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Review of Current Methodologies for Handling Risk in an Eternal Perspective, with Suggestions for Improvements

Master Thesis

Offshore Technology
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Abstract

At the heart of traditional risk assessment and risk management lies the notion that analytic tools are able to predict the future. There are, however, activities where risk is considered over long time frames, theoretically eternal, for which the future is truly unpredictable. This thesis reviews the methodologies and regulations of three activities where a safe strategy is needed for handling hazardous materials, with extreme consequences that could occur in a far future. These activities are: i) permanent nuclear waste disposal, ii) plugging and abandonment of wells in the oil and gas industry, and iii) carbon dioxide sequestration in deep geological formations.

The thesis is based on an understanding of risk as a combination of the consequences of an activity, with associated uncertainty, which goes beyond traditional probabilistic thinking about risk, and also includes the knowledge and surprise dimensions of risk. Current risk assessment and risk management of the three above-mentioned activities are reviewed with this new risk concept in mind, resulting in concerns about the effectiveness of currently used methods. In particular, concerns are raised related to the effectiveness of the current methodologies to see, study, plan and act in the occurrence of unforeseen events. Suggestions for improvements are given, aiming to provide more adaptive risk assessment and risk management strategies, and building resilience towards unexpected events.

Key words: Risk, Risk Assessment, Long-term perspective, Deep uncertainties, Deviations, Unforeseen Events

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List of Abbreviations

ALARP	As Low As Reasonably Practicable
BRC	Blue Ribbon Commission
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
DNV GL	Det Norske Veritas Germanischer Lloyd
P&A	Plugging and Abandonment
FEP	Features, Events and Processes
HSE	Health, Safety and Environment
IAEA	International Atomic Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
NCS	Norwegian Continental Shelf
NEA	Nuclear Energy Agency
NORSOK	Norsk Sokkels Konkuranseposisjon
NRC	Nuclear Regulatory Commission
PRA	Probabilistic Risk Assessment
PSA	Norwegian Petroleum Authority
PSAs	Probabilistic Safety Assessment
RM	Risk Measures
SoK	Strength of Knowledge

Chapter 1

1. Introduction

1.1. General

It was in 1982 that the United States Congress first established a policy for the handling of nuclear waste disposals at a national level. Since then, a lot of concerns have been raised about the effectiveness of these policies, and alternative solutions for storing nuclear waste in the long term have been proposed. In 2015, plans to permanently store nuclear waste underneath Yucca Mountain in Nevada were put on hold by President Barack Obama due to insecurities and societal constraints related to the storage location and method. Thus, the site, which has been considered since 1978 as a potential long-term geologic repository for over 70,000 metric tonnes of nuclear fuel waste, is now temporarily abandoned. It seems that the permanent disposal of hazardous energy fuels remains a thorn in the side for the development and safety policies of many countries. A comprehensive, safe and publically acceptable plan is still needed.

Moreover, at the 2015 United Nations Climate Change Conference held in Paris, 195 countries agreed to reduce CO_2 emissions as a part of their efforts to mitigate the greenhouse effects (Chappell, 2015). Though the Paris Agreement is not a firm commitment between the countries, it shows that thoughts and efforts are being focused on ways to reduce emissions and on means to store existing greenhouse gases. Energy source cannot be changed instantly from highly CO_2-emitting (like oil and gas, coal, etc.) to low CO_2-emitting and renewable resources. Countries like Norway have been processing and storing the CO_2produced by oil and gas operations for many years. This is mainly done by injecting CO_2into the subsurface and storing it under thick layers of soil and shale rock. However, knowledge about the effectiveness of the solution in the long term is poor, and the potential hazards inherent in the process are still unclear.

The risks and uncertainties involved in subsurface storage of both nuclear waste and CO2 are also relevant to the plugging and abandonment (P&A) of wells during the decommissioning phase of oil and gas fields. Operators must ensure that no hazardous emissions or leakages will ever occur in the future, from wells that have already been operated for decades. More and more fields, especially in North Sea, have become mature and costly for operators, resulting in cessation of production. It is estimated that, during the next fifteen years, around 30,000 wells will require P&A globally (Ouyang & Allen, 2016). Therefore, the need for a robust methodology for handling long-term risks related to such operations is urgent. DNV GL recently published a guideline for Risk Based Abandonment of Offshore Wells, with the aim to change the current perspective procedure to a more risk and performance based approach, in line with the traditional risk based standards (DNV GL, 2015).

All the above mentioned problems and challenges that operators face require a deep understanding of risk in a long term perspective. One needs to take one step back and ask some basic questions: What is meant with risk in a long term perspective? How does the time-frame of the activities or processes influence risk assessment from an assessor's perspective? How can risk analysts improve the validity of their assessment and enable more confidence that solutions are safe?

One main tool that is broadly used in industries to assess and quantify risk is probabilistic risk analysis. It has been a tradition for operational risk assessments, which handle relatively short term threats, to use frequentist probabilities. A frequentist probability of an event A, is interpreted as an expression of the fraction of times the event occurs when considering an infinite population of similar situations or scenarios to the one analyzed. However, in order to use such tools one needs to be confident that the conditions and the assumptions that the probabilities are based on, are stable. There are operations, like those mentioned above, which are characterized by great complexity, poor knowledge, limited experience and lack of historical data. In such cases, it may not be sensible to envision a sequence of similar situations, and risk descriptions in terms of frequentist probabilities are not suitable. In view of poor knowledge, it may even be difficult to justify assigning subjective probabilities to express 'degree of belief' about future consequences. These deep uncertainties make an assessor's job difficult when it comes to predicting and preparing for hazardous events in the far future.

Aven (2014) and N. Taleb (2010) have both examined activities with deep uncertainties, where surprising and potentially high-impact events, so called 'black swan' events, can occur. A black swan is defined in risk terminology as a surprising extreme event relative to the present knowledge/ beliefs (see Appendix B). The industries that face these concerns range from pharmaceutical companies, which supply the market with vaccines for new diseases, to nuclear power and oil and gas companies, as mentioned before. Although these fields are mature regarding the operation and production phase, they are young with regard to the waste disposal and handling. Scientists in these fields only have experience and historical data from a relative short term period, compared to the time span of the risk of concern. No one can tell for sure what the future consequences of those activities will be and what the threats that next generations will face are.

So, this raises a question about the risk management procedures of those activities. Generally, regulations on such operations are generic and prescriptive, applied uniformly to all cases. Deep geological disposal and capture has been the dominant solution, as mentioned before. However, it has been recognized recently that this solution is not without problems; it is known that concrete containers or plugs used for containment will not stand for eternity. Radioactive or oil and gas leakages will occur under external or internal loads such as tectonic movements and reservoir pressure increase. The long term hazards should not be overlooked by the current decision procedures (Louberge, et al., 2001).

In theory, the aforementioned uncertainties of those operations are called epistemic and are related to the lack of knowledge about the phenomena involved. Frequentist probabilities are not appropriate for such problems, and non-traditional techniques need to be applied in order to assess such risks. A more integrated perspective and new way of thinking about risk is needed A risk based approach using subjective probabilities and a more adaptive methodology could solve some of issues related to the dynamic nature of the examined risk. A more hybrid approach, which combines quantitative and qualitative techniques, could handle uncertainties related to long term consequences (Flage, et al., 2014). Analysts should include the time aspect in their risk assessment and must acknowledge the deep uncertainties in order to focus on how to handle unforeseen consequences.

1.2. Purpose

The purpose of the thesis is to review and discuss existing approaches and methods for assessing and handling risk in a long time perspective. This will not be done only by literature review of current theoretical methodologies, but also reviewing current regulations and standards for nuclear disposal management, plugging and abandonment of oil and gas wells and CO_2 injection.

The main aim of the review is to address the unique concerns related to risk in an eternal perspective and identify any inefficiency. After the concerns are raised and analyzed the aim is to give suggestions for improvement.

1.3. Preface

Chapter 2 describes real cases where long term risk is an issue. Focus is on three activities: permanent nuclear disposal, oil and gas plugging and abandonment in offshore wells and carbon capture and storage. Apart from some general information about the nature and the hazards of the operations, a brief review of the standards and the regulations of the activities is the focus of this chapter. For further details and more technical information, the reader is referred to Appendix A.

In Chapter 3, a short review of the current risk perspective is made, Focus is on both theoretical interpretation and practical implications, where emphasis is put on the knowledge and surprise dimension of risk. Some aspects of risks are 'hidden' by assumptions made during risk assessments and may easily be overlooked by the risk analysts. A hierarchical breakdown of the risk concept based on (Hafver, et al., 2015) is described which can help expose such 'hidden' risks.

Chapter 4 focuses on describing risk in an eternal perspective or over a relatively long time period. This is achieved through a search of existing literature, using key words: "long-term risk", "deep uncertainties", "black swans" etc. Here, it is explained also why unforeseen events should not come as a surprise in long term perspective. Additionally, many deviations from the initial risk assessment are expected and those are addressed thoroughly in this chapter.

Chapter 5 consists of two parts: The first sums up the information gathered from the review and the analysis on the previous chapters and highlights the gaps and the inconsistencies on which focus should be given. The second part of the chapter presents some suggestions, which aim to add value to the current methodologies of handling risk in an eternal perspective.

In Chapter 6, the conclusions of the review and the analysis are presented. Additionally, suggestions for further investigation and research are given.

The terminology used in the thesis is summarized in Appendix B. The reader is referred to this section when the meaning of the terms used in the discussion or the analysis, is not clear.

Chapter 2

2. Review of operations where risk is considered in an eternal perspective

2.1. General

In all aspects of life, nature and humans are constantly interacting. On one hand nature influences humans with its phenomena and on the other hand humans affect environment with their operations. These operations include risks with their consequences, which can be either instantly visible by those operating and the surrounding influenced stakeholders or they can be witnessed after many decades have passed. For example, in an industrial area where vessels are manufactured equipment might fall during operations injuring workers. Excessive noise from day to day operations can disturb the residents in the area. These are examples of operational risks that need to be handled during operation, a short term period. For instance, workers can be required to follow a certain safety procedure, receive proper training, utilize appropriate personal protective equipment, etc. Perhaps barriers might be built in order to protect inhabitants from noise pollution. On the other hand, the carbon emissions from the engines and the chronic effects on workers and the inhabitants in the area are not visible instantly. Companies might take measures and do tests but the long-term consequences are unknown. The long-term impact of any operations to human health is not easily predicted and great uncertainties exist.

This chapter presents some operations as an example of activities where the risks are assessed in a long-term perspective. The aim is to review the current methodologies and regulations that are used today when hazardous events need to be prevented over a long period of time. By doing so, it is possible to identify some of the challenges that occur in the risk assessment when risk based thinking is applied for mitigating hazards.

The first operation involves the nuclear power industry and the long-term management of its radioactive waste. Radioactive waste is extremely dangerous for human health, especially when a significant amount is released to the atmosphere. This is important to risk studies as radioactive waste is closely related to some of the most hazardous accidents in the history, like the Chernobyl accident. The high risk and historic examples, as well as its current relevance make radioactive waste disposal an important case to study in order to point out the many difficulties that need to be worked out by the industries, which are involved in hazardous waste treatment operations. The second example addresses an operation, which is related to the oil and gas industry and has drawn attention from many operators due to the economic recession; the permanent plugging and abandoning (P&A) of wells that were used for the production of hydrocarbons. The operation is linked to risk in an eternal perspective since it aims to isolate and trap the fuel which remains in the reservoir for eternity. The third and last operation which is described is that of carbon capture and storage (CCS). This operation has many similarities to P&A and it relates to risk in an eternal perspective in a sense that it aims to store great amounts of CO_2 in deep geologic formations permanently. However, it is useful to examine CCS as well, in order to identify inconsistencies and gaps between the regulations of the operations and the current risk perspective.

The text focuses on the risk concept of the operations and the way risk is treated by the current regulations. If further technical and detail information is needed, the reader is referred to Appendix A. The information given in this chapter is the background and the basis of the analysis and the discussion of the thesis.

2.2. Nuclear radioactive waste management

2.2.1. General

Nuclear radiation and power has been used for more than 50 years in various industries including medicine, research, military and electricity production. After processing the natural sources and using it for energy production, there comes a point where no more processing is possible. The remaining fuel is highly radioactive and dangerous to both humans and environment. Studies have shown that with current technology for handling this waste, radioactive waste needs thousands of years in order for the radioactivity to be diminished to natural levels (for more detailed information see Appendix A, Figure A 4). So, as the accumulation of hazardous radioactive wastes continues the world asks for permanent and safe radioactive waste management solutions.

2.2.2. Deep geologic disposal

Many ideas for a permanent solution have been suggested, such as deep geological disposal, near surface disposal, storage etc. (see Appendix A, Table A 2). Currently many nations that seek a proper waste treatment program and experts that investigate the problem have concluded that, deep geologic disposal is the most preferable. But, the uncertainties related to the effectiveness of this solution and the lack of acceptance by society keeps this method from being implemented. Based on a review of the current different national policies for handling highly radioactive waste fuel (see Table A 1, Appendix A), there is still no deep geologic permanent disposal facility in operation. Moreover, half of the examined countries prefer to reprocess the radioactive waste than disposing it permanently (see Appendix A, Table A 1). This attitude is in line with the general waste management hierarchy of preference as shown in Figure 1. It is usual that operators prefer to reuse, recycle, recover or avoid generating the waste than try to make a plan for permanent disposal.

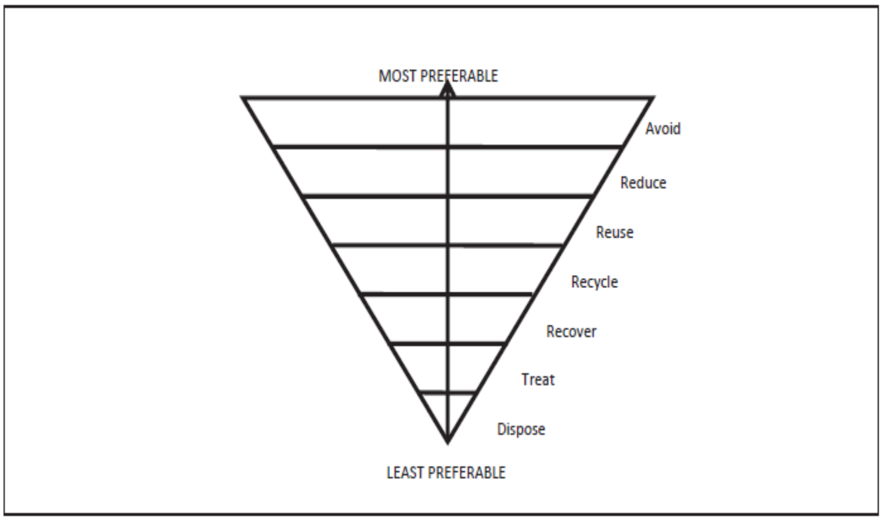


Figure 1: Typical waste management hierarchy (NEA, 2010)

However, the in nuclear industry a permanent solution is needed, but the geologic disposal solution, which is the most promising one, is still under discussion. David Wagman (2013) has expressed his concerns regarding the lack of permanent nuclear waste disposal sites (Wagman, 2013). One example which shows that nuclear waste disposal is a policy that has been in trouble for decades is the Obama Administration's decision to halt work on a geologic repository at Yucca Mountain in Nevada (BRC, 2012). The Blue Ribbon Commission on America's Nuclear Future underlines a problematic radioactive waste policy that has tied most U.S programs since 1987, with no timely solutions for handling radioactive waste material. Although all the production processes, from uranium mining to enrichment, are well known, the disposal remains still something of a black box.

2.2.3. Disposal vs. Storage

Let us go one step back and see the issue from a broader perspective, in order to understand the problem that operators face and judge the adequacy of the solution. Firstly, it is important to understand what it is meant by disposal and how it is different from storage. Disposal, as part of the final step in the procedure of waste management, is long term isolation of the waste (BRC, 2012). It relies on the passive operation of natural environmental and human made barriers that does not let humans to access the waste after the final positioning (BRC, 2012). That means that there is no need of continuous maintenance by humans. On the other hand, storage is supposed to be an intermediate stage in waste management that permits human access in order to manage waste for its later permanent disposal.

2.2.4. Current risk assessment and management methods

According to the Nuclear Regulatory Commission (NRC), after the position of the disposal is chosen, risk assessment of the potential nuclear plant can be based on a performance assessment of the disposal site (NRC, 2015). In terms of radioactive waste disposal, a performance assessment would mean a quantitative assessment of the potential leakages of radioactivity from the chosen isolated geologic formation into the environment. This performance assessment uses a model or a collection of models in order to estimate potential leakages and the impact of the radiation on local population. The primary objective of this assessment is to prove that the chosen disposal solution fulfills its purpose. In order to accomplish that four factors are assessed (NRC, 2015):

- Selected scenario (the environment, features and process on the area that is selected the waste to be disposed)

- Performance of the cask or other engineered barrier system used to store radioactive waste, limit the influx of water and reduce the release of radionuclides

- Release and migration of radionuclides through the engineered barrier system and geosphere

- Radiological dose(s) to the selected receptor groups

The NRC's concept of risk (NRC, 2015) is based on the two dimensional combination of the probability of an accident to occur and the related consequences. In other words, in order to understand and assess risk they examine three questions: 1) What can go wrong? 2) How likely is it? 3) What would be the consequences? However, they recognize that it is not possible for models and computers to capture every aspect of risk and replicate accurately all the phenomena of a realistically complex facility system. Therefore, in the nuclear industry, risk assessors use abstraction to simplify all the data that need to be used in the assessment. The level of abstraction reflects the level of uncertainty, needs of improvement in reliability aspects or other issues such as making models and results understandable to people. Nonetheless, since both the geologic formations and the processes create a complex system, it is essential the models and the assessment are detailed enough in order to provide valid results.

Here it is worth mentioning, that an additional complex risk assessment factor is the time dimension and the long-term perspective of the assessment. Through the glasses of risk assessment and management, in waste disposal operations, one needs to handle the risks of a potential leakage and migration of radioactive fuel to the environment for the lifespan of the radioactive material. This means wastes should be isolated for a long period until the level of radioactivity is as low as that of natural sources and that the risk assessment which is executed “today” should address a long period of time. Risk assessors should use the knowledge they have to predict what the future consequences of the activity would be. Since the current solution is disposal, the risk measures should be effective in an eternal risk perspective theoretically. This is extremely challenging in practice. So, regulations today suggest prescriptively to define the examined time span of risk as 1,000 years and uses predefined radioactive limits as the objective.

The suggested storage option of radioactive waste is to seal the waste at depths of thousands of meters and under many layers of rock formations (see Appendix A, Figure A 3). The decision of the waste process to be followed is made in a higher level according to snational legislation, national authorities' requirements, international and national standards and international agencies' recommendations. For example, IAEA standards for the disposal of radioactive waste set out the essential requirements that need to be followed by the organizations throughout the disposal process (IAEA, 2011). Those cover all the phases and aspects of the disposal process, from the planning and designing phase to the posterior of the closure of the disposal facility. Therefore a classification of the waste is done in order for the best solution to be found.

Each step of the current waste classification process is based on some assumptions. Those are related to the effectiveness of the manmade barriers to capture radioactivity but also the natural processes and the interaction between the environment and the waste. One example is the assumed impact to humans by radiation. Since no human interaction is required, the system of the barriers and the environment is supposed to interact passively in order to mitigate the risks. Those assumptions are based on the way humans understand nature and physics today. They are also related to risk assessments that use scenarios, probabilities and associated consequences. For example, during the lifetime of a nuclear facility and the power plant operations, safety is examined using probabilistic risk assessments (PRA). In international regime the probabilistic safety assessment (PSA) is broken down in three levels: Level 1 PSA examines the design and the operation of the facility by analyzing the systems and the procedures of the plant. Level 2 PSA informs about accidents and ways to mitigate those by implementing safety measures and barriers. Level 3 PSA is related to societal aspects and public health (IAEA, 2011).

However, in contrast to the general waste storage processes, where human intervention is possible, it would be meaningless to talk about probabilistic risk assessment in a long time perspective, such as in deep geological disposal practices. IAEA (2011) states that the estimation of radiation exposure doses to humans far into the future could lead to poor results with highly increased uncertainties to their validity. Uncertainties can become so large that acceptance criteria might no longer serve a useful tool for decision making. The standard also talks about an optimization of the risk assessment by using hybrid methodology in a structured qualitative manner, supported by quantitative analysis (IAEA, 2011). It also addresses the uncertainties related to modeling complex environmental systems and their performance over time.

2.2.5. Concerns

The idea of permanent abandonment of the plants without the need of any human interaction implies that there is confidence there will be no need for intervention for a long period of time. But, how valid is that assumption? Who can be certain that all the potential hazards have been identified and well assessed so that the implemented barriers and constraints are efficient over a long time period? Physical processes will eventually consume away the barriers. But, is there certainty about how these processes work and if the current best available solutions are efficient?

One example that highlights this knowledge gap is Washington State's Hanford Site radioactive waste leakage. In short, Hanford Nuclear Reservation Plant contained hundreds of thousands of gallons of nuclear waste using the best available nuclear storage technology, double-shell tanks. However, after almost only twenty years of use a leakage was reported in one of the storage tanks due to a crack on the inner shell. Although the initial estimates of leakage were small, enough to generate no concerns related to a direct human threat, recent photos have shown that the crack has increased in size causing significant amounts of radioactive waste to leak from the inner shell (see Figure 2). The potential consequences to the environment and humans are not clear. The bottom line is that barriers, which are expected to have been functioning for years and are part of the multi barrier system in deep geological disposal designs have deteriorated faster than expected, ultimately performing inadequately. This gives new insights into risk assessment about barrier integrity and the time span that they can be expected to perform efficiently.

Figure 2: Pictures from the AY-102 tank between the inner and outer shells, showing the leaked liquid that has been dried into white radioactive powder. (Wilkison, 2016)

The current assumption is that by the time that barriers fail, the radioactivity of the waste would have decayed to natural levels where no harm is considered for humans and environment anymore. There are events, like earthquakes or tectonic movements, which occur as a surprise and change the risk picture of the disposed facility. Cracks or failures of the barriers might occur without noticing them. So, the absence of monitoring system or emergency retrieval plan can decrease the feasibility of the solution.

Apart from the technical and physical performance concerns of the system, many governments face the problem of public disapproval regarding permanent radioactive waste disposal. The high radioactivity level of the waste, combined with lack of confidence of the public in the government's ability to adequately dispose of this waste, leads to local opposition to any trials of radioactive waste disposal sites. Although the technical community agrees on the geological disposal, this by itself is not enough to gain public confidence. Many argue that the waste management should be adaptable to the new societal situations and technical developments, but also to provide reversibility to the facility without risking long-term safety (NEA, 2010).

In relation to society, decisions around activities, like permanent geological disposal, consider the perceived risk as well as the actual risk. Perceived risk means how risk is considered by the different stakeholders. Societal acceptance of risk is not based only on scientific assessments, but also on the perception of the tradeoff between risk and benefit. Especially in long term perspective, that perception may be altered by global incidents and events. For instance, consider the public attitude towards nuclear power plants after Fukushima accident, where scientists had assessed a tsunami event as an event with negligible probability to occur. Societal confidence that other such accidents with “negligible” probability will be avoided in the future is shaken after the accident. This lack of confidence increases the pressure on governments and operators that consequently might need to implement stricter measures.

The aforementioned concerns related to the nuclear waste disposal are some of the issues that will addressed in the following chapters. The meaning of the fundamental issues, such as risk in an eternal perspective, surprises in a long time span, knowledge and uncertainties will be thoroughly studied. The degree to which permanent radioactive waste disposal is consistent with current theoretical methodologies of handling such risks will also be considered.

2.3. Plugging and abandonment in oil and gas

2.3.1. General

After the end of the production life of an offshore oil and gas field, the operators need to safely abandon the production area. This is an activity that is planned from the early beginning of the project, even before the production of the hydrocarbons has started. Operators need to remove and decommission all the structures used during the operation activities. Plug and abandonment (P&A) of the wells is one of the activities in the decommissioning methodology list (Byrd, Novemebr 2000), but one of the most costly, accounting for the half of the decommissioning cost if a drilling rig needs to be used:

- Project Management & Engineering
- Heavy Lift Vessel mobilization
- Cargo Barge Mobilization
- **Well P&A**
- Platform Removal Preparation
- Pipeline Abandonment
- Conductor Removal
- Platform Removal
- Site Clearance and Verification

- Onshore Disposal

Plugging of the wells is essential in order to control subsurface pressures and prevent hydrocarbons by leaking from reservoir formations to the seafloor. This has to be done according to current regulations for eternity. So, from a risk based perspective P&A differs from the rest decommissioning activities on the fact that during the risk assessment the examined future time period that risks need to be mitigated is very long (theoretically eternal).

P&A of wells in oil and gas industry is a relatively new operation. Nonetheless, having reached the lifetime of 20-50 years in many fields, the need to abandon oil and gas fields as safe as possible has increased. According to estimates, there are around 3,000 wells on Norwegian Continental Shelf (NCS) that will need plugging in the future. If one adds on those the average number of wells that are drilled annually, then the total number of wells that will need to be plugged in 20 years from now on, is close to 6,000 (DNV GL, 2016). Globally, the expected number of wells that need to be plugged grows up to 30,000 for the next 15 years. Therefore, industry needs an effective procedure of plugging and abandoning wells that can handle all the potential risks.

2.3.2. Hazards

The main risks from a plugged and abandoned well are environmental pollution and consequently sea life affection (for further information, see Appendix A). That could occur because of hydrocarbon leakage from the reservoir to the seabed and into the water column. During the production period, human intervention created a direct path from a depth of thousands of meters, where hydrocarbons were sealed for millions of years, to the surface. So, the danger of a blow out and a massive leakage of hydrocarbons increased. Therefore, the current means that are used are based on the idea of reconstructing the previous existing natural formation which has managed to trap the hydrocarbons. Depending on the amount and rate of the leakage, it can influence the environment locally or in a greater extent.

2.3.3. Current Standards and Regulations

The current P&A methodology that is used in Norway is based on designs implemented almost forty years ago and it is defined by NORSOK D-010 standard (NORSOK D-010, 2004). This standard describes prescriptively the number of barriers needed, the location where they need to be placed and the verification tests and criteria that are needed (see Appendix A, Figure A 11). Most of the current regulations in NCS are performance-based where companies have to show that their solutions meet the criteria set by regulators. This approach also stimulates developments of new technologies and innovations that can be implemented if the risk-based criteria can be met.

NORSOK D-010 (NORSOK D-010, 2004) describes methods and additional measures or analyses that need to be executed in order for the risks to be mitigated as low as reasonably practicable (ALARP principle). It is also mentioned that the uncertainties around the design of the barriers in a well abandonment should be accounted for techniques used during the plugging. However, the aforementioned uncertainties are related to activities and design or material factors during the operation of P&A. Considering the long-term risk and the uncertainties, the standard generally mentions that risk should be assessed related to issues such as: long term pressure development of the reservoir, deterioration of the barriers etc. All in all, the regulation concludes to a prescriptive number and size of plugs required. Moreover, the acceptance criteria and the requirements are the same for all types of wells. Obviously, the benefit is that operations and designs are straightforward and clear, but they may be non-effective and costly.

