University of Alberta

Development and Application of BowTie Risk Assessment Methodology for Carbon Geological Storage Projects

by

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"The only certainty is that nothing is certain"

Pliny the Elder

To My Wife, Sahar

I started doing my PhD when we were apart for roughly two years. Her love, patience, support and understanding have lightened up my spirit to finish this study and this thesis. She worth every letter of this thesis.

Abstract

The objective of this research is to develop a framework for risk assessment of CO_2 geological storage projects. This is achieved using the BowTie approach as a framework for capturing the failure of CO_2 geological storage, and using BowTie approach to combine different failure mechanisms such as wellbore leakage and caprock leakage in a linguistic manner. One of the major difficulties in expert judgment is subjective and dispersed opinion around risk. This research attempts to define dispersed opinions as experts plan knowledge level over different risk hazards by using the Dempster-Shafer theory. In this study, belief on experts' judgments propagate through the right hand side of the BowTie structure (which is fault tree structure) using Boolean algebra and the Dempster-Shafer theory, while expert-evaluated index on caprock and wellbore propagate through the fault tree section of the BowTie structure using fuzzy logic theory. Finally, risk and belief are combined to assign different belief values to different evaluations of calculated risk values. In this study, the concept of fuzzy logic is explored as one approach to characterizing the risks associated with CO_2 storage in the Weyburn project. The Weyburn-Midale CO_2 Monitoring and Storage Project is considered sufficiently well documented to demonstrate the applicability of fuzzy set theory to risk assessment of carbon sequestration projects. Public data available for the International Energy Agency Greenhouse Gas R&D Programme (IEA GHG) Weyburn-Midale CO_2 Monitoring and Storage Project is used for modelling and to assess the applicability of the proposed approach.

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I am extremely grateful to my wife, Sahar, for her support in all these years. For convincing me to stay and continue my PhD without having her in Canada. It was like abandoning her in middle of nowhere, but she always wants me to go on and finish my PhD. Without her help, it would not have been possible to reach this stage in my career. Thanks to my parents who call me every week and follow up on my thesis and defence status. Many thanks to them for their great support in all these six years.

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1. Introduction

Background

1.1.1. Review of climate change and carbon capture and storage (CCS)

Climate change caused by anthropogenic greenhouse gas emissions is a century-scale global issue. It represents clear risks characterized by significant uncertainties about both the costs and benefits of mitigation. Carbon dioxide removal is considered to be a potential key strategy to reduce global CO2 emission. Mounting global concerns over the increase of greenhouse gases were expressed at the Earth Summit in Rio de Janeiro in 1992, and in the ensuing Kyoto Protocol developed and ratified in 1992 (Meakin, 1992). Consequently, government, industry, and academic leaders from Canada, the United States, and the European Community prepared a joint proposal, coordinated and managed through the Petroleum Technology Research Centre in Regina, Saskatchewan, to use Weyburn Field as a pilot project under the Greenhouse Gas Research and Development Program of the IEA.

The ideology for carbon emission mitigation has been illustrated as a stabilization triangle that shows the amount of avoided emissions in eight identical wedges (initially seven wedges) (Pacala and Socolow, 2004). Each of the wedges reaches 1 GtC/year in 2054, with linear growth, the total avoided emission per wedge is 25 GtC, and the total area of the stabilization triangle is 175 GtC (see Figure 1). As shown in Figure 1, the arrow at the bottom right of the stabilization triangle points downward to emphasize that fossil fuel emissions must decline substantially below 7 GtC/year after 2054 to achieve stabilization at 500 ppm. Carbon capture and geological storage constitutes only one of stabilization wedges. One wedge would be a reduction in carbon emission of 15 and 20 times as large as the current carbon emission (in year 2012). To meet the 2054 targets for CCGS alone, 3500 Sleipner[1]-sized projects over the next 50 years have to be started and facilitated (Pacala and Socolow, 2004).

The CCGS process consists of “capture”, including purification, of site specific anthropogenic CO_2 emissions, “transport” of a concentrated CO_2 waste stream and “storage” of the CO_2 by injection into deep geological media consisting of active and depleted oil, gas and coalbed methane (CBM) reservoirs, saline aquifers and salt caverns. There is the potential capacity of 20 to 65 Gton for storing CO_2 in enhanced oil recoveries projects (Grimston et al., 2001). This capacity is roughly equal to world’s emission in next 10 years.

Understanding the risks associated with CO_2 sequestration is one of the key factors affecting public acceptance and is a valuable input to the formulation of standards and a regulatory

[1] Norway’s Sleipner project in the North Sea strips CO_2 from natural gas offshore and reinjects 0.3 million tons of carbon (or approximately 1MT CO2) a year (MtC/year) into a non–fossil-fuel–bearing formation.

framework required for large scale application of underground CO_2 sequestration. Substantial research efforts worldwide are now focused on risk assessment of CO_2 geological storage, and on the need to quantify the risks related to CO_2 geological storage. The risks associated with CCS may also affect its acceptability and act as a barrier for future extensions. Also, costs such as increased monitoring and stricter regulatory frameworks may also add to CCS deployment cost.

1.1.2. Geological storage risks

In CO_2 geologic reservoirs, the potential for leakage will depend on well and caprock integrity and CO_2 trapping mechanisms within the reservoir, which can be categorized into hydraulic trapping, solubility trapping, mineral trapping, and residual gas trapping (Reichle et al., 1999).

In CO_2 geological storage projects there are four main time domains: site selection, operation phase, abandonment and closure/post-closure phase. This study focuses on long-term risk assessment of the post-closure phase. Storing large amounts of CO_2 creates local risk as potential hazard of accidental release and exposure to high concentrations of CO_2 poses human or ecological risks, and global risk with greenhouse gases leaking back to the atmosphere.

After injecting CO_2 in a reservoir, it will primarily be trapped as a supercritical fluid (hydrodynamic trapping). In this state, CO_2 can be considered as a buoyant fluid with lower density than brine and in turn will rise up due to buoyancy effects until it reaches the caprock, where it will accumulate. Since CO_2 is highly soluble in water and also dissolves in oil, solubility trapping is also an important trapping mechanism. When the CO_2 is completely dissolved, leakage is no longer possible, since free CO_2 is not present anymore. Although solubility can provide reliable sequestration of CO_2, it takes hundreds of years for CO_2 to solve completely in reservoir liquid. CO_2 can also be trapped through a process called "residual trapping". Residual trapping happens relatively quickly as the porous rock acts like a tight, rigid sponge. As the supercritical CO_2 moves into formation it displaces fluid as it moves through the porous rock. As the CO_2 continues to move due to capillary forces some of the CO_2 will be left behind as residual droplets in the pore spaces (CO_2 Capture Project site). CO_2 can also react with minerals and organic materials present in the geologic formation to become part of solid matrix, also referred to as mineral trapping. However, the extent and timeframe for CO_2 reactions with minerals present in carbonate reservoir is low.

Leakage through or along wells, faults and fractures are generally considered to be the most likely leakage pathways. In general, CO_2 leakage through the caprock is less controllable and more dependent upon geological characteristics than CO_2 migration through or along wells and is an important element during the site characterization phase of any project.

Risk models need to be established for the leakage of the CO_2 (slowly and rapidly) from the storage reservoir through breaks in the seals and along wellbores both in the short (during the injection period) and in the long term (over the storage period).

1.1.3. Review of general concepts in risk assessment

Advances in technology in recent years have been accompanied by an increasing number of hazards and failures. Ironically, as our society and other industrialized nations have expended great effort to make life safer and healthier, many in the public have become more concerned about risk. Risk has therefore become an issue of growing concern (Wharton, 1992). Risk Assessment (RA) is defined as the process of risk analysis and risk evaluation. And risk analysis is defined as the use of available information to estimate the risk to individuals or populations, property, or the environment, from hazards. Risk evaluation is defined as "the stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks." While there are a multitude of definitions of "Risk", it is most commonly defined as multiplication of consequence to probability of occurrence. Risk assessments range in complexity from qualitative, through semi-quantitative to quantitative. As assessments become more complex, they also become more expensive and take longer to complete.

All these different methods differ in their accuracy and the inputs required for each method. Quantitative risk assessment comes into play when we have the ability to map a dollar amount or number of fatality or casualty to a specific risk. For example, let's say there are 500 records of pipeline leakage in Alberta and 50 of them cause a fatality or casualty. This database allows us to estimate the probability of fatal incident or probability of pipeline leakage per year or per month. When specific data in unavailable, qualitative risk assessments are typically undertaken. For most qualitative risk assessments, linguistic values are used to judge consequences and likelihood instead of numerical values. For example, the probability (or likelihood) and severity (consequence) of pipeline leakage in Alberta would be ranked based words like "high", "low" or "very low". In addition, qualitative risk assessments are performed when risk assessments must be conducted in a relatively short time or to meet a small budget, or the assessment team is not familiar with the complexities of quantitative risk assessment. In many cases, it is nearly impossible to perform a quantitative risk assessment because of complex physics or paucity of data available in the study. CO_2 leakage from geological storage sites is characterized by both these qualities: CO_2 leakage and the physics of CO_2 migration in heterogeneous is very complex and currently, the data available for these projects is very limited. Qualitative risk assessments are typically performed through interviews of a sample of personnel from all relevant groups within an organization charged with the security of the asset being assessed. In this research, experts involved in the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project (the "Weyburn project") provided assessments through prepared questionnaires and consequently would be considered as a semi-quantitative assessment (i.e., the semi-quantitative risk assessment provides an intermediary level between the textual evaluation of qualitative risk assessment and the numerical evaluation of quantitative risk assessment, by evaluating risk severity with a score). Whilst experts are answering questionnaires based on linguistic values, these values are processed in rated numbers and fuzzy sets numbers. This process as well as ranking and index methods are called semi-quantitative which is a qualitative method that processes the linguistic values in mathematical procedure.

1.1.4. Risk Assessment approaches in international CO_2 storage projects

The potential risk posed by injection of carbon dioxide into the deep sub-surface is related to a diverse range of factors and this makes long-term risk assessments for CO_2 geological storage very difficult and complex. Over the last decades, there has been substantial effort towards the developments of risk assessment approaches for CO_2 geological storage (e.g., TNO, FEP Database, TESLA, RISQUE). Policymakers at regulatory agencies and companies want access to methods that help them to quantify the potential risks as fully as possible. Predicting the global impact on climate change due to a release of CO_2 and local impact on humans, animals and plants due to sudden release of CO_2 is hard to quantify as a risk value or cost value. In addition, defining (presumably through regulations) what the acceptable limits for CO_2 levels in different domains as shallow subsurface, including soils from 300 m upwards; potable aquifer; and atmosphere, is very difficult and still is a current research.

A recent risk assessment that has been applied internationally is the RISQUE method. The predecessor of the current research initiative CO2CRC[2] , GEODISC, engaged Business Risk Strategies (a division of the URS Corporation) to apply their RISQUE (Risk Identification and Strategy using Quantitative Evaluation) method to achieve its risk assessment objectives.

In the RISQUE (Risk Identification and Strategy using Quantitative Evaluation) method, potential injection projects are compared based on 6 different key performance indicators (KPI):

1. Contamination,
2. Effectiveness,
3. Self-funding potential,
4. Wider community benefits,
5. Community safety, and
6. Community amenity (Bowden et al., 2004).

The RISQUE method is consistent with the Australian Risk Management Standard (Bowden et al., 2004).

A second approach that has been applied to international projects is a FEP (Features, Events and Processes) analysis developed by Quintessa Ltd. which is a world known consultant focus on mathematical and statistical modelling of different projects such as Nuclear Reactor Safety, and

[2] CO2CRC is a joint venture comprising participants from Australian and global industry, universities and other research bodies from Australia and New Zealand, and Australian Commonwealth, State and international government agencies

risk assessment of CO_2 Geological Storage, Nuclear Decommissioning and Site Restoration, and Radioactive repositories. Quintessa's on-line database (FEPs) for geological storage of CO_2 was established in 2004. The database continues to be developed (e.g. for the marine environment). This method focuses on all the features, events and processes that may directly or indirectly influence the long-term safety of a geological storage system. One example of this approach is the quantitative risk analysis methodology developed by the Netherlands Organization for Applied Scientific Research (TNO) in 2003. The steps in the TNO method start from defining of maximum allowable CO_2 concentration levels, and carry on with evaluation of contaminated area at any domain or location. The next step, which is the most significant part of TNO method, is to identify and evaluate the likely FEP's and their probabilities of occurrence, and based on the results of this step the most likely CO_2 containment failure scenarios will be identified using expert judgement. The final stage of this assessment uses the Monte Carlo procedure with assemblage of the flow simulation model of CO_2 spread after containment failure based on estimation of value ranges and probability distribution functions of critical parameters of the failure scenario by local domain experts. The TNO method ends with answering precise risk questions based on the outputs from the Monte Carlo simulations.(Wildenborg et al., 2003; TNO 2003).

TESLA decision support software developed by Quintessa which implements Evidence Support Logic (ESL). , Shell with assistance from Quintessa developed a decision support tool for evaluating sub-surface CO_2 storage risks. In Shell developed method potential risks associated with sub-surface CO_2 storage are classified into four categories: capacity; injectivity; containment; and monitoring. Each of these categories corresponds to a branch in the overall decision tree. Each mai category will be branched into lower level hypotheses or 'leaf hypotheses' which identifies failure scenarios which can cause sub-branch. These sub-branches are weighted using user-defined 'sufficiencies' (effectively weights).

1.1.5. IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project - Phase 1

In July 2000, a major research study, the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project (the "Weyburn Project"), was initiated with the assistance of the IEA GHG and Petroleum Technology Research Centre (PTRC) and the University of Regina. The Weyburn Project has been managed by PTRC in coordination with Cenovus (initially EnCana), the Weyburn oil field operator and was developed to assess the geological storage of CO_2 as part of an enhanced oil recovery (EOR) project planned for the Weyburn field in Saskatchewan, Canada. Over the period 2000-2004, the geological characterization at both a regional scale (100 km beyond the field) and a more detailed scale (10 km beyond the field) was undertaken. Also, regional "deep", regional "shallow", and local "shallow" hydrogeological studies were undertaken to understand the type of formation fluids, as well as their flow directions and flow rates. All of this information was assembled into a 3D geological model. The challenges faced in the first phase of the project were threefold:

1. Dealing with the volume of data (i.e., hundreds of wells within the study area);
2. Geological and geophysical mapping revealed the presence of numerous “discontinuities” in the geosphere; and
3. Little attention was paid to the downward movement of CO_2 to underneath the injection zone but the later simulations indicated possible downward movement of CO_2 from the reservoir.

1.1.6. Quantitative versus qualitative risk assessment

Risk assessments are generally conducted using two different methods: “qualitative” or “quantitative”. A qualitative method involves subjective evaluations of probability and impact while a quantitative method uses analytical/numerical estimates of probability and impact. A hybrid of these approaches is a “semi- quantitative” method which combines elements from each method. The use of qualitative method is appropriate when estimates of likelihood and severity, but not probability data, are sufficient for proper probability simulation. Textual terms (e.g., “very low” or “high”) are used in qualitative risk assessment to assessment likelihood and severity. The use of a quantitative method is appropriate when it is necessary to demonstrate risk analysis with numerical values using probability simulation (i.e., Monte Carlo simulation). Numerical values are used in quantitative risk assessment. The semi-quantitative risk assessment provides an intermediary level between the textual evaluation of qualitative risk assessment and the numerical evaluation of quantitative risk assessment, by evaluating risk severity with a score.

For geological storage risk assessment, the physics of carbon dioxide leakage through wells, faults and caprock is not well defined and the number of parameters associated with the CO_2 leakage process is large. This is compounded by heterogeneous geology present within the Weyburn field. Consequently, using qualitative and semi-quantitative risk analysis methods is the most appropriate approach for conducting a risk assessment for projects like the Weyburn Project. Phase 1 and 2 of the Weyburn Project involved many experts and so for this research, access to these experts at annual project meetings was used as an opportunity to complete questionnaires developed within this research. These subjective inputs for risk evaluation provided an excellent opportunity to develop a framework for risk assessment based on the BowTie methodology that incorporated uncertainties associated with these linguistic inputs and to assess the influence of these diverse and independent opinions for the Weyburn Project.

Research Objectives

The objective of this research was to develop a methodology for incorporating subjective risk evaluation procedures into the BowTie risk assessment methodology and apply it to the Weyburn Project. The subjective risk evaluation procedures include belief estimates for expert judgements, based on the Dempster-Shafer theory and expert judgement on risk levels (both likelihood and severity) using fuzzy logic theory. Ultimately, risk and belief are combined to assign different belief values to different evaluations of calculated risk values.

Scope and methodology

Firstly, it is very important to state that this research was not responsible for conducting a full field risk assessment for the long-term CO_2 geological storage element of the Weyburn Project. The Weyburn Project contracted URS to employ their RISQUE methodology in conducting the full field risk assessment. During this effort, URS identified appropriate experts outside the Weyburn Project and through facilitated expert workshops, completed a geosphere and biosphere risk assessment. For this research, the scope was limited to utilizing inputs from experts within the Weyburn Project obtained during annual research meetings within the project.

The research objective was achieved through initial integrated theoretical studies that developed the methodologies for embedding fuzzy logic and Dempster-Shafer theory within the BowTie framework. These initial studies were followed with implementation efforts to incorporate the results from expert judgement inputs received from members of the Weyburn Project. These steps are summarized below:

- The first step focused on incorporating fuzzy logic and evidence theory in a fault tree framework and the specific challenges for incorporating expert judgment into the process of geological storage risk assessment. While the main physics of CO_2 migration have been identified, the lack of a credible simulator, the heterogeneity of the Weyburn reservoir and caprock and the number of parameters involved in CO_2 convection and diffusion make a quantitative risk assessment nearly impossible to conduct. For this reason the semi-quantitative risk assessment based on experts opinion was chosen as the only practical method for dealing with risks involved in Weyburn geological storage project. This risk assessment covers all caprock, wellbores, pipelines and appurtenances that are a part of the project.

One of major difficulties with expert judgement is that it is subjective and generally offers a dispersed opinion for different concepts of risk. In this research, it is attempted to represent dispersed expert opinion on different risks based on the knowledge level of the expert (i.e. not all experts are equal!) by using the Dempster-Shafer concept. In this step, the belief of an experts' judgment propagates through the fault tree structure using Boolean algebra based on the Dempster-Shafer theory and simultaneously, the level of risk evaluated by experts propagates through the fault tree using the fuzzy logic theory. Finally risk and belief are combined and provide a computed "belief" value for a computed "risk" value.

- For the second phase in this research, risk perception and specifically geologic storage acceptability from the public's view, a broad, complex mix of scientific, social, political, legal, institutional, and psychological factors operating within our society's risk-perception was considered. A structured method is suggested for risk acceptability evaluation and the results of risk evaluation from the BowTie structure (as described above) are coupled with public perceived benefit and respondents' belief over Canada's condition in media openness and public trust in Canada's government and companies associated with the geological storage of CO_2. Finally, the risk perception of the geological disposal of CO_2 (GDC) is evaluated.

- Given the focus on wellbores as potential leakage paths, the third step in this research program developed an extensive wellbore interaction matrix for the assessment of long-term wellbore leakage. For an interaction matrix, state variables are placed along the leading diagonal of the interaction matrix and subsequent locations within the matrix define the relevant cause-effect processes for the interactions between the state variables. The interaction matrix is used to generate a wellbore integrity index that provides a measure of leakage potential within a wellbore.
- In the fourth and final step, the complete BowTie framework is utilized to demonstrate the full risk assessment approach. The BowTie structure can accommodate multiple outcomes and simultaneous multiple failure events and allows the coupling of different aspects such as cost, capital loss, CO_2 leakage rate and duration, CO_2 leakage rate reduction related to each barrier. This phase of the research develops the framework for semi-quantitative risk assessment of CO_2 geological storage projects and demonstrates its applicability on the Weyburn Project.

Organization of thesis

Chapter 2 is focused on incorporating fuzzy logic and evidence theory in fault tree framework and challenges to incorporating expert judgment into the process of Weyburn geological storage risk assessment. This risk assessment covers all caprock, wellbores, pipelines and appurtenances that are a part of the project.

Chapter 3 describes the structured method is suggested for risk acceptability evaluation and the results of risk evaluation from BowTie structure from the former step is coupled with public perceived benefit and respondents' belief over Canada's condition in media openness and public trust in Canada's government and companies in charge with Carbon Geologic Sequestration.

Chapter 4 the wellbore interaction matrix is developed for long-term wellbore leakage, and the wellbore index is evaluated using the presented interaction matrix.

Chapter 5 the BowTie framework considering fuzzy set theory and evidence theory is used for final risk assessment step. The risk assessment implemented with coupling different aspects such as cost, capital loss, CO_2 leakage rate and duration, CO_2 leakage rate reduction related to each barrier, and etc; and finally severity evaluation of long-term risk of Weyburn carbon dioxide storage project.

