SiO_2$ concentration<br>• Pore Pressure Prediction and Monitoring<br>• Well Tests | Schultz et al. (2014), DGMK (2014) |
| | Viscous Flow | • Small grain size<br>• Use of synthetic rubber as additive<br>• Pore Pressure Prediction and Monitoring<br>• Well Tests | Schultz et al. (2014), DGMK (2014), Talabani & Hareland (1995) |
| | Biochemical and geochemical reactions | • Pore Pressure Prediction and Monitoring<br>• Well Tests | Schultz et al. (2014) |
| Valves | Diffusion | • Well design, construction & completion<br>• Pore Pressure Prediction and Monitoring<br>• Avoid X20Cr13<br>• Well Tests | Schultz et al. (2014), Altfeld (2013) |
| | Blistering of elastomers | • Well design, construction & completion<br>• Pore Pressure Prediction and Monitoring<br>• Well Tests | Schultz et al. (2014) |
| Packers | $H_2$ embrittlement | • Well design, construction & completion<br>• Pore Pressure Prediction and Monitoring<br>• | Schultz et al. (2014) |

| | | | |
|---|---|---|---|
| | Blistering of elastomers | • Well design, construction & completion<br>• Pore Pressure Prediction and Monitoring<br>• Well Tests | Schultz et al. (2014) |
| **Reservoir** | **Threat** | **Preventive control / Monitoring** | **Source** |
| Caprock | *Leakage due to changes in the stress field* | | |
| | → Storage induced (Capillary leakage, hydraulic fracturing, shear-deformation fracturing) | • Pore Pressure Prediction and Monitoring<br>• Fault Slip Analysis<br>• Trap Analysis | Schultz et al. (2014) |
| | → Storage activated (Fault-Related Flow, Pre-existing fissures and fractures) | • Pore Pressure Prediction and Monitoring<br>• Fault Slip Analysis<br>• Trap Analysis | Schultz et al. (2014) |
| | → Tectonic | • Pore Pressure Prediction and Monitoring<br>• Fault Slip Analysis<br>• Trap Analysis | Schultz et al. (2014) |
| | Diffusion through caprock | • Pore Pressure Prediction and Monitoring<br>• Trap Analysis | Schultz et al. (2014) |
| | Microbiological and geochemical reactions | • Pore Pressure Prediction and Monitoring<br>• Trap Analysis | Schultz et al. (2014) |
| Storage space | *Microbiological* | | |
| | → Generation of H2S | • Pore Pressure Prediction and Monitoring | Schultz et al. (2014) |
| | → Temperature increase (influence on other reactions) | • Pore Pressure Prediction and Monitoring | Schultz et al. (2014) |
| | *Geochemical* | | |
| | → Change of pH (influence on other reactions) | • Pore Pressure Prediction and Monitoring | Schultz et al. (2014) |
| Formation water | Solubility of hydrogen in water | | |
| | pH Change | • Pore Pressure Prediction and Monitoring | Schultz et al. (2014) |

**Table 7: Identified preventive controls for underground hydrogen storage for the defined top-event.**

## 5.4 Draft Structure of the bow-tie analysis

By combining the results of the previous chapters (5.1, 5.2 and 5.3) a draft structure of a bow-tie has been created using the threats, consequences and barriers found in the literature review. This bow-tie diagram can be seen in Figure 24.

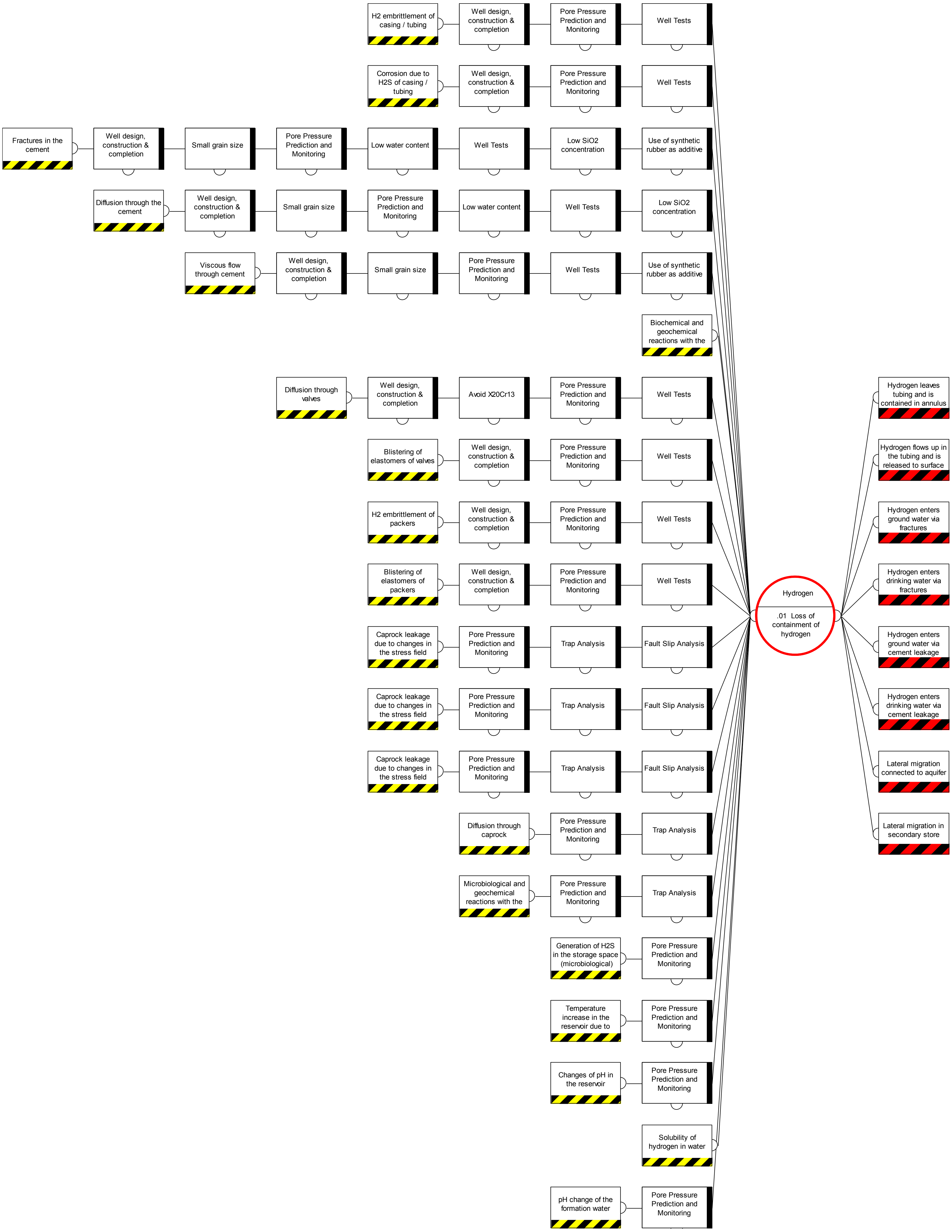


**Figure 24: Draft structure of the bow-tie diagram**

## 5.5 Quantitative Analysis

For this part a questionnaire similar to the exemplary questionnaire that can be found in Appendix B.2: "Questionnaire for the evaluation of the identified threats and consequences" can be used as a starting point. The proposed framework for the addition of quantitative analysis can be seen in Figure 25. The part of the qualitative analysis has been described in the previous sections. In the quantitative analysis both data uncertainty and model uncertainty are addressed. Using the results from the fuzzy logic approach and through the application of a fuzzy-rule-base (FRB), a risk values can be calculated.

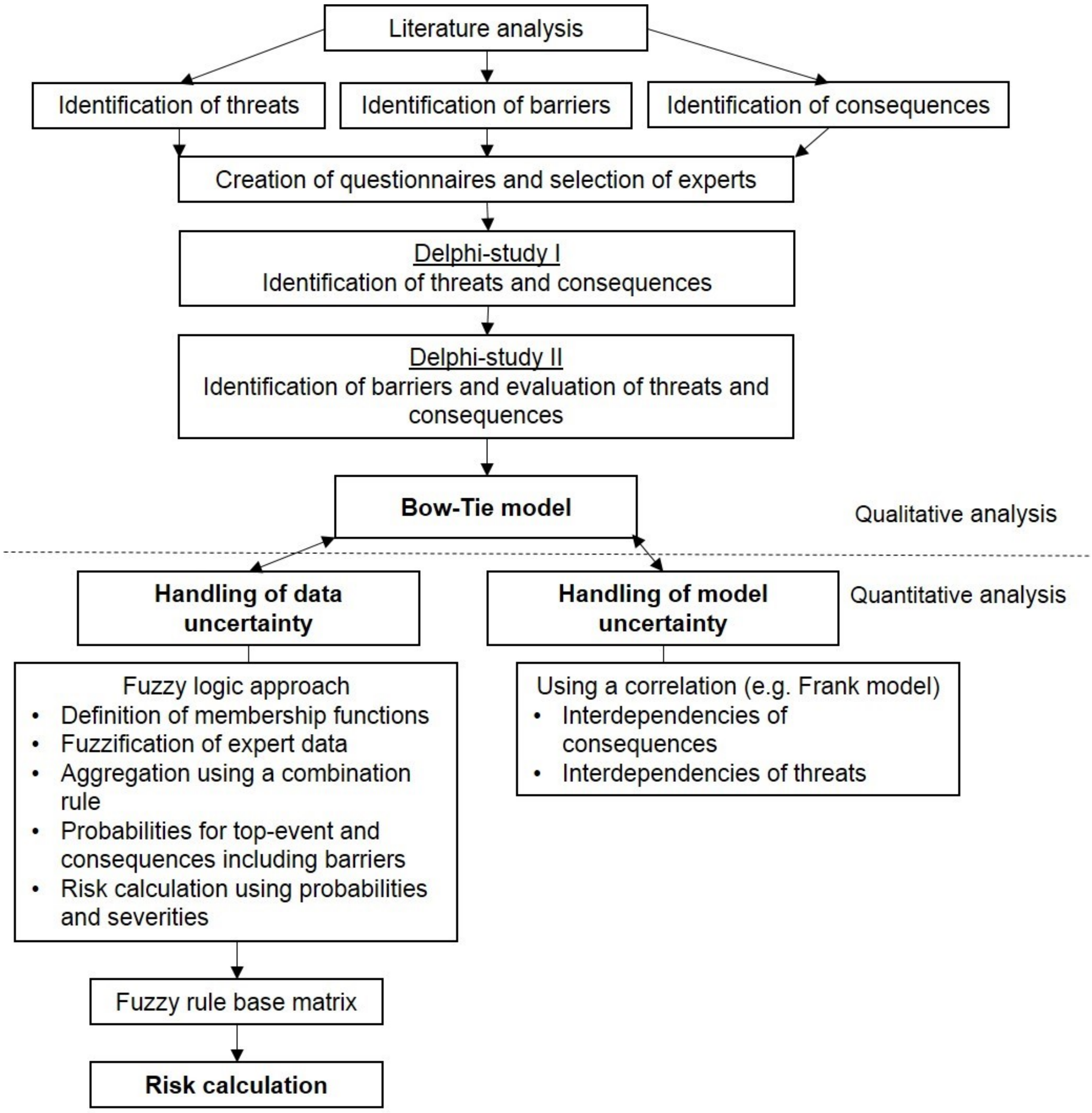


**Figure 25: Proposed framework including quantitative analysis**

#### Data uncertainty

For a project like the underground storage of a hydrogen-methane mixture exact values for probabilities, which would be needed for quantitative analysis are not available at the moment. Uncertainty may occur in different forms. Generally uncertainty can be described as either aleatory (inherent) or epistemic (model) uncertainty[224].

Natural variation is accounted for in the aleatory uncertainty and is often modeled with probabilistic methods like the Monte Carlo method, however a lack of exact input data often makes this approach not applicable. Epistemic uncertainty accounts for uncertainty due to vagueness, ambiguity, incompleteness and imprecision[225].

Instead, a fuzzy logic approach can be chosen to deal with the inherent uncertainty of the available information. Fuzzy logic is used to deal with uncertainty due to linguistics and subjectivity[225]. This approach has been shown to be applicable by many authors (e.g. Irani[226], Shahriar et al.[227], Ferdous et al.[228,229], Kim et al.[230], and Markowski et al.[231]) for bow tie analysis, event tree analysis and fault tree analysis.

An alternative approach would be the application of evidence theory. This method can be applied to deal with uncertainties due to incompleteness, ignorance or lack of consistency[225]. This way of dealing with epistemic uncertainty has been shown to be applicable by different authors (e.g. Irani[226], Curcurù et al.[232]) already.

The first part of the fuzzy logic approach is the definition of membership functions. Similar functions like seen in Irani[226] are used. The software used in our case was Maple 18. Maplesoft, a division of Waterloo Maple Inc., Waterloo, Ontario. The created membership functions can be seen in Figure 27 and a sample TFN can be seen in Figure 26. The full code used for handling data uncertainty and risk calculation can be found in Appendix D: Maple Code used for the exemplary calculation. The use of triangular fuzzy numbers (TFNs) was chosen, but also other types would be possible. The advantages of TFNs are computational simplicity and good representation of data[233].

[224] Huyse, L. & Thacker, B. H. (2003), p. 1

[225] Cf. Ferdous et al. (2009), p. 284

[226] Irani, M. (2012)

[227] Shahriar et al. (2012)

[228] Ferdous et al. (2012)

[229] Ferdous et al. (2009)

[230] Kim et al. (1996)

[231] Markowski et al. (2009)

[232] Curcurù et al. (2012)

[233] Cf. Ertuğrul & Karakaşoğlu (2007), p. 705

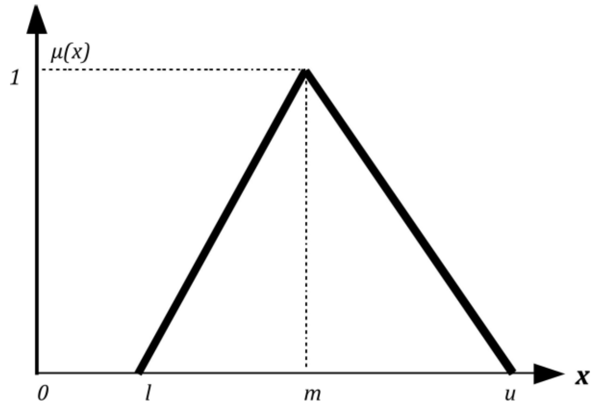


**Figure 26: Membership function of a TFN[234]**

Such a TFN can be described by three real numbers: ($p_l$, $p_m$, $p_u$) or (l,m,u)[235], but also other symbols can be found in the literature. For a general TFN A=(l,m,u) the membership function is defined as[236]:

$$\mu_A(x) = \begin{cases} 0, & x < l, u \le x \\ \dfrac{x-l}{m-l} & l \le x < m \\ \dfrac{u-x}{u-m} & m \le x < u \end{cases}$$

When using fuzzy numbers (marked with a tile "~"), the calculations for AND and OR gates in the fault tree change slightly from[237]:

$$P_{(AND)} = \prod_{i=1}^{n} P_i \xrightarrow{in\ fuzzy\ form} \tilde{P}_{(AND)} = \prod_{i=1}^{n} \tilde{P}_i$$

$$P_{(OR)} = 1 - \prod_{i=1}^{n} (1 - P_i) \xrightarrow{in\ fuzzy\ form} \tilde{P}_{(OR)} = \tilde{1} \ominus \prod_{i=1}^{n} (\tilde{1} \ominus \tilde{P}_i)$$

Where $\tilde{1}$ = (1,1,1), P is the probability of occurrence, $P_i$ is the probability of a basic event I and n is the number of basic events that are connected to the AND or OR gate. The computational simplicity for TFNs can be demonstrated with rules for multiplication (⊗), addition (⊕) and subtraction (⊖) for two TFNs A and B[238]:

$$A \otimes B = (l_a, m_a, u_a) \otimes (l_b, m_b, u_b) = (l_a * l_b, m_a * m_b, u_a * u_b)$$

$$A \oplus B = (l_a, m_a, u_a) \oplus (l_b, m_b, u_b) = (l_a + l_b, m_a + m_b, u_a + u_b)$$

$$A \ominus B = (l_a, m_a, u_a) \oplus (l_b, m_b, u_b) = (l_a - u_b, m_b + m_a, u_a + l_b)$$

234 Cobo et al. (2014), p. 262

235 Mokhtari et al. (2011), p. 469

236 Yun et al. (2009), p. 162

237 Cheong & Lan (2004), p. 68

238 Yang & Hung (2007), p. 131

The exemplary membership functions (Figure 27) created for the draft bow-tie represent different evaluations by experts. The scale for the experts is: 1-very low, 2-low, 3-medium, 4-high and 5-very high.

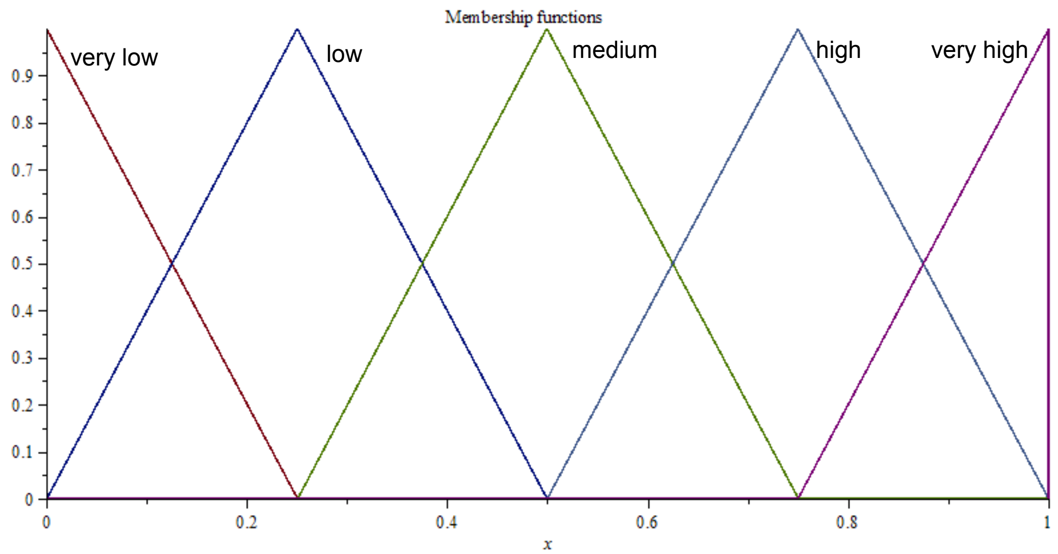


**Figure 27: Membership functions for likelihood for the draft bow-tie**

Aggregation of expert opinions is needed when more than one expert assessment should be included. One approach is the so-called Opinion Pool[239]:

$$P_{s\lambda}(\theta) = \sum_{i=1}^{k} \lambda_i p_{si}(\theta)$$

Where $\lambda_i$ are weight factors that sum to one, $p_{si}$ is expert i's probability distribution of the parameter $\theta$ and $P_{s\lambda}$ is the combined probability distribution. By using this rule of combination the unanimity property and the marginalization property are satisfied, and the Opinion Pool is the only combination method that satisfies the marginalization property[240]. The marginalization property says "*the assessed probabilities should not depend on the way in which events have been grouped together*"[241].

Using the combination rules and the rules for OR and AND operators the probability of the top-event can then be calculated, which again is a fuzzy number.