Trying to provide a more cost benefit solution to the industry, DNV GL has recently suggested a new guideline for a more risk based approach of plugging and abandonment of offshore wells (DNV GL, 2015). This provides an alternative solution based on functional requirements and environmental acceptance criteria, which are tailored to each well. The advantages of this approach for the operators are that it has explicit criteria for environmental condition and the P&A focus is given on higher-risk wells. It optimizes well abandonment design and let companies introduce new technologies if needed.

The risk methodology used is based on the ISO 31000 (ISO, 2009), which underlines the importance of establishing the context prior to executing any of the risk assessment processes. Therefore, before assessing wells for plugging and abandonment operators should specify the (inter alia) following input data (DNV GL, 2015):

- Well specific data (well design, well history and current status)
- Geology data (reservoir and overburden condition)
- Environmental data (environmental resource overview)
- Metocean data (ocean current including salinity and temperature profiles)

Those elements of an offshore well abandonment risk assessment are illustrated in Figure 3. Additionally, the guideline gives a categorization of the flow potential for hydrocarbon-bearing formations in order to provide fit-for-purpose design solutions. Those are shown in Table 1 and they are mainly three, considering the actions required, since the first two are treated in the same way. Those are based on acceptance criteria and limits of flow and reservoir pressures.

Table 1: Categorization of Flow Potential for Hydrocarbon-bearing Formations (DNV GL, 2015)

Categories of flow potential	**Definition**
No Flow Potential	Hydrocarbon-bearing formations that does not have moveable hydrocarbons.
Limited Flow Potential	Hydrocarbon-bearing formations where moveable hydrocarbons present or in the future cannot under any circumstances have an environmental or safety impact.
Moderate Flow Potential	Hydrocarbon-bearing formations where moveable hydrocarbons present or in the future may have an environmental impact, but no safety impact.
Significant Flow Potential	Hydrocarbon-bearing formations where moveable hydrocarbons present or in the future may have both an environmental and safety impact.

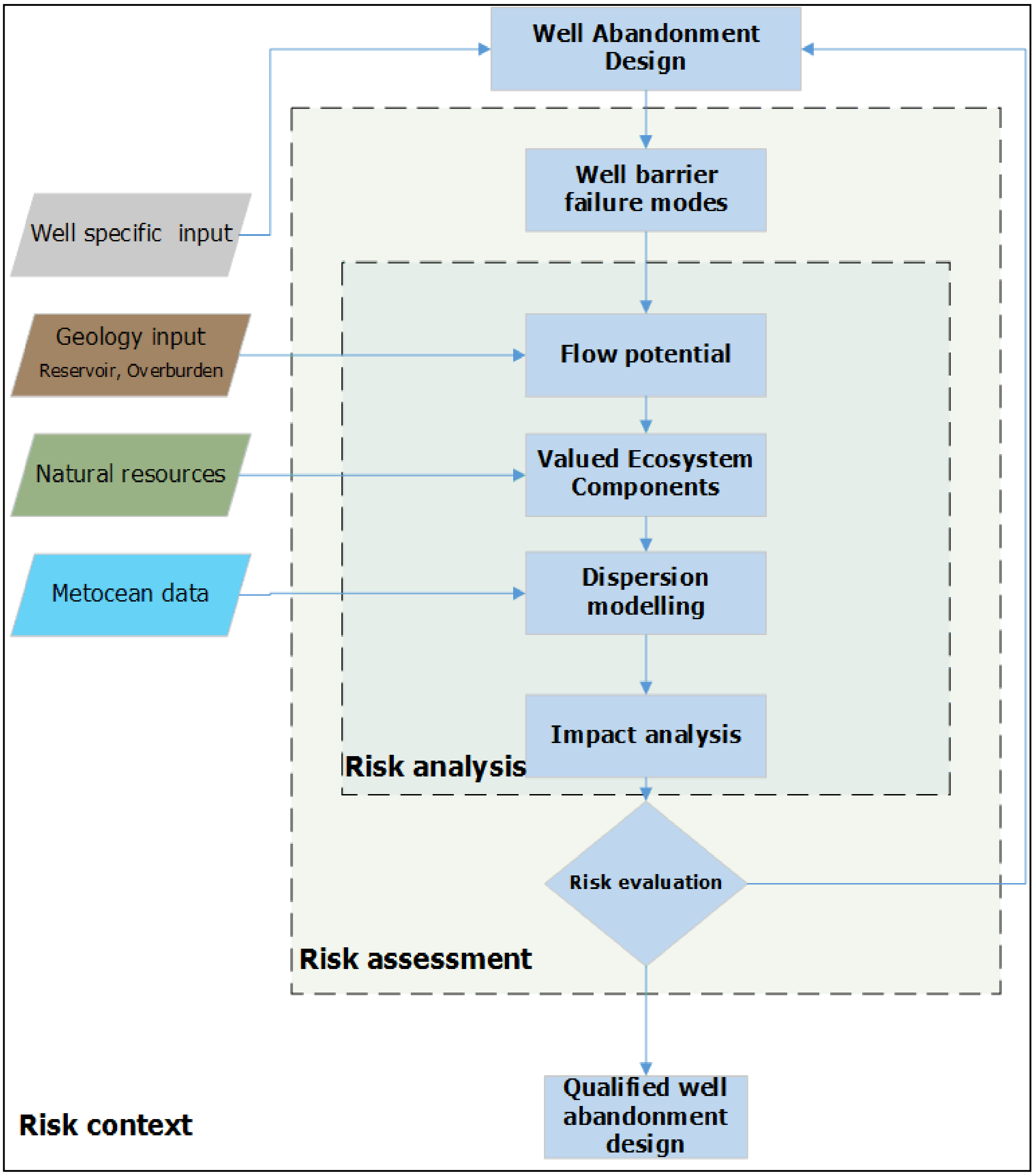


Figure 3: Elements in well abandonment risk assessment (DNV GL, 2015)

2.3.4. Concerns

Regardless the method used for permanent P&A by the industry, the aim remains the same, which is to secure environment in eternity. The used barriers should withstand all the loads and pressures permanently. This requirement itself raises concerns about the validity of those methods. Questions rise on how even the current best available techniques could capture all the uncertainties in such a long time period.

As mentioned previously, NORSOK D-010 (NORSOK D-010, 2004) requires that the plugs would withstand the long-term pressure development and the deterioration of the cement or any other material that is used. So, regarding the aforementioned question one could ask: How can one be sure that the barriers that are used and verified as safe can withstand for eternity, when it is certain that the physical processes will eventually decay those constraints? It seems that the current standards postpone the problem to an unknown time point in the far future.

Moreover, by totally abandoning the wells and leaving the field without monitoring, operators and governments have no indicators of the status of the plugs. No one can tell with certainty that the measures taken initially are still in place. No monitoring about surprising events, like earthquakes and tectonic movements is available to justify that the barriers are still effective.

Generally, there are concerns related to the validity of the choices and the assumptions that are taken today. Think of DNV GL's risk based methodology for instance (see Figure 4). During the risk analysis, the guideline categorizes each well depending on some flow potential criteria, dispersion models and ecosystem factors. All these are based on knowledge, technology and experience at the time of the analysis. Therefore, the assessment is based on assumptions that could change in time. The effectiveness of the measures that were taken could likewise change in time. New technologies can be proven more effective and robust than previous. Since P&A operations are new in oil and gas industry and the consequences of the first plugged wells are not yet observable, the related uncertainties of the validity of the current methodology could be considered weak in some cases.

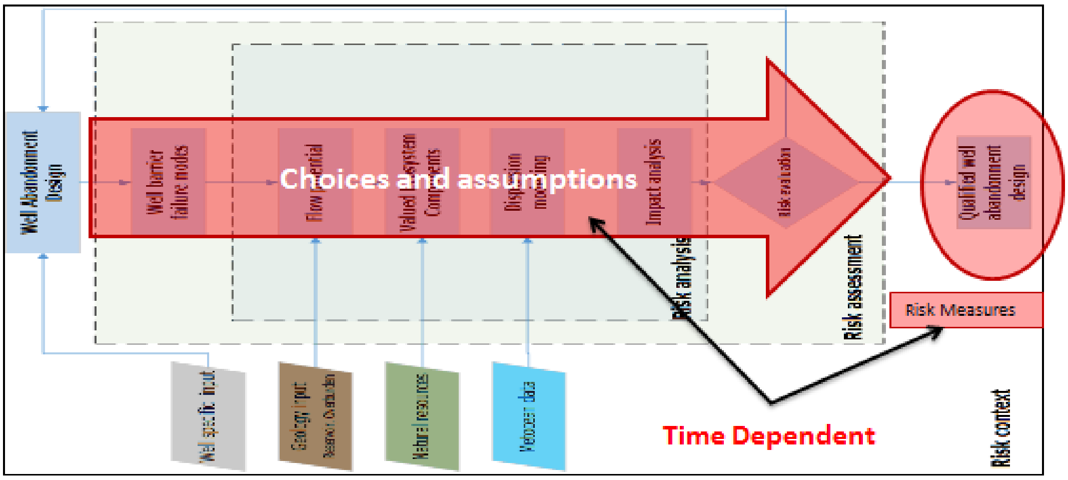


Figure 4: Schematic illustration of the factors in the proposed P&A risk based methodology that is time dependent

Lastly, what is an acceptable level of pollution related to the environment and what is not, is very sensitive. With the global warming concerns to increase and the water natural sources to reduce, societies' and governments' perspective towards P&A activities can change. What it is considered today as acceptable can be unacceptable in the future. Due to climatic changes the environment becomes more and more vulnerable. Friendlier energy solutions become more and more competitive and efficient, increasing the pressure to industries like oil and gas. So, the stringency of the authorities and the society can change.

To conclude, in this chapter P&A of wells in oil and gas industry was presented as an operation where risks are assessed in an eternal perspective. A review of the current methodologies and regulations was done in order to understand how those risks are handled. The DNV GL new proposal was mentioned as the most updated risk based standard that companies could follow in order to meet the requirements. This review gives the opportunity to identify some challenges and raise some concerns from a risk conceptualization, risk assessment and risk management perspective. The aim in this chapter was simply to address those in order to be examined thoroughly in the next chapters.

2.4. Carbon Capture and Storage

2.4.1. General

After the 2015 United Nations Climate Change Conference in Paris and the intergovernmental agreement to reduce global CO_2 emissions, apart from the renewable energy development acceleration, focus is given on how to improve and enhance carbon dioxide capture and storage (CCS) activities. But what is the context of those activities and how are those related to long term risks?

This question constitutes the point of departure for this chapter and, also the need to review the current methodologies that are used in order to handle such risks. The research and the review are based on the IPCC, (2005) (IPCC, 2005) unless otherwise stated.

Main aim of carbon dioxide capture and storage activity is to isolate CO_2 that is produced by industrial activities, like oil and gas refineries, cement production, power plants etc. and trap it permanently so that it is not emitted to the atmosphere. The process circle consists, firstly, of the CO_2 separation and capture. Then, the gas needs to be transported to a storage location. After it has been compressed, it will either be injected into deep geological formations (either offshore or onshore aquifers) or stored in the ocean or in mineral carbonates.

This chapter discusses mainly about the deep geological storage of carbon dioxide. The reason is that the method is currently suggested as the best available solution for retaining great amounts of CO_2 for very long periods of time. Geological storage is a method used broadly in many countries. In the North Sea, it has been used since 1996 at Sleipner field, where there has been stored almost 1Mt CO_2. In other places abroad like in Texas, CO_2 has been injected to recover oil in numerous projects, some of which started in 1970s. Nowadays, several additional storage sites are progressing around the world.

2.4.2. Potentials and increased interest

There are many reasons, which explain this increase of interest and wide credence in the validity of the CCS solution. The level of confidence in the existed technology has increased after years of research and experience. There is also a need of a great variety of alternative options of reducing emissions and balancing greenhouse effect. Moreover, the potentially great amount of CO_2 that can be captured in deep geological sites could make significant cuts to atmospheric emissions. Therefore, it is an attractive solution, which carries also great responsibility, such as to be safe, environmentally sustainable and applicable in a broad sense.

2.4.3. Hazards

However, there are many potential risks that geological storage activities pose to societies and environment, especially in long term; leaking abandoned wells, leakage across barriers or faults on the formations, lack of confinement between layers etc. (for further details, see Appendix A). Some of the questions that need to be answered related to the risk concept around CCS activities are:

- What are the hazards that can occur in the future?
- What are the current methodologies and regulations that govern those activities?
- Are there things that are still blurry and additional knowledge is needed related to risk on a long-term perspective?

The majority of the sites used for capture and storage of CO_2 are depleted oil and gas reservoirs. CO_2 is isolated under the already existing trap formations, either that being saline or salt or others. There are many critical factors that need to be fulfilled in order for a CCS project to be successful, such are: permeability, thickness and extend of reservoir, shape and thickness of the caprock etc. However, even the short history of this activity has shown that hazards exist in the abandonment of the sites. Some projects have leaked mainly due to improper plugging and leaky faults.

An improper abandonment of injection wells can leave wells partially open and let CO_2 migrate upwards to a shallower aquifer polluting the contained water. The impacts for the environment that are arising from the potential CO_2 release can be split into two main categories: local environmental impact and global effects. Those are threats that can influence the ecosystem instantly or in a long term period. Some of those threats but also possible scenarios of leaking are described thoroughly in Appendix A. Here, the main concern is how those risks are handled by the current risk treatment methodologies.

2.4.4. Current standards and regulations

Current standards and regulations regarding plugging and abandonment of CO_2 injection wells are similar to those in traditional P&As; prescriptive requirements of cement barrier lengths and sizes. Risk assessment methodologies focus on the probabilities and the consequences of hazards related to the operational phase of the injection. It is considered an integral part of the risk management activities, the site selection and characterization, the system design, monitoring and in some cases the remediation. There is a diversity of risk assessment methodologies. On the other hand, new suggestions arise in return to new types of problems that are identified. Since it is a new field, no well-established methodology of analyzing storage risks exist.

Many of the ongoing methods focus on the identification, classification and screening of factors that can affect the storage safety and the potential leak paths that can occur. The method used is the known FEP methodology, which examines Features, Events and Processes. In this case, *features* represent parameters like the permeability of the reservoir, the caprock thickness and the number of the injection wells. With saying *events*, it is meant processes such us seismic events, blowouts of the wells due to pressure increase and new well penetration of the site. *Processes* include physical and chemical processes. For example, chemical reactions, multiphase flows and pressure changes due to geomechanical actions.

As it is highlighted in Table 2 and in IPCC, most of the current risk assessments use models based on scenarios, probabilistic and quantitative risk methods, Health Safety and Environment reports applied on specific areas etc. Some of the models are designed to treat uncertainty explicitly. However, it is mentioned that the validity of those models in long-term perspective is low, since our understanding of the behavior of the abandoned wells in a long time span is poor.

Table 2: Current risk assessment models and efforts in CCS risk analysis (IPCC, 2005)

Project title	Description and status
Weyburn/ECOMatters	New model, CQUESTRA, developed to enable probabilistic risk assessment. A simple box model is used with explicit representation of transport between boxes caused by failure of wells.
Weyburn/Monitor Scientific	Scenario-based modelling that uses an industry standard reservoir simulation tool (Eclipse3000) based on a realistic model of known reservoir conditions. Initial treatment of wells involves assigning a uniform permeability.
NGCAS/ECL technology	Probabilistic risk assessment using fault tree and FEP (features, events and processes) database. Initial study focused on the Forties oil and gas field located offshore in the North Sea. Concluded that flow through caprock transport by advection in formation waters not important, work on assessing leakage due to well failures ongoing.
SAMARCADS (safety aspects of CO_2 storage)	Methods and tools for HSE risk assessment applied to two storage systems an onshore gas storage facility and an offshore formation.
RITE	Scenario-based analysis of leakage risks in a large offshore formation. Will assess scenarios involving rapid release through faults activated by seismic events.
Battelle	Probabilistic risk assessment of an onshore formation storage site that is intended to represent the Mountaineer site.
GEODISC	Completed a quantitative risk assessment for four sites in Australia: the Petrel Sub-basin; the Dongra depleted oil and gas field; the offshore Gippsland Basin; and, offshore Barrow Island. Also produced a risk assessment report that addressed the socio-political needs of stakeholders.
UK-DTI	Probabilistic risk assessment of failures in surface facilities that uses models and operational data. Assessment of risk of release from geological storage that uses an expert-based Delphi process.

As far as the risk management applications are concerned, monitoring is suggested as part of the remediation process when signals and warnings suggest so. For example, by injecting mud to the borehole to prevent blowouts and stabilize pressure. However, as mentioned before there are no legal frameworks on how and by whom this should be done after wells have been abandoned.

Moreover, regulators require the submission of no-migration petition. The operators are obliged to prove that the fluid will not migrate from the site for 1,000 years or more.

Currently, the operators simply present models that demonstrate that there will be no migration that satisfies regulators. So, no detailed requirements for monitoring or verification in a long term exist.

2.4.5. Concerns

As it is shown some regulations for CCS operations in the surface exist, but very few countries have developed comprehensive legal frameworks for long-term CO_2 disposal. Long-term assurance related to leakage of CO_2 and its impact to the environment is generally lacking nowadays. There is still great uncertainty about the pollution impact of a leakage in the sea and its reaction with the marine environment. There is also uncertainty regarding the range of the environmental risk that storage of great amount of CO_2 can pose. Especially in long term such a vulnerable issue with significant lack of knowledge can be amplified dramatically. Some claim that there is such lack of knowledge about farfetched climate consequences that any assumption or expressed knowledge today for the long future is meaningless.

As aforementioned, risk assessment is based on scenarios in order one to develop mathematical-physical models. However, in a long term perspective the validity of those could be challenged. Uncertainties related to the initial scenarios exist, in a sense that no one knows if those are adequate in a long time span. Furthermore, the validity of the initial model inputs and mathematic formulas is challenged. The knowledge related to the phenomena which are assessed changes. Therefore choices in the past might be proven wrong or less sufficient in the long future.

It should be mentioned here, that current methodologies highlight the importance of monitoring potential leakage from the abandoned wells. However, no thorough regulations exist that can define and implement such activities. Authorities are simply satisfied with model results that “prove” the validity of the current methodologies related to potential leakages. But, this, as it was mentioned before, conceals many assumptions and simplifications on which models are based that cannot be valid in a long time span. Requirements for reevaluation of the initial assumptions and the strength of knowledge, but also updating of the risk assessment, could add some value to those predictions.

Chapter 3

3. Risk

In this chapter the current risk concept is defined. Focus is put on the risk related to the time dimension, knowledge and uncertainty. This gives a common understanding of the conceptual risk framework upon which the further analysis will be based.

3.1. Risk concept

Until recently, there has been a broad adoption of the risk definition as the combination of probabilities and consequences. For instance, in nuclear risk assessments, the quantitative triplet risk definition by Kaplan and Garrick (Kaplan & Garrick , 1981) is widely used, which defines risk as a set of (s_i, p_i, c_i), where s_i represents different scenarios, p_i are the probabilities of each of those scenarios to occur, and c_i are the associated consequences. Probabilistic approach in risk definition is also used in finance. Financial risk is typically defined in terms of deviations from expectations

Over the last years, there has been a shift away from the aforementioned probabilistic approaches, towards a regime that defines risk in terms of uncertainty. Initially the International Organization for Standardization (ISO) (International Organization for Standarization , 2010) created a new definition of risk which states that:

Risk is the effect of uncertainty on objectives.

This definition is not precise in a sufficient manner. Many could easily challenge this definition by giving different interpretations, as it is mentioned by Aven (Aven, 2012)

Similarly, the Norwegian Petroleum Safety Authority (PSA) has defined risk as (Norwegian Petroleum Safety Authority (PSA), 2015):

Risk means the consequences of the activity with associated uncertainty.

According to this definition, risk related to an event A is defined as the two-dimensional combination of the (severity of the) consequences of the event and the uncertainty of what those consequences are (what will C be?) (Aven, 2010). In order to define C, one needs to have some reference value, objective, and highlight undesirable consequences related to this. When risk is concerned, there should be at least one negative outcome. Uncertainty is a main component of risk and when decisions are made based on risk analyses, one should take into consideration the background knowledge of these analyses

Consider a P&A operation, for example. In the decommissioning phase, operators need to plug and secure the wells from potential future hydrocarbon leakages. In this activity, one event could be a failure of the barriers, which hold the hydrocarbons deep below the surface. Risk is related to the consequences of a potential leakage and also the uncertainties related to those consequences; what will the actual consequences be? How large and severe? What or who will be affected? When will the consequences occur? When the scope of the risk assessment is to protect the environment, the consequences under consideration might be pollution at the local, regional or even global level. Hydrocarbon leakage can influence the general ecosystem and marine environment. However, hydrocarbon leaks are also associated with other types of risk. For example, it can also influence the company's economy, by forcing them to take measures to mitigate the pollution or pay fines. An accident will influence a company's reputation and trustworthiness among its clients and in the wider society. What the consequences will be is uncertain, no one knows what the future will be, and this is the risk.

Based on the discussion above, in this thesis, whenever the term risk is used, it should be understood according to Aven's definition, which says (Aven, 2008):

Risk: is defined as a two dimensional combination of the consequences, C, and associated uncertainties, U, to what the outcome will be (Aven, 2008):

$$R = C \& U$$

By using this definition it is highlighted that pure probability-based approaches for assessing risk are too narrow and a broader risk concept is sought. Probabilities should be seen just as one of the many available tools of describing uncertainties, but not the only one. Some of the problems of pure probabilistic approaches are summarized by Aven (2012), and the main issue is that sometimes the assigned probabilities can be the same but the knowledge behind those differs. Some aspects of the uncertainty are therefore "hidden" and not captured by the probabilities. That can mislead the decision makers if they are not aware of the knowledge aspect.

Furthermore, based on the recommended conceptual framework by Aven (2014), the consequences C can be split into risk sources RS, events A and consequences C. Hence, risk could be conceptualized as a combination (RS, A, C, U), as illustrated in Figure 5, Risk sources and influencing factors might trigger hazardous events (unless prevented by preventive barriers), which, in turn, may result in unwanted consequences if no effective mitigating barriers are activated. RS in a P&A example could be increased hydrocarbon pressure and enhanced degradation of the well plug. If the barriers are not sufficient leakage or blow out event (A) can occur. These leakages, depending on the effectiveness of the mitigating barriers or actions, can pollute the environment severely (C). The occurrence, though, of any of the RS, A or C is unknown, since assessors look forward in time. There will be uncertainty in relation to the risk sources, for example: How intense will the degradation be? How will the pressure develop? (When) will an earthquake hit the plugged well?

Risk assessors are called to describe consequences and associated uncertainty by executing risk assessments providing a clear picture of the risk to the management. However, a risk assessment is inevitably limited by the knowledge of those performing it, and may not capture all the various risk sources RS, events A and consequences C that may exist in the real world. There are hence additional dimensions to risk, related to knowledge and surprises.

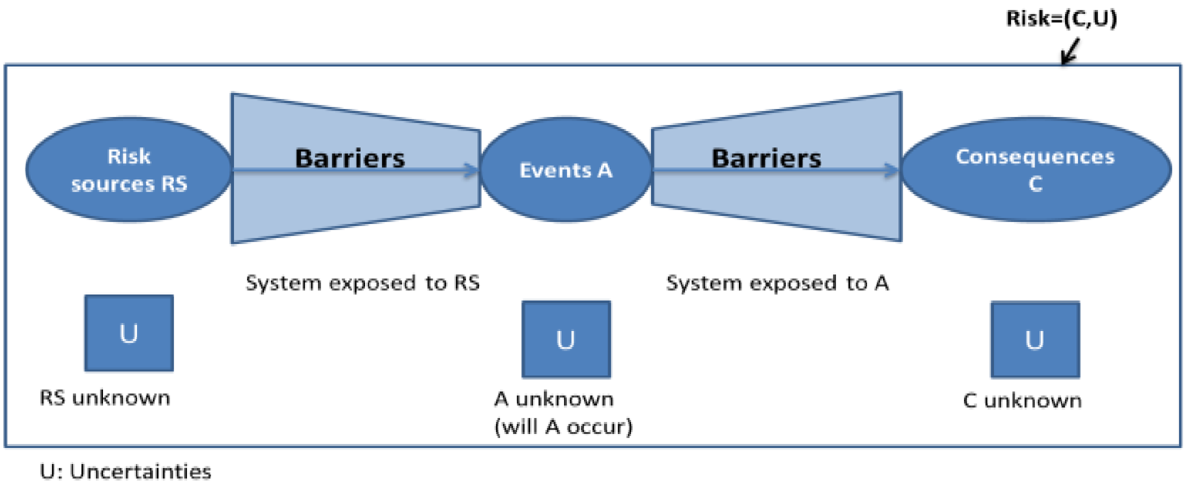


Figure 5: Conceptual framework for linking the risk, risk sources and events in line with the (C,U) perspective (Based on Aven (Aven, 2014))

3.2. Practical features of the new risk perspectives

For the purposes of this thesis, which is to address how the eternal perspective influences the different aspects of the new risk regime, the main message is that in practice, where risk description is based on probabilities, further insights about knowledge and lack of knowledge, surprises and black swans are needed (Aven, 2013). Figure 6 illustrates those new insights in risk which are essential in practice. Probabilities, which are used broadly in practice, can neither reflect the strength of knowledge upon which they were based, nor the assumptions which the probabilistic analysis is based on. This is covered by the (lack of) knowledge dimension. The surprises capture another aspect of risk, which is related to the part of risk that cannot be foreseen. What is considered surprising depends on available knowledge, hence a surprise must be understood relative to the knowledge of the assessors or experts conducting the analysis (i.e. surprise to who?).

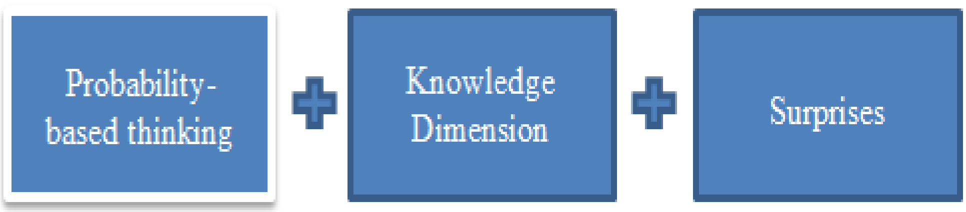


Figure 6: Basic features of the new risk perspectives compared to the traditional probability-based perspective (Aven, 2013).

