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## Risk Based Maintenance in hydrogen refuelling stations: Focus on Safety and Business Interruption risk

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## Abstract

Hydrogen FCVs (Fuel Cell Vehicles) could be one of the options to switch from fossil fuels to renewable sources with no greenhouse gas emissions. The potential future increase of FCVs will lead to the development of a network of new refuelling stations. However, related safety issues will have to be considered to avoid scenarios such as the accident recently occurred in Kjørbo (Norway).

The objective of this study is to develop effective inspection and maintenance planning while guaranteeing the control of such safety issues. The consolidated RBI (Risk Based Inspections) methodology is integrated with detailed risk assessment and study of business interruption costs through the use of three different software solutions: Synergi RBI (to plan maintenance through RBI), ExtendSim (to model the business) and Safeti (to analyse the risk towards humans).

The methodology is applied to a refuelling station with hydrogen production by electrolysis on site, focusing on the storage unit that is composed by pressure storage vessels and PRDs (Pressure Relief Devices). For every selected Risk target, the RBI methodology provides a maintenance plan. By elaborating the LoFs (Likelihoods of Failure) of the vessel and the connected PRD (calculated through RBI methodology), it is possible to model potential accident scenarios using SAFETI and obtain a set of related risk metrics describing the safety level. The maintenance plan and the LoFs are in turn used as input to ExtendSim that models how the profit is influenced by maintenance and accidents shutdowns.

The application of this approach to a case study and the results obtained show that there is the concrete possibility to support decision-making by:

- Prioritizing maintenance for equipment with higher risk;
- Assuring necessary safety levels; and
- Considering related business interruption costs.

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## 1. Introduction

The purposes of this chapter is to describe the context in which the thesis is developed in order to understand the relevance of the issue discussed and to propose the thesis problem formulation and objectives.

### 1.1 Alternative fuels: hydrogen

“The increase in energy demand in all sectors, the growth of the world's population, and the declining availability of low-cost fossil fuel sources are some of the most important issues the world faces in the 21st century” (FCHEA, s.d.). Fossil fuels such as oil, coal and natural gas cannot be a permanent and sustainable solution to meet global energy demand: any shortage of these types of energy sources could lead to fluctuations in oil prices and threaten global energy security and economy (Midilli A, 2007). As fossil fuels usage increases worldwide, greenhouse gas (GHG) emissions increase and the air quality in cities and industrial areas gets worse. (Jasem Alazemi, 2015).

It is easy to notice then that using hydrogen produced from primary energy sources with low emissions (in particular renewable energy) is an important alternative transport fuel to gasoline and diesel and also an energy store solution to have a reliable and continuous supply from variable and unstable renewable energy sources. A high number of studies show that hydrogen can have a fundamental role to play in a global energy effort to shift to sustainable energy sources (Jasem Alazemi, 2015); this could lead to a reduction of the climate change threat and also could provide a zero-emission fuel being a fundamental player in the gradual replacement of fossil fuels. For example, Dougherty and Kartha investigated the transition to hydrogen energy in the United States of America (USA) for light- and heavy-duty vehicles, marine vessels and trains. The study found that hydrogen fuel cell electric vehicles (FCEVs), electric and other low-emission vehicles, could reduce GHG pollution by 80% in 2100 compared with that of 1990. Furthermore, it would enable the USA to increase controllable air quality in urban areas and leave definitely gasoline fuel by the 2100s (Dougherty W, 2009).

Balta-Ozkan and Baldwin studied how hydrogen could impact the economy and showed how it could meet the United Kingdom (UK) government's climate and energy policy goal to reduce 80% of national GHG emissions by 2050 (Balta-Ozkan N, 2013).

Even if hydrogen cannot be a primary energy source, you can think at it as an energy carrier capable of replace fossil fuels in different applications; Hydrogen can release energy trough different ways such as direct combustion, catalytic combustion, steam production and fuel cell operations. Among these methods, the fuel cell is generally the most efficient and cleanest technology for releasing energy from hydrogen.

In a fuel cell, hydrogen and oxygen are combined in a catalysed electrochemical reaction to produce an electrical current, water and heat. This process can achieve efficiencies that are two to three times those of internal combustion engines (Cipriani G, 2014), while being quiet and pollution free. In addition to this it has to be noticed that developing hydrogen technologies for the production, storage, distribution and usage of such fuel can create different new jobs, contribute to GHG reduction and support global and national energy supplies.

The most concern in using hydrogen is related to safety issues. However, it has to be noted that it is a common situation when some new technologies start to be used, like the early years for gasoline and diesel. Regarding the material itself, "hydrogen gas is nontoxic, environmentally safe, and has low radiation level, which reduce the risk of a secondary fire" (Jasem Alazemi, 2015). Regarding fires, it is important to remember that hydrogen burns with a colourless flame that may not be visible. Therefore, hydrogen has a faster laminar burning velocity (2.37 m/s), and a lower ignition energy (0.02 mJ) than gasoline (0.24 mJ) or methane (0.29 mJ). The explosion limits by volume for hydrogen in air of 18.3–59% are much higher than those for gasoline (1.1–3.3%) and natural gas (5.7–14%). The self-ignition temperature of hydrogen (585 °C) is significantly higher than for gasoline (228–501 °C) and natural gas (540 °C). However it has to be considered that it is really difficult that hydrogen gas can explode in an open area due to its high volatility: since hydrogen is 14 times lighter than air, it rises at 20 m/s if gas is released. Hydrogen is thus usually safer than other fuels in the event of leaks but cold burns and increased duration of leakage are a concern about liquid hydrogen, although hydrogen disperses in air much faster than gasoline.

Hydrogen can be as safe as other fuels if appropriate standards and safe working practices are followed. For example, when stored at high pressures, the usual regulations and standards for pressurised gas vessels and usage must be implemented, and detection systems need to be employed to avoid any accident or components failure due to hydrogen attack (HA) or hydrogen embrittlement (HE). It is also important that all components used in hydrogen fuelling stations are certified by the appropriate safety authority. The California Energy Commission has identified 153 failure modes at hydrogen delivery stations (using liquid hydrogen and/or compressed hydrogen stations), and at on-site hydrogen production stations (using SMR (steam methane reforming) and electrolysis hydrogen production). According to their study, “stations with liquid hydrogen delivery have the most serious potential failures due to factors such as collisions, overfilling tanks, and relief valve venting” (Jasem Alazemi, 2015). Regarding stations with electrolyzers, two low-potential failure modes and one medium failure mode can be identified. The low failure modes are related to the electrolyser leak (oxygen, hydrogen) and high voltages electrocution hazard. The medium failure is related to the dryer failure, which causes moisture to go into downstream components.

Regarding the vehicles, automotive companies made a great effort of research and design and have produced many types of successful fuel cell vehicle. Some of these companies, like Ford and Nissan, have entered into agreements to develop and commercialise zero-emission vehicles based on hydrogen fuel cell vehicles (Jasem Alazemi, 2015).

In order to develop this new way of transport, “hydrogen fuelling stations are one of the most important parts of the distribution infrastructure required to support the operation of hydrogen-powered vehicles, both FCEVs and hydrogen internal combustion engine (HICE) vehicles. Without a hydrogen refuelling network, hydrogen vehicles cannot operate, and their commercial deployment will be very limited. Without a significant fleet of operational hydrogen fuel cell vehicles, it is not viable to invest in setting up a network of hydrogen fuelling stations” (Jasem Alazemi, 2015).

In order to have a substantial market penetration of hydrogen vehicles in the transport sector, to reach greenhouse gas reduction global targets and support energy security, the introduction of commercial hydrogen FCVs and the building of an “effective” network of fuelling stations to supply them with hydrogen must take place simultaneously.

### 1.1.1 Hydrogen production methods and refuelling stations

“Hydrogen gas can be manufactured from different sources and in different ways. Hydrogen molecules are very light, which makes it very difficult for our planet's gravitational force to retain hydrogen gas in its atmosphere. Hence hydrogen is only available on the Earth in the form of compounds with other elements, such as water, hydrocarbons, hydrides of diverse kinds, and in a wide variety of organic materials” (Jasem Alazemi, 2015). In order to produce Hydrogen for use as a fuel it is necessary to “extract” it from other hydrogen containing materials such as fossil fuels, water, biomass or other biological sources.

For over 100 years, hydrogen has been produced and used for industrial purposes: about 90% (45 billion kg) of hydrogen production currently comes from fossil fuel sources (Yilanci A, 2008).

Regarding this kind of hydrogen production, it could be obtained directly from fossil fuels by the following processes:

- by steam methane reforming;
- thermo cracking;
- partial oxidation;
- coal gasification.

As said before, one of the purpose of hydrogen FCVs shift from fossil fuels transport systems, is the reduction of GHG and the gaining of a less polluted urban environment; in order to reach this objective we have to consider different production methods that don't involve fossil fuels.

Among these alternative methods of producing hydrogen fuel is from biomass: this is possible via biochemical and thermochemical (via gasification) processes. Hydrogen can also be produced by dissociating water by electrolysis, photoelectrolysis or photolysis (also called photoelectrochemical or photocatalytic water splitting), water thermolysis (also called thermochemical water splitting), and photobiological processes. All these processes require inputs of energy. In the case of conventional electrolysis, for example, the electrical energy input can be electricity generated by fossil fuel, nuclear or renewable energy power stations.

Therefore, it is easy to understand that greenhouse gas emission and other environmental impacts of hydrogen production processes depend crucially on the primary energy source used to supply

the process energy, as well as the raw material input. The source of the required electricity (including its cost and efficiency, as well as emissions resulting from electricity generation) must be considered when evaluating the benefits and economic feasibility of hydrogen production via this technology. In many regions of the world, today's power grid is not the best source for providing the electricity required for electrolysis because of the greenhouse gases released and the amount of fuel required due to the low efficiency of the electricity generation process. Hydrogen production via electrolysis is being pursued for renewable energy options: these sources may result in virtually zero greenhouse gas and pollutant emissions (Energy.gov, s.d.). Hydrogen production via electrolysis may offer opportunities for synergy with variable power generation, which is characteristic of some renewable energy technologies (Energy.gov, s.d.). For example, if we think at wind power, even if the cost of wind derived energy has continued to drop, “the inherent variability of wind is an impediment to the effective use of wind power” (Energy.gov, s.d.). It is possible then to integrate hydrogen fuel and electric power generation at a wind farm in order to gain the possibility “to shift production to best match resource availability with system operational needs and market factors”; the excess electricity production from wind farms could be used to produce hydrogen through electrolysis. As an example can think at the different hydrogen refuelling stations present in Norway that have on-site hydrogen production using solar and/or other renewable energy sources as energy supply.

Among all the kinds of stations differentiated by their energy supply, we can divide hydrogen fuelling stations in two basic types:

- Stations in which the hydrogen is made elsewhere and delivered to the station for local storage and dispensing to vehicles;
- Stations in which hydrogen is produced on site, and then stored there ready for transfer to the vehicle's hydrogen storage.

Some stations may be a combination of both types using delivered hydrogen to supplement on-site production as required. After the production/supply, hydrogen stations are based on the same principle of the traditional gasoline stations like storing the fuel in a reservoir, transferring it to a dispenser, and then filling on-board hydrogen tanks as hydrogen-powered vehicles require

refuelling. Hydrogen dispensers for high-pressure gas look like LPG or compressed natural gas dispensers and connect to vehicle tanks in a similar way.

## 1.2 Problem formulation and objectives

If hydrogen fuel gains its place in the fuels market, the future increase of FCVs will lead to the development of a network of new refuelling stations. However, related safety issues will have to be considered to avoid scenarios such as the accident recently occurred in Kjørbo (Norway).

An important part of the risk management and control is related to the maintenance of the refuelling station; Plant maintenance is defined as a set of activities that are necessary to keep machinery, parts and types of equipment in good operating conditions to avoid production stoppage and loss. The objectives of maintenance management can be defined as (MBA TUTS, 2018):

- Minimizing the loss of production time due to equipment failure;
- Reducing loss due to the production stoppage;
- Keeping all productive assets in good working conditions;
- Improving the quality of the product and productivity;
- Helping to reduce the total maintenance cost of repair and of preventive maintenance.

Moreover, presently, there is an increased awareness of the need to assess risk resulting from:

- Off-site risk to the community;
- On-site risk to employees;
- Risk of damage to the environment;
- Business interruption risks.

In this work, the objective is then the development of an inspection planning approach capable of ensuring the functionality of existing equipment and facilities, reducing downtimes and considering the responsibility for Environment, Safety and Health.

By using Risk Based Inspections (RBI) - this methodology will be described in detail in the next chapter - it is possible to take into account some of the previous mentioned types of risks and



furthermore manage the overall risk of a plant by focusing inspection efforts on the process equipment with the highest risk: a large percent of the total unit risk will be concentrated in a relatively small percent of the equipment items: this can be related to cost optimization of the entire maintenance function.

In the RBI methodology, the maintenance plan is developed starting from the calculation of the risk  $R(t)$  for each equipment that can be determined as a combination of the probability of failure  $P_f(t)$  and the consequence of failure  $C$  :

$$R(t) = P_f(t) \cdot C$$

The premise of inspection planning using RBI is based on the fact that at some point in time, the risk will reach a specified risk target: when or before the risk target is reached, an inspection of the equipment is recommended.

The consequences of loss of containment are determined using well established consequence analysis techniques and are expressed as:

- affected impact area;
- financial impact.

If we think at the consequences in financial terms (financial impact), the risk target that we can fix will be expressed in money value.

In order to analyse in a more detailed way the risk to humans and the business interruption, the maintenance planning problem analysis will be based on three different software solutions:

- Synergi RBI (Risk Based Inspections): to plan inspection maintenance based on risk;
- ExtendSim: to model the business;
- Safeti: to analyze the related risk to humans.

An overview of the proposed process is showed in Figure 3: the start point is SYNERGI RBI which outputs will be processed in order to use them as inputs for SAFETI and ExtendSim.

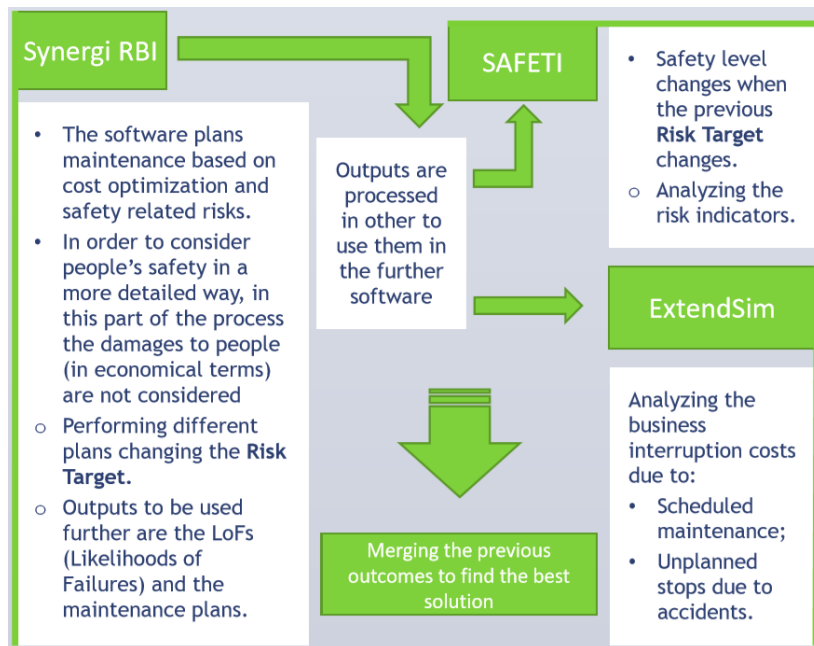


Figure 1 - Methodology general flowchart

As said before, the basis of RBI is to fix a risk target: in this work three different risk target will be used to perform different maintenance plans. For every selected Risk target, the maintenance plan for the equipment is provided by Synergi RBI based on cost optimization and safety related risks. In order to consider people’s safety in a more detailed way, in this part of the process the damages to people (in financial terms) are not considered as parts of the consequences of failure.

Not only the maintenance plan but also likelihood of failures (LoF) of the selected equipment are output of SYNERGI RBI: by elaborating the LoFs of the equipment, SAFETI can model potential accident scenarios and obtain a set of risk metrics, such as the F-N curves, that vary because of the likelihood of failures and so of the selected risk targets.

The maintenance plan and the LoFs are in turn used as input to ExtendSim that models how the profit is influenced by maintenance and accidents shutdowns.

Therefore, for every selected risk target, the proposed methodology provides a detailed maintenance plan for each equipment, a complete picture of the safety issues and a basic financial analysis of the influence on profits. Details about the methodology will be given in the “Method” chapter.

Once the proposed approach is conducted considering different risk targets, the best maintenance plan can be selected according to the company policies and standards, supporting decision-making by:

- Prioritizing maintenance for equipment with higher risk;
- Assuring necessary safety levels; and
- Considering related business interruption costs.

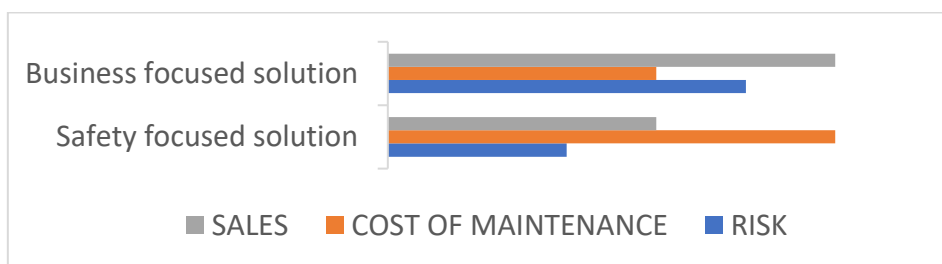


Figure 2 - Maintenance plans solutions

## 2. Methodology

In this chapter an overview of RBI methodology and the three different software will be given in order to understand the proposed methodology steps that will be described in the last section.

### 2.1 Risk based maintenance overview

As the main objective of the thesis work is to understand how to develop an effective inspection plan considering the goals reported in the previous chapter, the start point should be a way to plan inspections for a facility: one methodology is presented in some API (American Petroleum Institute) recommended practices.

API is a United States of America national trade association representing all facets of the natural gas and oil industry, which supports 10.3 million U.S. jobs and nearly 8 percent of the U.S. economy. Between API associates we can find large integrated companies as well as exploration and production, refining, marketing, pipeline, and marine businesses, and service and supply firms (API energy, 2020).

API was created in 1919 as a standards-setting organization with a domestic focus but in recent years the work has expanded to include a growing international dimension, and today API is recognized around the world for its numerous programs like producing standards. These standards collect the industry's wisdom on different kind of topics such as environmental protection, operating practices and safe, interchangeable equipment and materials (API energy, 2020).

Nowadays API continues to improve more than 700 standards and recommended practices: many of them have also been incorporated into state and federal regulations and they are also the most widely cited standards by the international regulatory community (API energy, 2020).

Among API's recommended practices regarding maintenance we can find:

- "API RECOMMENDED PRACTICE 580: Risk-Based Inspection"
- "API RECOMMENDED PRACTICE 581: Risk-Based Inspection Technology"

The first one, “API RECOMMENDED PRACTICE 580: Risk-Based Inspection”, is essentially a guide on how to use risk analysis to develop an effective inspection plan.

According to the guideline, inspection planning “is a systematic process that begins with identification of facilities or equipment and culminates in an inspection plan” (API, API recommended practice 580: Risk-Based Inspection, 2009).

Applying the methodology is then possible to obtain an inspection plan for every analysed equipment of a facility including:

- inspection methods;
- extent of inspection (percent of total area to be examined or specific locations);
- inspection interval and dates;
- possible risk mitigation activities;
- the residual level of risk after inspection.

“The expected outcome from the application of the RBI process should be the linkage of risks with appropriate inspection, process control or other risk mitigation activities to manage the risks” (API, API recommended practice 580: Risk-Based Inspection, 2009). The RBI process is then capable of generating:

- a ranking by relative risk of all equipment evaluated;
- a detailed description of the inspection plan to be employed for each equipment item, including:
  - inspection method(s) that should be used [e.g. visual, ultrasonic (UT), radiography];
  - extent of application of the inspection method(s) (e.g. percent of total area examined or specific locations);
  - timing of inspections/examinations (inspection intervals/due dates);
  - risk management achieved through implementation of the inspection plan;
- description of any other risk mitigation activities [such as repairs, replacements or safety equipment upgrades, equipment redesign or maintenance and controls on operating conditions];
- the expected risk levels of all equipment after the inspection plan;

### 2.1.1 RBI Benefits and Limitations

The purpose of using this methodology is to plan inspections managing the risk: these equipment plans highlight risks from a safety, health and environment perspective and/or from an economic standpoint. RBI plans should include cost-effective actions along with a projected risk mitigation (API, API recommended practice 580: Risk-Based Inspection, 2009).

Implementation of these plans provides one of the following:

- an overall reduction in risk for the facilities and equipment assessed,
- an acceptance and understanding of the current risk.

The RBI plans also identify equipment that does not require inspection or some other form of mitigation because of the acceptable level of risk associated with the equipment's current operation. In this way, inspection and maintenance activities can be focused and more cost effective. This often results in a significant reduction in the amount of inspection data that is collected. In some cases, in addition to risk reductions and process safety improvements, RBI plans may result in cost reductions.

RBI is based on proven risk assessment and management principles: however, this methodology will not compensate for (API, API recommended practice 580: Risk-Based Inspection, 2009):

- inaccurate or missing information;
- inadequate designs or faulty equipment installation;
- not effectively executing the plans;
- lack of qualified personnel or teamwork;
- lack of sound engineering or operational judgment.

### 2.1.2 RBI as a Continuous Improvement Tool

RBI is capable of continuously improving the inspection of facilities and systematically reducing the risk associated with pressure boundary failures. As new data such as inspection results and industry experiences with similar processes becomes available or when changes occur (e.g. operating conditions), reassessment of the RBI program can be made: that will provide a view of

the current new risks: risk management plans should then be modified according to changes (API, API recommended practice 580: Risk-Based Inspection, 2009).

### 2.1.3 Industry Scope

Risk Based Inspections methodology provided by API is based on risk management concepts and principles that can be generally used in every facility even if the targets of the guidelines are hydrocarbon and chemical process industry.

This recommended practice, according to API, “is intended to promote consistency and quality in the identification, assessment, and management of risks pertaining to material deterioration, which could lead to loss of containment” (API, API recommended practice 580: Risk-Based Inspection, 2009).

The RBI process is focused on maintaining the mechanical integrity of pressure equipment items and minimizing the risk of loss of containment due to deterioration.

Thinking about risk management, RBI can support a preliminary hazard analysis by focusing on the mechanical integrity related damage mechanisms and risk management through inspection.

### 2.1.4 Equipment Covered

The following types of equipment and associated components/internals are covered by API 580 and API 581 (API, API recommended practice 580: Risk-Based Inspection, 2009):

- Pressure Vessels: all pressure containing components;
- Process Piping: pipe and piping components;
- Storage Tanks: atmospheric and pressurized;
- Rotating Equipment: pressure containing components;
- Boilers and Heaters: pressurized components;
- Heat exchangers (shells, floating heads, channels, and bundles);
- Pressure-relief devices.

The following equipment is contrarywise not covered:

- instrument and control systems,

- electrical systems,
- structural systems,
- machinery components (except pump and compressor casings).

However, these systems and components may be covered by other types of RBI.

## 2.2 Risk assessment concepts

“Risk is something that we as individuals live with on a day-to-day basis. Knowingly or unknowingly, people are constantly making decisions based on risk. Simple decisions such as driving to work or walking across a busy street involve risk. More important decisions such as buying a house, investing money, and getting married all imply an acceptance of risk. Life is not risk-free and even the most cautious, risk-adverse individuals inherently take risks. Some people take more risks than others (knowingly or unknowingly), e.g. sky divers, mountain climbers, coal miners, and people who drive while intoxicated” (API, API recommended practice 580: Risk-Based Inspection, 2009).

We can define Risk as the combination of the probability of occurrence of one event during a certain period of time and the consequences of this event.

Risk can be therefore expressed as a number through equations as the following one

$$\text{Risk} = \text{Probability of Occurrence} \times \text{Associated Consequences}$$

A proper risk assessment should be a rational, logical, structured process, which contains at least two key steps:

- Determine how big the risk is;
- Determine whether the risk is acceptable.

After determining the magnitude of the risk it is necessary to start the risk management process in which risk reduction is involved: through risk management it is possible to define if a risk is acceptable or not and to determine if risk reduction is required.



Through RBI methodology it is possible to plan maintenance basing the decisions on the fact that “the ultimate goal of inspection is the safety and reliability of operating facilities” (API, API recommended practice 580: Risk-Based Inspection, 2009).

Therefore RBI is a risk-based approach that focuses attention specifically on the equipment and associated damage mechanisms representing the highest risk to the facility: this way RBI provides a better knowledge of the link between the mechanisms that lead to equipment failure (loss of containment) and the inspection approaches that will effectively reduce the associated risks (API, API recommended practice 580: Risk-Based Inspection, 2009).

### 2.2.1 Inspection Optimization

After determining the risk associated with each equipment and inspection techniques/process monitoring to reduce risk it is possible to plan, optimize and implement an RBI program.

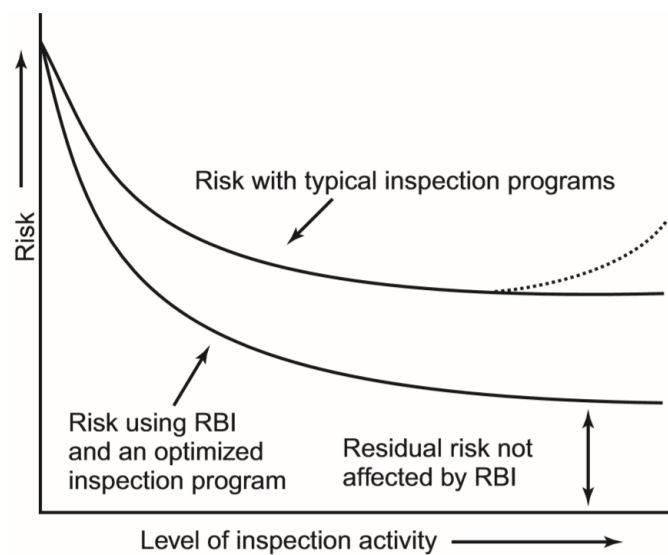


Figure 3 - Risk and inspection activity (API, API recommended practice 580: Risk-Based Inspection, 2009)

In Figure 1 we can see general curves that show how risk is influenced by the level of inspection activity.

The upper curve represent the reduction of risk in a typical inspection planning: the starting point represents the situation in which there is no inspection and so the level of risk is obviously high due to uncertainty. With an initial investment in inspection activities, risk generally is significantly reduced. Following the curve is expected that a point is reached where additional inspection

activity provides no appreciable benefits comparing them to its cost and, eventually, may produce very little additional risk reduction. Furthermore, if excessive inspection is applied, the level of risk may even go up because invasive inspections can cause additional deterioration such as inspection damage to protective coatings or glass-lined vessels: this case is represented by the dotted line at the end of the upper curve (API, API recommended practice 580: Risk-Based Inspection, 2009).

Through an RBI program is possible to assess the optimum combination of methods and frequencies of inspection: each available inspection method can be analysed and its relative effectiveness in reducing failure probability can be estimated. Knowing this information and merging it with the costs, an optimization program can be developed successfully.

The conceptual result of this procedure can be seen in the lower curve: with the application of an effective RBI program lower risks can be achieved with the same level of inspection activity. This is because, through RBI, inspection activities are focused on higher risk items and away from lower risk items.

Of course risk cannot be reduced to zero only by inspection efforts: this is shown in the last part of the lower curve. There are a lot of residual risk factors for loss of containment such as the ones proposed by API RBI 580 (API, API recommended practice 580: Risk-Based Inspection, 2009):

- human error;
- natural disasters;
- external events (e.g. collisions or falling objects);
- secondary effects from nearby units;
- consequential effects from associated equipment in the same unit (domino effects);
- deliberate acts (e.g. sabotage);
- fundamental limitations of inspection methods;
- design errors;
- unknown or unanticipated mechanisms of damage;

### 2.2.2 RBI objectives and key parameters

“The objective of RBI is to determine what incident could occur (consequence) in the event of an equipment failure, and how likely (probability) it is that the incident could happen” (API, API recommended practice 580: Risk-Based Inspection, 2009).

Combining the probability of the different failures modes of an equipment with its consequences will determine the risk associate with such equipment. Some failures have low probability but high consequences in terms of environment, safety and business interruption. Similarly, some failures have high probability of occurrence but a low level of consequences. However, if the probability and consequence combination, so the Risk, is high enough to be unacceptable, then a mitigation action to reduce the probability and/or the consequence of the event is demanded.