Additionally so called Fuzzy Possibility Scores (FPSs) can be calculated for each event. What this basically does is defuzzifying values to get a crisp value. This can be done e.g. with the so called Center of Gravity (COG) method. Analog to the formula for trapezoidal

[239] Stone, M. (1961), p. 1340

[240] Cf. Clemen & Winkler (1999), p. 189

[241] Bedford & Cooke (2001), p. 197

fuzzy numbers by Purba et al.[242] the adopted and in the example used formula for triangles is:

$$FPS(A) = \frac{\int_l^m (x * f_A^L(x))\,dx + \int_m^u (x * f_A^R(x))\,dx}{\int_l^m f_A^L(x)\,dx + \int_m^u f_A^R(x)\,dx}$$

The calculated TFNs can be plotted together with the calculated COGs for the individual TFNs. This can be seen in Figure 28. Here the COGs for the TFNs have been calculated for an exemplary calculation of the draft bow-tie. The COGs are plotted at the corresponding x values. For better visualization the values are slightly offset of the x-axis.

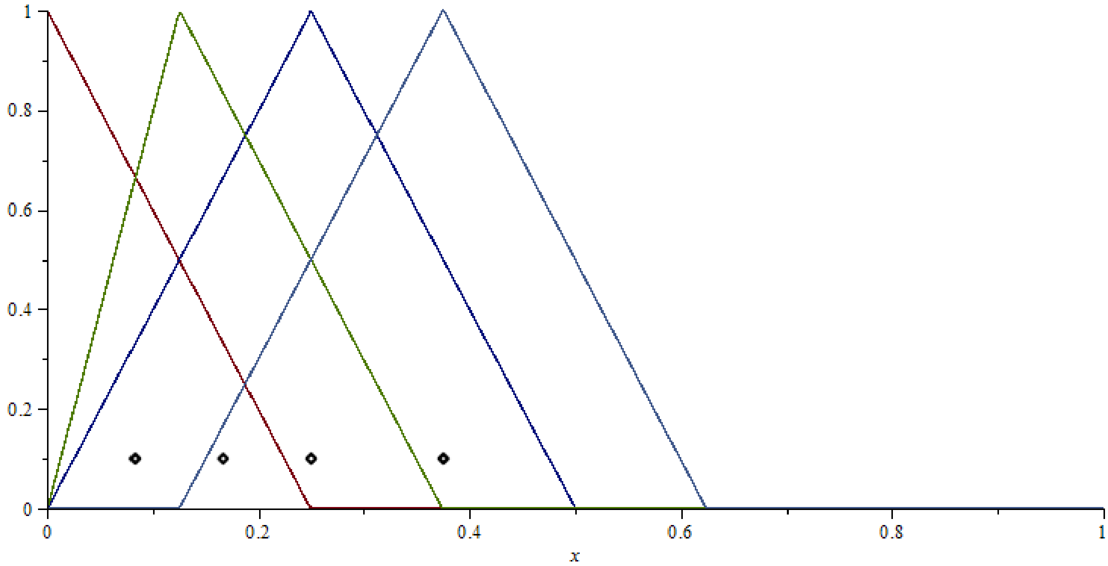


**Figure 28: TFNs with calculated COGs**

It is also possible to include barriers into the calculation that reduce the likelihood in the fault tree and reduce the severity in the event tree. Irani[243] showed that the following equation can be used to model barriers:

$$P_{Event} = P_{Failure} * P_{Barrier} * (1 - P_{Applied\ Escalator})$$

Converted into fuzzy set theory this equation can be written as:

$$P_{Event} = \min(\mu_{Failure}(x), \mu_{Barrier}(x), \mu_{Escalator}(x), inverse\lfloor\mu_{Escalator\ Controller}(x)\rfloor)$$

Where $P_{Event}$ is the probability of the top event, $P_{Failure}$ is the failure probability, $P_{Barrier}$ is the barrier probability and $P_{Applied\ Escalator}$ is the effective escalator probability that consist of the escalator probability and the escalator control probability. For the draft-bow tie barriers have also been modeled with high to very high barrier efficiency. The difference between the probability of the top event with and without barriers can be seen in Figure 29. The full code for handling data uncertainty and risk calculation can be found in Appendix D: Maple Code used for the exemplary calculation.

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[242] Purba et al. (2010), p. 195

[243] Irani, M. (2012), p. 116

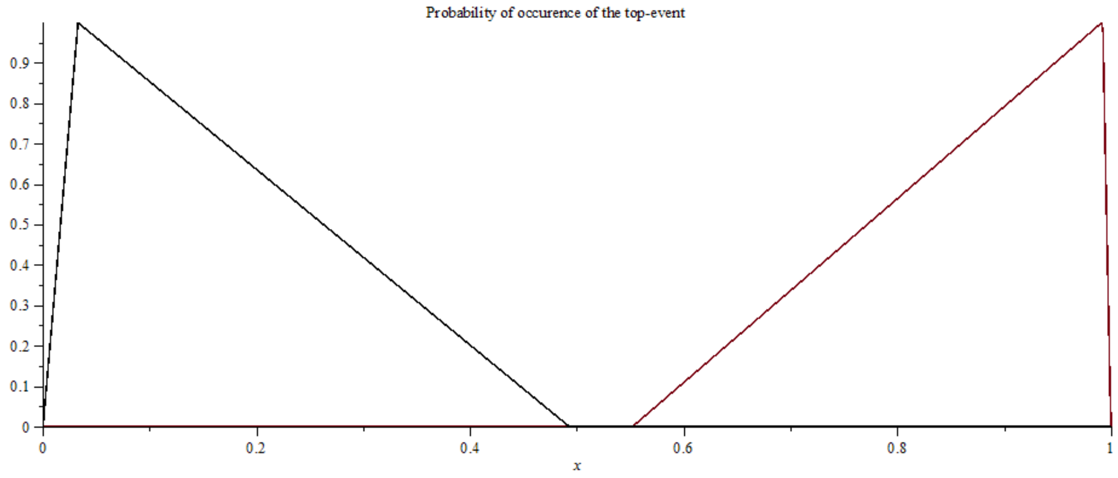



**Figure 29: Probability of occurrence of the top event with (black) and without (red) barrier modeling**

### Model uncertainty

If no model uncertainty is incorporated the threats in the fault tree are considered to be independent of each other. But it is possible to deal with interdependencies using correlation methods[244] (e.g. Frank model[245]). The here used approach to include dependencies in the fault tree analysis is based on an approach published by Li[246], which is based on the work of Misra and Weber[247]. A dependence factor, d, is used, which can also be described as a fuzzy number. The dependence factor states that for:

- d = 0 → independent
- d = 1 → complete or perfect dependency

and the conjunction and disjunction of the probabilities of the events can then be calculated with[246]

$$p(A \cap B) = [1 - (1 - d)(1 - p(A))]p(B)$$

$$p(A \cup B) = 1 - [1 - p(A)][1 - (1 - d)p(B)]$$

A code was created and tested with a simple example given in Li[246]. The sample calculation can be seen in Figure 32. The results can then be compared with the results from Li[246] (see Figure 31) and show perfect agreement. The sample calculation has been done using the fault tree (Figure 30) and equal failure probabilities of (0.4,0.5,0.6) and a dependency of B on C of (0.6,0.7,0.8).

---

[244] Cf. Shahriar et al. (2012), p. 507

[245] Frank, M. (1979)

[246] Li, H. (2007), pp. 125

[247] Misra & Weber (1989)

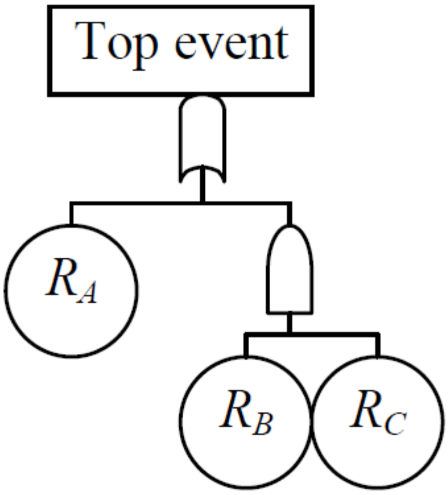



**Figure 30: Fault tree used for the sample calculation of dependencies[248]**

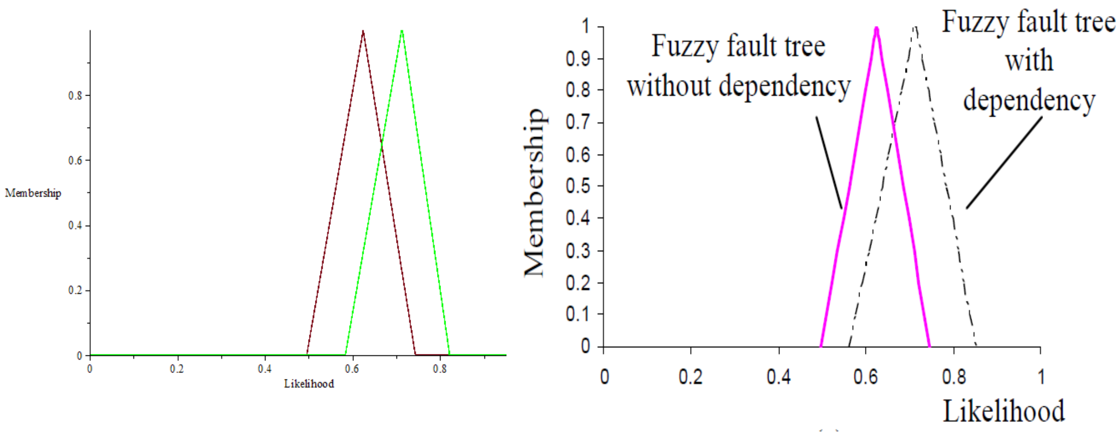



**Figure 31: Comparison of results of Li[248] (right) and Maple code (left, green with dependency and red without dependency)**

[248] Li, H. (2007), p. 124

```
Ra := Vector(3, [0.4, 0.5, 0.6]) : Rb := Vector(3, [0.4, 0.5, 0.6]) :
Rc := Vector(3, [0.4, 0.5, 0.6]) : De := Vector(3, [0.6, 0.7, 0.8]) :
MF_TopEvent := Vector(3, 1) :
RbRc := Vector(3, [Rc(1) Rb(1), Rc(2) Rb(2), Rc(3) Rb(3)]) : MF_TopEvent(3) := 1 − (1
    − Ra(3)) (1 − RbRc(3)) : MF_TopEvent(2) := 1 − (1 − Ra(2)) (1 − RbRc(2)) :
    MF_TopEvent(1) := 1 − (1 − Ra(1)) (1 − RbRc(1)) : MF_TE :=
    piecewise( MF_TopEvent(1) ≤ x and x < MF_TopEvent(2),
    (x − MF_TopEvent(1)) / (MF_TopEvent(2) − MF_TopEvent(1)), MF_TopEvent(2) ≤ x and x
    < MF_TopEvent(3), (MF_TopEvent(3) − x) / (MF_TopEvent(3) − MF_TopEvent(2)), 0) : plot(MF_TE, x = 0 ..1,
    labels = ["Likelihood", "Membership"]) : TE := plot(MF_TE, x = 0 ..1, labels
    = ["Likelihood", "Membership"]) :
#with dependency now. B has influence on C
MF_TopEventD := Vector(3, 1) :
RbRcD := Vector(3) :
RbRcD(1) := (1-(1-De(1))*(1-Rb(1)))*Rc(1);
RbRcD(2) := (1-(1-De(2))*(1-Rb(2)))*Rc(2);
RbRcD(3) := (1-(1-De(3))*(1-Rb(3)))*Rc(3);

MF_TopEventD(3) := 1-((1-Ra(3))*(1-RbRcD(3))) :
MF_TopEventD(2) := 1-((1-Ra(2))*(1-RbRcD(2))) :
MF_TopEventD(1) := 1-((1-Ra(1))*(1-RbRcD(1)));

MF_TED := piecewise(x ≥ MF_TopEventD(1) and x < MF_TopEventD(2), (x
    -MF_TopEventD(1))/(MF_TopEventD(2)-MF_TopEventD(1)), x
    ≥ MF_TopEventD(2) and x < MF_TopEventD(3), (MF_TopEventD(3)-x)
    /(MF_TopEventD(3)-MF_TopEventD(2)), 0);

TED := plot(MF_TED, x = 0 ..1, color = green);
plot(MF_TED, x = 0 ..1, title = "Probability of occurence of the top-event", labels
    = ["Likelihood", "Membership"]);
```

**Figure 32: Sample code for including dependencies**

### Fuzzy rule base matrix and definition of risk membership functions

A fuzzy rule base is needed to combine fuzzy likelihood and consequence to risk[249]. Risk can be seen as a multiplication of probability and severity. This can be written as:

$$R = L \otimes S$$

Where R is the risk, L is the likelihood and S is the severity. Because both L and S are TFNs also R will be a TFN. Linguistic risk levels can be defined in a simple matrix. This matrix could take a form like Table 8 , which is analog to the representation chosen by Li[250]. Other forms of this table are possible and can be adopted based on the application. This table is to be read like this: If both severity and likelihood are low then the risk is

[249] ISO Guide 73 (2009), Access 17.02.2015

[250] Li, H. (2007), p. 93

considered to be very low. If both likelihood and severity are very high then the risk level is considered to be very high.

| Risk level | Likelihood | Severity |
|---|---|---|
| Very low | Very Low | Very Low |
| Low | Low | Low |
| Medium | Medium | Medium |
| High | High | High |
| Very High | Very High | Very High |

**Table 8: Risk levels based on likelihood and severity**

Using the definition of risk it is now possible to determine the membership functions for risk. Before the risk membership functions can be calculated, the severity membership functions are needed. The calculation procedure is the same as for the likelihood TFNs and also a 5 granular scale has been used with the linguistic scale: very low, low, medium, high and very high. The calculated severity membership functions can be seen in Figure 33 and the membership functions for risk can be seen in Figure 34.

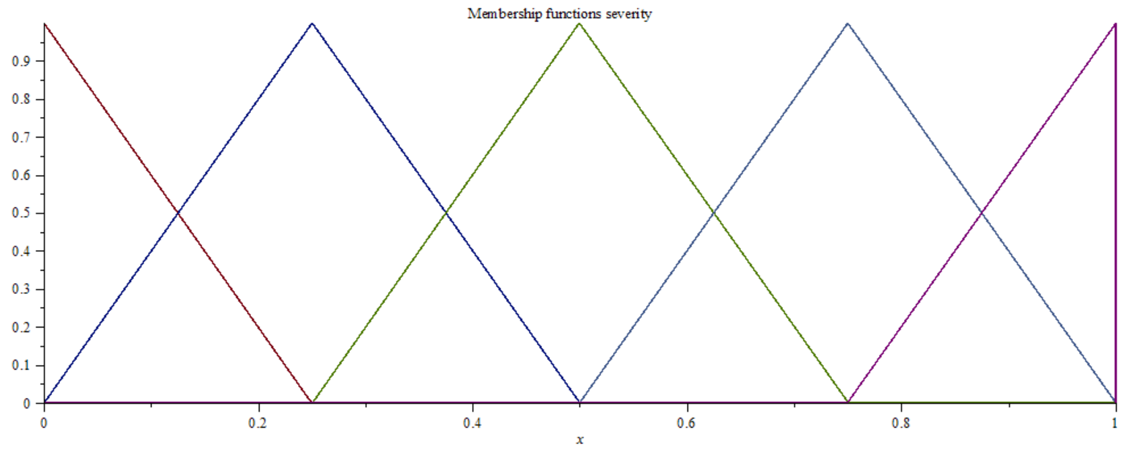



**Figure 33: Membership functions for severity used for the draft bow-tie**

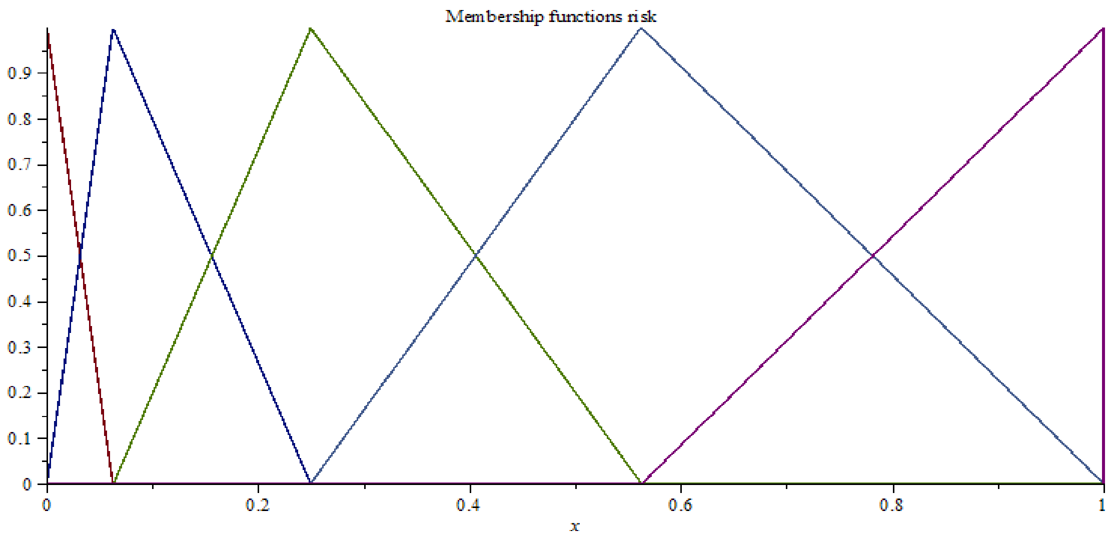



**Figure 34: Membership functions for risk as used for the draft bow-tie**

### Risk calculation

When the risk level has to be determined using the bow-tie it is very unlikely that exactly one of the defined risk-levels is obtained. Also multiple risk levels could be determined, depending on the type of analyzed risk. Risk could be financial, safety, environmental, quality or other of nature, and the severity for each category can be different.

When risks levels are determined and are to be matched to the predefined TFNs for risk, a method has to be chosen to assign the calculated risk to the risks linguistic risk scale (Table 8). One method is to use the Overlap Area (OA) method, shown by Li[251] using the following equations:

$$C_{A,B} = \frac{OA_{A,B}}{AR_B}$$

$$OA_{A,B} = \int_0^1 \min(\mu_A(x), \mu_B(x))\, dx$$

$$AR_B = \int_0^1 \mu_B(x) dx$$

where $C_{A,B}$ is the degree of intersection between two TFNs A and B, $OA_{A,B}$ is the overlapping area of the two TFNs (see Figure 35) and $A_{RB}$ is the area of B. $\mu_A(x)$ and $\mu_B(x)$ are the membership functions for A and B. In Figure 35 also a specific alpha-cut is shown, which Li[252] used in the calculations. However, here a different method was chosen without the use of alpha-cuts.

[251] Li, H. (2007), p. 99

[252] Li, H. (2007)

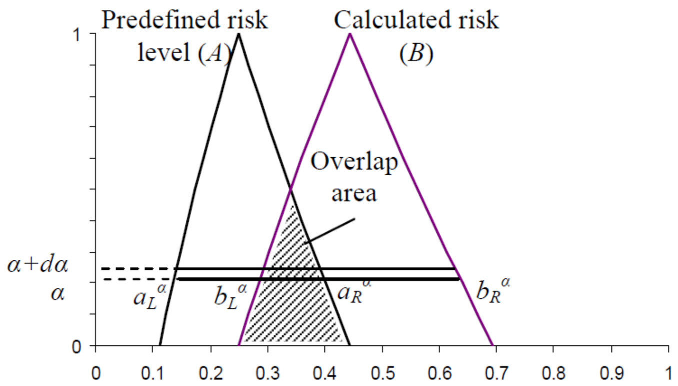



**Figure 35: Predefined risk (A) and calculated risk (B) areas used for the overlap method[253]**

The calculation procedure that was used to calculate the degree of intersection area consists of:

- Calculation of the intersections between the TFNs
- Identification of the 27 possible cases of overlapping (Appendix C: Figure A 3)
- Calculation of the overlapping areas
- Calculation of the degree of intersection

A possible code to find the intersections-points, which are needed for the calculation of the overlapping are can be seen in Figure 36. The results for an exemplary run of the code for the draft-bow tie can be seen in Appendix C Figure A 4. For calculating the overlapping areas a code has been written and can be seen in Appendix C Figure A 5. For the calculation of $C_{A,B}$ for all included risk levels and events also a simple code can be used (see Figure 37).