3.3. From risk definition to decision-making and the hierarchical breakdown concept.

According the ISO 31000 structure of risk analysis (see Appendix B) there are five framework steps (ISO, 2009):

- Establishing the Context
- Hazard Identification
- Risk Analysis
- Risk Evaluation
- Risk Treatment

This methodology is well understood and broadly adopted in many industries, especially in the oil and gas industry (e.g. see Vinnem 2013). However, for our purposes, it is important to understand what the elements of this methodology are. Therefore, the transition from the ontological existence of risk to the specific risk description and decision making is considered according the hierarchical break-down of the risk concept, proposed by Hafver et al (Hafver, et al., 2015). Figure 8, shows a schematic interpretation of this framework, with some alterations. This is done in order to connect risk to risk measures and highlight the information that is lost due to assumptions and choices that the analysts have to make. It illustrates how one moves from the real world (Level 1) and the fundamental definition of risk of an activity A, R= C&U (here it is avoided the (RS,A,C,U) concept to be used for reasons of simplicity but risk sources and events are included in C), to the final goal of the risk assessment (Level 4), which is to compare risk and inform stakeholders about the risk, so that decisions and measures to control or mitigate risk can be taken.

According to this framework, going from level 1 to level 2, the scope of the risk assessment is chosen. This is biased by the involved stakeholders' preferences. Risk analysts need to choose specific attributes that will characterize consequences of the examined activity (**Y=** ***{****Y1, Y2, … , Yi* ***})***. Each of the attributes of the **Y** vector has an outcome space, a set of possible future outcomes of the attributes that are unknown but analysts want to measure. Those automatically create a frame in which analysts chose to work and are different for each attribute. For example, in a P&A activity, focus might be given only to a potential oil and gas leakage from the reservoir through the plugged well and its impacts on the environment, described in terms of leak volumes, leak rates, hydrocarbon concentrations etc, hydrocarbon dispersion and effect on populations of selected species.

Other aspects of the risk, such as consequences to humans in the area, or the cost and reputation impact to the company may not be considered in the risk assessments part of the (e.g. because it is beyond the mandate given to the risk analysts, or beyond the requirements set by environmental authorities) In summary, the risk analysts will, either consciously or without know in it, exclude certain aspects of risk from the scope of the risk assessment.

Having selected a set of attributes, risk analysts need to choose a model to quantify the uncertainty associated with these. Hence, going from level 2 to 3, analysts are forced to make choices and assumptions in order to express their uncertainty based on their previous experience, knowledge, available data or validated models. In general, it might be denoted the method used for describing uncertainty by Q. The measure Q could, for example, be the two dimensional combination of the probability, P, and the strength of knowledge, SoK, that probability assignments are based on; *Q= (P, SoK)*. Every model introduces an error, since the true **Y** will never be the same as the model prediction g(**X**), where **X** are the input attributes to the model. This is because of uncertainty regarding both the input attributes and the structure of the model g itself.

Transitioning from Level 3 to Level 4, analysts are strictly focused on particular results of the analysis. The risk measure, M= f (**Y**, Q), is a function of the attributes **Y** and the associated measure of uncertainty Q. For example, a risk assessment may report the expected consequence $E[Y|K]$, i.e. the probabilistic expectation value for the attribute Y, computed based on the model g and available knowledge K. In this step, aspects of risk are lost for two reasons: Firstly, a particular risk measure will not reflect all risk (e.g. the expected consequence does not say anything about most likely or worst consequence). Secondly, risk measures are conditional on the knowledge and assumptions used to compute them, which is associated with additional uncertainties. In order for risk measures to provide an improved picture of risk, they should reflect the strength of knowledge that are based on, and they should be informative and suitable for supporting the decisions faced (Johansen & Rausand, 2014).

The point of the abovementioned hierarchical description is that, during the risk assessment, analysts need to make assumptions and choices. They do this based on their knowledge at the time of the assessment. They use models and methodologies during the risk analysis which are simplifications of the real world and introduce errors (see Figure 9). Therefore, there will always be a part of risk that is not captured in the risk assessment.

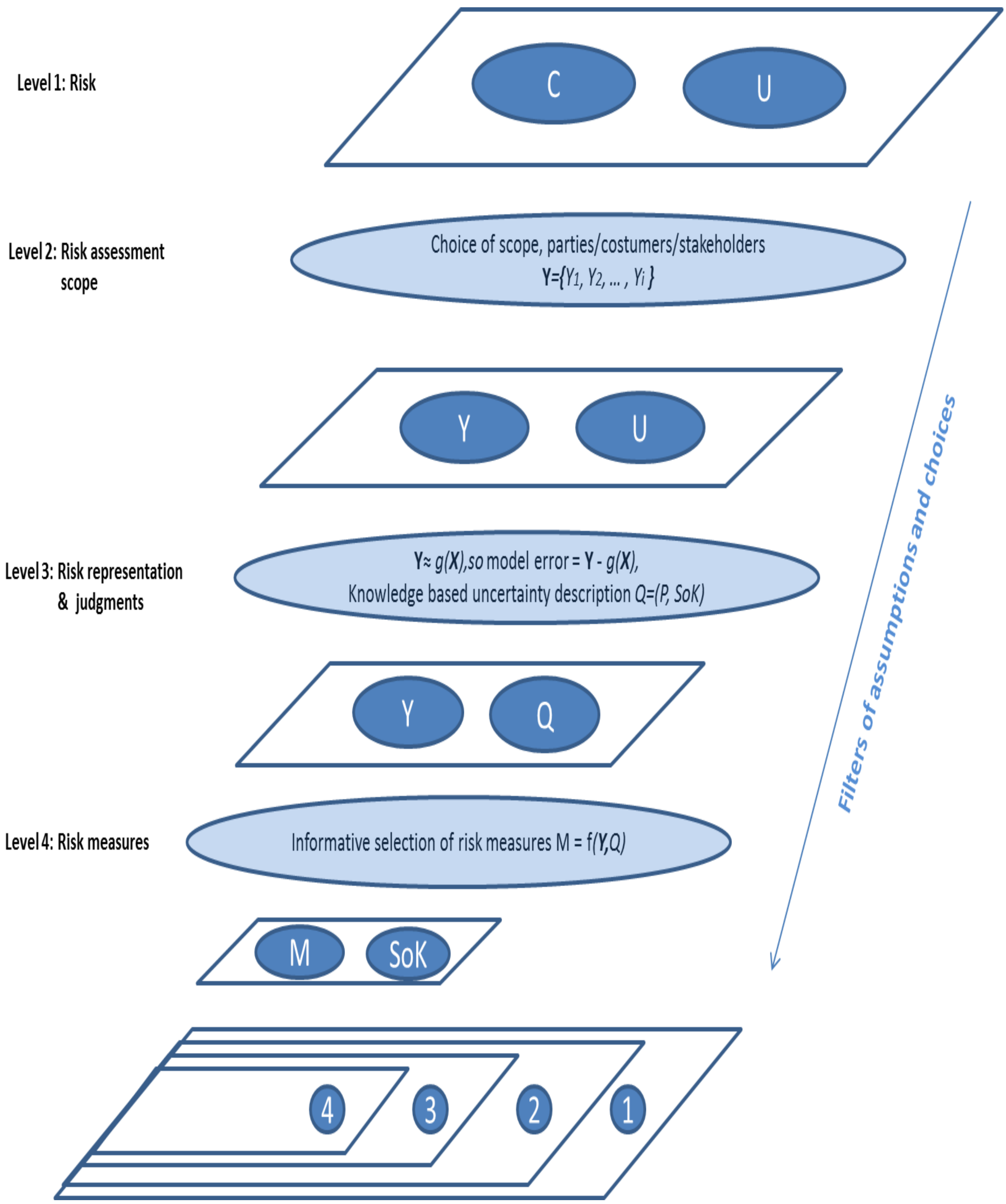


Figure 7: The transition from the real world (risk definition), to the risk description and picture of the case examined, after having been "filtered" by analysts and experts through the risk assessment.

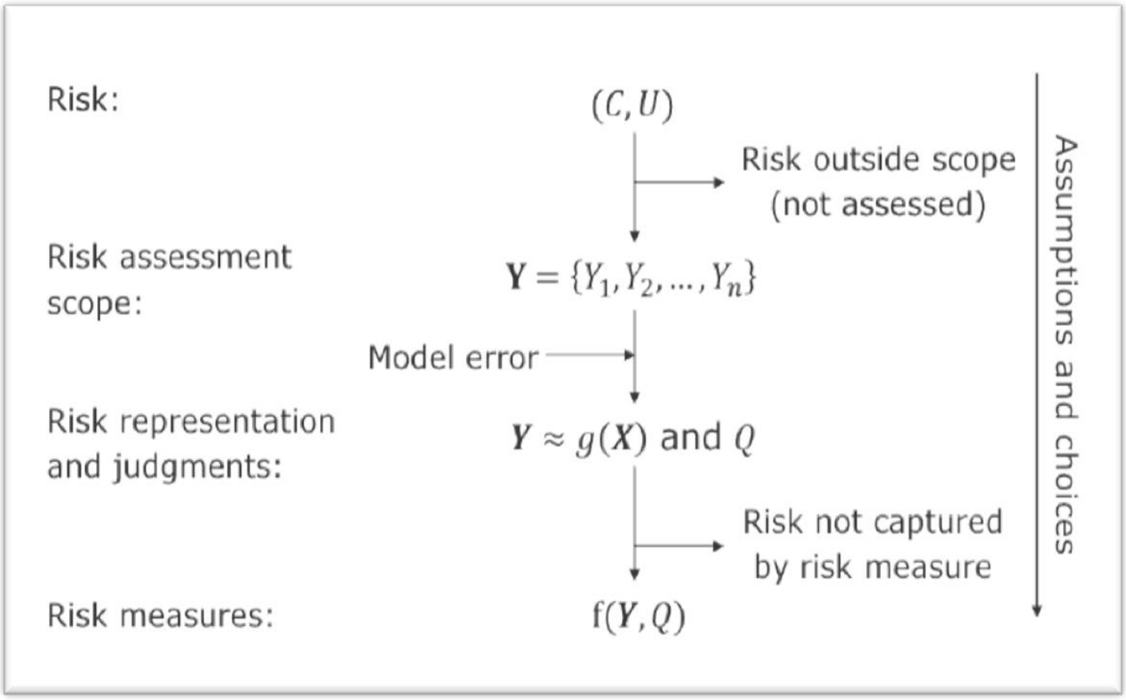


Figure 8: Summary of what is lost and introduced when progressing from risk to risk measures (Hafver, et al., 2015)

Chapter 4

4. Risk in an eternal perspective and deep uncertainties

Here it is presented how risk in an eternal perspective is understood and differentiates from the aforementioned traditional regimes. The time dimension is introduced and focus is given on aspects of the risk concept and risk assessment that are influenced when those are used for handling risk in a long time future period.

4.1. The time factor

In complex operations, where consequences of an event might show up after a long time period (regarding human perspective), uncertainties of the severity of an event are related not only to the type of the event but also the time that this will happen. Some might argue that there is no risk related to when this event will occur and that the severity of the event depends on its nature. However, when risk is considered in an eternal perspective time is an important factor. In the long term, the environment around the area of concern might alter. The knowledge changes related to the concerned phenomena.

For example, at a nuclear waste disposal plant, in the beginning of the operation, the direct threat of a radioactive leakage to people might be low since there might be no residents or there is less waste fuel buried. Considering, though, that this plant and the disposals are going to remain there for thousands of years, it is certain that the environment and the world on the surface changes. So it is possible, in the future, more residents will move into the area near the plant. This automatically increases the risk of the same leakage because of the increased number of people exposed to the same danger.

Similarly think of the environments around activities such as plugging and abandonment or carbon capture and storage in reservoirs deep below the surface. Both of these activities are supposed to prevent polluting leakages to the environment form occurring for thousands of years. For CO_2 wells, as recommended by the Intergovernmental Panel on Climate Change, IPCC (2005), the time span is 1000 years. During that period nature alters and the natural characteristic of the system might change. For instance, the pressure in the reservoir might be increased due to continuous natural processes and oil accumulation from the source rock. Or the risk environment can alter due to enhanced injection activity or an increase in the number of plugged wells in the area. So, an unexpected event, like an earthquake with excessive tectonic movement, can lead to different consequences from those that were initially assessed.

The time dimension has always been included in risk assessments, but most of the time explicitly in the probability part of it. For example, the probability of a barrier failure increases with time since the barrier integrity decays with time. Then, risk measures (RM) are implemented based on assumptions and knowledge at the time of the rsik assessment. For example, there may be assumptions, a, regarding the number of people exposed to the risk of radioactive waste leakage, the level of radioactivity, the pressure in the reservoir, etc. Then it can be assumed that mathematically, RM are considered as dependent on both assumptions and time, RM = RM(a, t). However, as explained with the previous examples, assumptions are also time dependent, a(t). In long term perspective, the knowledge related to the environment changes and, consequently, the assumptions that the risk measures were based on change as well. In mathematical terms, the time variation of a risk measure therefor has two contributions, i.e.

.

$$\frac{dRM}{dt} = \frac{dRM(a(t),t)}{dt} = \frac{\partial RM(a(t),t)}{\partial t} + \frac{\partial a(t)}{\partial t}\frac{\partial RM(a(t),t)}{\partial a} \quad (1)$$

where RM = a risk measure, a = the assumptions upon which the RM is based and t = time

So, time can be an influencing factor both on the risk measures and the assumptions upon which the measures are based on. Then time influences the risk measures and the adequacy of our system both explicitly and implicitly. This influence is important to be addressed and assessed when risk is concerned in an eternal perspective.

4.2. Uncertainties and strength of knowledge

All the aforementioned examples testify the dynamic nature of risk. They also show that there is deep uncertainty regarding those phenomena. Trying to use probabilities in describing those uncertainties, one has to use subjective probabilities (even those in some cases might be meaningless, as it is explained below). Any attempt of using frequentist probabilities for describing those uncertainties in the long future would imply that the assessor has on his mind a "hypothetical" model and a situation where an event could be repeated an infinite number of times.

To understand this, keep in mind Figure 6 with the three features of risk, probabilities, knowledge dimension and surprises. Depending on the nature and the complexity of the activity for which risk is considered, one needs to use different probabilities. The knowledge dimension and the level of exposure to surprises vary as well. Let us think of three examples in order to elaborate more and understand the meaning of the aforementioned:

Example 1: One has an urn filled with balls, which is well defined and described, and is attempting to draw a specific ball out of it. In this example, it is sound to use frequentist probabilities to describe the chance of drawing a specific ball, since knowledge of the activity and the system is strong. The uncertainties are low. No surprises exist even if the activity is repeated again and again for eternity.

Example 2: An operation offshore in a specific oil and gas field. The same operation has been performed many times previously in the specific field, and also in other fields around the world. There are dominating explanations and beliefs around the uncertainties of the outcome of the activity for a specific short time period, let us say here a time period three hours. Subjective probabilities which are based on some knowledge are commonly used here, which express assessors degree of belief about the event. However, there might be events coming as surprises, either because they were not foreseen or because, during the assessment, assessors judged the probability of their occurrence to be negligible. For instance, suppose an unexpectedly high wave, higher than what one expect to occurs every one hundred years, hit the platform, leading to fatalities. This is an event that was identified in the risk assessment, but the probability of its occurrence was assessed as being negligible.

Example 3: A global defense security consultant assesses the risk of a terrorist attack occurrence anywhere in the world in an eternal time period (this is an extreme case, but it is chosen here for the purpose of illustrating a point). Trying to assess risk like terrorist attack in advance under such deep uncertainties and poor knowledge by addressing probabilities is meaningless. An unwanted event will come as no surprise to the assessors because of the broadness of the assessment and the long time period under consideration. In this example the uncertainties dominate to such a degree that any negative outcome will come as no surprise.

Table 3: An alternative uncertainty-knowledge classification taxonomy (based on Aven 2013)

	Example 1 (Low uncertainties)	**Example 2 (Moderate uncertainties)**	**Example 3 (Deep Uncertainties)**
Probabilities (as a practical tool of describing uncertainties)	Frequentist probabilities	Subjective probabilities	Meaningless to use probabilities
Knowledge	Strong knowledge	Some dominating explanations and beliefs	Poor knowledge
Surprises	No surprises	A surprise might occur	No surprises

The aforementioned examples, summarized in Table 3, show that based on the nature of the activity and the time interval in which risk is assessed, the strength of knowledge, the degree of uncertainty and the possibility of a surprise to occur vary. In a particular time, an activity could be characterized as one with deep uncertainties, but by gaining some knowledge it could be moved to moderate or low. Since in this thesis focus is on complex operations like those described in Chapter 2, it could be argued that in an early stage compared to the time span of concern, there are moderate uncertainties and there are some dominating explanations and beliefs that subjective probabilities could be based on. However, it is believed that in a long term perspective an assessed activity fits better to the third type of examples. The reason is that the uncertainties around the assumptions and the choices of the risk assessment become greater.

This uncertainty is caused by a lack of knowledge. According to Flage and Aven (Flage & Aven, 2009), knowledge is considered weak if at least one of the following conditions is true:

- The assumptions made represent strong simplifications
- Data are not available, or are unreliable
- There is lack of agreement/consensus among experts
- The phenomena involved are not well understood; models are nonexistent or known/believed to give poor predictions

For assessing risk in eternity, one easily understands that more or less all of the above are true. So, finding a concrete solution today, in order to handle risk in a long term perspective, would definitely require strong simplifications. During the risk assessment, one needs to produce results based on knowledge from history and experience of a relative small period compared to the one examined. Therefore, the assumption that this knowledge is valid enough to describe long term future could be easily challenged. For example, the nature of the problem might be assumed to be well understood based on decades of research in the past. However, in a thousand of years perspective, that might not be sufficient. The data used will not be reliable for such a long term. Experts might come to an agreement, but this is going to be related to current data and experience that might hide issues related to the first condition. Last but not least, no matter how strongly someone believes that the phenomena around a topic are well understood, history has proven that in a time span of 1,000 years, the way science sees the world and describes the phenomena has changed dramatically.

4.3. The risk concept in an eternal perspective

4.3.1. Schematic interpretation of the risk concept

Let's look at this issue from a more explicit perspective using the schematic illustration of risk concept in relation the time dimension (see Figure 9) (Aven & Ylonen, 2014). The examined activity is considered for a period of time, which can be long or short based on the nature of the activity. Think of the plugging operation during the decommissioning phase of a well. The decommission activity is considered for period from d0 to d2 where our main interest is on a plugging operation of a specific well during the future time interval D when risk is assessed, which is from d1 to d2 (see Figure 9 (A)). The point s shows the present, the time that the assessment is executed (now). This point defines what needs to be assessed and how far in the future needs to be considered. It indicates also what can be considered as history (from d0 to s). In most of the operations the time interval of the history is similarly long as the future time interval which is assessed. Therefore, it is assumed that in a Bayesian conceptual framework where subjective probabilities need to be assigned based on prior knowledge, that the knowledge is strong. That the background knowledge can be assumed strong because it is proportional to the length of the time that risk is assessed for. To elaborate more on this, think of the second phase of the P&A abandonment operation. When operators abandon a plugged well, the risk of a potential leakage still exists. An assessment of future hazards needs to be executed. In line with the previous schematic illustration (see Figure 9 (B)), there is still a history interval (d0, s) and a future interval (d1, d2). However, the future interval is much longer. It is theoretically eternal, (d1, +∞). The uniqueness of this problem is that the interval D is very long.

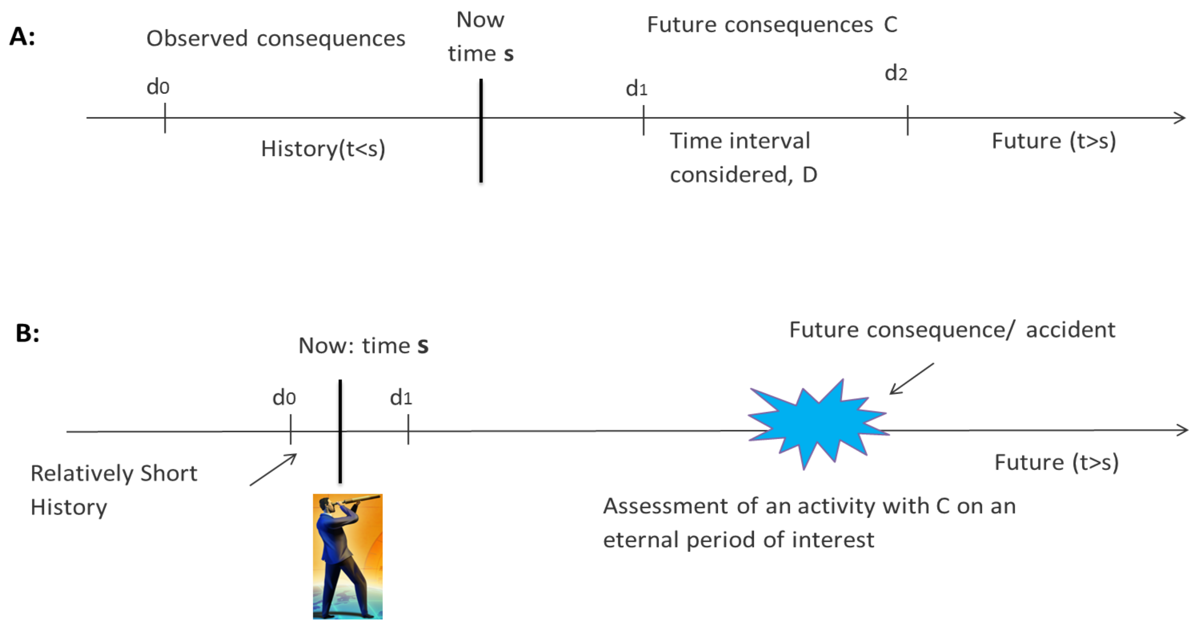


Figure 9: A schematic illustration of some of the fundamental components of the risk concept in relation to the time dimension. The first case (A) refers to common cases where future assessment interval is relative small and well defined, whereas the second case (B) refers to risk assessment with long (eternal) future interval (based on Aven (2014)).

Events like those discussed above could be included in the category of black swans. A black swan is a type of event on which there has been a lot of focus recently by industries. This focus increased mainly because of recent disasters, such as the Macondo accident in the Gulf of Mexico in 2010 and the Fukushima Daiichi nuclear disaster in Japan in 2011 (Aven & Ylonen, 2014), which apparently occurred unexpectedly and with extreme consequences for both humans and environment. At the nuclear plant of Fukushima, during the risk assessment, hazard identification might have revealed the threat of a natural phenomenon like tsunamis, but experts assessed this as an event with negligible probability of occurrence. No one had understood that there is a possibility a tsunami to outstrip all the safety system constraints simultaneously and in the same time block the emergency response actions. However, climate change seems to alter weather patterns and thus the behavior of natural phenomena. Events, which used to be rare, occur with greater frequency. Therefore, a deeper assessment of the knowledge behind the simplifications and the assumptions made during the analysis is essential, and emphasis should be on knowledge building. New risk perspectives are needed, where weight is given to the knowledge and surprise dimensions (Aven & Ylonen, 2014).

During the assessment the assessor should have in mind that, for a long time period, the environment alters and consequently the foundations that the assessment was based change. Most of the variables and the data change. From natural processes and phenomena to the number of stakeholders and population which is exposed to risk. Therefore the possibility of an unforeseen event to occur is much higher. Think of one's life, for example, it is easier to manage the risk of an unexpected accident occurring the next minute when you work at your office than predicting and preventing one unforeseen accident by occurring one time during a whole life span. The possibility of being unable to handle and prevent such an event is much higher in the latter occasion, due to the period of time risk is assessed, which makes the environment more dynamic and increases the number of possible risk sources. Furthermore, it could be claimed that it is almost certain that at least one surprising event will happen with in in a long time period.

4.3.2. A macro perspective explanation of the occurrence of an unforeseen event in a long time period

Aven (2014) uses the example of an activity in an operation of an offshore installation and the macro perspective to explain that, whether an event will be characterized as black swan or not, is related to who considers it as a surprise, and when. Briefly, if one regards independently and uniquely an activity in a specific offshore installation, then the occurrence of an unexpected extreme event that sets in danger humans, environment etc. in a period of a year will be seen as a black swan. However, from a macro perspective and considering all the offshore installations in a year, that same event would not come as surprise.

Inspired by this example, it is presented here a similar example of a macro perspective, which shows that, in a long-term or eternal perspective, an extreme consequence does not come as a surprise. This is illustrated in Figures 9 and 10. Think of the activity in an offshore oil and gas installation. Let C denote the consequences of this activity to the values concerned, such as environment, humans and assets. Then in the first case, Figure 10, the time interval, D, for which risk is concerned, is relative short and close to the presence. The assessment is done today, at time s, and there is risk related to the activity, i.e. uncertainty regarding what C will be. If a negative outcome occurs (for example a leakage) then that will come as surprise. Now from a macro perspective, thinking of the same installation but "zooming out" in time, then the assessor has to consider of numerous such time intervals. Here these are presented by D1, D2, … , D∞, implying that each interval is different since the environment, the operations, the activities and the load that those are exposed cannot be the same. Now, risk is linked to the occurrence of any leakage at any time in the long future, theoretically eternity. Then coming back and checking the accident based on the initial assessment should not come as surprise to the assessor, since the accident occurred after many intervals Di and many combinations and unforeseen events which led to that outcome. In short multiplicity makes the event much more probable when seen in the macro perspective.

All in all, when one uses a unique assessment to assess risk in an eternal perspective or relatively long period, extreme events do not come as a surprise, but as an outcome of the deep uncertainties and poor knowledge of the assessor when the assessment was made. After that time many factors upon which the assessment was based may change, and new ones may show up.