The last chapter integrates the different aspects of this study that were discussed in the previous chapters and summarizes the main conclusions. The recommendations for future research are also given in this chapter.

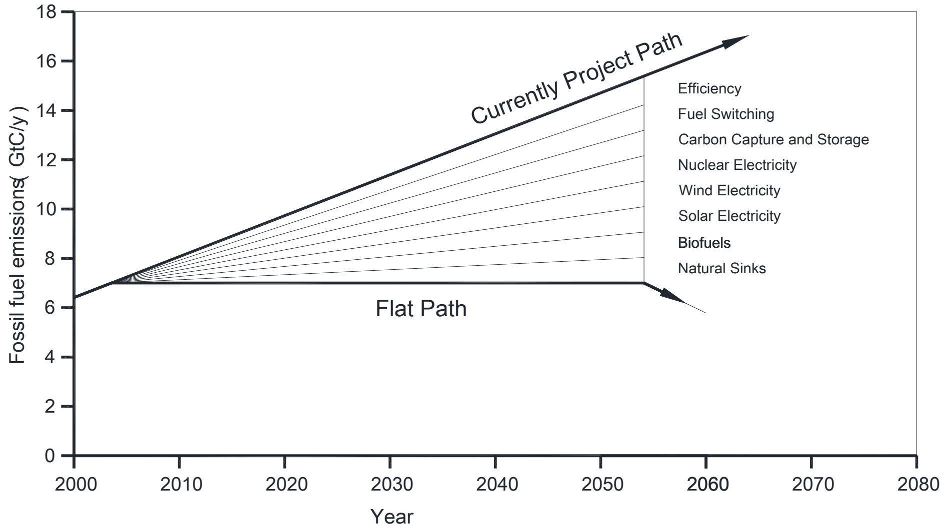


Figure 1. A stabilization triangle of avoided emissions and allowed emissions (reproduced from Pacala et al., 2004)

2. Fuzzy Logic and Belief Theory in a Fault Tree System

Introduction

One of the difficulties in expert judgement is its subjective nature and the diverse opinions that exist for the concept of risk and for this thesis, risk associated with the geological storage of CO_2. This chapter describes the use of the Dempster-Shafer theory to manage expert opinion (belief) and an expert's knowledge level related to different risk hazards. This chapter also discusses the development of a fault tree framework that incorporates fuzzy logic theory to enable qualitative risk assessment in a linguistic manner.

At the same time that the level of risk is evaluated using fuzzy logic theory within the fault tree, the expert's degree of belief in that evaluation is propagated through the fault tree structure using Boolean algebra and Dempster-Shafer theory and simultaneously level of risk evaluated by experts is propagate through the fault tree using the fuzzy logic theory.

Publicly available data for the IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project (the "Weyburn Project") are used for modelling and to assess the applicability of the fuzzy logic approach and will cover caprock, wellbores, pipelines and other related elements of the Weyburn Project.

Methodology

The proposed framework for this study is presented in Figure 2. Each of the elements contained within this framework, from the questionnaire inputs to the generation of the final results from the fault tree, are discussed subsequently.

As it shown, the first stage is the consequence inputs using air FAM (see Figure 8) and water FAM (see Figure 9) and likelihood inputs is processed through the fault tree (illustrated in Figure 3) and then is presented firstly in fuzzified format for different membership functions (see Figure 13) and secondly in defuzzified format (see Figure 15 and Figure 16). The process of defuzzification from Figure 13 into Figure 15 is presented in Figure 14. As it is presented in Figure 14 the center of gravity of fuzzified risk values for each belief value is evaluated, the collection of these COGs are resulting the defuzzified risk value-belief graph. Then the Gaussian probability function is fitted into defuzzified risk value-belief data to show the results in Gaussian bell function for better estimate of risk variation. The belief values discussed in this section are calculated based on evidence theory. The evidence theory was applied to the input of different experts for evaluation of degree of agreement on each risk value. Evidence theory or the Dempster-Shafer method is discussed in Section 2.1.7. In this study in parallel the fuzzy risk values and the belief values for the various risk compounds in air and water were specified and analysed through the mathematical suggested method suggested in following section. In this study the MATLAB software (MATLAB®) is used for programing and the data processing is conducted in Microsoft Excel. Then the resulted vectors from Microsoft Excel are processed in MATLAB software (MATLAB®).

2.1.1. A fault tree representing possible leakage paths of CO_2

To explore the potential of using fuzzy logic to assess geological storage risks, a basic fault tree was constructed to represent possible leakage paths of CO_2. A fault tree is a logical diagram that shows the relationship between system failure and failures of components of the system (Vincoli, 1993). CO_2 leakage via different routes within the fault tree represents leakage paths within the geological storage system, and each initiating fault "box" (referred to as leafs of the tree) acts as an event trigger. Utilizing the Weyburn Project as an analogue for the development of the fault tree, Figure 3 illustrates the fault tree developed to assess the risk of CO_2 leakage scenarios. Figure 3 was constructed based on personal communication with researchers involved in Weyburn project and literature studies describing leakage scenarios for geological storage projects (Gasda et al. (2004), Celia et al., (2004, 2005), Bachu and Celia (2009), Chang and Bryant (2009), Esposito and Benson (2010)). While the fault tree developed in this research was divided into two sections: the "operational period" fault tree and the "long-term period" fault tree, only the long-term period is considered for this thesis.

Wells, faults and fractures are generally considered the most likely leakage pathways (Gasda et al. (2004); Loizzo et al. (2010, 2011)), Chang and Bryant (2009)). In general, CO_2 leakage through the caprock is less controllable and more dependent on geological characteristics than CO_2 migration through or along wells. Caprock related leakage generally takes more time to develop, and as such, is only considered in the long-term period section and is not considered within the operational period.

2.1.2. Basic concepts of the fuzzy logic approach and fuzzy sets theory

Fuzzy set theory (FST), formulated by Lofti Zadeh in 1965, has had a wide range of successful applications. Fuzzy logic provides a language with syntax to translate qualitative knowledge into numerical reasoning. It is easy to use, and mathematics associated with fuzzy logic (fuzzy mathematics) is developed in understandable terms, with the unique ability to consider verbal assessments (e.g. likely, not likely for probability evaluation and low, high and moderate for consequence evaluation) mathematically. The significance of fuzzy variables is that they facilitate gradual transition between states and consequently are capable of expressing and dealing with uncertainties of observation and measurement. Both fuzzy set theory and probability theory are mathematical frameworks for characterizing uncertainties. Since the 1960's, these frameworks have been used to formalize different types of uncertainties, but fuzzy set theory and fuzzy logic have been applied more successfully in risk assessments than have the more recent "possibility theory" (Dubois and Parade, 1988), and "Dempster-Shafer theory" (DST) (Dempster, 1968; Shafer, 1976).

Kangari (1989), Tah (2000), Carr (2001), Cho (2002), Abdel Gawad and Fayek (2008), and Sadeghi et al. (2010) applied fuzzy logic to risk management in construction projects. Chun and Ahn (1992) and Huang (2001) applied fuzzy logic to conventional event tree analysis and Huang (2001) introduced the concept of fuzzy event tree analysis (FETA). Pillay (2003), Sharma et al. (2005) and Wang et al. (2009) assessed the traditional method of failure modes and effects analysis (FMEA) and by applying the fuzzy logic concept within a FMEA, and Pillay (2003) developed the concept of a fuzzy risk priority number (RPN) ranking system.

Fuzzy logic incorporates a continuous gradation of values for truth, ranging from zero (designated as 100% falsity) to one (designated as 100% trueness). The "truth" of a statement or value is defined as the confidence that a statement or value is correct. The rules or rule base of a fuzzy logic system consist of a collection of IF-THEN rules, and an inference engine uses these IF-THEN rules to map fuzzy inputs to a set of fuzzy outputs using fuzzy logic principles. A fuzzy set is simply a collection of variables showing which object can belong to a different fraction of contribution of a different property, called "grade of membership" or "membership grade". Freksa (1994) and Vadiee and Jamshidi (1994) have shown that these fuzzy IF-THEN rules provide a convenient framework to incorporate the knowledge of human experts. The most straightforward way to apply logic to a system (in this case, the fault tree shown in Figure 3), is to add a fuzzifier to the input and a defuzzifier to the output of the fuzzy logic system. The fuzzifier maps deterministic or discrete points into fuzzy sets, and the defuzzifier maps fuzzy sets back into deterministic points. For conducting risk assessments of geological storage, it is useful to be concerned with fuzzy sets of descriptive words, where grade of membership represents confidence that the descriptor is true. This assumes that experts will, in general, be more comfortable using descriptive words to describe risk in geological storage projects as opposed to choosing quantitative numbers (ranking or scaling numbers).

Mathematically, a fuzzy subset defined as 'A' can be characterized as a set of ordered pairs of element 'X' and membership grades $\mu_A(x)$, and is often written as:

$$A = \{(x, \mu_A(x)) \mid x \in X\} \quad (1)$$

where $\mu_A(x)$ is defined as a number between 0 and 1, and represents a confidence measure of element X, where X is a set of different properties.

The fuzzy logic approach provides a method for performing computations based on "degrees of truth" rather than the usual "true or false" (1 or 0). In fuzzy logic theory membership grades $\mu_A(x)$ define the "states of truth" or "degrees of truth".

Although the definition of states by crisp (or deterministic) sets (i.e., being binary such as yes/no or true/false choices) is mathematically correct, it is unrealistic in the face of uncertainty errors. A measurement that falls close to each precisely defined border between states of a crisp variable is taken as evidential support for only one of the states, despite the inevitable uncertainty involved in choosing one of the two states. The uncertainty is greatest at each border, where any measurement should be regarded as equal evidence for the two states on either side of the border. This is defined with a membership function, which applies probability of occurrence in a mathematical form. The main idea of the membership functions in fuzzy theory is using diffuse boundaries instead of determining the exact boundary as in an ordinary or crisp set. Figure 4 illustrates three different examples of membership functions (i.e., triangle, trapezoid and Gaussian), that can be used to determine membership grades. This provides an opportunity to assess the sensitivity of fault tree outcomes against the assumptions of the membership function. For this study, triangular fuzzy numbers (TFN) have been used. The triangular membership function provided computational simplicity in comparison to Gaussian, exponential or other more complex membership functions and as long as extended trapezoid or any other membership function with a large plateau on any section was not used, was found to be sufficient for this research. Also, the same membership function (i.e. triangular) was used for both likelihood and severity assessments.

In fuzzy logic analysis and fuzzy sets theory, verbal statements such as ‘high’ or ‘very low’ are used to introduce degrees of belief, which is very similar to the verbal categories in membership functions. Despite the symmetric appearance of the triangular membership function, they are really non-symmetric since they can be mapped onto unsymmetrical sets of boundaries. It also must be noted that the definitions of TFNs are not fixed and can be changed or modified based on expert opinion for any risk assessment.

Boolean algebra is used in the fault tree approach to deal with probability of different components and produce a final risk value for a “top” event. To adapt fuzzy set theory to a fault tree, Boolean algebra operators must be defined. In a fault tree, the “OR” gate results in false only if all the antecedent branches are false and the “AND” gate results in true only if all the antecedent branches are true. The “OR” and “AND” operators in fuzzy set theory are defined as “max” and “min”, respectively (Sadiqa et al., 2008; Li, 2007). Fuzzy calculations in the fault tree for this study are illustrated in Figure 5. As illustrated in Figure 5, “OR” and “AND” gates are substituted by “max” and “min” operators, respectively.

The “max” and “min” operators or functions can be defined as “union” and “intersection”and are expressed as follows:

For max function;

$$\mu_{A \cup B} = \max\left(\mu_A(x), \mu_B(x)\right) \quad (2)$$

For min function;

$$\mu_{A \cap B} = \min\left(\mu_A(x), \mu_B(x)\right) \quad (3)$$

where, $\mu_A(x)$ and $\mu_B(x)$ are membership grades for A and B which are antecedent branches in Figure 5, and $\mu_{A \cup B}$ and $\mu_{A \cap B}$ are combination result of “OR” and “AND” gates in Figure 5. Figure

6 provides a simple schematic illustrating how “max” and “min” can be substituted by “union” and “intersection”.

2.1.3. Consequence rules for impacts of CO_2 concentration in air

In order to complete a risk assessment using the fault tree approach adopted for this study, it is important to develop a set of consequence rules that quantify the impact of CO_2 exposure on humans and environment. Under normal conditions, the atmospheric concentration of CO_2 is ranging between 0.028 to 0.037 (0.039)% (280 to 370 (390) ppm) (Rice, 2003; IPCC, 2005), a non-toxic amount. Most people with normal cardiovascular, pulmonary-respiratory and neurological function can tolerate exposure to CO_2 concentrations of up to 0.5−1.5% for one to several hours without harm. High concentrations of CO_2 can cause headaches, respiratory problems and asphyxiation in humans (IPCC, 2005). Rice (2004) describes asphyxia as “when atmospheric oxygen concentration falls below 16%. Unconsciousness, leading to death, will occur when the atmospheric oxygen concentration is reduced to less than 8% although, if strenuous exertion is being undertaken, this can occur at higher oxygen concentrations”. Rice (2004) also indicated that there might be certain groups that are more sensitive to elevated CO_2 levels than the general population.

Several mortality and morbidity incidents have been reported from CO_2 asphyxiation due to volcanic CO_2 emissions (e.g., one death in Vesuvius (Perret, 1924); six deaths in Rabaul, New Guinea (Itikarai and Stewart, 1993); three deaths in Hakkoda, Japan (Hayakawa, 1999); one death and one injury in two incidents in Mammoth Mountain, US (Sorey et al., 1998; Hill, 2000); and 149 deaths and 1000 injuries in Dieng, Indonesia (Cronin et al., 2002)). The most devastating incident related to CO_2 asphyxiation occurred in 1986, when 1746 people died due to the sudden release of CO_2 from Lake Nyos in Cameroon (Othman-Chande, 1987; UNDP, 2011).

The possible health effects of CO_2 exposures are evaluated based on elevated CO_2 concentrations versus specific periods of exposure, shown in Figure 7, based on studies conducted by many authors. The range of consequences for exposure to concentrations of CO_2 have been qualitatively divided into five levels of severity (or five zones). The main reason for the divisions of severity is to stay consistent with other categorization in this study (i.e., likelihood and risk), and to remain consistent with the use of linguistic rankings ranging from “very low” to “very high” including “high”, “moderate” and “low” rankings. Zone 1 (or “very low severity” or “very low consequence”) denotes conditions in which the effects of CO_2 exposure are not noticeable. In Zone 2 (or “low severity” or “low consequence”), small hearing loss occurs and respiration depth doubles. In Zone 3 (or “moderate severity” or “moderate consequence”), mental depression, headache, dizziness, and nausea occur, while in Zone 4 (or “high severity” or “high consequence”), dizziness and unconsciousness occur. Finally, Zone 5 (or “very high severity” or “very high consequence”) engenders harsh convulsions and death. Zones and their respective designations of severity are shown in Table 1. It should be noted that Curves 1 to 3 in Figure 7 are categorized from the work of Fleming et al. (1992), while Curve 4 is shifted to a higher concentration to fit the Zone 5 data of other researchers.

Equations 4 to 6, inclusive, are defined by fitting them to zones suggested by Fleming et al. (1992), Equation 7 just a shift of Equation 6 as what just discussed. In comparing the impact of different concentrations, it is important to remember that normal concentrations of CO_2 in the air are ranging between 280 to 390 ppm (Rice, 2003; IPCC, 2005) and 600 ppm is considered as indoor acceptable level (Health Canada, 1995; Bright et al. 1992; Rajhans 1983; Bell and Khati 1983). The curves defining the boundaries for zones shown in Figure 7 are expressed in Equations 4 to 7:

For Curve 1:

$$CO_2\,\text{Concentration} = 2.5\exp(-0.25t) + 0.0025t + 1 \qquad 4$$

For Curve 2:

$$CO_2\,\text{Concentration} = 6\exp(-0.7t) - 0.009t + 3 \qquad 5$$

For Curve 3:

$$CO_2\,\text{Concentration} = 4\exp(-0.35t) - 0.009t + 6.7 \qquad 6$$

For Curve 4:

$$CO_2\,\text{Concentration} = 4\exp(-0.35t) - 0.009t + 11 \qquad 7$$

where t is time of exposure.

The fuzzy rules established from the divisions illustrated in Figure 7 are shown in Figure 8. Carbon dioxide concentration (due to leakage) is converted to carbon dioxide leakage flux based on the work Grogan et al. (1992) conducted on indoor concentration of a hazardous gas. In most circumstances, experts providing judgement on the geological storage of CO_2 are dealing with leakage flux rate from wells or fractures rather than carbon dioxide concentrations that results from a leakage incident.

2.1.4. Consequence rules for impacts of CO_2 concentration in water

The variation of acidity on the pH scale is used to express the severity categorization of CO_2 concentration in water. The acidity of soil, or more precisely the acidity of the soil solution, is very important because soil solution carries nutrients such as nitrogen (N), potassium (K), and phosphorus (P) that plants need in specific amounts to grow, thrive, and fight off diseases. If the pH of the soil solution is increased above 5.5, nitrogen is made available to plants in the form of nitrate. Phosphorus, on the other hand, is available to plants when soil pH is between 6.0 and 7.0. In acidic soils, plants are more likely to take up toxic metals and some plants eventually die of toxicity (poisoning). Humans and animals are also sensitive to the acidity of water they consume. Water of pH less than 5.5 could severely affect humans and animals, and is considered dangerous in the long term; for example, ionic imbalance in fish begins at a pH of 5.5 (Potts and McWilliams, 1989), acidity lower than 5.5 is harmful to freshwater shrimp, snails, and clams

(Western U.P., 2004), and toxic metals such as aluminium and lead (which are trapped in sediments) are released into the water with pH higher than 5.5 (CEES).

A major concern in the variation of acidity in potable water is changes in the concentration of dissolved ions that exceed the maximum permissible concentrations in domestic wells. The major elements are lead (Pb), arsenic (As) and uranium (U). But barium (Ba), cadmium (Cd), mercury (Hg), antimony (Sb), selenium (Se), and zinc (Zn) can also be potentially hazardous. Very small amounts of lead and arsenic contained in the aquifer solid phase can provide a long-lasting source of contamination (Birkholzer et al., 2008).

The addition of CO_2 to water initially leads to an increase in the amount of dissolved CO_2, which reacts with the water to form carbonic acid. Carbonic acid dissociates to form bicarbonate ions, which can further dissociate into carbonate ions. This phenomenon happens as a result of carbonic acid short-lived intermediate in CO_2-HCO_3^-/CO_3^{2-} proton transfer reactions (Hage et al., 1998). The net effect of dissolving anthropogenic CO_2 in water is the removal of carbonate ions, the production of bicarbonate ions, and a lowering of pH. In Figure 9, the variation of acidity on the pH scale with CO_2 concentration is illustrated by comparing data from the IEA Greenhouse Gas R&D Programme (2000) with Lake Nyos data (Nojiri et al., 1993). It must be noted that the data from the former are based on theoretical calculations, while the data from the latter, as well as that reported by Nishikawa et al. (1992) for ocean sequestration, are experimental.

The buffering effect described in the study conducted by Wilkin and Digiulio (2010) is also presented in Figure 9. The buffering happens when an aqueous solution consisting of a mixture of a weak acid and its conjugate base or a weak base and its conjugate acid, in this case weak acid (*carbonic acid*) and its conjugate base (*bicarbonate* and *carbonate*). Buffering has the property that the pH of the solution changes very little when a small amount of strong acid or base is added to it, and it helps the solution of keeping pH at a nearly constant value and moderate acid or base leakage in the solution. The curves assigned to the buffering effect are for pure water and a 1 vol% calcite present in the water. The curve representing the Weyburn aquifer is shown by a bold yellow line. The impact of buffering is illustrated by the bold red line branching from this line. The yellow line is bounded by two lines described by Equation A.7 (Appendix A). The interception of the yellow line at pH equal to 8.07 is believed to be the in situ pH in Weyburn aquifers (Draude, 2004). It has been estimated that the buffering can be strong in the Weyburn aquifer by having 66 ppm, 6 ppm and 849 ppm, for calcium, carbonate and bicarbonate, respectively (Draude, 2004). The bold red curve is presenting the buffering effect and this line is parallel to the end part of the 1 vol% calcite curve. The estimated cation exchange capacity (CEC) for the Weyburn aquifer of 38.6 meq/100g (Draude, 2004) is high in comparison to CEC values of common aquifers which range from 0.5 to 1.0 meq/100g. The CEC is increasing the capacity for chemical reaction in the aquifer that can increase the buffering effect by increasing the chemical reactions and also decrease the buffering effect in long term by using all the calcites in aquifer formation which can dissipate by the flowing aquifer. The flow velocity is slow in Weyburn aquifer and CEC can increase the pH in the aquifer.