Determining the risk leads to consider both probability and consequences and this is the basis of an effective risk-based decision-making. However, decision making is based on the fact that the company should define risk acceptability criteria in order to account for the fact that not every failure will lead to serious consequence (e.g. ambient temperature water leaks) and that some serious consequence incidents have very low probabilities (e.g. rupture of a clean propane vessel) (API, API recommended practice 580: Risk-Based Inspection, 2009).

After defining the risk for each equipment and the risk acceptance criteria, maintenance planning is possible.

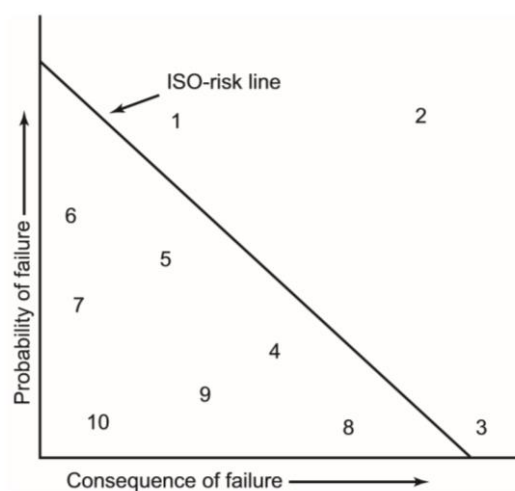


Figure 4 - Items risk-based ranking (API, API recommended practice 580: Risk-Based Inspection, 2009)

Figure 2 shows the risk associated with the operation of different equipment items in a process plant: this is the result of determining the probability and consequence for each equipment item. The points in the graph represent the risk associated with each equipment item.

It is then possible to order the items by risk producing a risk-based ranking of the equipment items to be inspected: from this list, an inspection plan can be developed that focuses attention on the areas of highest risk. A company defined acceptable risk level could be plotted as an ISO-risk line in the same graph: In this way the acceptable risk line would separate the unacceptable from the acceptable risk items.

It must be said that since risk is dynamic because it changes with time it is really important that any RBI process have the ability to be easily updated (including changes in the inspection plan) when changes occur or new information is discovered. According to API 580, those changes might include (API, API recommended practice 580: Risk-Based Inspection, 2009):

- new data from inspection activities (i.e. changes in rates of deterioration are noted in external, internal, or onstream inspections);
- changes in operation or operating variables;
- changes in the process fluids, however small;
- changes in process equipment, including additions;
- equipment leaks or failures.

However, the objective of RBI is to “direct management’s decision process of prioritizing resources to manage risk” (API, API recommended practice 580: Risk-Based Inspection, 2009): inspection influences the uncertainty of the risk by improving knowledge of the deterioration state and predictability of the probability of failure.

Such probability due to deterioration is a function of four factors (API, API recommended practice 580: Risk-Based Inspection, 2009):

- deterioration type and mechanism;
- rate of deterioration;

- probability of identifying and detecting deterioration and predicting future deterioration states with inspections;
- tolerance of the equipment to the type of deterioration.

The output of the application of RBI methodology is a maintenance plan for every equipment that also states the level of risk associated with such equipment before and after the inspection: a complete maintenance plan should include, for risks considered unacceptable, the mitigation actions that are recommended to reduce the unmitigated risk to acceptable levels.

As said, a way to reduce the level of risk could be the inspection plan itself for those equipment items where inspection is a cost-effective means of risk management: the plans should describe the type, scope and timing of inspection and examination recommended.

“Ranking of the equipment by the unmitigated risk level allows users to assign priorities to the various inspection and examination tasks. The level of the unmitigated risk should be used to evaluate the urgency for performing the inspection” (API, API recommended practice 580: Risk-Based Inspection, 2009).

Considering all said before, RBI can be an effective way to plan the maintenance of a facility taking into account a time varying risk, priorities, costs and so optimization.

## 2.3 Software overview

### 2.3.1 What is Synergi RBI

The first software to be used in the process mentioned in the “Problem formulation and objectives” section is Synergi Plant - RBI that is, according to the software developer, a “software for supporting improved plant safety and cost reduction through optimization of your risk based inspection strategy according to API 580 and API 581” (DNV-GL, s.d.).

As claimed by the developer, with the Synergi Plant - RBI software modules it is possible improve safety and potentially reduce costs by optimizing the inspection strategy to focus resources on high-risk areas. The RBI software is based on the extensively used risk-based inspection

methodology (DNV-GL, s.d.). Synergi Plant - RBI software comes in several variants: RBI Onshore, RBI Power Plant, RBI Offshore, RBI AST and RBI Bespoke: in this work the software RBI Onshore will be used.

The application of risk-based inspection (RBI) technology to safety-critical equipment in the onshore refinery, petrochemical and gas processing includes qualitative and quantitative RBI methodology. As said before, API 580 presents guidelines for developing an RBI programme whereas API 581 provides RBI methods to establish a risk-based inspection programme. Synergi Plant's Risk Based Inspection modules use both API 580 and API 581 (DNV-GL, s.d.).

RBI Onshore software implements the API 580 / API 581 RBI methodology with qualitative and quantitative approaches and some extensions. The methodology applies to various types of vessels (separators, columns, drums, storage tanks etc.), pipes and pressure relief devices.

The probability of failure used in the software is based on API RBI 581 following equation:

$$P_f(t) = gff \cdot D_f(t) \cdot F_{MS}$$

Where  $gff$  is the generic failure frequency,  $D_f(t)$  is the damage factor and  $F_{MS}$  is the management systems factor.

The  $gff$  is the failure frequency prior to any specific damage occurring from exposure to the operating environment, and are provided for several discrete hole sizes for various types of processing equipment (four hole sizes to model the release scenarios) (API, API recommended practice 581: Risk based inspection technology, 2008).

The  $D_f(t)$  accounts for the influence of the facility's management system on the mechanical integrity of the plant equipment (the probability that accumulating damage which results in loss of containment will be discovered in time and is directly proportional to the quality of a facility's mechanical integrity program) (API, API recommended practice 581: Risk based inspection technology, 2008).

The damage factor is determined based on the applicable damage mechanisms (local and general corrosion, cracking, creep, etc.) relevant to the materials of construction and the process service, the physical condition of the component, and the inspection techniques used to quantify damage.

Methods for determining damage factors are provided in API RBI 581 for the following damage mechanisms (API, API recommended practice 581: Risk based inspection technology, 2008):

- Thinning (both general and local);
- Component Linings;
- External Damage (corrosion and stress corrosion cracking);
- Stress Corrosion Cracking (internal based on process fluid, operating conditions and materials of construction);
- High Temperature Hydrogen Attack;
- Mechanical Fatigue (Piping Only);
- Brittle fracture.

If more than one damage mechanism is present, then the principal of superposition is used.

It should be noted that damage mechanisms are not the only causes of loss of containment. Other causes of loss of containment could include but are not limited to (API, API recommended practice 581: Risk based inspection technology, 2008):

- seismic activity;
- weather extremes;
- overpressure due to pressure-relief device failure;
- operator error;
- inadvertent substitution of materials of construction;
- design error;
- sabotage.

After selecting all the correct inputs, the software can calculate the POF that is typically expressed in terms of frequency and is called Likelihood of Failure. Frequency is expressed as a number of events occurring during a specific time frame. For probability analysis, the time frame is typically

expressed as a fixed interval (e.g. one year) and the frequency is expressed as events per interval (e.g. number of failures per year). For a qualitative analysis, the Likelihood of Failure may be categorized (e.g. high, medium and low, or one through five): it is appropriate to associate an event frequency with each probability category to provide guidance to the individuals who are responsible for determining the probability. If this is done, the change from one category to the next could be one or more orders of magnitude or other appropriate demarcations that will provide adequate discrimination.

Regarding the consequences of loss of containment, those are determined using well established consequence analysis techniques and are expressed as an affected impact area or in financial terms. Impact areas from such event outcomes as pool fires, flash fires, fireballs, jet fires and vapor cloud explosions are quantified based on the effects of thermal radiation and overpressure on surrounding equipment and personnel. Additionally, cloud dispersion analysis methods are used to quantify the magnitude of flammable releases and to determine the extent and duration of personnel exposure to toxic releases. Event trees are utilized to assess the probability of each of the various event outcomes and to provide a mechanism for probability-weighting the loss of containment consequences (API, API recommended practice 581: Risk based inspection technology, 2008).

Knowing the likelihood of failures and the consequences, an  $R(t)$  curve can be drawn.

As said before, the risk target is defined as the level of acceptable risk defined for inspection planning purposes. The risk target is in terms of area for area-based consequence analysis and in terms of financial limits for financial-based consequence analysis.

In planning inspections using API RBI, a plan date is typically chosen far enough out into the future to include a time period covering one or several future maintenance turnarounds. Within this period, three cases are possible based on predicted risk and the specified risk target:

- Case A: the results of an inspection plan will be the number of inspections required, as well as the type or inspection effectiveness required, to reduce the risk at the future plan date down below the risk target;



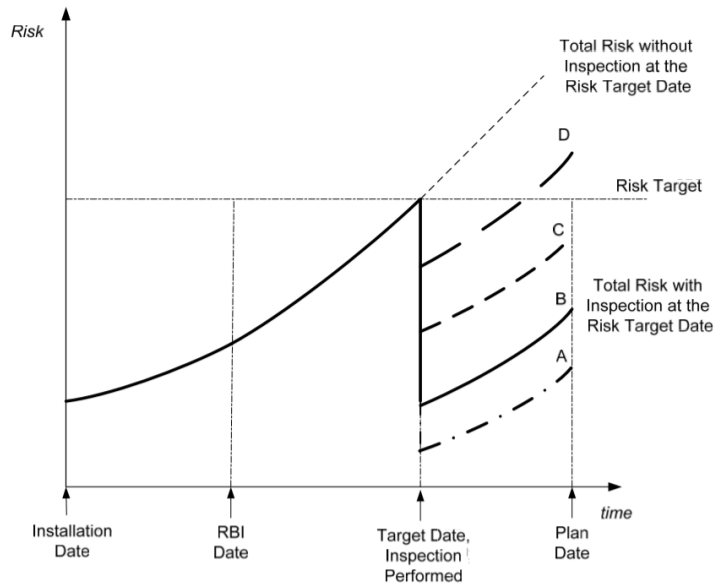


Figure 5 - Case A: inspection planning (API, API recommended practice 581: Risk based inspection technology, 2008)

- Case B: The current risk at the time of the RBI analysis exceeds the risk target; An immediate inspection will be recommended at a level sufficient to reduce the risk at the future plan date down below the risk target;

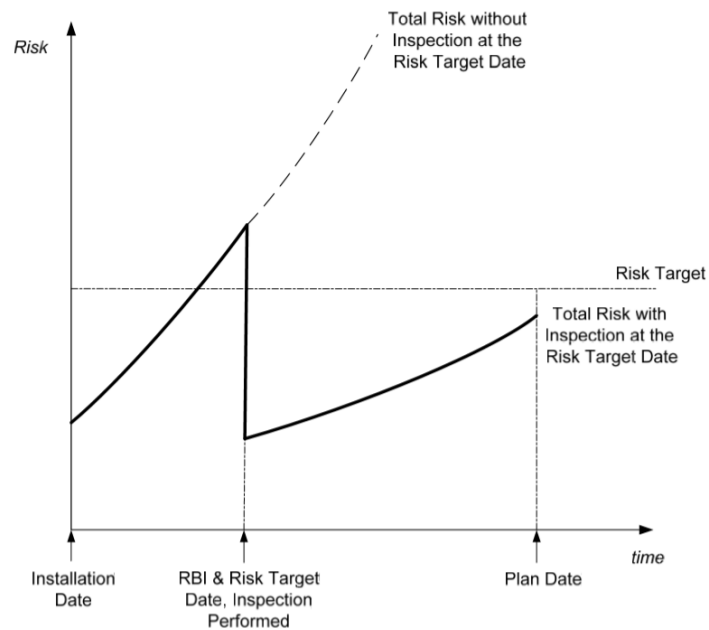


Figure 6 - Case B: inspection planning (API, API recommended practice 581: Risk based inspection technology, 2008)

- Case C: the predicted future risk at the plan date will not exceed the risk target and so no inspection is recommended during the plan period; the inspection due date for inspection scheduling purposes should be adjusted to the plan date.

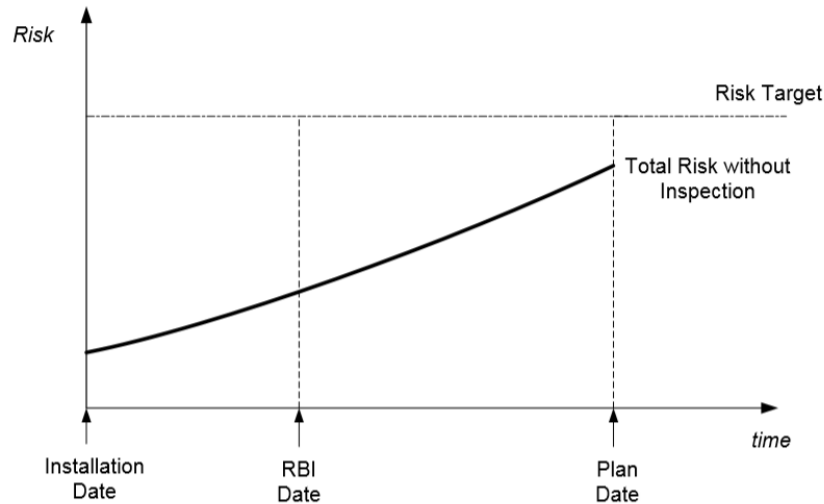


Figure 7 - Case C: inspection planning (API, API recommended practice 581: Risk based inspection technology, 2008)

Once all the inputs are set in the software for each equipment (e.g. materials, substances, geometry, dimensions etc.) it is possible to obtain a huge number of outputs other than the maintenance plan for the selected items.

For a selected item, the software provides different results categories; the most useful ones are:

- A general “Screening”: Consequences of failures level, likelihood level, remaining life;
- “Consequence” in which we can find, among others, the following information:
  - Current total CoF;
  - Outage Time [day]/ Outage Cost [USD]/ Equipment Damage Cost [USD]/ Safety Cost [USD]/ Non-Flammable Non-Toxicity Area [m2]/ Injury Count/ Total Cost [USD] for four different hole sizes (small, medium, large, rupture), release rates;
  - Current risk total cost (Likelihood x Cost), Current risk category total cost;
  - In this section we can also find, regarding the likelihood:
    - Current LoF at the evaluation date;
    - Future LoF at the inspection date;

- Hole size distribution.
- “Likelihood of Failure” in which we can find, in addition to all the likelihood information that are also present in the “consequence” section, for example:
  - Calculated corrosion factor;
  - Current and future damage factor;
  - Damage factor curve that shows its dependence by the time;
  - Remaining life results.
- “Risk”: a summary of all the risk related factors (likelihoods, consequences, etc.);
- “PoF degradation mechanism” that contains the detailed LoF and damage factor-time curves for each of the selected damage factors;
- “Inspection”: in which we can find for example:
  - Inspection date and suggested effectiveness/inspection tasks;
  - Future damage factor/ damage category with and without inspection.

In addition to all this information about each equipment the software provides a risk ranking of all the items, an easy to visualize risk matrix and the detailed complete inspection plan.

The inspection plan provided will be then useful because it optimizes the maintenance for each selected risk target; other output will be elaborated in order to use them in the further software.

### 2.3.2 What is SAFETI

The second software used in the proposed methodology to understand the level of safety given by each maintenance plan is Safeti.

DNV GL’s Safeti software provides a user-friendly, industry standard method for carrying out quantitative risk analysis (QRA) of onshore process, chemical and petrochemical facilities or analysis of chemical transport risk. This software allows to quickly identify major risk contributors: time and effort can then be directed to mitigating these highest risk activities (DNV-GL, s.d.).

Safeti is an advanced tool for quantifying process plant risks, it is designed to perform all the analytical, data processing and results presentation elements of a QRA within a structured framework.

Benefits of this software include (DNV-GL, s.d.):

- Risk ranking and hazard zone identification for guidance concerning possible mitigation including operation, emergency response or land use planning;
- It generates F-N Curves for comparison with user-defined acceptance criteria;
- It incorporates advanced consequence modelling for hazard analysis;
- It enables the integration of QRA into plant lifecycle management activities.

Through this software complex consequences from accident scenarios, taking account of local population, land usage and weather conditions, to quantify the risks associated with the release of hazardous chemicals.

This software includes integrated dispersion modelling, toxic and flammable effect models, ignition source input and population data definition, risk ranking of failure scenarios and can calculate various risk metrics such as:

- Individual Risk
- Potential Loss of Life
- FN Curves
- Risk contours

Another feature of the software is that it is possible to overlay results on geographical information systems (GIS), aerial maps, plans and photographs.

After adding the aerial map of the facility it is possible to insert all the equipment in the “Scenario” tab; at the Equipment level, you can define the process material and operating conditions. There are six types of item covered:

- Pressure Vessel: for modelling releases from pressurised containment;
- Atmospheric Storage Tank: for modelling releases from unpressurised containment
- Standalones item: for performing detailed modelling of specific hazards such as fire, explosion and pool vaporisation, separate from the modelling of a particular release from containment;

- Long pipeline: for modelling the time-dependent release from a long pipeline, including the effects of the closure of valves on the pipeline;
- Warehouse: for modelling a fire in a warehouse. The effects of the fire are modelled as a toxic plume which contains a mixture of hydrogen chloride, nitrogen dioxide and sulfur dioxide;

Next level of the analysis is to define the scenario: it is a hazardous event associated with the equipment item to which it belongs. The types of scenario under a given equipment item depends on the type of the equipment item.

If we take as an example the pressure vessel, it is possible to model the release of material through all the stages in its dispersion to a harmless concentration. The modelling includes discharge calculations to obtain the release rate and state, fire, explosion and toxic calculations where applicable, as well as representative effect zones for the dispersing cloud.

Other than the “Scenario” tab we can find the following:

- “Weather” tab: it is possible to define different kind of “Weather” that represent a particular set of weather conditions for use in the modelling of a release and its effects (i.e. a particular combination of wind speed, atmospheric stability, atmospheric temperature, etc.)

In the calculations for a given Scenario, the program performs a separate run of the consequence and risk calculations for each separate weather condition, giving a set of results that are specific to that Weather.

- “Parameters” tab: Parameters are background inputs that are applied to all calculations and are not specific to a particular Equipment item or Scenario. Some of the parameters in the program are used to provide default values for the aspects of Equipment item and Scenario input that are usually shared between groups of Equipment or Scenarios. Other parameters deal with advanced modelling assumptions and do not appear in the Equipment or Scenario input data.
- “Material” tab: the program is supplied with a set of System Materials that contains full property data for more than sixty materials. You can define three types of material: Pure Components, Mixtures and Warehouse Materials;

- “Map” tab: it is used to describe various aspects of the surroundings such as buildings, the local terrain and bunds around equipment and to define the images and other graphical data that you want to use as the background for displaying consequence results;
- “Risk” tab: it defines data that are specific to the risk calculations; It contains:
  - Categories: the program is supplied with a default list of Categories for Populations, with a different display style defined for each Category. Each Population is assigned to a Category, and the Category determines the style that will be used when displaying the Population in a GIS View. The Category is also used in the risk results, where some forms of results provide an analysis according to the populations assigned to each Category.
  - Ignitions: the ignition sources are used in modelling the location and probability of delayed ignition, and the input data for each ignition includes the probability that it will ignite a flammable cloud. You can define ignition sources on the GIS View as points, straight lines, polylines, rectangular areas and polygon areas. The distribution and strength of ignition sources typically varies according to the time of day like for day and night.
  - Populations: the risk modelling calculates fatalities for each population, and also considers populations as a potential cause of delayed ignition. The input data for each population includes the proportion of people indoors and out of doors. It is possible to define populations on the GIS View as points and as areas. As with ignitions, the distribution of population varies according to the time of day.
  - Vulnerabilities: Vulnerability data specify the criteria for causing fatalities or other types of damage from different types of hazardous effect. The program is supplied with two sets of data for personnel vulnerabilities, one for people out of doors, and one for people indoors.
  - Risk transects: a risk transect is a line drawn on the map; it is useful to view a Risk Transect Graph that shows the levels of risk along the line.
  - Risk ranking points: a Risk Ranking Point is a location drawn on the map, as a location of interest for detailed risk contribution results.

- Plant Boundaries: it is possible to draw the boundary of the plant as a polygon on the GIS View. The risk calculations uses the boundary to distinguish between onsite and offsite sources of ignition.

## Available risk results

The risk results are organised in three categories:

### 1. Societal Risk Results

These results present the risk in terms of the number of fatalities caused by the different alternative outcomes of the hazardous events, and the frequency of the outcomes. The F-N Curves show the results in the form of a graph of the frequency F of outcomes that cause N or more fatalities. The other types of societal risk results are reports in the form of tables or grids that list the individual outcomes, and give different types of analysis of the results, with different levels of grouping (DNV-GL, 2018).

### 2. Risk Ranking Point Results

These results list all of the individual outcomes that contribute to the risk of exceeding vulnerability criteria at a given Risk Ranking Point. The different types of risk ranking point results give different types of analysis of the results, with different levels of grouping (DNV-GL, 2018).

### 3. Risk Contour Results

These results present the geographical distribution of the risk of exceeding vulnerability criteria, in the forms of contours for a given level of risk displayed in a GIS View. The different types of risk contour results allow to compare different aspects of the risk levels (DNV-GL, 2018).

It has to be said that all these calculations are possible if among all the inputs the user provides the likelihoods of each failure: those data will come from the elaboration of Synergi outputs.

#### 2.3.3 What is ExtendSim

Last software to be used, in order to consider Business Interruption issues, is ExtendSim.

“Invention, innovation, quality, productivity, and speed are the keys to making companies competitive: one way to maximize competitiveness is to improve operational systems and processes” (Imagine-that-inc) through:

- Eliminating nonessential, non-value-adding steps and operations;
- Implementing and inserting technology where appropriate;
- Managing the deployment and utilization of critical resources;
- Identifying key cost drivers for reduction or elimination.

“Simulating a system or process provides a quick and cost-effective method for determining the impact, value, and cost of changes, thus validating proposed enhancements and reducing the resistance to change” (Imagine-that-inc). Through simulations it is possible to save time, to make non-disruptive modifications to the existing system that are also more flexible than real systems. Simulations can also provide metrics to use for analysis and strategic planning in order to help organizations answer questions about “how they do work: what they do, why they do it, how much it costs, how it can be changed, and what the effects of changes will be” (Imagine-that-inc).

Thanks to a simulation the organization can easily see how a real-world activity will perform under different conditions and test various hypotheses or alternatives at a lower cost comparing it to performing the actual activity. It has to be noticed that it also allows to see the impact of possible modifications on systems that are not accessible in the reality, for systems and processes that are still in a design phase, or where such changes would be dangerous or not permitted.

Therefore a simulation helps the organization not only to understand complex systems but also to produce better results faster because, according to ExtendSim manual, it is possible to (Imagine-that-inc):

- Predict the course and results of certain actions;
- Identify problem areas before implementation;
- Explore the potential effects of modifications;
- Confirm that all variables are known;
- Optimize operations;
- Evaluate ideas and identify inefficiencies;



- Understand why observed events occur;
- Communicate the integrity and feasibility of the plan.

### Systems, models, and simulation

“All professions use models of one form or another. But the word “model” does not always have the same meaning to business professionals, managers, scientists, and engineers. Even within a specific discipline, such as manufacturing, modelling has many different definitions” (Imagine-that-inc).

It is easily possible to see the reality as composed by systems, where a system is a “set of interacting or interdependent components that form a whole” (Imagine-that-inc). The components are able to interact with each other following the rules or policies of the system.

Therefore, components are internal parts of a system that could be “individual entities, generalized substances, or any other parts of the system that are involved in one or more of its processes” (Imagine-that-inc). Operating policies and availability of resources are the rules that the system follows when operating and that the components of the system use to interact. An important variable in the system is the time that causes changes to its state through the activities and interactions of components, defining the system behaviour. An example of a complex system could be the supply chain operations composed of planning, selling, distribution, production, and sourcing subsystems.

Once defined a system, we can say that “a model is an abstracted and simplified representation of a system at one point in time” (Imagine-that-inc). It has to be said that they are an abstraction because they can only try to behave exactly like the real system. While building a model, it is necessary to “simplify” because, in order to keep the process of modelling efficient, reliable, and easy to analyse, “a model should capture only the most important aspects of the real system”.

Among all the kinds of models that can be built, we can find four major categories:

- A “scaled representation of a physical object”, such as board model of a weight scale.
- A “graphical or symbolic visualization”, such as flow charts or a facility plant sketch.

- An “analytical or mathematical formula that yields a static, quantitative solution”. This kind of models could be, for example, a collection of “several independent sample observations that have been transformed according to the rules of the model”. A practical example could be a spreadsheet model.
- A “mathematical description that incorporates data and assumptions to logically describe the behaviour of a system”. This kind of model “is typically dynamic, it has a time component and shows how the system evolves over time”.

Regarding ExtendSim, the software allows the user to build “mathematically-based, dynamic models of systems”.

The Merriam-Webster OnLine Dictionary defines simulation as “the imitative representation of the functioning of one system or process by the functioning of another” (Imagine-that-inc). Once the model is built, the simulations run in simulation time, an abstraction of real time. As the simulation time goes on, the model is capable of determine if there have been changes in that amount of time, then it can recalculate its values, and finally output the results. These results will be reflective of the behaviour of the real system if the model built by the user is valid. When performing a simulation, then, it means that you “create a logical model that corresponds to the real system in certain aspects” (Imagine-that-inc) and this could be useful in order to reduce uncertainty in taking informed, data based decisions. “In summary, Simulation is the act of creating a mathematical model of a system then causing the model to replicate over time to represent the operation of the system” (Imagine-that-inc).

In the end, a simulation could be seen both as an “analysis tool”, if the system models something that already exists in order to see how changes would affect it, and as a “design tool”, if it is created in order to predict the behaviour or performance of a non-existing possible future system.

In order to specify the system it is important to choose the appropriate “modelling methodology”. The three main modelling methodologies are:

- Continuous process modelling: it describes “a time-based system where state variables, which describe the system at any point in time, change continuously as time advances” (Imagine-that-inc);

- Discrete event models: they simulate "event-based systems and processes that usually involve queues. In a discrete event model, nothing happens between points in time unless an event occurs" (Imagine-that-inc);
- Discrete rate models: this kind of models have some aspects of both continuous and discrete event modeling.

Regarding the thesis work, the interest is to model the business interruption risk due to planned and unplanned stops. In order to get this output, the system could substantially be composed by two parts. The first one should be a generating item that can "create" cars going to a refuelling station. These cars need to be refuelled and so different items should model this "action" and therefore provide an estimate of the station profit. It is easy to understand that the model records changes every time that a car is "generated" and flows through the items ( that is, the components like the refuelling dispenser); It has to be said that in order to model the system failures it is necessary to build a distribution: failures depend on the passing of time and this can seem like a continuous model. A change of the system, however, occurs only when an event (that is, the failure) occurs: this means that the modelling methodology that is relevant for the study is the "discrete event models" one.

Those consideration match with the ExtendSim guide that states that "In discrete event models, the system changes state as events occur and only when those events occur" (Imagine-that-inc); The variable "time" has no "direct" effect on the model.

Therefore, regarding a facility, ExtedSim can be used to model the business interruption: if the model describes the process of "selling" with associated incomes, it is possible to introduce the maintenance plan and the unplanned shutdowns due to accidents with their relative LoF as a variable of the system. This way it is possible to predict how maintenance and unplanned stops can affect the business of the facility and can help to take decisions based on numerical values such as the total profit of a certain period: simulating the process changing these variables is a way to understand how do they affect the target (e.g. the sales income).

## 2.4 Methodology steps

Once all the important information about all the methodology basis (RBI methodology) and the three software are clear, it is possible to explain the main steps that have to be followed in order to develop and choose the best maintenance plan for the facility.

### 2.4.1 Maintenance Plan and LoFs

The first step of the procedure is to choose a risk target because, as stated before, the basis of RBI is to fix a risk target: in this work three different risk target will be used to perform different maintenance plans.

Once the Risk target is selected, the software optimizes the maintenance program based on this target and on the Service start date, Current evaluation date and Future evaluation date. The service start date is to be intended as the date in which the facility started to be productive, the Current evaluation date is the date in which the analysis is performed and the Future evaluation date is the date that defines the time frame in which the maintenance plan will be planned.