In order to determine to what degree a calculated risk belongs to a certain risk level the following equation can be used[254]:

$$r_{ij} = \frac{C_{R_i,R}}{\sum_{i=1}^{5} C_{R_i,R}}$$

where r is the degree of a risk j belonging to risk level i.

The created code for calculating the r-values can be seen in Figure 38. The calculated risk levels for the sample calculation of the draft bow-tie can be seen in Figure 39. When barriers (here modeled as highly effective barriers) are included the risk levels are decreasing, as can be seen in Figure 40.

[253] Li, H. (2007), p. 99

[254] Li, H. (2007), p. 101

```
AR := Vector(Number_of_consequences) :
Boundary := Matrix(Number_of_consequences, Number_of_options) : for i to
    Number_of_consequences do
        for j to Number_of_options do
            Boundary(i, j) := Vector(3)
        end do
    end do : for i to Number_of_consequences do
        AR(i) := ∫_0^1 MF_Risk(i) dx;
        for j to Number_of_options do
            s := 0;
            s := solve({MF_Risk(i) = RMembership_function(j)}, x, useassumptions)
            assuming 0 < x and x < 1 and 0.0001 < MF_Risk(j);
            number := nops([s]);
            if 1 < number then
                counter := 1;
                a := Vector(number);
                b := Vector(number);
                for n to number do a(n) := s_n; b(n) := rhs(a(n)_1) end do;
                x := 0;
                for n to number do
                    if min(Consequence_Risks(i, 1), RMinX(j)) < b(n) and b(n)
                     < max(Consequence_Risks(i, 3), RMaxX(j)) then
                        Boundary(i, j)(counter) := b(n); counter := counter + 1
                    end if
                end do
            end if;
            if number = 1 then
                x := 0;
                a := 0;
                b := 0;
                a := s_1;
                b := rhs(a);
                if min(Consequence_Risks(i, 1), RMinX(j)) < b and b
                 < max(Consequence_Risks(i, 3), RMaxX(j)) then
                    Boundary(i, j)(1) := b
                end if
            end if;
            unassign('x')
        end do
    end do :
```

**Figure 36: Sample code for calculating the intersection between TFNs**

```
C := Matrix(Number_of_consequences, Number_of_options) :
for i to Number_of_consequences do
        for j to Number_of_options do
            C(i, j) := OA(i, j) / AR(i)
        end do
    end do :
```

**Figure 37: Sample code for calculation of C values for all possible risk levels and events**

```
r := Matrix(Number_of_consequences, Number_of_options) :
C_sum := Vector(Number_of_consequences) :
for i from 1 to Number_of_consequences do
 for j from 1 to Number_of_options do
  C_sum(i) := C_sum(i) + C(i,j) :
 end do:
end do:
C_sum;

for i from 1 to Number_of_consequences do
 for j from 1 to Number_of_options do
  r(i,j) := C(i,j) / C_sum(i) :
 end do:
end do:
```

**Figure 38: Sample code for calculation of r, the degrees of calculated risk**

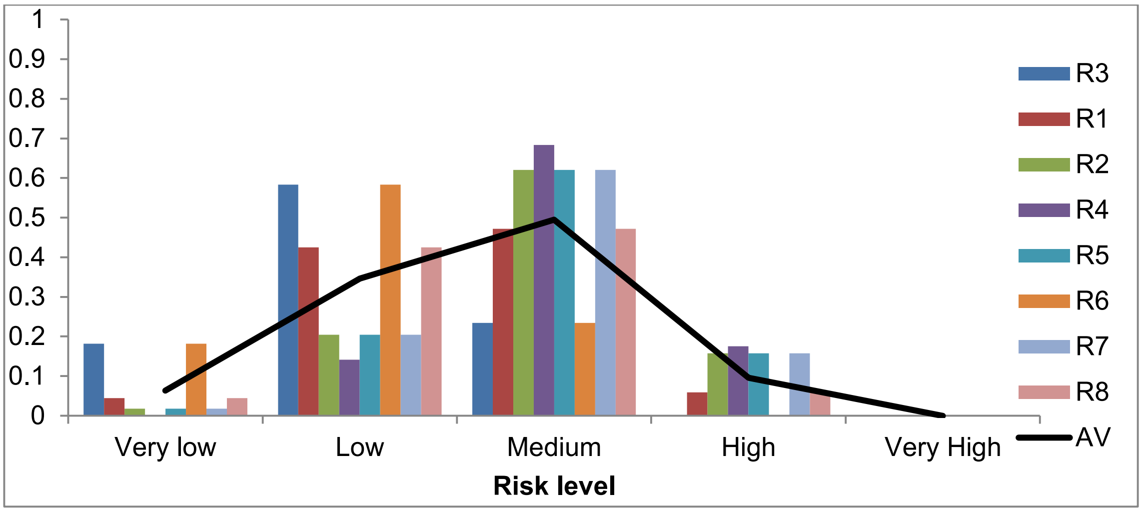



**Figure 39: Calculated risk levels for different consequences (R1-R8) without barriers**

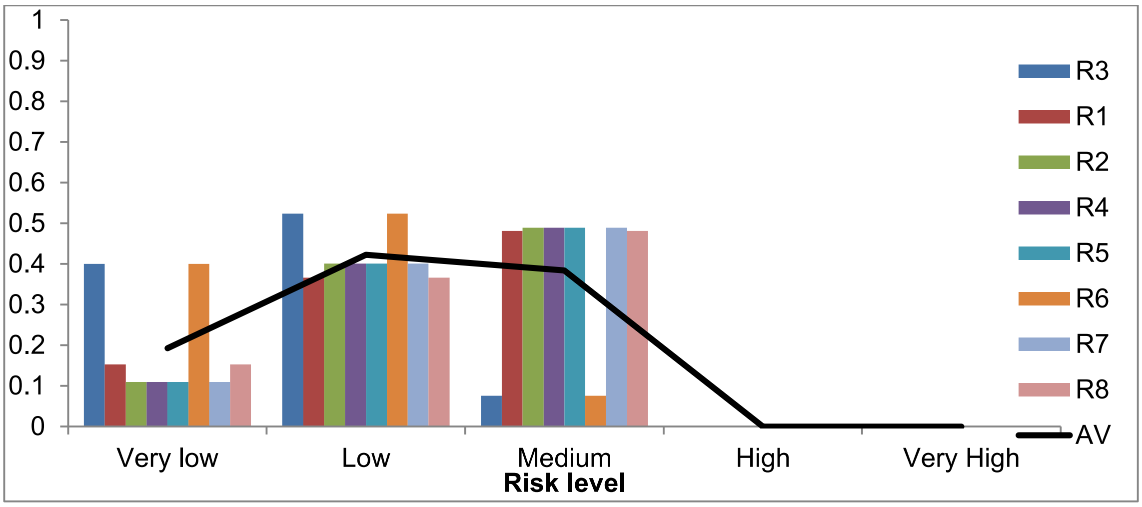


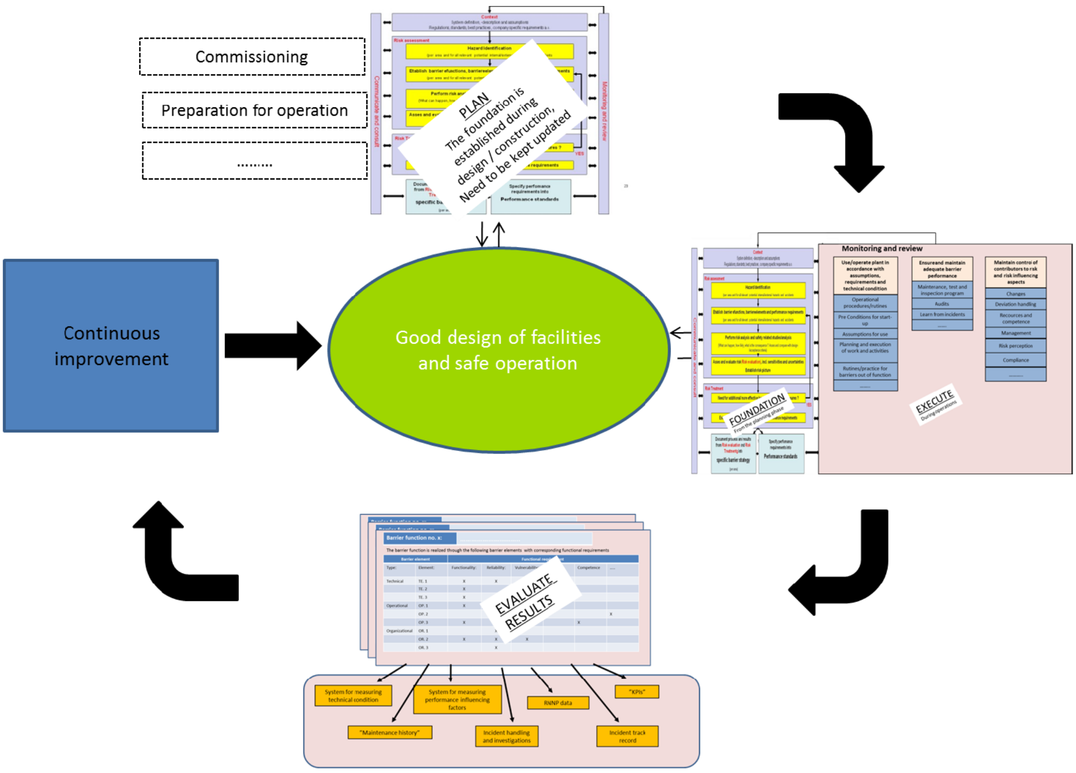

**Figure 40: Calculated risk levels for different consequences (R1-R8) and an average (black line) including barriers that reduce the likelihood**

## 5.6 Barrier monitoring

The Petroleum Safety Authority (PSA) of Norway stated in 2013 that "*failure or weakening of barriers is a frequent cause of undesirable incidents in the petroleum sector*"[255]. Therefore the PSA developed a model for barrier management (

Figure 41). This model is applied in the planning, design and construction phase and can be seen as a process of continuous improvement, with a typical PDCA (plan-do-check-act) cycle. Eventually this process should lead to barriers that meet all requirements and to a commissioning of the facilities.

Measuring of barrier performance has to be conducted to find malfunctioning barriers or ineffective barriers. Depending on the type of barrier many different measuring mechanisms can be applied. E.g. for a technical barrier the testing and the maintenance of the control mechanism could be sufficient. Generally, maintenance and its quality is a necessary condition to maintain or improve the performance of a barrier over time[256]. In the PSA (2013) "Principles for barrier management in the petroleum industry"[257] considerations regarding the maintenance can be found.




255 PSA (2013), Access 10.02.2015

256 Cf. PSA (2013), p. 26

257 PSA (2013)

**Figure 41: PSA barrier management model**[258]

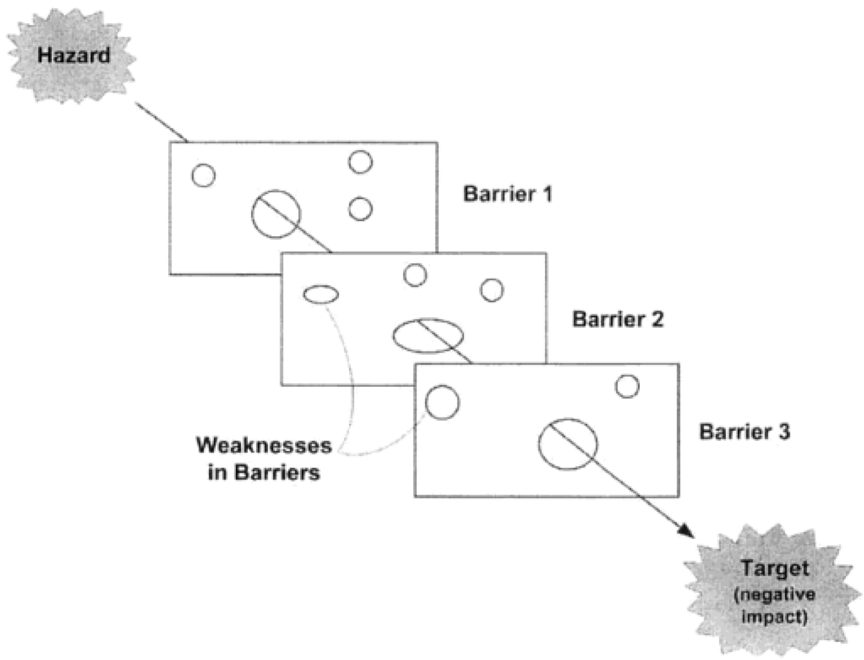



**Figure 42: Swiss cheese model or Hazard-Barrier-Target Theory**[259]

For the top-event to occur usually at least one barrier has to fail. Regardless of the amount of barriers, it is always theoretically possible that a top-event occurs. This can be described with the so-called Swiss cheese model or Hazard-Barrier-Target concept[260] (Figure 42).

Incident investigation should therefore also focus on the barriers. Most incident investigations try to find the so called root causes, which are very often understood as the shortcomings of the safety management system. This is leading to many investigations that are mainly focused only on the system failures and not enough on the failures of the barriers[261]. To find the root causes a technique called Systematic Cause Analysis Technique (SCAT) can be applied. It can be seen in Figure 43 that this method starts with the consequence and breaks down this event by going through the classification of the type of event, finding the immediate causes (e.g. wrong material or other specific causes) and then finding the root causes, the deficiencies in the safety management system.

The Barrier-based Systematic Cause Analysis Technique (BSCAT) uses a similar approach, but applies the SCAT to every barrier (Figure 43). Using the BSCAT ensures

[258] PSA (2013), p. 8

[259] Center for Chemical Process Safety (CCPS) (2003), p. 39

[260] Cf. Center for Chemical Process Safety (CCPS) (2003), p. 38

[261] Cf. Pitbaldo, R. & Fisher, M. (2012), p. 1

that there will be at least on root cause found for every failed barrier. This helps to understand why each barrier has failed and how the performance of this barrier can be improved[262].

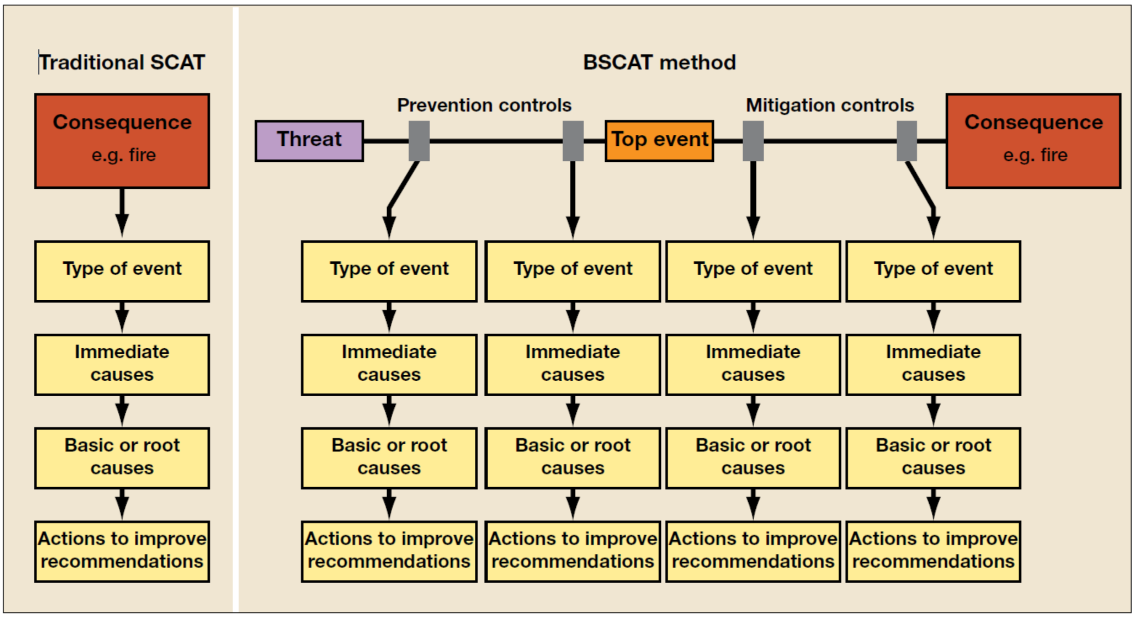



**Figure 43: SCAT and BSCAT method comparison[263]**

## 5.7 Current studies within the project Underground Sun Storage

Within the project Underground Sun Storage studies regarding the storage of hydrogen in porous rocks are conducted within multiple work packages (WP) of this project (see Figure 2 for a list of these work packages). At the time of the writing of this thesis some of these WP have not been completed and therefore only preliminary results are available. The here presented results have been presented on 21 November 2014 at the second stakeholder workshop of the Underground Sun Storage project. After completion of these work packages relevant findings should be included in the risk assessment process.

### 5.7.1 WP 2 Geochemistry and Reactive Transportmodelling[264265]

Research, conducted at the Montanuniversitaet Leoben, Reservoir Engineering Institute, by Azizmohamadi, S and Hassannayebi, N. focused on the geochemical modeling of underground hydrogen storage. A geochemical model was created, using field data in the form of core analysis and water analysis. Using the GEMS simulator (geochemical

[262] Cf. Pitbaldo, R. & Fisher, M. (2012), p. 6

[263] Pitbaldo, R. & Fisher, M. (2012), p. 6

[264] Azizmohammadi, S. & Hassannayebi, N. (2014)

[265] Rockmann, R. (2014)

software) research dealing with pure hydrogen injection and hydrogen / methane into the porous medium has been performed.

The presenters drew the following conclusions from their studies for the equilibrium conditions[266]:

- Injection of pure $H_2$ increases the pH. This is in agreement with the analysis of Pichler[267], but contradictory to Pudlo[268].
- Only methane is produced in the gas phase when hydrogen is injected.
- A critical amount of hydrogen is needed for hydrogen to be present in the gas phase. Over this critical amount the reactions with minerals and aqueous phases decrease and more hydrogen is in the gas phase.
- The change in the pH triggers the formation of pyrrhotite from pyrite at reservoir conditions.
- High concentrations of $K^+$ are observed due to the dissolution of muscovite.
- Mineral abundance could be portrayed in three categories:
    - Minerals existing in the beginning and dissolving during hydrogen injection
    - Minerals that first precipitate and then dissolve
    - Minerals that precipitate and remain constant afterwards
- For gas mixtures of 5 % hydrogen and 95 % methane the following conclusions have been drawn:
    - Same trends as for pure hydrogen injection could be observed for aqueous and mineral phases
    - High uncertainty is present
    - Injected methane mostly stays in the gas phase

Also at DBI Gas- und Umwelttechnik GmbH laboratory investigations for WP 2 have been conducted with project leader Rockmann, R.. The focus was on investigations of the cap rock, gas mixing and permeability measurements of gas mixtures, the influence of formation waters on cores and reservoir alteration. The results regarding these topics are as follows[269]:

- Cap rock permeabilities are in the same order of magnitude for both methane and hydrogen, therefore impermeability of the cap rock to hydrogen is confirmed.