Figure 9 also provides a severity categorization of CO_2 concentration in water contamination. The critical pH limits for each level of severity are determined by comparing the suitable level of acidity for different trees and plants, and referencing these limits to related CO_2 concentrations using the graph in Figure 9. The acidity levels of three volcanic lakes are given for comparison. This graph is used as the fuzzy associative memory (FAM) for the water contamination section of the fuzzy fault tree. The hazards posed by gaseous atmospheric CO_2 and by CO_2 dissolved in ground water vary greatly according to local conditions and the particular situation. For example, carbon dioxide will react differently depending on whether the formation rock is limestone, sandstone, or another matrix material. Freshwater and brine solutions also react differently, with different capacities to buffer acidification due to CO_2. Also, the presence of heavy metals determines whether the reservoir poses a contamination hazard with changing the heavy metals content in the solution (Holloway et al., 1996). Figure 9 represents the FAM identification for CO_2 leakage risk for water contamination. Recall that Figure 2 illustrates the overall flowchart of the proposed framework and defines the location of FAM identification. For clarity during expert elicitation, the categories for CO_2 concentration, duration, and probability were illustrated as shown in Figure 10. This method of classification is very useful in qualitative inquiries because experts can envision the classification of all parameters and they can adapt their ideas to the categories assumed by the risk system modeler.

2.1.5. Severity Assessment for CO_2 Leakage Pathways using the Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) was developed by Saaty (1980) and is often referred to, eponymously, as the Saaty method. AHP is used to construct a matrix expressing the relative values of a set of attributes. An application in the present study would be a comparison of different possible CO_2 leakage paths. For example, experts were asked to choose whether air contamination, in relation to water contamination, was 'very much more severe', 'rather more severe', 'as severe', and so on, down to 'very much less severe'. Each of these judgments is assigned a number on a scale. Saaty (1972) argues that a decision maker naturally finds it easier to compare two things than to compare all the items in a list. That is why in AHP, experts are asked to make pairwise comparisons between verbal phrases. The pairwise comparison values are calculated using the Overall Preference Matrix (OPM). The values in entered into the OPM are based on responses obtained from the petroleum engineers involved in geological storage projects. It should be noted that geometric averaging was used for populating the ranking values in the OPM matrixes.

The Relative Value Vector (RVV) is calculated using the OPM by normalizing the geometric average of each row of the OPM. The RVV of the judgment of experts over the verbal probability phrases is shown in Figure 11. AHP also evaluates the consistency of the decision maker by finding the Consistency Ratio (CR) parameter, and allows for the revision of responses. In this analysis, the CR parameter equals 0.038, well below the critical limit of 0.1 (i.e., acceptable limit for AHP evaluation); which indicates that the experts are consistent in their choices.

In this study, the AHP was used to assess the relative weights associated with the leakage pathways as assessed by a group of thirty researchers in attendance at the 3rd PRISM held for the Weyburn project which will be discussed in Section 2.1.5.

By using the AHP method, the weight factor related to each branch of the fault tree is calculated and considered for the calculation of the final fuzzified output. The survey results for AHP calculations are shown in Figure 11. The AHP procedure is very advantageous in this study, allowing experts to consider their degree of perceived risk on different branches of the fault tree. For this research AHP provides the ability to adjust subjective inputs based on the environmental and human activities on the ground surface above geological storage sites. Assumed the same procedure will be used for In Salah, Algerian CCS project, which is in middle of desert; AHP makes this possible for experts by suggesting less weight for factors of human asphyxiation, because a lack of population close to the In Salah decreases risks to humans.

2.1.6. Proposed fuzzified fault tree (FFT) procedure for Risk Assessment of CO_2 leakage

The risk assessment of failure is the product of the probability of the occurrence and consequences of failure. In this study, the fault tree structure was used as the main risk assessment system, and fuzzy logic and the Dempster-Shafer theory act as compilers of this system. Although fault tree analysis was developed in 1962 at Bell Telephone Laboratories (Misra, 2008), there are still many difficulties in performing a fault tree analysis without having imprecise failure input data. The fuzzified fault tree provides one solution to this problem. In fuzzified fault tree assessment, the probabilities of occurrence of different failures are assumed to be independent of each other and their joint probability or fuzzy numbers in a fuzzified fault tree at each junction are calculated based on Boolean algebra conversion calculations in fuzzy set theory, as discussed in Section 2.1.2.

The first step of the process is fuzzification, which means conversion of linguistic values to fuzzy numbers. The rules used for fuzzifying verbal inputs are shown in Figure 8 and Figure 9 for air contamination and water contamination, respectively. These rules are defined based on the duration of exposure to various percentages of contamination as shown in Figure 10. For example, duration of medium severity denotes exposure between three and fifteen minutes, and low severity of contamination denotes contamination levels of one to five percent of CO_2 gas in ambient air. Figure 7 illustrated that contamination levels of one to five percent of CO_2 gas in ambient air for three to fifteen minutes causes headache and dizziness in human beings which, based on Table 1, is equal to a “medium” classification. Figure 8 shows the location of rules based on concentration curves evaluated in Figure 7 for air contamination. The same procedure is used to suggest rules for water contamination in Figure 9. In this figure, CO_2 of acidity on pH scale with CO_2 concentration, which is used for severity categorization of CO_2 concentration in water contamination for experts' opinion linguistic classification. Figure 10 presents all of the rules for parameters used in this study, and was given to experts to better explain the boundaries of the range of linguistic values, from "very low" to "very high".

The same triangular fuzzy membership function was used to estimate likelihood (probability). The likelihood fuzzy values are adapted in a manner consistent with traditional Failure Modes and Effects Analysis (FMEA) scale values for probability of failure occurrence.

Fuzzification rules are then applied for calculation of risk fuzzy numbers. A risk matrix is used for FAM identification. This study uses a risk matrix suggested by Shell (Table 2). The risk values from each expert are then weighted based on the implemented questions, e.g. "What is the porosity of competent shale caprock?" or "What is the permeability of class G cement having a porosity of 20%?" In the weighting procedure, the answer that falls within an acceptable range is assigned a value of 1, and the weighting factor regarding the question is reduced linearly. The sum of the weights for each question asked of an expert is the expert's weight factor. The weighted average method is then used to evaluate risk for each component.

Finally, all fuzzified risk values go through the fault tree and final results are presented in what is termed an "*undefuzzified*" format (see Figure 13) and "*defuzzified*" format (see Figure 15). Put simply, defuzzifying is converting fuzzy set confidences into fuzzy numbers, and defuzzification is the reverse. Defuzzification makes it possible to present outputs in fuzzy numbers for better decision-making. Most experts surveyed agreed that defuzzified data are more meaningful output for the user. Fuzzy control engineers have many different ways of defuzzifying, but it is usually possible to use quite simple methods. The center of gravity (COG) method was used in this study since it is simple (Pedrycz et al., 2008) and is widely adopted in current risk assessment practice in comparison with other

. The process of defuzzification from Figure 13 into Figure 15 is presented in Figure 14. As it is presented in Figure 14 the center of gravity of fuzzified risk values for each belief value is evaluated, the collection of these COGs are resulting the defuzzified risk value-belief graph. Then the Gaussian probability function is fitted into defuzzified risk value-belief data to show the results in Gaussian bell function for better estimate of risk variation (see Figure 14 for process illustration and see Figure 15 for normal cumulative function fitted on defuzzified results). The belief values discussed in this section are calculated based on evidence theory. The evidence theory was applied to the input of different experts for evaluation of degree of agreement on each risk value. Evidence theory or the Dempster-Shafer method is discussed in the following section.

2.1.7. Application of the Evidence theory (or Dempster-Shafer theory)

The Dempster-Shafer theory (DST) of evidence, also known as the theory of belief functions (or as it is called in this study "evidence theory"), is a generalization of the Bayesian theory of subjective probability which was first described by Dempster (1967) and extended by Shafer (1976). The degree of belief may or may not have the mathematical property of probability, whereas the Bayesian theory requires probabilities for each failure. This makes the DST theory more flexible in qualitative risk analysis problems.

The Dempster-Shafer theory was originally applied in artificial intelligence and sensor fusion, but Ferson et al. (2003) includes expert opinions in reliability analysis by using DST theory. A fundamental difference between Dempster-Shafer theory and probability theory is the treatment of ignorance. DST theory does not require belief to be assigned to ignorance or refutation of experts' judgment and only considers belief on total experts' opinion. Thus, having no beliefs on the opinions of experts does not imply a belief contradictory to those experts. DST theory provides two limits of belief, a lower and upper bound of belief regarding the opinions of experts. The lower bound is called the support (Spt) or belief (Bel), and the upper bound is called plausibility (PIs). Figure 12 illustrates the concepts of belief, plausibility, ignorance, and doubt.

Generally speaking, there are two parts to solutions using the Dempster-Shafer theory: obtaining degrees of belief for a question from subjective probabilities for a related question, and using appropriate mathematical rules to combine such degrees of belief when they are based on independent pieces of evidence. In this study, degrees of belief are processed through experts' inputs for different failures separately. An assessment by one expert of likelihood or severity rating as "moderate" is used in the fuzzy logic section of the methodology. The evidence theory (or DST) elements of the methodology deal more with "how many or what percentage of the experts believe in the answer "moderate". For example, assume that in the group of 10 experts, for specific severity rating 2 of the experts answered "very low"; 1 answered "low"; 3 of the experts answered "moderate"; 1 of the experts answered "high" and 3 other experts answered "very high". degree of belief of answer "moderate" is the total number of experts who answered "moderate" and lower severities range (i.e., "very low", "low" and "moderate") divided by the total number of experts (i.e., [2+1+3]/10 = 0.6); that is 0.6 or 60%. This concept of belief is supporting Shafer's framework (Shafer, 1976) that mentioned "belief in a hypothesis is constituted by the sum of the masses of all sets enclosed by it". Plausibility measures the extent to which evidence is either in favor of hypothesis or not has any evidence to reject the hypothesis. The second part is called uncertainty; which in this study for the experts which are familiar with the CCS site and different physics associated with CO_2 leakage CCS one order of rating in scale of 5 could be acceptable. For example for the same question and set of experts as mentioned for belief evaluation, the plausibility of answer "moderate" is the total number of experts who answered "high" (i.e., the next sever answer for "moderate" answer) and lower severities range (i.e., "very low", "low", “moderate” and “high”) divided by the total number of experts (i.e., [2+1+3+1]/10 = 0.7); that is 0.7 or 70%. This yields the degree of belief and degree of plausibility for each answer. The second part (the mathematical process) is implemented through the Guth (1991) method, which was developed to infer fault tree rationales (Boolean algebra) and rule-based expert systems. Guth(1991) used the truth tables for “AND” and “OR” gate functions in Table 3 and Table 4 are generated the following mathematical functions for “AND” and “OR” gates, as:

$$AND\{m(A),m(B)\} = Bel_A \otimes Bel_B = m\left(Bel_A^L \times Bel_B^L, Bel_A^U \times Bel_B^U\right) \quad 8$$

$$OR\{m(A),m(B)\} = Bel_A \oplus Bel_B = m\left(1-\left(1-Bel_A^L\right)\left(1-Bel_B^L\right), 1-\left(1-Bel_A^U\right)\left(1-Bel_B^U\right)\right) \quad 9$$

where Bel^L and Bel^U are degree of belief and degree of plausibility, respectively. The Bel^L and Bel^U are basically the lower/upper bound of each failure, and are the topic of many probabilistic studies, but Guth theory is one of the most suitable techniques for implementing fault tree.

Expert Opinion and Risk Estimation for the Weyburn Project

The expert opinion survey was conducted at the 3rd **PR**oject **I**ntegration and **S**ponsors **M**eeting (PRISM) in the Weyburn Project using researchers involved in the project. PRISM meetings allowed researchers to discuss various aspects of the project and the expert opinion survey conducted during the PRISM allowed the capture of these researchers (“experts”) opinions on issues related to the framework highlighted in Figure 2 over the range of these experts’ knowledge and experience. The final result of this survey is a 3-D graph shown in Figure 13. This graph has three axes, the “belief (agreement)” axis, the “fuzzy variable” axis (or in this study, the risk qualitative values axis), and the z-axis showing the fuzzy dominating factor (membership degree) for each risk value. In this figure, the Fuzzy Variable defines the “very low” to “very high” risk definition, and degree of belief is defined by the agreement of the audience over each final part of output. This graph is defuzzified using the COG approach and is shown in Figure 15.

It is clearly much easier to make decisions based on a defuzzified graph. Based on Figure 13 and Figure 15 for 50% belief, the fuzzified CO_2 leakage risk equals:

$$X = \left\{\frac{0.20}{Very Low}, \frac{0.30}{Low}, \frac{0.30}{Medium}, \frac{0.0}{High}, \frac{0.20}{Very High}\right\} \quad 10$$

where X shows the dominating factor for each fuzzy variable on 50% agreement. The X value corresponds to the mean fuzzy value in Figure 13 and ranges around the Low risk value. However, in most risk assessments, regulators wish to see the degree of agreement on each risk value, and most prefer to see the range of risk based on different percentiles. Figure 16 shows the final survey results after defuzzification, assuming that belief have the normal probability distribution function. The shaded zone boundaries represent range of values which audience have agreement of 75% (the area of shaded zone is equal to 75%). It should be noted that the nearest meaningful fuzzy values (4.3 and 6.7) are chosen to represent 12.5% and 87.5% probability.

Discussion and conclusion

The definition of risk can affect policy debates, the allocation of resources towards safety measures, and the distribution of political power in society. Society can direct capital such that it reduces general public risk. The proposed methodology is structured in FFT (Fuzzy Fault Tree) format, using fuzzy logic and Dempster-Shafer methods as compilers for adapting the opinions of experts to the system. A lack of data leaves qualitative risk assessment based on the linguistic input of experts as the only possible and justifiable method.

The objective of this study was to develop a methodology for incorporating subjective risk evaluation procedures into the "fault tree". This methodology was applied to the Weyburn project, using the expert panel in 3rd PRISM. This study cannot be considered as full field risk assessment of the Weyburn project, due to limitations for expert to be involved in all aspect of this research, validation with other CO_2 storage projects. Ultimately, risk and belief are combined to assign different belief values to different evaluations of calculated risk values.

The risk value of the Weyburn Project is evaluated as "medium" to "high" for 75% percentile interval, as it is shown in Figure 16. This result shows that the "medium" to "high" risk value will be resulted considering the inputs from experts considering all leakage pathways included in suggested fault tree (see Figure 3). The 75% percentile interval can be a reasonable range and can be accepted agreement range for this methodology. The 75% percentile interval suggestion can be on conservative side if the expert panel is not well defined and the methodology is not well presented to the panel, since experts mostly stays on the conservative side if they are not well confident on methodology or risk associated questions.

This methodology can be used in future for sub-surface geological CO_2 storage field risk assessment. Future validation and feedbacks from different geological storage projects can build up consistency and reliance on this methodology.

Table 1. Proposed categorization of risk hazard severity for exposure to CO_2

Severity	Proposed Zones	Risk Hazard Circumstance
Very High	Zone 5	Death and convulsion and asphyxiation
High	Zone 4	Near unconsciousness
Medium	Zone 3	Headache and dizziness
Low	Zone 2	Mild headache and sweating and difficult breathing
Very Low	Zone 1	Not noticeable effects

Table 2. The risk matrix suggested by Shell is used as the fuzzy associative memory (FAM) for fuzzified risk value evaluation in this study

Risk Factor Severity	VH	M	M	H	VH	VH
	H	L	M	M	H	VH
	M	L	L	M	M	H
	L	VL	L	L	M	M
	VL	VL	VL	L	L	M
Risk Factor Effect		VL	L	M	H	VH
		Risk factor likelihood				

Table 3. Boolean truth table for the AND operator

		Truth value of A		
	AND Function	**True**	**False**	**(True, False)**
Truth value of B	**True**	*True*	*False*	*(True, False)*
	False	*False*	*False*	*False*
	(True, False)	*(True, False)*	*False*	*(True, False)*

Table 4. Boolean truth table for the OR operator

		Truth value of A		
	OR Function	**True**	**False**	**(True, False)**
Truth value of B	**True**	*True*	*True*	*True*
	False	*True*	*False*	*(True, False)*
	(True, False)	*True*	*(True, False)*	*(True, False)*

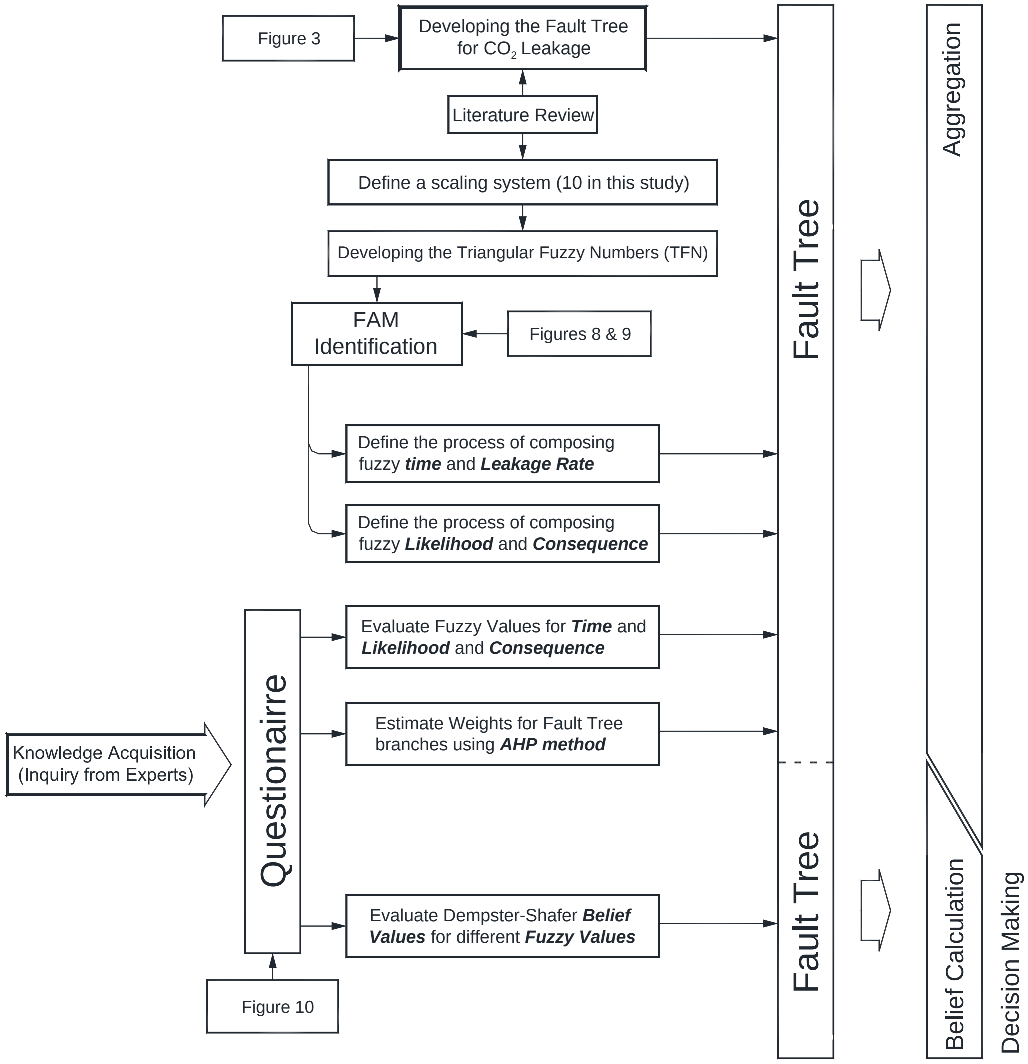


Figure 2. Proposed framework for incorporating the fuzzy aggregated risk values and the belief values for the Geological Storage Projects using the Evidence theory (Dempster-Shafer Method) and the Fuzzy Sets Theory