The main input for the program is then the Risk Total cost that is defined by the following equation:

$$RiskTotalCost = CoF (\$) \times LoF$$

During the evaluation period, according to the software, the maximum Financial consequences are calculated for the selected system as a  $Risktgt_{max}$  in financial terms (\$).

Then, different cases can be studied, assuming different percentages of the  $Risktgt_{max}$  and selecting a likelihood of occurrence.

The output of the cases, for each selected equipment, are:

- Maintenance plan;
- Likelihoods of failure:
  - LoF at the evaluation time;
  - LoF without inspection at the inspection date;

- LoF with inspection at the inspection date.

The maintenance plan for the selected case will be assumed as the chosen one that has to be implemented with a safety-oriented analysis and a business interruption simulation.

In order to have the inputs for SAFETI, the “LoF Without inspection” of the different equipment at the inspection date of the first one to be inspected are chosen assuming that this will be the LoFs right before the inspection will occur: this represents the maximum risk that the company will accept before the inspection is completed.

Regarding the failure scenarios to be analysed, they depend on the kind of equipment to be analysed and can be addressed to one of the following:

- Small leak: hole size of 22 mm;
- Medium leak: hole size of 44 mm;
- Large leak: hole size of 88 mm;
- Catastrophic rupture: all material released.

Once these scenarios are defined, it is necessary to calculate their LoFs considering damage mechanisms (provided by the RBI software), human error and so on.

Once the LoFs are calculated for each scenario, for every selected risk target, the output (in addition to the maintenance plan) to be used in the next steps will be:

- LoF for the small leak scenario;
- LoF for the medium leak scenario;
- LoF for the large leak scenario;
- LoF for the rupture scenario;

#### 2.4.2 Safety issues: F-N curves and risk contours

After defining the layout and all the necessary data in Safeti, the main input to provide are the LoFs for the selected scenarios: these LoFs are the one that have been calculated in the previous step. This way it is possible to obtain a set of risk indicators (for every selected risk target) that can be used after to take decisions on which maintenance plan is the best option to choose.

### 2.4.3 Business interruption: Expected income from hydrogen fuel sales

Once the business model is built, the main inputs that have to be provided to ExtendSim are the TBF (time between failures) distribution and the TTR (Time to repair) distribution.

Regarding the time between failures it is possible to obtain it by first calculating the total LoF, as the failure of the system occurs when at least one of the failure scenarios occurs:

$$Total\ LoF = SmallLeakLoFs + MediumLeakLoF + LargeLeakLoF + RuptureLoF$$

The mean TBF will therefore be:

$$TBF = \frac{1}{Total\ LoF}$$

Regarding the TTR distribution it is possible to use an Interpolate empirical distribution once the LoF and the outage time for every scenario are known: those inputs come from Synergi RBI that provides the outage time for every hole size (small/medium/large leak and rupture) other than the associated LoF.

Another important input is the maintenance plan in terms of the days that are spent to perform maintenance and that influence also the TBF: the time between failures is restored after the maintenance is performed.

In this way the simulation will give the expected profit as it is influenced by unplanned shutdowns due to failures and the maintenance plan.

### 2.4.4 Results

Once the previous steps are performed, the output for every risk target will be:

- Maintenance plan;
- Associated risk indicators;
- Associated expected profit.

### 3. Case study description

The case study of this work is a refuelling station with on-site production via electrolysis.

The station that has been chosen for the application of the proposed methodology is located in Sandvika, the administrative centre of the municipality of Bærum in Norway. Sandvika is situated approximately 15 kilometers west of Oslo and it is the main transportation hub for Western Bærum and has a combined bus and railway station.

The station was opened in 2016 and is owned by Uno-X Hydrogen as a joint venture between Uno-X, Nel, and Nippon Gases (formerly Praxair) (Løkke, 2019).



Figure 8 - Station location (Google earth, s.d.)

The station was built using Nel ASA technology: Nel is a technology company with roots going back to technology developed by NorskHydro in 1927 and it is the world's largest electrolyzer manufacturer with more than 3500 units delivered in over 80 countries since 1927 and the world leading manufacturer of hydrogen refuelling stations; approximately 50 stations have been delivered to 9 countries until the present day (Løkke, 2019).

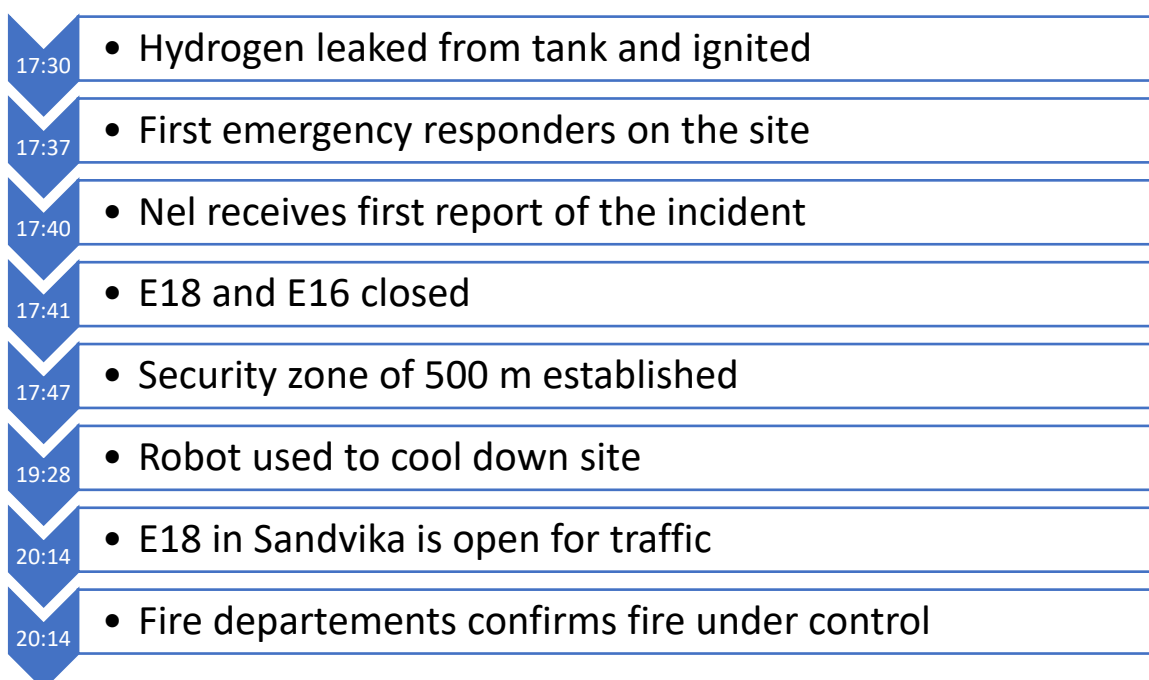
All hydrogen solutions from Nel are certified by third parties and comply with all relevant international standards, including directives in Europe below (Løkke, 2019):

- Mechanical and Safety Instrumented System IEC61511;
- DIRECTIVE 2014/68/EU Safety of pressure vessel equipment and material;
- DIRECTIVE 2014/34/EU Equipment used in potentially explosive atmospheres (ATEX);
- DIRECTIVE 2014/30/EU Electromagnetic compatibility;
- DIRECTIVE 2014/35/EU Low-voltage electrical equipment;
- DIRECTIVE 2006/42/EC Machinery Directive;
- ISO/TS 19880-1:2016 Gaseous hydrogen -- Fuelling stations -- Part 1: General requirements;
- SAE J2601\_201407 Fuelling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles;

### 3.1 The accident

The choice of this station is due to an accident occurred on June 10, 2019 that caused the station to close for accident investigation and repairs.

In the following scheme it is possible to understand the events chain regarding the accident (Løkke, 2019):





Talking about root causes it seems that the accident was caused by an assembly error in the high-pressure storage unit: the unit consists of steel tanks and other components by third parties, some of which are designed by Nel.

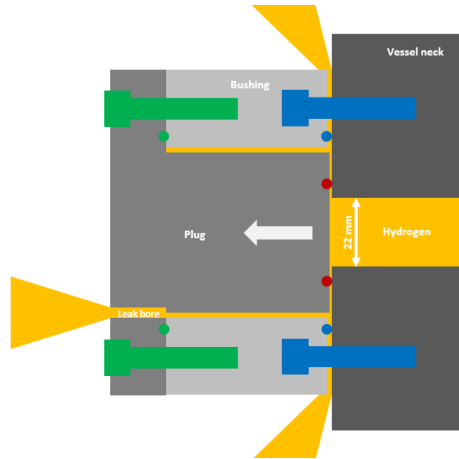


Figure 9 - Plug assembly (Løkke, 2019)

Referring to Figure 9 that shows the plug assembly it is possible to understand the failure mechanism described below.

The starting condition was that the green bolts were torqued properly while the blue bolts not. This condition led to the red sealing fail causing a small leak on the red sealing area that started to be worn out. The leak exceeded the capacity of the leak bore, causing a pressure increase inside the blue sealing area: the insufficient pre-tension of the bolts then lifted the plug and the blue sealings failed immediately (Løkke, 2019).

All these events led to the spread out of Hydrogen gas in an uncontrolled way till a cloud formed, ignited and exploded causing a fire on the site, damages to cars and to the windows of the close office buildings: pictures about the site after the accident are shown in Figure 11 and 12.

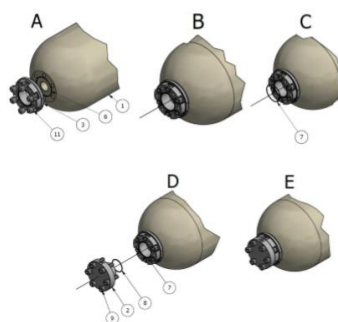


Figure 10 - Plug parts (Løkke, 2019)



*Figure 11 - Accident consequences 1 (NewsBeezer, 2019)*



*Figure 12 - Accident consequences 2 (Norway Today, 2019)*

After the accident Nel decided to take the following decisions (Løkke, 2019):

- **With verified plug solution**
  - Inspect all high-pressure storage units in Europe;
  - Check/re-torque all plugs.

- **Updated routines for assembly of high pressure storage units**
  - Introduce new safety systems/routines (aerospace standard);
  - Torque verification, double witness and documentation/markings.
- **Improved leak detection**
  - Software update to increase leak detection frequency;
  - Consider additional detection hardware/modifications.
- **Ignition control measures (site dependent)**
  - Smooth surface/no gravel around high-pressure storage unit;
  - Additional ventilation in compound and higher extent of EX-equipment.

### 3.2 Specifications of the site

Kjørbo station is a H2Station®CAR-200, a new product generation for 70MPa fast hydrogen fuelling, designed for use in Europe and USA with the following key characteristics (Løkke, 2019):

- 1/3 footprint and 3 times capacity vs. previous CAR-100. (From 30 sm to 10 sm)
- 1 hose configuration with 200kg per day, prepared for upgrades.
- Peak "rush hour" capacity of up to 100kg per 3 hours (one hose).
- Flexible dimensioning of hydrogen storage to fit any demand and supply sources ranging from onsite production to trucked delivery.

In general, a gaseous hydrogen filling station based on onsite production of hydrogen can be divided into several main blocks as shown in Figure 13.

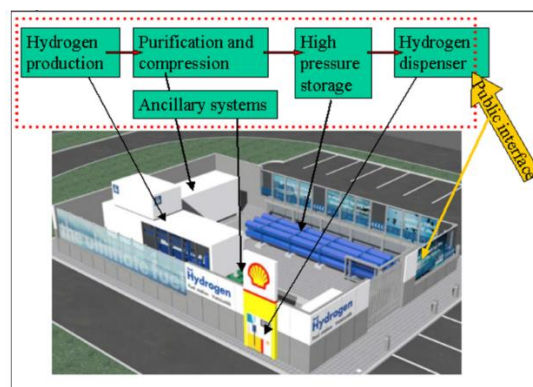


Figure 13 - Illustration of main blocks of a hydrogen filling station based on hydrogen production onsite (Nilsen Sandra, 2003)

Regarding Kjørbo, station aerial photo and layout can be seen in the following Figures 14 and 15 respectively.

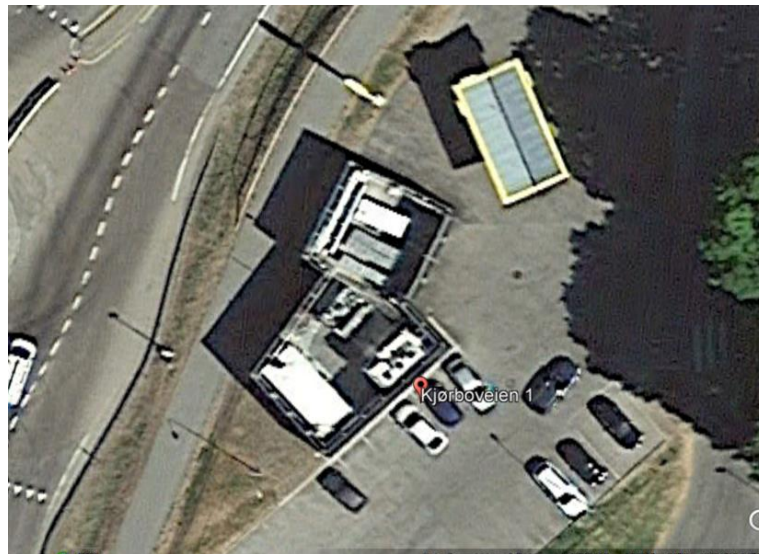


Figure 14 - Kjørbo aerial photo (Google earth, s.d.)

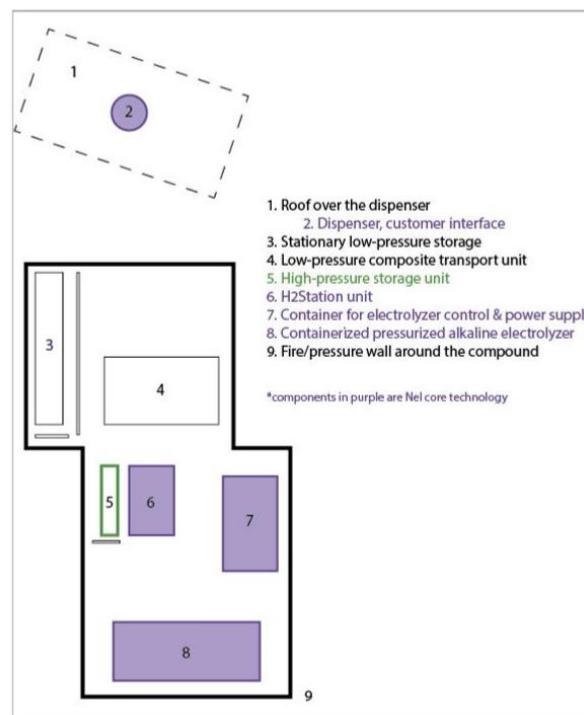


Figure 15 - Kjørbo layout (Løkke, 2019)

Regarding the production method, electrolysis is a promising option for hydrogen production from renewable resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen: this reaction takes place in a unit called electrolyser. Electrolysers can range in size



from small-scale, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production (Nilsen Sandra, 2003).

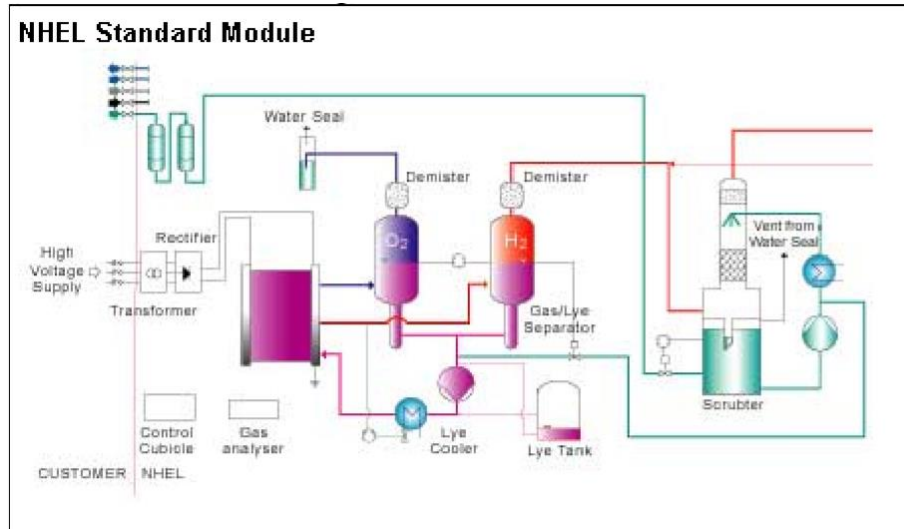


Figure 16 - Simplified flow diagram for hydrogen production by water electrolysis (Nilsen Sandra, 2003)

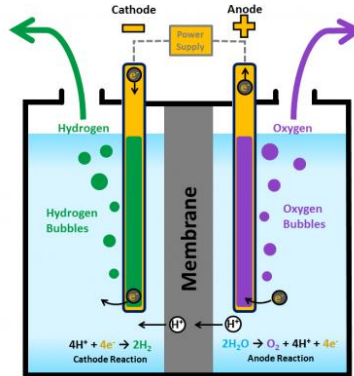


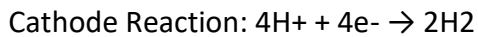
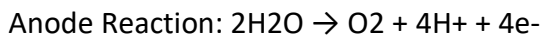
Figure 17 - electrolyser scheme (Energy.gov, s.d.)

Like fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte as shown in Figure 17 . Different electrolyzers function in slightly different ways, mainly due to the different type of electrolyte material involved (Energy.gov, s.d.):

- POLYMER ELECTROLYTE MEMBRANE ELECTROLYZERS

In a polymer electrolyte membrane (PEM) electrolyser, the electrolyte is a solid specialty plastic material.

- Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons);
- The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode;
- At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas:



- **ALKALINE ELECTROLYZERS**

Alkaline electrolyzers operate via transport of hydroxide ions (OH<sup>-</sup>) through the electrolyte from the cathode to the anode with hydrogen being generated on the cathode side. Electrolyzers using a liquid alkaline solution of sodium or potassium hydroxide as the electrolyte have been commercially available for many years. Newer approaches using solid alkaline exchange membranes as the electrolyte are showing promise on the lab scale.

- **SOLID OXIDE ELECTROLYZERS**

Solid oxide electrolyzers, which use a solid ceramic material as the electrolyte that selectively conducts negatively charged oxygen ions (O<sup>2-</sup>) at elevated temperatures, generate hydrogen in a slightly different way.

- Water at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions;
- The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit;

Solid oxide electrolyzers must operate at temperatures high enough for the solid oxide membranes to function properly (about 700°–800°C, compared to PEM electrolyzers, which operate at 70°–90°C, and commercial alkaline electrolyzers, which operate at 100°–150°C). The solid oxide electrolyzers can effectively use heat available at these elevated temperatures (from various sources, including nuclear energy) to decrease the amount of electrical energy needed to produce hydrogen from water (Energy.gov, s.d.).

Regarding Kjørbo refuelling station source of energy, the electricity is mainly produced through a solar farm right next to the facility. As said before, "it is important to note that today's grid electricity is not the ideal source of electricity for electrolysis because most of the electricity is generated using technologies that result in greenhouse gas emissions and are energy intensive" (Energy.gov, s.d.). Electricity generation using renewable energy technologies as a growing portion of the grid mix is a possible option to overcome these limitations for hydrogen production via electrolysis. The other option that is possible to follow until these goals are reached is, as in Kjørbo station, to use locally produced renewable energy when possible and then to use energy from the grid only when necessary.

Energy production/use and hydrogen production via electrolysis are part of the first unit of the station; in addition to the so called "production unit" we can find:

- Compression unit

The produced hydrogen is dried and purified and then transferred to the compression unit where it will be compressed to different pressure. The compressors are expected to be located inside a container or some type of weather shed.

- Storage unit

The produced and compressed hydrogen is then transported in a pipeline to different kinds of pressure storage vessels. The vessels are divided into several vessel banks, called the high-pressure bank, the medium pressure bank and the low-pressure bank to be able to carry out a three stage "cascade filling" of the vehicles. This system is able "to ensure that the on-board vehicle storage tank reaches the optimum fill pressure within the required time" (Jasem Alazemi, 2015). Each vessel bank is equipped with its own pressure relief devices and pressure monitoring instruments. Typical storage pressure today is in the order of 350 – 450 bar until 900 bar. "The storage cascades will be filled from the production side, one at a time, and the produced hydrogen will first flow to the high pressure bank, then to the medium pressure bank, and the low pressure bank will be the last filled vessel bank. This is to increase the efficiency of the filling process" (Jasem Alazemi, 2015).

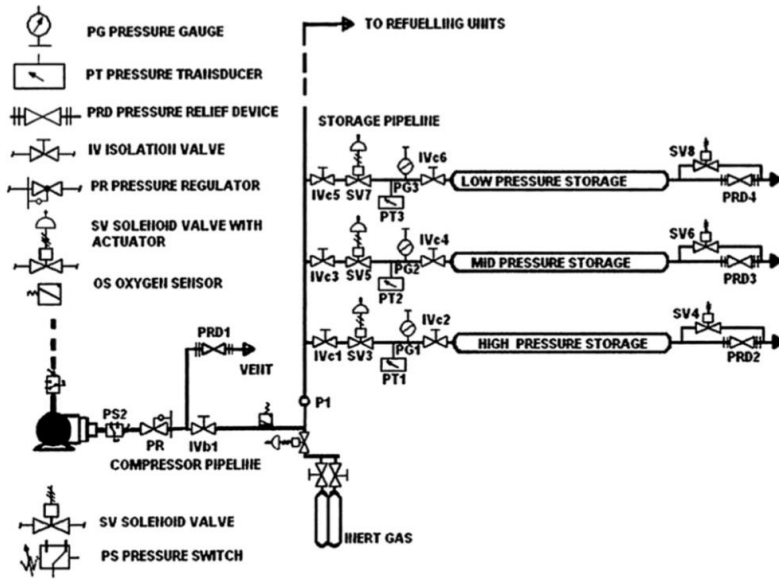


Figure 18 - Compression and storage units of the plant (Casamirra M., 2009)

Talking about Kjørbo, as the system described before, hydrogen is produced in situ and, due to the needed very high pressure, it is stored in form of compressed gas by a three-stage compressor and is sent to three storage vessels, respectively, at low (200 bar), medium (400 bar) and high pressure (900 bar). Some assumptions about the storage unit are taken: the three-stage compressor is equipped with internal and external pressure switches that operate based on downstream pressure. An external pressure switch (PS2), downstream the compressor, has the task of switching off the compressor when the storage pressure equals the set point value. Moreover, a pressure regulator (PR) in the compression unit and a pressure relief system (PRD1) in the compressor pipeline reduces unwanted higher gas pressure in the line. Of course, each storage vessel is protected by pressure relief devices able to ensure that the maximum allowable pressure is not exceeded. “Such devices consist of a redundant system provided by mechanical valve (PRD) and solenoid one (SV) which act venting gas in case of pressure excess or control system malfunction. All pressure relief devices are set 10% above the maximum allowable working pressure” (Casamirra M., 2009). Regarding the storage pipelines, they are equipped with pressure gauges (PG), connected with pressure transducers (PT), and solenoid valves actuated by a Programmable Logic Controller (PLC). “This last unit is also used to control major safety functions of the station, including regulation of the dispenser interactions. It is equipped by backup batteries to ensure the PLC system functionality in case of electrical



power loss” (Casamirra M., 2009). The refuelling of the cars is performed in “cascade”: the vehicle connects to the dispenser and then the PLC opens the solenoid valve (SV7) of the storage low pressure gas line; If necessary the operation is completed, in succession, by the other stages at higher pressures. This process is performed in order to regulate the hydrogen outflow from storage vessel mainly to optimize the refuelling time (Casamirra M., 2009). Another advantage is the reduction of the abrupt pressure change in the distribution network. At the end of the refuelling process, an appropriate inert gas is used in order to purge the circuit systems. Usually these kind of stations are equipped also with manual emergency shut-down, “panic buttons”, “placed inside as well outside the facility to initiate immediate shut-down of all processes hydrogen lines, if needed (Casamirra M., 2009)”. As in most of places where “explosion/fires” risk is present, a standby engine-driven generator is installed to ensure electric power necessary for emergency lighting and the fire pumps, in the event of external power failure or fire which interrupts the normal-conditions electricity supply.

- Dispenser/refuelling

“The Fuel Gas Dispenser is a "stand-alone" unit, which provides the mechanical interface between the hydrogen fuel station storage tanks and the vehicle together with safety features and metering equipment” (Nilsen Sandra, 2003). The dispenser is the “component” that allows the previous explained cascade filling system connecting the storage unit to the in-vehicle vessel. Usually this compressed gas hydrogen dispenser is also equipped with a vent stack line to the atmosphere.

- Purging system

“Inert gas purging systems, which can be initiated automatically or manually will be an important ancillary part of the filling station” (Nilsen Sandra, 2003). These systems are usually used only during start up and shutdown or when an emergency situation requires it.

- Manning

In order to allow customers to refuel their cars and to guarantee them a certain level of safety, manning is an important “part” of the station. “Future hydrogen filling stations, including the production unit, may be fully automated and can be unattended” (Nilsen Sandra, 2003). In nowadays stations, however, operation personnel is located at a certain

distance from the station or at the station. The personnel is necessary in order to connect the car to the dispenser, as in LPG refuelling stations, while monitoring and shut down to failsafe conditions may be carried out automatically or by emergency buttons at the filling station area or from a remote location.

### 3.3 System boundaries

Once all the units present at the station have been described, in order to show the method that this thesis proposes, the focus of the study will be on the storage unit that, as said before, is composed by:

- High pressure storage vessels and its PRV;
- Medium pressure storage vessels and its PRV;
- Low pressure storage vessels and its PRV.

The methodology will be applied, in order to show the feasibility of the procedure, to one Low pressure storage vessel and its PRV.

Technical data about materials, dimensions, pressure and so on will be defined in the “application of the method” chapter.

## 4. Application of the method and results

In this chapter the input and data necessary to carry out the analysis in the three mentioned different steps (see “Methodology steps”) are described for each of them in the “Application of the method” section; In the second part, “Results”, the calculations and results of each step, for the three different cases, will be presented.

### 4.1 Application of the method

First to be defined, as reported in the “Methodology chapter”, are the different cases that will be studied: the 95%, the 50% and the 20% of the maximum risk target will be assumed. Furthermore, a likelihood of occurrence of  $10^{-3}$  (likelihood to pay this amount every year only due to one vessel: must be reasonably low) will be selected.

During the evaluation period, according to the software, the maximum Financial consequences due to one vessel are approximately 395000 \$.

$$Risktgt_{max} = 395000 \$$$

The three different case are then shown in Table 1 .

*Table 1 - Risk target total cost*

<b>CASE STUDY</b>	<b>Financial Consequences (\$)</b>	<b>Selected frequency</b>	<b>Risk target total cost</b>
<b>A</b>	$FC = 395000 \cdot 0.95 = 375250$	$10^{-3}$	375,25
<b>B</b>	$FC = 395000 \cdot 0.50 = 197500$	$10^{-3}$	197,50
<b>C</b>	$FC = 395000 \cdot 0.20 = 79000$	$10^{-3}$	79,00

Regarding the failure scenarios to be analysed, the following will be considered:

- Small leak: hole size of 22 mm;
- Medium leak: hole size of 44 mm;
- Leak from PRV: hole size to be defined later;
- Large leak: hole size of 88 mm;
- Vessel rupture: all material released.

Small/medium/large leak LoF calculation

- Small leak: Regarding the small leak scenario it will be considered that it can be caused independently by the vessel leak due to damage mechanisms, a leak from the PRV and human error (e.g. the error that caused Kjørbo accident). There will be then two events which LoFs will be assumed as the sum of vessel leak LoFs (in one case due to damages, in the second due to the PRV) and the human error likelihood; the vessel leak due to damage mechanisms LoF and the leak from the PRV LoF are provided by the software while the LoF of the human error will be given by literature.
- Medium/large leak: A medium or large leak can be caused independently by the vessel leak due to damages and human error (e.g. the error that caused Kjørbo accident). The vessel leak due to damages LoF will be provided by the software.