---

[266] Cf. Azizmohammadi, S. & Hassannayebi, N. (2014), p. 19

[267] Pichler, M. (2013)

[268] Pudlo (2013)

[269] Cf. Rockmann, R. (2014), pp. 4

- The stability of concrete is not significantly influenced by the presence of hydrogen for investigated exposure times of 2 and 6 months. A 12-month exposure time concrete core test is still ongoing.

Investigations regarding the gas mixing and permeability of gas mixtures and tests regarding the influence of formation waters on cores are still ongoing. Also thin-sections of reservoir cores are in preparation.

### 5.7.2 WP 3 Microbial Processes in Hydrogen Exposed Reservoirs[270]

At IFA-Tulln (Department of BOKU, University of Natural Resources and Life Sciences, Vienna) simulation experiments in high-pressure bioreactors are performed. They investigated the conditions that minimize microbial hydrogen consumption and $H_2S$ generation, adverse changes in the reservoir for a hydrogen concentration of 10 % and the influence of $CO_2$ in the reservoir. The experiments have not been finished yet but preliminary results have already been presented by Schritter, J. & Loibner, A. P.[271] at the second stakeholder workshop on 21 November 2014:

- Microbial hydrogen consumption was observed when $CO_2$ was present
- Over-stoichiometric amounts of hydrogen decrease slowly
- No significant $H_2S$ generation could be found
- Reactors without microorganisms show a constant hydrogen concentration
- Different redox-reactions could be catalyzed by many microorganisms present in the reservoir
- Available electron acceptors and environmental conditions control the dominant processes in the reservoir.

### 5.7.3 WP 4 Demixing of Natural Gas and Hydrogen[272]

At the Montanuniversitaet Leoben, Chair of Process Technology and Industrial Environmental Protection, experiments dealing with the demixing of natural gas and hydrogen are conducted. Both static and dynamic reservoir conditions are modeled. For the static experiments reactor pressures of 10, 25 and 40 bar have been chosen with a gas mixture consisting of 7 % hydrogen and 93 % methane. The three reactors were held at a temperature of approximately 40 °C and have been filled with dry sand and all three reactors had a volume of 124 liters[273].

[270] Schritter, J. & Loibner, A.P. (2014)

[271] Cf. Schritter, J. & Loibner, A.P. (2014), p. 22

[272] VTiU (2014)

[273] Cf. VTiU (2014), pp. 4

The static test with 10 bar pressure is scheduled to continue until April 2015[274], but the preliminary results show that no demixing of natural gas and hydrogen occurs under static conditions.

Dynamic test have not started yet and are scheduled to start in January 2015[275]. These tests will consist of measurements of the gas during depletion of the reactors starting with 25 and 40 bar.

### 5.7.4 WP 5 Materials and Corrosion[276]

This WP, conducted at the Montanuniversitaet Leoben, by Vidic, K.J., Mori, G., Visser, A. and Oberndorfer, M. focused on the testing of different steel types regarding their susceptibility against hydrogen embrittlement. The main steel types investigated were L80 and P110, but also investigations regarding 42CrMo4, L360 and P235 have been performed[277]. They conducted SSRT (slow strain rate testing), CLT (constant load testing) and immersion tests with hydrogen (determination of absorbed hydrogen).

They concluded on basis of the test results[278]:

- No significant reduction of ductility of L80, P110, 42CrMo4 GM, 42CrMo4 WBH, L360 and P235 for $H_2$ pressures of up to 10 bar
- L80 and P110 do not fail in the CLT with 100 % $_{Rp0.1}$ within 720 hours under low-pressure $H_2$ exposure
- No hydrogen absorption could be measured for L80 and P110 at low hydrogen pressures
- $H_2S$ caused a critical reduction of fracture elongation and increased the absorption of hydrogen

### 5.7.5 Modeling of Coupled Hydrodynamic and Bioreactive Processes in UHS[279]

This modeling of coupled hydrodynamic and bioreactive processes was not part of a WP in the Underground Sun Storage project, but was also presented at the stakeholder workshop on 21 November 2014 by Hagemann, B. and Panfilov, M. (not present at the meeting).

Main points of their conclusions were[280]:

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[274] VTiU (2014), pp. 31

[275] VTiU (2014), p. 37

[276] Vidic, K.J. et al. (2014)

[277] Cf. Vidic, K.J. et al. (2014), pp. 2

[278] Cf. Vidic, K.J. et al. (2014), p. 23

[279] Hagemann, B. & Panfilov, M. (2014)

[280] Cf. Hagemann, B. & Panfilov; M. (2014), p. 30

- Hydrogen spreads laterally faster than methane
- Lateral fingers appear during fast hydrogen injection
- Partial transformation of the injected hydrogen in methane and water occurs because of microorganisms.
- Methanogenic archaea, sulfate-reducing bacteria and iron-reducing bacteria are important for underground hydrogen storage.
- All available kinetic models fail in the reproduction of batch culture experiments (lag and stationary phases are not modeled).

# 6 Summary and conclusion

Currently ongoing research projects examine the possibility of renewable energy storage in existing underground gas storages. One approach is to store a mixture of hydrogen, generated via electrolysis, and methane in subsurface natural gas storage. Different underground storage options exist. The storage in a porous medium and more specifically in a depleted gas field is of special interest because RAG has launched a pilot project, called “Underground Sun Storage”, for the storage of a hydrogen-methane gas mixture in such a storage type.

Due to the uniqueness of this project a lot of research is still ongoing regarding the effects of hydrogen on the storage system. Although other instances of hydrogen subsurface storage are known, like town gas operations in various European countries, the experience of the industry with this type of storage is still considered to be low. Therefore the uncertainties concerning the interaction of hydrogen with the system are high. Consequently a thorough safety risk analysis is required.

The bow-tie analysis lends itself well for multiple reasons. It provides an easily understandable way of communicating and understanding risk. The implementation of barriers, both preventive and mitigative, and the good visualization of these controls within the bow-tie diagram provides an additional benefit. The bow-tie analysis was found to be heavily used within the E & P industry, and thus the experience with such a method is already high. Also the possibility of a quantitative analysis using fuzzy logic exists, which was demonstrated by Irani (2012), Li (2007) and others. A Maple code has been created to calculate risk values in both fuzzy and non-fuzzy form.

It was found that using the available literature the fault tree side (left side) of the bow-tie could be populated with many threats for the top-event “Loss of containment of hydrogen”. The event tree side (right side) of the bow-tie is lacking consequences for the chosen top-event. Only analogies to the carbon dioxide storage could be drawn to populate this side of the diagram.

On the topic of threats the highest uncertainties and biggest challenges can be found in the microbiological activity caused by hydrogen. The bacterial population in the subsurface is difficult to quantify and qualify in terms of bacterial type. Disinfectant experiments conducted in the 1970's did not show promise. Hence no specific preventive control for the threats caused by microbiological activity could be found. Preliminary results from experiments conducted within the Underground Sun Storage project show that for this case no significant amounts of $H_2S$ are produced, although many redox reactions could be catalyzed by the presence of bacteria in the porous medium.

It can be concluded that for the consequences of the loss of containment of hydrogen still major uncertainties exist and further research should be conducted. It is essential to incorporate expert opinions. Exemplary questionnaires, like provided, should be used to complete the threats, consequences and barriers of the bow-tie diagram. Also a barrier monitoring and performance optimization procedures following a PDCA cycle are suggested. In case of quantitative analysis the high uncertainty and low experience with this type of project should be taken into account by the application of fuzzy logic to the bow-tie analysis.

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# Appendix A: Supplementary Tables and Figures

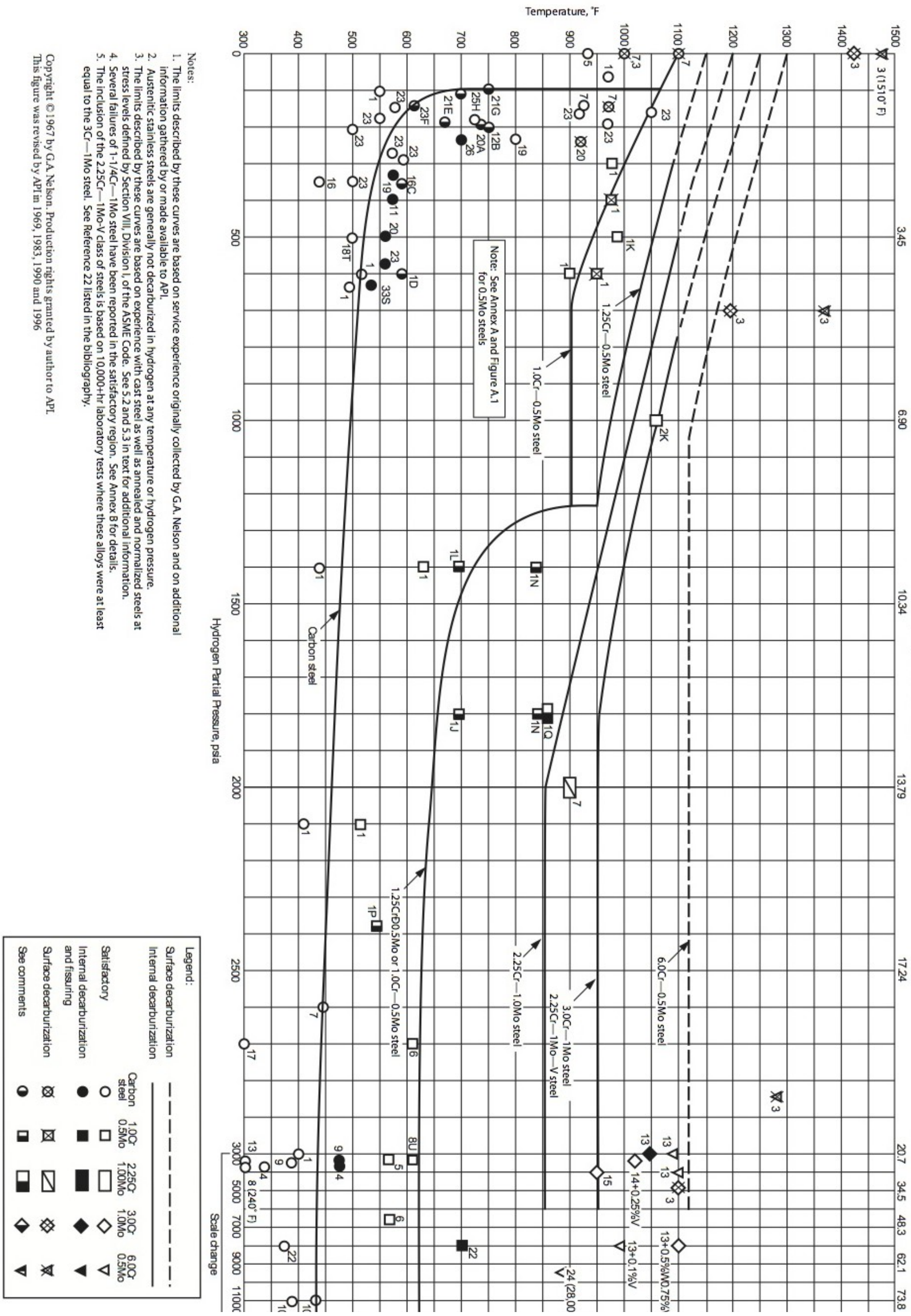


**Figure A 1: Operating Limits for Steels in Hydrogen Service to Avoid Decarburization and Fissuring (API 941)**

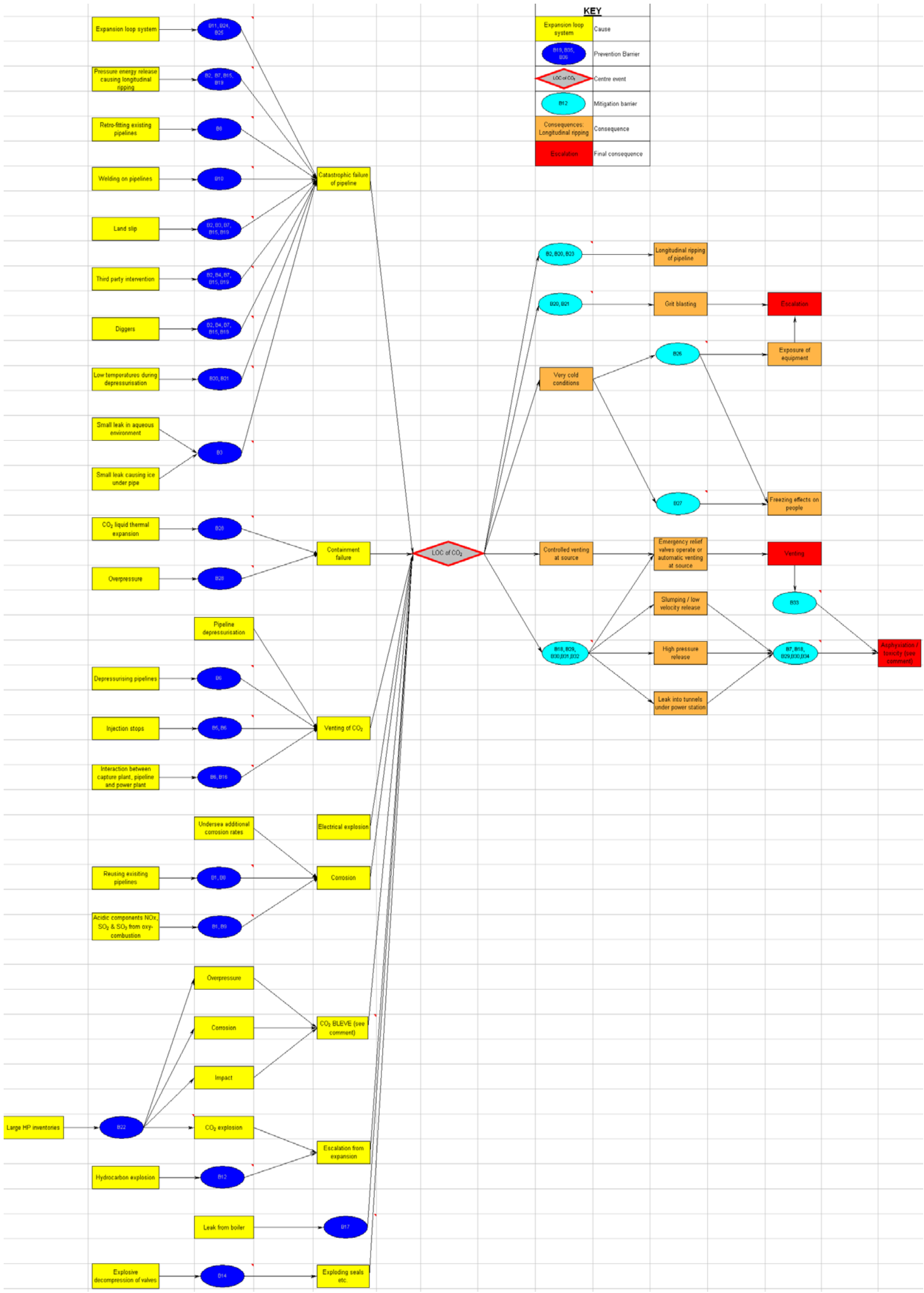


**Figure A 2: Bow tie for loss of containment of CO2 (IEA (2009), p 30)**

# Appendix B: Questionnaires

## B.1: Questionnaire for the identification of threats and consequences

This questionnaire has been prepared to identify threats and consequences for the underground storage of hydrogen in a porous medium. Consider the event “Loss of containment of hydrogen” and mark either YES or NO in the boxes next to the statements. For causes /threats YES means that this could be a threat leading to the event “Loss of containment of hydrogen”, NO means that this is not a cause. For consequences YES means that this is a possible consequence for the top-event “Loss of containment”, NO means that this is not a possible consequence.

Room for additional consequences /threats is below every category and at the end of the questionnaire for consequences / threats that do not fit into one of the categories. Additional comments are welcome. Please write them at the end of the questionnaire.

| **Part 1: Threats / Causes** | | | |
|---|---|---|---|
| Category | Threat / Cause | YES | NO |
| Casing / Tubing | H2 Embrittlement | ☐ | ☐ |
| | Corrosion due to redox reactions | ☐ | ☐ |
| | Corrosion due to H2S | ☐ | ☐ |
| | Additional Threats: Please write down additional threats in the next rows | | |
| | | | |
| | | | |
| | | | |
| Cement | Fractures | ☐ | ☐ |
| | Diffusion | ☐ | ☐ |
| | Viscous Flow | ☐ | ☐ |
| | Biochemical and geochemical reactions | ☐ | ☐ |
| | Additional Threats: Please write down additional threats in the next rows | | |
| | | | |
| | | | |

| | | | |
|---|---|---|---|
| Valves | Diffusion | ☐ | ☐ |
| | Blistering of elastomers | ☐ | ☐ |
| | Additional Threats: Please write down additional threats in the next rows | | |
| | | | |
| | | | |
| | | | |
| Packers | $H_2$ embrittlement | ☐ | ☐ |
| | Blistering of elastomers | ☐ | ☐ |
| | Additional Threats: Please write down additional threats in the next rows | | |
| | | | |
| | | | |
| | | | |
| Caprock | Leakage due to changes in the stress field: | | |
| | → Storage induced (Capillary leakage, hydraulic fracturing, shear-deformation fracturing) | ☐ | ☐ |
| | → Storage activated (Fault-Related Flow, Pre-existing fissures and fractures) | ☐ | ☐ |
| | → Tectonic | ☐ | ☐ |
| | Diffusion through caprock | ☐ | ☐ |
| | Microbiological and geochemical reactions | ☐ | ☐ |
| | Additional Threats: Please write down additional threats in the next rows | | |
| | | | |
| | | | |
| | | | |
| Storage space | Microbiological: | | |
| | → In-situ self-organization (CH4 / CO2 ratio) | ☐ | ☐ |

| | | | |
|---|---|---|---|
| | → Generation of $H_2S$ | ☐ | ☐ |
| | → Generation of $CH_4$ | ☐ | ☐ |
| | → Accumulation of biomass (loss of k) | ☐ | ☐ |
| | → Temperature increase (influence on other reactions) | ☐ | ☐ |
| | → Dissolution of rock matrix | ☐ | ☐ |
| | → Precipitation (e.g. illite) | ☐ | ☐ |
| | Geochemical: | | |
| | → $H_2 + O_2 \rightarrow H_2O$ | ☐ | ☐ |
| | → $H_2 + S \rightarrow H_2S$ | ☐ | ☐ |
| | → $H_2 + 3\, Fe_2O_3 \rightarrow 2\, Fe_3O_4 + H_2O$ | ☐ | ☐ |
| | → $FeS_2 + 2\, H_2SO_4 + H_2 \rightarrow FeSO_4 + 2\, H_2S$ | ☐ | ☐ |
| | → Change of pH (influence on other reactions) | ☐ | ☐ |
| | Additional Threats: Please write down additional threats in the next rows | | |
| | | | |
| | | | |
| | | | |
| Formation water | Diffusion of hydrogen into water | ☐ | ☐ |
| | pH Change | ☐ | ☐ |
| | Additional Threats: Please write down additional threats in the next rows | | |
| | | | |
| | | | |
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| | |
|---|---|
| Additional threats not fitting in the proposed categories | |
| Category | Threat |
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| Comments |
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| Part 2: Consequences | | |
|---|---|---|
| Consequence | YES | NO |
| Hydrogen leaves tubing and is contained in annulus / casing | ☐ | ☐ |
| Hydrogen flows up in the tubing and is released to the surface | ☐ | ☐ |
| Hydrogen enters ground water via fractures | ☐ | ☐ |
| Hydrogen enters drinking water via fractures | ☐ | ☐ |
| Hydrogen enters ground water via cement leakage | ☐ | ☐ |
| Hydrogen enters drinking water via cement leakage | ☐ | ☐ |
| Lateral migration connected to aquifer | ☐ | ☐ |
| Lateral migration in secondary store | ☐ | ☐ |
| Deep release | ☐ | ☐ |
| Additional Threats: Please write down additional threats in the next rows | | |
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| Comments | | |
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# B.2: Questionnaire for the evaluation of the identified threats and consequences

This questionnaire has been prepared for the evaluation of the previously identified threats and consequences for the top-event “loss of containment of hydrogen” in case of hydrogen underground storage in a porous medium. Both likelihood and impact of the threats and consequences should be evaluated. This questionnaire only contains threats / consequences identified from the literature review and therefore causes / consequences found using the questionnaires for the identification of threats / causes and consequences are not included.