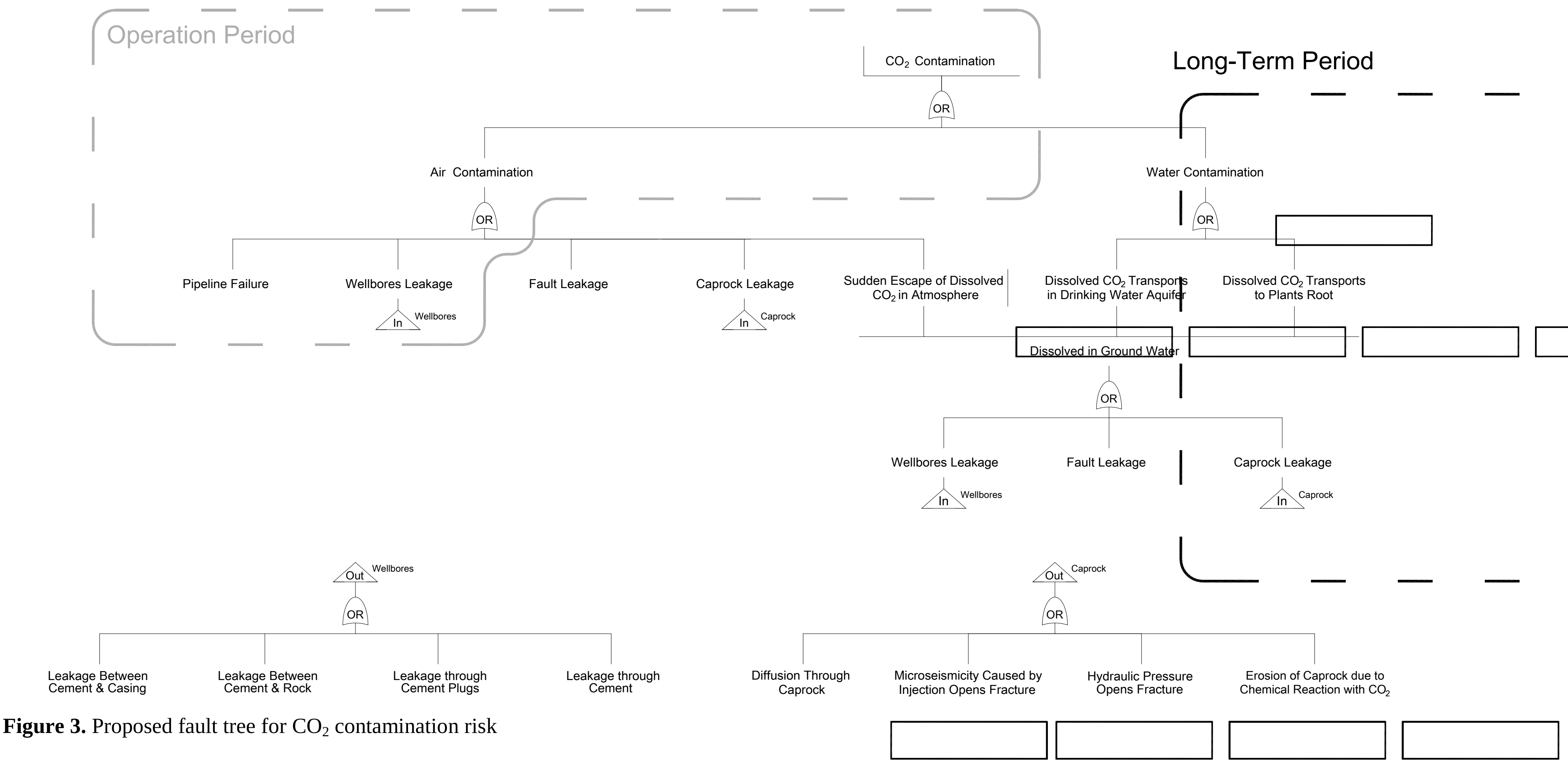


Figure 3. Proposed fault tree for CO_2 contamination risk

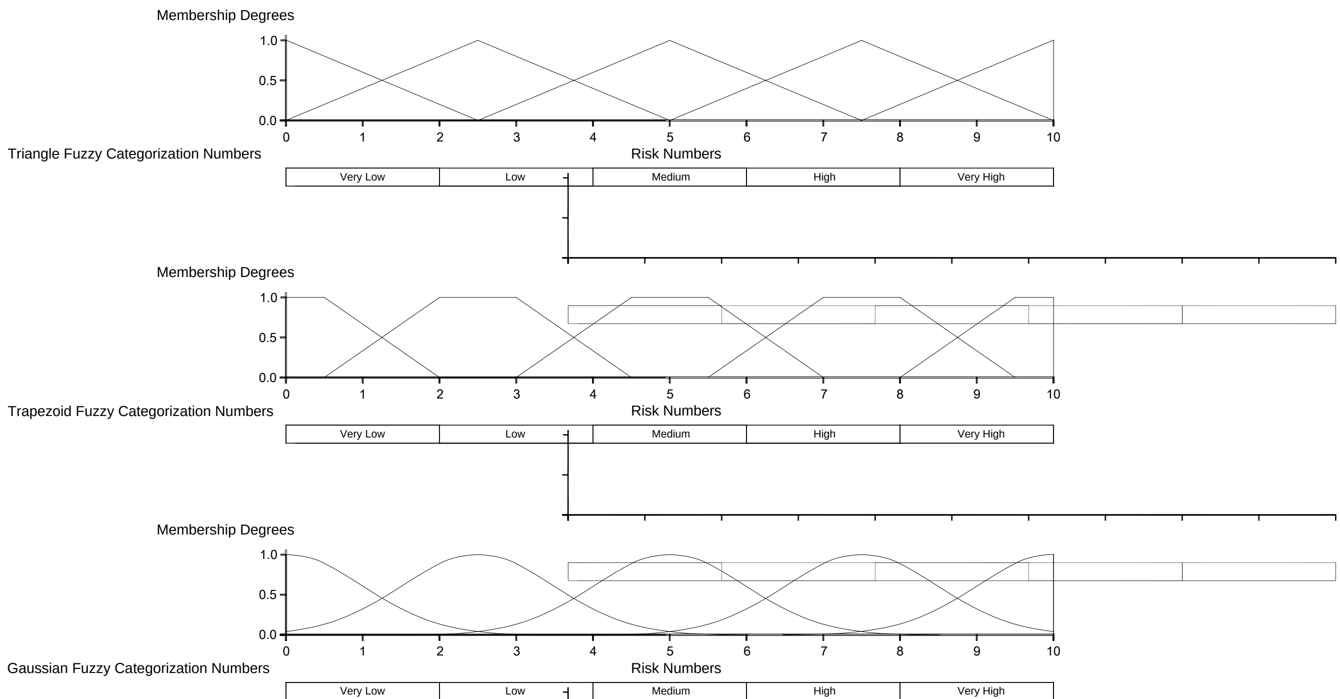


Figure 4. Proposed fuzzy membership function (triangular, trapezoid and Gaussian)

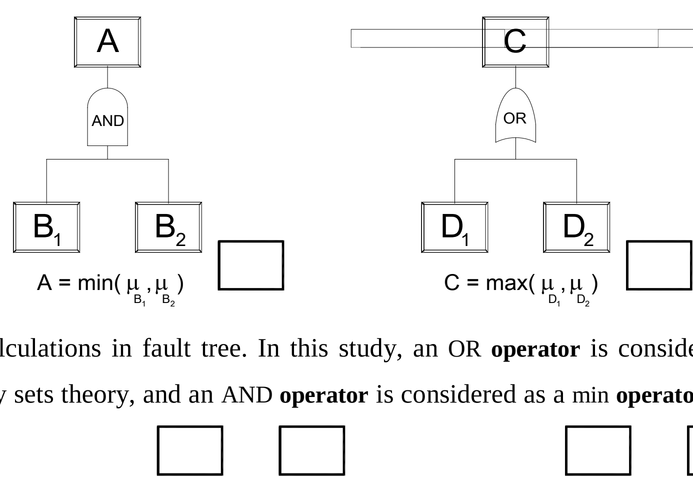


Figure 5. Fuzzy calculations in fault tree. In this study, an OR **operator** is considered as a max **operator** in the fuzzy sets theory, and an AND **operator** is considered as a min **operator** in the fuzzy sets theory.

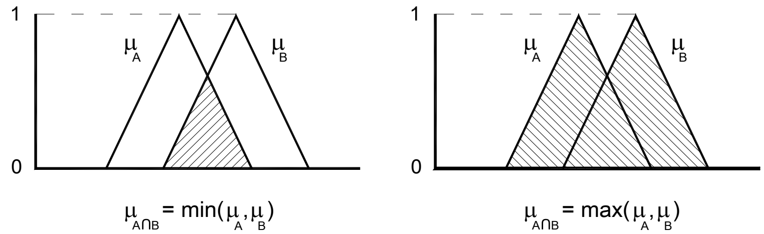
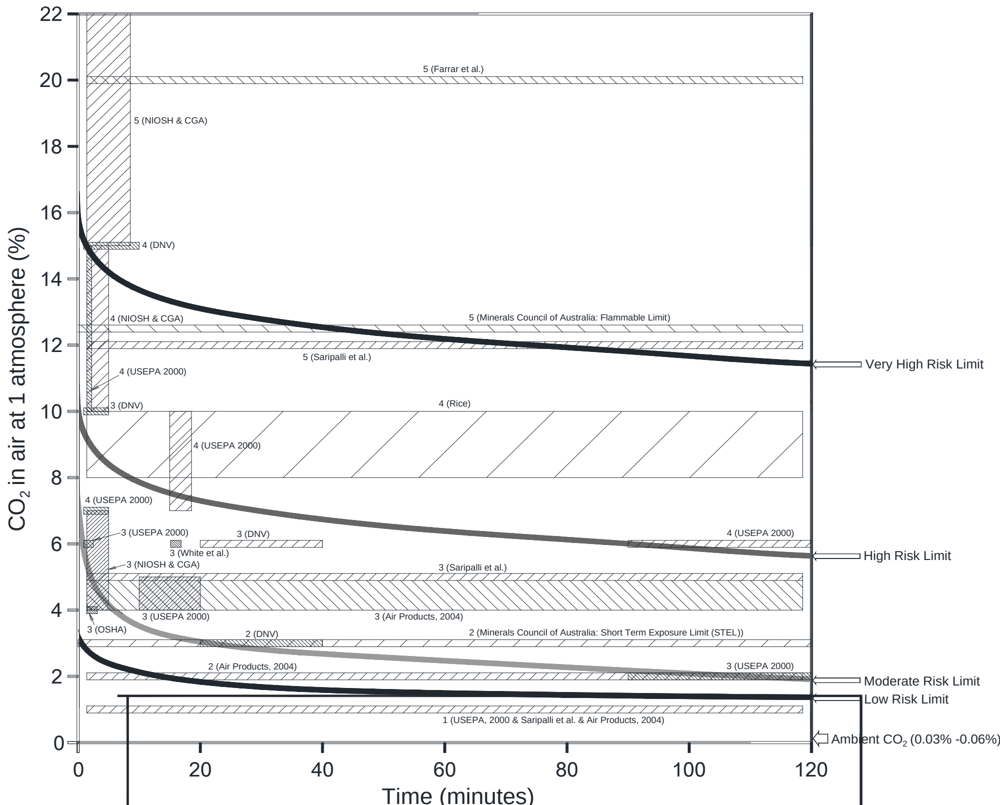


Figure 6. Illustration of min **operator** and max **operator** in fuzzy sets theory.



References in this Graph:

Air Products, 2004

CGA: Compressed Gas Association, 1997

DNV: Det Norske Veritas, 2001

USEPA: United States Environmental Protection Agency, 2000

OSHA: Occupational Safety and Health Agency, 1989

NIOSH: National Institutes of Occupational Safety and Health, 1976 and 1997

Rice, 2003, 2004

Saripalli et al., 2003

Minerals Council of Australia, 2007

Figure 7. Effects of different CO_2 concentration on human beings health condition by variation of time duration. Each data point is labelled with zone classification and references.

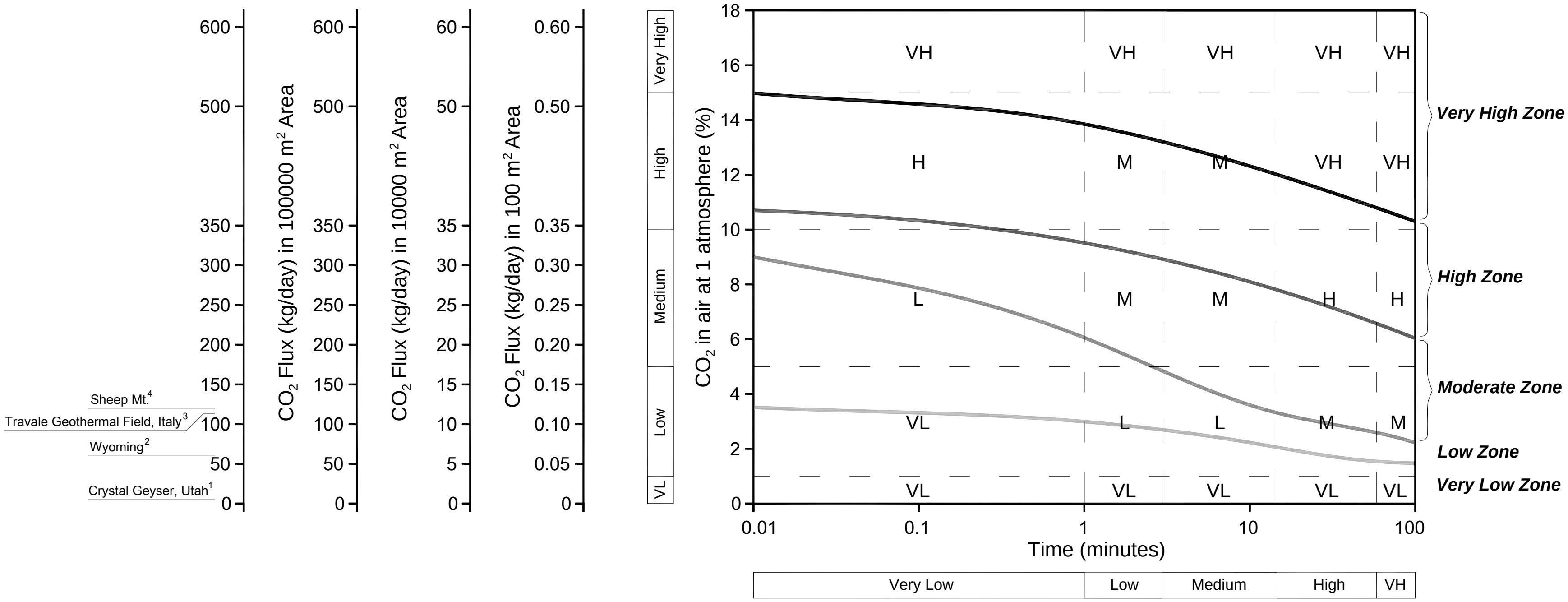


Figure 8. Proposed fuzzy rules for CO_2 contamination consequence severity based on effects of different CO_2 concentration with different time periods on human beings health condition, in this figure the horizontal axis is showing the time severity and the vertical axis is showing the contamination severity, and the results of this table is coming as risk of hazard (reference 1: Gouveia et al., 2005, 2: Araktingi et al., 1984, 3: Ferrara and Stefani, 1978, 4: Lynch, 1983)

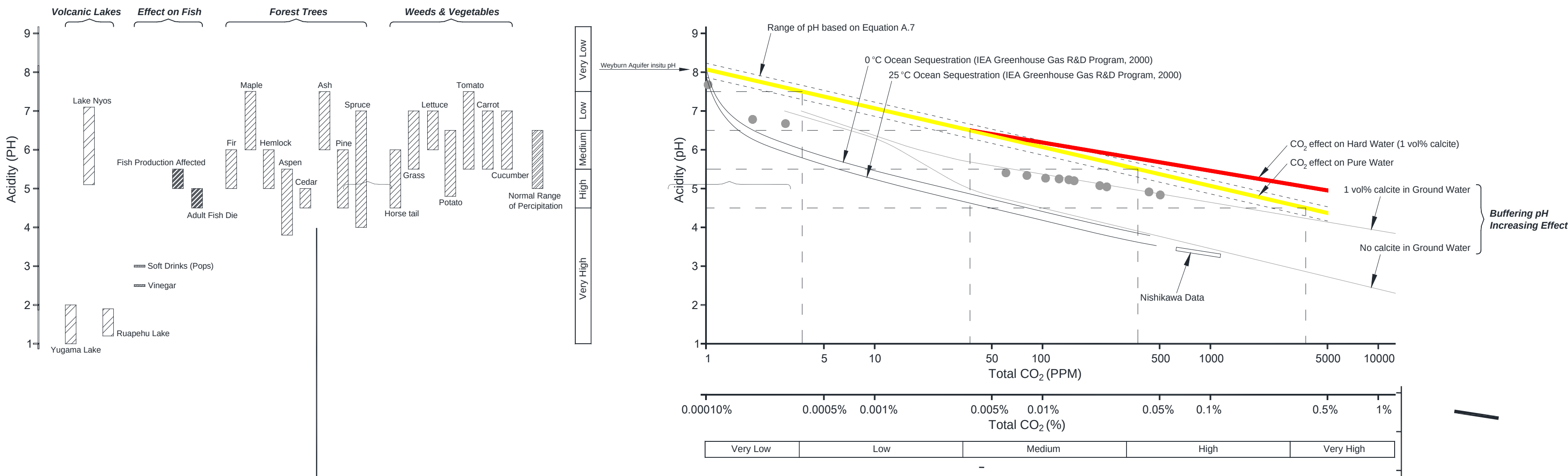


Figure 9. Variation of acidity on pH scale with CO_2 concentration, which is used for severity categorization of CO_2 concentration in water contamination for experts' opinion linguistic characterization. On the left side the level of acidity which plants such as vegetable crops, forest trees, weeds and fish can tolerate is given, also the acidity level of three volcanic lakes is given for better experts understanding. The soil science education site is used for pH evaluation of different plants and trees. The buffering effect is also considered in this figure after Wilkin and Digiulio (2010).

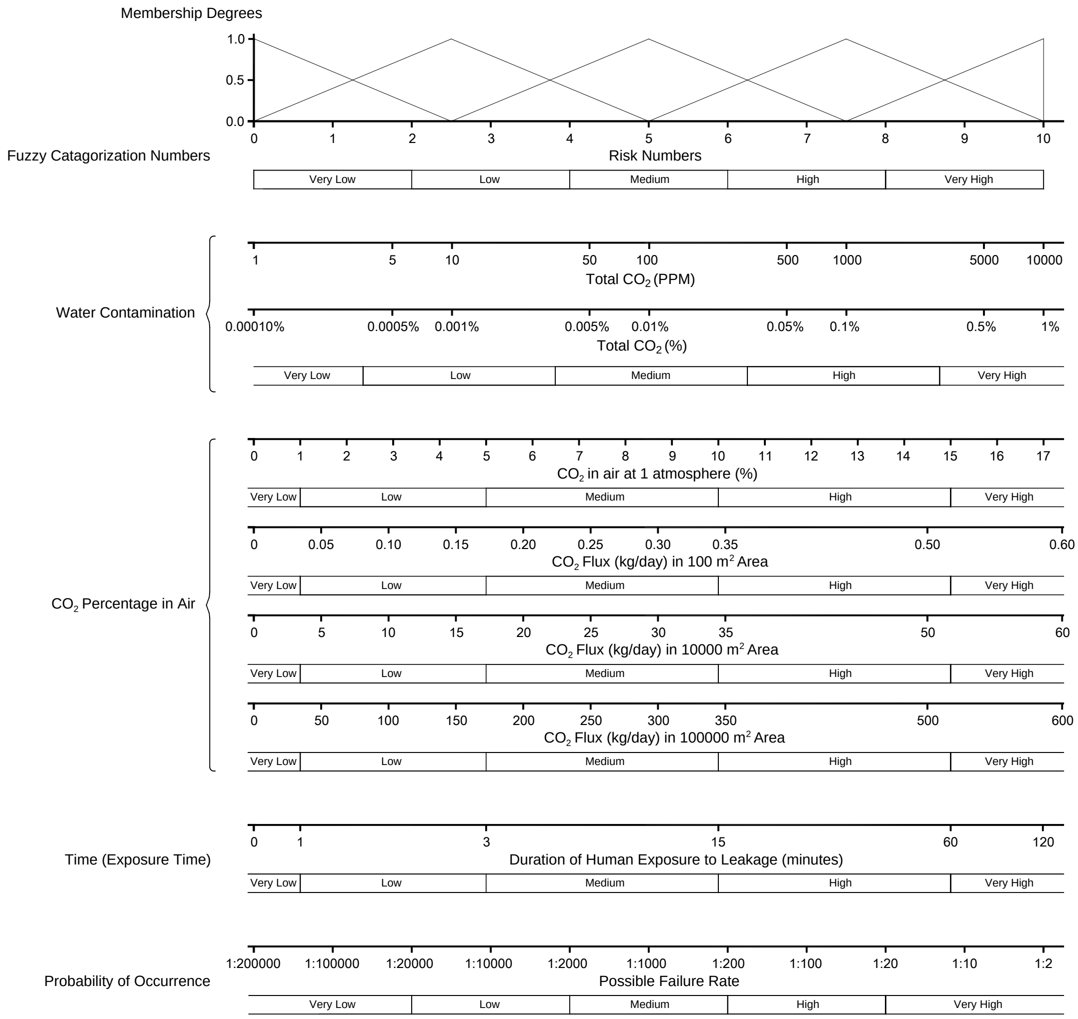


Figure 10. Categories for different experts' opinion for CO_2 concentration and duration and probability

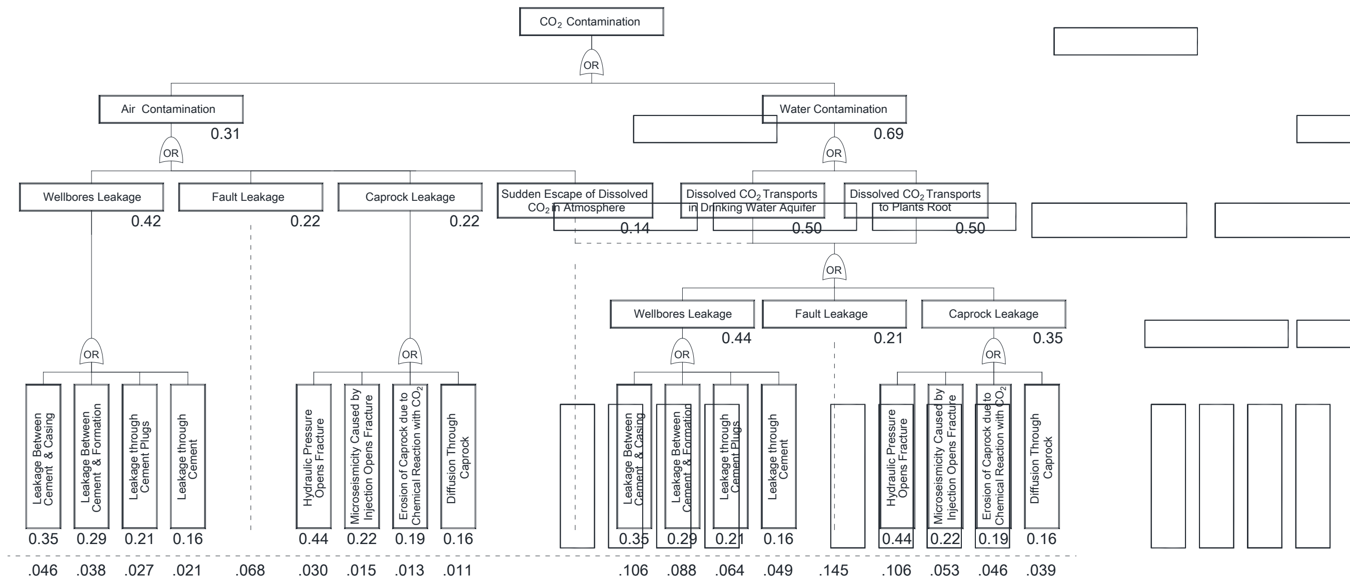


Figure 11. Analytic Hierarchy Process (AHP) calculated weight factors for fault tree presented in the study.