Rupture LoF calculation

Regarding the rupture, it will be assumed that it can be caused independently by the vessel rupture due to damages mechanisms and the PRV fail to open in different demand cases (cases in which the PRD should open). Regarding the demand cases, it should be noticed that Synergi RBI provides a lot of different causes (the same that are described in API 581) with the relative LoF:

- Fire
- Blocked Discharge with Administrative Controls in Place
- Blocked Discharge without Administrative Controls
- Loss of Cooling Water Utility
- Thermal Relief with Administrative Controls in Place

- Thermal Relief without Administrative Controls
- Electrical Power Supply failure
- Control Valve Failure, Initiating event is same direction as CV normal fail position (i.e. Fail safe)
- Control Valve Failure, Initiating event is opposite direction as CV normal fail position (i.e. Fail opposite)
- Runaway Chemical Reaction
- Overfilling with Administrative Controls in Place
- Overfilling without Administrative Controls

It has to be noticed that not every demand case is applicable to gaseous hydrogen storage but it is possible to consider only the cases that are likely to occur in the specific situation.

Once the Lofs are combined as described before, for every selected risk target, the output (in addition to the maintenance plan) to be used in the next steps will be:

- LoF for the small leak scenario;
- LoF for the medium leak scenario;
- LoF for the PRV leak scenario;
- LoF for the large leak scenario;
- LoF for the rupture scenario;

#### 4.1.1 Maintenance plan and Lofs

In order to plan maintenance for the vessel and the connected PRV it is necessary to set in the first software, Synergi RBI, the necessary input.

First to define are Service start date, Current evaluation date and Future evaluation date in the “low pressure storage” section of the program “assets”.

The “Service start date”, the date in which the facility started to be productive will be assumed as 10/01/2020 even if the facility started to operate earlier; This assumption is necessary because, if the date is fixed in the past, it is important to give as input also the previous maintenance results,

such as the wall thickness of the vessel or revealed damages, and these data are unfortunately missing.

Regarding the “Current evaluation date”, the date in which the analysis is performed, it will be assumed as coincident with the “Service start date”; Therefore the “Future evaluation date” that states the period in which the maintenance plan will be performed, will be fixed in order to take into account a period of 30 years: this date will be then 10/01/2050.

“Consequence” data

In this section it also important to define the “Consequence” data that will be used to perform the analysis:

- Injury Cost [USD]: 0
- Outage Cost Per Time [USD/AvgeYear]: 1875600,00
- Equipment Cost [USD/m<sup>2</sup>]: 8400,00
- Environment Clean Up Cost [USD/m<sup>3</sup>]: 0
- Population Density [/m<sup>2</sup>]: 0,000671
- Worst Case Equipment Damage Cost [USD]: 2100000,00
- Worst Case Potential Fatality Count []: 0

Regarding the “Injury Cost” and the “Worst Case Potential Fatality Count”, in order to consider people’s safety in a more detailed way, in this part of the process the damages to people are not quantified. Furthermore, being hydrogen a gaseous substance that doesn’t affect environment directly, the “Environment Clean Up Cost” will be also set to zero.

In order to know the value of the “Outage Cost Per Time” we can assume that it is linked to the loss of sales of the refuelling stations. For data about the kilometres run by cars in Norway we can refer to “Statistics Norway”, the national statistical institute of Norway and the main producer of official statistics. This organization is “responsible for collecting, producing and communicating statistics related to the economy, population and society at national, regional and local levels” (Statistics Norway, s.d.). According to their statistics, in the municipality of Bærum, in 2018, the “Road traffic volume” was 2126.7 million km. However, we have to consider that hydrogen fuel for

cars is a new developing technology and so nowadays stations are still founded by the government in order to cover the expenses of maintaining a station even if the number of hydrogen cars isn't business-sustainable. In a near future we can think that a considerable part of the motor pool will be composed by FCVs; in order to perform a realistic analysis of a possible business we have to project the number of hydrogen cars in the future, assuming for example the number of FCVs probably present in 2030. In the databases of "Statistics Norway" we can find the hydrogen FCVs and "all fuels" traffic volume trend in the country that are shown respectively in Figure 19 and 20.

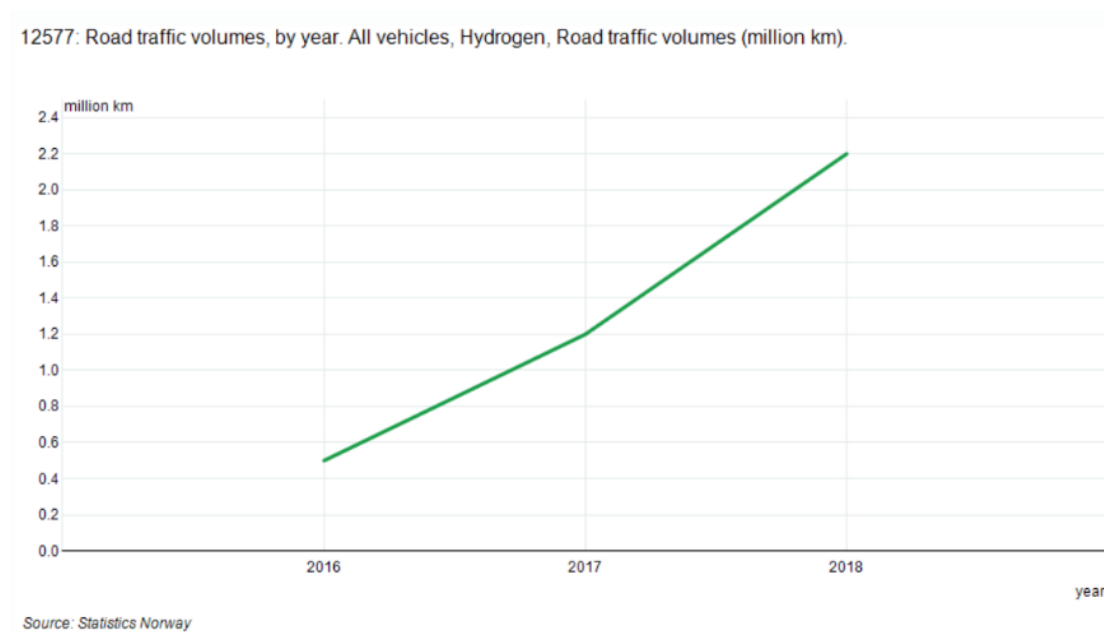


Figure 19 - Hydrogen FCVs traffic volume (Statistics Norway, s.d.)

[\(https://www.ssb.no/en/statbank/table/12577/chartViewLine/\)](https://www.ssb.no/en/statbank/table/12577/chartViewLine/)

12577: Road traffic volumes, by year. All vehicles, All types of fuel, Road traffic volumes (million km).

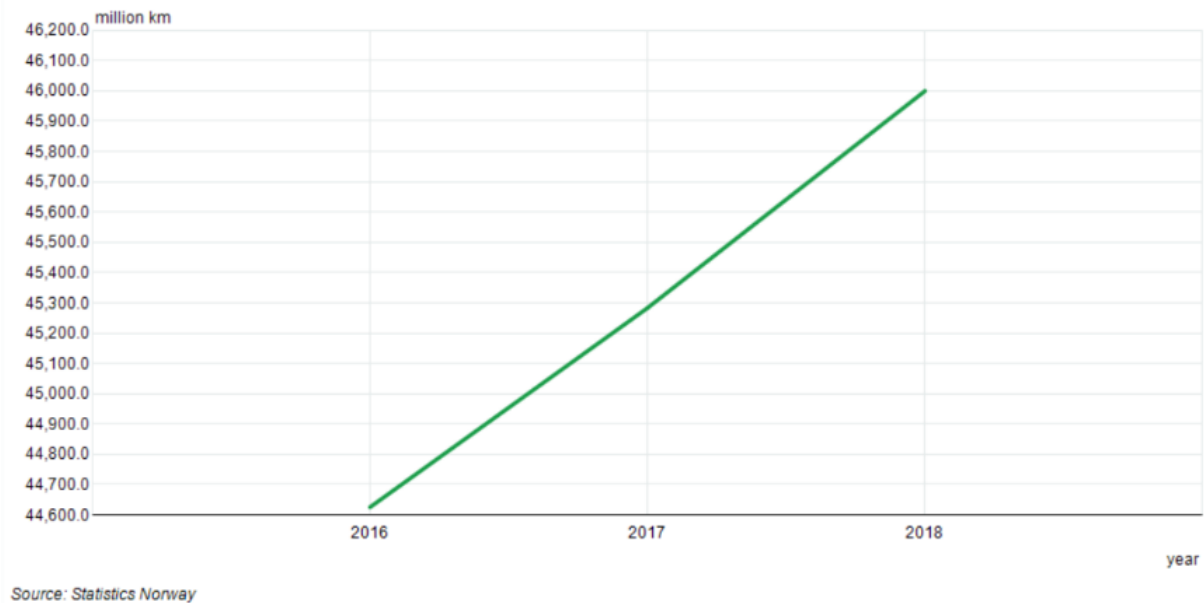


Figure 20 - "All fuels" traffic volume (Statistics Norway, s.d.)

(<https://www.ssb.no/en/statbank/table/12577/chartViewLine/>)

We can now calculate the percentage of FCVs road traffic volumes (rtv) in comparison with the "all vehicles" traffic volume year by year.

$$FCVrtv_{\%}(2016) = \frac{0.5}{44625.1} \cdot 100 = 0.00112 \%$$

$$FCVrtv_{\%}(2017) = \frac{1.2}{45283.4} \cdot 100 = 0.0026 \%$$

$$FCVrtv_{\%}(2018) = \frac{2.2}{46000.0} \cdot 100 = 0.0048 \%$$



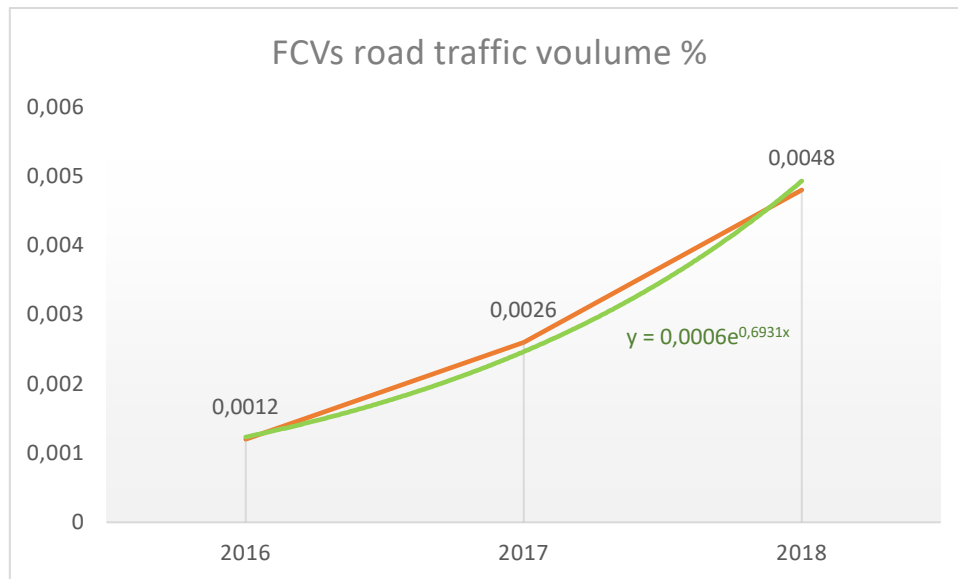


Figure 21 - FCVs road traffic volume (%)

With an exponential trend line that could model at least the first years of FCVs traffic volume growth we can predict an approximate value for 2030 through the following equation:

$$y = 0,0006e^{0,6931x}$$

Knowing that 2016 corresponds to  $x=1$ , the value of  $x$  for 2030 will be 14. Then hydrogen road traffic volume share in 2030 could approximately be 9.8 %. Assuming that this share of road traffic volumes is the actual value, then the considered FCVs road traffic volume per year in Bærum can be calculated as:

$$FCVs_{rtv} = 0.098 \cdot 2126.7 = 208.4 \text{ million km}$$

Considering that the number of hydrogen refuelling station in the region of Akershus is 11, the average road traffic volume per station per month (km/month) can be easily calculated as 1578787,879 km/month. Considering that the average consumption of hydrogen per 100 km is about 1kg (Greenstat, s.d.) and that the price per kg of hydrogen in Oslo is 90 NOK (Ulleberg, 2020) (Norwegian crowns) that corresponds to 9.9 \$, it is easy to know that the “average profit per station per year” is 1875600 \$/station·year. The “Outage Cost Per Time” will be assumed then as coincident with this value.

To have an estimate of the “Equipment Cost” and the “Worst Case Equipment Damage Cost” we can refer to a work presented in 2017, “Comparison of conventional vs. modular hydrogen

refuelling stations, and on-site production vs. delivery” by Ethan S. Hecht, Joseph Pratt. This work was prepared by Sandia National Laboratories (Albuquerque, New Mexico 87185 and Livermore, California 94550). Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration. A participant of the work was NREL , a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy (Hecht). The report aims to presents layouts, bills of materials, piping and instrumentation diagrams, and detailed analyses of five new station designs with on-site production or hydrogen delivery. In this report we can find the economic results of the five different station concepts that are shown in Figure 22.

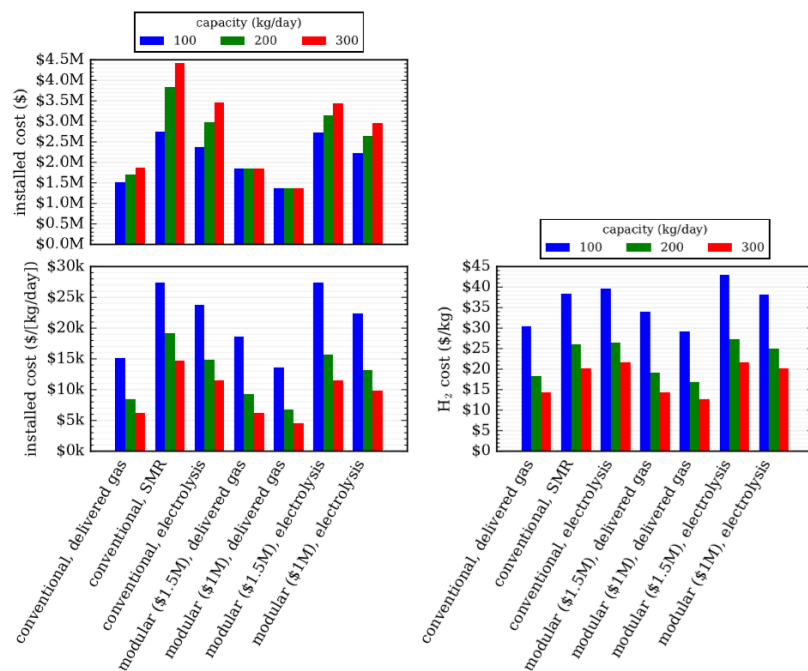


Figure 22 - Installed cost and hydrogen cost for different kinds of stations (Hecht)

Installed cost (which includes site preparation, engineering & design, permitting, component capital and installation costs) are shown in the left frames. The top frame is the total investment in 2016\$, while the bottom left frame is the installed cost per mass of hydrogen dispensed (kg/day).

Kjørbo station has a capacity of 200 kg/day and falls in the “conventional, electrolysis” category: the installed cost is then approximately 3 Million dollars. In order to consider that costs such as

site preparation, engineering & design and similar are not part of the mere “equipment cost”, a reduction factor of 0.7 will be assumed. According to this logic, the “Worst Case Equipment Damage Cost” (Equip.dmg.worst case) will be calculated as:

$$\text{Equip.dmg.worst case} = 3000000 \cdot 0.7 = 2100000.00 \$$$

Regarding the “Equipment Cost”, we need to know the area occupied by the facility. In order to get this value, measures from google maps aerial image of the station are used: those measures are shown in Figure 23.

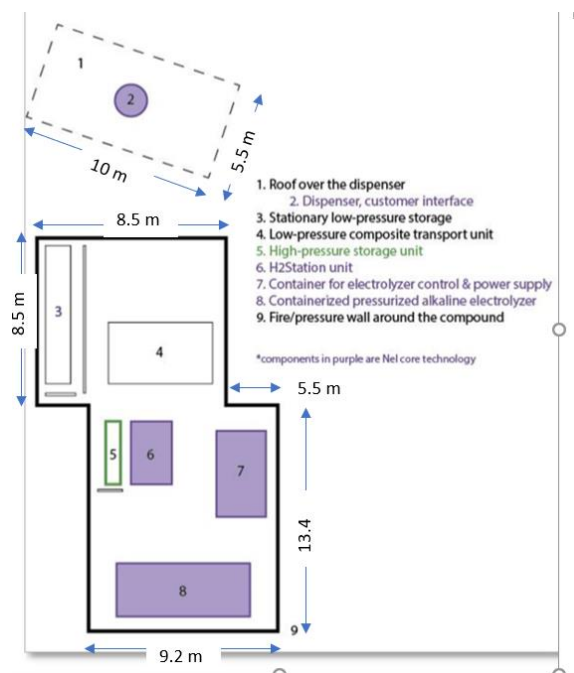


Figure 23 - Station measures (Løkke, 2019)

According to these measures and to the simplified layout of the station, the area of the facility is approximately given by the following equation x:

$$\text{Area}_{\text{facility}} = 8.5 \cdot 8.5 + 13.4 \cdot 9.2 + 10 \cdot 5.5 \approx 250 \text{ m}^2$$

The “Equipment Cost”, expressed as  $\$/\text{m}^2$  will be then:

$$\text{“Equipment Cost”} = \frac{\text{Equip.dmg.worst case}}{\text{Area}_{\text{facility}}} = 8400 \text{ \$/m}^2$$

“Population Density” data is derived from the municipality website of Bærum, where the station is located: the population on 1<sup>st</sup> January 2019 was 126.841 inhabitants (Bærum Kommune, s.d.). Considering that the extension for the municipality is 189 km<sup>2</sup>, the approximate “Population Density” value to use in the program will be then 670 inhabitants per km<sup>2</sup>.

“Equipment” data

Regarding the vessel and the pressure relief valve, construction data are based on assumptions or calculations while operating conditions were assumed according to what stated in the “Case study description” chapter; These data for the vessel are shown in Table 2. Regarding the PRV, calculations and assumptions are described later.

Table 2 - Vessel technical data

<b>Group</b>		
Plant: Kjørbo Refuelling station	Production Unit: Storage Unit	Process Unit: Low pressure storage
<b>Construction Data</b>		
Material: Carbon Steel \ SA-612	Outside Diameter (mm): 400	Nominal Thickness (mm): 31
Length (m): 4	Insulation: No	External Coating: No
Liner: No		
<b>Operating Conditions Data</b>		
Chemical For CoF: Hydrogen		
Pressure (bar): Likelihood Pressure: 200 [Operating Pressure]	Consequence Pressure: 200 [Operating Pressure]	Operating Temperature (degC): 25

Regarding the valve, some calculations were performed in order to design the orifice area. The software calculates for the medium hole size a release rate of 0.35252 kg/s for an orifice diameter of 44 mm that is comparable to a PRV orifice size. Assuming that this is the release rate that the valve has to relief, it is necessary only to determine the necessary PRV orifice area.

The maximum allowable pressure (MAWP) of the vessel is set to 220 bar and so, according to ASME Code, the set pressure of the valve should be, considering fire contingencies, 0.9 times the MAWP of the vessel; according to this, the set pressure will be:

$$P_{set} = 0.9 \cdot MAWP = 198 \text{ bar}$$

According to ASME code, then the maximum accumulated pressure (MAP) in fire contingencies shall be limited to 121% of the MWP:

$$MAP = 1.21 \cdot 220 = 266 \text{ bar}$$

It is possible now to calculate the allowable (AOP) overpressure according to the following equation:

$$AOP = MAP - MAWP = 46 \text{ bar}$$

The upstream relieving pressure (P1) is the calculated as:

$$P_1 = P_{set} + AOP = 244 \text{ bar}$$

It is necessary now to understand if the gas flow is critical or subcritical through the calculation of the so-called Critical flow pressure,  $P_{cf}$ , that can be obtained from the following equation.

$$P_{cf} = P_1 \cdot \left[ \frac{2}{k+1} \right]^{\frac{k}{k-1}} = 244 \cdot \left[ \frac{2}{1.4+1} \right]^{\frac{1.4}{1.4-1}} = 128.9 \text{ bar}$$

As this pressure is more than downstream pressure (atmospheric pressure), we are in critical flow conditions and so the following equation has to be applied in order to obtain the required effective discharge area:

$$A = \frac{13160 \cdot W}{C \cdot P_1 \cdot K_d \cdot K_b \cdot K_c} \cdot \sqrt{\frac{T \cdot Z}{M}} \quad [mm^2]$$

Values to be used in this equation are:

- $W = 0.35252 \text{ kg/s} = 1269.072 \text{ kg/hr}$

- $P_1 = 244 \text{ bar} = 22500 \text{ kPa}$
- T is the relieving temperature =  $25^\circ\text{C} = 298.15 \text{ K}$
- Z is the compressibility factor that, according to the Figure 24 is (at 224 bar and 298 K) 1.14
- M is the molecular weight of the gas:  $2.016 \text{ g/mol}$
- $K_d$  is the rated coefficient of discharge: 0.975
- $K_b$  is the back pressure corrector factor: 1 for conventional valves
- $K_c$  is the combination correction factor for installation with rupture disks: 1 for a rupture disk not installed
- C is a function of k (=1.4) : 355

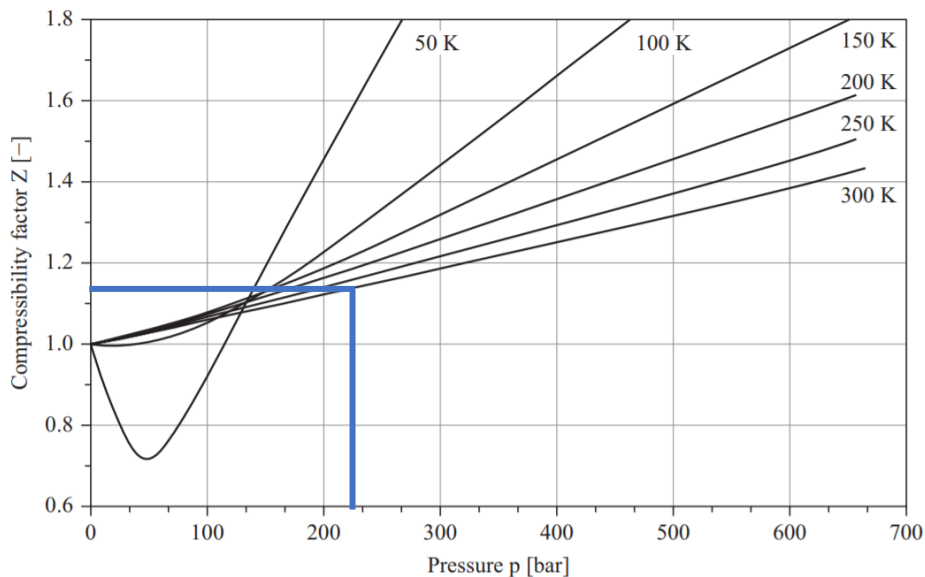


Figure 24 - Hydrogen compressibility factor (Makridis, 2016)

The effective discharge area is then:

$$A = \frac{13160 \cdot 1269.072}{355 \cdot 22500 \cdot 0.975 \cdot 1 \cdot 1} \cdot \sqrt{\frac{298.15 \cdot 1.14}{2.016}} = 27.79 \text{ mm}^2$$

Technical data for the PRV that will be used are  $30 \text{ mm}^2$  (diameter of: 3 mm) for the leak orifice area a W of 0.35252 kg/s and a set pressure of 198 bar; the effective flow rate could be slightly different from the previous value but, for the level of accuracy of the data used in the previous equations, it can be taken as an input data for the program with a good level of confidence.

“Active damage mechanisms” data

Last important input for the program is the definition of the active damage mechanisms.

In this case, considering an outdoor gaseous hydrogen vessel, the main damage mechanism that can occur is “External thinning”: only this damage will be considered in this study.

“As a general rule, plants located in areas with high annual rainfalls or warmer, marine locations are more prone to external corrosion than plants located in cooler, drier, mid-continent locations. Regardless of the climate, units located near cooling towers and steam vents are highly susceptible to external corrosion, as are units whose operating temperatures cycle through the dew point on a regular basis. Mitigation of external corrosion is accomplished through proper painting. A regular program of inspection for paint deterioration and repainting will prevent most occurrences of external corrosion” (API, API recommended practice 581: Risk based inspection technology, 2008).

If we consider the component as uninsulated or with a damaged insulation for precautionary reasons (this is acceptable thinking that this application is useful to show the applicability of the method) and “subject to any of the following, then the component should be evaluated for external damage from corrosion” (API, API recommended practice 581: Risk based inspection technology, 2008):

- Areas exposed to mist overspray from cooling towers,
- Areas exposed to steam vents,
- Areas exposed to deluge systems,
- Areas subject to process spills, ingress of moisture, or acid vapors.
- Carbon steel systems, operating between  $-23^{\circ}\text{C}$  and  $121^{\circ}\text{C}$  ( $-10^{\circ}\text{F}$  and  $250^{\circ}\text{F}$ ). External corrosion is particularly aggressive where operating temperatures cause frequent or continuous condensation and re-evaporation of atmospheric moisture,
- Systems that do not normally operate between  $-12^{\circ}\text{C}$  and  $177^{\circ}\text{C}$  ( $10^{\circ}\text{F}$  and  $350^{\circ}\text{F}$ ) but cool or heat into this range intermittently or are subjected to frequent outages,
- Systems with deteriorated coating and/or wrappings,
- Cold service equipment consistently operating below the atmospheric dew point.

- Un-insulated nozzles or other protrusions components of insulated equipment in cold service conditions.

Once these main inputs and other secondary ones are available it is possible to set the risk target and perform the analysis in order to get the output described in the “Methodology” chapter.

#### 4.1.2 Safety issues: F-N curves and risk contours

In order to perform the “safety” analysis it is necessary to define some important input to provide to the program: some of these come from the previous program output while others have to be defined as will be shown in this paragraph.

##### “Pressure vessels” data

In addition to some of the same data used in the previous software as material and mass inventory, the following important input/conditions were defined:

- “Explosion” parameters: a “multi-energy” explosion method was chosen to be used by the program in order to perform the analysis;
- “Fireball” parameters: “time-varying Martinsen model”;
- “Jet fire” parameters: “cone model”
- “Ignition” parameters: the “probability of immediate ignition” is calculated based on the material reactivity, the “probability of delayed ignition” and the “conditional explosion probability” are calculated by the program as a function of the material and the populations/buildings defined in the “map” section.

##### “Scenarios” data

As stated in the “Methodology” chapter, five scenarios will be considered:

- Small leak from the vessel;
- Small leak from the PRV;
- Medium leak from the vessel;



- Large leak from the vessel;
- Vessel rupture.

In addition to the “Pressure vessels” data that are applied to all the different scenarios, for each of them is necessary to define the orifice diameter and the event frequencies (events/AvgYear); the orifice sizes were defined in the “Methodology” chapter and the events LoFs come from the previous step “Maintenance plan and Lofs”.

#### “Risk” data

The other important input category is related to the “Risk” tab in which the populations are defined on the map in order to perform the risk analysis and calculate the ignition probabilities.

The map of the site, with the location of the population, personnel, customers and the vessel/PRD is shown in Figure 25; Four populations were selected for the analysis:

- “Customers”: 2 people near the refuelling point with a fraction of population indoors for societal risk of 0,5. (Red dot on the map)
- “Parking lots population” : 3 people corresponding to a density of 0,000714569 people/m<sup>2</sup> (Red area on the map)
- “Office buildings population” : default value of 0,01 people/m<sup>2</sup> with a fraction of population indoors for societal risk of 0,9 (default value) (Red area on the right of the map)
- “Operator”: 1 person near the station facilities with a fraction of population indoors for societal risk of 0,9. (yellow dot on the map)

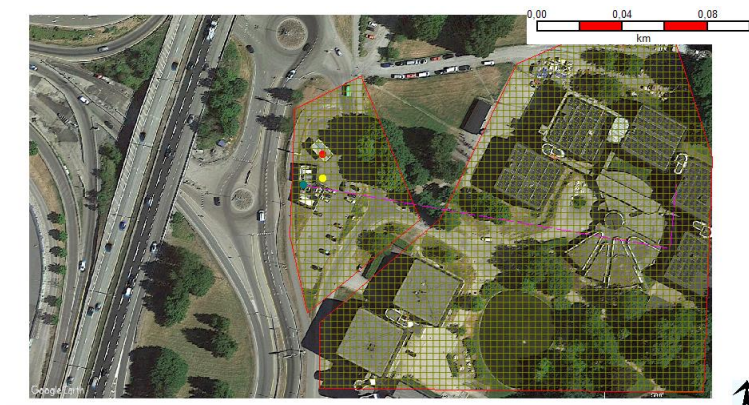


Figure 25 - Map: populations

## Acceptability criteria

According to European Integrated Hydrogen Project (EIHP2) report on “Risk acceptance criteria for Hydrogen Refuelling Stations”, “Quantitative risk acceptance criteria are an important part of an enterprises risk or safety management system. Acceptance criteria are based on the established safety goals and quantification of these. Risk results from QRA (Quantitative Risk Analysis) of installations, plants, procedures etc. are compared with these criteria to determine whether the risk level is acceptable or not. If the estimated risk level is too high compared to the acceptance criteria, risk reducing measures must be identified and implemented. The criteria will also be used for establishing safety distances” (Norsk Hydro ASA, 2003).