The following spectrum of likelihood applies, as it was used in Tucker et al. (2013):

- 1 … never heard of in the industry
- 2 … heard of in the industry
- 3 … has happened in the organization or more than once per year in the industry
- 4 … has happened at an underground storage location or more than once per year in the organization
- 5 … has happened more than once per year at an underground storage location

The following spectrum of impact / severity applies:

- 1 … insignificant
- 2 … minor
- 3 … moderate
- 4 … major
- 5 … catastrophic

| **Part 1: Evaluation of threats / causes** | | | |
|---|---|---|---|
| **Well** | **Threat** | **Likelihood** | **Impact** |
| Casing / Tubing | $H_2$ embrittlement | | |
| | Corrosion due to H2S | | |
| Cement | Fractures | | |
| | Diffusion | | |
| | Viscous Flow | | |
| | Biochemical and geo-chemical reactions | | |
| Valves | Diffusion | | |
| | Blistering of elastomers | | |
| Packers | $H_2$ embrittlement | | |
| | Blistering of elastomers | | |
| **Well** | **Threat** | **Likelihood** | **Impact** |
| Caprock | *Leakage due to changes in the stress field* | | |

| | | | |
|---|---|---|---|
| | → Storage induced (Capillary leakage, hydraulic fracturing, shear-deformation fracturing) | | |
| | → Storage activated (Fault-Related Flow, Pre-existing fissures and fractures) | | |
| | → Tectonic | | |
| | Diffusion through caprock | | |
| | Microbiological and geochemical reactions | | |
| Storage space | *Microbiological* | | |
| | → In-situ self-organization ($CH_4$ / $CO_2$ ratio) | | |
| | → Generation of $H_2S$ | | |
| | → Generation of $CH_4$ | | |
| | → Accumulation of biomass (loss of k) | | |
| | → Temperature increase (influence on other reactions) | | |
| | → Dissolution of rock matrix | | |
| | → Precipitation (e.g. illite) | | |
| | *Geochemical* | | |
| | → $H_2 + O_2 \rightarrow H_2O$ | | |
| | → $H_2 + S \rightarrow H_2S$ | | |
| | → $H_2 + 3\ Fe_2O_3 \rightarrow 2\ Fe_3O_4 + H_2O$ | | |
| | → $FeS_2 + 2\ H_2SO_4 + H_2 \rightarrow FeSO_4 + 2\ H_2S$ | | |
| | → Change of pH (influence on other reactions) | | |
| Formation water | Solubility of hydrogen in water | | |
| | pH change | | |

| Part 2: Evaluation of consequences | | |
|---|---|---|
| **Consequences** | **Likelihood** | **Severity** |
| Hydrogen leaves tubing and is contained in annulus /casing | | |
| Hydrogen flows up in the tubing and is released to the surface | | |
| Hydrogen enters ground water via fractures | | |
| Hydrogen enters drinking water via fractures | | |
| Hydrogen enters ground water via cement leakage | | |
| Hydrogen enters drinking water via cement leakage | | |
| Deep release (above secondary seal) | | |
| Lateral migration connected to aquifer | | |
| Lateral migration in secondary store | | |

# B.3: Questionnaire for the identification of barriers

This questionnaire has been prepared for the identification of preventive and recovery controls for the listed threats and consequences of the top-event “loss of containment of hydrogen” in case of hydrogen underground storage in a porous medium.

| Well | Threat | Preventive control / Monitoring from literature analysis |
|---|---|---|
| Casing / Tubing | $H_2$ embrittlement | • Well design construction & completion |
| | | • Pore Pressure Prediction and Monitoring |
| | | • Well Tests |
| | | |
| | | |
| | | |
| | | |
| | Corrosion due to H2S | • Well design, construction & completion |
| | | • Pore Pressure Prediction and Monitoring |
| | | • Well Tests |
| | | |
| | | |
| | | |
| | | |
| Cement | Fractures | • Small grain size |
| | | • Low water content |
| | | • Low $SiO_2$ concentration |
| | | • Use of synthetic rubber |

| | | |
|---|---|---|
| | | • Pore Pressure Prediction and Monitoring |
| | | • Well Tests |
| | | |
| | | |
| | | |
| | | |
| | Diffusion | • Small grain size |
| | | • Low water content |
| | | • Low $SiO_2$ concentration |
| | | • Pore Pressure Prediction and Monitoring |
| | | • Well Tests |
| | | |
| | | |
| | | |
| | | |
| | Viscous Flow | • Small grain size |
| | | • Use of synthetic rubber as additive |
| | | • Pore Pressure Prediction and Monitoring |
| | | • Well Tests |
| | | |
| | | |
| | | |
| | | |
| | Biochemical and geochemical reactions | • Pore Pressure Prediction and Monitoring |
| | | • Well Tests |
| | | |
| | | |
| | | |
| | | |
| Valves | Diffusion | • Well design, construction & completion |
| | | • Pore Pressure Prediction and Monitoring |
| | | • Well Tests |
| | | • Avoid X20Cr13 |
| | | □ |
| | | □ |
| | | □ |
| | | □ |
| | Blistering of elastomers | • Well design, construction & completion |
| | | • Pore Pressure Prediction and Monitoring |
| | | • Well Tests |
| | | |

| | | |
|---|---|---|
| | | |
| | | |
| Packers | $H_2$ embrittlement | • Well design, construction & completion |
| | | • Pore Pressure Prediction and Monitoring |
| | | |
| | | |
| | | |
| | | |
| | Blistering of elasto-mers | • Well design, construction & completion |
| | | • Pore Pressure Prediction and Monitoring |
| | | • Well Tests |
| | | |
| | | |
| | | |
| | | |

| **Reservoir** | **Threat** | **Preventive control / Monitoring from litera-ture analysis** |
|---|---|---|
| Caprock | *Leakage due to changes in the stress field* | |
| | → Storage induced (Capillary leakage, hydraulic fractur-ing, shear-defor-mation fracturing) | • Pore Pressure Prediction and Monitoring |
| | | • Fault Slip Analysis |
| | | • Trap Analysis |
| | | |
| | | |
| | | |
| | | |
| | → Storage acti-vated (Fault-Re-lated Flow, Pre-ex-isting fissures and fractures) | • Pore Pressure Prediction and Monitoring |
| | | • Fault Slip Analysis |
| | | • Trap Analysis |
| | | |
| | | |
| | | |
| | | |
| | → Tectonic | • Pore Pressure Prediction and Monitoring |
| | | • Fault Slip Analysis |
| | | • Trap Analysis |
| | | |
| | | |

| | | |
|---|---|---|
| | | |
| | | |
| | Diffusion through caprock | • Pore Pressure Prediction and Monitoring |
| | | • Trap Analysis |
| | | |
| | | |
| | | |
| | | |
| | Microbiological and geochemical reactions | • Pore Pressure Prediction and Monitoring |
| | | • Trap Analysis |
| | | |
| | | |
| | | |
| | | |
| Storage space | *Microbiological* | |
| | → Generation of H2S | • Pore Pressure Prediction and Monitoring |
| | | |
| | | |
| | | |
| | | |
| | → Temperature increase (influence on other reactions) | • Pore Pressure Prediction and Monitoring |
| | | |
| | | |
| | | |
| | | |
| | *Geochemical* | |
| | → Change of pH (influence on other reactions) | • Pore Pressure Prediction and Monitoring |
| | | |
| | | |
| | | |
| | | |
| Formation water | Solubility of hydrogen in water | |
| | | |
| | | |
| | | |
| | | |
| | pH Change | • Pore Pressure Prediction and Monitoring |
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# Appendix C: Quantitative Analysis

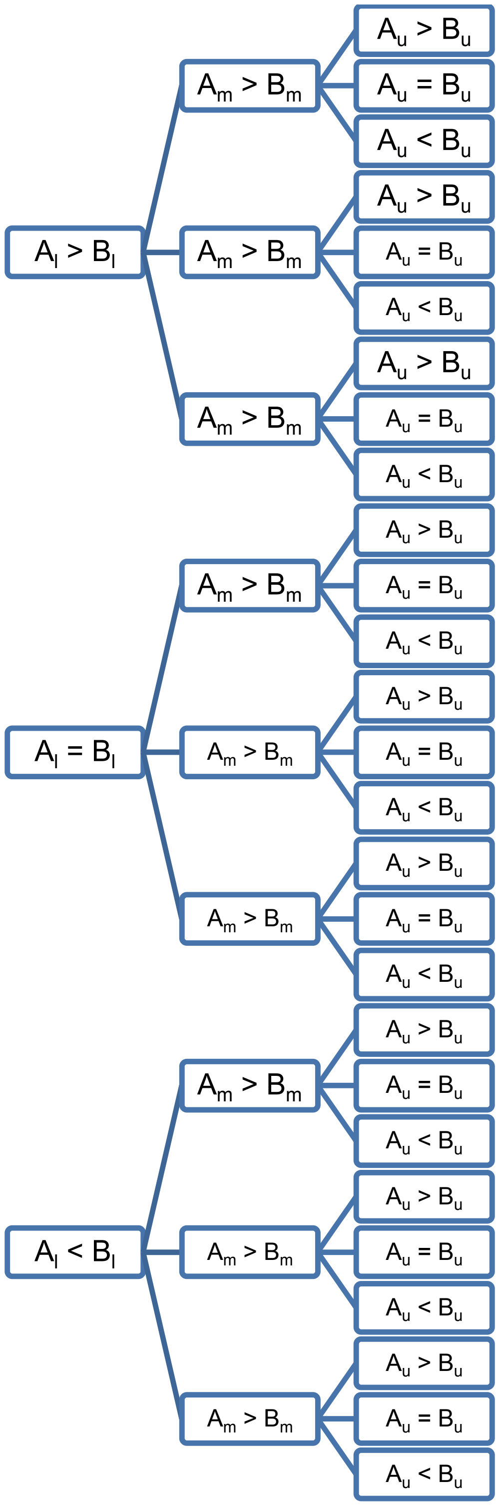



**Figure A 3: 27 Possibilities for overlapping two TFNs A and B**

$$\begin{bmatrix}0.04153983389\\0\\0\end{bmatrix}\begin{bmatrix}0.09951723444\\0\\0\end{bmatrix}\begin{bmatrix}0.1961526926\\0\\0\end{bmatrix}\begin{bmatrix}0.3193260987\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\end{bmatrix}$$

$$\begin{bmatrix}0.04990451552\\0\\0\end{bmatrix}\begin{bmatrix}0.1423391362\\0\\0\end{bmatrix}\begin{bmatrix}0.2491729018\\0\\0\end{bmatrix}\begin{bmatrix}0.3883982460\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\end{bmatrix}$$

$$\begin{bmatrix}0\\0\\0\end{bmatrix}\begin{bmatrix}0.05006394799\\0\\0\end{bmatrix}\begin{bmatrix}0.1428814343\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\end{bmatrix}$$

$$\begin{bmatrix}0\\0\\0\end{bmatrix}\begin{bmatrix}0.1573580989\\0\\0\end{bmatrix}\begin{bmatrix}0.2491729018\\0.2042082918\\0\end{bmatrix}\begin{bmatrix}0.3883982460\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\end{bmatrix}$$

$$\begin{bmatrix}0.04990451552\\0\\0\end{bmatrix}\begin{bmatrix}0.1423391362\\0\\0\end{bmatrix}\begin{bmatrix}0.2491729018\\0\\0\end{bmatrix}\begin{bmatrix}0.3883982460\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\end{bmatrix}$$

$$\begin{bmatrix}0\\0\\0\end{bmatrix}\begin{bmatrix}0.05006394799\\0\\0\end{bmatrix}\begin{bmatrix}0.1428814343\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\end{bmatrix}$$

$$\begin{bmatrix}0.04990451552\\0\\0\end{bmatrix}\begin{bmatrix}0.1423391362\\0\\0\end{bmatrix}\begin{bmatrix}0.2491729018\\0\\0\end{bmatrix}\begin{bmatrix}0.3883982460\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\end{bmatrix}$$

$$\begin{bmatrix}0.04153983389\\0\\0\end{bmatrix}\begin{bmatrix}0.09951723444\\0\\0\end{bmatrix}\begin{bmatrix}0.1961526926\\0\\0\end{bmatrix}\begin{bmatrix}0.3193260987\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\end{bmatrix}$$

**Figure A 4: Result of the intersection calculation for the draft bow-tie**

```
#Calculation of the overlapping area
OA := Matrix(Number_of_consequences, Number_of_options) :
for i from 1 to Number_of_consequences do
 for j from 1 to Number_of_options do

  if Consequence_Risks(i, 1) > RMinX(j) then

   if Consequence_Risks(i, 2) > RHighX(j) and Consequence_Risks(i, 1) < RMaxX(j) then
    if Consequence_Risks(i, 3) > RMaxX(j) then
     OA(i, j) := int(MF_Risk(i), x = 0 ..Boundary(i, j)(1)) + int(RMembership_function(j), x
       = Boundary(i, j)(1) ..1) :
    end if:
    if Consequence_Risks(i, 3) = RMaxX(j) then
     OA(i, j) := int(MF_Risk(i), x = 0 ..Boundary(i, j)(1)) + int(RMembership_function(j), x
       = Boundary(i, j)(1) ..1) :
    end if:
    if Consequence_Risks(i, 3) < RMaxX(j) then
     OA(i, j) := int(MF_Risk(i), x = 0 ..Boundary(i, j)(1)) + int(RMembership_function(j), x
       = Boundary(i, j)(1) ..Boundary(i, j)(2)) + int(MF_Risk(i), x = 0 ..1) :
    end if:
   end if:

   if Consequence_Risks(i, 2) = RHighX(j) then
    if Consequence_Risks(i, 3) > RMaxX(j) then
     OA(i, j) := int(MF_Risk(i), x = 0 ..Consequence_Risks(i, 2))
       + int(RMembership_function(j), x = Consequence_Risks(i, 2) ..1) :
    end if:
    if Consequence_Risks(i, 3) = RMaxX(j) then
     OA(i, j) := int(MF_Risk(i), x = 0 ..Consequence_Risks(i, 2))
       + int(RMembership_function(j), x = Consequence_Risks(i, 2) ..1) :
    end if:
    if Consequence_Risks(i, 3) < RMaxX(j) then
     OA(i, j) := int(MF_Risk(i), x = 0 ..1) :
    end if:
   end if:

   if Consequence_Risks(i, 2) < RHighX(j) then
    if Consequence_Risks(i, 3) > RMaxX(j) then
     OA(i, j) := int(MF_Risk(i), x = 0 ..Boundary(i, j)(1)) + int(RMembership_function(j), x
       = Boundary(i, j)(1) ..Boundary(i, j)(2)) + int(MF_Risk(i), x = Boundary(i, j)(2)
       ..Boundary(i, j)(3)) + int(RMembership_function(j), x = Boundary(i, j)(2) ..1) :
    end if:
    if Consequence_Risks(i, 3) = RMaxX(j) then
     OA(i, j) := int(MF_Risk(i), x = 0 ..Boundary(i, j)(1)) + int(RMembership_function(j), x
       = Boundary(i, j)(1) ..Boundary(i, j)(2)) + int(MF_Risk(i), x = Boundary(i, j)(2) ..1) :
    end if:
    if Consequence_Risks(i, 3) < RMaxX(j) then
     OA(i, j) := int(MF_Risk(i), x = 0 ..Boundary(i, j)(1)) + int(RMembership_function(j), x
       = Boundary(i, j)(1) ..Boundary(i, j)(2)) + int(MF_Risk(i), x = Boundary(i, j)(2) ..1) :
```

```
  end if:
 end if:

end if:

if Consequence_Risks(i, 1) = RMinX(j) then

  if Consequence_Risks(i, 2) > RHighX(j) then
  if Consequence_Risks(i, 3) > RMaxX(j) then
   OA(i, j) := int(MF_Risk(i), x = 0 ..Boundary(i, j)(1)) + int(RMembership_function(j), x
     = Boundary(i, j)(1) ..1) :
  end if:
  if Consequence_Risks(i, 3) = RMaxX(j) then
   OA(i, j) := int(MF_Risk(i), x = 0 ..Boundary(i, j)(1)) + int(RMembership_function(j), x
     = Boundary(i, j)(1) ..1) :
  end if:
  if Consequence_Risks(i, 3) < RMaxX(j) then
   OA(i, j) := int(MF_Risk(i), x = 0 ..Boundary(i, j)(1)) + int(RMembership_function(j), x
     = Boundary(i, j)(1) ..Boundary(i, j)(1)) + int(MF_Risk(i), x = Boundary(i, j)(2) ..1) :
  end if:
 end if:

 if Consequence_Risks(i, 2) = RHighX(j) then
  if Consequence_Risks(i, 3) > RMaxX(j) then
   OA(i, j) := int(MF_Risk(i), x = 0 ..Consequence_Risks(i, 2))
     + int(RMembership_function(j), x = Consequence_Risks(i, 2) ..1) :
  end if:
  if Consequence_Risks(i, 3) = RMaxX(j) then
   OA(i, j) := int(MF_Risk(i), x = 1) :
  end if:
  if Consequence_Risks(i, 3) < RMaxX(j) then
   OA(i, j) := int(MF_Risk(i), x = 1) :
  end if:
 end if:

 if Consequence_Risks(i, 2) < RHighX(j) then
  if Consequence_Risks(i, 3) > RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..Boundary(i, j)(1)) + int(MF_Risk(i), x
     = Boundary(i, j)(1) ..Boundary(i, j)(2)) + int(RMembership_function(j), x
     = Boundary(i, j)(2) ..1) :
  end if:
  if Consequence_Risks(i, 3) = RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..Boundary(i, j)(1)) + int(MF_Risk(i), x
     = Boundary(i, j)(1) ..1) :
  end if:
  if Consequence_Risks(i, 3) < RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..Boundary(i, j)(1)) + int(MF_Risk(i), x
     = Boundary(i, j)(1) ..1) :
  end if:
```

```
 end if:

end if:

if Consequence_Risks(i, 1) < RMinX(j) and Consequence_Risks(i, 3) > RMinX(j) then

 if Consequence_Risks(i, 2) > RHighX(j) then
  if Consequence_Risks(i, 3) > RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..Boundary(i, j)(1)) + int(MF_Risk(i), x
    = Boundary(i, j)(1) ..Boundary(i, j)(2)) + int(RMembership_function(j), x
    = Boundary(i, j)(1) ..1) :
  end if:
  if Consequence_Risks(i, 3) = RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..Boundary(i, j)(1)) + int(MF_Risk(i), x
    = Boundary(i, j)(1) ..Boundary(i, j)(2)) + int(RMembership_function(j), x
    = Boundary(i, j)(2) ..1) :
  end if:
  if Consequence_Risks(i, 3) < RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..Boundary(i, j)(1)) + int(MF_Risk(i), x
    = Boundary(i, j)(1) ..Boundary(i, j)(2)) + int(RMembership_function(j), x
    = Boundary(i, j)(2) ..Boundary(i, j)(3)) + int(MF_Risk(i), x = Boundary(i, j)(3) ..1) :
  end if:
 end if:

 if Consequence_Risks(i, 2) = RHighX(j) then
  if Consequence_Risks(i, 3) > RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..1) :
  end if:
  if Consequence_Risks(i, 3) = RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..1) :
  end if:
  if Consequence_Risks(i, 3) < RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..Consequence_Risks(i, 2))
    + int(MF_Risk(i), x = Consequence_Risks(i, 2) ..1) :
  end if:
 end if:

 if Consequence_Risks(i, 2) < RHighX(j) then
  if Consequence_Risks(i, 3) > RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..Boundary(i, j)(1)) + int(MF_Risk(i), x
    = Boundary(i, j)(1) ..Boundary(i, j)(2)) + int(RMembership_function(j), x
    = Boundary(i, j)(2) ..1) :
  end if:
  if Consequence_Risks(i, 3) = RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..Boundary(i, j)(1)) + int(MF_Risk(i), x
    = Boundary(i, j)(1) ..1) :
  end if:
  if Consequence_Risks(i, 3) < RMaxX(j) then
   OA(i, j) := int(RMembership_function(j), x = 0 ..Boundary(i, j)(1)) + int(MF_Risk(i), x
```

```
      = Boundary(i, j)(1)..1) :
    end if:
   end if:

  end if:


 end do:
end do:
```