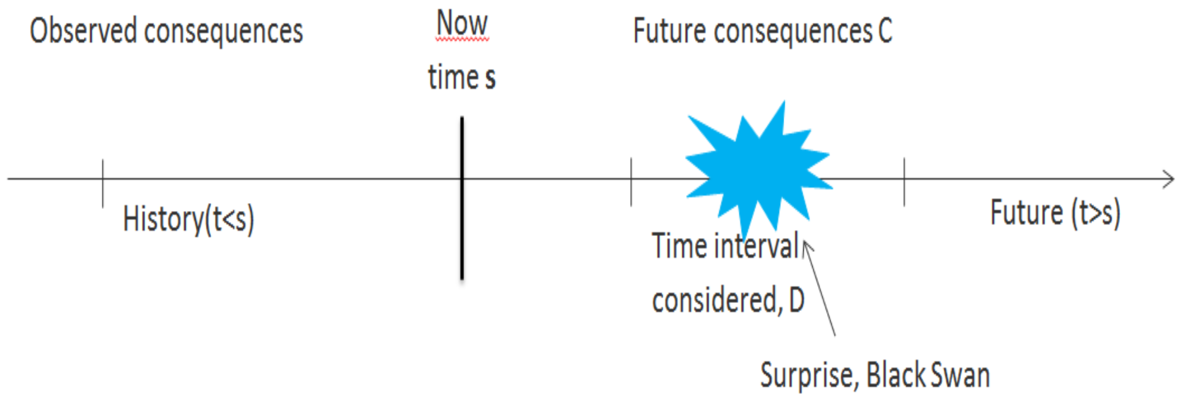


Figure 10: Illustration of the relationship between risk, black swan and the time dimension for an activity with relative short considered time interval for example temporary plugging of a well. C: consequences of the activity. D: The time interval considered (based on Aven 2014)

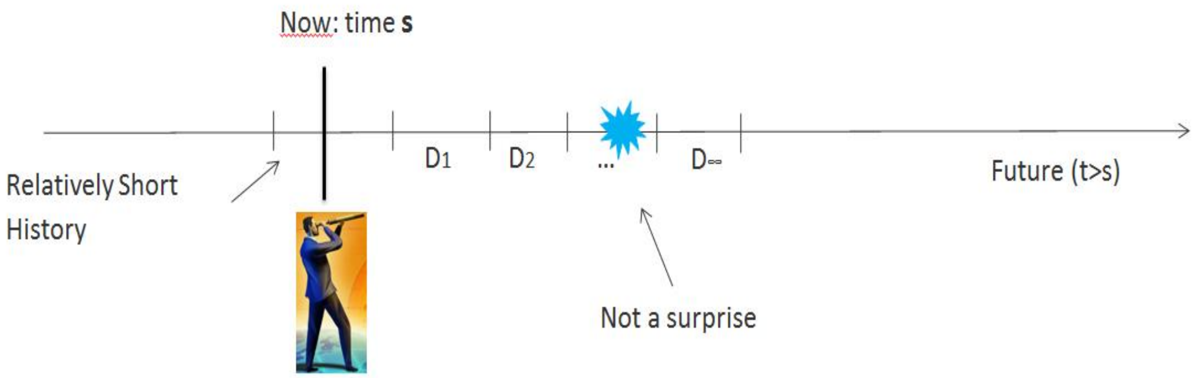


Figure 11: Illustration of the relationship between risk, black swan and the time dimension when the perspective is macro for example permanent plugging and abandonment of a well (based on Aven 2014)

4.3.3. Are we at the mercy of unforeseen events in eternity?

Here, it is examined from a more mathematical point of view what happens when one assess failures of barriers or hazards in an eternal perspective. For the sake of argument, let us here present a probabilistic approach of explaining failures in an eternal perspective. Assuming that there is complete knowledge of the system the cumulative probability that a hazard has occurred at time t is F(t):

$$F(t) = 1 - e^{-\int_0^\infty \lambda(t)dt} \quad (2)$$

Where $\lambda(t)$ is the hazard rate and $\lambda(t)dt$ the probability of a hazard to occur in a time interval [t, t + dt]. In order the cumulative probability of a hazard to be less than one in eternity, the following needs to be fulfilled:

$$F(t) < 1 \quad (3)$$

$$1 - e^{-\int_0^\infty \lambda(t)dt} < 1 \quad (4)$$

$$\ldots$$

$$\int_0^\infty \lambda(t)dt < \infty \quad (5)$$

Generally, this means that the hazard rate should decrease faster than 1/t in order to avoid the certain occurrence of a hazard for eternity. The point of this example is that even in an eternal perspective, it is not certain that an event will occur 'sooner or later'- the event may also never happen. This depends, though, on the hazard rate, the frequency with which a hazard occurs, and how this changes in time. In reality there are many uncertainties related to this issue and it is difficult to talk frequencies. Complex systems as those described in Chapter 2 have many components or barriers that need to function in order a hazard to be prevented. One can say that the hazard rate of a system is the sum of all the possible risk sources and events, failures, which can occur in a system or its components. So, it can be said that:

$$\lambda(t) = \sum_{i=0}^{\infty} \lambda_i(t) \quad (6)$$

Where λ_i denotes the failure rate of i different possible failures (accidents) of the system. Based on the assessor's knowledge, some of those failure modes have been identified during the assessment. However, there will always be a number of not identified events that come as a surprise. Then, one could split the total failures to the sum of the known and the unknown failures (surprises):

$$\lambda(t) = \sum_{i=0}^{m} \lambda_i(t)^{known} + \sum_{i=m+1}^{\infty} \lambda_i(t)^{unknown}, \quad (7)$$

where, m is the number of identified failures/hazard.

In long term perspective, the environment and the system's state can change, and the possibility of occurrence of an unexpected outcome increases. It can be said that the surprising factor dominates in the long term. So, it should not be a surprise that the total failure rate of the system deviates from the one that was initially assessed (known). The challenge here for the assessors is to increase as much as possible the number of the known failures compared to the unknown one. It depends on the nature of the problem and our knowledge about it.

For instance, think of the nuclear waste disposal. Current scientific knowledge claims that the radioactivity of the waste decays in time and that the waste becomes less hazardous. In the same time, the barriers, i.e. the container tanks, are deteriorating in time as well. So, according the current performance assessment of the barriers scientists assume that the barriers would decay slower than the hazard decays. Therefore, by the time that there would be no sufficient barrier constraints the hazard rate would have been dropped to non-dangerous levels.

In reality, though, the system performance might deviate from the planned one. In line with the practical features of the new risk perspective (Probabilities, Knowledge, Surprises (P, K, S)), the probability dimension which is based on some strength of knowledge is important in order to assess risk today. This would give non-conservative solutions. However, the surprise factor and the knowledge development in time are important factors when risk is concerned in eternal perspective. The domain knowledge needs to be updated in order to capture the deviations, avoiding the domination of the surprising, unknown, factors.

4.4. Identification of the deviations in the initial risk analysis using the hierarchy breakdown concept

What are the aspects of the initial assessment which could change in time? The answer to that question is given in this part of the thesis based on the hierarchical breakdown of risk described in section 3.3. This is illustrated in Figure 12.

Let us think of two assessments; one of them is the initial risk assessment that was done before the activity and it tried to predict the long term future. The second one is an update of the old risk assessment but done some time far into the future (let us assume here, in 1,000 years). These two assessments may be compared in relation to the hierarchical framework described in Section 3.3 in order to identify the aspects that it is believed that they could change.

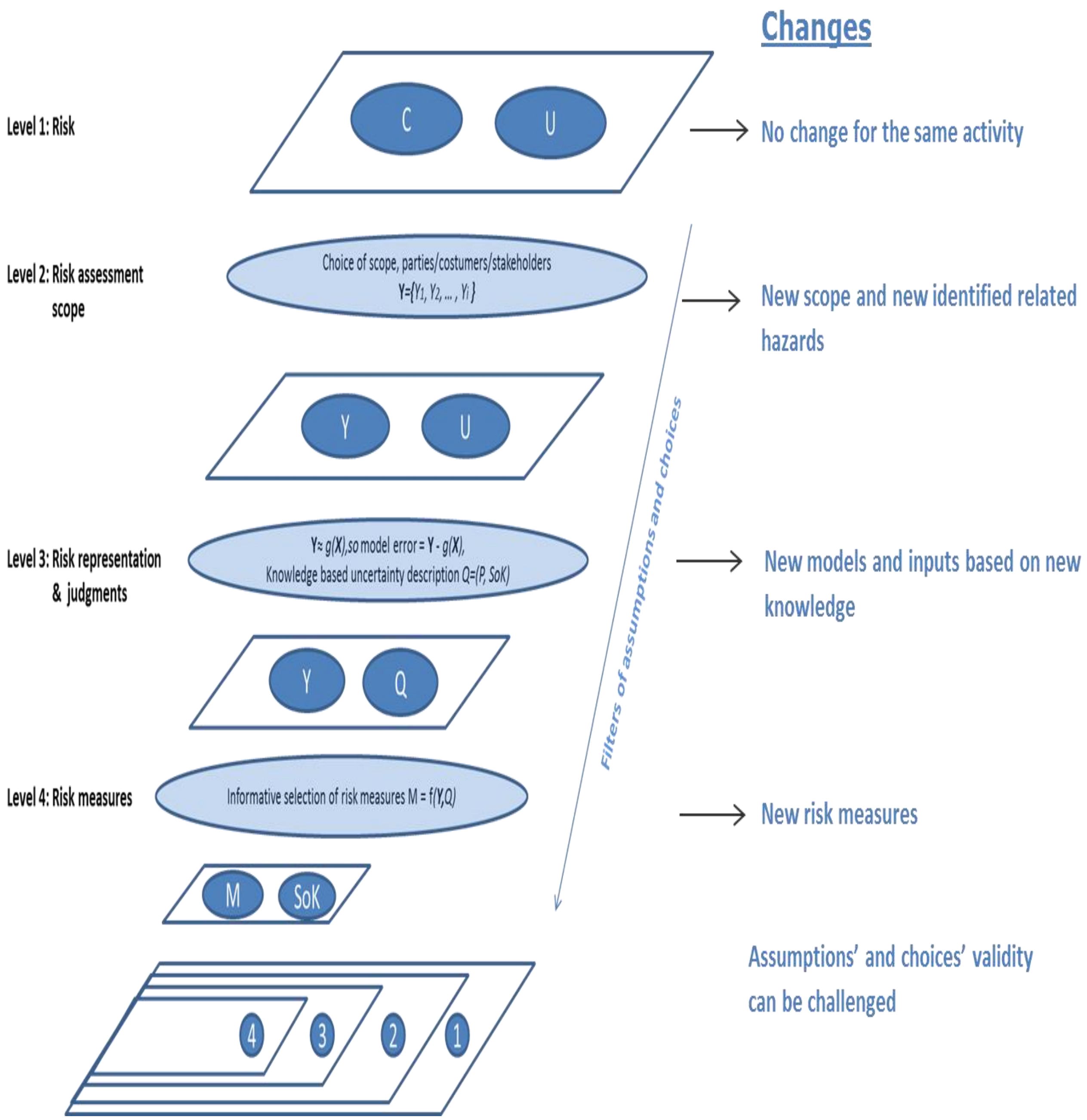


Figure 12: Illustration of all the deviations that can occur in the initial assessment based on the hierarchical breakdown concept.

4.4.1. Changes in Level 1

At the top level of the hierarchy, risk exists inter-subjectively in sense that no one knows the future consequences of the activity (Hafver, et al., 2015). So, as long as there is the activity the existence of the risk will not change. Think, of the three cases which were described in Chapter 2. The activity of the nuclear waste disposal or isolation of hydrocarbons and CO2 will still be the ones concerned about. The risk faced at the time of the second risk assessment is conditional on events that may already have happened up to that point (e.g. the nuclear waste may have been removed from the storage site), but all such eventualities are already included in the risk faced at the time of the first risk assessment. What has changed is simply that the time interval of interest now starts at a later point, and is conditioned on a different past.

4.4.2. Changes in Level 2

Each assessment has a scope and the assessors are focusing on particular aspects of the activity. They identify only the hazards that a related to this. But in long term the initial scope might deviate and new hazards might occur. For example, think of the first oil and gas production plants. The first risk assessment would have been focused on preventing fatalities due to accidents, explosions etc. Later on, though, it was proven that excessive human exposure to hydrocarbon gases can be fatal in long term or that burning and release of gas to the atmosphere pollutes the environment. Therefore, nowadays, the scope of the assessment has changed focusing also on how to secure both humans and environment not only during the operation but also in long term. In the same line and considering new hazards occurrence, no one in the past would have identified the threat of an explosion caused by cyber terrorism. However, nowadays this threat exists and more focus is given on securing networks and systems to prevent hacking incidents. New technologies and innovation, additional system and operation complexity or increased demand for safety are some of the reasons, which ask for a broader risk assessment scope. Also, they inherit new hazards and risk sources. Internet and digitalization introduced a new hazard of cyber terrorism that was not there before computers were invented. The environment, changes and the risk assessment should be updated following those changes.

Consequently, level 2 can alter in time. New attributes **Y** might be introduced in order to capture the new identified consequences. The initial number of the attributes can change. Mathematically it could be shown that:

$$\boldsymbol{Y} = \{Y_1, Y_2, \dots, Y_n\} \tag{8}$$

New updated number of attributes

$$\boldsymbol{Y'} = \{Y_1, Y_2, \dots, Y_m\} \tag{9}$$

Where Y_i = corresponds to some attributes, and n the initial number of those, m is the new update number of the attributes.

The number of the new attributes, m, might be greater or less than the previous number, n, depending on the situation. The uncertainties related to the new attributes and the estimation of the values that those would take need to be described.

4.4.3. Changes in Level 3

The assessors might want to quantify the associate uncertainties by using a model for **Y.** As it was mentioned before that causal relationship between the attributes **Y** and some set of inputs **X** might be shown mathematically as:

$$\boldsymbol{Y} \approx g(\boldsymbol{X}) \tag{10}$$

Where **X** = $\{X_1, X_2, \ldots, X_i\}$, g = causal relationship

In time, though the model or the inputs used might be proven inadequate or irrelevant because of the new identified attributes or new identified relationships. New updated relationship between **Y** and **X** could be shown mathematically:

$$\boldsymbol{Y}' \approx g'(\boldsymbol{X}') \tag{11}$$

Where **X'**=$\{X_1, X_2, \ldots, X_j\}$ and g'(X) is the updated relationship between Y' and X'

The measure Q of uncertainties related to the input attributes **X** will be based on some Strength of knowledge (SoK) since the assessor will never know their exact value/ state. This knowledge but also the general strength of knowledge around the way risk was assessed will change as well in a long time period.

As an example consider a following model for environmental damage due to hydrocarbon leakage from a plugged well offshore.

$$Y_1 = X_1 \times X_2 \times X_3 \tag{12}$$

Here Y_1 denotes the level of environmental damage, X_1 could be a coefficient with appropriate units, X_2 shows the volume of leakage of hydrocarbons and X_3 the number of marine species exposed to the leakage. A probability model for estimating the value of X_2 could be used, based for example on physical models of well integrity, concrete plug degradation etc. This would be based on scenarios and assumptions of experts during the analysis. Similarly for X_3 the assessor might use subjective probabilities based on some knowledge gained from pollution dispersion models, experiments on fish species etc. After many years though it is expected that changes that affect this part of the assessment have occurred. Those changes could be divided in three categories:

1. *Physical or condition changes:* real changes in the physical components of the system or the environmental conditions that could increase the possibility of a hazard to occur. In the P&A example that could be a significant degradation of the concrete plug or an increase of the acidity or pressure of the reservoir. Then a X_2 input might need to change. Additionally, new endangered species might be witnessed in the area and the X_3 value might need to be altered.

2. *Changes in knowledge:* Changes in the knowledge on which the concerned risks are assessed. That influences the confidence one has for the initial inputs and outputs of the analysis, the models that were used and general the strength of knowledge behind the assumptions made in the original assessment. For example, new scientific understanding of the natural processes in the reservoir in a P&A or the degradation rate of the barriers etc., or new data collected during the previous years could change the knowledge around the system performance.

3. *Changes in the context:* All the changes that are not related to the aforementioned two types of changes and do not imply real change in risk but may affect the way risk level is judged. For example, new regulations and standards focusing more on the environmental impact might be implemented asking for more conservative solutions and increases safety factor during the calculations. Then a new X_4 safety factor might need to be implemented on the formula.

Then, it is sound to implement a new formula trying to capture all the aforementioned changes. For example:

$$Y_1' = X_1' \times X_2' \times X_3' \times X_4 \tag{13}$$

Where Y_1', X_1', X_2', X_3' and X_4 are the new attributes as described above

All in all, in a long term perspective, it would be expected that at least one of the types of changes have occurred additionally to the changes inherited from level 2. Consequently, an update of the way uncertainties are quantified is needed. That would recover again the confidence of the analysis and the strength of knowledge behind the estimations.

4.4.4. Changes in Level 4

Here, it is meaningful to consider how the final decision is influenced by the aforementioned changes. As mentioned before, the overall risk assessment might change in time. Therefore, the risk description changes as well. This covers the identified events and consequences, the assigned probabilities of their occurrence, uncertainty intervals, strength of knowledge judgments as well as the examination of black swans, changes (Aven, 2013). The risk assessment provides important insights for the decision makers to support their decisions and implement the best risk mitigating measures choosing among alternatives. In a long term perspective, the initial risk measures that were chosen could be proven inadequate to capture all the risks. New alternative solutions can show up, which are able to replace the old more effectively.

It could be that some events have taken place since the previous risk assessment, that make previous risk measures used irrelevant. For example, an initial risk assessment may consider probability of leaks exceeding some magnitude as a measure of risk. If, at the time of the new assessment, a leak has already been detected, it may be more informative to focus on risk measure that reflect the consequences the leak may have on the ecosystem, i.e. effects on a particular species population.

Those measures take also into consideration other aspects which may not be included in the assessment, for instance, the benefits of the activity, strategic and political aspects etc. Decisions makers should be aware that those can deviate in long term as well. Think of the CCS activity for example. Based on the new regulations and the transnational agreements, the implementation of new higher taxation for CO_2 emissions make the solution of storage more attractive, and may increase the tolerability of risks related to the storage. In the future such a solution might even be mandatory.

There is a step of transition between the risk analysis and the decision. In practice this is supported by the implementation of risk acceptance criteria. If the risk assessment shows probability results below the assigned limits the risk is considered acceptable. Otherwise, if the results exceed the limits, the risk is considered unacceptable. However, such criteria should be used with care since assessments might be driven by the desire of the assessors to satisfy decision makers to meet the criteria instead of finding the overall best solution (Aven & Vinnem, 2005). Based on the improved procedure suggested by Aven (2013) and shown in Table 4, decision makers should take decision by using approaches that reflect other aspects than pure probabilities (Aven, 2013):

1. If risk is found acceptable according to probability with large margins, the risk is judged as acceptable unless the strength of knowledge is weak (in this case the probability based approach should not be given much weight)
2. If risk is found acceptable according to probability, and the strength of knowledge is strong, the risk is judged as acceptable.
3. If risk is found acceptable according to probability with moderate or small margins, and the strength of knowledge is not strong, the risk is judged as unacceptable and measures are required to reduce risk

4. If risk is found unacceptable according to probability, the risk is judged unacceptable and measures are required to reduce risk.

Depending on the time perspective it is sound to say that the strength of knowledge deviates. In short term the assumptions up on which the probabilities were based might be valid and the knowledge strong. On the other hand, as long as the distance between the time of the initial assessment and the examined time increases, the strength of knowledge decreases. It cannot be of certainty that the assumptions are still valid, for example the assumption for the condition of the barriers. Then the probability of an unwanted event to occur might increase, decreasing the margin with the limits.

Table 4: Procedure for using acceptance criteria in view of consideration strength of knowledge (Aven, 2013)

Probability Based Justification	Above limits	*Unacceptable risk*	*Unacceptable risk*	*Unacceptable risk*
	Small margin below limits	*Acceptable risk*	*Unacceptable risk*	*Unacceptable risk*
	Large margins	*Acceptable risk*	*Acceptable risk*	*Further Considerations needed*
		Strong	Medium	Poor
	Strength of Knowledge			

P&A EXAMPLE

For instance, think of the P&A operation and three specific time points in the future: 1 year, 10 years and 1,000 years. Consider, also, that the assessed risk is the potential blow out of the plugged well. Then, assuming that the tests of the measures are faultless, risk is acceptable according probabilities with large margins and strong knowledge for the first year. So, it is placed in the far down left side of the Table 5, T_1. In ten years from the initial assessment, the well would have been exposed to various stresses and many processes, such as barrier degradation and so on. Which of those occurred and how severe they were for the system cannot be said with certainty, since the well is abandoned and there is no monitoring. Then, the probability of a blowout is thought to increase during the assessment and the margin from the limit to decrease. If no significantly severe event has occurred, the probability results show that risk is still acceptable with large margins but, now, with medium knowledge. Then, the situation could be placed in the bottom and middle of the table, where risk is considered still acceptable. Whereas, in on thousand years from the initial assessment it sound to consider that the current knowledge is poor, since many events and deviations from the initial plan might have occurred. Then, risk might be considered acceptable according to probabilities with small margins, but the knowledge is poor, and therefore the overall risk is unacceptable (see T_3 in Table 5).

Table 5: On the new procedure of using acceptance criteria in view of consideration the strength of knowledge in the P&A example

Probability Based justification	Above limits	*Unacceptable risk*	*Unacceptable risk*	*Unacceptable risk*
	Small margin below limits	*Acceptable risk*	*Unacceptable risk*	*Unacceptable risk* T_3
	Large margins	*Acceptable risk* T_1	*Acceptable risk* T_2	*Further Considerations needed*
		Strong	Medium	Poor
	Strength of Knowledge			

However, even if the probabilities have shown the risk to be acceptable according to large margins for a blowout to occur in 1,000 years or eternity the strength of knowledge is considered poor.

Further considerations are needed. The examined period is so long that, as it was mentioned before, many changes might occur changing the overall risk assessment description. Given that both some events have occurred and new knowledge has been gained, the knowledge based probability outcome will change. It is important the deviations on the higher level to be witnessed. They should also be included in the new risk description, which is going to be used as an insight by the decision makers in order to implement new measures if it is needed. They will decide if the deviation is critical enough to call for new measures and which these would be so that the system would return to the preferable level of risk.

4.4.5. Deviation of the assumptions

The term assumptions refers to conditions or inputs that it is acknowledged that there is a possibility to deviate in real life (Berner & Flage, 2016). From the first moment that one starts to assess the risk related to an activity, every step in the risk assessment is based on a number of assumptions. These are associated with uncertainty, relating to the strength of knowledge of a risk assessment (Berner & Flage, 2016). For example, in an oil and gas offshore operation assessors might want to assess the risk of an explosion threatening the living quarters, assuming that this is the most critical case, since the greatest number of people is exposed to the risk. Therefore, assessors choose to examine the wind scenario where a flammable cloud drifts in the direction of the living quarter. However, a real life leak, may deviate from that scenario; more workers might be on the field instead of the living quarters or a chain of different explosions under different conditions might result in a greater hazard for the whole platform and consequently all the personnel. So, it is important one to address the level of the deviation of the assumptions during the assessment and their importance in sense of how much the deviation can alter the consequences.

From a long term perspective, in a similar way as in all the levels and the other factors of the risk assessment, deviations from the initial assumptions will occur. It is almost certain that after hundreds of years, looking back on the initial risk assessment, one can see many deviations from the assumptions upon which the risk assessment was based. The questions is which of the deviations altered the expected outcome or led to an accident. In the long term, both critical and non-critical deviations will occur. Both will add important knowledge to the assessors, but mainly the second will force them to update their risk assessment reducing the gap from the initial one.

4.5. Conclusions

In this chapter the concerns related to risk in an eternal perspective were addressed. One can easily notice that many challenges occur for the risk assessors. The main concern though is how to handle the "foreseen unforeseen" events. Those are all the unknown events that are known to occur eventually, as a consequence of the numerous deviations from the initial risk assessment. Time is an important factor on those operations. The theoretical eternal time span in which risk is assessed, allows many risk sources and hazardous events to occur, which need to be mitigated. Especially in complex operations like those discussed in Chapter 2. The deep uncertainties due to the lack of knowledge of what can happen in such a long future ask for a more dynamic methodology.

Chapter 5

5. Comparison and suggestions for improvements

In this chapter, summing up and addressing the concerns related to the activities described in Chapter 2 based on the analysis of Chapter 4 are of topic. That allows highlighting the inconsistencies that exist upon which suggestions for improvements will be given. These suggestions are more generic and formalized in a way that can improve any methodology of handling risks in an eternal perspective.

5.1. Comparison of the three examined activities

After having addressed the concerns related to the current methodologies for handling risk in a long-term perspective in the three different operations, some similarities regarding the approaches that were used, use can easily be seen. However, there are some inconsistences with the current risk concepts that were underlined in Chapter 3. But, also, they lack capturing some of the concerns related to the risk assessment in long-term perspective that were addressed in Chapter 4.

In Table 4, it is highlighted which are the approaches that are mostly used by the standards, but also, which of the important aspects of risk in an eternal perspective are not captured by the current methodologies. High (H) means that a lot of effort and focus is directed to the approach and that it is highly covered by the current methodologies in the application area. Medium (M) means that not much effort is invested into the approach apart from some comments related to them. Low (L) denotes that low or none effort is given by the current regulations related to the examined approach.

For example, all the three activities are focusing on probabilistic approaches of assessing risk and the performance of the implemented barriers. A lot of models or methodologies of combining modeling tools have been developed. Much effort is given into finding the best way to represent reality and predict the future. The aforementioned efforts aim to understand and explain the environment of the system and the related processes. They implement prescriptively the best available barrier solution and they examine the effectiveness of their performance by checking the probabilistic results with some predefined acceptance criteria. For instance, the probability of a specific radioactive leakage of the plant after 1,000 of years should be lower than a predetermined value.

However, according to the current risk concept and as it was explained in Chapter 4, risk is more than probabilities and consequences. The uncertainty dimension should also be covered through the assessment of the strength of knowledge upon which the probabilities and the surprises were based. All the aforementioned methods are based on current knowledge and assumptions. A state of the art barrier is characterized as such, based on the current best available techniques. The modeling of the natural processes and the scenarios that are used are based on our current understanding of nature and assumptions in order to simplify the world. But, the strength of knowledge upon which the risk assessments were based is not addressed properly in the current methodologies, so any changes related to it would not be captured.

Table 6: Level of focus on different risk assessment aspects based on the current methodologies

Activities / **Focused areas of the Assessment Approach**	Permanent Nuclear Waste Disposal	Plugging and Abandonment of wells in oil and gas industry	CO_2 Deep Geological Capture and Storage
Probabilistic Approach	H	H	H
Prescriptive Barrier Implementation	H	H	H
Performance Based Analysis of Barriers	H	H	H
Strength of Knowledge Assessment	M	L	L
Unforeseen events and resilience	L	L	M
Deviations over time	L	L	M
H: high focus, M: medium focus, L: low focus on the specific approach			

In a long time perspective reality will deviate from those initial assessments. Then, evaluation of those changes and possible actions will be needed in order to mitigate risk and put the system back to the favorite performance condition. In the three examined operations, the current methodologies do not allow any observation of these deviations. Solutions are made by using the best available technique at the time of the assessment which no one knows if it is good enough for the desired purposes.

This is related also to the unforeseen events. As it was explained in Chapter 4, there is an almost certainty that unpredicted events will occur in a long time perspective. Current methodologies on the three activities are not resilient enough to handle such events. Here it is meant that the system is resilient, if it has low probability of failing due to any type of event, also including unforeseen events (Aven & Krohn, 2013). In order to avert such unwanted events, one should be preoccupied with their existence and the possibility of their occurrence. All the deviations, both the expected and unexpected ones, should be noticed in order for actions to be taken. Out of the three activities, only in carbon dioxide storage the need of monitoring the area where the plant is in order to identify possible failures is mentioned. However, the exact means of how this will be achieved is not clear yet.

P&A EXAMPLE

Let us here use an example in order to understand what is meant with expected and unexpected deviations and the need of witnessing those. This example is applicable to all the three operations examined in Chapter 2. But here, for better understanding, think of an old abandoned offshore oil and gas facility and the hazard of hydrocarbon leakage to the sea through the plugged wells. For the sake of argument, assume that one is able to monitor the hydrocarbon leakage rate (the volume of the leaking hydrocarbons per time), in real time in the area. Then, for a very long time period of historical records it can be assumed that a possible illustration of the variation of the leakage rate could be the one shown in Figure 13. This is data recorded right after the well was plugged and abandoned. In general, four different focus areas with different characteristics of variations can be identified.