In this report is also stated that “risk acceptance criteria must be established for all groups of people that are exposed to accidents originating from a refuelling station” (Norsk Hydro ASA, 2003).

Among all the people affected by risk coming from a refuelling station, we can identify three different main groups.

“Third party risk will consider how events on the refuelling station can affect areas outside the refuelling station boundaries and include people living and working in the vicinity of the refuelling station or visiting/travelling through the neighbourhood of the refuelling station” (Norsk Hydro ASA, 2003). According to the report, both societal and individual risk measures should be considered (FN curves and risk contours).

Second party are refuelling station customers, “people visiting the refuelling station area to use the facilities” (Norsk Hydro ASA, 2003). This group is “exposed to the risks at the refuelling station for a limited period of time, while visiting the facilities” (Norsk Hydro ASA, 2003). Individual risk contribution on these people will be relatively low, due to the low exposure. In the thesis work, however, they will be considered.

First party is “hydrogen refuelling station personnel” that “ includes personnel involved in operation, inspection and maintenance of the hydrogen and/or the conventional re-fuelling station” (Norsk Hydro ASA, 2003). Generally a higher risk level can be seen as acceptable for this

group than for third party. “An individual risk criterion, setting limits to the risk of each individual working at the station, is the most relevant” (Norsk Hydro ASA, 2003).

A risk acceptance criteria can be the comparison with the general risk in everyday life; in this case, it is a common approach to consider the “natural fatality risk for the age group with the lowest individual fatality risk” (Norsk Hydro ASA, 2003). This value is related to the “age group between 5 and 15 years”. According to Dutch data, the base death rate is  $1 \cdot 10^{-4}$  per annum for the age group 10 to 14 years. UK data suggest a base death rate of  $2.8 \cdot 10^{-4}$  per annum for the age group 5 to 14 years. Merging these data, the report sets the base death at  $1 \cdot 10^{-4}$ , the lowest value among the considered ones. “Further process plants should not lead to more than a 1% increase in the natural fatality rate, i.e.  $1 \cdot 10^{-6}$ ”. This risk level is recognised and applied as acceptance criteria by Dutch authorities, for process industry in general and by Australian authorities for LPG refuelling stations (Norsk Hydro ASA, 2003).

Third party (based on general societal risk comparison): “No residential area, third party working premises or public assembly area outside the station shall be exposed to fatal exposure levels caused by major accidents at the station of probability greater than  $10^{-6}$  per year. If there are buildings surrounding the facility, fatal exposure due to collapse of these shall be taken into account” (Norsk Hydro ASA, 2003). Regarding the societal risk the report proposes to use the Dutch VROM criteria. This is a FN curve (Frequency of N or more fatalities, as function of N) as shown in Figure 26. If the calculated risk is above the curve the risk must be reduced.

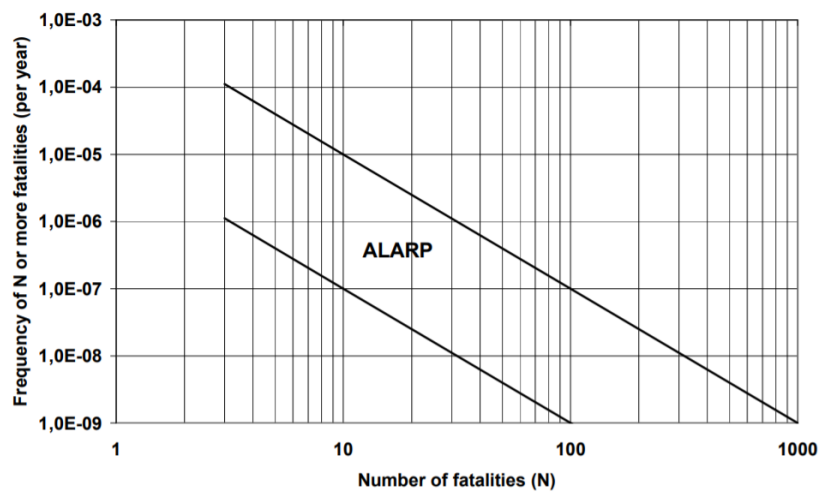


Figure 26 - Dutch VROM criteria (Norsk Hydro ASA, 2003)

The upper line in Figure x represents the risk acceptance curve. The region between this line and the lower line denotes the ALARP area (As Low As Reasonable Practical). For scenarios with risk levels that lay between these lines the risk should be reduced if practical, typically subject to cost benefit analysis. For scenarios with risk levels above the upper curve, measures to reduce the risk must be implemented. “The slope of the FN curve is designed to reflect the society’s aversion to single accidents with multiple fatalities as opposed to several accidents with few fatalities” (Norsk Hydro ASA, 2003).

Refuelling station customers: “The probability of a major accident causing one or more fatalities among customers shall not exceed  $10^{-4}$  per year” (Norsk Hydro ASA, 2003).

Hydrogen refuelling station personnel: “The individual probability of fatality should not exceed a value of  $10^{-4}$  per year” (Norsk Hydro ASA, 2003).

#### 4.1.3 Business interruption: Expected income from hydrogen fuel sales

Regarding the business interruption part of the methodology, ExtendSim requires as a first step the creation of the model. The basis of the model are the “items” connected one to each other as it is shown in Figure 27.

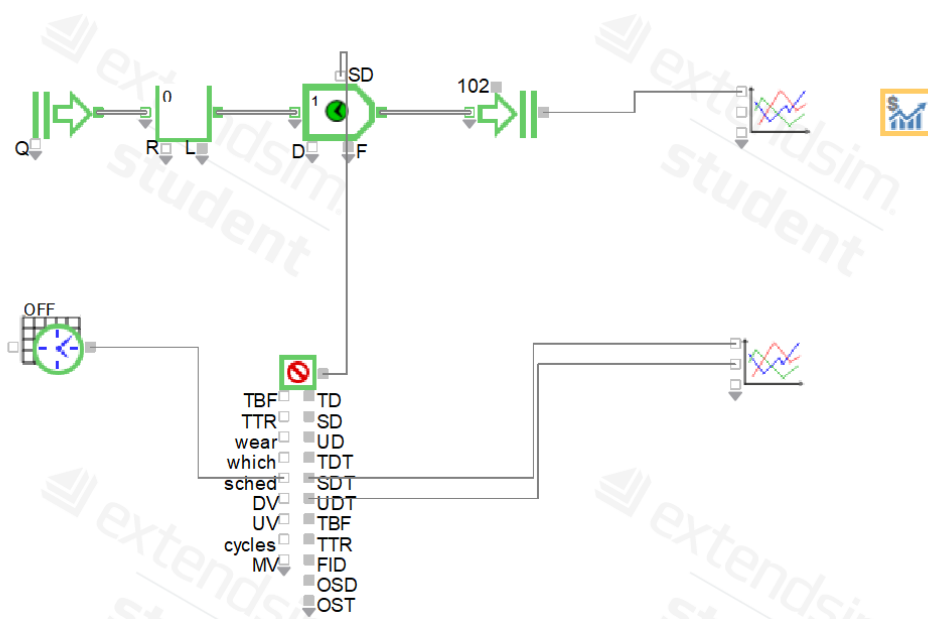


Figure 27 - ExtendSim model

The first item is the “create” item (first item on the upper-left side) that is used to generate cars that need to be refuelled: the main input is the distribution of the Time Between Arrivals, from now on TBA. In order to calculate a mean TBA we can refer to the previous calculated “traffic volume”, the monthly  $FCVs_{rtv}$  that is equal to 1578787,879 km/month. Starting from this date, and knowing that an FCV vessel is about 100-150 liters (e.g. 122.4 l (Toyota, s.d.) for the Toyota Mirai), we can calculate the average number of cars that need to be refuelled at one station.

The traffic volume per station per day is obtained through the following equation:

$$FCVs_{rtv}(dayly) = \frac{1578787,879}{30} = 52626.26 \text{ km/day}$$

Since we know that an average car consumption is equal to 1kg/100km (Greenstat, s.d.), we can calculate the average number of hydrogen kilos needed in order to run this amount of kilometres as in the formula below:

$$Hydrogen_{kg}(dayly) = \frac{52626.26 \text{ km/day}}{100 \text{ kg/km}} = 526.26 \text{ kg/day}$$

Now we have to calculate the mass of hydrogen present in one car vessel in order to know the average number of cars that need to be full-refuelled in one day at one station. This can be done through the ideal gas law (knowing that the storage pressure is 700 bar and assuming a vessel volume of 125 l):

$$P \cdot V = nRT$$

$$n = \frac{P \cdot V}{R \cdot T} = \frac{700000 \cdot 125}{83.14472 \cdot 298.15} = 3529.7 \text{ mol}$$

The mass of the hydrogen contained in a full FCV tank is then:

$$Hydrogen_{kg}(FCVtank) = 3529.7 \text{ mol} \cdot 2.016 \frac{\text{g}}{\text{mol}} = 7271.2 \text{ g} = 7.27 \text{ kg}$$

Assuming that every car refuels completely its tank and considering that hydrogen average price in solo is 90 NOK/kg (Ulleberg, 2020), the income for the station for every car is then:

$$Income_{per\ car} = 7.27\ kg \cdot 90 \frac{NOK}{kg} = 645.3\ NOK$$

It is possible now to determine the average number of cars that need to be refuelled at one station during one day:

$$Cars_{number}(day) = \frac{526.26}{7.27} = 72.3\ cars/day$$

The mean TBA, that will be assumed as a constant, will be then calculated through the following formula:

$$TBA = \frac{24\ hrs/day}{72.3\ cars/day} = 0.33\ hrs = 19.9\ mins \approx 20\ mins$$

After the “create” item, we need to model the “refuelling” process: this is obtained through the two connected items “queue” and “activity”. The first item is necessary in order to handle the problem that occurs when the activity is impossible to be performed: when a shutdown occurs, car can’t be refuelled and so they wait in the queue for a small amount of time before being discarded. The second item contains the information about process profit that is obtained every time a car passes through it and it is connected to the “shutdown” item.

The “shutdown” item contains the information about the MTBF and MTTR that come from the “maintenance and LoFs” output elaboration as describes in the last paragraphs of the “Methodology” chapter. This item is also connected to the “Shift” item that contains the information regarding the scheduled maintenance timing and duration. Thanks to these two items, a signal is sent to the “activity” item when a scheduled or unscheduled stop occurs: the activity then will stop for a certain amount of time depending on the MTTR distribution.

Last part of the model contains the “exit” item that allows to end the process and “chart”s that, properly connected to different items output, show the trend of the selected quantities such as the profit, shutdown periods and so on.

## 4.2 Results

In the following paragraph the rough results of every case will be shown following the same methodology steps described before; The results will be merged in next chapter in order to provide a general and more understandable overview of every case.

### 4.2.1 Case 1

#### 4.2.1.1 Maintenance plan and LoFs results

Regarding the vessel, once the risk total cost is set, the maintenance plan provided by the software can be seen in Figure 28. The specs of the inspection to be conducted are shown in Figure 29.

#### Likelihood Status

Current Status (10/01/2020)			Future Status W.O. Insp. (10/01/2050)			Future Status With Insp. (10/01/2050)		
Damage Factor	Damage Factor Category	LoF (/AvgeYear)	Damage Factor	Damage Factor Category	LoF (/AvgeYear)	Damage Factor	Damage Factor Category	LoF (/AvgeYear)
3,11507	2	9,53211E-05	282,195	4	0,00863516	14,4709	3	0,000442811

#### Risk Status

Risk Type	Current Status (10/01/2020)				Future Status W.O. Insp. (10/01/2050)				Future Status With Insp. (10/01/2050)			
	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category
Total Cost	395578 USD	C	37,7069 USD/Avge Year	2. MEDIUM	395578 USD	C	3415,88 USD/Avge Year	3. MEDIUM HIGH	395578 USD	C	175,166 USD/Avge Year	2. MEDIUM

#### Damage Results & Inspection Plan

Damage Mechanism	Current Status (10/01/2020)		Future Status W.O. Insp. (10/01/2050)		Inspection Plan					Future Status With Insp. (10/01/2050)	
	Damage Factor	Damage Factor Category	Damage Factor	Damage Factor Category	Target Damage Factor	Target Driver	Inspection Date	Inspection Effectiveness	Inspection Task	Damage Factor	Damage Factor Category
External Thinning (0,127 mm/AvgeYear)	3,11507	2	282,195	4	31,0004	Risk Total Cost	06/08/2038	Highly	NonIntr +95VT +UT/RT follow-up	14,4709	3

Figure 28 - Case 1 maintenance plan

#### Inspection Plan Report (Tag)

Tag	Tag Type	Parent	Damage Mechanism	Current Status			Future Status W.O. Insp.			Inspection Plan				Future Status With Insp.			
				Damage Factor	Criteria Met	Criteria Met	Damage Factor	Criteria Met	Criteria Met	Target Damage Factor	Inspection Date	Inspection Effectiveness	Inspection Task	Inspection Task Description	Damage Factor	Criteria Met	
Low pressure vessel	Drum	Low pressure storage	External Thinning (0,127 mm/AvgeYear)	3,11507	2	Yes	282,195	4	No	31,0004	06/08/2038	Highly	NonIntr +95VT +UT/RT follow-up	Visual inspection of >95% of the exposed surface area with follow-up by UT, RT or pit gauge as required.	14,4709	3	Yes

Figure 29 - Case 1 inspection specifications

Regarding the valve, a bench test is planned on 5/01/2040. We also can obtain information about the trend of the LoF of the valve regarding the “Vessel rupture due to valve fail to open” and “Valve leakage” fails as shown respectively in Figure 30 and 31.

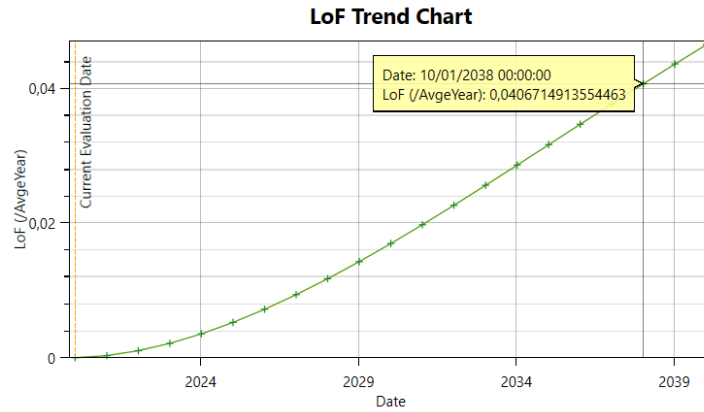


Figure 30 - "Vessel rupture due to valve fail to open" LoF trend chart (Case1)

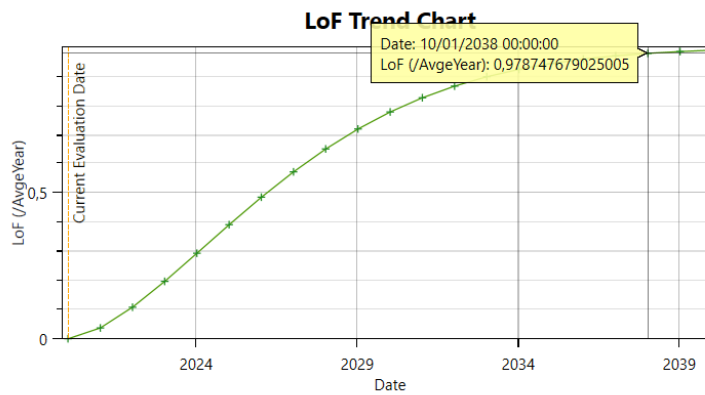


Figure 31 - "Valve leakage" LoF trend chart (Case 1)

As we can see in Figure 30 and 31, likelihoods of these failures are considerably high in 2038 due to the fact that the inspection of the valve is planned in 2040 and especially that only generic data are provided: this will lead to an overestimation of the frequencies but doesn't affect the purpose of showing the method applicability.

For the vessel, we are able to see the trend of the damage factor (that is strictly linked to the likelihood of failures) and how it is influenced by maintenance in Figure 32,



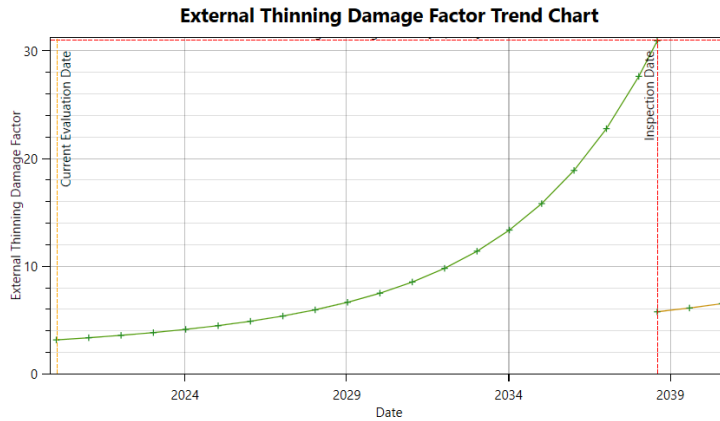


Figure 32 - External thinning damage factor trend chart (Case 1)

Once we have the maintenance plan in all its details, it is necessary to obtain the Likelihoods of Failures for the selected scenarios.

As stated before, we need to calculate the maximum risk that the company accepts through the definition of its risk target: the likelihoods to be used are then the LoFs at the time immediately before the inspection of the vessel takes place, so on 6/08/2038. First step is then calculation of the LoFs for the vessel and PRV at this date: for example in Figure 33 we can see the LoF of the vessel and the associated risk category with and without the scheduled inspection of that day.

**Likelihood Status**

Current Status (10/01/2020)			Future Status W.O. Insp. (06/08/2038)			Future Status With Insp. (06/08/2038)		
Damage Factor	Damage Factor Category	LoF (/AveYear)	Damage Factor	Damage Factor Category	LoF (/AveYear)	Damage Factor	Damage Factor Category	LoF (/AveYear)
3,11507	2	9,53211E-05	30,9297	3	0,000946448	19,1062	3	0,000584651

**Risk Status**

Risk Type	Current Status (10/01/2020)				Future Status W.O. Insp. (06/08/2038)				Future Status With Insp. (06/08/2038)			
	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category
Total Cost	395578 USD	C	37,7069 USD/AveYear	2. MEDIUM	395578 USD	C	374,394 USD/AveYear	2. MEDIUM	395578 USD	C	231,275 USD/AveYear	2. MEDIUM

Figure 33 - Likelihood and risk status with and without maintenance (Case 1)

Other data necessary to go on with the calculations are aggregated in Table 3.

Table 3 - LoF without inspection (Case 1)

Equipment	LoF W/o inspections at 6/08/2038				
	LoF	Hole size distribution / LoF (for the PRV)			
		Small Leak	Medium Leak	Large Leak	Rupture
Vessel	0,000946448	0,261437	0,653594	0,065359	0,019607
PRV		0,964337			0,042354

It is possible now to calculate the LoF of all the scenarios linked to the failures: results are shown in Table 4. These results will be used then as input for the SAFETI analysis.

Table 4 - LoF of all the scenarios (Case 1)

Scenario	Likelihood from damages/PRV fails	Human error	Final Likelihood
Small leak from vessel	0,00024744	0,001	0,001247
Small leak from PRV	0,964337	0,001	0,965337
Medium leak from vessel	0,00061859	0,001	0,001619
Large leak from vessel	6,1859E-05	0,001	0,001062
Vessel rupture	1,8557E-05 0,042354	0,001	0,043373

Last to be done in order to be able to perform all the further analysis is to obtain data regarding the Outage Time linked to every possible case excluding the PRV leak due to the fact that this will not probably lead to a shutdown. These data are directly provided by the software and are shown in Table 5.

*Table 5 - Outage time and frequency (Case 1)*

<b>Scenario</b>	<b>Outage Time [day]</b>	<b>Frequency [events/year]</b>
Small Leak	2	0,001247
Medium Leak	7,75732423069662	0,001619
Large Leak	26,9494932758666	0,001062
Rupture	26,9494932758666	0,043373
	total	0,047301
	TBF (1/total)	21,14 years

#### *4.2.1.2 Safety issues results*

Once all the likelihoods of the five different scenarios are set in the software, it is possible to obtain the associated consequence data and different risk metrics.

The consequences of the five different scenarios are the same for the three different case studies because they depend only on the storage vessel and PRV data and the scenarios-associated hole sizes. Some samples of the consequences data are reported below while a complete report of only a selected scenario (as an example) can be found in “attachment A” where the data are valid for all the cases except from the Likelihoods that are different for case 2 and 3 and can be found on the “maintenance and LoFs results” sections.

In order to show a sample of the consequences, the “large leak” scenario is selected. First step of the consequence analysis is the dispersion of the gas through the leak hole: a fixed concentration of 2000 ppm depending on the distance downwind and on the time is shown in Figure 34 and 35 respectively where also the dependence on the weather category can be seen.

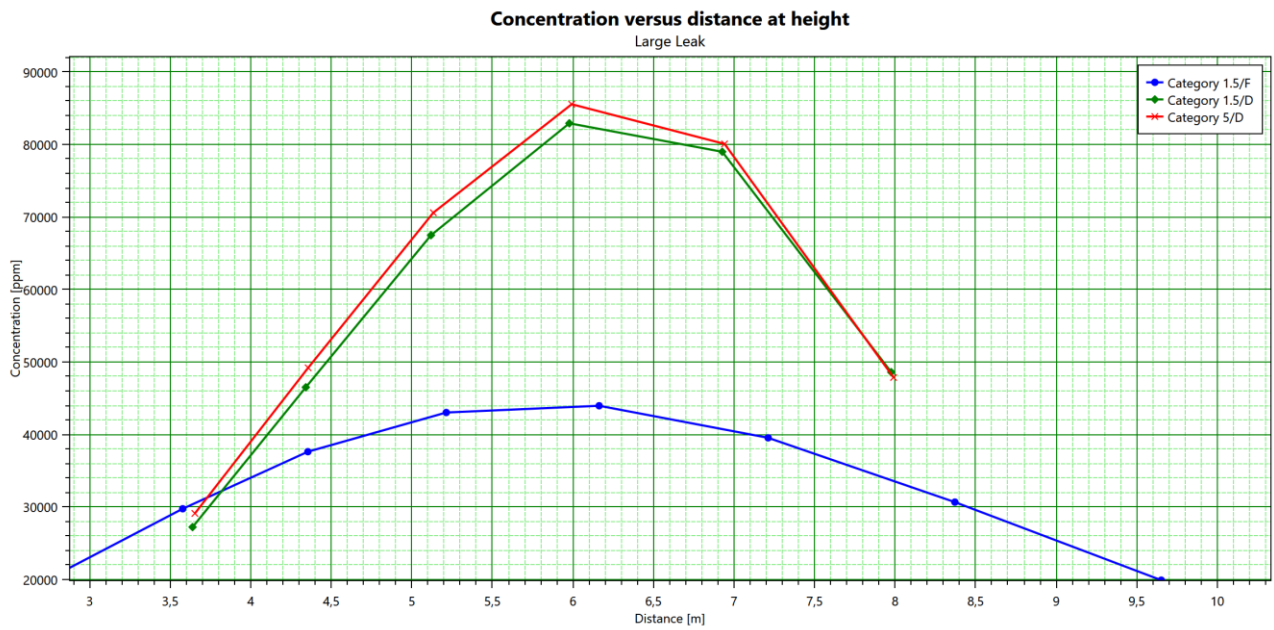


Figure 34 - Dispersion: concentration vs distance

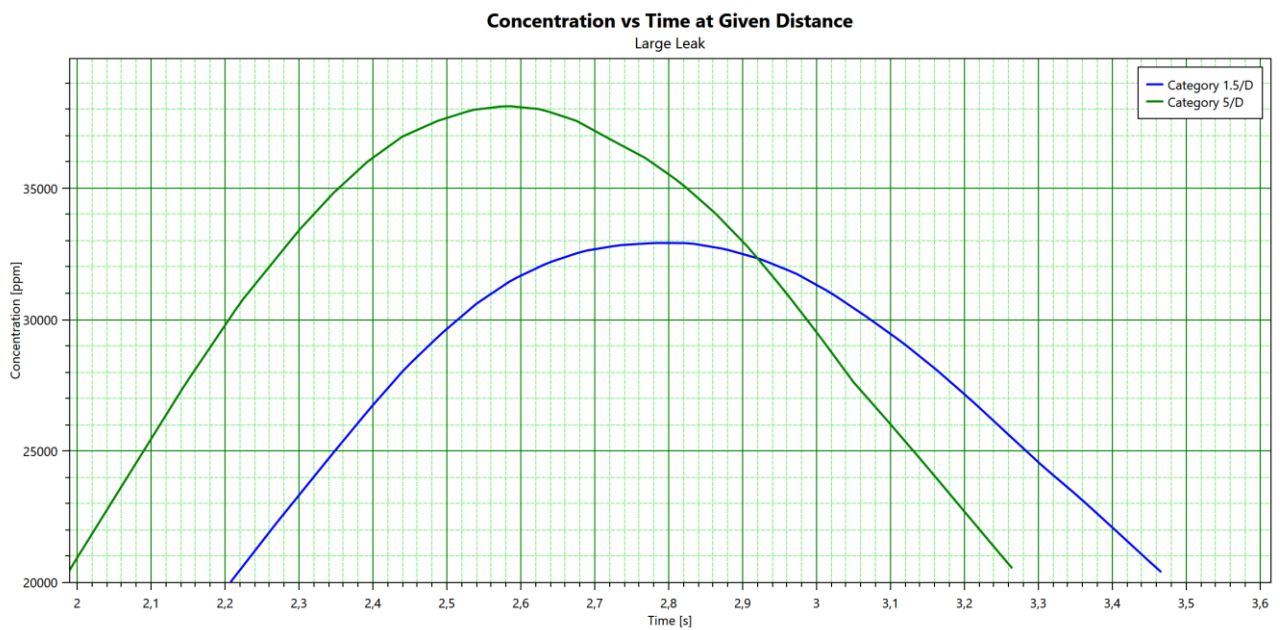


Figure 35 - Dispersion: concentration vs time

Another useful information is the maximum concentration vs the distance downwind as shown in Figure 36.

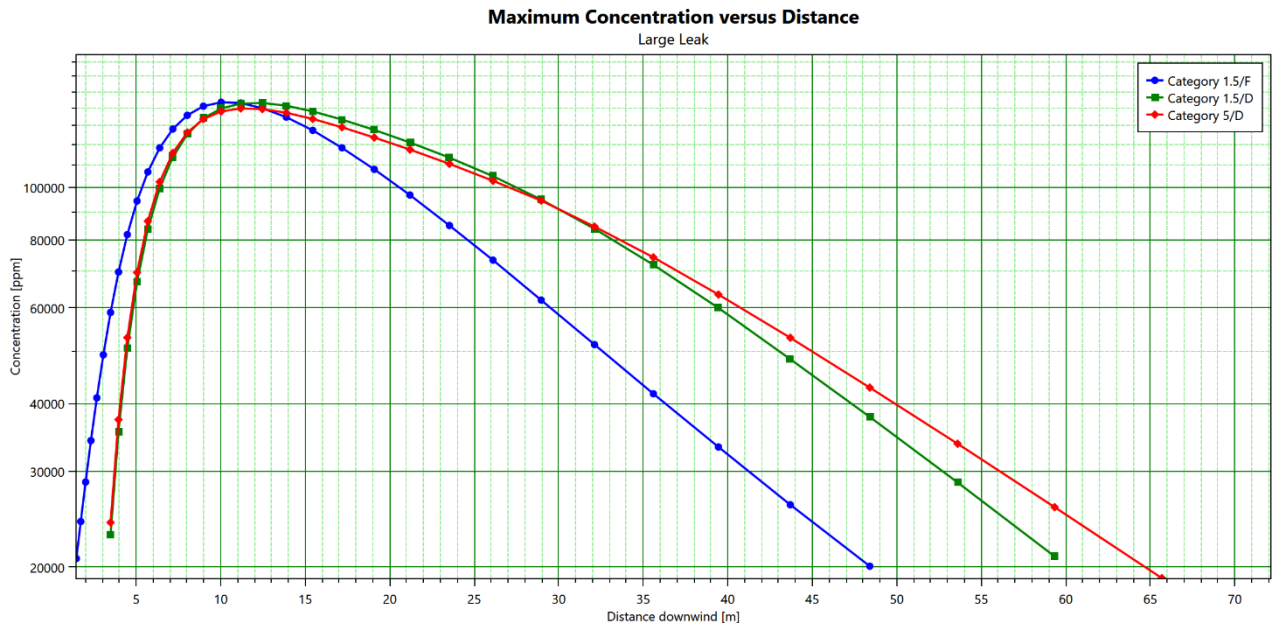


Figure 36 - Dispersion: maximum concentration vs distance

Regarding the cloud footprint, it is possible to see, for example, the final cloud footprint and side view in Figure 37 and 38 respectively.