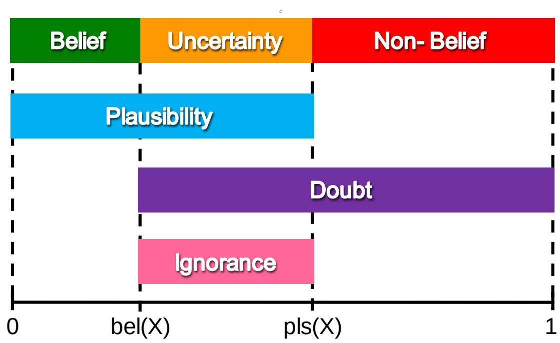
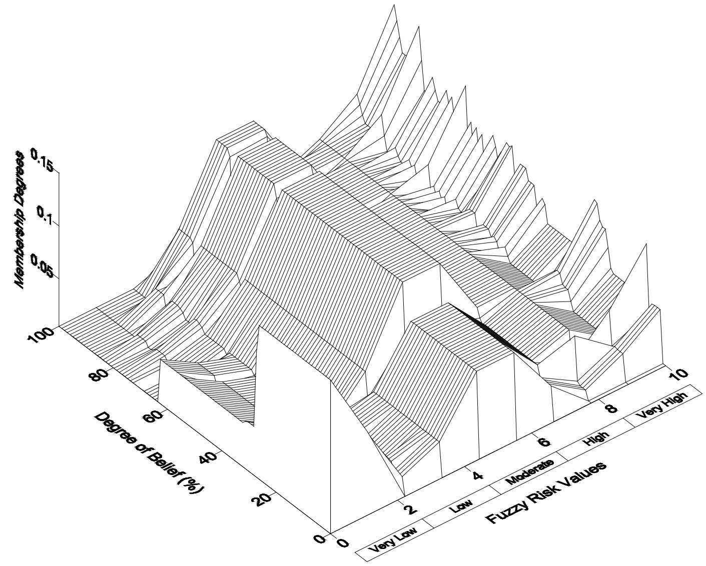
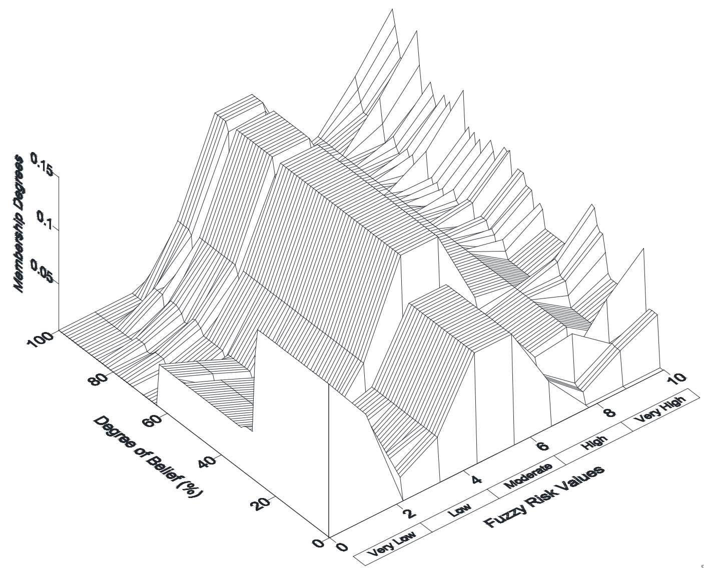


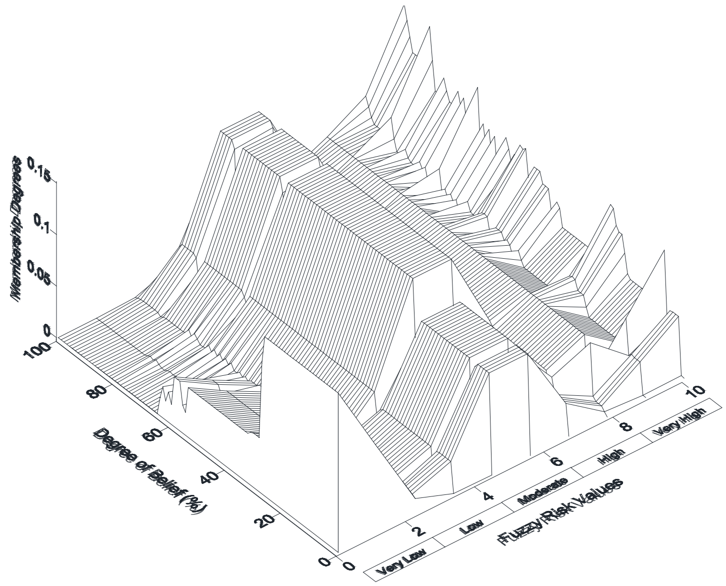
Figure 12. Definition of different concepts in Dempster-Shafer theory (evidence theory)



a. Results of survey using Triangle membership function



b. Results of survey using Trapezoid membership function



c. Results of survey using Gaussian membership function

Figure 13. Final results of survey, in this figure the fuzzy risk variable are defining the very low to very high risk definition and degree of belief is defining the agreement of audience over each final part of output. In this figure different membership functions is studied.

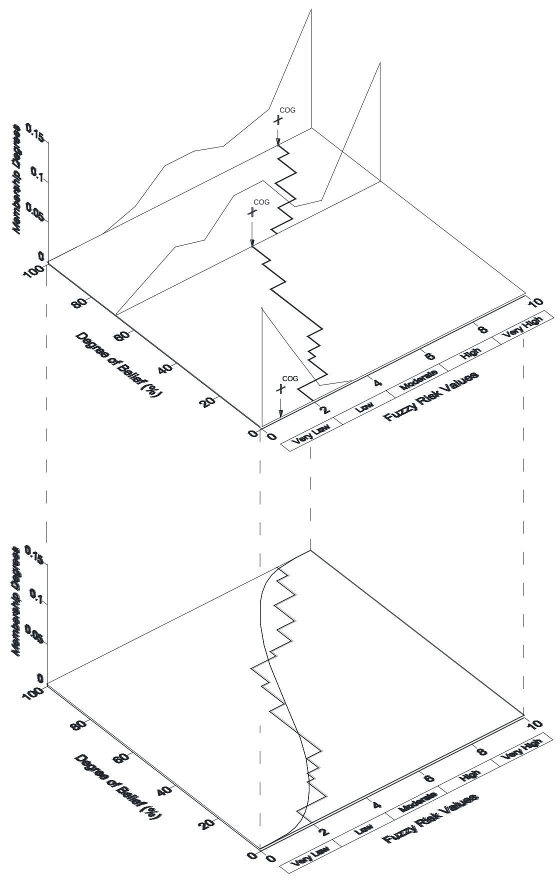


Figure 14. Illustration of defuzzification process of data in Figure 13 into Figure 15.

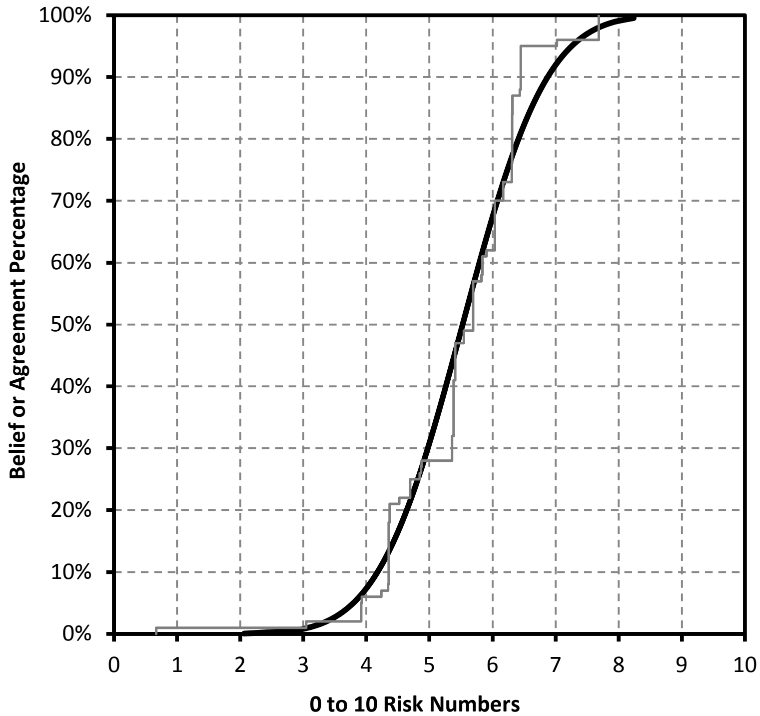


Figure 15. Final results of survey after defuzzification, this graph shows the Risk Values versus the Belief Agreement

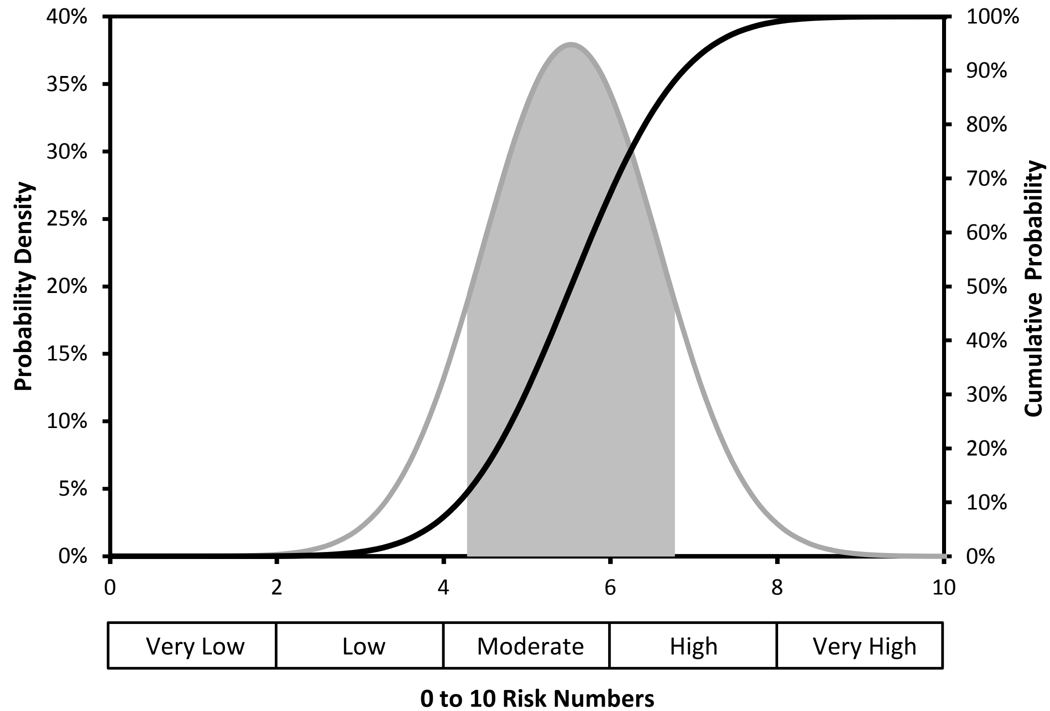


Figure 16. Final results of survey after defuzzification, the boundaries of audience agreement based on 12.5% probability and 87.5% probability is shown, it must be noted that the nearest meaningful fuzzy values 4.3 and 6.7 are chosen as 12.5% and 87.5% probability, the range of 4.3 to 6.7 covers the 75% of total probability

3. Evaluation of Public Acceptability for the Geological Storage of CO_2

Introduction

Modern technological systems are usually introduced because they provide some benefit to society. But they also pose risks. These risks are usually accepted as the price we have to pay for the benefit the technology offers us, provided the risk is less than the benefit. If the risk is too high, the technology will be rejected. For hazardous technologies, reduction of risk below some level may persuade people to accept it. The concept of socially acceptable risk, or acceptable risk, is used widely in the planning of industrial development and has been used in other areas of engineering, such as dam engineering. When evaluating acceptable risk, one usually considers the risk to individuals from the hazard and the societal risk, or the annual probability of an event leading to a number of lives being lost. In most cases, social acceptability over new technologies is unknown, and politicians are reluctant to proceed unless they are assured that the public will accept the technology and that its implementation will be politically feasible. This chapter discusses research conducted to better understand issues related to the public's acceptability perceptions of geologic carbon storage.

The goal of the research was to provide structure for a public acceptability analysis that allows decision-makers to forecast both public (and political) acceptability for large-scale geologic carbon storage developments. The idea of risk acceptance or risk tolerance is a fundamental factor in the concept of safety integrity regulations and the acceptability of new technologies. The factors affecting acceptability are discussed and numerical values and empirical factors are proposed to obtain a measure of social tolerability and public perceived acceptability limits for geologic storage but also new technologies in general. By looking beyond current perceptions of risk and risk acceptability, a discussion is provided on how individuals (and society) deal with decisions on risk within a broad complex mix of scientific, social, political, legal, institutional, and psychological factors. Finally, a structured method is suggested for risk acceptability evaluation. The need for risk reduction is also discussed, as well as a systematic approach for establishing risk acceptance criteria and for identifying the effects of hazardous failures. Finally, it evaluates public concern over risk and evaluates the distance to meet tolerable risk level for further risk mitigation. The ALARP principle is used to evaluate tolerable risk limits and a new definition of ALARP is introduced. The principles of this approach are discussed in later sections.

Background

The results of risk evaluation from former risk assessment studies are coupled with public perceived benefit and respondents' belief over the state of media openness in Canada and public trust in Canada's government and companies that would be charged with operating geological storage projects. Respondents' in this study are from the same experts group who were questioned for risk evaluation of geological storage discussed in Chapter 2. In this study the unamplified risk perception of geological disposal of carbon (GDC) is evaluated and illustrated in a cognitive map and the acceptability of GDC was evaluated. Risk communication is also discussed as the only way to control stigmatization for GDC and also reduce public risk perception.

Insight into the risks associated with CO_2 sequestration is key to gaining public acceptance and is indispensable in facilitating the formulation of the standards and regulatory framework required for large-scale application of underground CO_2 sequestration. Increasing effort is now focused on the assessment and quantification of risk associated with CO_2 geological storage.

During the past several decades, the field of risk assessment has developed to impart rationality to the management of technological hazards. Risk assessment methods are thought to have originated from safety improvement efforts in the United States space program, the evolution of operations research during the Second World War, and from efforts to facilitate the deployment of chemical facilities and nuclear power plants (Renn, 1998b). Developments were driven by two primary factors. First, due to the increasing complexity, scale, and social costs of industrialization, regulators and the public became more interested in the community impacts of large facilities (Bohnenblust and Slovic, 1998). Secondly, the increased scale and capital costs of such projects limited the iterative trial and error processes traditionally used to manage hazards, and risk assessment methods are used in place of costly test-based methods (Otway and von Winterfeldt, 1982).

There are two different approaches in risk analysis: that of natural science and that of social science. Natural science considers a process from the failure trigger to the receiver of the hazard (for example the process of “farm to fork” in assessing food safety). In social science, the emphasis of research is on human information processing systems, “how people process incoming risk information” and how the stigma ripples through society. This study focuses on the social science approach.

In the study of risk, the phrase “stigma” is used for technologies, places, and products perceived to be improperly dangerous. Stigma plays out socially in opposition to many technological activities, particularly those involving the use of chemicals and radiation, and in the large and rapidly growing number of lawsuits claiming devaluation of property due to perceptions of risk (Flynn, Slovic, and Kunreuther, 2001). Public evaluations of advanced technologies tend to be ambiguous and often inaccurate, and can contribute to the stigmatization of these technologies. It is not surprising that nuclear energy, promoted in the 1950s as cheap and safe, is now severely stigmatized. Today, stigmatization reflects public perceptions of abnormally high risk, distrust of management, and the disappointment of failed promises.

The stigmatization of carbon geological storage can be attributed to extensive media coverage of wellbore plug failures and groundwater contamination. Several studies have mentioned that stigmatization is a product of risk perception, and can take place before or without any demonstrated physical impacts. The decline of tourism in Southwest Asian countries following the tsunami was primarily due to risk-induced stigma. A World Tourism Organization report suggests that most tourists understand that there is a very small risk of a second tsunami in the Indian Ocean (WTO, 2005). This implies that looking only at the process of risk-induced stigmatization may downplay or even completely ignore other important focus points and scientific results. In another example, Gregory et al. (1993) conducted several surveys in Nevada that showed a majority of Nevadans worry that tourists in Las Vegas might have negative imagery associated with plans to create the nation's first geological repository for high-level nuclear waste at nearby Yucca Mountain.

In the field of disaster studies, the idea that disaster in a society is a combination of physical impact and historically accumulated vulnerability is dominant over all other interpretations of the experience. Most anthropologists and sociologists insist that:

"… the crucial point about understanding why disasters occur is that it is not only natural events that cause them. They are also the product of the social, political, and economic environment" (Blaikie et al., 1994).

The concept of vulnerability has been introduced to conceptualize society as the situational base of disaster. From this viewpoint:

… a disaster becomes unavoidable in the context of a historically produced pattern of "vulnerability," evidenced in the location, sociopolitical organization, production and distribution systems and ideology of a society. A society's pattern of vulnerability is a core element of a disaster (Oliver-Smith and Hoffman, 2002). The concept of vulnerability based on the multidimensional view of disaster can be applied to our analysis of CO_2 leakage risk assessment. Based on Flynn, Slovic, and Kunreuther (2001), risk-induced stigma involves three stages:

- Risk-related attributes receive high visibility, particularly through communication processes, leading to the perception and imagery of high risk. This process is mostly referred to as the "social amplification of risk",
- Marks are placed upon the company, place, technology, or product to identify it as risky. This process is mostly referred to as "marking",
- The "social amplification of risk" and "marking" alters the identity of the company, place, technology, or product.