**Figure A 5: Maple code for calculation of overlapping areas**

# Appendix D: Maple Code used for the exemplary calculation

```
> restart:
with(LinearAlgebra):
with(plots):
```

## Obtain assessments

```
#Experts Decision for Likelihood: 1 = very low , 5 = very high
interface(rtablesize=20):
low:=1: high:=5:
Number_of_Experts:=2:
Number_of_events:=20:
Number_of_options:=5:
> Exp_Decision_Likelihood:=Matrix(Number_of_Experts,Num-
ber_of_events,[2,2,1,2,2,1,2,2,2,2,1,3,1,2,1,2,3,1,3,1,1,1,1,2,2
,1,2,3,2,3,1,2,1,2,2,3,2,1,2,2]): #input of the questionnaire
data
#random2:=rand(low..high): #random number generator for testing
purposes
#random3:=rand(low..high):
#for i from 1 to Number_of_Experts do
 #for j from 1 to Number_of_events do
  #g:=random3():
  #Exp_Decision_Likelihood(i,j):=g:
 #end do:
#end do:
Exp_Decision_Severity:Exp_Decision_Likelihood;
```

$$\begin{bmatrix} 2 & 2 & 1 & 2 & 2 & 1 & 2 & 2 & 2 & 2 & 1 & 3 & 1 & 2 & 1 & 2 & 3 & 1 & 3 & 1 \\ 1 & 1 & 1 & 2 & 2 & 1 & 2 & 3 & 2 & 3 & 1 & 2 & 1 & 2 & 2 & 3 & 2 & 1 & 2 & 2 \end{bmatrix}$$

```
>
```

1.2 Input of Barriers: 1 =highly effective , 5 = not effective. Can be for input for each expert individually

```
> Max_Barriers:=3: #Maximum amount of barriers per event
```

```
> Barriers:=Matrix(Max_Barriers,Number_of_events):
> random2:=rand(low..2): #random number generator for numbers 1
and 2
random3:=rand(low..high):
for i from 1 to Max_Barriers do
 for j from 1 to Number_of_events do
  g:=random2():
  Barriers(i,j):=g:
 end do:
end do:
Barriers;
```

$$\begin{bmatrix} 1 & 1 & 1 & 2 & 1 & 2 & 2 & 2 & 1 & 2 & 2 & 2 & 1 & 1 & 2 & 1 & 2 & 1 & 2 & 1 \\ 2 & 2 & 2 & 2 & 1 & 1 & 1 & 2 & 1 & 2 & 1 & 2 & 2 & 1 & 1 & 2 & 2 & 2 & 2 & 1 \\ 1 & 1 & 2 & 1 & 2 & 1 & 2 & 1 & 2 & 1 & 1 & 2 & 1 & 1 & 1 & 1 & 1 & 2 & 1 & 1 \end{bmatrix}$$

# Creation of TFNs & transformation of assessments into fuzzy numbers

```
> #Define Membership functions: Triangles. Mapping on a scale
from 0 to 1 on an axis x for a certain number of possible deci-
sions (1-5)
MaxX_absolut:=1: MinX_absolut:=0:
Intervall_length:=0.5: #equals the base lenght of the triangle

#TFN defined as TFN(MinX,HighX,MaxX)
MinX:=Vector(Number_of_options):
MaxX:=Vector(Number_of_options):
HighX:=Vector(Number_of_options):
for i from 1 to Number_of_options do
 if i=1 then
  MinX(i):=MinX_absolut:
  HighX(i):=MinX_absolut:
  MaxX(i):=HighX(i)+1/2*Intervall_length:
 elif i=(high-low+1) then
  MaxX(i):=MaxX_absolut:
  HighX(i):=MaxX_absolut:
  MinX(i):=HighX(i)-1/2*Intervall_length:
```

```
 else
  HighX(i):=(i-1)/(Number_of_options-1):
  MinX(i):=HighX(i)-1/2*Intervall_length:
  MaxX(i):=HighX(i)+1/2*Intervall_length:
 end if:
end do:
"MinX"; evalf(MinX);"HighX"; evalf(HighX);"MaxX";evalf(MaxX);
Membership_function:=Vector(Number_of_options):
for i from 1 to (Number_of_options) do
 Membership_function(i):=piecewise(x>MinX(i) and x<HighX(i),(x-
MinX(i))/(HighX(i)-MinX(i)+0.0001),x>=HighX(i) and
x<MaxX(i),(MaxX(i)-x)/(MaxX(i)-HighX(i)+0.0001),0):
end do:
Membership_function:
plot({seq(Membership_function(i),i=1..Number_of_op-
tions)},x=MinX_absolut..MaxX_absolut,title="Membership func-
tions");
```

"MinX"

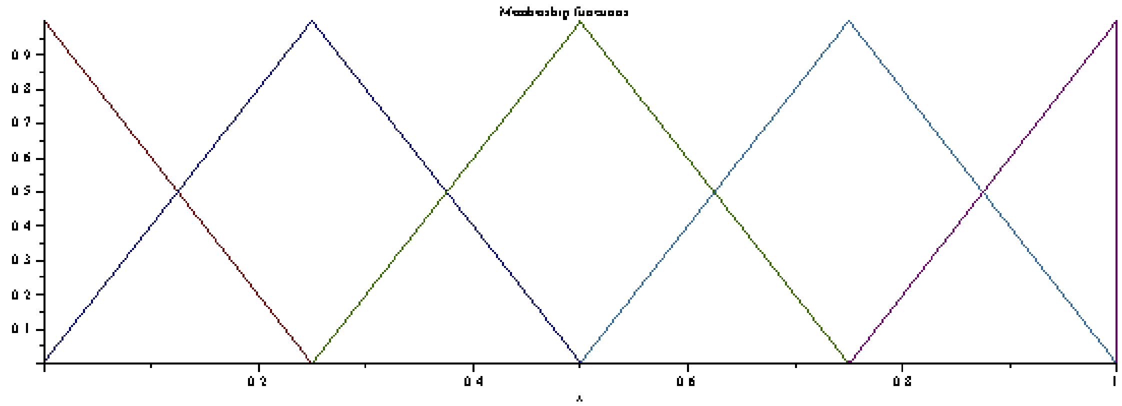
$$\begin{bmatrix} 0. \\ 0. \\ 0.2500000000 \\ 0.5000000000 \\ 0.7500000000 \end{bmatrix}$$

"HighX"

$$\begin{bmatrix} 0. \\ 0.2500000000 \\ 0.5000000000 \\ 0.7500000000 \\ 1. \end{bmatrix}$$

"MaxX"

$$\begin{bmatrix} 0.2500000000 \\ 0.5000000000 \\ 0.7500000000 \\ 1.000000000 \\ 1. \end{bmatrix}$$



# Aggregation of experts' opinions into one fuzzy number

Using the weighted average approach

$$"Mi = \sum_{j=1}^{m} w_j \cdot A_{i,j} \quad j = 1, 2,\ldots, n"$$

where A is the assessment in fuzzy numbers. W is the weight of the expert. i is a specific event. j is the expert. M is a fuzzy number.

```
> Expert_weights:=Vector(Number_of_Experts,1): #initialize with 1 as standard, both experts have equal weights. Can be changed and the sum of the expert weights normalizes it
Sum_Exp_weights:=0:
for i from 1 to Number_of_Experts do
 Sum_Exp_weights:=Sum_Exp_weights+Expert_weights(i):
end do:
Sum_Exp_weights;
Expert_weights:=Expert_weights/Sum_Exp_weights;
```

$$2$$

$$Expert\_weights := \begin{bmatrix} \frac{1}{2} \\ \frac{1}{2} \end{bmatrix}$$

```
> interface(rtablesize=21):
M:=Matrix(Number_of_events,3): #This is the matrix that contains for all events the aggregated TFNs. Rows for the threats, the columns represent the triangle edge-coordinates (MinX, HighX, MaxX)
for i from 1 to Number_of_events do
```

```
 for e from 1 to Number_of_Experts do
  if Exp_Decision_Likelihood(e,i)>0 then
   M(i,1):=M(i,1)+Expert_weights(e)*MinX(Exp_Decision_Likeli-
hood(e,i)):
   M(i,2):=M(i,2)+Expert_weights(e)*HighX(Exp_Decision_Likeli-
hood(e,i)):
   M(i,3):=M(i,3)+Expert_weights(e)*MaxX(Exp_Decision_Likeli-
hood(e,i)):
  end if:
 end do:
end do:
evalf(M);

B:=Matrix(3*Max_Barriers,Number_of_events): #Create the TFNs for
the barriers. Columns for the events, rows for the barriers.
Max_Barriers is the maximum amount of barriers for a threat
for j from 1 to Number_of_events do
  if Barriers(1,j)>0 then
   B(1,j):=MinX(Barriers(1,j)):
   B(2,j):=HighX(Barriers(1,j)):
   B(3,j):=MaxX(Barriers(1,j)):
  end if:
  if Barriers(2,j)>0 then
   B(4,j):=MinX(Barriers(2,j)):
   B(5,j):=HighX(Barriers(2,j)):
   B(6,j):=MaxX(Barriers(2,j)):
  end if:
  if Barriers(3,j)>0 then
   B(7,j):=MinX(Barriers(2,j)):
   B(8,j):=HighX(Barriers(2,j)):
   B(9,j):=MaxX(Barriers(2,j)):
  end if:
end do:
```

| | | |
|---|---|---|
| 0. | 0.1250000000 | 0.3750000000 |
| 0. | 0.1250000000 | 0.3750000000 |
| 0. | 0. | 0.2500000000 |
| 0. | 0.2500000000 | 0.5000000000 |
| 0. | 0.2500000000 | 0.5000000000 |
| 0. | 0. | 0.2500000000 |
| 0. | 0.2500000000 | 0.5000000000 |
| 0.1250000000 | 0.3750000000 | 0.6250000000 |
| 0. | 0.2500000000 | 0.5000000000 |
| 0.1250000000 | 0.3750000000 | 0.6250000000 |
| 0. | 0. | 0.2500000000 |
| 0.1250000000 | 0.3750000000 | 0.6250000000 |
| 0. | 0. | 0.2500000000 |
| 0. | 0.2500000000 | 0.5000000000 |
| 0. | 0.1250000000 | 0.3750000000 |
| 0.1250000000 | 0.3750000000 | 0.6250000000 |
| 0.1250000000 | 0.3750000000 | 0.6250000000 |
| 0. | 0. | 0.2500000000 |
| 0.1250000000 | 0.3750000000 | 0.6250000000 |
| 0. | 0.1250000000 | 0.3750000000 |

# Convert Fuzzy numbers for failure rates into Fuzzy Possibility Scores (FPSs)

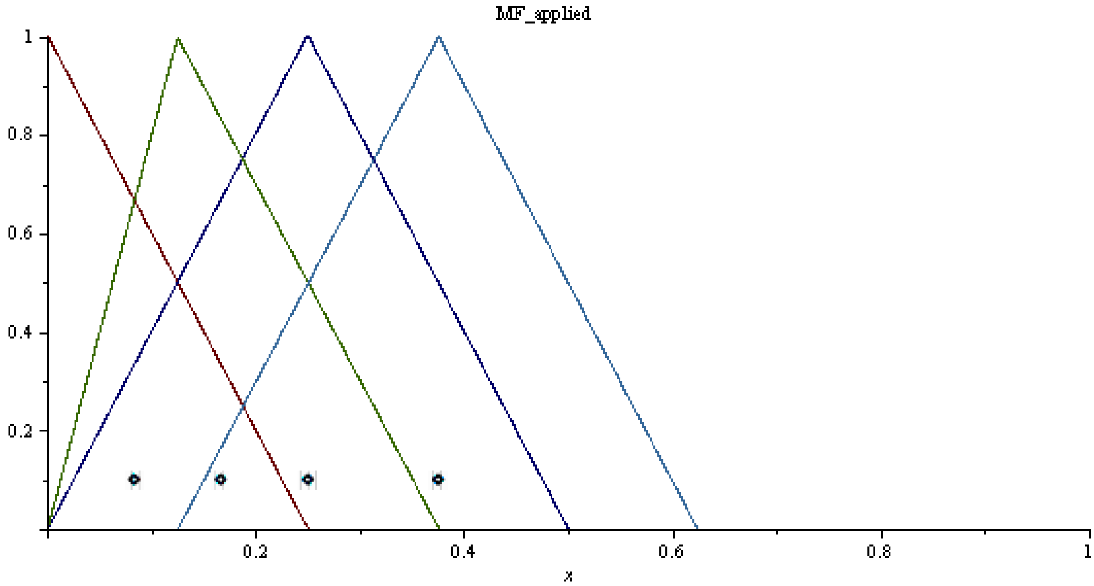
This is done by basically calculating the "center of gravity" of the individual fuzzy numbers --> defiuzzification

```
> FPS:=Vector(Number_of_events): #FPS for every threat
Area:=Vector(Number_of_events):
for i from 1 to Number_of_events do
 Area(i):=int((x-M(i,1))/(M(i,2)-M(i,1)+0.0001),x=M(i,1)..M(i,2))+int((M(i,3)-x)/(M(i,3)-M(i,2)),x=M(i,2)..M(i,3)):
 FPS(i):=(int(x*(x-M(i,1))/(M(i,2)-M(i,1)+0.0001),x=M(i,1)..M(i,2))+int(x*(M(i,3)-x)/(M(i,3)-M(i,2)),x=M(i,2)..M(i,3)))/Area(i):
end do:
evalf(FPS):evalf(Area):
> MF_applied:=Vector(Number_of_events): #Vector containing all the membership-functions for all threats
for i from 1 to Number_of_events do
```

```
 MF_applied(i):=piecewise(x>=M(i,1) and x<M(i,2),(x-M(i,1))/(M(i,2)-M(i,1)+0.0001),x>=M(i,2) and x<M(i,3),(M(i,3)-x)/(M(i,3)-M(i,2)),0):
end do:
MF_applied:
AA:=plot({seq(MF_applied(i),i=1..Number_of_events)},x=MinX_absolut..MaxX_absolut,title="MF_applied");
plotvector:=Vector(Number_of_events,0.1):
BB:=pointplot(FPS,plotvector);
display({AA,BB});
```

$AA := PLOT(\ldots)$

$BB := PLOT(\ldots)$




# Obtain the possibility failure rate of the top event by integrating FPSs of the vague basic events.

This is done to ensure compatibility with known values for possible inputs. Not used here, but could be used if there will be a known probability in the future.

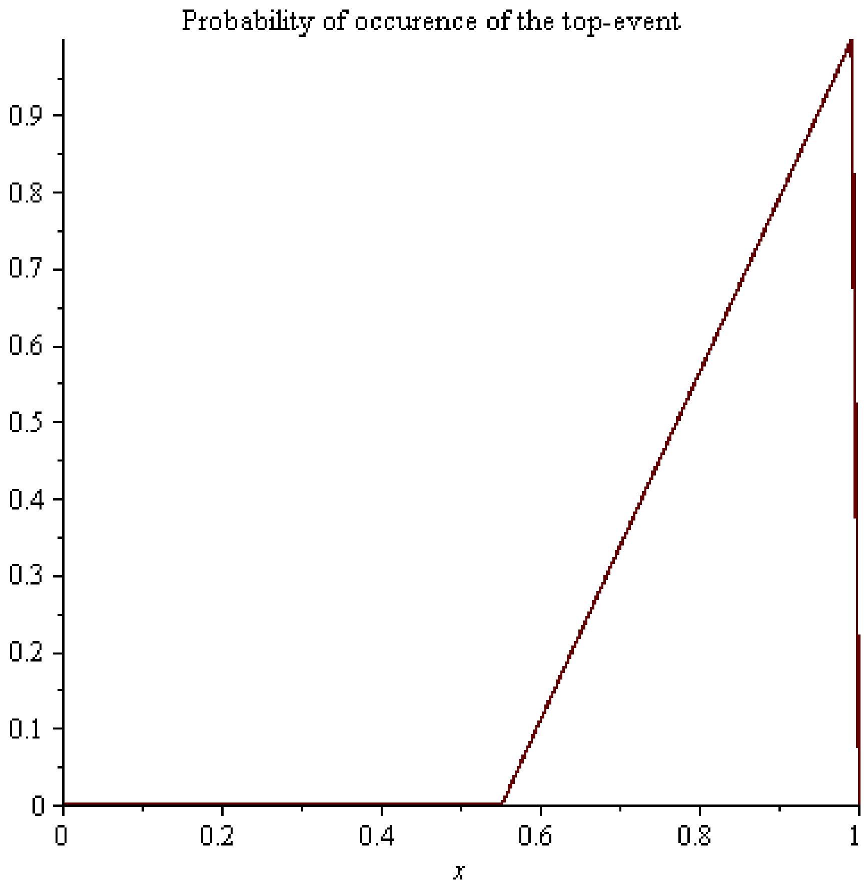
```
> FFP:=Vector(Number_of_events):
for i from 1 to Number_of_events do
 k:=((1-FPS(i))/FPS(i))^(1/3)*2.301;
 FFP(i):=1/10^k;
end do:
evalf(FFP):
```