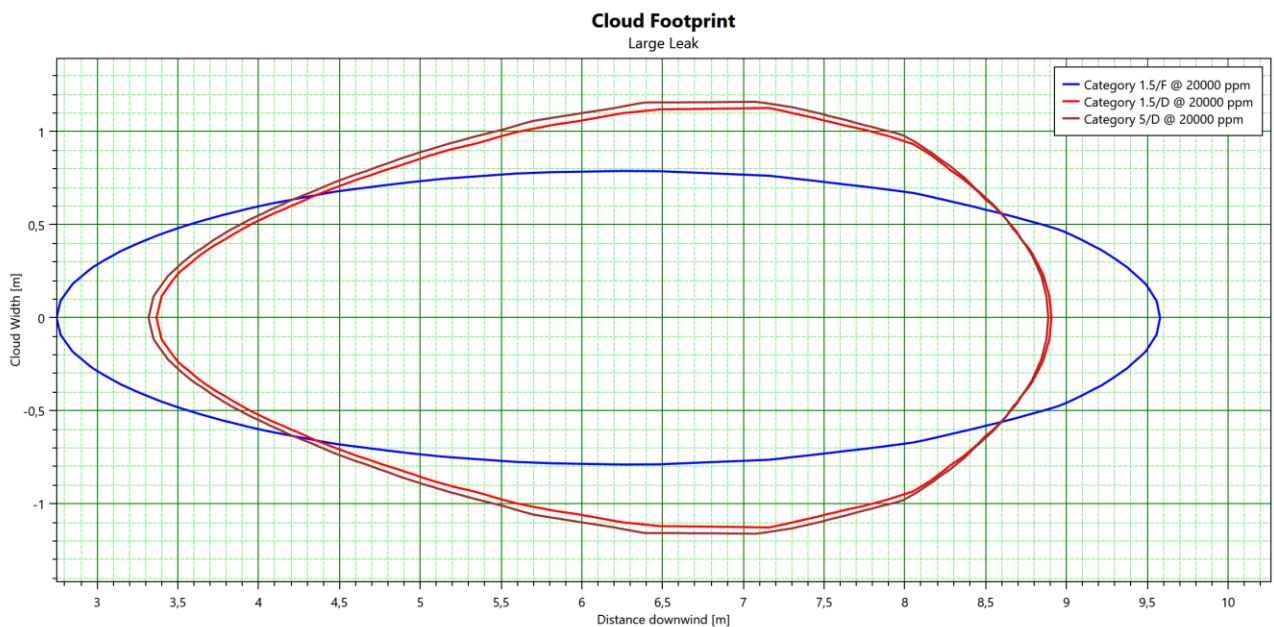


Figure 37 - Cloud footprint

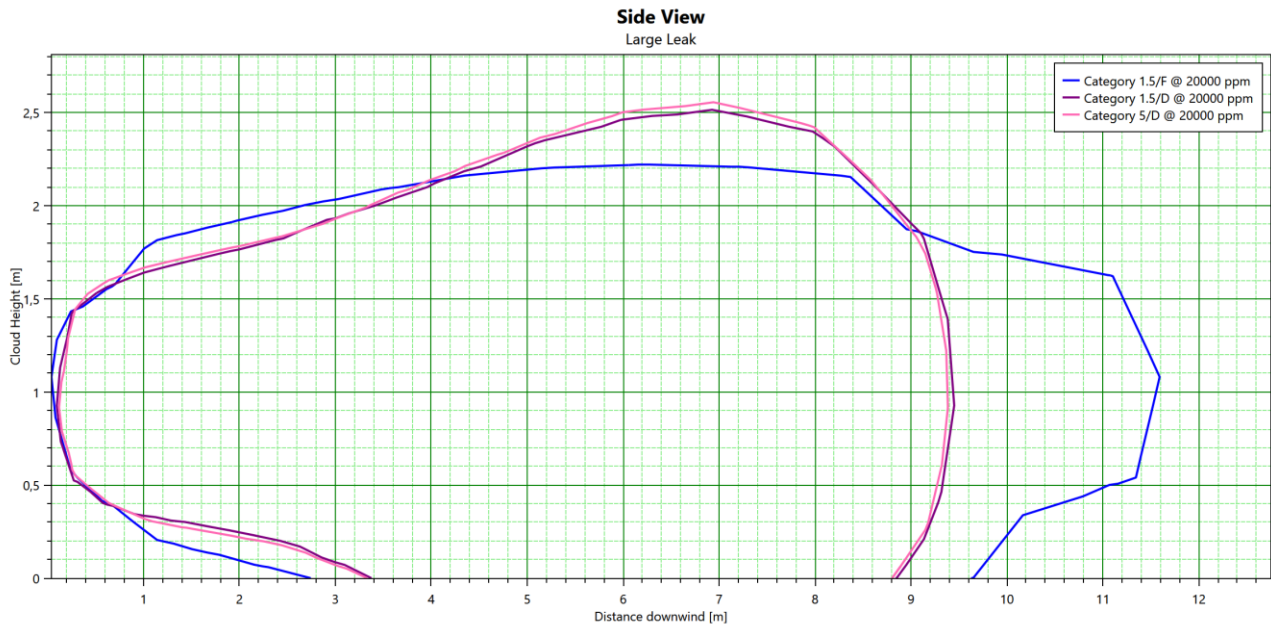


Figure 38 - Cloud side view

After the dispersion takes place, four different scenarios are possible. If the ignition source is close to the leak hole, a jet fire occurs: it is interesting to see, for example, the radiation level vs the distance as shown in Figure 39; Figure 40 is then useful to understand the dimensions of the area affected by such radiation level.

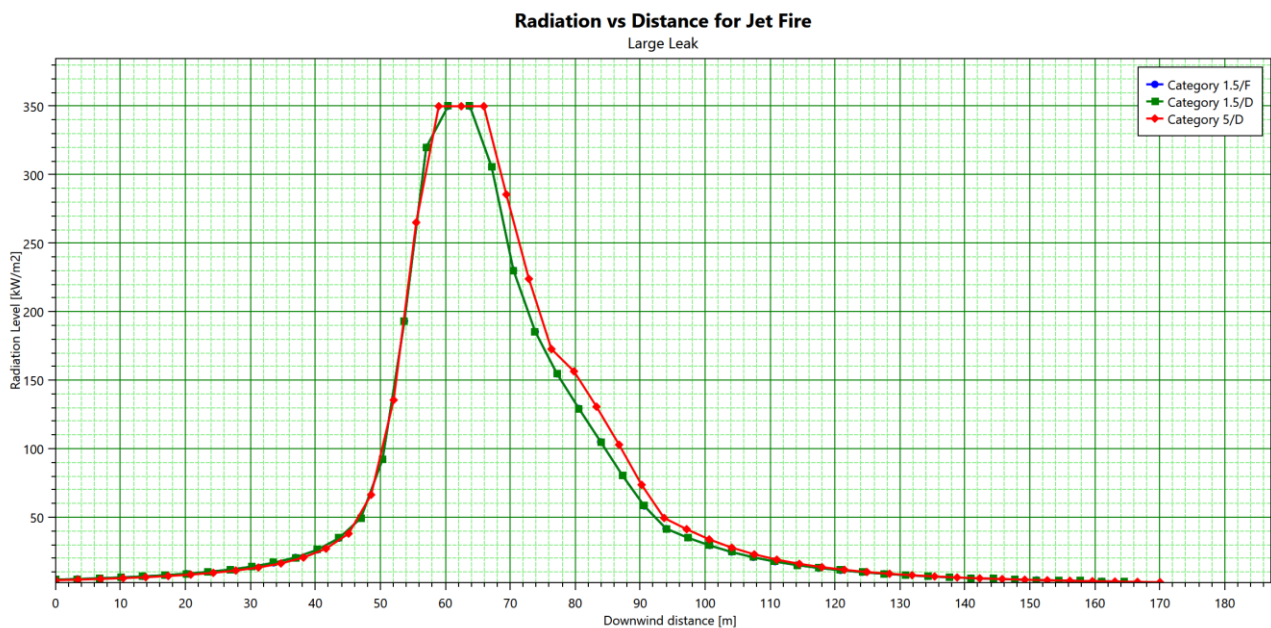


Figure 39 - Jet fire: radiation level vs distance

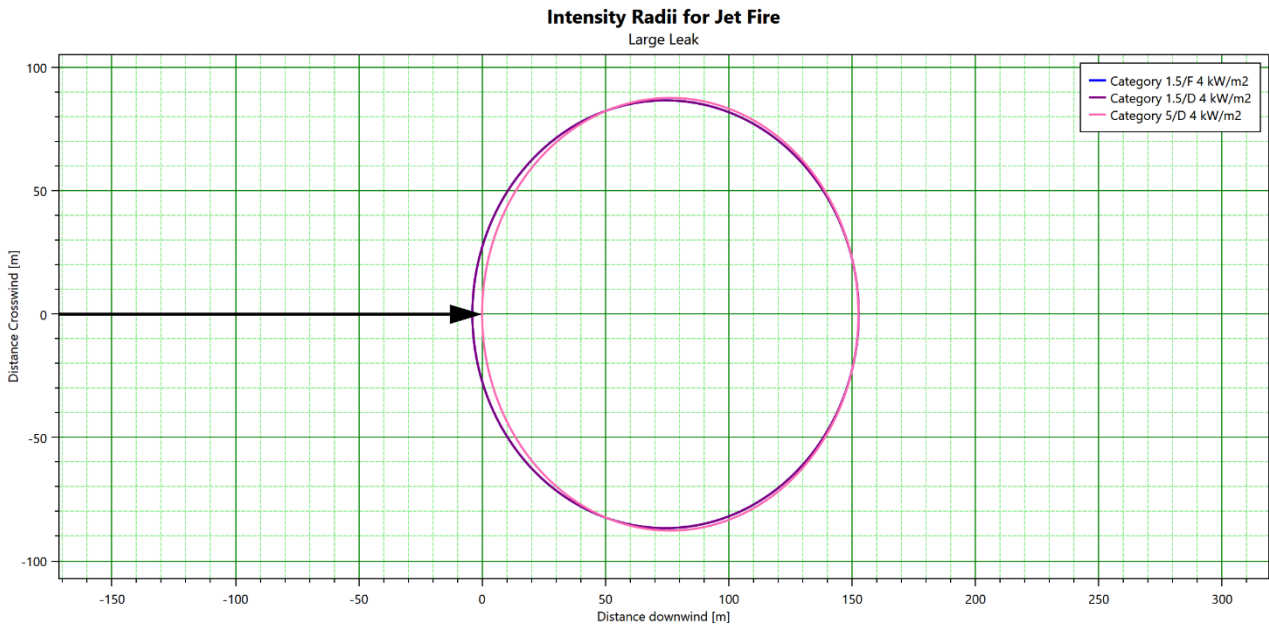


Figure 40 - Jet fire: intensity radii

If the ignition takes place after the cloud formation but before the cloud dispersion takes place, the consequent event is a fireball: in Figure 41 the radiation level vs the distance is presented, while the fireball dimensions vs time and fireball intensity radii at its maximum dimensions vs time are shown in Figure 42 and 43 respectively.

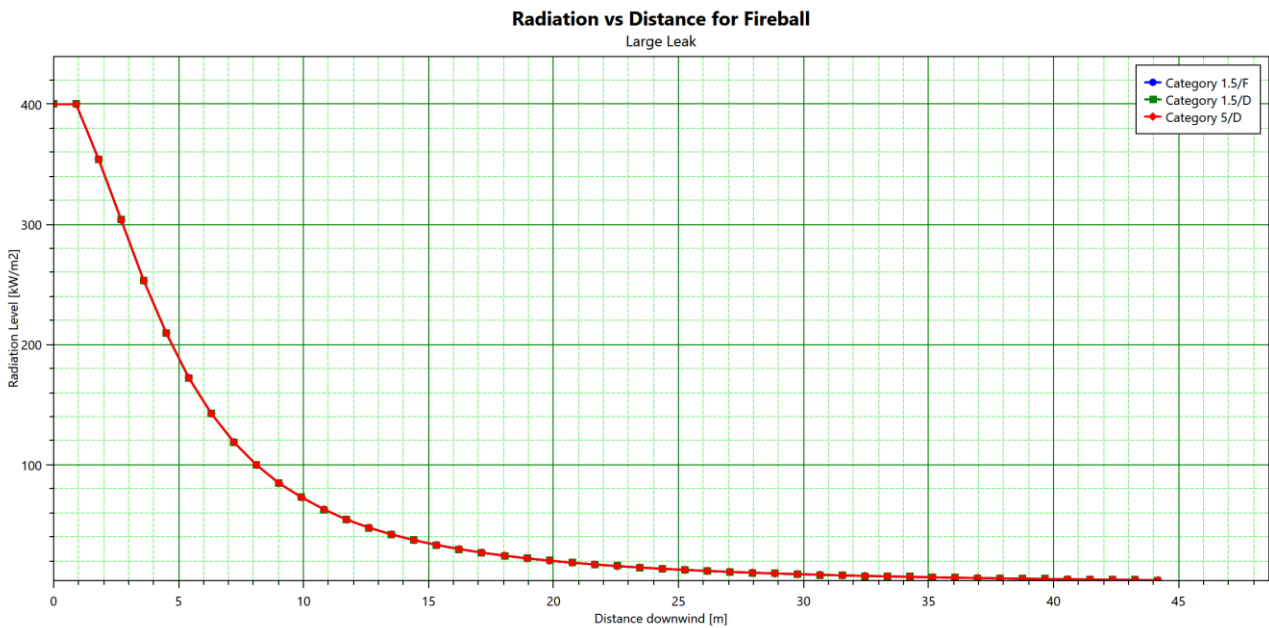


Figure 41 - Fireball: radiation vs distance



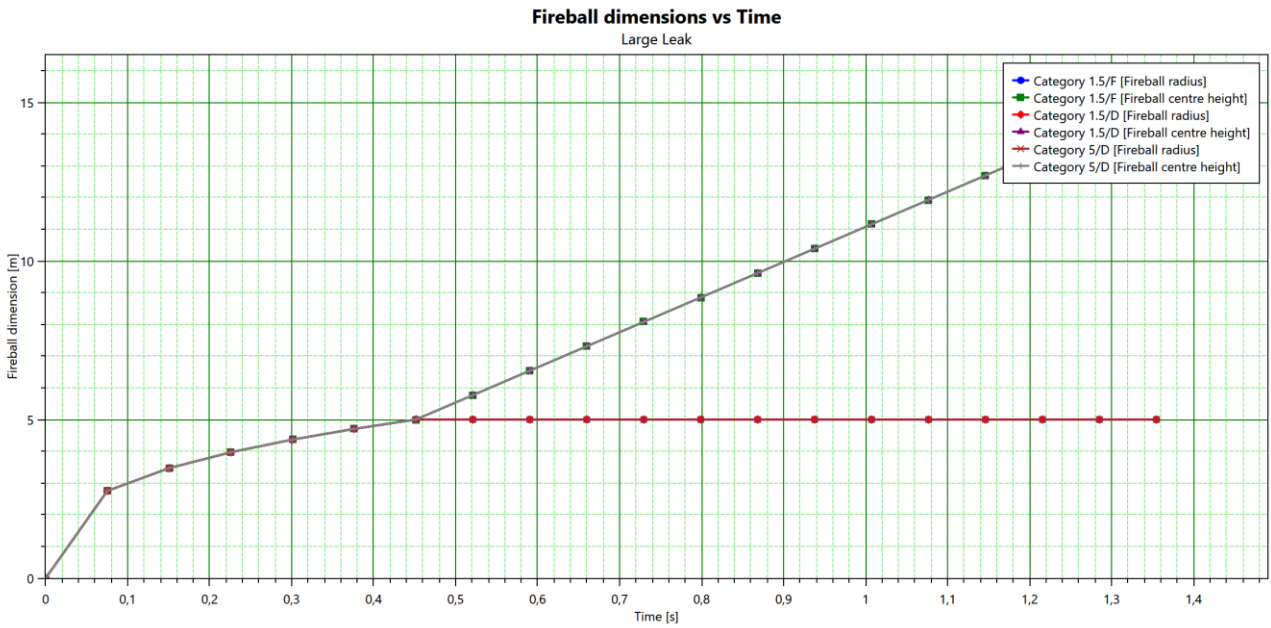


Figure 42 - Fireball dimensions vs time

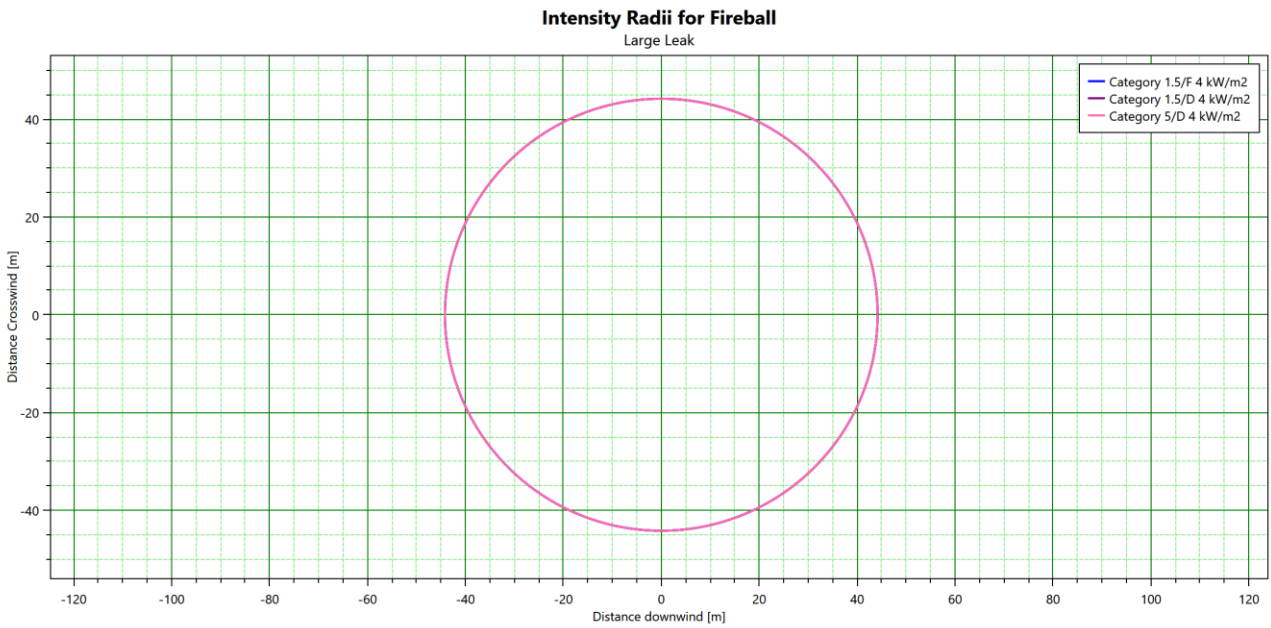


Figure 43 - Fireball: intensity radii

If the ignition occurs after the cloud dispersion, depending on the boundary conditions such as the confinement level and flame velocity, a flash fire or an explosion can take place. The flash fire envelope is shown in Figure 44 while explosion worst case radii and explosion overpressure vs distance can be seen in Figure 45 and 46 respectively.



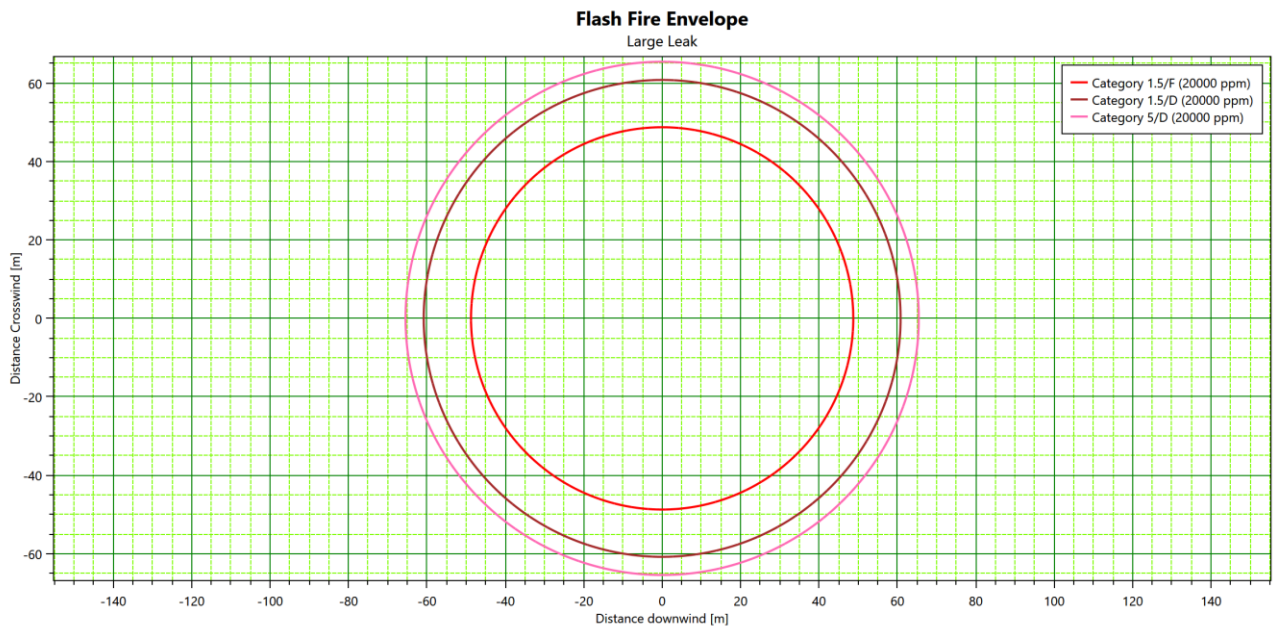


Figure 44 - Flash fire envelope

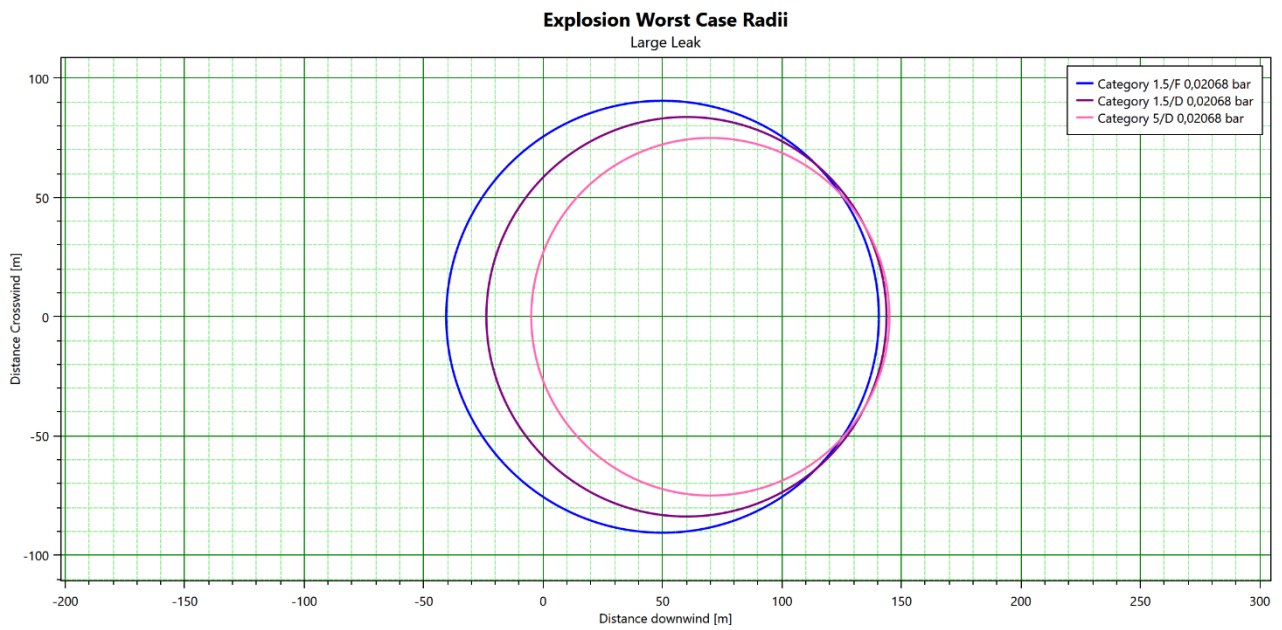


Figure 45 - Explosion: worst case radii

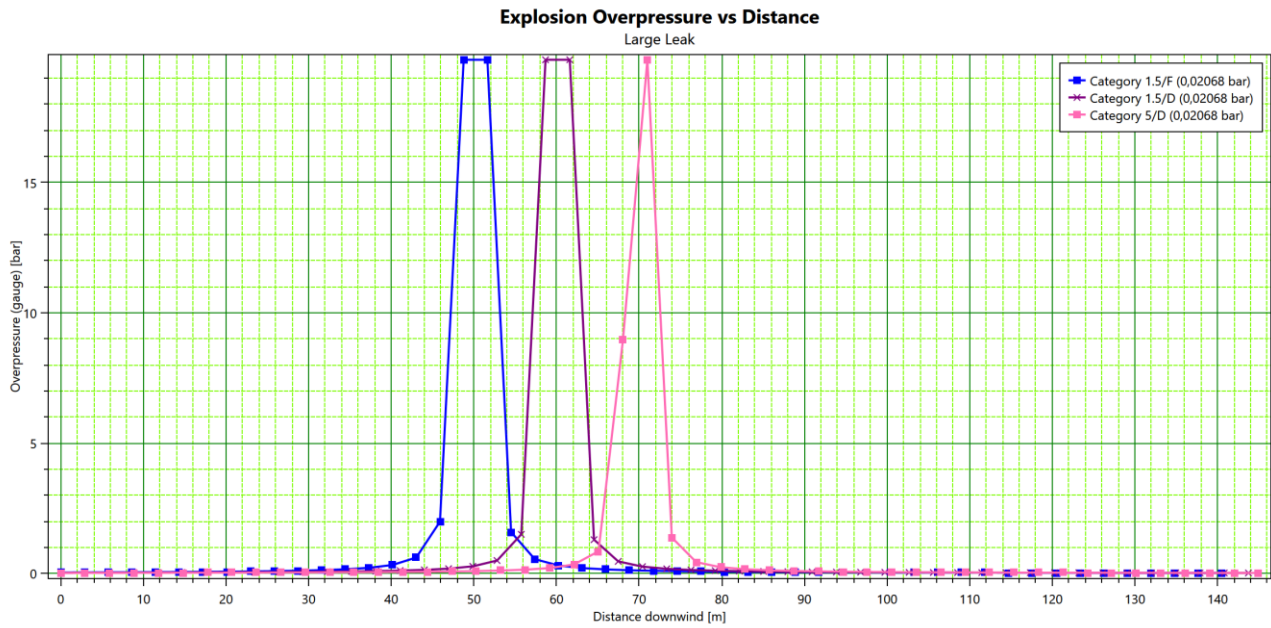


Figure 46 - Explosion: overpressure vs distance

Regarding the Risk metrics, in order to compare the results with the Risk acceptance criteria described before, F-N curves and individual risk contours seem to be the most appropriate information to analyse.

- "Third party" risk

Considering the F-N curve, as stated in the Risk acceptance criteria, only the "third party" should be considered: customers and personnel populations were so excluded from the calculations of the curve.