"Risk perception" is a critical part of "risk amplification and stigmatization". Some types of risks that are new, involuntary, potentially catastrophic, and that involve dread are all likely to generate strong public concerns and elicit high media coverage. The responsibility of the managers of the facility or technology involved in the risk event and the character of their early response to the event are important compounding factors. If managers betray a history of failures or seek to conceal their responsibility, then a risk event is likely to be strongly amplified through media revelation and intensified public concerns. A lack of trust can be another compounding factor. If high levels of trust exist in those responsible for risk management, risk events may undergo only limited social amplification through media coverage and public perception. Contending social groups and watchdog organizations can also influence risk amplification and stigmatization. To the extent that risk becomes a volatile issue in a community, it may be brought to greater public attention and subjected to value-based interpretations. As such, social conflicts can outlive a particular risk event and can become anchors for subsequent risk debates, contributing to an image of the place and the emergence of risk-based stigma (Flynn, Slovic, and Kunreuther, 2001).

The consequences of a risk event can ripple to other places, technologies, and through society as a whole, or even into the future. Such rippling has been apparent in a number of well-publicized accidents. It contributed to the abandonment of ocean sequestration, once considered the safest way to handle greenhouse gases. In this case, media coverage of fishermen's complaints and rapid tourism decline in places where ocean sequestration was used made governments and experts abandon this method.

It is important to note that there is likely no jurisdiction that is isolated from stigma. An interesting question is whether a stigma becomes associated with other nearby places or with the broader geographic areas of which they are a part - Does "distance decay" attenuate stigma as one moves away from the stigmatized place or facility? (Flynn, Slovic, and Kunreuther, 2001)

A conceptual model of social responses to hazards, termed the "social amplification of risk", was developed by Kasperson et al., (Kasperson et al., 1988; Kasperson et al., 1992; Kasperson et al., 1999). It incorporates earlier work by Slovic et al. (1987) on the perception of risks. Social amplification is triggered by the occurrence of an adverse event that has potential consequences for public, such as a major or minor accident, a discovery of groundwater contamination, an incident of carbon leakage, and so on. Through the process of risk amplification, the adverse impacts of such an event sometimes extend far beyond the direct damages to victims (Slovic, 1987). Kasperson et al. (1988) use the analogy of dropping a stone into a pond to explain the secondary effects of risk events, and how they spread outwards from the victims of a risk event to social arenas. This is called the "ripple effect" in risk framework. The suggested stigmatization map of CO_2 leakage in carbon dioxide geological storage is illustrated in Figure 17. This conceptual model points to three mechanisms that are likely to contribute to social stigmatization. First, extensive media coverage of an event can contribute to heightened perceptions of risk and propagation of amplified impacts (Burns et al. 1990). Second, a risk event may come onto the agenda of social groups, watchdog organizations, or "partisans", as Mazur (1981) terms them. This may trigger special interest and concern in society (Flynn et al., 2001). Third, "misinterpretation of the risk" may cause great concern in society. The results of these amplifiers are “loss of trust” and “different interpretation of the risk”, which themselves can result in “secondary impacts” such as economic losses for companies and people living nearby, different social behaviour over carbon dioxide sequestration technology and the company, regulatory constraints over carbon dioxide sequestration technology, investor flight, loss of confidence in the company and litigation of the company. In this study, lack of trust is not considered a result of the risk event and social communication. As shown in Figure 16, perceptions of risk in carbon dioxide sequestration projects are related to the location of CO_2 leakage in historical events. For example people ***working*** in the Near Field (as noted in Figure 16), have likely higher probability that they may be exposed to CO_2 leakage than people ***living*** nearby which are not willing to live or work in such a hazardous area even with very small probability CO_2 leakage. This is called the ‘location amplifier factor’.

Methodology

The acceptability of the new technologies in public view is evaluated from perceived risk and perceived benefit. But perceived risk and perceived benefit can be changed as a result of accidental failure, lack of trust in government and companies dealing with that technology. Acceptability variation based on perceived risk and perceived benefit variation is also explored along with a proposed framework for considering race and gender effect, media effect and trust variation effect on acceptability of perceived risk of the new technologies. In this section the suggested process and literature review on race and gender effect, media effect and trust variation effect is presented and considered independently and the combination of all these effects is embedded in the final result.

3.1.1. Risk perception

During the last forty years, industrialized countries have grown healthier and safer and spent a great deal of effort and billions of dollars doing so. Despite this, the public in these countries has become more concerned about risk and feel more vulnerable to life’s hazards and believe that land, air, and water are more contaminated by toxic substances than ever before (Slovic and Peters, 2006). Risk in the modern world is perceived in two fundamental ways. Risk as feelings refers to our instinctive and intuitive reactions to danger. Risk as analysis brings logic, reason, and scientific deliberation to bear on risk assessment and decision-making (Slovic and Peters, 2006).

Strong visceral emotions such as fear and anger sometimes play a role in risk as feelings. These two emotions appear to have opposite effects, such that fear amplifies risk estimates, and anger attenuates them (Lerner et al., 2003; Lerner et al., 2001; Lerner et al., 2000). Lerner has explained these differences by proposing that fear arises from appraisals of uncertainty control, whereas anger arises from appraisals of certainty and individual control. Several studies show that feelings of dread are the major determinant of public perception and acceptance of risk for a wide range of hazards (Fischhoff, Slovic, Lichtenstein, Read and Combs, 1978).

Research has found that whereas risk and benefit tend to be positively correlated across hazardous activities in the world, they are negatively correlated in people's minds (Fischhoff, Slovic, Lichtenstein, Read and Combs, 1978; McDaniels et al., 1997). For instance, the benefit of using rollerblades is much less than the risk, but most people consider rollerblading a low-risk activity. Several explanations have been offered for the observed associations. Alhakami and Slovic (1994) speculate that people may assess hazards as favourable or unfavourable. If people prefer consistency among their beliefs, risks are devalued and benefits elevated for technologies perceived as favourable. For technologies perceived as unfavourable, the opposite is true, resulting in higher perceived risks and lower perceived benefits. Gregory and Mendelsohn (1993) concluded that people incorporate some benefits in their risk assessments. In other words, risk ratings are "net" measures. Frewer et al. (1998a) assumed that the favourability of a technology is affected by perceptions of risks and benefits that are functionally related to each other. They also argued that it may be possible to change perceived risks by changing perceptions of benefits. Finucane et al. (2000) suggested a positive correlation between risk and benefit in the environment; the positive correlation was initially presented for correlation between risk and benefit in nuclear leakage scenario by Finucane et al. (1998). They showed that for low benefits the low risk is expected for technologies causing hazardous leakage.

A study by Alhakami and Slovic (1994) suggested that risk and benefit are inversely related in people's minds because an affective feeling is referred to when the risk or benefit of specific hazards is judged. If this affective feeling or affective evaluation was 'liked', people tended to judge its risk as low and its benefits as high, the opposite being true if it was 'disliked'. Zajonc (1980) proposed a model illustrating this affective evaluation, which can mislead public in many cases.

To study the relationship between perceived benefit and perceived risk, Alhakami and Slovic (1994) used a 7-point scale, ranging from (1) 'not at all risky' to (7) 'very risky' and (1) 'not at all beneficial' to (7) 'very beneficial'. This study investigates the new relationship between 'perceived benefit' and 'perceived risk' for voluntary and involuntary hazards. The suggested acceptability limit in Figure 19 is a trend line based on data for voluntary exposure from work by Alhakami and Slovic (1994). The acceptability limit trend line is modified such that it does not decline, and for better regression a weighted averaging is used for curve fitting. Figure 19 implies a negative correlation between risk and benefit, although according to number of studies across hazardous activities, risk and benefit are positively correlated (Gregory and Mendelsohn, 1993; McDaniels et al., 1997; Fischhoff et al., 1978).

Multiple studies look at the correlation between perceived benefit and perceived risk. Gregory et al. (1993) did so based on survey data collected by Slovic et al., the most reliable data available for this purpose. The same data are used to evaluate acceptable and unacceptable regions. In these studies there is not much difference between voluntary and involuntary trends, which support considering suggested acceptability limit in Figure 19 for both voluntary and involuntary exposure.

For this research, for acceptability evaluation, the ALARP midline is considered equal to the voluntary trend line, the only difference being that the perceived benefit axis is upside down. The resulting graph is shown in Figure 19. The ALARP region in Figure 19 implies that the acceptability of a perceived high-risk technology could be increased by identifying and emphasizing its benefits (hence reducing the perceived risk). The ALARP region's band shrinkage in higher risks implies less tolerability in higher risks.

According to Starr's (1972) prominent approach to determining socially acceptable levels of risk revealed society's success in associating more beneficial activities within increasing perceived risk and that society has also imposed less stringent standards upon voluntarily-incurred risks. The suggested ALARP region in this study roughly fit the involuntary acceptable limit presented by Starr (1972), and the rest of the proposed ALARP region is on the safe side.

As with most standard approaches when applying the ALARP principle, three regions are considered:

- The risk is so low that it is considered negligible (e.g. the green ellipse in Section A of Figure 21)
- The risk is so high that it is intolerable (e.g. the red ellipse in Section A of Figure 21)
- The risk is intermediate, called the 'ALARP region' (e.g. the orange ellipse in Section A of Figure 21).

The ALARP principle (As Low As Reasonably Practicable) or sometimes called AFAIRP (As Far As Is Reasonably Practicable), an established concept in United Kingdom Health and Safety Law (1992), is a way of evaluating the highest risk that the public would tolerate for each perceived benefit. There are different approaches containing ideas similar to the ALARP principle, such as: the German MEM principle (Minimal Endogenous Mortality) and the French GAMAB principle ("Globalement Au Moins Aussi Bon", that is, "globally at least as good").

A simple example illustrates ALARP. People know that motor traffic can and does kill people and pollutes the environment quite considerably. However, people drive because they believe that the chances of killing someone or getting killed in a road accident are so unlikely that they are willing to take the risk. A mechanism is needed to calculate the trade off between the benefits and risks of this technology. This would entail calculating the risks that are acceptable for an individual driving a car, considering all of driving's benefits. The ALARP principle defines a level of risk which is the least acceptable to the general public. In this study, the ALARP region is considered 4.5 to 5.5 on the 7-point scale. This is shown schematically in Figure 18. Acceptability factors lower than 4.5 are considered unacceptable or intolerable, and those higher than 5.5 are considered acceptable. In Figure 18 a three-part framework for risk evaluation known as the tolerability of risk (TOR) which is adopted by HSE (1992, 2001). The framework presented in Figure 18 is an inverted triangle that represents increasing levels of 'societal risk' for a particular hazardous activity from the bottom of the triangle to the top. The top zone represents an unacceptable region. For practical purposes, a particular risk falling into unacceptable region is regarded as unacceptable no matter the benefits associated with the activity. The bottom zone represents a broadly acceptable region. Risks falling into this region are generally regarded as insignificant and adequately controlled. Regulators would not usually require further action to reduce risks unless reasonably practicable measures are available. Risk levels in this region are comparable to those regarded as insignificant or trivial by the public in their daily lives. Finally, as already discussed, the middle zone is known as the tolerable, or ALARP, region.

The idea of ALARP is not new in the risk world. It is usually calculated using the statistical probability of fatalities per hour (or per year) of exposure of the individual to the activity versus the amount of money lost or number of fatalities. The most famous study using ALARP considering fatality and probability was done by Starr (1969), who proposed a correlation between probable money loss by an individual in hazardous events happening in one activity, and contribution of the activity to that individual's annual income. In our studies, the concepts of probability of fatalities per year and contribution of the activity to the individual's annual income are replaced with perceived risk and perceived benefit, respectively.

To provide some level of verification to the establishment of the ALARP zone described above, the ALARP region was compared to the results of a survey conducted by Tokushige et al. (2007) related to Japanese social trust of new technologies. In Figure 19 the size of the circles implies the perceived acceptability evaluated by Tokushige et al. (2007). Orange circles in Figure 19have acceptability ratings between 4.5 and 5.5, and green and red circles are for acceptable and unacceptable technologies, respectively. Based on these results, the ALARP region proposed in this study reasonably captures the variability in the results from the Japanese survey. What is more difficult to assess is the width of the ALARP region because it is strongly influenced by social trust. In this study, social trust is defined as the reliance on the character, ability, strength, or truth of the government or the company in charge with the specific technology. Social trust is discussed in Section 3.1.4.

3.1.2. The impact of media coverage

As seen in Section A of Figure 20, according to Penny Chan's thesis (from risk, media and stigma by Flynn, Slovic, and Kunreuther (2001), Chapter 14), in the early 1980s, when the risk of blood transmitting AIDS was at its highest, risk estimates were at their lowest. This can be attributed to poor scientific data and lack of experience. However, Penny Chan's theory illustrates that public risk perception became "unreasonable" compared to experts' estimates when the media began covering the impact of AIDS on sufferers, causing stigmatization. This may be why Picard (1995) said:

"… We journalists are guilty of the same "crime" (or maybe more) as the main players in the blood systems (the real risk providers) … a failure to inform the public".

Media coverage of a risk incident can be shown to have an amplifying effect on social panic. The physical risks of watching and hearing about a risk are sometimes greater than exposure to the risk itself.

During the time of preparing this thesis (and any preceding time) there had been no indication of CO_2 movement outside the injection horizon at approximately 1400 m depth. But on January 11, 2011 a family (the Kerr's) having property on the border with the Weyburn CO_2-EOR commercial project held a press conference in Calgary and claimed that injected CO_2 was indeed leaking into a gravel pit located on their property. Immediately following the press conference signs of media stigmatization and trust reduction began to appear. An approximate timeline for this event is illustrated in Section B of Figure 20.

The Kerr Case starts in the fall of 2003, since landowners Jane and Cameron Kerr dug a gravel pit on their farm, located near the Weyburn project (Canadian Business, 2007). The Kerr's claimed that in their gravel pit "at first, the water remained clear, but by spring 2005 it was bubbling and churning a cream and blood colour. After several gaseous explosions rocked the pit and a slick that looked like petroleum contaminants covered the surface" (Canadian Business, 2007). In July 2010, the Kerr's engaged a geochemical consulting firm in Saskatchewan to study CO_2 levels on the property. The firms report mentioned: "A geochemical soil gas survey of the Kerr property, ... showed high concentrations of CO_2 that averaged about 23,000 ppm (2.3%) over most of the property and a major anomaly with concentrations as high as 110,607 ppm (11%) in the north central part of the property, ..., the provenance or source of the high concentrations of CO_2 in soils of the Kerr property is clearly the ... CO_2 injected into the Weyburn reservoir ... CO_2 could enter the home in dangerous concentrations ...".

Over the weeks following 'The Kerr Case' (the press conference) the media stigmatization starts with phrases such as, "if authorities can't even recognize a problem now, how are they going to regulate more carbon storage?"; "A growing number of Alberta-based experts say we must bury CO_2. Others say that might bury us" (Canadian Business by Nikiforuk, 2007); "Those researchers have said there's no possibility of CO_2 leakage" (Leaderpost, 2011); “Cenovus (company owns Weyburn project) refused to conduct further studies” (Robinson, 2011); “Suspected problems with a carbon capture project in Saskatchewan led two Alberta opposition parties to question ... to fund similar projects” (Canadian Business, 2011); "Why should Alberta taxpayers be on the hook for billions of dollars in this experiment” (CBC News, 2011); "It's pretty clear that there isn't any workable carbon capture and storage technology and why should we be the guinea pig?" (CBC News, 2011). The evaluated variation of risk stigmatization is illustrated in Section B of Figure 20 in comparison with HIV (or AIDS case) shown in Section A of Figure 20.

As it can be seen from media and public response the Weyburn and CCS risk ellipse in acceptability graph is pushing toward right side of the graph. The situation is more or less the same as public opinion over nuclear plants after Fukushima plant failure, which was caused by a devastating 9.0 Richter earthquake (the third largest earthquake in recorded history) in combination with 14 metres Tsunami waves.

The Kerr case has only recently been resolved but only after a significant technical effort was initiated by Cenovus, the Weyburn Research Project and a third party to examine the source of the CO_2 found in the gravel pits. It was found be shallow biogenic CO_2 and was not linked to the CO_2 being injected into the reservoir at 1400 m depth. The Kerr case has provided a perfect example of how media coverage, in particular, negative media coverage can result in a substantial impact on perceived risk for the geological storage of CO_2.

The conceptual framework of the social amplification of risk by media coverage, as outlined in Figure 22, is one that links technical assessment of media coverage with socio-cultural perspectives of risk and panic-related behaviour. The framework considers the ‘secondary impacts’ of increased censorship and amplification of political and industrial pressure. These are generated and spread outwards from the concerns of the risk event’s victims to institutional and social arenas and the amplification impact of dissemination of news regarding the risk event by media coverage. The outline in Figure 22 is modified and adapted to media coverage from Hill’s work on media violence in 2001 (Flynn, Slovic, and Kunreuther, 2001). Ben Goldacre, author of the Bad Science column in the Saturday Guardian thinks that the media are not the only guilty ones when it comes to publication bias. Academics are just as guilty in the filtering out of certain types of studies from scientific journals. For example, negative studies of failed drug trials do not get prominence in major journals (Goldacre, 2006). Both communities are guilty of inflating news to gain attention. According to Edelman Japan Trust Barometer (2007) the variation of trust in media sources in Japan and the United States, the highest trust in Japan is of articles in business magazines and in United States is of newspaper articles, and the highest trust in both countries is of TV programs, weblogs and product advertisments which can shows people high trust on written document rather than TV shows. It also can be the reason why Goldacre believes that writers of scientific articles (it may include academics) are guiltier than members of the general media such as TV and radio (Flynn, Slovic, and Kunreuther, 2001).

Numerous investigations of societal risk perception have been conducted in a variety of countries. In most, mean risk ratings (the overall average of people's perceived risk on a scale of 0 to 100 over a number of selected risk situations), vary considerably from one country to another (Kone and Mullet, 1994). The results of several studies are tabulated in Table 5, with the lowest mean ratings in the former Soviet Union (roughly 16 of 100) and the highest in the United States, France, and Burkina Faso (roughly 40). In Table 6 the mean risk rating of perceived risk in different countries is tabulated. It is assumed the difference between the mean perceived risk in different countries associated with effect of the media on that specific public, and the more open media will cause higher mean perceived risk in that public. This assumption can be supported by the lowest perceived risk in Soviet Union which believed to experience the most extreme prohibition against the free exercise of journalism and freedom of speech, and on the other end of spectrum United States known to have the highest standard in freedom of speech, or of the press, in turn the highest mean perceive risk.

A number of hypotheses have been put forward to account for these differences. The first concerns the effect of the size of a country. A small country like Norway is likely to have few accidents, and a large one like the United States to have many. As a consequence, the inhabitants tend to be diversely informed. However, Goszczynska et al. (1991) showed that this hypothesis is flawed. Hungary, which has ten times the inhabitants of Norway, has a lower mean rating. The ex-Soviet Union, which has five times the inhabitants of France, has the lowest mean rating obtained to date.

Another hypothesis concerns the role of the media. In the former communist bloc, accidents were rarely reported. Reports were less rare in Poland, where there was an independent Catholic press and numerous underground newspapers. Accidents are systematically reported in France and the United States. According to Goszyznska et al. (1991), this hypothesis is the more plausible of the two. They base their conclusions on the fact that in terms of mean ratings as well as associations, Poland emerges as more similar to Western countries than Hungary or the Soviet Union (Kone and Mullet, 1994).

In this study, according to Table 5, the levels of "media effect" in amplification of social risk are tabulated in Table 6. The media amplification factor is found by dividing normalized numbers by the medium normalized media coverage rate, which is equal to 1.5. The media effect is applied after perceived risk is found based on public judgment through a survey where people where asked different question. The level of media coverage in Canada is calculated through the first question of the questionnaire (see Appendix B) and through comparison with the countries mentioned in Table 6. Then the amplification factor based on the public's judgment is used to increase perceived risk. For example if perceived risk before media effect or media stigmatization is 3 and media amplification factor is 1.5 then the stigmatized perceived risk would be 4.5, i.e. 3×1.5. This concept is shown in Section B of Figure 21, with the end result that media amplification would cause a technology to move from the ALARP zone into the unacceptable zone. As it can be seen in Section B of Figure 21 the amplification effect of media coverage makes risk less acceptable by increasing perceived risk (for this research it has been assumed media effect does not have any effect on perceived benefit).