# Calc Top Event probability using the weighted average approach

```
> MF_TopEvent:=Vector(3,1): #TFN of the Top-Event
Prob:=Matrix(Number_of_events,3):
Prob_sum:=Vector(3,1):
for i from 1 to (Number_of_events) do
 Prob(i,1):=1-M(i,1):
 Prob(i,2):=1-M(i,2):
 Prob(i,3):=1-M(i,3):
end do:

for i from 1 to 3 do
 for j from 1 to Number_of_events do #by changing the loop end-
number here a sensitivity-analysis to certain events can be con-
ducted
 Prob_sum(i):=Prob_sum(i)*Prob(j,i):
 end do:
end do:
MF_TopEvent:=Vector(3,1)-Prob_sum;

MF_TE:=piecewise(x>=MF_TopEvent(1) and x<MF_TopEvent(2),(x-
MF_TopEvent(1))/(MF_TopEvent(2)-
MF_TopEvent(1)),x>=MF_TopEvent(2) and
x<MF_TopEvent(3),(MF_TopEvent(3)-x)/(MF_TopEvent(3)-
MF_TopEvent(2)),0);
plot(MF_TE,x=0..1,title="Probability of occurence of the top-
event");
TE:=plot(MF_TE,x=0..1,title="Probability of occurence of the
top-event");
```

$$MF\_TopEvent := \begin{bmatrix} 0.551204681400000 \\ 0.991708776292398 \\ 0.999996853237150 \end{bmatrix}$$

$$MF\_TE := \begin{cases} 2.27012645647317\,x - 1.25130433017800 & 0.551204681400000 \le x \textbf{ and } x < ( \\ 120.654870834710 - 120.655250508170\,x & 0.991708776292398 \le x \textbf{ and } x < ( \\ 0 & \textit{otherwise} \end{cases}$$




*TE := PLOT(...)*

# Including barriers

barrier probabilities can be included here for every event --> reduction of the probability of the top-event

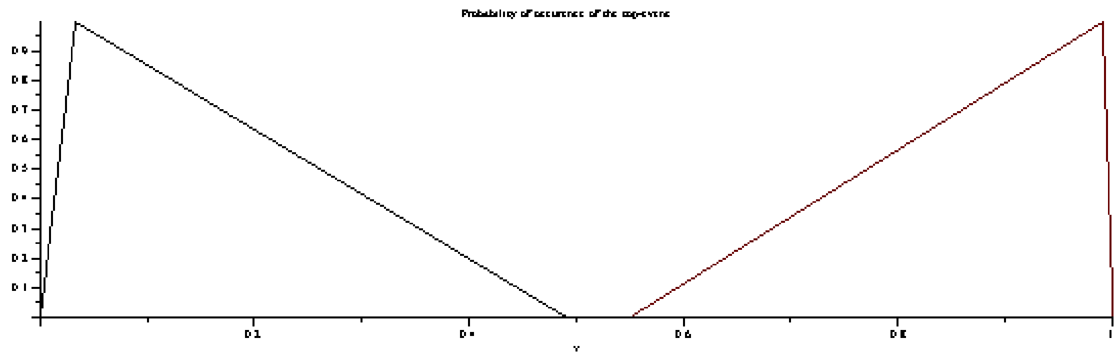
```
> MF_TopEvent_B:=Vector(3,1): #TFN for the top-event including
barriers
M_B:=Matrix(Number_of_events,3): #Probability TFNs for the
threats including barriers

for i from 1 to (Number_of_events) do #Include the barrier TFNs
in the Event TFNs using the multiplication rule for TFNs
 M_B(i,1):=M(i,1)*B(1,i)*B(4,i)*B(7,i):
 M_B(i,2):=M(i,2)*B(2,i)*B(5,i)*B(8,i):
 M_B(i,3):=M(i,3)*B(3,i)*B(6,i)*B(9,i):
end do:

Prob_sum:=Vector(3,1):
for i from 1 to (Number_of_events) do
```

```
 Prob(i,1):=1-M_B(i,1):
 Prob(i,2):=1-M_B(i,2):
 Prob(i,3):=1-M_B(i,3):
end do:

for i from 1 to 3 do
 for j from 1 to Number_of_events do #by changing the loop end-
number here a sensitivity-analysis to certain events could be
conducted
 Prob_sum(i):=Prob_sum(i)*Prob(j,i):
 end do:
end do:

MF_TopEvent_B:=Vector(3,1)-Prob_sum;
MF_TE_B:=piecewise(x>=MF_TopEvent_B(1) and
x<MF_TopEvent_B(2),(x-MF_TopEvent_B(1))/(MF_TopEvent_B(2)-
MF_TopEvent_B(1)),x>=MF_TopEvent_B(2) and
x<MF_TopEvent_B(3),(MF_TopEvent_B(3)-x)/(MF_TopEvent_B(3)-
MF_TopEvent_B(2)),0);
TE_B:=plot(MF_TE_B,x=0..1,title="Probability with and without
barriers",color=black);
display({TE_B,TE}); #comparision between the probability using
barriers and without barriers
```

$$MF\_TopEvent\_B := \begin{bmatrix} 0. \\ 0.0327487003677348 \\ 0.492581696500000 \end{bmatrix}$$

$$MF\_TE\_B := \begin{cases} 30.5355629008483\,x & 0. \leq x \textbf{ and } x < 0.0327 \\ 1.07121868296358 - 2.17470257334983\,x & 0.0327487003677348 \leq x \textbf{ and } x \\ 0 & otherwise \end{cases}$$

$$TE\_B := PLOT(...)$$



# Risk Evaluation

Experts Decision for Severity: 1 = very low, 5 = very high

```
> #Creating the TFNs for severity
MaxX_absolut:=1: MinX_absolut:=0:
Intervall_length:=0.5: #equals the base lenght of the triangle
#TFN for severity: TFN=TFN(SminX,SHighX, SMaxX)
SMinX:=Vector(Number_of_options):
SMaxX:=Vector(Number_of_options):
SHighX:=Vector(Number_of_options):
for i from 1 to Number_of_options do
 if i=1 then
  SMinX(i):=MinX_absolut:
  SHighX(i):=MinX_absolut:
  SMaxX(i):=HighX(i)+1/2*Intervall_length:
 elif i=(high-low+1) then
  SMaxX(i):=MaxX_absolut:
  SHighX(i):=MaxX_absolut:
  SMinX(i):=HighX(i)-1/2*Intervall_length:
 else
  SHighX(i):=(i-1)/(Number_of_options-1):
  SMinX(i):=HighX(i)-1/2*Intervall_length:
  SMaxX(i):=HighX(i)+1/2*Intervall_length:
 end if:
end do:
"SMinX"; evalf(SMinX);"SHighX";
evalf(SHighX);"SMaxX";evalf(SMaxX);
SMembership_function:=Vector(Number_of_options):
for i from 1 to (Number_of_options) do
```

```
 SMembership_function(i):=piecewise(x>SMinX(i) and
x<SHighX(i),(x-SMinX(i))/(SHighX(i)-
SMinX(i)+0.0001),x>=SHighX(i) and x<SMaxX(i),(SMaxX(i)-
x)/(SMaxX(i)-SHighX(i)+0.0001),0): #correction factor of 0.0001
still in there, could be avoided by using a IF functions (will
be implemented)
end do:
Membership_function:
plot({seq(SMembership_function(i),i=1..Number_of_op-
tions)},x=MinX_absolut..MaxX_absolut,title="Membership functions
severity");
```

"SMinX"

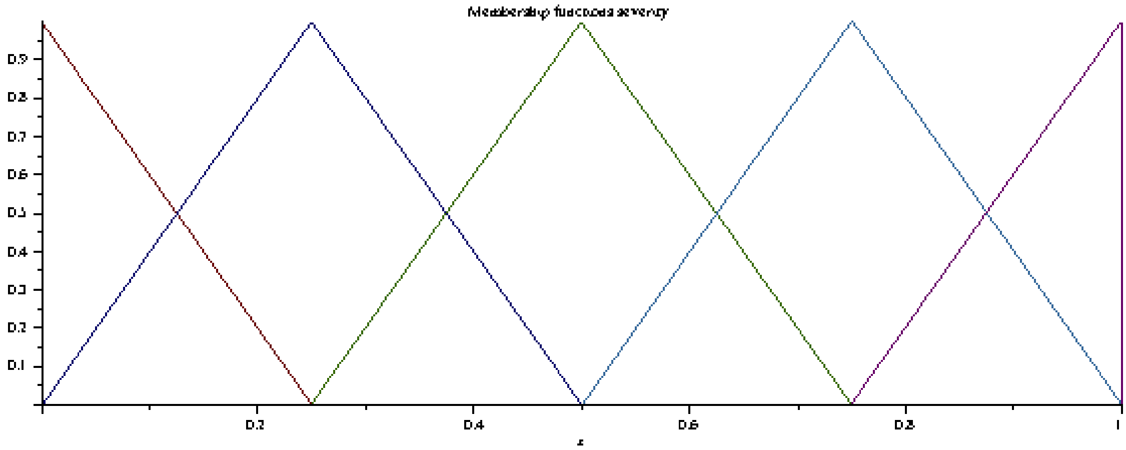
$$\begin{bmatrix} 0. \\ 0. \\ 0.2500000000 \\ 0.5000000000 \\ 0.7500000000 \end{bmatrix}$$

"SHighX"

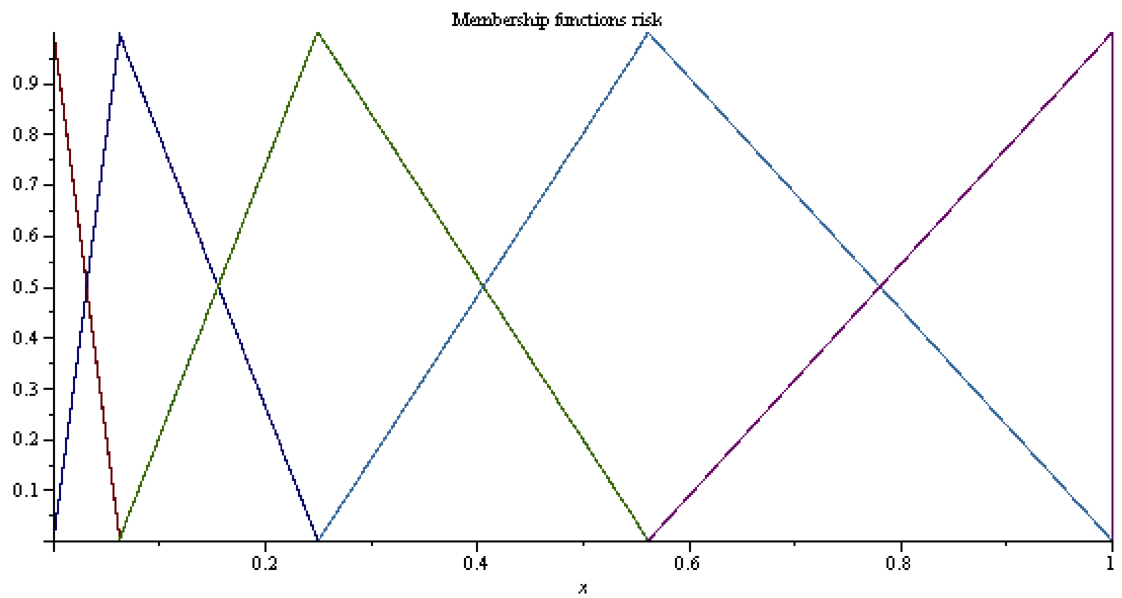
$$\begin{bmatrix} 0. \\ 0.2500000000 \\ 0.5000000000 \\ 0.7500000000 \\ 1. \end{bmatrix}$$

"SMaxX"

$$\begin{bmatrix} 0.2500000000 \\ 0.5000000000 \\ 0.7500000000 \\ 1.000000000 \\ 1. \end{bmatrix}$$



```
> #Calculation of Risk membership functions using the severity
and likelihood functions. Risk TFNs=TFN(RMinX,RHighX,RMaxX)
> RMinX:=Vector(Number_of_options,1): #number of options con-
trols the granularity of the scale. Here a 5 granular scale is
used
RMaxX:=Vector(Number_of_options,1):
RHighX:=Vector(Number_of_options,1):
for i from 1 to Number_of_options do
  RHighX(i):=RHighX(i)*HighX(i)*SHighX(i):
  RMinX(i):=RMinX(i)*MinX(i)*SMinX(i):
  RMaxX(i):=RMaxX(i)*MaxX(i)*SMaxX(i):
end do:
RMinX:
> RMembership_function:=Vector(Number_of_options):
for i from 1 to (Number_of_options) do
 RMembership_function(i):=piecewise(x>RMinX(i) and
x<RHighX(i),(x-RMinX(i))/(RHighX(i)-
RMinX(i)+0.0001),x>=RHighX(i) and x<RMaxX(i),(RMaxX(i)-
x)/(RMaxX(i)-RHighX(i)+0.0001),0):
end do:
RMembership_function:
plot({seq(RMembership_function(i),i=1..Number_of_op-
tions)},x=MinX_absolut..MaxX_absolut,title="Membership functions
risk");
```



```
> #Calculation of membership functions for severity for the ex-
pert decisions
Number_of_consequences:=8:
Exp_Decision_Severity:=Matrix(Number_of_Experts,Number_of_conse-
quences,[1,4,1,1,4,1,3,2,4,2,1,3,4,1,2,3]); #input of the ques-
tionnaire data
```

$$Exp\_Decision\_Severity := \begin{bmatrix} 1 & 4 & 1 & 1 & 4 & 1 & 3 & 2 \\ 4 & 2 & 1 & 3 & 4 & 1 & 2 & 3 \end{bmatrix}$$

```
> S:=Matrix(Number_of_consequences,3): #This is the matrix that
contains the aggregated TFNs for severity
for i from 1 to Number_of_consequences do
 for e from 1 to Number_of_Experts do
  if Exp_Decision_Severity(e,i)>0 then
   S(i,1):=S(i,1)+Expert_weights(e)*SMinX(Exp_Decision_Sever-
ity(e,i)):
   S(i,2):=S(i,2)+Expert_weights(e)*SHighX(Exp_Decision_Sever-
ity(e,i)):
   S(i,3):=S(i,3)+Expert_weights(e)*SMaxX(Exp_Decision_Sever-
ity(e,i)):
  end if:
 end do:
end do:
evalf(S);
```

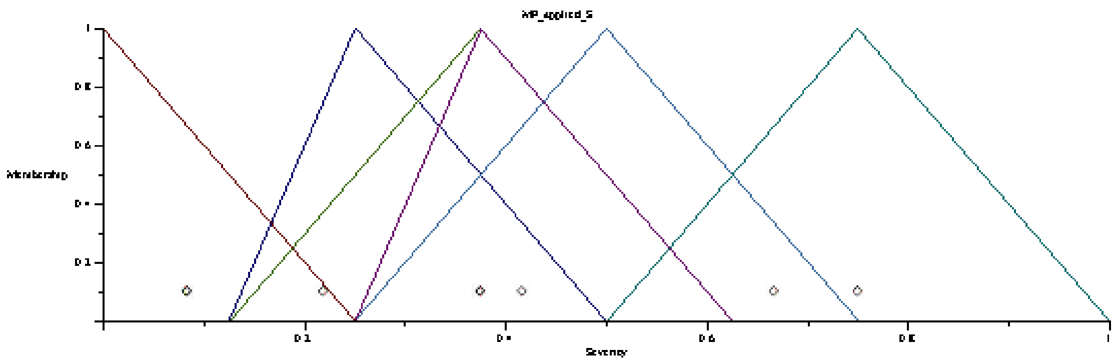
$$\begin{bmatrix} 0.2500000000 & 0.3750000000 & 0.6250000000 \\ 0.2500000000 & 0.5000000000 & 0.7500000000 \\ 0. & 0. & 0.2500000000 \\ 0.1250000000 & 0.2500000000 & 0.5000000000 \\ 0.5000000000 & 0.7500000000 & 1.000000000 \\ 0. & 0. & 0.2500000000 \\ 0.1250000000 & 0.3750000000 & 0.6250000000 \\ 0.1250000000 & 0.3750000000 & 0.6250000000 \end{bmatrix}$$

```
> COG_S:=Vector(Number_of_consequences): #Center of Gravity
method to calculate crisp values for the aggregated severity de-
cisions
Area_S:=Vector(Number_of_consequences):
for i from 1 to Number_of_consequences do
```

```
 Area_S(i):=int((x-S(i,1))/(S(i,2)-
S(i,1)+0.0001),x=S(i,1)..S(i,2))+int((S(i,3)-x)/(S(i,3)-
S(i,2)),x=S(i,2)..S(i,3)):
 COG_S(i):=(int(x*(x-S(i,1))/(S(i,2)-
S(i,1)+0.0001),x=S(i,1)..S(i,2))+int(x*(S(i,3)-x)/(S(i,3)-
S(i,2)),x=S(i,2)..S(i,3)))/Area(i):


end do:
evalf(COG_S):evalf(Area_S):
> with(plots):
MF_appliedS:=Vector(Number_of_consequences): #Vector that con-
tains the membership functions for the severity-inputs by the
experts
for i from 1 to Number_of_consequences do
 MF_appliedS(i):=piecewise(x>=S(i,1) and x<S(i,2),(x-
S(i,1))/(S(i,2)-S(i,1)+0.0001),x>=S(i,2) and x<S(i,3),(S(i,3)-
x)/(S(i,3)-S(i,2)),0):
end do:
MF_applied_S:
AAS:=plot({seq(MF_appliedS(i),i=1..Number_of_conse-
quences)},x=MinX_absolut..MaxX_absolut,title="MF_applied_S",la-
bels=["Severity","Membership"]);
plotvector:=Vector(Number_of_consequences,0.1):
BBS:=pointplot(COG_S,plotvector);
display({AAS,BBS});
```

$AAS := PLOT(\ldots)$

$BBS := PLOT(\ldots)$



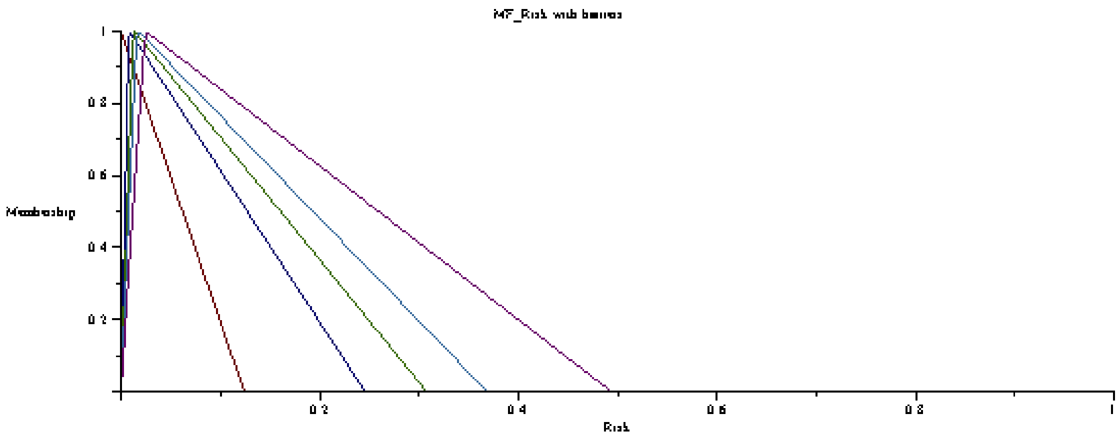
# Risk Calculations for the example

No likelihoods on the right hand side and no barriers on the right hand side --> probability of the consequences is the same as for the top-event. Risk values for all consequences can be calculated