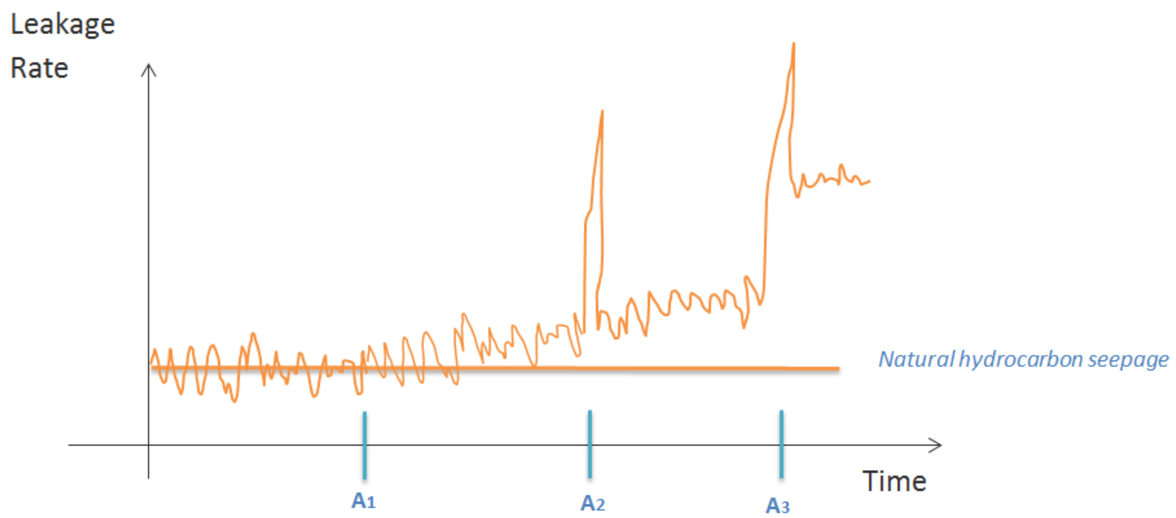


Figure 13: Historical records of hydrocarbon leakages on a plugged and abandoned well over a very long period.

During the first period (from the beginning until event A_1), the records show a normal variation close to the natural hydrocarbon seepage of the area. Then no actions are needed since the variations are low and show an expected variation. Those might be because of numerous different natural processes in the area, which were included in the assessment and create the natural seepage in the area. Then the abandoned well system is considered to perform properly without any failures of the barriers.

Suddenly, the results show that the rate of leakage, the volume of the leaking hydrocarbons per time, has a tendency to increase. This might occurred either because of a unique event, a continuous process or both, that suddenly started to affect the system and is witnessed by the monitoring results. Event A_1 could represent many possible events that were identified during the assessment and were expected before plugging the well. Such causal events could be, for example, physical changes of the system, such as barrier degradation or pressure development in the reservoir etc. If the indicator, the leakage rate, does not exceed the limit, the variation should be treated as normal or common cause variation (see Aven (2014)). However, the responsible group for monitoring should be alerted and observing continuously the trend and inform the decision makers. Then it is important to follow a broader management and judgment process considering the total risk picture of the plugged well system.

Events A_2 and A_3 caused unexpected variation, which led to high leakage volumes. Regardless the nature of the events, whether they have occurred because of internal or external sources, their outcome is what should concern the risk assessors. Both occasions show unexpected variance and significant deviation that were considered here to have exceeded the limit. Then attention should be given, and actions should be taken in order to mitigate the risk of an environmental pollution.

In this example there is also a difference between the two special cause variations, which are related to the state of the system after the accident. So, after event A_1 the leakage rate is back to normal levels, following the previous trend. Then, this could be translated as a false alarm or that the system passively balanced its state and mitigated the risks. Depending on the management judgments, after a reassessment of the risks has been executed, no actions might be necessary. On the other hand, after event A_3 the leakage rate remained high on levels above the limit. Then, it is reasonable to assume that the barriers of the system have failed and quick actions are needed in order to mitigate the consequences. For instance, such an event could be a blow out of the well, where great volume of hydrocarbons is leaking to the environment.

The aforementioned example highlights one of the concerns that were addressed in Chapter 4, which is related to the deviations from the planned performance that can occur in reality. Here, it is noted the need of observation of the system performance during the long time period that risk is assessed. This will add new knowledge to the assessors, who will update the risk or quality assessment of the system. The current methodologies are not resilient and sensitive to the operations, increasing the doubts of a good performance of the system in the future.

To conclude, after the comparison, it is evident that there is inconsistency between the new risk concept and the current methodologies of the three activities concerned. Those were chosen as representative examples of operations, where risk in an eternal perspective is concerned. However, after the review and the analysis it was proven that the way the activities are executed do not capture important aspects of risk, such as the deviation of the strength of knowledge and the occurrence of unforeseen events. It was shown, that in long time period those two aspects could change the risk assessment outcome that was initially estimated. The need understand the dynamic behavior of risk in time is vital in such operations and suggestions towards that direction are addresses in section 5.2.

5.2. Suggestions for improvement

It seems that even the best risk approach is not adequate enough to capture all the issues related to activities where uncertainties for the consequences exist for a very long period of time. Risk approaches are based on risk conceptualization, risk assessment and risk management. Since the future cannot fully be predicted, the validity of any risk approach done today will change in a long-term perspective. So, building resilience towards such changes requires both, a broader risk approach, but also a broader way of understanding, assessing and managing risks. An integrated approach where additional focus and equal importance is given on quality and socio-political aspects is essential. Quality improvement will add validity to the system and it will drive it to more positive consequences in the future obtaining the favorable performance. Regulatory framework and civil engagement will add transparency and trustworthiness to the solutions taken today regarding to the future generations.

The main aim of this chapter is to give suggestions towards this direction. It is the belief, that this will improve the inconsistences raised before. Obviously, there are many different routes that one can choose in order for improvements to be obtained; in this thesis the suggestion is based on three main pillars (see Figure 14):

1) An inclusive and up-to-date risk approach
2) Quality improvement over time
3) Adequate societal and governmental policies

Additionally, the importance that these pillars should be founded on the concept and the ideas of collective mindfulness, which is the fourth, last but not least aspect of the suggested approach, were highlighted. Collective mindfulness is a concept that has been studied a lot in the literature (see e.g. (Le Coze, 2013), (Weick & Sutcliffe, 2007), (Weick & Sutcliffe, 2006)). Here it is presented as mentioned by Aven (2014), which captures five main characteristics: preoccupation with failure, reluctance to simplify, sensitivity to operations, commitment to resilience and deference to expertise.

The suggested route presents a new way of thinking on understanding, assessing and managing risk mainly related to the capture of the foreseen unforeseen events. By foreseen unforeseen event, all these events occurring because of deviation from the initially planned performance are meant and which are foreseen to occur in a very long period of time. As highlighted throughout the thesis assessors should be aware of the occurrence of such events. It is a comprehensive approach that covers many aspects of risk apart from the probabilistic approach. It also involves broader stakeholders who are considered to be affected by the examined activities. These effects are not temporary and might not influence those that take the decision today. They will remain and be transferred to the next generations, so a transparent solution and methodology is needed.

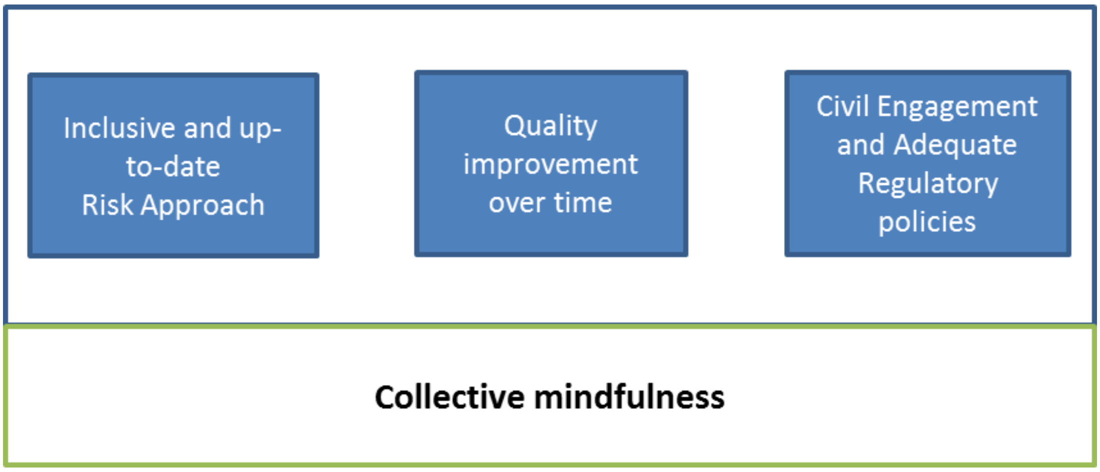


Figure 14: Main building blocks of the suggested framework for handling risk in a long perspective. This has three characteristics: 1)An inclusive and up-to-date risk approach , 2)Quality improvement over time, 3) Civil engagement and adequate regulatory policies, all based on the collective mindfulness concept.

5.2.1. Inclusive and up-to-date risk approach

By saying inclusive and up-to-date risk approach, the need of a comprehensive risk approach which includes all the aspects of risk, probabilities, knowledge and surprises, as well as an updated approach which reflects the most recently prevailing risk conceptualization, risk assessment and risk management methods is highlighted. It is based on three characteristics (see Figure 15):

Figure 15: The main building blocks of the suggested risk approach based on (Aven & Krohn, 2013)

i) An appropriate and prevailing risk conceptualization

It is important the participants in the risk assessment and management to have a common and suitable understanding of risk in line with the idea of looking beyond probabilities. The discussed risk concept was presented in Chapter 2 and captures the understanding of risk definition and the risk description, the distinguishing between robustness and resilience in line with foreseen and unforeseen events, the practical risk concept of probabilities, knowledge ad surprises, etc. The bottom line is that assessors, decision makers and anyone else that is involved in the activity should have a common and updated framework related to risk aspects and the most updated risk approach. The update is important, since it will add validity to the conceptualization. For many years the science of risk has been developing and it will continue for the next generations.

ii) A state-of-the-art risk assessment

A risk assessment should be seen as a supporting tool for decision makers. It gives a useful insight about the risks, where to mitigate it and what alternatives exist. It identifies and describes hazards related to the activity based on the knowledge and assumptions. A state-of the art risk assessment does not simply assign probabilities to the different outcomes. It goes beyond those numbers and assesses also the knowledge that risk description was based on. In long term, focus should be given to the validity of the risk assessment and assessing this by updating and improving it over time. A state-of-the-art risk assessment is one that is in highest possible level at one period of time.

iii) A state-of-the-art risk management

Risk management refers to all the actions taken to manage risk, and is concerned with finding a trade-off between value creation and avoiding the undesirable consequences. It should not be driven only by the results of the risk assessment, but include them in a wider decision making context. Based on Aven (2013), this is called a managerial review and judgments process that takes into consideration other aspects, as well as which were not included in the risk assessment. It considers the limitations, simplification and assumptions that the assessment was based on. In long term, new measures and updated risk management solutions could be used. Cautionary and precautionary principles have a very important role in the examined activities, since weight should be given to the deep uncertainties. Based on these principles, risk management should build on robustness and resilience. A state-of-the-art risk management on handling risk in a long term perspective cannot use probability-based risk acceptance criteria. On the contrary, the ALARP principle that focuses also on the uncertainty dimension and strength of knowledge that supports the probabilistic analysis should be used (Aven, 2013).

5.2.2. Quality improvement over time

Here, quality refers to aspects of the quality theory and quality discourse as firstly mentioned by Shewhart (1931, 1939) and discussed by many others later on (Deming , 2000), (Aven & Krohn, 2013). It covers issues that sometimes are claimed to be non-measurable, but they are important for increasing the quality of the system enhancing its resilience. For example, the benefit of the training especially in long term cannot be measured, maybe the cost, but not the benefits. But emphasizing the cautionary principle and thinking of the unexpected outcomes that can occur as a surprise in long term due to current deep uncertainties is a cornerstone on building resilience.

The quality theory concepts and ideas are also discussed in relation to continuous improvement over the long period of time focusing on the deviations and changes as aforementioned in the thesis. However, nowadays focus is given on deviations from the objectives, like the objective performance and goal of components. Focus should be given on the overall performance, since components are not always independent and sometimes meeting one goal might decrease the flexibility regarding other aspects and therefore losing as a whole. History, like for example Macondo accident, has shown that a combination of small deviations and incidents occurring at the same time can lead to major accidents. It is not only important to distinguish between common-cause deviations and special cause variation and act only on the occurrence of the latter, but also consider the implications of the former at the whole system.

Finally, over time, knowledge should be gained, which will be built on theory. Otherwise, observation and experience have no meaning. In P&A, for example, knowledge and experience is relatively new. New operations will be held but every time will be based on new theories and knowledge which was gained from the previous experience. In long term this is highly important, so is the activity to improve continuously using the basic steps: plan, do, study and act. This is something what lacks from in the current operations that were discussed in the thesis, but are essential in order to validate the goodness of the risk management solutions. All the key aspects of the quality management and improvement over time are summarized in the list shown in Figure 16.

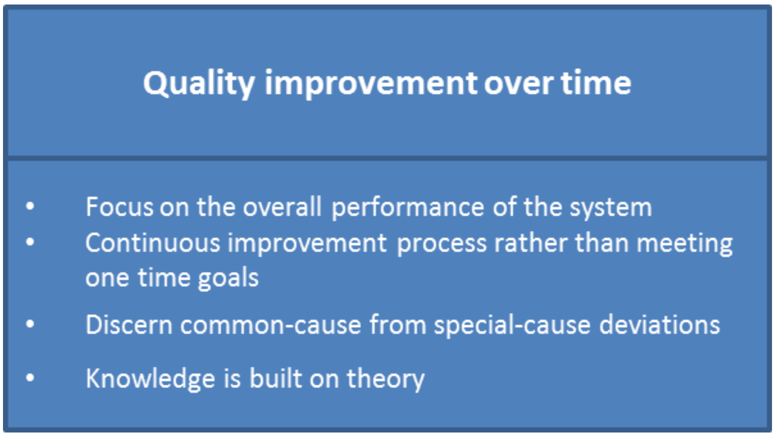


Figure 16: The key characteristics of the suggested ideas related to quality improvement over time (based on (Aven & Krohn, 2013)

5.2.3. Civil Engagement and Adequate regulatory policies

This is the third and last main pillar of the suggested route, which adds a more socio-political character to the way risks should be handled in a long time perspective (see Figure 17). As the consequences of the operations will last for a very long period of time, a question is raised on who should take the responsibility for maintaining acceptable risk or for a potential future accident. For instance, think of the P&A operation and the accident of a significant hydrocarbon leakage one hundred years after the abandonment of the well. Based on the current methodologies, it is not clear who is responsible to monitor this leakage and who is responsible to act in order to mitigate the failure. The importance of a comprehensive regulatory framework between government and operators, but also among the influenced countries is great. Those should engage the interests of the societies affected, since it is not only on the jurisdiction of the decision maker or the current government to decide upon issues that can influence many generations in the future.

This is a sensitive issue and at least stakeholders like society should feel that they are engaged on the final decision in a wider perspective. That will add transparency and trustworthiness to the solution. Think of the nuclear waste management and the Yucca Mountain disposal plant, where societies raised concerns resulting in halt to the operation. Moreover, consequences that pollute the environment should not be seen as a local problem but also from a broader point of view as well. Intergovernmental agreements upon solutions are necessary in order to add validity on these. A general safety oversight of the operations is important in a macro perspective. In the P&A example a general overview of the safety situation of all the plugged wells will be needed. With thousands of wells plugged in the North Continental Shelf, countries need to have knowledge about the situation and be preoccupied with the idea that leakages might occur and action will be needed. This is in line with the first characteristic of the collective mindfulness concept. Countries should be sensitive to operations in order to observe the signals and the warnings before or after accidents. Finally, the main purpose of the solutions is to transfer a safer world to the next generations by implementing enduing solutions and giving maintains a flow of knowledge through generations.

Civil Engagement and Adequate regulatory policies

- Deference to societal interest
- Both intergovernmental and governmental adequate strategies
- Safety oversight
- Enduing and safe solutions for future generations

Figure 17: The key characteristics of the suggested ideas related to quality improvement over time

5.2.4. Collective mindfulness

The collective mindfulness concept, as it was formed in the High Reliability Organizations (HROs) studies, consists of five main characteristics, which are show in Figure 18.

Collective mindfulness

I. Preoccupation with failure
II. Reluctance to simplify
III. Sensitivity to operations
IV. Commitment to resilience
V. Deference to expertise

Figure 18: The key characteristics of the collective mindfulness concept based on Aven (2013)

The first characteristic of the collective mindfulness concept is preoccupation with failures. Risk is, to a large extent, about variations, accidents, not observing the goals, etc. It is important, therefore, that those hazards are identified in the risk assessment. It is essential for assessors to check a list of all the potential failures and if the means implemented are not sufficient, new measures should proposed. Especially, in long term, on should be ready to see failures and deviations since these will occur sooner or later.

Assessment should not be oversimplified. Assessors should handle risk in a complex world, out of the traditional regimes of using only probabilities and losses, illustrated just on matrices. Avoiding great simplifications means that one should not come to risk judgments conclusions derived only by such simple tools.

Moreover, assessors should be focused on observing failures and be sensitive to operations. It is vital that signals and warnings of unwilling or unexpected outcomes are detected. In a long term, it is almost certain that such indicators will occur. Therefore, it is essential that those risks are understood. There is, of course, a challenge here of identifying the “false” alarms or those that are not that influencing. Therefore, acting critically is important in order for one to take the right decision to solve the problem and obtain the best possible outcome.

One additional characteristic is commitment to resilience. Perfection is almost impossible to be achieved, especially in long term perspective. Therefore, moving to a more resilient system in order to deal with unknown accidents and hazards could be the only way to secure success in the future. By definition, resilience is related to the risk of an activity given the occurrence of any type of event A. Those can even be surprises, unexpected events to the assessors who were involved in the risk assessment. Resilience is in line with cautionary principle, which states that in case of risk, caution should be shown, meaning that actions and measures should be taken to mitigate risk.

Last but not least, in a complex risk picture, experts from different fields need to work together, in order to come on agreements. For example, in the P&A paradigm, geoscience experts, drilling and reservoir engineers, climate researchers and others need to cooperate and share their knowledge, in order to explain the environment and the possible phenomena as thorough as possible. The need of such joints and communication is greater when long-term risk is concerned. It is meaningful for the sake of validity that different experts are involved, expressing potentially a variety of opinions about the issue. It is important to note here that a common conceptual framework would be essential in order for such a communication to be held.

Chapter 6

6. Discussion and conclusions

6.1. Discussion

The main goal of the thesis was to review current methodologies of handling risk in an eternal perspective. The reason of the review was to identify any inconsistencies related to the current risk perspective. In order to understand these inconsistences, an analysis of the uniqueness of these activities was done. In this way it is clear what is different, when risk is assessed in a very long time period, compared to traditional risk assessment methodologies. Having understood this and after highlighting some of the common and critical gaps of the current methodologies, suggestions were given aiming to improve the way risk is understood, assessed and managed today.

Firstly, the permanent disposal of nuclear radioactive waste was reviewed, because it is an activity that handles highly dangerous materials and aims to find permanent solutions in order to mitigate potential catastrophic consequences for both the environment and humans. The review showed that although the deep geological disposal is considered as the best solution, it has not been implemented yet. Deep uncertainties related to the phenomena and the firm disagreement by the society has halted current trials of establishment of the method. Probabilistic approaches assessing different scenarios are used currently based on assumptions and simplifications that are not adequately examined. The deviations from the initial assessment over time and the long-term consequences of the activity are still unclear.

The second activity, which was examined, was that of plugging and abandonment of wells in the oil and gas industry. Since most of the oil and gas production operations come to an end, the need for safely abandoning the wells in the fields is increasing. The review showed that regulations define prescriptive barrier solutions of specific lengths and position of concrete plugs throughout the borehole. It also highlighted the lack of robustness and resilience in a sense that if a foreseen or unforeseen event occurs there are normally no means to mitigate them apart from completely replugging the well. Signals and warnings of deviations from the desired performance of the system are missing. Similarly, carbon dioxide capture and storage, the third activity which was examined, showed common inconsistencies with the current prevailing risk concept.

All the activities showed common based implications focusing and implementing solutions based on probabilistic risk assessments, performance based assessments or using conservatively the best available techniques. Although, some of them mention the uncertainty factor and the fact that there is lack of knowledge in eternity, no trials were done to build on resilience for the future.

In the thesis, the need for a critical update of the risk assessment was highlighted. The validity of the risk assessment and the measures that were taken after the risk management will change in time. The main cause is that the environment around the system is dynamic and changes, for example, the pressure in the reservoir in P&A, the level of degradation of the barriers, etc. Current solutions and estimations are based on some knowledge and assumptions that might be proven inadequate over time. New hazards might occur and, therefore, new models will be needed, as well as new measures in order to mitigate risks.

Based on these needs for handling risk in an eternal perspective, suggestions were given characterized by three main pillars, which should be based on the collective mindfulness concept. These do not focus only on the risk based approach, which includes a common and up-to-date conceptual framework and state-of-the-art risk assessment and risk management, but they are also based on the continuous quality improvement and management of the system and the commitment to engage society establishing an adequate regulatory policy. A continuous update of knowledge and information based on new theories and experience gained through years will make the system more resilient to unforeseen events. Avoiding stable procedures but being more dynamic allowing stressors, deviations and variances will lead the system to a high performance in long term.

6.2. Conclusion

Current methodologies of activities that deal with risk in a long time perspective are inadequate to handle the associated deep uncertainties. They lack resilience in handling both foreseen and unforeseen hazards that may eventually occur. Fundamental improvements of the current practices are needed so that they are able to capture critical deviations from the planned performance, in line with the new non-probabilistic and time dependent risk concept.

Since the future cannot be fully predict, the validity of any risk assessment done today will change in a long-term perspective. Building resilience towards such changes requires both (i) a broader, but inclusive assessment methodology and (ii) a continuous observation of occurred changes and potential update of the assessments. In this thesis it the kind of changes to current approaches which are needed in a risk assessment framework in order to build resilience towards future changes and events was addressed. A framework, where risk the two dimensional combination of the uncertainties and the future consequences is used, and uncertainty is characterized along probability, knowledge and surprise dimensions.

Here, a suggestion of further research and efforts are needed, in order to determine how uncertainties propagate in time, or how knowledge changes and in which ways these should should be assessed in long term perspective. New technologies or joints of different research fields might be needed in order to capture all the uncovered aspects of risk. For example, in P&A or CCS, the use of satellites combined with sensors in the subsurface or the seabed of the ocean and involving digitalization for covering real time the field could help monitoring the level of seepage in the ocean and identify failures on existing plugged wells. History has shown that our understanding of nature is constantly changing and if humans do not want to be in the mercy of unforeseen and catastrophic events, establishment to non-stable approaches are needed, methodologies that are flexible and agree to their environment.

Appendix A

Further information in detail about the operations discussed in Chapter 2

This appendix provides further information related to more technical or detail issues on the operations discussed in Chapter 2. The aim is to give the reader a better understanding of what was discussed in the main part of the thesis, where focus was given on the risk aspects. Believing that the technical issues of the activities are also important, here, some of them are presented to provide further clarification. This would give the opportunity to some of the readers to add some background knowledge to the discussed issues in case they do not have any. Here, work of different researchers and additional information of reports are presented, to which our justifications were based.

A1. Nuclear waste disposal

In the current methodology of the nuclear power production and treatment, the chain starts from the mines where uranium is collected and after series of processes is enriched enough to be used in the reactors. After the reactors, there is a need of temporary storage, around five years (depending on the radioactivity of the waste), in pools where all the radioactive fuel is cooling off. But since those pools hold three - quarters of the spent nuclear fuel (SNF), there is one quarter held in dry casks on concrete pads. This is a storage method demand that increases since the wet storage pools are filled. After the temporary storage, there is reprocessing of the fuel that either is sent back to conversion or mixed to enriched uranium and again in the reactor or is sent to permanent disposal. However, not all nuclear waste is the same and there is also a variety of disposal techniques from landfills to long term geologic storage.

As shown in Figure A 1, the permanent disposal of highly radioactive waste, which is the last stage of the whole nuclear fuel production chain, remains recently a “black box”.

All the nations are still working on the possible solutions for permanent disposal, but no such facility has yet been put into operation. Until now every nation that considers long term waste disposal management plans to use deep mined geologic repository as a solution. Many other thoughts have been shared as possible solutions, such as deep boreholes, which might hold promise in the long-term but they are still at early development stage (BRC, 2012).

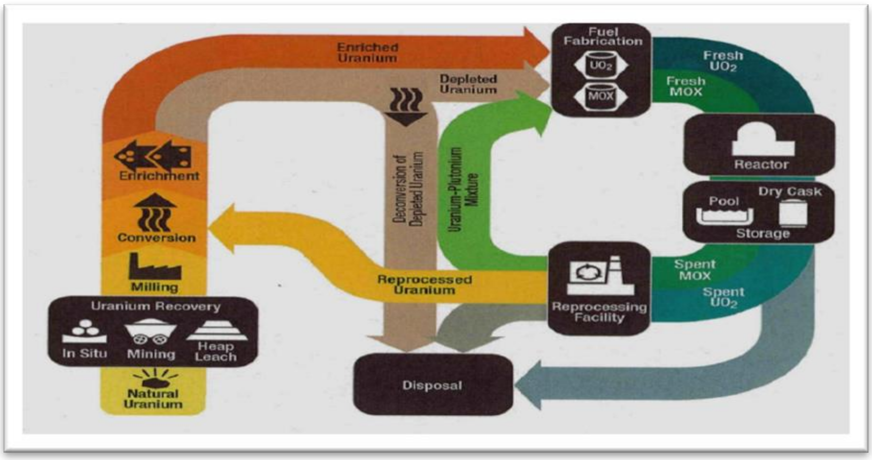


Figure A 1: Nuclear fuel cycle (Wagman, 2013)

Each country, depending on the plants that facilitates, has in place different measures or plans to dispose wastes. Focusing here only on the disposal options, the countries that do so are examined. From those countries, when intermediate or high level waste disposal is concerned, only Finland and Sweden have achieved to select publicly acceptable sites. All the rest are in preliminary stages of site selection. And only in New Mexico in USA there is a disposal facility under operation; capturing radioactive fuels under thick layers of salt formation.