3.1.3. Race and gender effect

Based on several studies, gender is strongly related to risk judgments and public attitudes. Several dozen studies have documented the finding that men tend to judge risks smaller and less problematic than do women (Brody, 1984, Steger and Witt, 1989; Gwartney-Gibbs and Lach, 1991, Gutteling and Wiegman, 1993, Stern et al., 1993; Flynn et al., 1994). A number of hypotheses have been put forward to explain these differences in risk perception for different genders. One approach has been to focus on biological and social factors. Based on a study by Steger (1989), women have been characterized as more concerned about human health and safety because they give birth and are responsible for maintaining life. Also, they have been characterized as physically more vulnerable to violence such as rape, and this may sensitize them to other risks (Baumer et al., 1978, and Riger. et al., 1978). A lack of knowledge technology has also been suggested as a basis for these differences. In general, women are discouraged from studying science and there are relatively few women scientists (Grigoriu, and Mihaescu, 1988). However, Barke et al. (1997) have found that female physical scientists judge risks from nuclear technologies to be higher than do male physical scientists. Similarly Slovic et al. (1997) and Slovic (1997,1999) found that female toxicologists of the British Toxicological Society were more likely than male toxicologists to judge societal risks as ‘moderate’ or ‘high’. The same results were reported by Kraus et al. (1992) and Slovic et al. (1995). Certainly, the female scientists in these studies cannot be accused of lacking knowledge. On the other hand, some risk regulators and health risk communicators seem to believe that arming people with more information should reduce their scientific illiteracy and improve their decision making (Slovic et al., 1995).

Flynn et al. (1994) conducted a study where 1512 Americans were asked, for each of 25 hazard items, to indicate whether the hazard posed (1) little or no risk, (2) slight risk, (3) moderate risk, or (4) high risk to society. Results showed that the percentage of high-risk responses was greater for women than for men on every item, and risk-acceptance advocates are predominantly white males. As shown by Flynn et al. (1994), the average risk perception of white men is roughly 10% less than that of others (ranging from 0.78 to 0.97) and there are no sizeable differences between others (ranging from 0.875 to 1.0). Flynn (1994) explained this concept through this hypothesis:

“Perhaps white males see less risk in the world because they create, manage, control and benefit from so much of it. Perhaps women and non-white males see the world as more dangerous because in many ways they are more vulnerable, because they benefit less from many of its technologies and institutions, and because they have less power and control.”

Flynn et al. (1994) also noted these low-risk white males (LRWM) were found to be better educated, had higher household incomes, and were politically more conservative. They also held very different attitudes, characterized by trust in institutions and authorities. This explanation led us away from biology and toward socio-political explanations (Barke et al., 1997). Finally, Flynn et al. (1994) suggested that the roles of gender or race in perceived risk relate more to socio-political factors than anything else. However, in this study, the anti-egalitarian method is applied, which considers lower risk perception for white male citizens in the area of hazardous events. It is expected that the present research will find that white males differ from others in that they have lower risk perceptions across a range of hazards. Based on the data in Flynn et al. (1994), it is suggested to apply a 10 percent lower risk perception to white males because of their general agreement on lower risk associated with technologies. In this research, white males’ percentage effect on risk perception is applied with the conversion parameter (α) as:

$$\alpha_{\text{Race\&Gender}} = \frac{100 - \begin{bmatrix} \text{Habitant's White} \\ \text{Male Percentage} \end{bmatrix} \times 0.1}{100 - \begin{bmatrix} \text{Experts' White} \\ \text{Male Percentage} \end{bmatrix} \times 0.1} \qquad 11$$

The parameter α from Equation 11 is used as the amplifier for evaluated risk. The parameter α is used because of different percentages of white males among experts and the public in the geographical region of Weyburn and within the population of experts in the Weyburn Project that participated in answering the questionnaire. This race amplification effect is shown in Sections C and D of Figure 21. The increase in the white male population in the general public in comparison with the white male population in survey respondent data set is illustrated in Section C of Figure 21 for cases where risk increase causing acceptability change from acceptable to unacceptable and it is illustrated for cases where risk increase causing acceptability change from ALARP zone to unacceptable zone in Section D of Figure 21.

3.1.4. Trust

Risk managers have become aware that in democratic countries, perceptions of a technology’s risks and perceived benefits are important components of the entire decision process, from initial decisions and designs to developing a technology, to the acceptance of management approaches to risk mitigation. There is a considerable body of literature suggesting that trust in companies and regulators is a potentially important influence on the way in which the public perceives the risks of some potential hazards and their acceptance of new technologies (Cvetkovich and Lofstedt, 1999;

Dunlap, Kraft and Rosa, 1993; Frewer, 1999; Slovic, 1993). Generally, social trust helps to reduce uncertainty in social risk perception. In recent studies, Siegrist (1999), Sjöberg (2002), and others showed fairly modest relationships between trust and risk perception. Whereas the role of trust in risk perception has been questioned in work by Eiser, Miles and Frewer (2002). Eiser et. al (2002) challenge the notion of trust in public risk perception, suggesting that trust, risk, and acceptance all reflect similar notions in the public view. However, in the risk world, the dominant assumption is that acceptance of new technologies is largely based on perceptions of associated risks (Flynn, Slovic and Mertz, 1993), which are influenced by trust in the information provided by various sources (McGuire, 1985; Worcester, 1999). It has been recognized that individuals who trust an institution seem to find risk estimates provided by that institution more credible (Johnson, 1999; Johnson and Slovic, 1995; Sandman, 1993).

Social trust is assured reliance on character and truth of technology and highly values the qualities of caring and openness. Social trust reflects a social relationship in which individuals interact with social organizations (Earle and Cvetkovich, 1999). Social trust has influenced the risk perception of a nuclear waste repository (Flynn, Burns, Mertz, and Slovic, 1992), of hazardous waste disposal (Bord and O'Connor, 1992; Groothuis and Miller, 1997), of a chemical plant (Jungermann, Pfister and Fischer, 1996), and of food irradiation (Bord and O'Connor, 1990). People who trusted these institutions and technologies perceived fewer risks and more benefits associated with biotechnology than people who did not.

If a member of the public trusts the information they receive, there should be a direct influence on public risk perceptions. In other words, if the information provided is designed to be reassuring and to play down the probability of negative consequences, this should lead to lower estimates of perceived risk when it is trusted than when it is distrusted (Eiser et al., 2002). Lower perceptions of risk should, in turn, lead to greater acceptance of the technology, although other factors such as perceived benefits (Alkhami and Slovic, 1994; Frewer et al., 1998b). The extent to which people trust or distrust risk managers might determine how people react to risk-related information. Such information from a trusted source contributes to the way that an individual perceives and responds to a particular risk (Frewer, Howard, Hedderley and Shepherd, 1997; Petty and Cacioppo, 1986). If it is from a distrusted source it might be disregarded as unreliable, and can even influence risk attitudes in the opposite way.

In parallel with the growth of social risk communication, there has been a decline in public confidence and perceived trust in government and industry. Survey data indicate that ratings of confidence in government and industry have severely decreased during the past thirty years (Lipset et al., 1983; National Civic Review, 1992 courtesy of Strama (1998)). Strama (1998) argued that cynicism and lack of confidence in government in past thirty years are major reasons why young voters avoid the polls. While some researchers have attributed declining social trust to government is result of specific political events such as the Watergate scandal and the ineffectiveness of political leaders in dealing with social problems (Arterton, 1974, 1975; Dennis and Webster, 1975; Greenstein, 1975; Hawkins et al., 1975; Hershey and Hill, 1975; Jaros and Shoemaker, 1976; Lang and Lang, 1973; McLeod et al., 1977; Robinson, 1974; Sniderman et al., 1975; Zimmer, 1979), increasing evidence has pointed the finger at the mass media as being the culprit in social distrust of government (Sweetser and Kaid, 2008). Since it is impossible to exclude the public in a democratic country, the response of government to this crisis of confidence has been to search for methods of risk communication in which experts and laypeople come into alignment.

Trust is fragile. It is typically created slowly, but can be destroyed in an instant. Therefore, once trust is lost, it may take a long time to rebuild (Slovic, 1993). President Lincoln observed this idea in a letter to Alexander McClure: “If you once forfeit the confidence of your fellow citizens, you can never regain their respect and esteem’’ (Courtesy of Slovic, 1993).

Slovic (1993) calls the fact that trust is easier to destroy than to create the “Asymmetry Principle”. Slovic presented his idea by considering negative and positive trust builders, in which negative (trust-destroying) events are more visible or noticeable than positive (trust-building) events.

Several things can contribute to social trust. Kasperson (1986) has argued that trust is composed of perceptions of competence, absence of bias, caring, and commitment to due process. More recently, Kasperson et al. (1992) expanded this list and identified four components of trust: (1) commitment to a goal (e.g., to the protection of public health) and fulfilling fiduciary responsibilities; (2) competence; (3) caring; and (4) predictability. The authors argue that perceptions of commitment to a goal are in turn based on perceptions of objectivity, fairness, and accuracy of information. Perception of commitment to a goal is based on three factors: (a) perceptions of objectivity, (b) fairness and (c) information accuracy, all of which can be understood as indicators of “openness and honesty” (Peters et al., 1997). Competence and predictability can be understood as factors relating to knowledge and expertise (Peters et al., 1997).

Several things can contribute to a loss of trust. Based on Edelman Japan Trust Barometer (2007), environmental crises caused by a company are one of three most important reasons that people lose trust in a company (this reason comes first in Japan and second in Europe). The Barometer also mentioned that environmental crises could cause loss of trust in 68%, 37%, 58%, and 47% of situations in Japan, United States, Europe, and China, respectively. Based on the same study, among different industry sectors, people trust media the least and technologies the most. Also, different studies show that perceived trust between different age categories is nearly identical (Jong-Sung , 2005).

Government is not seen as trustworthy compared to other groups. Scepticism about the information provided by government and its representatives contributes to the current divide between the public and risk regulators. To some extent, the media have appeared to fill the information void for some sections of the public. Trust in technologies is highest and the media have the lowest trustability among industry sectors. These results support the idea that the greatest enemy of these technologies is media stigmatization.

Over a 22-year period (1983 to 2006), Ipsos MORI, a market research firm, tracked the trust profiles of several professions to identify those to whom the public look for reliable information. According to Ipsos MORI (2006) from 1983 to 2005 doctors are the most trusted of the professions covered, and journalists, politicians, and government ministers the least. This begs the question: " If journalists enjoy such low levels of trust from the public, are they capable of influencing opinions about risk issues?" or "Is media stigmatization due to the ineptitude of government ministers or to the media ripple effect?

There are always many difficulties in social trust evaluation. Renn and Levine (1991) have proposed a set of five attributes that determine perceptions of trust and credibility: (1) competence; (2) objectivity; (3) fairness; (4) consistency; and (5) faith or goodwill. Also, Covello (1992, 1993) has offered a set of four factors that determine perceptions of trust and credibility: (1) caring and empathy; (2) dedication and commitment; (3) competence and expertise; and (4) honesty and openness. Several results indicate some support for the causal hypothesis between trust and factors believed to affect trust. Peters et al. (1997) empirically check causal hypotheses for perceptions of trust and credibility based on three factors: (1) Knowledge and Expertise; (2) Openness and Honesty; and (3) Concern and Care. Based on the multiple linear regression dependent variable model, they suggested Equation 12:

$$\begin{bmatrix} \text{Trust \&} \\ \text{Credibility} \end{bmatrix} = \beta_0 + \beta_1 \times \begin{bmatrix} \text{Knowledge} \\ \text{\& Expertise} \end{bmatrix} + \beta_2 \times \begin{bmatrix} \text{Openness} \\ \text{\& Honesty} \end{bmatrix} + \beta_3 \times \begin{bmatrix} \text{Concern} \\ \text{\& Care} \end{bmatrix} + \varepsilon \qquad 12$$

where β_0 is constant, β_1 applies to knowledge and expertise, β_2 applies to openness and honesty, β_3 applies to concern and care, and ε is the random error term associated with linear regression. The parameters shown in Equation 12 are tabulated in Table 7.

For evaluating trust in government and company, participants in the Weyburn Project were asked to put a value on knowledge and expertise, openness and honesty, and concern and care in a 7-point system. Seven response categories were used that ranged from "strongly agree" (1) to "strongly disagree" (7). The parameters in Table 7 are adapted to the seven-point system. The proposed method for application of trust is illustrated in Figure 23. By this concept, a reduction in trust causes a reduction in the ALARP band (see Sections A and B of Figure 23); and an increase in trust causes an increase in the ALARP band (see Sections C and D of Figure 23). As shown in Sections A and B of Figure 23 the reduction in the ALARP band as a result of trust reduction can cause the technology acceptability to change from tolerable (in ALARP zone) to unacceptable. And an as shown in Sections C and D of Figure 23 the increase in the ALARP band can cause the technology acceptability to change from unacceptable to tolerable (in ALARP zone).

There is still one unknown parameter, the correlation between ALARP band thickness and social trust evaluated rank. For this reason, the trustworthiness of government is calculated through comparison with social trust of government in other countries. The trust in government for different countries reported by Edelman Japan Trust Barometer (2007) is converted from percentage values to a seven-point system. Since in this report the highest estimate of trust over government is 78% (for China) the maximum trust value is suggested to be 80%. According to this assumption the conversion calculation was directed such that 80% of the population trusted with a trust score of 7, and such that the average of rated results would equal 4, defining moderate trust. In new converted trust values the social trust evaluated in Japan is equal to 5 and that in Canada is equal to 3.7 based on studies by Edelman Japan Trust Barometer (2007). Based on this converted data and Figure 19, the upper and lower bounds of the ALARP region are evaluated by the following equations:

$$\begin{aligned}&\text{Perceived Benefit (Upper Bound)} = 0.1792\times(\text{Perceived Risk}+2)^2\\&-0.475\times(\text{Perceived Risk}+2)+2.05-(\text{Trust Rate}-1)\times 0.325\end{aligned} \quad 13$$

$$\begin{aligned}&\text{Perceived Benefit (Lower Bound)} = 0.1792\times(\text{Perceived Risk}+2)^2\\&-0.475\times(\text{Perceived Risk}+2)+2.05\end{aligned} \quad 14$$

The difference between Equations 13 and 14 is the trust portion. As it can be seen Equation 14 is a fixed line for different trust values. But the Equation 13 which shows the upper bound of the ALARP region is varied by the evaluated trust for different countries or different society.

3.1.5. Public perception and acceptance of geological storage

Public support for CCS is another important contributor to the successful deployment of this technology. Research has shown that Canadians are supportive of using CCS to mitigate climate change and view it as having a net positive environmental impact. In other parts of the world, attitudes range from rejecting to supportive. Public perceptions of CCS are impacted by understanding of the technology, perceived risk, cost, attitude towards the urgency of climate change, trust in actors and stakeholders, and location (NIMBY: Not In My Back Yard).

A survey was administered by Sharp et al. (2005, 2006) to aid understanding of Canadian perceptions of geological storage. This survey was conducted in two phases, first through focus groups, and subsequently through national surveys (in Toronto and Edmonton in August 2004 and of 1,967 Canadians in Alberta and Saskatchewan in March 2005). The results showed that a strong majority of Canadians believe that climate change is occurring and that some action should be taken to address it. However, climate change was ranked very low in importance compared to other national issues, and was the lowest ranked environmental issue. Knowledge of geological storage was low, although it was higher than in the United States. Respondents across Canada were slightly supportive of geological storage development in Canada. They believed that geological storage was less risky than normal oil and gas industry operations, nuclear power, or coal-burning power plants, all of which are used extensively in Canada. However, geological storage was much less popular than energy efficiency and renewable energy alternatives, and it will have to be used in combination with these technologies in order to retain public support. Also, the most important benefits of geological storage were seen to be its usefulness as a bridging technology while long-term climate change solutions are developed, the potential for its use as part of Enhanced Oil Recovery (EOR), and its potential to reduce greenhouse gas (GHG) emissions faster and more cheaply than alternatives. However, the risks were considered more important than the benefits, with the public most concerned about unknown future impacts, contamination of groundwater, risk of leakage, and harm to plants and animals (Sharp et al., 2005 and Sharp et al., 2006).

In Table 8 (from Japanese and Canadian surveys), the average public perceived benefits of carbon storage for each different survey are calculated in the last row, both for when information was provided and when it was not. Deployment support items were not consistent with other results. These benefit values with risk perceived values from Canadian surveys were used for evaluation of unamplified risk numbers and benefit numbers of geological storage.

Processing of survey inputs and geological storage acceptability evaluation

The survey in this study was conducted to evaluate the prospect media effect and the trust effect in the case of CO_2 leakage from carbon geological storage in the Weyburn zone. In most risk and public perception studies it is assumed that experts and the public agree on the degree of risk related to technologies and activities. In other words, technical risk obtained by experts is considered equal to the risk perception of the public before media stigmatization and other social effects.

In this research, a small survey was initially conducted with the public followed by the main survey of experts (within the Weyburn Project). The purpose of the first survey was to evaluate the model and debug the program that had been used for processing the survey input data and the second survey data was mainly used to calculate the perceived trust and media stigmatization.

To evaluate stigmatized risk perception, respondents were asked to answer two sets of questions. The first evaluated media stigmatization based on conditions of freedom of speech and media coverage in Canada comparing to 5 given countries. The media effect factors of these countries are suggested in Table 6 based on past studies presented in Table 5.

The second set of questions consisted of two categories of three questions each. The form of the questionnaire is provided in Appendix F The answers of these questions were used to evaluate trust of government and companies regarding geological sequestration. The seven-point system was used to evaluate trust. There were two public surveys conducted for trust evaluation. Respondents in the first survey were asked to answer each question with a number between 1 and 7, that is, from “strongly agree” to “strongly disagree”, respectively. Feedback from respondents indicated that they were not comfortable in completing the first survey using this format. Therefore, the second survey was changed to multiple-choice questions to make it easier and more comfortable for the respondents.

The same racial and gender breakdowns were expected for respondents of the questionnaires and people living in the Weyburn region. Therefore, race conversion factor (α) assumed white males’ percentage effect to equal 1, meaning no amplification occurs because of race and gender effects.

Sixteen people were questioned in the first survey: two middle-aged people with no university studies, nine graduate students with no experience in Canadian companies, and five second-year undergraduate students. All could be considered more or less unfamiliar with technical issues around geological storage and Canadian companies’ current practices in CO_2 injection and well abandonment. However, the second survey questioned 39 experts through the 3rd PRISM gathering at the University of Alberta in Edmonton. The results of these two surveys are presented in Table 9 and Table 10.

The average responses to questionnaires appear in Table 9, and the evaluated results for social trust are calculated from average responses in Table 10. The method of evaluating social trust from ‘knowledge and expertise’, ‘openness and honesty’, and ‘concern and care’ was discussed in previous chapters. Perceived trust is marginally higher among experts and is consistent in all of the subtrusts’ elements (i.e., ‘knowledge and expertise’, ‘openness and honesty’, and ‘concern and care’). However, the important contradiction is the inconsistency of results in Table 10 with those gathered by Trust Barometer (2006). When converted to the seven-point system, Trust Barometer’s (2006) Canadian respondents’ level of trust in government is 3.7. Trust Barometer (2007) also found a lower level of trust in media than did the present survey. It is hypothesized that trust in media and government is higher in universities because of greater interaction between universities and companies or universities and government.

As shown in Table 11, the level of trust Canadian respondents have in media fallen enormously in 2007, and respondents did not remain consistent in their views of media. On the other side, the results for Canadians’ perceived social trust are quite different and they have remained fairly consistent in their views of government, which received nearly equal trust scores in 2005 and 2007. Perhaps abandonment of the Kyoto Accord and a perceived lack of vision on the issue of global warming on the part of the Canadian government blemished its image in the following years.

The perceived risk of geological storage compared to other energy technologies in two different surveys (the first in Canada as a whole, and the second in Alberta and Saskatchewan) is shown in Figure 24 (Sharp et al., 2005 and Sharp et al., 2006). Risk perceptions around geological storage are roughly equal to 3.6 for both surveys.

In Chapter 2, the fault tree system considering fuzzy set theory and evidence (or belief) theory was used to compile a range of expert opinion to evaluate risk of geological storage. The result of this evaluation (Figure 15) yielded a risk value ranging from 4.3 to 6.7 (on a scale of 10), which corresponds to a range from 3.0 to 4.7, on a scale of 7 (to be consistent with the scale chosen by Sharp et al., 2005). The range 3.0 to 4.7 corresponds reasonably well with the results shown in Figure 23, although the range of values obtained from the fault tree capture a larger range of uncertainty regarding the perceived risk of geological storage

In the next chapters, the BowTie risk assessment framework, which also incorporates fuzzy set theory and evidence theory, is discussed and used to evaluate expert opinion on risk. It will be shown that the results from this assessment yielded perceived risk values ranging between 3.2 to 3.4 in scale of 7 showing much more alignment with the results of Sharp et al. (2005, 2006) shown in Figure 23.