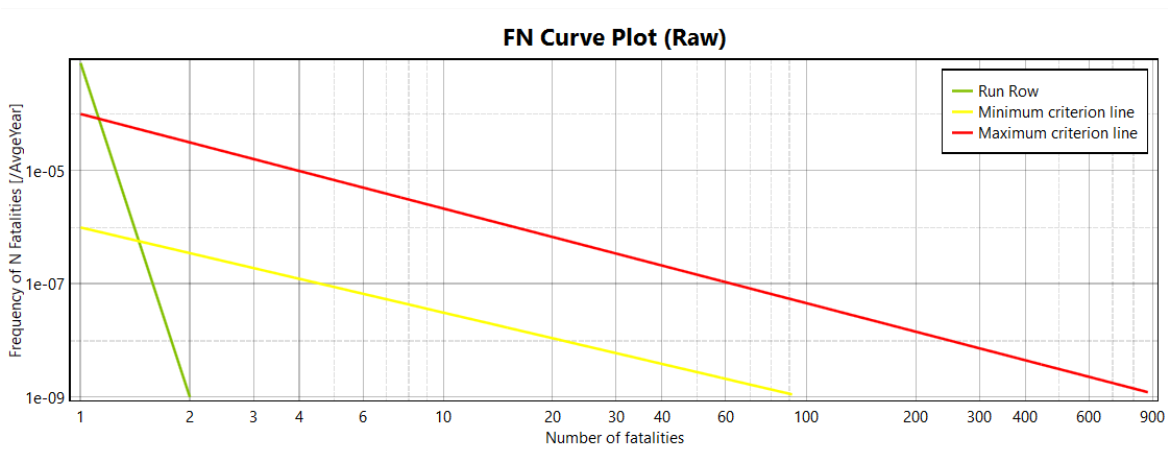


Figure 47 - F-N curve (Case 1)

As we can see in Figure 47, due to the relatively small dimensions of the consequences affected areas (depending on the fact that only one vessel was considered), the maximum numbers of deaths is calculated as two and the F-N curve is sensibly fixed on the left side of the F-N plane where the acceptability criteria are usually not considered. It is then more useful to calculate the individual risk contours also for the “third part” risk in order to have a direct comparison with the individual risk limits: in Figure 48 it is possible to see the risk contours for different risk levels as shown in the map legend.



Figure 48 - Individual risk (Case 1)

If we take a closer look to the map, it is possible to know that the risk for the people “visiting/travelling through the neighbourhood of the refuelling station” (Norsk Hydro ASA, 2003) on the parking lot side is between the values of  $10^{-6}$  and  $10^{-7}$ . It is useful then to define a “risk transect” (line on which the individual risk is calculated point by point) from the first available point where people can be exposed until the closest building: this line is the purple dotted line on the map. Individual risk along the line is shown in Figure 49.

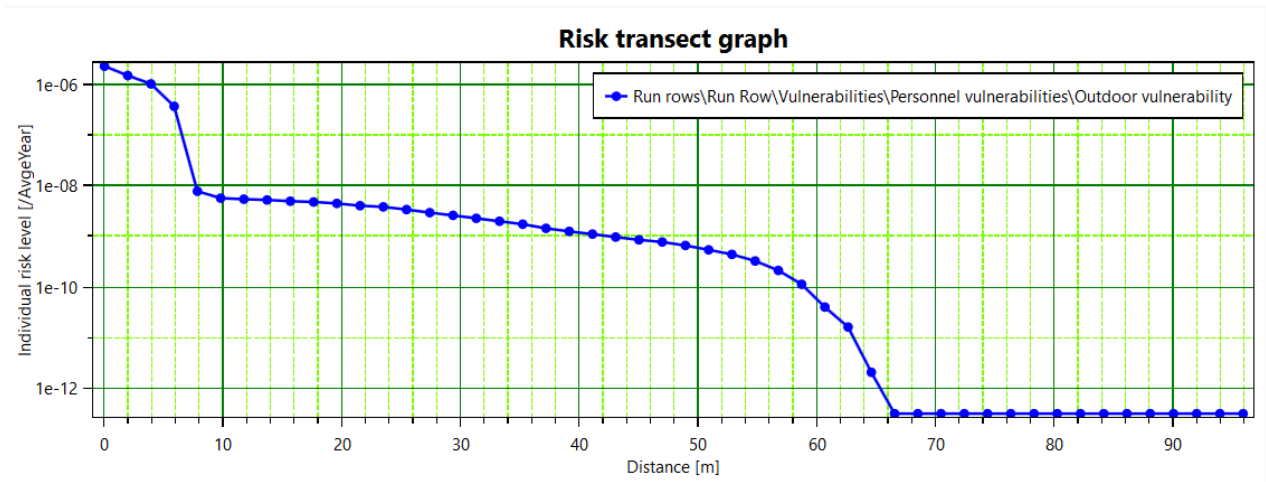


Figure 49 - Risk transect graph (Case 1)

As you can see from Figure 49, the Individual Risk equals the acceptance value of  $10^{-6}$  4 meters away from the facility boundaries.

It can be easily seen that the risk for people driving along the road next to the facility has comparable values to risk for people passing through the parking lot (see figure 50)

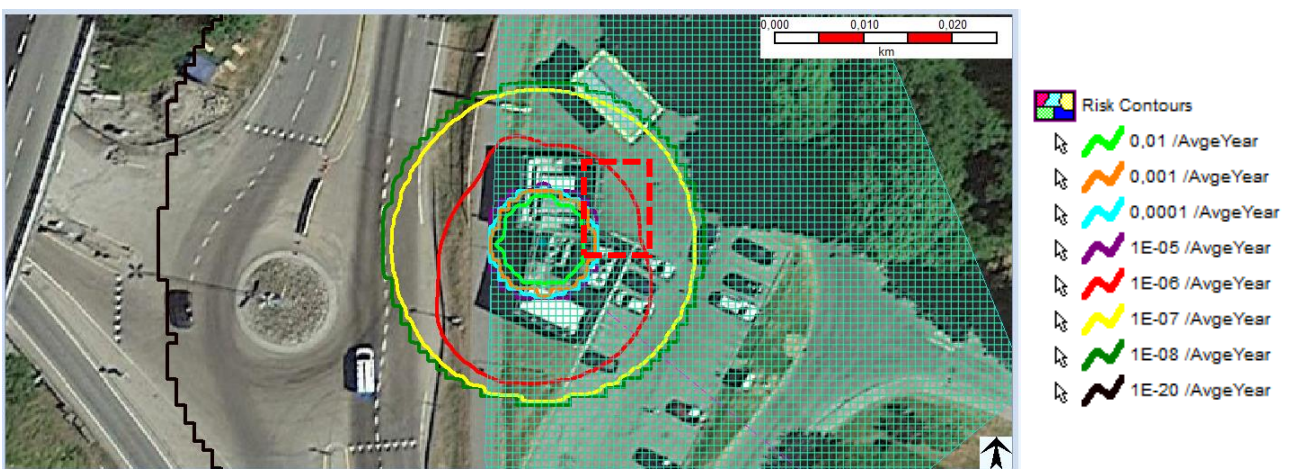


Figure 50 - Individual risk detail (Case 1)

- “Second party” risk

Referring to Figure 50, risk for the customers that usually could be exposed in the area between the facility boundaries and the dispenser, starts from a value of  $10^{-5}$  in the red dotted area and decreases moving away from the facility boundaries.

- “First party” risk

Thinking at the operator/s, they can be exposed at individual risk levels higher than the acceptance value of  $10^{-6}$  as it can be seen on Figure 50 if they operate inside the facility boundaries.

#### 4.2.1.3 Business interruption results

After setting the data provided by the first step of the methodology as input, you can obtain different metrics and trend charts.

As the model built for this thesis is relatively simple, essential data useful to understand the business interruption costs are reported in Table 6 for 5 simulations for the selected time frame.

Table 6 - Business Interruption (Case 1)

Simulation time frame (years)	Simulation number	Number of downs	Unscheduled downtime (days)	Total income (NOK)
30	1	1	3,85	508572172,5
	2	1	8,99	508328726,6
	3	1	14,94	508046916,8
	4	1	2,16	508652215,9
	5	1	23,69	507632490,5
				Mean total income

#### 4.2.2 Case 2

##### 4.2.2.1 Maintenance plan and Lofs results

###### Inspection

The first inspection is fixed on 2035, so after 15 years: this means that, in the evaluation period, at least two inspections are required. Inspection data are provided in Figure 51 and 52.



### Likelihood Status

Current Status (10/01/2020)			Future Status W.O. Insp. (10/01/2050)			Future Status With Insp. (10/01/2050)		
Damage Factor	Damage Factor Category	LoF (/AvgeYear)	Damage Factor	Damage Factor Category	LoF (/AvgeYear)	Damage Factor	Damage Factor Category	LoF (/AvgeYear)
3,11507	2	9,53211E-05	282,195	4	0,00863516	14,4709	3	0,000442811

### Risk Status

Risk Type	Current Status (10/01/2020)			Future Status W.O. Insp. (10/01/2050)			Future Status With Insp. (10/01/2050)					
	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category
Total Cost	395578 USD	C	37,7069 USD/Avge Year	2. MEDIUM	395578 USD	C	3415,88 USD/Avge Year	3. MEDIUM HIGH	395578 USD	C	175,166 USD/Avge Year	2. MEDIUM

### Damage Results & Inspection Plan

Damage Mechanism	Current Status (10/01/2020)		Future Status W.O. Insp. (10/01/2050)		Inspection Plan				Future Status With Insp. (10/01/2050)		
	Damage Factor	Damage Factor Category	Damage Factor	Damage Factor Category	Target Damage Factor	Target Driver	Inspection Date	Inspection Effectiveness	Inspection Task	Damage Factor	Damage Factor Category
External Thinning (0,127 mm/AvgeYear)	3,11507	2	282,195	4	16,316	Risk Total Cost	18/03/2035	Highly	NonIntr +95VT +UT/RT follow-up	14,4709	3

Figure 51 - Case 2 maintenance plan

### Inspection Plan Report (Tag)



Tag	Tag Type	Parent	Damage Mechanism	Current Status			Future Status W.O. Insp.			Inspection Plan				Future Status With Insp.			
				Damage Factor	Criteria Met	Criteria Met	Damage Factor	Criteria Met	Criteria Met	Target Damage Factor	Inspection Date	Inspection Effectiveness	Inspection Task	Inspection Task Description	Damage Factor	Criteria Met	Criteria Met
Low pressure vessel	Drum	Low pressure storage	External Thinning (0,127 mm/AvgeYear)	3,11507	2	Yes	282,195	4	No	16,316	18/03/2035	Highly	NonIntr +95VT +UT/RT follow-up	Visual inspection of >95% of the exposed surface area with follow-up by UT, RT or pat gauge as required.	14,4709	3	Yes

Figure 52 - Case 2 inspection specifications

Regarding the valve, a bench test is planned on 5/01/2040; LoF trend charts of the valve regarding the “Vessel rupture due to valve fail to open” and “valve leakage” fails as shown respectively in Figure 53 and 54.

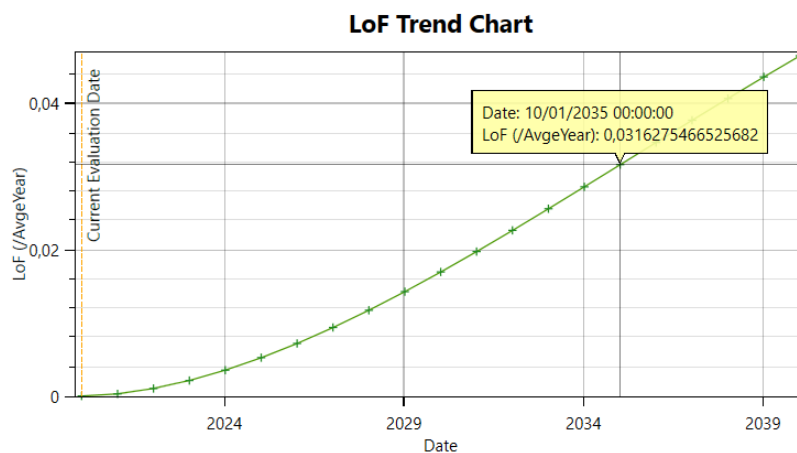


Figure 53 - “Vessel rupture due to valve fail to open” LoF trend chart (Case 2)

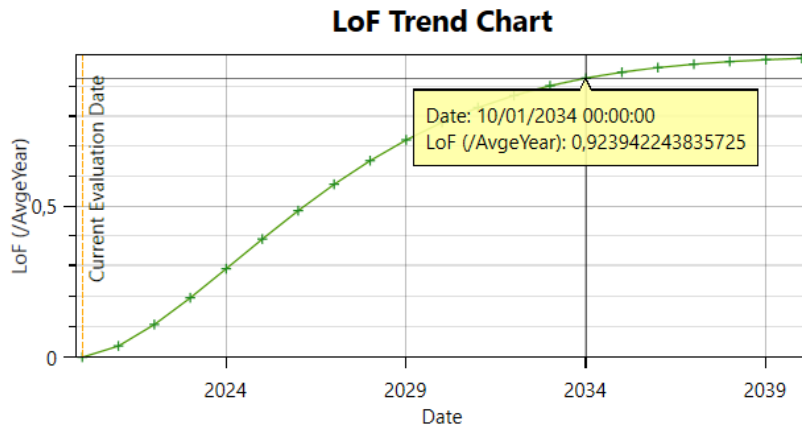


Figure 54 - "Valve leakage" LoF trend chart (Case 2)

Trend of vessel damage factor is shown in Figure 55.

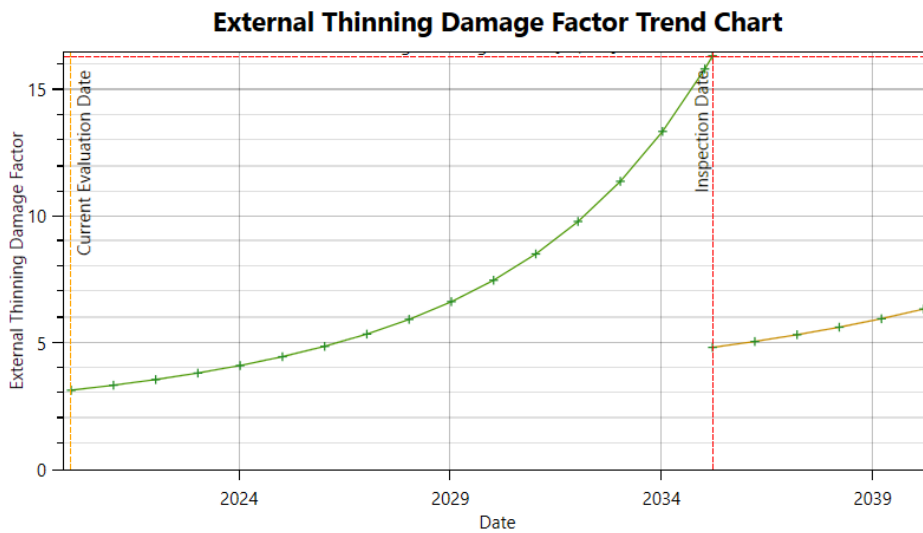


Figure 55 - External thinning damage factor trend chart (Case 2)

LoF of the vessel and the associated risk category with and without the scheduled inspection of that day are shown in Figure 56.

**Likelihood Status**

Current Status (10/01/2020)			Future Status W.O. Insp. (18/03/2035)			Future Status With Insp. (18/03/2035)		
Damage Factor	Damage Factor Category	LoF (/AveYear)	Damage Factor	Damage Factor Category	LoF (/AveYear)	Damage Factor	Damage Factor Category	LoF (/AveYear)
3,11507	2	9,53211E-05	16,3084	3	0,000499038	10,9812	3	0,000336024

**Risk Status**

Risk Type	Current Status (10/01/2020)				Future Status W.O. Insp. (18/03/2035)				Future Status With Insp. (18/03/2035)			
	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category
Total Cost	395578 USD	C	37,7069 USD/AveYear	2. MEDIUM	395578 USD	C	197,409 USD/AveYear	2. MEDIUM	395578 USD	C	132,924 USD/AveYear	2. MEDIUM

Figure 56 - Likelihood and risk status with and without maintenance (Case 2)

Other data

Table 7 - LoF without inspection (Case 2)

Equipment	LoF W/o inspections at 18/03/2035				
	LoF	Hole size distribution / LoF (for the PRV)			
		Small Leak	Medium Leak	Large Leak	Rupture
Vessel	0,0004990	0,261437	0,653594	0,065359	0,019607
PRV		0,9106			0,009787

LoF of all the scenarios are presented in Table 8.



Table 8 - LoF of all the scenarios (Case 2)

Scenario	Likelihood from damages/PRV fails	Human error	Final Likelihood
Small leak from vessel	0,000130457	0,001	0,00113
Small leak from PRV	0,9106	0,001	0,9116
Medium leak from vessel	0,000326143	0,001	0,001326
Large leak from vessel	3,26141E-05	0,001	0,001033
Vessel rupture	9,78389E-06 0,0321860	0,001	0,032196

Outage Time linked to every possible case is shown in Table 9.

Table 9 - Outage time and frequency (Case 2)

Scenario	Outage Time [day]	Frequency [events/year]
Small Leak	2	0,00113
Medium Leak	7,75732423069662	0,001326
Large Leak	26,9494932758666	0,001033
Rupture	26,9494932758666	0,032196
	total	0,035685
	TBF (1/total)	28,02298

#### 4.2.2.2 Safety issues results

- “Third party” risk

The Individual risk map and the Risk transect results (along the same line defined in the first Case) are reported in Figure 57 and 58 respectively.

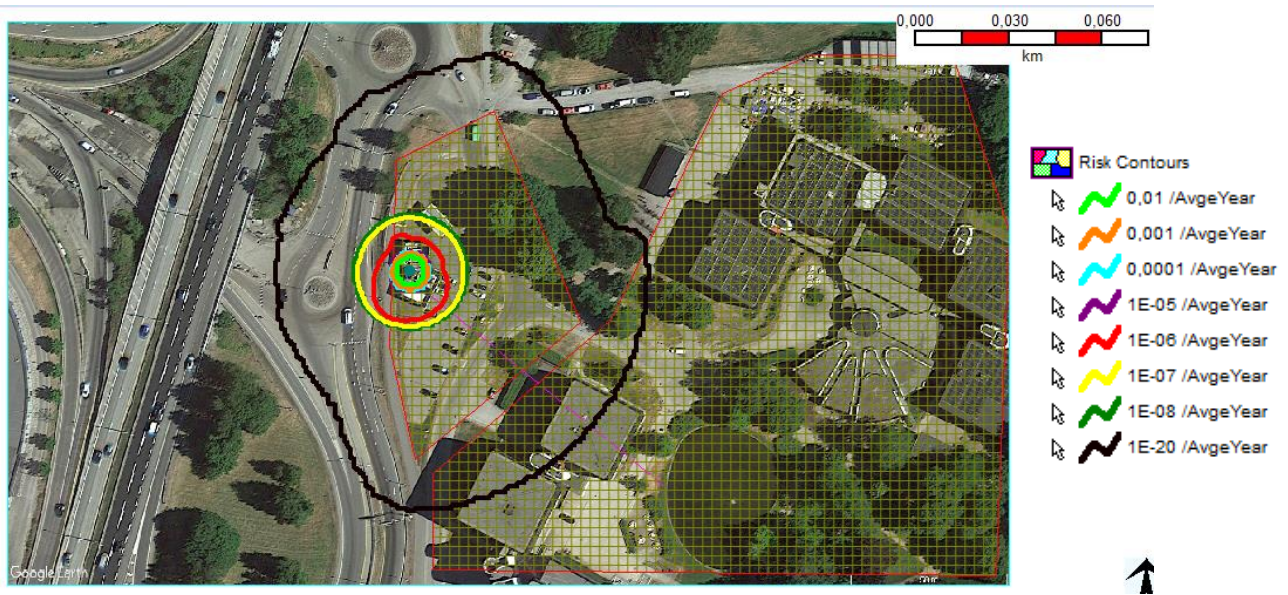


Figure 57 - Individual risk (Case 2)

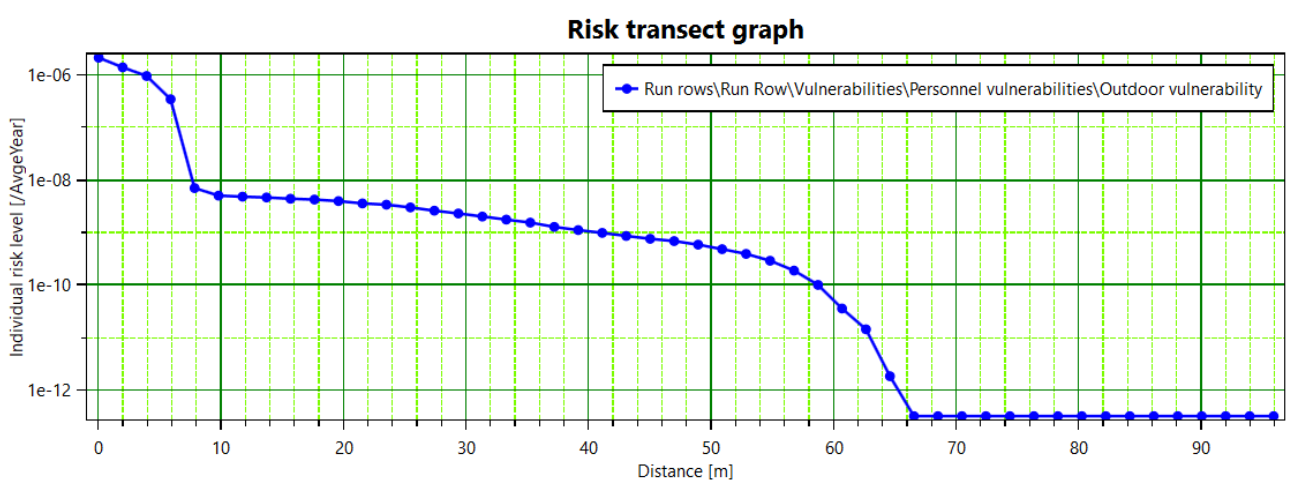


Figure 58 - Risk transect graph (Case 2)

As the human error is not influenced by the maintenance plan and the PRV LoFs values are overestimated it is difficult to see a considerable differences with the Case 1: if the model was applied to all the facility equipment, the difference would be more significative.

#### 4.2.2.3 Business interruption results

Table 10 – Business Interruption (Case 2)

Simulation time frame (years)	Simulation number	Number of downs	Unscheduled downtime (days)	Total income (NOK)
30	1	1	22,00	507712534
	2	1	7,2	508413506,4
	3	1	15,21	508034128,8
	4	1	6,17	508462290,3
	5	1	3,88	508570751,6
				Mean total income

#### 4.2.3 Case 3

##### 4.2.3.1 Maintenance plan and Lofs results

First inspection is calculated to happen on 2028, after 8 years from the “current evaluation date”: this means that approximately 6 inspections will be performed in the evaluation period. Details can be found in Table 59.

**Likelihood Status**

Current Status (10/01/2020)			Future Status W.O. Insp. (10/01/2050)			Future Status With Insp. (10/01/2050)		
Damage Factor	Damage Factor Category	LoF (/AvgeYear)	Damage Factor	Damage Factor Category	LoF (/AvgeYear)	Damage Factor	Damage Factor Category	LoF (/AvgeYear)
3,11507	2	9,53211E-05	282,195	4	0,00863516	14,4709	3	0,000442811

**Risk Status**

Risk Type	Current Status (10/01/2020)				Future Status W.O. Insp. (10/01/2050)				Future Status With Insp. (10/01/2050)			
	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category
Total Cost	395578 USD	C	37,7069 USD/Avge Year	2. MEDIUM	395578 USD	C	3415,88 USD/Avge Year	3. MEDIUM HIGH	395578 USD	C	175,166 USD/Avge Year	2. MEDIUM

**Damage Results & Inspection Plan**

Damage Mechanism	Current Status (10/01/2020)		Future Status W.O. Insp. (10/01/2050)		Inspection Plan					Future Status With Insp. (10/01/2050)	
	Damage Factor	CoF	Damage Factor	Risk Category	Target Damage Factor	Target Driver	Inspection Date	Inspection Effectiveness	Inspection Task	Damage Factor	CoF
External Thinning (0,127 mm/AvgeYear)	3,11507	2	282,195	4	6,5264	Risk Total Cost	26/11/2028	Highly	NonIntr +95VT +UT/RT follow-up	14,4709	3

Figure 59 – Case 3 maintenance plan

**Inspection Plan Report (Tag)**



Tag	Tag Type	Parent	Damage Mechanism	Current Status			Future Status W.O. Insp.			Inspection Plan					Future Status With Insp.		
				Damage Factor	CoF	Criteria Met	Damage Factor	CoF	Criteria Met	Target Damage Factor	Inspection Date	Inspection Effectiveness	Inspection Task	Inspection Task Description	Damage Factor	CoF	Criteria Met
Low pressure vessel	Drum	Low pressure storage	External Thinning (0,127 mm/AvgeYear)	3,11507	2	Yes	282,195	4	No	6,5264	26/11/2028	Highly	NonIntr +95VT +UT/RT follow-up	Visual inspection of >95% of the exposed surface area with follow-up by UT, RT or pit gauge as required.	14,4709	3	No

Figure 60 – Case 3 inspection specifications

Regarding the valve, a bench test is planned on 5/01/2040; LoF trend charts of the valve regarding the “Vessel rupture due to valve fail to open” and “valve leakage” fails as shown respectively in Figure 61 and 62.

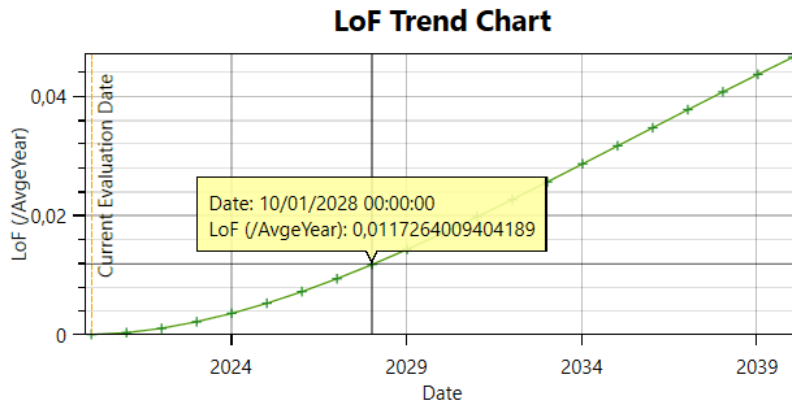


Figure 61 – “Vessel rupture due to valve fail to open” LoF trend chart (Case 3)

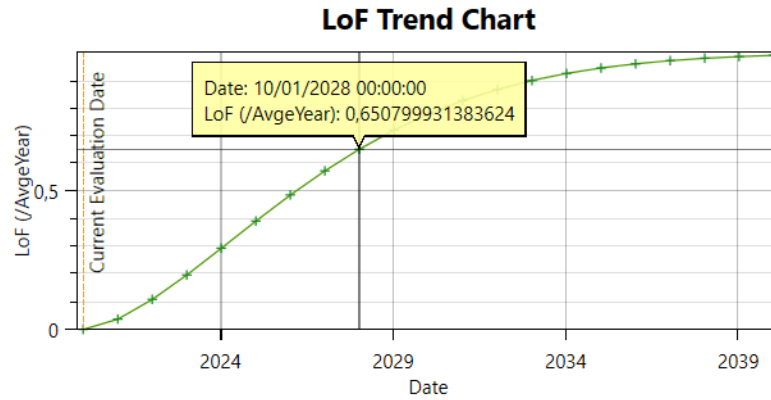


Figure 62 – “Valve leakage” LoF trend chart (Case3)

Trend of vessel damage factor is shown in Figure 63.

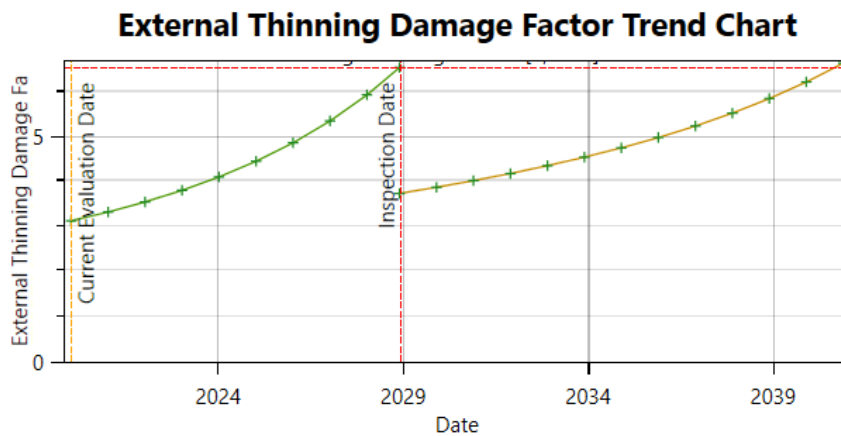


Figure 63 – External thinning damage factor trend chart (Case 3)

LoF of the vessel and the associated risk category with and without the scheduled inspection of that day are shown in Figure 64.