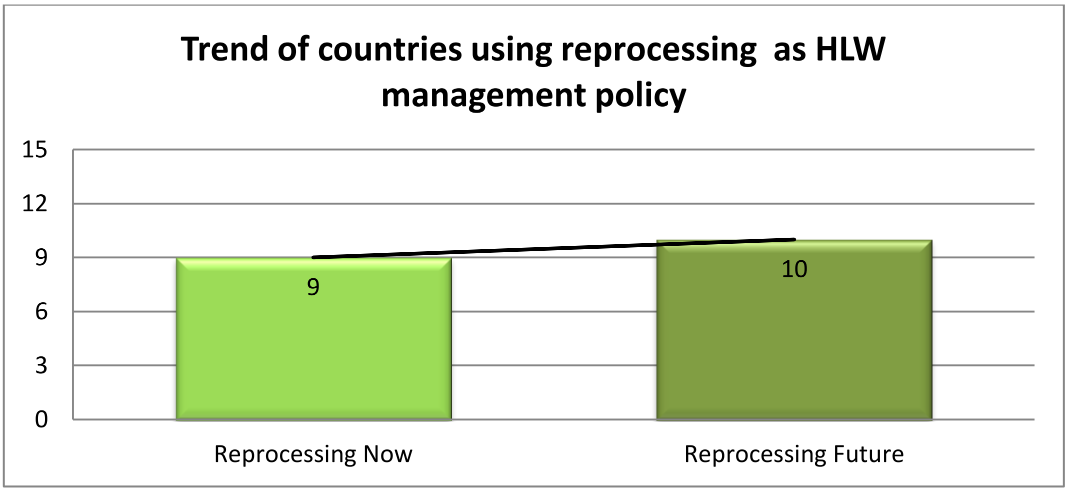
Table A 1: Waste management for used fuel and HLW from nuclear power reactors (World Nuclear Association, 2015)

Country	Policy	Facilities and progress towards final repositories
Belgium	Reprocessing	• Central waste storage at Dessel • Underground laboratory established 1984 at Mol • Construction of repository to begin about 2035
Canada	Direct disposal	• Nuclear Waste Management Organisation set up 2002 • Deep geological repository confirmed as policy, retrievable • Repository site search from 2009, planned for use 2025
China	Reprocessing	• Central used fuel storage at LanZhou • Repository site selection to be completed by 2020 • Underground research laboratory from 2020, disposal from 2050
Finland	Direct disposal	• Program start 1983, two used fuel storages in operation • Posiva Oy set up 1995 to implement deep geological disposal • Underground research laboratory Onkalo under construction • Repository planned from this, near Olkiluoto, open in 2020
France	Reprocessing	• Underground rock laboratories in clay and granite • Parliamentary confirmation in 2006 of deep geological disposal, containers to be retrievable and policy "reversible" • Bure clay deposit is likely repository site,operating 2025

Country	Policy	Facilities and progress towards final repositories
Germany	Reprocessing but moving to direct disposal	• Repository planning started 1973 • Used fuel storage at Ahaus and Gorleben salt dome • Geological repository may be operational at Gorleben after 2025
India	Reprocessing	• Research on deep geological disposal for HLW
Japan	Reprocessing	• Underground laboratory at Mizunami in granite since 1996 • • Used fuel and HLW storage facility at Rokkasho since 1995 • Used fuel storage under construction at Mutsu, start up 2013 • NUMO set up 2000, site selection for deep geological repository under way to 2025, operation from 2035, retrievable
Russia	Reprocessing	• Underground laboratory in granite or gneiss in Krasnoyarsk region from 2015, may evolve into repository • Sites for final repository under investigation on Kola peninsula • Pool storage for used VVER-1000 fuel at Zheleznogorsk since 1985 • Dry storage for used RBMK and other fuel at Zheleznogorsk from 2012 • Various interim storage facilities in operation
South Korea	Direct disposal, wants to change	• Waste program confirmed 1998, KRWM seat up 2009 • Central interim storage planned from 2016
Spain	Direct disposal	• ENRESA established 1984, its plan accepted 1999 • Central interim storage at Villar de Canas from 2016 (volunteered location) • Research on deep geological disposal, decision after 2010
Sweden	Direct disposal	• Central used fuel storage facility – CLAB – in operation since 1985 • Underground research laboratory at Aspo for HLW repository • Osthammar site selected for repository (volunteered location)
Switzerland	Reprocessing	• Central interim storage for HLW and used fuel at ZZL Wurenlingen since 2001 • Smaller used fuel storage at Beznau • Underground research laboratory for high-level waste repository at Grimsel since 1983 • Deep repository by 2020, containers to be retrievable
United Kingdom	Reprocessing	• Low-level waste repository in operation since 1959 • HLW from reprocessing is vitrified and stored at Sellafield • Repository location to be on basis of community agreement • New NDA subsidiary to progress geological disposal

Country	Policy	Facilities and progress towards final repositories
USA	Direct disposal but reconsidering	• DoE responsible for used fuel from 1998, accumulated $32 billion waste fund • Considerable research and development on repository in welded tuffs at Yucca Mountain, Nevada • The 2002 Congress decision that geological repository be at Yucca Mountain was countered politically in 2009 • Central interim storage for used fuel now likely

Table A 1 and the column charts in Figure A 2 show the inconsistency among the different national policies around the world. Both reveal the Gordian knot of permanent disposal that governments are asked to solve, since even the countries that have agreed on the deep geological disposal do not operate any yet. Primarily, governments try to avoid and reduce the waste generation at source. The more they process the radioactive wastes and preserve them in pools to decay significantly the lower their activity level is and easier to handle in the future.



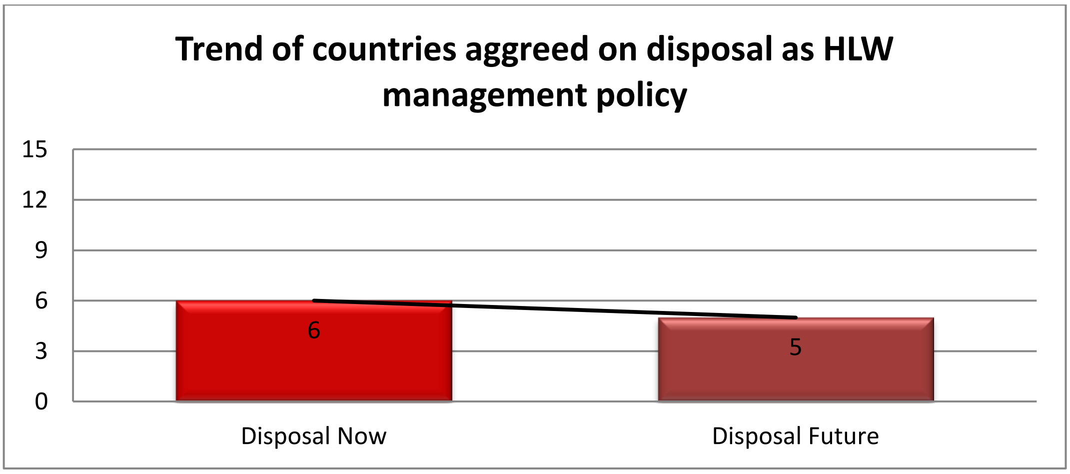


Figure A 2: Column charts of the waste treatment policy trends among fifteen examined countries based on current statements

In deep geological disposal waste is buried in depths of 250m to 1,000m for mine repositories or 2,000m to 5,000m for boreholes. As shown in Table A 2, there are many different types of deep geological disposal depending on the geologic formations in each nation and the waste fuel that needs to be disposed. Deep geologic disposal is achieved by using both engineered and natural barriers (rock, salt etc) and it is considered to pass no responsibility to next generations for maintenance. It is a multi-barrier concept where the waste is firstly packaged (into steel and glass, as mentioned before) then disposed in a man-made repository under natural geologic barriers (see one example in Figure A 3).

Table A 2: Disposal options (World Nuclear Association, 2015)

Option	Types	Comments
Deep geological disposal Mined repositories or Deep Boreholes (commonly-accepted)	Mined repositories Deep boreholes Disposal in clay, Europe Disposal in layered salt strata or domes	• At depths between 250m and 1,000m for mined repositories, or 2,000m to 5,000m for boreholes • Combination of engineered and natural barriers (rock, salt, clay) • Most countries with high-level and long-lived radioactive waste have investigated deep geological disposal and it is official policy in various countries (variations also include multinational facilities). • The only purpose-built deep geological repository for long-lived ILW that is currently licensed for disposal operations is in the USA. • Well advanced in Finland, Sweden, France and the USA • Commenced in Canada, UK
Near-Surface disposal (commonly-accepted)	At ground level or in caverns below ground level	• Only for low level radioactive waste (LLW) or intermediate low level waste (ILW) • At ground level or in depths of tens of meters • Interim waste storage • Not concerned for the purpose of the thesis

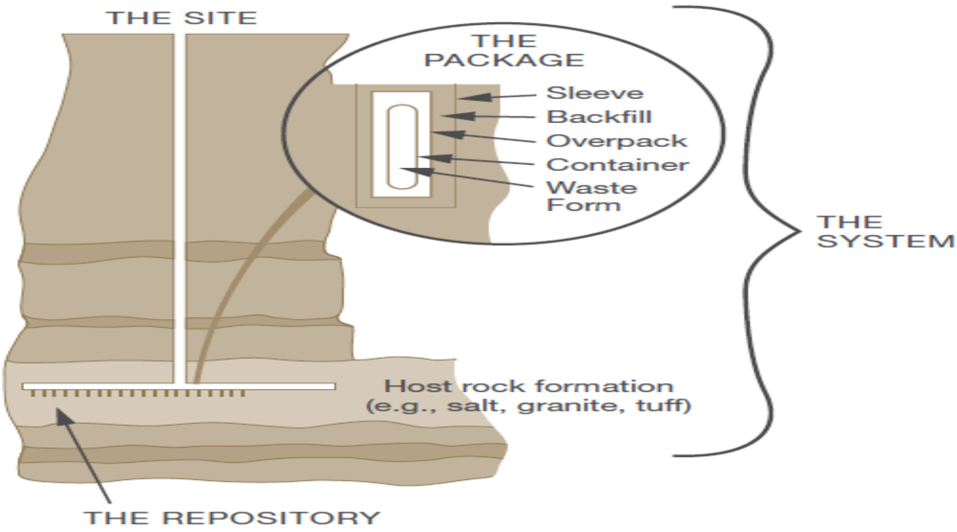


Figure A 3: Mined geologic disposal concept (BRC, 2012)

Although radioactive waste is extremely dangerous for exposed populations and ecosystems, it has the ability to diminish over time. During the first few hundred years the activity of the wastes declines significantly and it continues to do so gradually thereafter (see Figure A 4). Today's waste management methods take advantage of this decline by storing high-level waste in ponds or in pools. After recycling the used fuels higher radioactive fuels are generated. Those in liquid state are solidified and vitrified into glass, encapsulated into heavy steel cylinders and stored for eventual geologic disposal. The temporary storage can last for 40-50 years when the heat and radioactivity of the waste has fallen to one thousandth of the level at removal (World Nuclear Association, 2015). On the other hand, permanent disposal aims to keep the waste buried for more than 1,000 years. Then according to studies the radioactivity has decayed to natural levels.

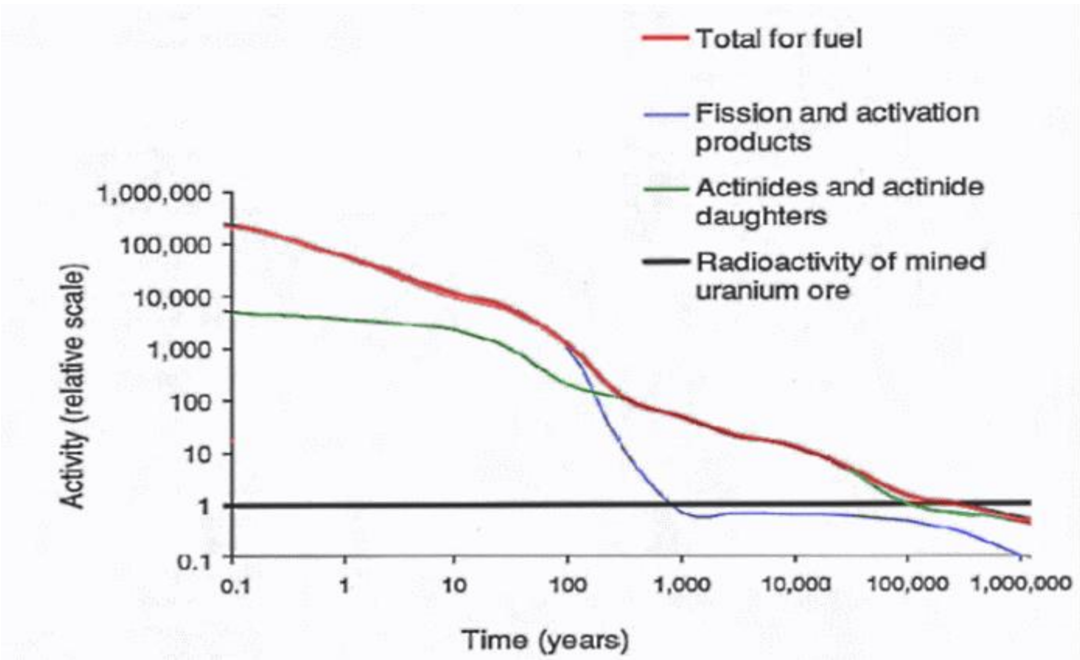


Figure A 4: Relative activity of spent nuclear fuel with a burn-up of 38 MWd/kg U (NEA, 2010)

Hazards

Main safety focus on the nuclear industry safety management is to protect people and environment from radioactive substances. Apart from the operational hazards during the production, there is that of spent fuel and the high level radioactive wastes (HLW) that need to be disposed. The hazards that first arise if they are constituent (see Figure A 5), which are radioactive, are leaked into air or water. As long as those remain trapped under the sealing structures, there is no harm. However, in short term, high levels of temperature and overheating might damage those barriers, therefore excessive cooling is needed. By contrast, in long term, in geologic disposal corrosion process or unexpected disruptive events might be the reason of radioactive leakages to the environment. Likewise, HLW, which are produced by the chemical reprocessing of the spent fuel, can mobilize radioactive material to groundwater after corrosion or seismic and volcanic activity has occurred.

Radiation has the ability to change the structure of molecules, including those that are found in the tissues of living organisms like humans. Humans are continuously exposed to radioactivity by means such as medical operations, space, industrial etc. However, those quantities are relatively small compared to an accumulated leakage of radioactive disposed fuel. High exposure to radiation (more than 5Sv) could lead to death within a few few weeks or months (see Figure A 6). Moreover any lower exposure to radiation could potentially lead to cancer or genetic effects for humans (BRC, 2012). Both of them, and especially the latter, are long-term risks that humanity is exposed to and its consequences are very difficult to handle.

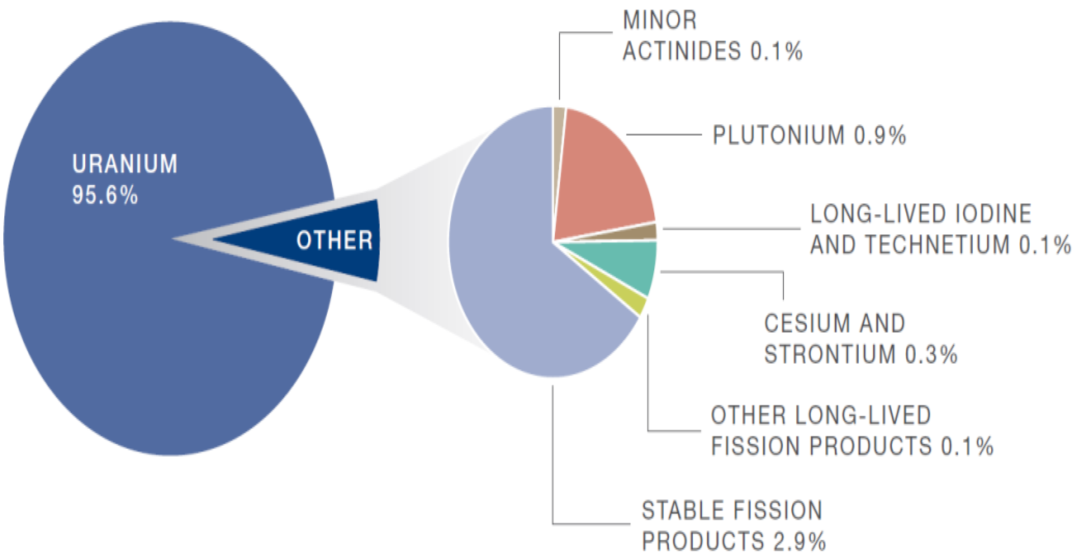
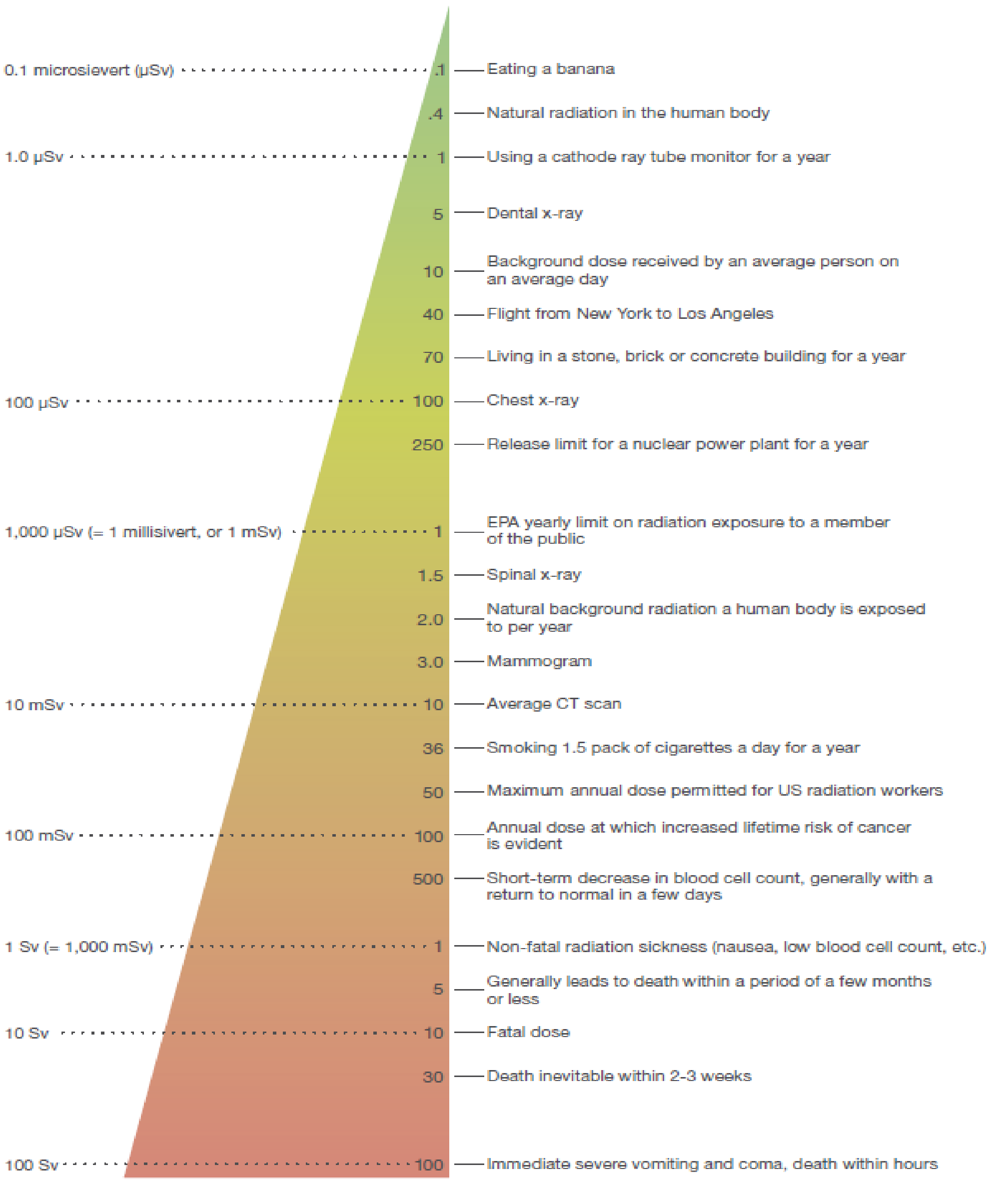


Figure A 5: Composition of spent nuclear fuel after 10 years of cooling (BRC, 2012)



Source: BRC staff using information from various sources[15]

Note: Risk depends on both the total dose and how quickly it was received.
Rem is an older term for radiation exposure, now replaced by the sievert, with 1 Sv = 100 rem.

Figure A 6: Comparison of radiation doses (BRC, 2012)

Methodology and Regulations

Here the general waste disposal methodology that is currently used in nuclear industry is presented. The decision of the waste process to be followed is being developed in a higher level according to national legislation, national authorities' requirements, international and national standards and international agencies' recommendations. For example, IAEA disposal of radioactive waste standards set out the essential requirements that need to be followed by the organizations throughout the disposal process (IAEA, 2011). Those cover all the phases and aspects of the disposal process, from the planning and designing phase to the posterior of the closure of the disposal facility (see Figure A 7). The requirements aim to drive governments, national authorities and operators to meet predefined acceptance criteria regarding radiation exposure. For closed disposal facilities, for instance, the standards set six acceptance criteria related to radiation protection of human and the environment that need to be met; annual public dose exposure of 1mSv, dose constraint of 0.3mSv in case of a natural processes etc. In a lower level, operator is in charge of executing the safety assessment and the regulatory authority verifies the assessment.

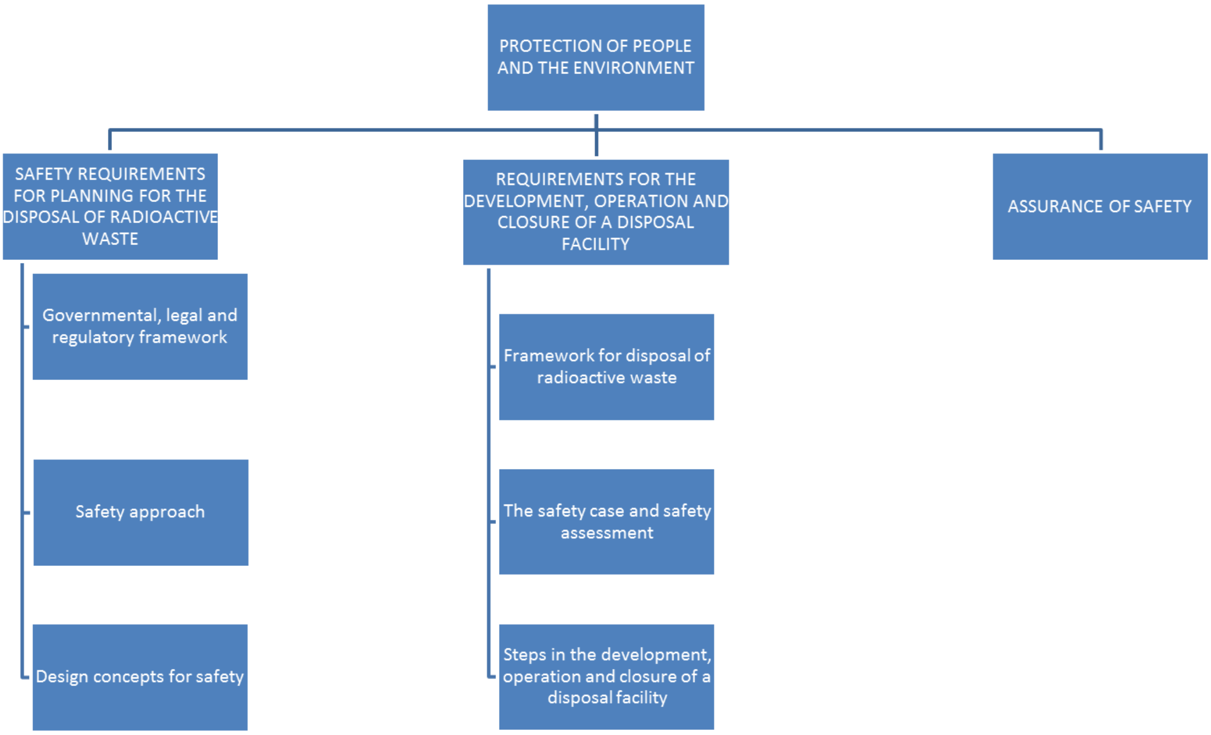


Figure A 7: A schematic illustration of the topics covered by the requirements according IAEA 2011

The first step of the waste management methodology is the waste characterization based on the activity of the waste and the time it needs to recover to its natural levels (Figure A 8). In order for poor characterization to be avoided the point of origin, physical state, type of waste and prior processes need to be examined. In relation to the regulatory control, the concepts of exclusion, exemption and clearance are used (Maringer, et al., 2013).

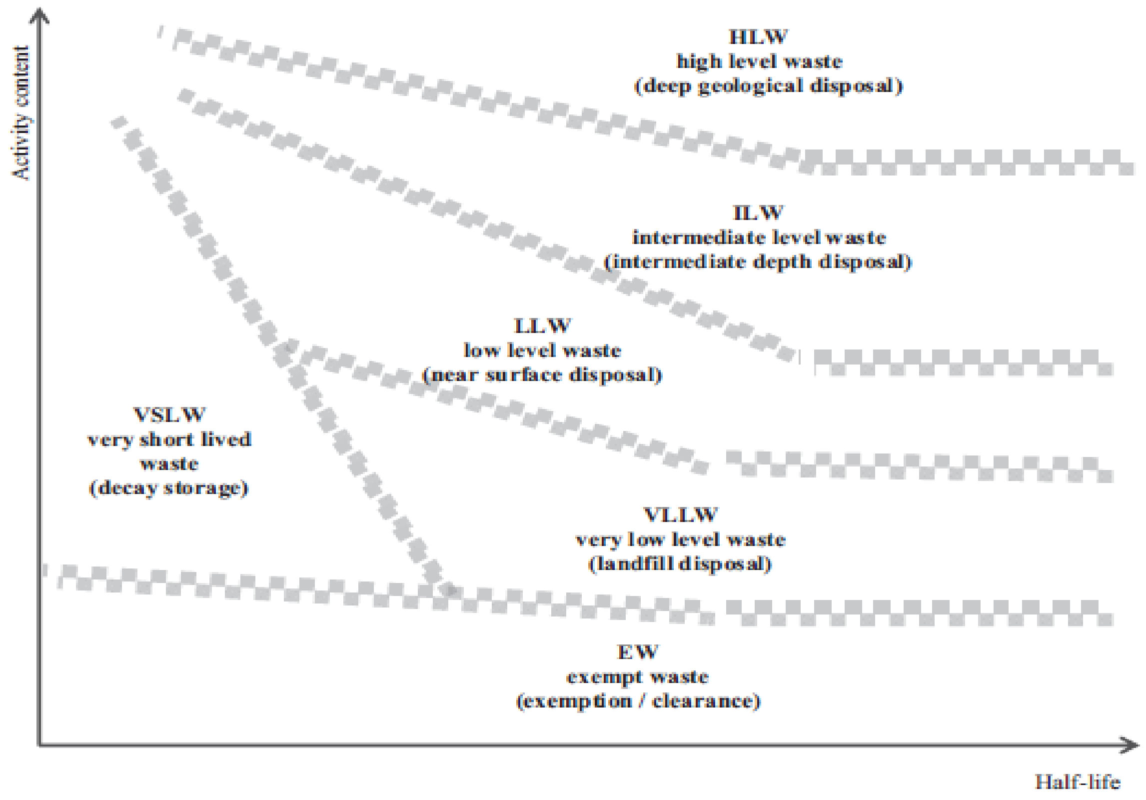


Figure A 8: Conceptual illustration of waste classification scheme (IAEA, 2009)

Exclusion refers to the category of exposure that is deliberately excluded from the range of control by the regulatory authority.