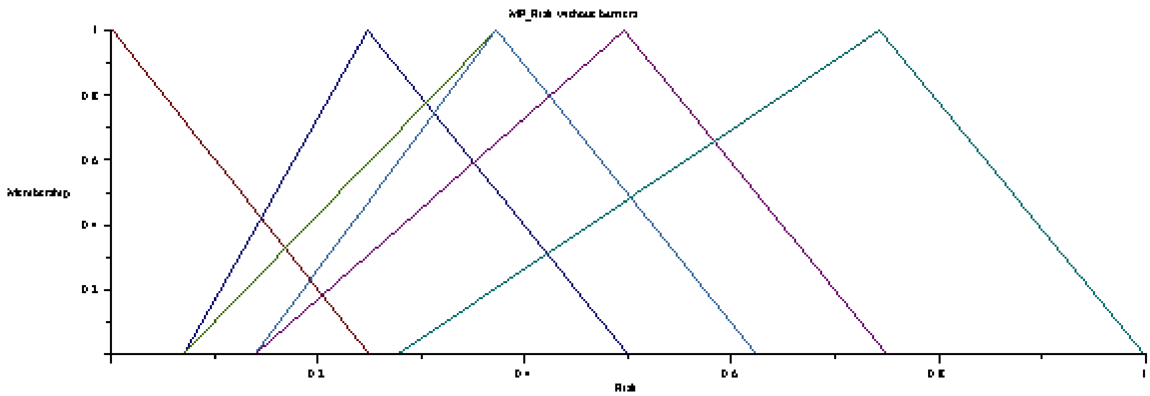
```
> Consequence_Risks:=Matrix(Number_of_consequences,3): #without
the barriers in in the fault tree
for c from 1 to Number_of_consequences do
 Consequence_Risks(c,1):=MF_TopEvent(1)*S(c,1):
 Consequence_Risks(c,2):=MF_TopEvent(2)*S(c,2):
 Consequence_Risks(c,3):=MF_TopEvent(3)*S(c,3):
end do:
Consequence_Risks:

#with barriers of fault tree accounted for

Consequence_Risks_FTB:=Matrix(Number_of_consequences,3):
for c from 1 to Number_of_consequences do
 Consequence_Risks_FTB(c,1):=MF_TopEvent_B(1)*S(c,1):
 Consequence_Risks_FTB(c,2):=MF_TopEvent_B(2)*S(c,2):
 Consequence_Risks_FTB(c,3):=MF_TopEvent_B(3)*S(c,3):
end do:
Consequence_Risks_FTB:

#creation of the membership functions and plotting

#with barriers
with(plots):
MF_Risk_B:=Vector(Number_of_consequences):
for i from 1 to Number_of_consequences do
 MF_Risk_B(i):=piecewise(x>=Consequence_Risks_FTB(i,1) and
x<Consequence_Risks_FTB(i,2),(x-Conse-
quence_Risks_FTB(i,1))/(Consequence_Risks_FTB(i,2)-Conse-
quence_Risks_FTB(i,1)+0.0001),x>=Consequence_Risks_FTB(i,2) and
x<Consequence_Risks_FTB(i,3),(Consequence_Risks_FTB(i,3)-
x)/(Consequence_Risks_FTB(i,3)-Consequence_Risks_FTB(i,2)),0):
end do:
```

```
MF_Risk_B:
AAR:=plot({seq(MF_Risk_B(i),i=1..Number_of_conse-
quences)},x=MinX_absolut..MaxX_absolut,title="MF_Risk with bar-
riers",labels=["Risk","Membership"]);
display({AAR});

#without barriers
MF_Risk:=Vector(Number_of_consequences):
for i from 1 to Number_of_consequences do
 MF_Risk(i):=piecewise(x>=Consequence_Risks(i,1) and x<Conse-
quence_Risks(i,2),(x-Consequence_Risks(i,1))/(Conse-
quence_Risks(i,2)-Consequence_Risks(i,1)+0.0001),x>=Conse-
quence_Risks(i,2) and x<Consequence_Risks(i,3),(Conse-
quence_Risks(i,3)-x)/(Consequence_Risks(i,3)-Conse-
quence_Risks(i,2)),0):
end do:
MF_Risk:
AAR:=plot({seq(MF_Risk(i),i=1..Number_of_conse-
quences)},x=MinX_absolut..MaxX_absolut,title="MF_Risk without
barriers",labels=["Risk","Membership"]);
display({AAR});
```

$AAR := PLOT(...)$




$AAR := PLOT(...)$




# Overlapp Area method

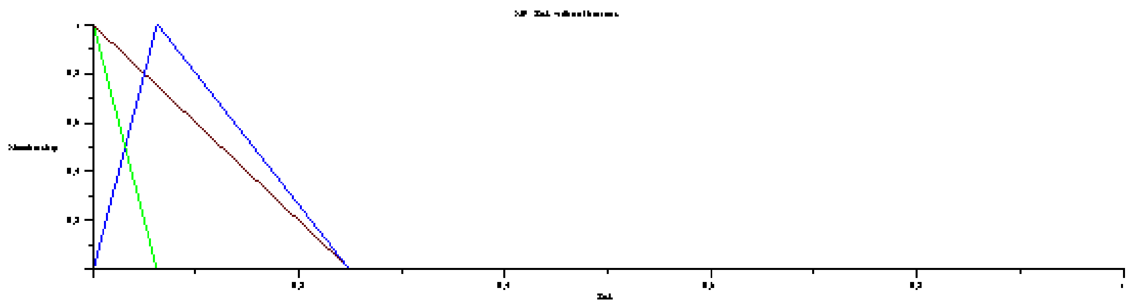
```
> #test section: by changing the numbers different TFNs are dis-
played
Test:=plot((MF_Risk(3)),x=MinX_absolut..MaxX_absolut,ti-
tle="MF_Risk without barriers",labels=["Risk","Membership"]);
Test2:=plot(RMembership_function(1),x=MinX_absolut..MaxX_ab-
solut,title="Membership functions risk",color=green);
Test3:=plot(RMembership_function(2),x=MinX_absolut..MaxX_ab-
solut,title="Membership functions risk",color=blue);
```

*Test* := *PLOT*(...)

*Test2* := *PLOT*(...)

*Test3* := *PLOT*(...)

```
> display({Test,Test2,Test3});
```



```
> #INCLUDING BOUNDARIES INTO THE NEXT CALCULATIONS. COMMENT OUT
IF NOT WANTED
#overwrite MF_Risk with MF_Risk_B
#overwrite Consequence_Risks with Consequence_Risks_FTB

MF_Risk:=MF_Risk_B:
Consequence_Risks:=Consequence_Risks_FTB:
> AR:=Vector(Number_of_consequences):
```

```
Boundary:=Matrix(Number_of_consequences,Number_of_options):
#boundary vector has entries that are vectors with dimension 3,
which is the maximum number of intersects
for i from 1 to Number_of_consequences do
 for j from 1 to Number_of_options do
 Boundary(i,j):=Vector(3):
end do:
end do:

for i from 1 to Number_of_consequences do #calculation of the
integration boundaries for every option(risk level) and every
threat
 AR(i):=int(MF_Risk(i),x=0..1):
 for j from 1 to Number_of_options do
  s:=0:
  s:=solve({MF_Risk(i)=RMembership_function(j)},x,useassump-
tions) assuming x>0 and x<1 and MF_Risk(j)>0.0001:

  number:=nops([s]); #number of solutions

  if number> 1 then
   counter:=1:
   a:=Vector(number);
   b:=Vector(number):
   for n from 1 to number do
    a(n):=s[n];
    b(n):=rhs(a(n)[1]);
   end do:
   x:=0:
   for n from 1 to number do
    if b(n)>min(Consequence_Risks(i,1),RMinX(j)) and
b(n)<max(Consequence_Risks(i,3),RMaxX(j)) then
     Boundary(i,j)(counter):=b(n):
     counter:=counter+1:
    end if:
   end do:
  end if:
```

```
  if number=1 then
   x:=0:
   a:=0:
   b:=0:
   a:=s[1]:
   b:=rhs(a):
   if b>min(Consequence_Risks(i,1),RMinX(j)) and b<max(Conse-
quence_Risks(i,3),RMaxX(j)) then
     Boundary(i,j)(1):=b:
    end if:
  end if:
 unassign('x'):
 end do:
end do:
AR;Boundary;
```

$$\begin{bmatrix} 0.2435484528 \\ 0.3060482487 \\ 0.1249996067 \\ 0.2154989486 \\ 0.3621472669 \\ 0.1249996067 \\ 0.2779987405 \\ 0.2779987405 \end{bmatrix}$$

| | | | | |
|---|---|---|---|---|
| [0, 0, 0] | [0.2000971588, 0, 0] | [0, 0, 0] | [0.1378011704, 0.4572174023, 0] | [0.6020958485, 0, 0] |
| [0, 0, 0] | [0.2114322009, 0, 0] | [0, 0, 0] | [0, 0, 0] | [0.6811118795, 0, 0] |
| [0, 0, 0] | [0, 0, 0] | [0.1428814343, 0, 0] | [0, 0, 0] | [0.5625000000, 0, 0] |
| [0, 0, 0] | [0.1573580989, 0, 0] | [0.2491729018, 0.2042082918, 0] | [0.3883982460, 0, 0] | [0, 0, 0] |
| [0, 0, 0] | [0, 0, 0] | [0, 0, 0] | [0, 0, 0] | [0.8384360178, 0, 0] |
| [0, 0, 0] | [0, 0, 0] | [0.1428814343, 0, 0] | [0, 0, 0] | [0.5625000000, 0, 0] |
| [0, 0, 0] | [0.1807623225, 0, 0] | [0, 0, 0] | [0.4572174023, 0, 0] | [0.6020958485, 0, 0] |
| [0, 0, 0] | [0.1807623225, 0, 0] | [0, 0, 0] | [0.4572174023, 0, 0] | [0.6020958485, 0, 0] |

```
> #Calculation of the overlapping area
OA:=Matrix(Number_of_consequences,Number_of_options):
for i from 1 to Number_of_consequences do
 for j from 1 to Number_of_options do


  if Consequence_Risks(i,1)>RMinX(j)then


   if Consequence_Risks(i,2)>RHighX(j) and Conse-
quence_Risks(i,1)<RMaxX(j) then
    if Consequence_Risks(i,3)>RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Boundary(i,j)(1))+int(RMember-
ship_function(j),x=Boundary(i,j)(1)..1):
    end if:
```

```
    if Consequence_Risks(i,3)=RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Boundary(i,j)(1))+int(RMember-
ship_function(j),x=Boundary(i,j)(1)..1):
    end if:
    if Consequence_Risks(i,3)<RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Boundary(i,j)(1))+int(RMember-
ship_function(j),x=Boundary(i,j)(1)..Bound-
ary(i,j)(2))+int(MF_Risk(i),x=0..1):
    end if:
   end if:

   if Consequence_Risks(i,2)=RHighX(j) then
    if Consequence_Risks(i,3)>RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Conse-
quence_Risks(i,2))+int(RMembership_function(j),x=Conse-
quence_Risks(i,2)..1):
    end if:
    if Consequence_Risks(i,3)=RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Conse-
quence_Risks(i,2))+int(RMembership_function(j),x=Conse-
quence_Risks(i,2)..1):
    end if:
    if Consequence_Risks(i,3)<RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..1):
    end if:
   end if:

   if Consequence_Risks(i,2)<RHighX(j) then
    if Consequence_Risks(i,3)>RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Boundary(i,j)(1))+int(RMember-
ship_function(j),x=Boundary(i,j)(1)..Bound-
ary(i,j)(2))+int(MF_Risk(i),x=Boundary(i,j)(2)..Bound-
ary(i,j)(3))+int(RMembership_function(j),x=Boundary(i,j)(2)..1):
    end if:
    if Consequence_Risks(i,3)=RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Boundary(i,j)(1))+int(RMember-
ship_function(j),x=Boundary(i,j)(1)..Bound-
ary(i,j)(2))+int(MF_Risk(i),x=Boundary(i,j)(2)..1):
```

```
    end if:
    if Consequence_Risks(i,3)<RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Boundary(i,j)(1))+int(RMember-
ship_function(j),x=Boundary(i,j)(1)..Bound-
ary(i,j)(2))+int(MF_Risk(i),x=Boundary(i,j)(2)..1):
    end if:
   end if:

  end if:

  if Consequence_Risks(i,1)=RMinX(j)then

    if Consequence_Risks(i,2)>RHighX(j) then
    if Consequence_Risks(i,3)>RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Boundary(i,j)(1))+int(RMember-
ship_function(j),x=Boundary(i,j)(1)..1):
    end if:
    if Consequence_Risks(i,3)=RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Boundary(i,j)(1))+int(RMember-
ship_function(j),x=Boundary(i,j)(1)..1):
    end if:
    if Consequence_Risks(i,3)<RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Boundary(i,j)(1))+int(RMember-
ship_function(j),x=Boundary(i,j)(1)..Bound-
ary(i,j)(1))+int(MF_Risk(i),x=Boundary(i,j)(2)..1):
    end if:
   end if:

   if Consequence_Risks(i,2)=RHighX(j) then
    if Consequence_Risks(i,3)>RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=0..Conse-
quence_Risks(i,2))+int(RMembership_function(j),x=Conse-
quence_Risks(i,2)..1):
    end if:
    if Consequence_Risks(i,3)=RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=1):
    end if:
```

```
    if Consequence_Risks(i,3)<RMaxX(j) then
     OA(i,j):=int(MF_Risk(i),x=1):
    end if:
   end if:

   if Consequence_Risks(i,2)<RHighX(j) then
    if Consequence_Risks(i,3)>RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..Bound-
ary(i,j)(1))+int(MF_Risk(i),x=Boundary(i,j)(1)..Bound-
ary(i,j)(2))+int(RMembership_function(j),x=Boundary(i,j)(2)..1):
    end if:
    if Consequence_Risks(i,3)=RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..Bound-
ary(i,j)(1))+int(MF_Risk(i),x=Boundary(i,j)(1)..1):
    end if:
    if Consequence_Risks(i,3)<RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..Bound-
ary(i,j)(1))+int(MF_Risk(i),x=Boundary(i,j)(1)..1):
    end if:
   end if:

  end if:

  if Consequence_Risks(i,1)<RMinX(j) and Conse-
quence_Risks(i,3)>RMinX(j) then

   if Consequence_Risks(i,2)>RHighX(j) then
    if Consequence_Risks(i,3)>RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..Bound-
ary(i,j)(1))+int(MF_Risk(i),x=Boundary(i,j)(1)..Bound-
ary(i,j)(2))+int(RMembership_function(j),x=Boundary(i,j)(1)..1):
    end if:
    if Consequence_Risks(i,3)=RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..Bound-
ary(i,j)(1))+int(MF_Risk(i),x=Boundary(i,j)(1)..Bound-
ary(i,j)(2))+int(RMembership_function(j),x=Boundary(i,j)(2)..1):
    end if:
```

```
    if Consequence_Risks(i,3)<RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..Bound-
ary(i,j)(1))+int(MF_Risk(i),x=Boundary(i,j)(1)..Bound-
ary(i,j)(2))+int(RMembership_function(j),x=Bound-
ary(i,j)(2)..Boundary(i,j)(3))+int(MF_Risk(i),x=Bound-
ary(i,j)(3)..1):
    end if:
   end if:

   if Consequence_Risks(i,2)=RHighX(j) then
    if Consequence_Risks(i,3)>RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..1):
    end if:
    if Consequence_Risks(i,3)=RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..1):
    end if:
    if Consequence_Risks(i,3)<RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..Conse-
quence_Risks(i,2))+int(MF_Risk(i),x=Consequence_Risks(i,2)..1):
    end if:
   end if:

   if Consequence_Risks(i,2)<RHighX(j) then
    if Consequence_Risks(i,3)>RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..Bound-
ary(i,j)(1))+int(MF_Risk(i),x=Boundary(i,j)(1)..Bound-
ary(i,j)(2))+int(RMembership_function(j),x=Boundary(i,j)(2)..1):
    end if:
    if Consequence_Risks(i,3)=RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..Bound-
ary(i,j)(1))+int(MF_Risk(i),x=Boundary(i,j)(1)..1):
    end if:
    if Consequence_Risks(i,3)<RMaxX(j) then
     OA(i,j):=int(RMembership_function(j),x=0..Bound-
ary(i,j)(1))+int(MF_Risk(i),x=Boundary(i,j)(1)..1):
    end if:
   end if:
```

```
  end if:
 end do:
end do:
OA;
```

| | | | | |
|---|---|---|---|---|
| 0 | 0.01492281548 | 0.2499000425 | 0.2435484528 | 0.002827539613 |
| 0 | 0.01153321406 | 0.2499000425 | 0.3060482487 | 0.02541070327 |
| 0.03120007986 | 0.1249996067 | 0.04016912499 | 0 | 0 |
| 0 | 0.04471586903 | 0.2157471381 | 0.05534124081 | 0 |
| 0 | 0 | 0.2499000425 | 0.3621472669 | 0.1379354885 |
| 0.03120007986 | 0.1249996067 | 0.04016912499 | 0 | 0 |
| 0 | 0.03341925072 | 0.2499000425 | 0.1242900165 | 0.002827539613 |
| 0 | 0.03341925072 | 0.2499000425 | 0.1242900165 | 0.002827539613 |

```
> C:=Matrix(Number_of_consequences,Number_of_options):
for i from 1 to Number_of_consequences do
 for j from 1 to Number_of_options do
  C(i,j):=OA(i,j)/AR(i):
 end do:
end do:
C;
```

| | | | | |
|---|---|---|---|---|
| 0. | 0.06127247087 | 1.026079368 | 1.000000000 | 0.01160976217 |
| 0. | 0.03768430014 | 0.8165380575 | 1.000000000 | 0.08302842241 |
| 0.2496014242 | 1.000000000 | 0.3213540110 | 0. | 0. |
| 0. | 0.2074992445 | 1.001151697 | 0.2568051546 | 0. |
| 0. | 0. | 0.6900508863 | 1.000000000 | 0.3808823125 |
| 0.2496014242 | 1.000000000 | 0.3213540110 | 0. | 0. |
| 0. | 0.1202136767 | 0.8989250888 | 0.4470884159 | 0.01017105188 |
| 0. | 0.1202136767 | 0.8989250888 | 0.4470884159 | 0.01017105188 |

```
> r:=Matrix(Number_of_consequences,Number_of_options):
C_sum:=Vector(Number_of_consequences):
for i from 1 to Number_of_consequences do
 for j from 1 to Number_of_options do
  C_sum(i):=C_sum(i)+C(i,j):
 end do:
end do:
C_sum:
```

```
for i from 1 to Number_of_consequences do
 for j from 1 to Number_of_options do
  r(i,j):=C(i,j)/C_sum(i): #calculation of the degree of risk for all chosen risks (here the degrees of risk for all conse-quences are calculated)
 end do:
end do:
r;
#check if the sum equals 1 for every row
check:=Vector(Number_of_consequences):
for i from 1 to Number_of_consequences do
 for j from 1 to Number_of_options do
  check(i):=check(i)+r(i,j):
 end do:
end do:
check;
```

| | | | | |
|---|---|---|---|---|
| 0. | 0.02919180172 | 0.4888509478 | 0.4764260573 | 0.005531193217 |
| 0. | 0.01945246353 | 0.4214932140 | 0.5161954303 | 0.04285889223 |
| 0.1588851082 | 0.6365552948 | 0.2045595972 | 0. | 0. |
| 0. | 0.1415936274 | 0.6831673082 | 0.1752390639 | 0. |
| 0. | 0. | 0.3332076993 | 0.4828740980 | 0.1839182031 |
| 0.1588851082 | 0.6365552948 | 0.2045595972 | 0. | 0. |
| 0. | 0.08142361182 | 0.6088635628 | 0.3028237271 | 0.006889097837 |
| 0. | 0.08142361182 | 0.6088635628 | 0.3028237271 | 0.006889097837 |

| |
|---|
| 1.000000000 |
| 1.000000000 |
| 1.000000000 |
| 0.9999999995 |
| 1.000000000 |
| 1.000000000 |
| 0.9999999995 |
| 0.9999999995 |