**Likelihood Status**

Current Status (10/01/2020)			Future Status W.O. Insp. (26/11/2028)			Future Status With Insp. (26/11/2028)		
Damage Factor	Damage Factor Category	LoF (/Avge Year)	Damage Factor	Damage Factor Category	LoF (/Avge Year)	Damage Factor	Damage Factor Category	LoF (/Avge Year)
3,11507	2	9,53211E-05	6,51524	2	0,000199366	5,26461	2	0,000161097

**Risk Status**

Risk Type	Current Status (10/01/2020)				Future Status W.O. Insp. (26/11/2028)				Future Status With Insp. (26/11/2028)			
	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category	CoF	CoF Category	Risk	Risk Category
Total Cost	395578 USD	C	37,7069 USD/AvgeYear	2. MEDIUM	395578 USD	C	78,8649 USD/AvgeYear	2. MEDIUM	395578 USD	C	63,7265 USD/AvgeYear	2. MEDIUM

Figure 64 – Likelihood and risk status with and without maintenance (Case 3)

Other data

Table 11 – LoF without inspection (Case 3)

Equipment	LoF W/o inspections at 26/11/2028				
	LoF	Hole size distribution / LoF (for the PRV)			
		Small Leak	Medium Leak	Large Leak	Rupture
Vessel	0,000199366	0,261437	0,653594	0,065359	0,019607
PRV		0,640724			0,0139495

LoF of all the scenarios

Table 12 – LoF of all the scenarios (Case 3)

Scenario	Likelihood from damages/PRV fails	Human error	Final Likelihood
Small leak from vessel	5,21216E-05	0,001	0,001052
Small leak from PRV	0,640724	0,001	0,641724
Medium leak from vessel	0,000130304	0,001	0,001013
Large leak from vessel	1,30304E-05	0,001	0,001004
Vessel rupture	3,90897E-06 0,0139495	0,001	0,014953



Outage Time linked to every possible case

Table 13 – Outage time and frequency (Case 3)

Scenario	Outage Time [day]	Frequency [events/year]
Small Leak	2	0,001052
Medium Leak	7,75732423069662	0,001013
Large Leak	26,9494932758666	0,001004
Rupture	26,9494932758666	0,014953
	total	0,018022
	TBF (1/total)	55,48774

4.2.3.2 Safety issues results

Figure 65 shows the Individual risk map for Case 3.

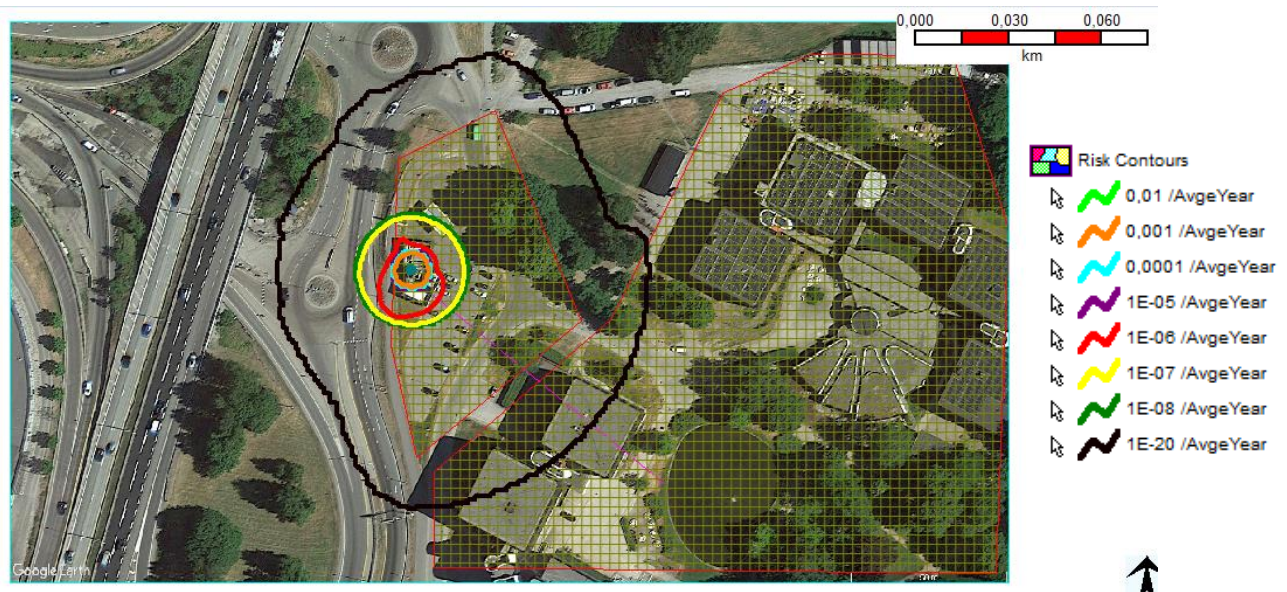


Figure 65 – Individual risk (Case 3)

If we take a closer look to the map it is now possible to see a difference with the first two cases as shown in Figure 66 that compares Case 1 and Case 3 result.

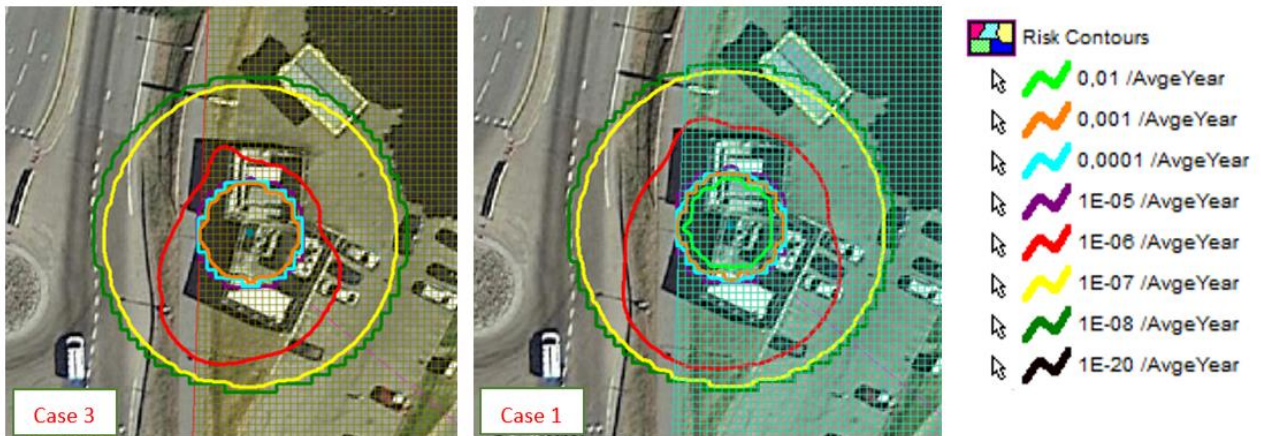


Figure 66 – Case 3 vs Case 1 Individual risk

It is easy to notice that in Case 3 the area with an Individual Risk over  $10^{-6}$  is sensibly smaller on the parking lot and customer area allowing a better safety level for the “third party”.

Figure 67 shows the Risk transect results along the same line defined in the previous Cases.

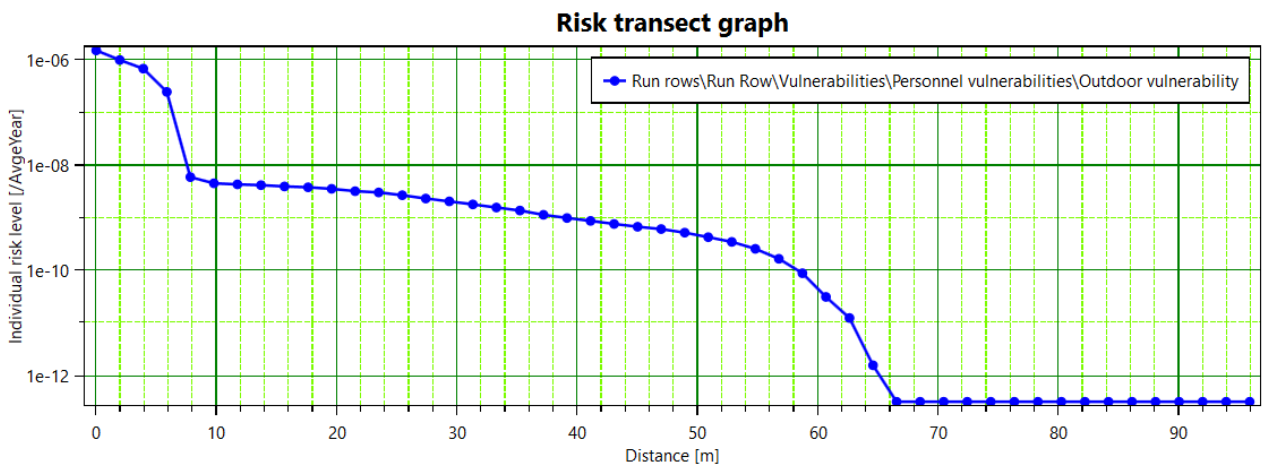


Figure 67 – Risk transect graph (Case 3)

It can be seen that now the Risk acceptance level of  $10^{-6}$  is reached two meters away from the facility boundaries instead of the four meters necessary in the Case 1.



#### *4.2.3.3 Business interruption results*

All the five simulations reported 0 shutdowns during the evaluation period due to the high TBF value. Discussion about Business interruption results that may seem of little use will be provided in the next chapter.

## 5. Discussion

After all the results for each case are presented, a summary to understand the main differences between the three different maintenance plans is given in Table 14.

Table 14 - Results summary

Case study	Accepted financial consequences	Number of planned inspections (vessel)	Safety issues	Business interruption
1	375250 \$	1	<p>“Third party” and “Second party” risk is not acceptable in some areas around the facility</p> <p>Risk for the operators inside the facility is not acceptable if the exposition is not limited</p>	One failure given by the simulation with different outage periods
2	197500 \$	2	Similar to the Case 1	One failure given by the simulation with different outage periods
3	79000 \$	6	<p>“Third party” and “Second party” risk is not acceptable in smaller areas than in the first case.</p>	No failures in the simulations due to the high TBF

Results found are addressed only to one vessel and its PRV but, if the methodology is applied to a whole facility, significative differences would be present between different maintenance plans. However, it was shown that, changing the risk target, maintenance costs (linked to the number of inspections) and safety issues are different for each case.

As an example, as shown before, individual risk contours change from case one to case three allowing to ensure different levels of safety. If we consider that, for example, fire barriers were not

taken into account in the safety analysis, the third case (that in some small areas falls in the unacceptability criteria) could be an option to ensure an acceptable level of safety if the appropriate physical and organisational barriers are applied. This may not be possible in case one where unacceptable areas have a greater extension.

Regarding the business interruption, results show little difference between Case 1 and Case 2 mainly because the risk targets are not so different and then the TBFs compared to the evaluation period are relatively high. In the third Case, the analysis showed no business interruption due to the high TBF. Limitations about the works' specific application are linked to the fact that only one vessel and its PRV were considered: failures and consequent outage days linked to only one equipment are not enough to perform a significative business interruption analysis. It was shown, however, that elaborating RBI output properly, it is possible to conduct this analysis.

Conducting the analysis considering all the equipment would be useful to take planning decisions other than optimise maintenance. RBI provides a risk-based maintenance that can also take into account the results given by each inspection: the maintenance plan changes basing on these results and this allows to better optimise the number and timing of inspections in the long term.

Benefits of the methodology presented and applied in this work are that it is possible to start selecting different risk targets that the company would accept and then check all the safety issues and the business interruption risks. This allows to take a strategic decision not only based on a fixed financial target but taking into account different aspects. As it was shown, once different plans are performed, a closer look on safety and expected incomes is possible and this could help with the company strategic decisions: if an RBI methodology is applied alone, only the financial risk and number of inspections are the parameters that can be considered.

### 5.1 Limitations and further work

Some limitations can be found regarding the methodology itself: once the inspection plan is performed by an RBI methodology that is proven and validated, one aspect is not taken into account considering the LoFs of the selected scenarios. "If excessive inspection is applied, the level of risk may even go up because invasive inspections can cause additional deterioration such as inspection damage to protective coatings" (API, API recommended practice 580: Risk-Based

Inspection, 2009) and this means that, for example, in Case 3, the high number of inspection could lead to an increase of the Lofs that the methodology is not able to consider.

Another limitation regards the Business Interruption model: Synergi RBI gives as output likelihoods of failure even if it could calculate probabilities according to API recommended practices: using likelihoods in a simulation model decreases its power to give more confident results.

Limitations about the model application are instead addressed to the system boundaries that include only one vessel and its PRV: this limits safety and business interruption differences between the three cases. The lack of previous inspection data and construction details of the equipment, on the contrary, lead to less confident LoFs data.

The previous mentioned limitations regarding the methodology lead to possible further work: it would be interesting to implement Sinergy RBI with the ability to show not only likelihoods but also time-dependent probabilities of failures to use in the business interruption analysis; Another possible implementation of the methodology could be a more detailed business interruption tool using a detailed model of the system able to show the failure links between every equipment ( e.g. series and parallel) and in which individual probability of failure distributions from an improved RBI software could be used for each equipment.

## 6. Conclusions

Hydrogen fuel is one of the practicable options to reach the global goal of no greenhouse gas emissions: if hydrogen FCVs will gain their place in the transport sector, a huge network of new refuelling stations will be created worldwide.

In the thesis work, an important part of a facility management (in particular Hydrogen refuelling stations) such as maintenance was considered and analysed: a new approach to take inspection planning decisions was proposed. In addition to the validated RBI methodology, a more complete approach to the planning problem was developed considering safety issues and business interruption in a more detailed way. After the methodology development, a description about all the steps that need to be performed was proposed.

A refuelling station with hydrogen production by electrolysis on site was chosen in order to show the applicability of the methodology, focusing on the storage unit and in particular on one pressure vessel and its PRD.

The application of the method allowed to show that it is possible to obtain risk and business interruption metrics, modelling potential accident scenarios and understanding how the profit is influenced by maintenance and accidents shutdowns. It was shown that there is the possibility to support decision-making by prioritizing maintenance for equipment with higher risk (thanks to RBI methodology) but also assuring necessary safety levels and considering related business interruption costs: through the analysis of different options it is possible to select the best maintenance plan according to the management objectives and standards basing the choice on the safety and business interruption analysis.

The proposed methodology could be also improved through a more detailed Business Interruption model and the creation of a “merging tool” in order to connect the three different software. As a matter of fact, it was shown that, with a not so complicated elaboration of the RBI output, it is possible to conduct a more complete safety and business analysis: it would be then not so difficult to improve an RBI software with such analysis details.

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## Attachment A

In order to understand the Discharge and Consequences data, the position of the origin of the reference system is defined: it coincides with the pressure vessel (green dot pointed by the yellow arrow in the following map).



Complete Input and Consequence data for the “large leak” scenario are provided below as an example.

# Input Report

## Workspace: safeti case 1

### Study

Study  
safeti case 1

Tab	Group	Field	Value	Units
Material	Modelling of mixtures	Multi or pseudo-component modelling	PC modelling	
Bund, building and terrain	Terrain and bund definition	Type of terrain for dispersion	Land	



		Type of pool substrate and bunds	Concrete, no bund	
Toxic parameters	Indoor toxic calculations	Specify the downwind building type	Unselected	
		Building type (downwind building type)	Buildings\Building type	
Dispersion	Distances of interest	Distances of interest		m

## Pressure vessel

Pressure vessel

safeti case 1 society\Study

Tab	Group	Field	Value	Units
Material	Material	Material	HYDROGEN	
		Specify volume inventory?	No	
		Mass inventory	5,1315	kg
		Volume inventory	0,348218	m3
		Material to track	HYDROGEN	
		Type of risk effects to model	Flammable only	
	Phase	Specified condition	Pressure/temperature	
		Temperature	15	degC
		Pressure (gauge)	200	bar
		Fluid state	Vapour	
		Liquid mole fraction	0	fraction

	Modelling of mixtures	Multi or pseudo-component modelling	PC modelling	
Scenario	Pipe dimensions	Pipe length		m
	Release location	Elevation	1	m
		Tank head	0	m
	Direction	Outdoor release direction	Horizontal	
		Outdoor release angle	0	deg
Discharge parameters	Model settings	Atmospheric expansion method	DNV GL recommended	
		Phase change upstream of orifice?	Disallow liquid phase change only (metastable liquid)	
	Droplet break-up mechanism	Droplet break-up mechanism - instantaneous	Use flashing correlation	
		Droplet break-up mechanism - continuous	Do not force correlation	
Short pipe	Pipe characteristics	Pipe roughness	0,045	mm
	Frequencies	Frequency of bends in pipe	0	/m
		Frequency of couplings in pipe	0	/m
		Frequency of junctions in pipe	0	/m
	Frequencies of valves	Frequency of excess flow valves	0	/m
		Frequency of non-return valves	0	/m
		Frequency of shut-off valves	0	/m

	Velocity head losses	Excess flow valve velocity head losses	0	
		Non-return valve velocity head losses	0	
		Shut-off valve velocity head losses	0	
Time varying releases	Modelling of time-varying leaks and line ruptures	Vacuum relief valve	Operating	
		Vacuum relief valve set point	0	bar
	Inventory data for time-varying releases	Tank volume	0,348218	m3
		Tank vapour volume	0,348218	m3
		Tank liquid volume	0	m3
		Tank liquid level	0	m
		Maximum vapour release height		m
		Minimum mass inventory	0,1	kg
		Maximum mass inventory	1E+09	kg
	Safety system modelling for time-varying releases	Safety system modelling (isolation and blowdown)	No	
Dispersion	Dispersion scope	Concentration of interest		ppm
		Averaging time for concentration of interest		

		Specify user-defined averaging time	No	
		User defined averaging time		s
	Distances of interest	Distances of interest		m
	Averaging time for reports	ERPG [1 hr]	No	
		IDLH [30 mins]	No	
		STEL [15 mins]	No	
Bund, building and terrain	Terrain and bund definition	Type of terrain for dispersion	Land	
		Type of pool substrate and bunds	Concrete, no bund	
	Building definition	Release building		
		In-building release?	Outdoor	
		Building wake effect	Roof/lee	
		Wind or release angle from North	0	deg
		Handling of droplets	Trapped	
		Indoor mass modification factor	3	
Explosion parameters	Explosion method (Consequence calculations only)	Explosion method	Multi-Energy: Uniform confined	
	Ignition	Supply late ignition location	No ignition location	
		Location of late ignition		m

	Vapour liquid method	Use explosion mass modification factor	Yes	
		Explosion mass modification factor	3	
Fireball	Result types to calculate	Calculate probit	No	
		Calculate dose	No	
		Calculate lethality	No	
	Radiation levels	Number of input radiation levels	3	
		Intensity levels	4; 12,5; 37,5	kW/m2
		Probit levels	2,73; 3,72; 7,5	
		Dose levels	1,27E+06; 5,8E+06; 2,51E+07	
		Lethality levels	0,01; 0,1; 0,99	fraction
	Parameters	Mass modification factor	3	
		Fireball maximum exposure duration	20	s
	Calculation method	Fireball model	Martinsen time varying	
		TNO model flame temperature	1726,85	degC
Jet fire	Jet fire method	Jet fire method	Cone model	
	Result types to calculate	Calculate probit	No	
		Calculate dose	No	
		Calculate lethality	No	

	Radiation levels	Number of input radiation levels	3	
		Intensity levels	4; 12,5; 37,5	kW/m2
		Probit levels	2,73; 3,72; 7,5	
		Dose levels	1,27E+06; 5,8E+06; 2,51E+07	
		Lethality levels	0,01; 0,1; 0,99	fraction
	Parameters	Rate modification factor	3	
		Jet fire maximum exposure duration	20	s
	Cone model data	Crosswind angle	0	deg
		Horizontal options	Use standard method	
		Correlation	Recommended	
		Flame-shape adjustment if grounded	Yes	
	Surface emissive power	Calculation method for surface emissive power	Calculate SEP	
		Flame emissive power		kW/m2
		Emissivity fraction		fraction

## Large Leak

Leak

safeti case 1 \Study\Pressure vessel

Tab	Group	Field	Value	Units
Scenario	Hole	Orifice diameter	88	mm

		Use specified discharge coefficient?	No	
		Discharge coefficient		fraction
	Release location	Elevation	1	m
		Tank head	0	m
	Direction	Outdoor release direction	Horizontal	
		Outdoor release angle	0	deg
Material	Material	Material characteristics	Flammable only	
		Material to track	HYDROGEN	
		Type of risk effects to model	Flammable only	
	Phase	Phase to be released	Vapour	
Discharge parameters	Model settings	Atmospheric expansion method	DNV GL recommended	
		Phase change upstream of orifice?	Disallow liquid phase change only (metastable liquid)	
	Droplet break-up mechanism	Droplet break-up mechanism - continuous	Do not force correlation	
Dispersion	Dispersion scope	Concentration of interest		ppm
		Averaging time for concentration of interest		
		Specify user-defined averaging time	No	
		User defined averaging time		s
	Distances of interest	Distances of interest		m

	Averaging time for reports	ERPG [1 hr]	No	
		IDLH [30 mins]	No	
		STEL [15 mins]	No	
Bund, building and terrain	Terrain and bund definition	Type of terrain for dispersion	Land	
		Type of pool substrate and bunds	Concrete, no bund	
Explosion parameters	Explosion method	Explosion method	Multi-Energy: Uniform confined	
	Ignition	Supply late ignition location	No ignition location	
		Location of late ignition		m
	Vapour liquid method	Use explosion mass modification factor	Yes	
		Explosion mass modification factor	3	
Fireball	Result types to calculate	Calculate probit	No	
		Calculate dose	No	
		Calculate lethality	No	
	Radiation levels	Number of input radiation levels	3	
		Intensity levels	4; 12,5; 37,5	kW/m <sup>2</sup>
		Probit levels	2,73; 3,72; 7,5	
		Dose levels	1,27E+06; 5,8E+06; 2,51E+07	
		Lethality levels	0,01; 0,1; 0,99	fraction
	Parameters	Mass modification factor	3	
		Fireball maximum exposure duration	20	s
	Calculation method	Fireball model	Martinsen time varying	



		TNO model flame temperature	1726,85	degC
Jet fire	Jet fire method	Jet fire method	Cone model	
	Result types to calculate	Calculate probit	No	
		Calculate dose	No	
		Calculate lethality	No	
	Radiation levels	Number of input radiation levels	3	
		Intensity levels	4; 12,5; 37,5	kW/m2
		Probit levels	2,73; 3,72; 7,5	
		Dose levels	1,27E+06; 5,8E+06; 2,51E+07	
		Lethality levels	0,01; 0,1; 0,99	fraction
	Parameters	Rate modification factor	3	
		Jet fire maximum exposure duration	20	s
	Cone model data	Correlation	Recommended	
		Horizontal options	Use standard method	
		Flame-shape adjustment if grounded	Yes	
	Surface emissive power	Calculation method for surface emissive power	Calculate SEP	
		Flame emissive power		kW/m2
		Emissivity fraction		fraction

# Consequence Summary Report

## Workspace: safeti case 1

### Study: Study

#### Summary Basis

These tables will only report global values set in the parameters. Values that are modified in the study tree will not be reported.

The report is context sensitive, and filters up to the study level. You will need to generate multiple summary reports if you have multiple studies in your workspace.

#### Discharge Results (after atmospheric expansion)

Path	Scenario	Weather	Peak Flowrate [kg/s]	Temperature [degC]	Liquid mass fraction in material [fraction]	Droplet diameter [um]	Expanded diameter [m]	Velocity [m/s]	End time of release [s]
Study\Pre ssure vessel	Large Leak	Catego ry 1.5/F	64,227 7	-132,209	0	0	0,4728 59	2100, 3	0,0798 955
		Catego ry 1.5/D	64,227 7	-132,209	0	0	0,4728 59	2100, 3	0,0798 955
		Catego ry 5/D	64,227 7	-132,209	0	0	0,4728 59	2100, 3	0,0798 955

#### Dispersion Results

##### Input dispersion parameters

Core averaging time	18,75	s
Flammable averaging time	18,75	s
Toxic averaging time	600	s
Height of interest	0	m

### Distance downwind to defined concentrations

The reported concentration of interest is defined at the scenario

Path	Scenario	Weather	Distance to UFL [m]	Distance to LFL [m]	Distance to LFL fraction [m]
Study\Pressure vessel	Large Leak	Category 1.5/F	n/a	36,5442	48,7496
		Category 1.5/D	n/a	47,9993	60,8132
		Category 5/D	n/a	50,5951	65,4481

### Jet Fire Results

#### Distance downwind to defined radiation levels

The reported radiations are defined in the parameters

Path	Scenario	Weather	Flame length [m]	Distance downwind to intensity level 1 (4 kW/m <sup>2</sup> ) [m]	Distance downwind to intensity level 2 (12,5 kW/m <sup>2</sup> ) [m]	Distance downwind to intensity level 3 (37,5 kW/m <sup>2</sup> ) [m]
Study\Pressure vessel	Large Leak	Category 1.5/F	83,9413	152,645	118,37	95,9744
		Category 1.5/D	83,9413	152,645	118,37	95,9744
		Category 5/D	86,3797	152,544	119,766	98,7615

### Fireball Results

#### Distance downwind to defined radiation levels

The reported radiations are defined in the parameters

Path	Scenario	Weather	Fireball diameter [m]	Distance downwind to intensity level 1 (4 kW/m <sup>2</sup> ) [m]	Distance downwind to intensity level 2 (12,5 kW/m <sup>2</sup> ) [m]	Distance downwind to intensity level 3 (37,5 kW/m <sup>2</sup> ) [m]
Study\Pressure vessel	Large Leak	Category 1.5/F	10,0041	44,1787	25,2835	14,3808
		Category 1.5/D	10,0041	44,1787	25,2835	14,3808
		Category 5/D	10,0041	44,1787	25,2835	14,3808

## Flash Fire Results

### Distance downwind to defined concentrations

The reported LFL and LFL fraction are defined in the respective material property

Path	Scenario	Weather	Distance downwind to LFL [m]	Distance downwind to LFL Fraction [m]
Study\Pressure vessel	Large Leak	Category 1.5/F	36,5442	48,7496
		Category 1.5/D	47,9993	60,8132
		Category 5/D	50,5951	65,4481

### Maximum distance to LFL fraction at any height

Path	Scenario	Weather	Max flash fire distance [m]	Height of the max flash fire distance [m]	Time [s]
Study\Pressure vessel	Large Leak	Category 1.5/F	51,5145	2,16129	2,41304

		Category 1.5/D	66,1049	4,17104	4,22749
		Category 5/D	71,7661	3,97097	4,27021

## Explosion Results

Explosion scenarios for worst-case maximum downwind distance to defined overpressures. The worst-case explosion will be modelled in the risk calculations if ignition conditions are present at the time for the scenario.

The reported overpressures are defined in the explosion parameters

Path	Scenario	Weather	Overpressure level [bar]	Maximum distance [m]	Diameter [m]
Study\Pressure vessel	Large Leak	Category 1.5/F	0,02068	140,553	181,105
			0,1379	67,5995	35,199
			0,2068	63,1955	26,3909
		Category 1.5/D	0,02068	143,743	167,487
			0,1379	76,2761	32,5521
			0,2068	72,2032	24,4064
		Category 5/D	0,02068	144,955	149,91
			0,1379	84,568	29,136
			0,2068	80,9225	21,8451

## Supplementary data for worst-case explosion scenarios

Path	Scenario	Weather	Overpressure level [bar]	Explosion flammable mass [kg]	Ignition time [s]	Ignition source [m]	Cloud centre [m]	Explosion centre [m]
Study\Pressure vessel	Large Leak	Category 1.5/F	0,02068	3,41859	1,9833	50	35,37	50
			0,1379	3,41859	1,9833	50	35,37	50
			0,2068	3,41859	1,9833	50	35,37	50
		Category 1.5/D	0,02068	2,70392	3,1688	60	51,73	60
			0,1379	2,70392	7	60	99	60
			0,2068	2,70392	3,1688	60	51,73	60
		Category 5/D	0,02068	2,70392	3,1688	60	51,73	60
			0,1379	2,70392	7	60	99	60
			0,2068	2,70392	3,1688	60	51,73	60

					3,1688		51,73	
					7		99	

Categor	0,02068	1,93886	3,8327	70	63,33	70
y 5/D	0,1379	1,93886	1	70	11	70
	0,2068	1,93886	3,8327	70	63,33	70
			1		11	
			3,8327		63,33	
			1		11	