Exemption is employed in a practice concept and it can be submitted to both natural and artificial origin radionuclides by using two main acceptance criteria (Maringer, et al., 2013):

i) *the effective dose of activity that people will be exposed by the exempted practice should not be over 10 µSv in a year,*

ii) *the collective effective dose caused by one year of activity of the practice is less than approximately 1 Sv or an evaluation performed for the optimization of protection points towards exemption as the optimum solution.*

Lastly, with the term clearance process of dismissal within authorized process posterior to the regulatory control is defined. Figure A 9 summarizes schematically the role and the place of each of the three processes.

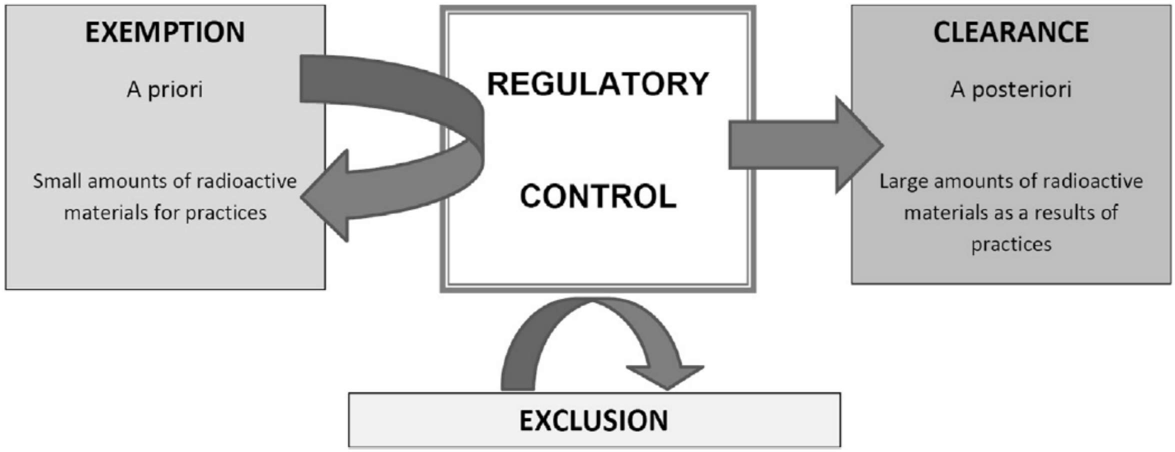


Figure A 9: Relation of exclusion, exemption and clearance to regulatory control (Maringer, et al., 2013)

According to the International Atomic Energy Agency (IAEA) and its report of 2009 (IAEA, 2009), about countries, which choose the waste classification process, follow some steps as shown in Figure A 10 in order to determine the disposal options. According to this, all the possible waste treatment options are assessed before the final decision for permanent disposal is made (the option of landfill disposal, low level disposal, and intermediate disposal).

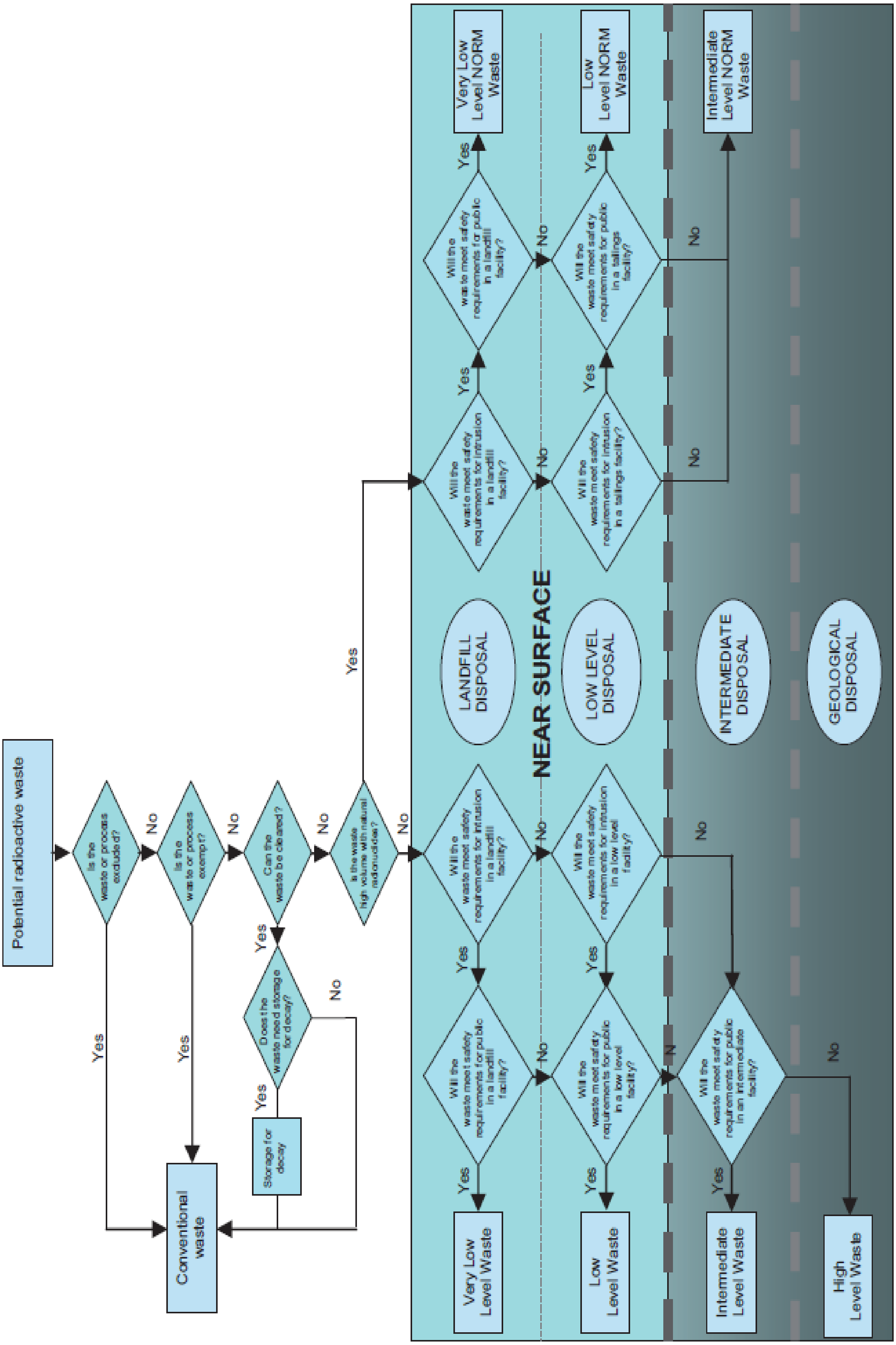


Figure A 10: An illustration of the use of the classification scheme (IAEA, 2009)

A2. P&A of offshore wells

The current standard for P&A, NORSOK D-010 (NORSOK D-010, 2004) requires complete containment of the hydrocarbons indefinitely. The proposed plugging design is that of Figure A 11 and it aims to isolate the fluids in the geologic reservoir trap and prevent those from migrating to the seabed and from there to the environment.

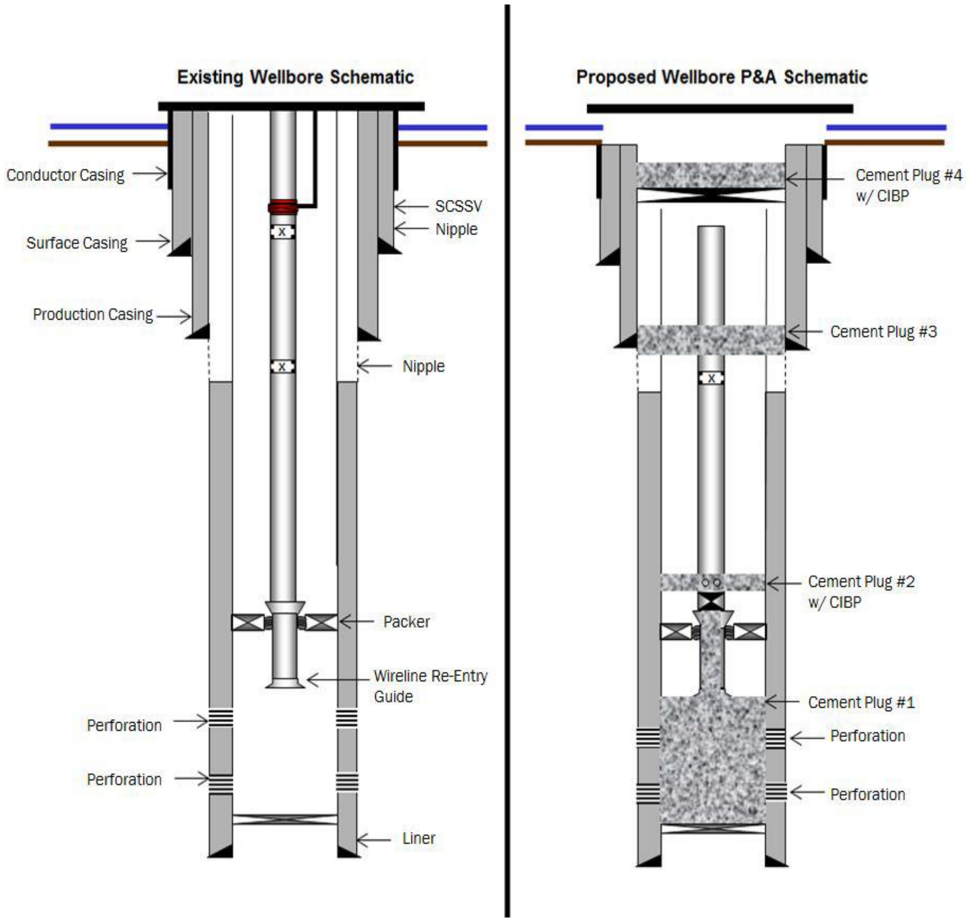


Figure A 11: Schematic of well barriers in permanent plugging and abandonment (TSB Offshore, 2015)

In order to do so, operators should secure that the design and the barriers used are robust enough to withhold for eternity. There are four criteria that need to be fulfilled in order for the aforementioned goal to be achieved:

1. <u>Length</u>

The length of a plug must be sufficient so that it can be qualified as permanent. The length of the cement plug is based on some requirements and it varies prescriptively from fifty to some hundreds of meters.

2. <u>Cross Section</u>

The barriers must extend across the full cross section of the well and seal the structure both vertically and horizontally.

3. <u>Positioning</u>

The plugs should be positioned in a depth with sufficient formation integrity. Therefore, it is important that operators examine and know the minimum formation stress at the base of the barrier.

4. <u>Verification</u>

All the three aforementioned criteria must be verified. This is done through logging, pressure testing and load testing. Operators need to know the number of well barriers you need which varies from well to well depending on permeability, pressure and the existence or not of hydrocarbons.

Hazards

The main risks from a P&A activity is environmental pollution and consequently sea life affection. That can occur because of hydrocarbon leakage from the reservoir to the seabed. There are many ways that a leakage can occur. For instance, improper abandoned wells can leak in a short or long term perspective. Unexpected events, such as geologic tectonic moves and earthquakes can break formations and barriers. Related to the first example, the integrity of the plugs is critical, since as seen in Figure A 12 liquid can find various paths through the plugged borehole system. Note, here, that focus is given on potential hazards related to the engineered/man made parts of the system and not the natural, since the latter could not have been prevented in any case.

Some of the main threats that are related to improperly abandoned wells are (King, 2009): i) Contaminated surface water entry (minerals, bacteria, waste, etc.), ii) Surface leakage from the zones that are in relatively shallow depths through well or leaking cement sheath, iii) leakage from an aquifer to surface and the opposite, iv) Danger of open well to surface egress falling down the well.

Depending on the quantity of leakage, the effect can be hazardous for the environment instantly or in long term. All wells either plugged or not, interact with the marine environment in some extent. Wells create a preferable pathway for gas and oil migration. Therefore, natural seepage or hydrocarbons originated by deeper sources aggregate around wells. Natural processes, like corrosion or faults on the barriers could potential lead to accumulation of hydrocarbons on the seabed and leakage to the sea. Some of those can dissolve within the water column or reach the sea surface in a droplet form. However, how hazardous the consequences of a leakage are to the environment varies and it is not easily predicted. Apart from the hydrocarbon quantity leaked, it depends on the marine conditions, the location and the vulnerability of the environment.

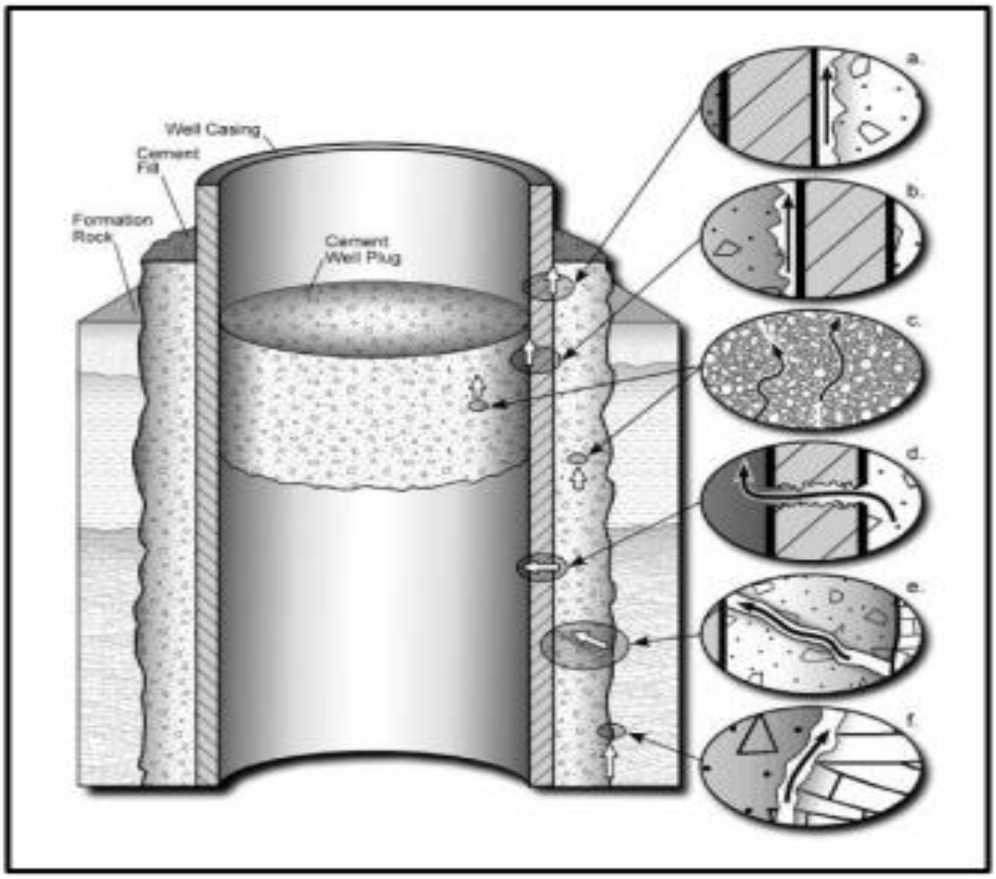


Figure A 12: Failure modes for seepage pathways (Nygaard, 2010)

Standards and regulations

Current operations are done according to NORSOK D-010 standards, which, according to the industry, are narrow and demand significant expenditures by operators. Most of the current regulations in NCS are performance-based where companies have to show that their solutions meet the criteria. The positive outcome of it is that new technologies and innovations can be implemented. The current standard for P&A in Norway, NORSOK D-010 (NORSOK D-010, 2004), requires complete containment of the hydrocarbons for eternal perspective. The deep uncertainties and the lack of knowledge related to the consequences in such far future make the current regulations conservative and prescriptive.

The standard requires permanent well barriers with fixed dimension and positions depending on the quality of the well casing and the number or type of reservoir. Permanent well barriers should have the following properties: i) impermeable, ii) long term integrity, iii) non-shrinking, iv) ductile (non-brittle) able to withstand mechanical loads, v) resistance to chemicals/ substances, wetting, to ensure bonding to steel (NORSOK D-010, 2004). The material used, nowadays, and it is believed to fulfill or the abovementioned criteria is cement and a combination of this with other barriers (see Table A 3).

Table A 3: Well barrier elements, features, requirements and guidelines (NORSOK D-010, 2004)

Element Name	Additional features, requirements and guidelines
Casing	Accepted as permanent WBE if cement is present inside and outside
Casing cement	Accepted as a permanent WBE together with casing and cement inside the casing. Should alternative materials be used for the same function a separate WBEAC shall be developed.
Cement plug	Cased hole cement plugs used in permanent abandonment shall be set in areas with verified cement in casing annulus. Should alternative materials be used for the same function a separate WBEAC shall be developed. A cement plug installed using a pressure tested mechanical plug as a foundation should be verified by documenting the strength development using a sample slurry subjected to an ultrasonic compressive strength analysis or one that have been tested under representative temperature and/or pressure.
Completion string	Accepted as permanent WBE if cement is present inside and outside the tubing.
Liner top packer	Not accepted as a permanent WBE.
WBE = well barrier element WBEAC = well barrier element acceptance criteria	

Additionally, NORSOK D-010 (NORSOK D-010, 2004) defines the requirements that the barriers should fulfill regarding design, selection and constructions. Appropriate barriers should be selected, such that:

- It can withstand the maximum anticipated differential pressure it may become exposed to,
- It can be leak tested and function tested or verified by other methods,
- No single failure of well barrier or WBE leads to uncontrolled outflow from the borehole / well to the external environment,

- Re-establishment of a lost well barrier or another alternative well barrier can be done,
- It can operate competently and withstand the environment for which it may be exposed to over time,
- Its physical location and integrity status of the well barrier is known at all times when such monitoring is possible.

The standard also adds that the barriers, either primary or secondary, shall, to the extent possible, be independent of each other. Whereas, if common WBEs exists operators should perform risk analysis and apply reducing measures in order to mitigate risk as low as reasonably practicable (ALARP principle).

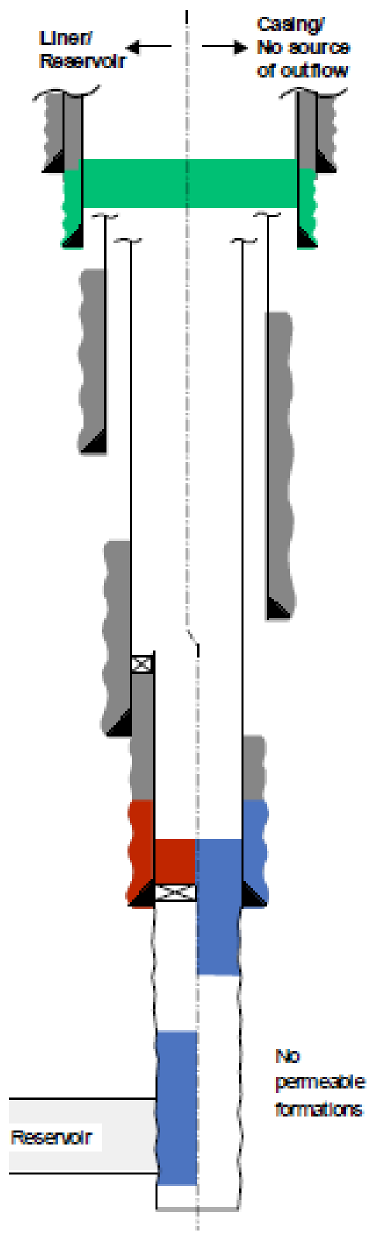
As far as the plugging and abandonment program is concerned, the standard requires the following information (NORSOK D-010, 2004):

a) Well configuration (original, intermediate and present) including depths and specification of permeable formations, casing strings, primary cement behind casing status, well bores, side-tracks, etc.
b) Stratigraphic sequence of each wellbore showing reservoir(s) and information about their current and future production potential, where reservoir fluids and pressures (initial, current and in an eternal perspective) are included.
c) Logs, data and information from primary cementing operations in the well.
d) Estimated formation fracture gradient.
e) Specific well conditions such as scale build up, casing wear, collapsed casing, fill, or similar issues

It is also mentioned that the uncertainties around the design of the abandonment well barriers should be accounted for. Those are related to (NORSOK D-010, 2004):

- Downhole placement techniques,
- Minimum volumes required to mix a homogenous slurry,
- Surface volume control,
- Pump efficiency/ -parameters,
- Contamination of fluids,
- Shrinkage of cement.

9.8.3 Permanent abandonment - Open hole



Well barrier elements	See Table	Comments
Primary well barrier		
1. Cement plug	24	Open hole.
or, ("primary well barrier, last open hole"):		
1. Casing cement	22	
2. Cement plug	24	Transition plug across casing shoe.
Secondary well barrier, reservoir		
1. Casing cement	22	
2. Cement plug	24	Cased hole cement plug installed on top of a mechanical plug.
Open hole to surface well barrier		
1. Cement plug	24	Cased hole cement plug.
2. Casing cement	22	Surface casing.

Notes

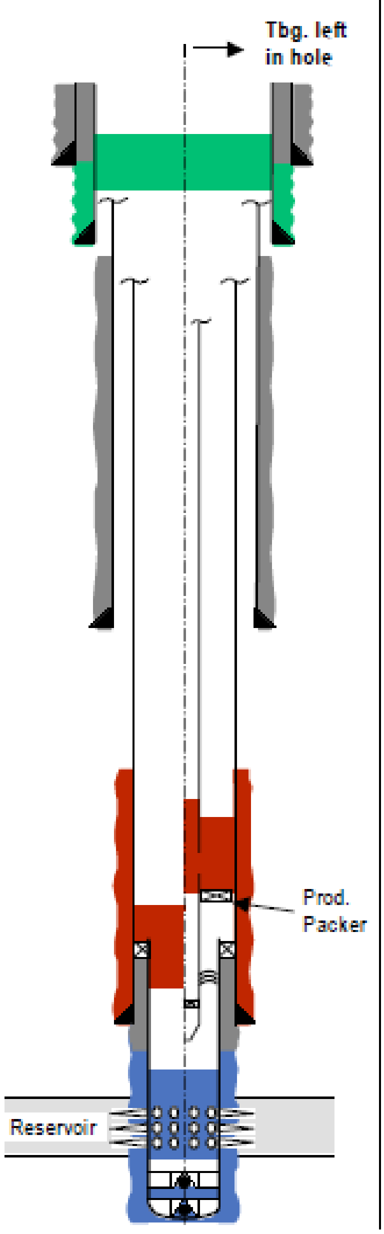
a. Verification of primary well barrier in the "liner case" to be carried out as detailed in Table 22.

b. The well barrier in deepest casing shoe can for both cases be designed either way, if casing/liner cement is verified and O.K.

c. The secondary well barrier shall as a minimum be positioned at a depth where the estimated formation fracture pressure exceeds the contained pressure below the well barrier.

Figure A 13: wellbore design of permanent abandonment- open hole

9.8.4 Permanent abandonment - Perforated well



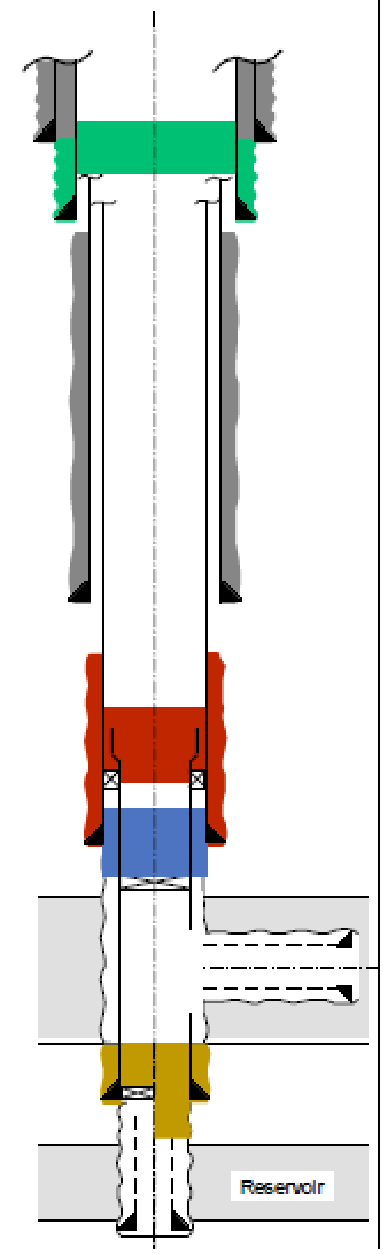
Well barrier elements	See Table	Comments
Primary well barrier		
1. Liner cement	22	
2. Cement plug	24	Across and above perforations.
Secondary well barrier, reservoir		
1. Casing cement	22	
2. Cement plug	24	Across liner top.
or, for tubing left in hole case:		
1. Casing cement	22	
2. Cement plug	24	Inside and outside of tubing.
Open holes to surface well barrier		
1. Cement plug	24	
2. Casing cement	22	Surface casing.

Notes

1. Cement plugs inside casing shall be set in areas with verified cement in casing annulus.
2. The secondary well barrier shall as a minimum be positioned at a depth where the estimated formation fracture pressure exceeds the contained pressure below the well barrier.

Figure A 14: wellbore design of permanent abandonment- Perforated well

9.8.5 Permanent abandonment - Multibore with slotted liners or sand screens



Well barrier elements	See Table	Comments
Barrier between reservoirs		
1. Casing cement	22	
2. Cement plug	24	Cased hole.
or,		
2. Cement plug	24	Transition plug across casing shoe.
Primary well barrier		
1. Cement plug	24	Across wellbore and casing shoe.
Secondary well barrier, reservoir		
1. Casing cement	22	
2. Cement plug	24	Casing plug across liner top.
Open Holes to surface wellbarrier		
1. Cement plug	24	Cased hole cement plug.
2. Casing cement	22	Surface casing.

Notes

1. The "well barrier between reservoirs" may act as the primary well barrier for the "deep" reservoir, and "primary well barrier" may be the secondary well barrier for "deep" reservoir, if the latter is designed to take the differential pressures for both formations.
2. Secondary well barrier shall not be set higher than the formation integrity at this depth, considering that the design criteria may be initial reservoir pressure, as applicable in each case.

Figure A 15: wellbore design of permanent abandonment- Multibore well

15.22 Table 22 – Casing cement

Features	Acceptance criteria	See
A. Description	This element consists of cement in solid state located in the annulus between concentric casing strings, or the casing/liner and the formation.	
B. Function	The purpose of the element is to provide a continuous, permanent and impermeable hydraulic seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids, resist pressures from above or below, and support casing or liner strings structurally.	
C. Design, construction and selection	1. A design and installation specification (cementing programme) shall be issued for each primary casing cementing job. 2. The properties of the set cement shall be capable to provide lasting zonal isolation and structural support. 3. Cement slurries used for isolating permeable and abnormally pressured hydrocarbon bearing zones should be designed to prevent gas migration. 4. The cement placement technique applied should ensure a job that meets requirements whilst at the same time imposing minimum overbalance on weak formations. ECD and the risk of lost returns during cementing shall be assessed and mitigated. 5. Cement height in casing annulus along hole (TOC): 5.1 **General:** Shall be 100 m above a casing shoe, where the cement column in consecutive operations is pressure tested/the casing shoe is drilled out. 5.2 **Conductor**: No requirement as this is not defined as a WBE. 5.3 **Surface casing**: Shall be defined based on load conditions from wellhead equipment and operations. TOC should be inside the conductor shoe, or to surface/seabed if no conductor is installed 5.4 **Casing through hydrocarbon bearing formations**: Shall be defined based on requirements for zonal isolation. Cement should cover potential cross-flow interval between different reservoir zones. For cemented casing strings which are not drilled out, the height above a point of potential inflow/ leakage point / permeable formation with hydrocarbons, shall be 200 m, or to previous casing shoe, whichever is less. 6. Temperature exposure, cyclic or development over time, shall not lead to reduction in strength or isolation capability. 7. Requirements to achieve the along hole pressure integrity in slant wells to be identified.	ISO 10426-1 Class 'G'
D. Initial verification	1. The cement shall be verified through formation strength test when the casing shoe is drilled out. Alternatively the verification may be through exposing the cement column for differential pressure from fluid column above cement in annulus. In the latter case the pressure integrity acceptance criteria and verification requirements shall be defined. 2. The verification requirements for having obtained the minimum cement height shall be described, which can be • verification by logs (cement bond, temperature, LWD sonic), or • estimation on the basis of records from the cement operation (volumes pumped, returns during cementing, etc.). 3. The strength development of the cement slurry shall be verified through observation of representative surface samples from the mixing cured under a representative temperature and pressure. For HPHT wells such equipment should be used on the rig site.	
E. Use	None	
F. Monitoring	1. The annuli pressure above the cement well barrier shall be monitored regularly when access to this annulus exists. 2. Surface casing by conductor annulus outlet to be visually observed regularly.	WBEAC for "wellhead"
G. Failure modes	Non-fulfilment of the above requirements (shall) and the following: 1. Pressure build-up in annulus as a result of e.g. micro-annulus, channelling in the cement column, etc.	

Figure A 16: Acceptance criteria of casing cement

15.24 Table 24 – Cement plug

<table>
<tr><th>Features</th><th>Acceptance criteria</th><th>See</th></tr>
<tr><td>A. Description</td><td>The element consists of cement in solid state that forms a plug in the wellbore.</td><td></td></tr>
<tr><td>B. Function</td><td>The purpose of the plug is to prevent flow of formation fluids inside a wellbore between formation zones and/or to surface/seabed.</td><td></td></tr>
<tr><td>C. Design, construction and selection</td><td>1. A design and installation specification (cementing program) shall be issued for each cement plug installation.
2. The properties of the set cement plug shall be capable to provide lasting zonal isolation .
3. Cement slurries used in plugs to isolate permeable and abnormally pressured hydrocarbon bearing zones should be designed to prevent gas migration.
4. Permanent cement plugs should be designed to provide a lasting seal with the expected static and dynamic conditions and loads down hole
5. It shall be designed for the highest differential pressure and highest downhole temperature expected, inclusive installation and test loads.
6. A minimum cement batch volume shall be defined for the plug in order that homogenous slurry can be made, to account for contamination on surface, downhole and whilst spotting downhole.
7. The firm plug length shall be 100 m MD. If a plug is set inside casing and with a mechanical plug as a foundation, the minimum length shall be 50 m MD.
8. It shall extend minimum 50 m MD above any source of inflow/ leakage point. A plug in transition from open hole to casing should extend at least 50 m MD below casing shoe.
9. A casing/ liner with shoe installed in permeable formations should have a 25 m MD shoe track plug.</td><td>API Standard 10A Class 'G'</td></tr>
<tr><td>D. Initial verification</td><td>1. Cased hole plugs should be tested either in the direction of flow or from above.
2. The strength development of the cement slurry should be verified through observation of representative surface samples from the mixing cured under a representative temperature and pressure.
3. The plug installation shall be verified through documentation of job performance; records fm. cement operation (volumes pumped, returns during cementing, etc.).
4. Its position shall be verified, by means of:
<table>
<tr><th>Plug type</th><th>Verification</th></tr>
<tr><td>Open hole</td><td>Tagging, or measure to confirm depth of firm plug.</td></tr>
<tr><td>Cased hole</td><td>Tagging, or measure to confirm depth of firm plug
Pressure test, which shall
a. be 7000 kPa (~1000 psi) above estimated formation strength below casing/ potential leak path, or 3500 kPa (~500 psi) for surface casing plugs, and
b. not exceed casing pressure test, less casing wear factor which ever is lower
If a mechanical plug is used as a foundation for the cement plug and this is tagged and pressure tested the cement plug does not have to be verified.</td></tr>
</table></td><td></td></tr>
<tr><td>E. Use</td><td>Ageing test may be required to document long term integrity.</td><td></td></tr>
<tr><td>F. Monitoring</td><td>For temporary suspended wells: The fluid level/ pressure above the shallowest set plug shall be monitored regularly when access to the bore exists.</td><td></td></tr>
<tr><td>G. Failure modes</td><td>Non-compliance with above mentioned requirements and the following:
a. Loss or gain in fluid column above plug.
b. Pressure build-up in a conduit which should be protected by the plug.</td><td></td></tr>
</table>

Figure A 17: Acceptance criteria of cement plug

DNV GL's P&A Guideline 2015

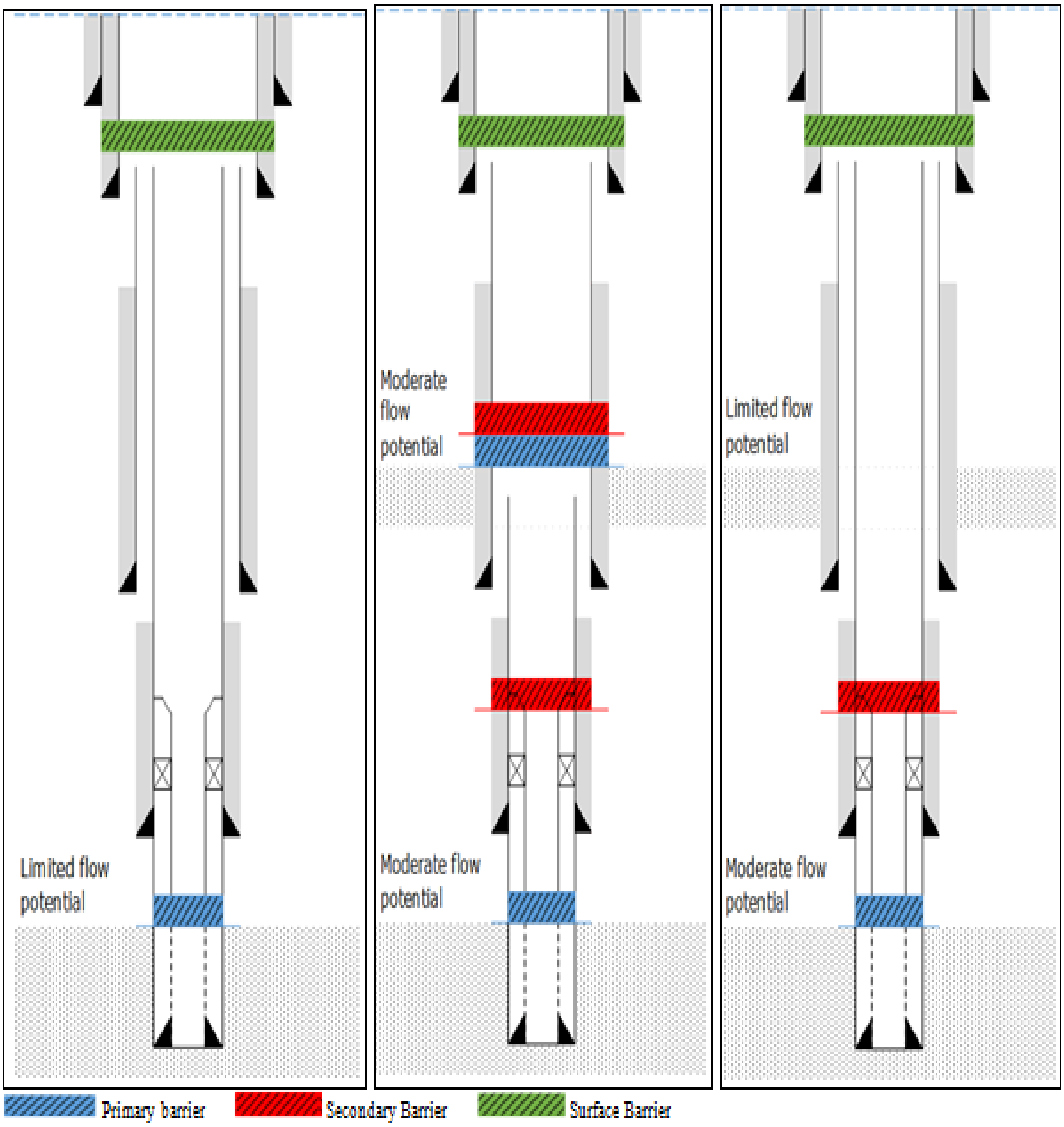


Figure 3-1: Example of permanent abandonment for one hydrocarbon-bearing formation with limited flow potential (DNV GL, 2015)

Figure 3-2: Example of permanent abandonment for two hydrocarbon-bearing formations with moderate flow potential in overburden (DNV GL, 2015)

Figure 3-3: Example of permanent abandonment for hydrocarbon-bearing formation with moderate flow potential and with limited flow potential in the overburden (DNVGL 2015)

Figure A 18: Examples of permanent abandonment for different flow potentials and number of hydrocarbon-bearing formations.

A3. CO_2 Capture and Storage

CO_2 capture and geologic storage aim to prevent CO_2 to the atmosphere by capturing CO_2 from different sources. This is achieved by transporting it with pipelines and injecting it into deep geologic formations appropriate for this purpose (see Figure A 19).

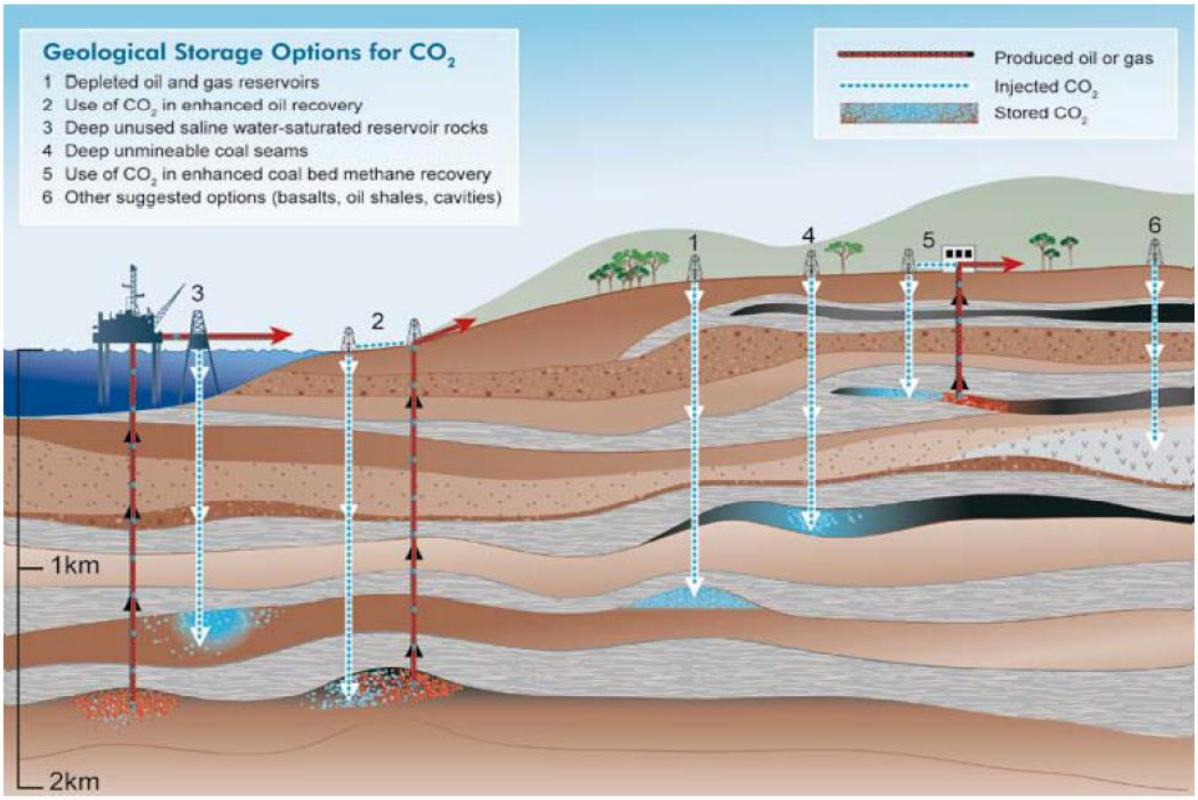


Figure A 19: Options for storing CO_2 in deep underground geological formations (IPCC, 2005)

Important aspect of the activity is the process of characterization of the storage site. It is important for both, the maximum capacity of the site and its capability to meet the safety requirements to be assessed. The characterization is done by collecting and analyzing all the geological data. When this is done and the total amount of CO_2 has been injected the field needs to be abandoned. The barrier system is the same as in oil and gas plugging and abandonment (see Figure A 20). In a broad sense, the technique is the same with plugs and casings of cement. However, particular care should be taken to use sealing material that can resist degradation from CO_2.

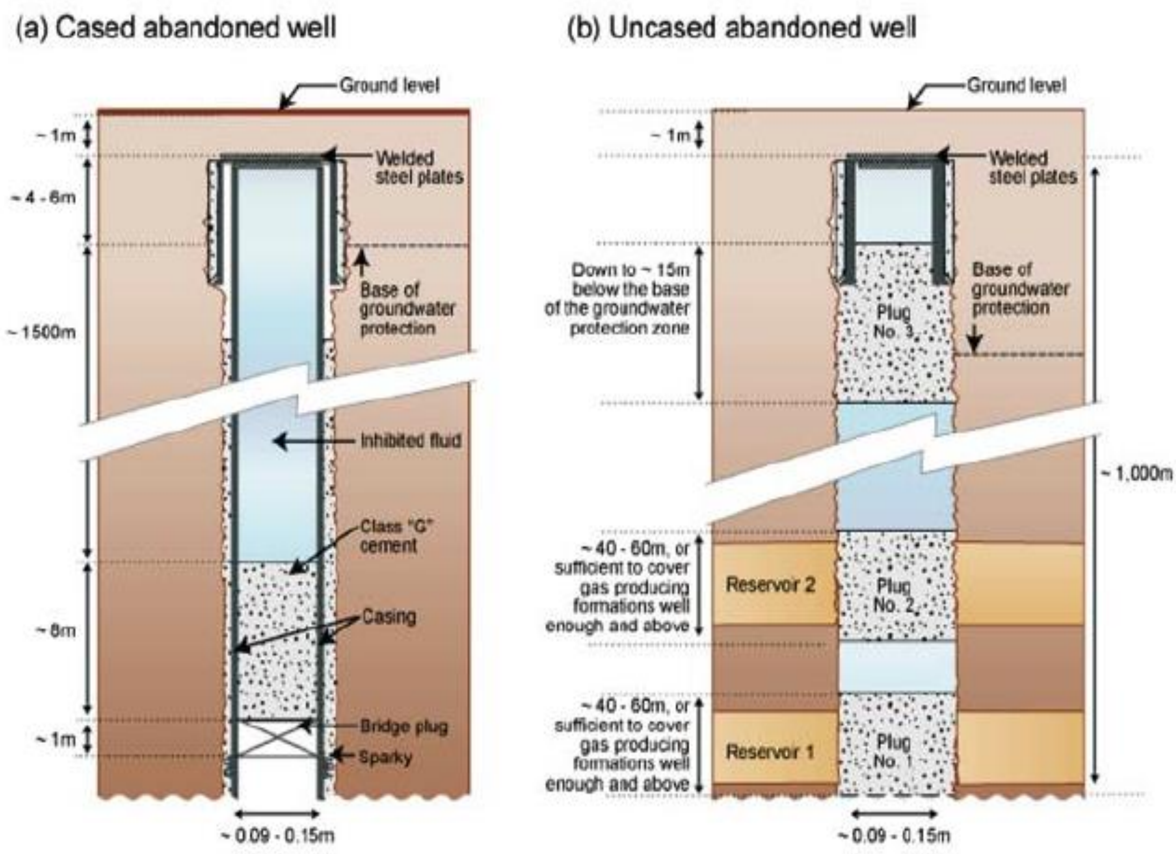


Figure A 20: Examples of how cased and uncased wells are abandoned today. Special requirements may be developed for abandoning CO2 storage wells, including use of corrosion-resistant cement plugs and removing all or part of the casing in the injection interval and caprock. (IPCC, 2005)

The environmental risks of CO_2 geological storage can be both local and global. Global effects are related, not only to the uncertainties of the consequences of any leakages that can occur, but also the general effectiveness of the solution. Locally, health, safety and environment can be threatened because of three reasons:

I. Direct effects of elevated gas-phase CO_2 accumulated in shallow subsurface aquifers
II. Effects of dissolved CO_2 on ground water chemistry
III. Effects of displacements of fluids by the injected CO_2

As in plugging and abandonment of offshore oil and gas wells, here as well, CO_2 can escape from formations in the following ways (see Figure A 21):

- Through the pores of the seals rocks if pressure increases
- Through openings, fractures or faults of the caprock
- Through manmade pathways, such as poorly abandoned preexisting wells

The consequences of such leakages vary. Drinkable water in the shallow aquifer can be polluted, especially in onshore sites. Escaped CO_2 will either migrate from the bottom of the seabed to the atmosphere or it will be dissolved. The latter will have a biological impact on the marine organisms. In case of sudden and great leakages in fields where operations are still executed, workers on the platforms are in danger.

Similarly to the P&A of oil and gas production wells, CO_2 injection abandoned wells are the most vulnerable and may provide possible pathways. All the cement plugs and anthropomorphic barriers that have been used according to current regulations consisting of different physical properties. Therefore, several potential pathways are inherited as a result of the uncertainty of the barrier integrity, as showed in Figure A 12. Additionally, in CCS the increased concentration of carbon dioxide lets the fluid to corrode the cement barriers faster than in the conventional cases without CO_2 injection.

Lastly, CO_2 effect on human health and safety is relatively well understood. For instance, it is known that physiological and toxicological negative responses to increased CO_2 concentrations exist. Concentration variations from 2% to 10% can cause from strong effects on respiratory physiology to death respectively.

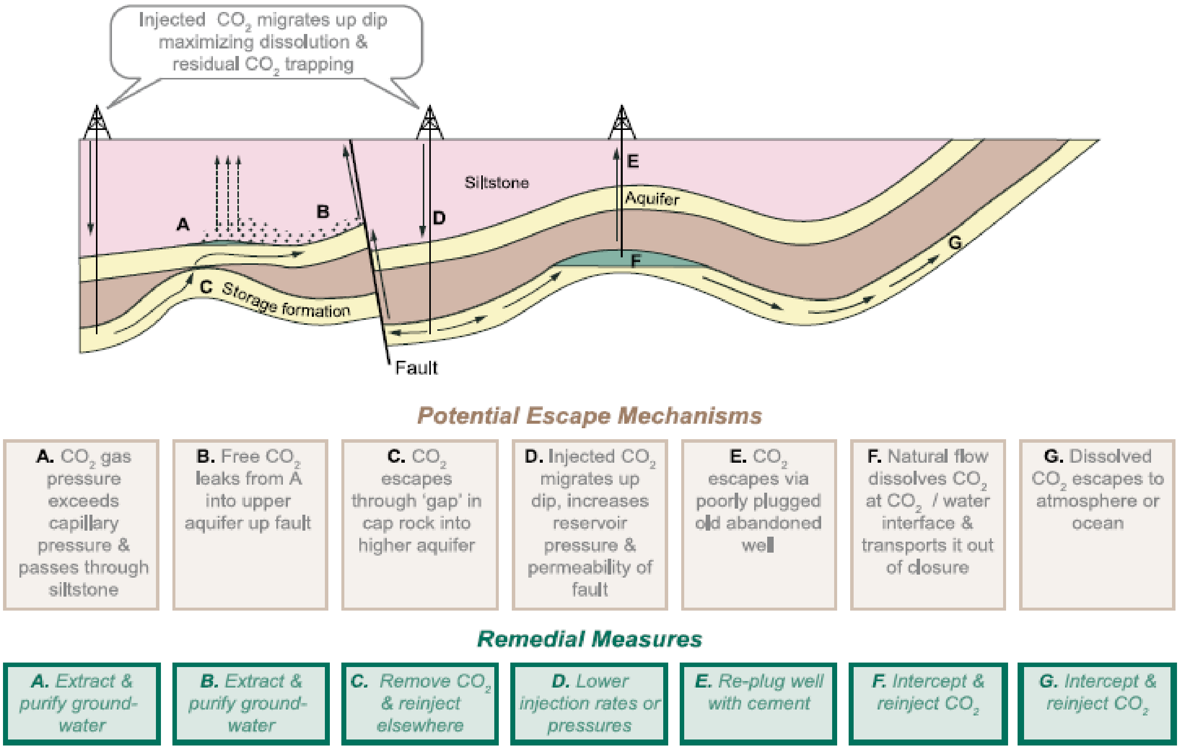


Figure A 21: Some of the potential stored CO_2 escape routes (IPCC, 2005)

Appendix B

A summary of risk definitions and terminology

This appendix summarizes the terminology used in the thesis related to risk assessment and risk management. This is done because it is considered important for the reader to have the same conceptual framework and a common language. Unless otherwise stated, it is in line with the international standards ISO (2009a) and Aven (2014), which are considered the most recent and updated terminologies.

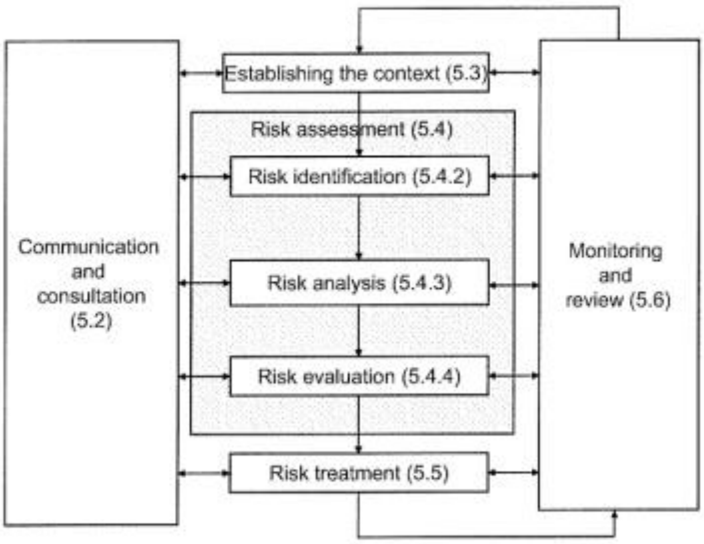
- *Aleatory (stochastic) uncertainty:* variation of quantities in a population
- *Black swan:* a surprising extreme event relative to the present knowledge/ beliefs (Aven, 2014). The concept must always be seen in relation to whose knowledge/ beliefs we are talking about, and at what time. Building on this definition Aven and Krohn (2014) distinguish between three types of such events:

  a) Events that were completely unknown to the scientific environment (unknown unknowns)
  b) Events not on the list of known events from the perspective of those who carried out a risk analysis (or another stakeholder), but known to others (unknown knowns – unknown events to some, known to others).
  c) Events on the list of known events in the risk analysis but judged to have negligible probability of occurrence, and thus not believed to occur.

- *Collective mindfulness,* its concept is based on five characteristics:
  I. Preoccupation with failure
  II. Reluctance to simplify
  III. Sensitivity to operations
  IV. Commitment to resilience
  V. Deference to expertise

- *Cask:* A heavily shielded container used for the dry storage or shipment (or both) of radioactive materials such as spent nuclear fuel or other high-level radioactive waste. Casks are often made from lead, concrete, or steel. Casks must meet regulatory requirements and are not intended for long-term disposal in a repository.
- *Epistemic uncertainty about something:* not knowing about something, where something refers to true value of a quantity or the true future consequences of an activity
- *Hazard:* A risk source or an associated event where the consequences relate to harm

- *Probability:* either a knowledge-based (subjective) measure of uncertainty about an event conditional on some background knowledge or a frequentist probability (chance). If knowledge based probability is equal to 0.10, it means that the uncertainty (degree of belief) is the same as randomly drawing a specific ball out of an urn containing ten balls. A frequentist probability is the fraction of times an event A occurs when the situation under consideration can be repeated over and over again infinitely.
- *Resilience:* (C,U| any A, including new types of A) and resilience description:(C', Q,K| any A, including new types of A). Hence the resilience is considered high if a person has a low probability of dying due to any type of virus attack, also including new types of viruses. We say that the system is resilient if the resilience is considered high (Aven & Krohn, 2013).
- *Risk acceptance criterion:* a reference by which risk is assessed to be acceptable or unacceptable
- *Risk analysis:* systematic use of data, information and knowledge to identify risk sources, causes and consequences of the sources, and to describe risk
- *Risk Analysis Structure ISO 31000* (ISO, 2009)



- *Risk assessment:* the overall process of risk analysis and risk evaluation
- *Risk evaluation:* process of comparing the result of risk analysis against risk criteria to determine the significance of the risk
- *Risk level:* assessed magnitude of risk
- *Risk management:* coordinated activities to direct and control an organization with respect to risk
- *Risk source:* element, which alone or in combination, has the intrinsic potential to give rise to an event with a consequence
- *Uncertainty about something:* not knowing about something, where something refers to the true value of a quantity or the true future consequences of an activity

- *Vulnerability (in a wide sense):* the combination of the consequence C of a stress A and associated uncertainties U, given A and S, where S is a set of stress types (known or unknown)
- *Robustness:* the antonym of vulnerability.

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