The unamplified risk perception of geological storage based on these two studies combined with surveyed benefit value when information is not provided is illustrated in Sections A and B of Figure 25. The risk values for geological disposal of carbon dioxide (GDC) technology in Sections A and B of Figure 25 are amplified as the results of media stigmatization and final amplified risk perception of geological storage is presented in Sections C and D of Figure 25. Cases of amplified risk perception of geological storage (or geological disposal of carbon dioxide (GDC))(see in Sections C and D of Figure 25) are dramatically in the unacceptable zone, both when information is provided (see Section D of Figure 25) and when it is not (see section C of Figure 25). For the case of unamplified risk perception of geological storage, which is risk perception before media stigmatization (see Sections A and B of Figure 25), results are barely in the ALARP region. This means that in cases of probable failure, governments and companies in charge will have a hard time gaining public trust for future projects. In the next section, risk communication is discussed as the only way to control stigmatization of geological storage (or geological disposal of carbon dioxide (GDC)) and to reduce public risk perception.

Risk Communication between experts and the public

In the 1970s, regulators and industry asked why the public were not rational, or why they did not think about a particular risk in the same ways that experts do. If the public and experts agreed on technical risk priorities, then the public would quickly adopt emerging technologies and reduce other lifestyle related activities, such as smoking or unhealthy dietary choices (Sjöberg, 1996; WMHIC, 2004). The response was to develop a program of risk communication to try to “align” public views with those of experts. However, this activity failed to take into account the dynamics of human risk perception. The public still did not agree with the views of experts regarding risk mitigation priorities and risk acceptability. Thus, activities in the 1990s focused on the question of public trust (Blind, 2007; WMHIC, 2004). It was argued that consumer risk-related concerns would disappear if consumer trust in risk management were developed so that risk researchers focused on what caused trust and distrust, particularly regarding the activities of regulators and industry (WMHIC, 2004).

Risk assessment methods were integrated into public decision making processes tasked with determining whether large projects were in the public interest. However, as the public began to take a greater interest in questions of community development they became more uncomfortable with risk assessment results and more likely to oppose the construction of large industrial facilities. Over the past forty years, a large take-back of power from the experts to the public over environmental policy was happened. In the 1970's, the environmental policies were largely in the hands of established authorities, such as the environmental protection agency (EPA) (Covello and Sandman, 2001). In the 1980's, however, the public reasserted its claim over environmental policymaking, people starts to become visibly upset, and even outraged when they felt excluded from policy makings (Covello and Sandman, 2001). In turn, policy-makers in the 1990s have accepted that the general public should be involved in policy discussions over environmental issues (Eden, 1996). In this crucible, the current version of risk communication was born (Covello and Sandman, 2001). The risk communication in its current format addressed a fundamental question made clear by that dialogue: "The risks that kill people and the risks that alarm them are often completely different. There is virtually no correlation between the ranking of hazards according to statistics on expected annual mortality and the ranking of the same hazards by how upsetting they are. There are many risks that make people furious even though they cause little harm – and others that kill many, but without making anybody mad" (Covello and Sandman, 2001).Faced with this initial wave of resistance, the technical community applied improved methodologies to prove to the public that proposed technologies and facilities were safe. Much to the surprise of technical analysts, however, these efforts were unsuccessful, and studies consistently showed that the public rate risk differently than do risk experts (Gregory and Mendelsohn, 1993, Renn, 1998). In contrast to technical risk experts, the public was found consistently to overestimate the danger from high-hazard low-probability events (Slovic et al., 1979). As a result, the public reacted negatively to the practice of conducting "worst-case" risk assessments, since from the public's perspective, the small probabilities of occurrence were far outweighed by the consequences of the "worst case scenarios." In some literature, the discrepancy between expert assessments and lay perceptions of risk is called the "objective perceived risk dichotomy".

Public negative reaction to technical risk assessments made them ineffective for convincing the public (Slovic, 1993, Slovic, 1999, Slovic, 2001). For a time, such findings led some experts to insist that the public was acting irrationally and was overly susceptible to media influence (Cohen, 1998). Slovic et al. (1979, 1985) showed that while people are irrational in risk evaluation, they are approximately accurate in their judgments of the likelihood of incidents, and that the small inaccuracies in their judgments are also systematic. Slovic et al. (1982) discussed this unusual accuracy, saying that "because frequently occurring events are generally easier to imagine and recall than are rare events, availability is often an appropriate cue" to event frequency. Thus, "availability" is a major factor in public judgment; however, such judgment is also affected by factors such as disproportionate exposure, memorability, and imaginability (Lichtenstein et al., 1978). The other primary concept is people's "overestimation of low frequencies and underestimation of … high frequencies" (Lichtenstein et al., 1978) regarding mortality rates.

Risk experts were vowed immoral, self-serving, and influenced by funding by the public in the period of public criticism of their risk assessment's evaluations (Fischhoff, 1998). Such dialogues did little to further regulatory decisions and are thought to have been counterproductive. As the National Research Council (NRC) discussed in their 1996 work "Understanding Risk", "When lay and expert values differ, reducing different kinds of hazards to a common metric and presenting comparisons only on that metric have a great potential to produce misunderstanding and conflict and to engender mistrust of expertise" (Stern et al., 1996). However, there can be other reasons such as lack of knowledge. Most people do not possess deep knowledge of science and technology (Gregory and Miller, 1998). Three out of four people in the United States and Europe have difficulty understanding concepts that define basic scientific literacy, such as molecules or radiation (Miller, 1998). As such, most people cannot assess benefits and risks associated with different technologies. When there is insufficient knowledge for making first hand risk assessments, social trust is needed to reduce the complexity people face (Earle and Cvetkovich, 1995; Luhmann, 1989).

While expert risk assessments are much different from public perceptions of risk, the same is not true of politicians. Sjöberg (1996) compares politicians' perceptions of risk to those of the public. They were found to be very similar (Sjöberg, 1996), as might be expected in a democracy (Sjöberg, 2001).

Differing perceptions of risk between experts and the public may be due to social and demographic factors. It is generally assumed by scientists who conduct risk research that experts' risk assessments are based more strongly on actual or perceived knowledge about a technology than are lay people's risk assessments. In the case of carbon storage, surveys show that most people are not familiar with it. The public perception of an emerging technology has a major influence on its acceptance and commercial success. If the public perception turns negative, potentially beneficial technologies will be severely constrained, as is the case, for instance, with gene technology (Slovic, 1993). It seems plausible that the evaluation of new technologies such as carbon storage is guided by people's theories and values. For instance, people who associate the technological revolution with positive outcomes - and who are not afraid of possible negative side effects of technological progress - may assess carbon storage applications more positively than people for whom the perceived negative effects outweigh the positive effects. In general, there are three principal reasons that expert risk assessments fail to convince the public that a facility is safe. Individuals may be resistant to change initially-formed opinions, the technical risk assessment may not address the issues of public concern, or the risk dispute may simply be a surrogate argument for general opposition to the project (Slovic, 1999, Slovic, 2001). Demographic factors such as age could also have an effect on differing perceptions of risk between experts and the public. Since experts tend to be older than people are in general (Sjöberg, 2003).The present research suggests that improving the communication of risk information among lay people, technical experts, and decision makers increases trust and acceptability. This concept is illustrated in Figure 26. Those who promote and regulate health and safety need to understand how people think about and respond to risk. Without such an understanding, policies may be ineffective. Although risk communication is suggested, public participation may destroy trust in institutions rather than create it. This may be one of the reasons for the continued decline in public confidence in regulatory activities. Risk assessment and risk communication are being separated from risk management. As public reliance on the decisions of expert or elite groups is no longer a tenable way to conduct risk analyses, it is important to structure the method in regulation to incorporate risk management, risk assessment, and risk communication.

Risk communication is useful to improve communication among the public, experts, and policy makers for the development of CO_2 geological storage. It may reduce existing discrepancies between public reaction and the judgment of experts. Trust and confidence are also important predictors of how carbon storage is perceived. The ways in which governmental agencies regulate carbon storage may, therefore, strongly influence the risk perceptions of the public and of experts." Based on the discussion, experts may not be inclined to initiate risk assessments that are expected by the public.

A questionnaire to investigate how the public agree with the risk assessment approach was used in this study. This questionnaire is discussed in the following sections to determine the extent to which the public would agree with the ideas and risk analysis used in this study. To increase understanding of the contrast in perceived risk for carbon storage between experts and the general public in carbon storage projects, Figure 27 shows the schematic of different behaviour for these two groups of people.

Based on Edelman Trust Barometer (2007), "companies which respect their employees by listening to them and providing an environment of engagement will earn the most trust". The same structure can be used to increase social trust among the public, by providing an environment of engagement and listening to people's concerns.

Consequently, risk communication remains a difficult task and has achieved only limited progress thus far (Fischhoff, 1995). Providing information about probabilities is not a proper way to communicate with the public. Probabilities are hard to understand, and are based on complicated models with which people are unfamiliar. People want to avoid disastrous consequences no matter how small their probability. In the public eye, any probability of failure greater than zero is unsafe. Thus, communication may have the paradoxical effect of increasing social risk (Scholderer and Frewer, 2003). For instance, one study finds that increasing public knowledge of a new technology may actually lessen its acceptance (Jallinoja and Aro, 2000). One of the main attempts to increase trust is involving the general public in policy discussions over contentious issues such as the environment, which mostly starts from 1990s (Eden, 1996). The author decide not to elaborate this section since it is mainly focused in environmental policy studies.Discussion and conclusion

The definition of risk can affect the outcome of policy debates, the allocation of resources among safety measures, and the distribution of political power in society. Society can direct capital such that it reduces general public risk. The purpose of this study is to elucidate how the general public perceive CO_2 geological storage technology. It also attempts to identify and evaluate the public factors that would influence public acceptance. As mentioned, public acceptance is key to the implementation of geological carbon storage technology. The aim of research was to characterize different factors affecting risk stigmatization, to provide an overview of findings from previous research on lay risk perception, and to evaluate the amplified general public perception based on these discussions.

Some technologies such as nuclear and chemical have been stigmatized in ways that equally hazardous technologies such as medicine have not. As a result, it has been difficult, if not impossible, to find host sites for the disposal of high-level or low-level radioactive waste, or for incinerators, landfills, and other chemical facilities. The same problems are besetting CO_2 sequestration projects. Ocean sequestration, which is more reliable than CO_2 geological storage methods, is abandoned due to public perception. The risks of CO_2 geological storage fall into two broad categories: local and global. Local risks include leakage impacts on humans and the environment, and global risks consider global warming and greenhouse gas problems. The public is more concerned about local risks, while experts focus more on global risks. Although a high concentration of CO_2 can kill humans, in most situations this is impossible. This small bubble of gas is a cause for concern for many people, and media stigmatization can turn this into a big story.

Our world is in a period of propaganda, and the media can contribute to stigmatization which could doom CO_2 sequestration forever.

Risk perceptions would be more accurate if people used more complete information about the attributes of products or technologies (Bettman et al., 1987). Others seem to believe that if people just listened to the facts, they would reach the same conclusions as experts (Wandersman and Hallman, 1993). However, extensive efforts to educate the public about risks and risk assessment, such as advertising campaigns for nuclear power, have failed to move public opinion to coincide with the experts (Adler and Pittle, 1984; Svenson et al., 1985). In this study, risk communication is proposed as the only means for controlling stigmatization of CO_2 sequestration in the public mind. The government's priorities must facilitate rapid adoption of emerging technologies such that stigmatization is reduced to the levels proposed in Figure 25.

Table 5. The various "Mean Ratings" for different countries

Country	Mean Rating from 100	Normalized to Lowest Mean	Reference
Former Soviet Union	16	1	Mechitov and Rebrik (1990)
Hungary	21.0	1.31	Englander et al. (1986)
	22.8	1.43	Teigen et al. (1988)
Norway	27.14	1.70	Teigen et al. (1988)
Poland	33.04	2.07	Modified from Goszczynska et al. (1991)
United States	39.59	2.47	Karpowicz and Mullet (1993)
France	40.31	2.52	Karpowicz and Mullet (1993)
Burkina Faso	41.68	2.61	Kone and Mullet (1994)

Table 6. The suggested "Amplification Factor" for the country to which risk assessment is applied

Media Effect	Very Low	Low	Medium	High	Very High
Similar Country	Former Soviet Union	Hungary	Norway	Poland	United States or France
Normalized to Isolated Situation	1	1.25	1.5	2.0	2.5
Amplification Factor	0.67	0.83	1	1.33	1.67

Table 7. Parameters for Evaluation of Trust and Credibility modified for 7-point system of Peters et al. (1997)

Independent Variable	Estimate of Parameter	
	Industry	Government
β_0	2.513	0.888
β_1	0.0284	0.131
β_2	0.169	0.333
β_3	0.415	0.423

Table 8. The Public Response to different aspects of Carbon Storage Benefits and Public Support over its Development, ratings adapted to the 1-7 scale (italicized numbers are not considered in averaging)

Question Items	**Edmonton (2005) Information Not Provided**	**Edmonton (2005) Information Provided**	**Toronto (2004) Information Not Provided**	**Toronto (2004) Information Provided**	**Japan (2004) Information Not Provided**	**Japan (2004) Information Provided**
Social benefit					4.99	6.05
Personal benefit					4.33	5.35
Benefit to future generation					5.04	6.06
Contribution to society					5.12	6.03
Personal necessity					4.12	5.10
Deployment Support	*2.35*	*2.88*	*4.15*	*4.15*	*4.54*	*5.58*
Climate change Importance	5.65	5.65	6.4	6.4		
Reduction of Emissions of GHG	5.8	5.8	6.25	6.25		
Controlling Acid Rain	5.4		5.71			
Reducing Air Pollution	5.90		6.14			
Controlling Acid Rain	5.40		5.71			
Public Perceived Benefit	**5.63**	**5.73**	**6.04**	**6.33**	**4.72**	**5.72**

Table 9. Social Trust and Media Effect Evaluation in Canada based on the first and second surveys

Different Social Parameters	**Evaluated Value (1st survey)**	**Evaluated Value (2nd survey)**
Social Trust on Industry	5.348	5.79
Social Trust on Government	5.391	5.60
Media	1.58	1.50

Table 10. Average responses to questionnaires in 7-point system

Different Parameters	**1st survey**		**2nd survey**	
	Industry	**Government**	**Industry**	**Government**
Knowledge & Expertise	5.125	4.625	5.53	4.66
Openness & Honesty	4.25	4.875	4.95	5.37
Concern & Care	4.75	5.375	5.51	5.47

Table 11. Trust in Media in Canada in different years (Edelman Japan Trust Barometer, 2007)

Country	**Year (%)**		
	2005	**2006**	**2007**
Article in Business Magazines	47%	53%	38%
Radio	37%	42%	29%
Newspaper	30%	51%	29%
Television	38%	45%	34%
Average	**38%**	**48%**	**33%**

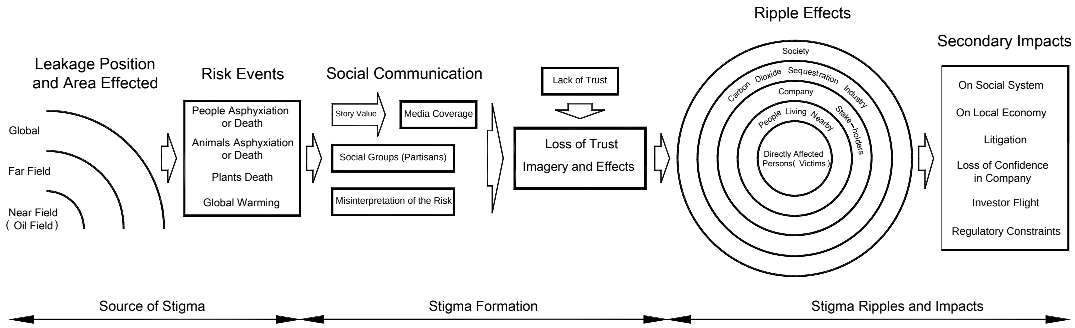


Figure 17. The Suggested Map for Social Amplification and Attenuation of Carbon Dioxide Geological Storage Risk (Modified from Slovic et al., 1987)

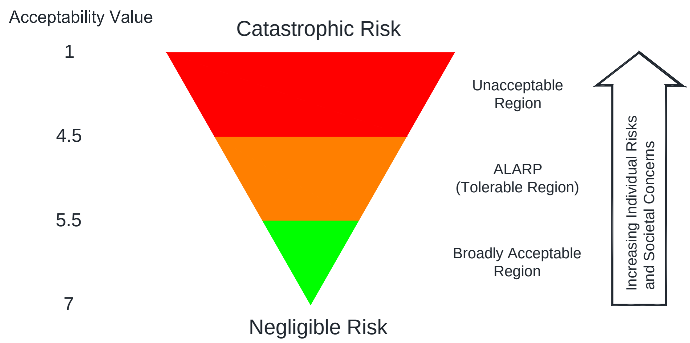


Figure 18. The HSE framework for the tolerability of risk considering the risk levels categorizations based on suggested acceptability evaluation limits in this study (modified from health and safety executive (HSE), 1992 and 2001b)

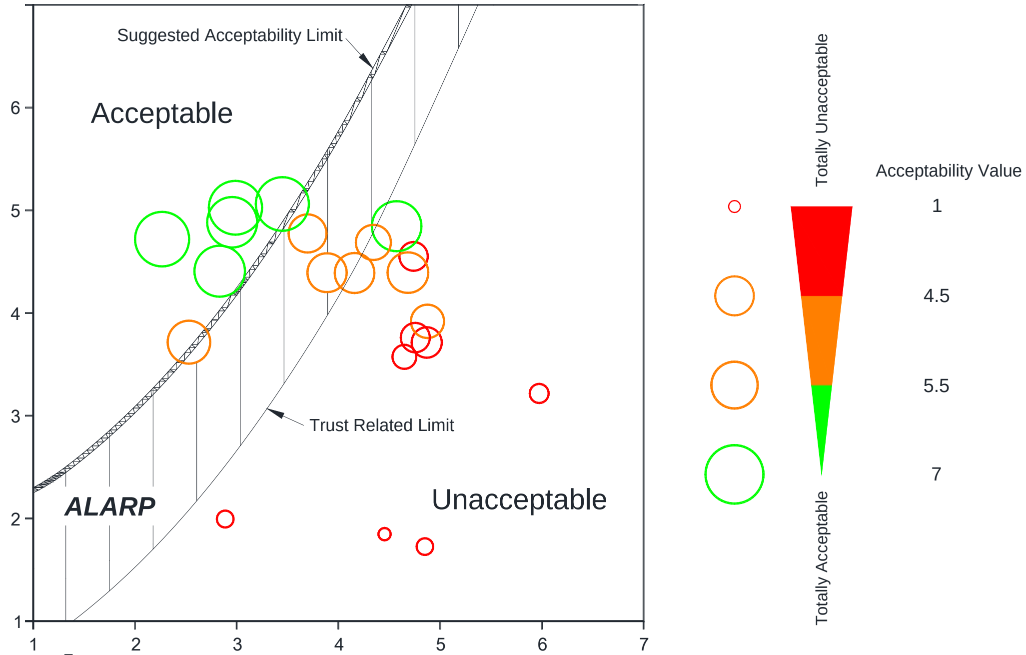
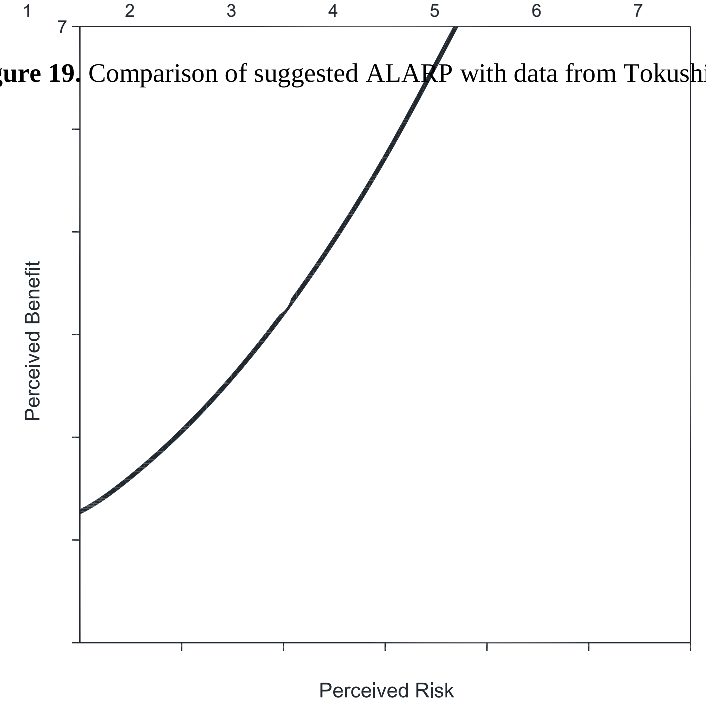


Figure 19. Comparison of suggested ALARP with data from Tokushige et al. work (2007)



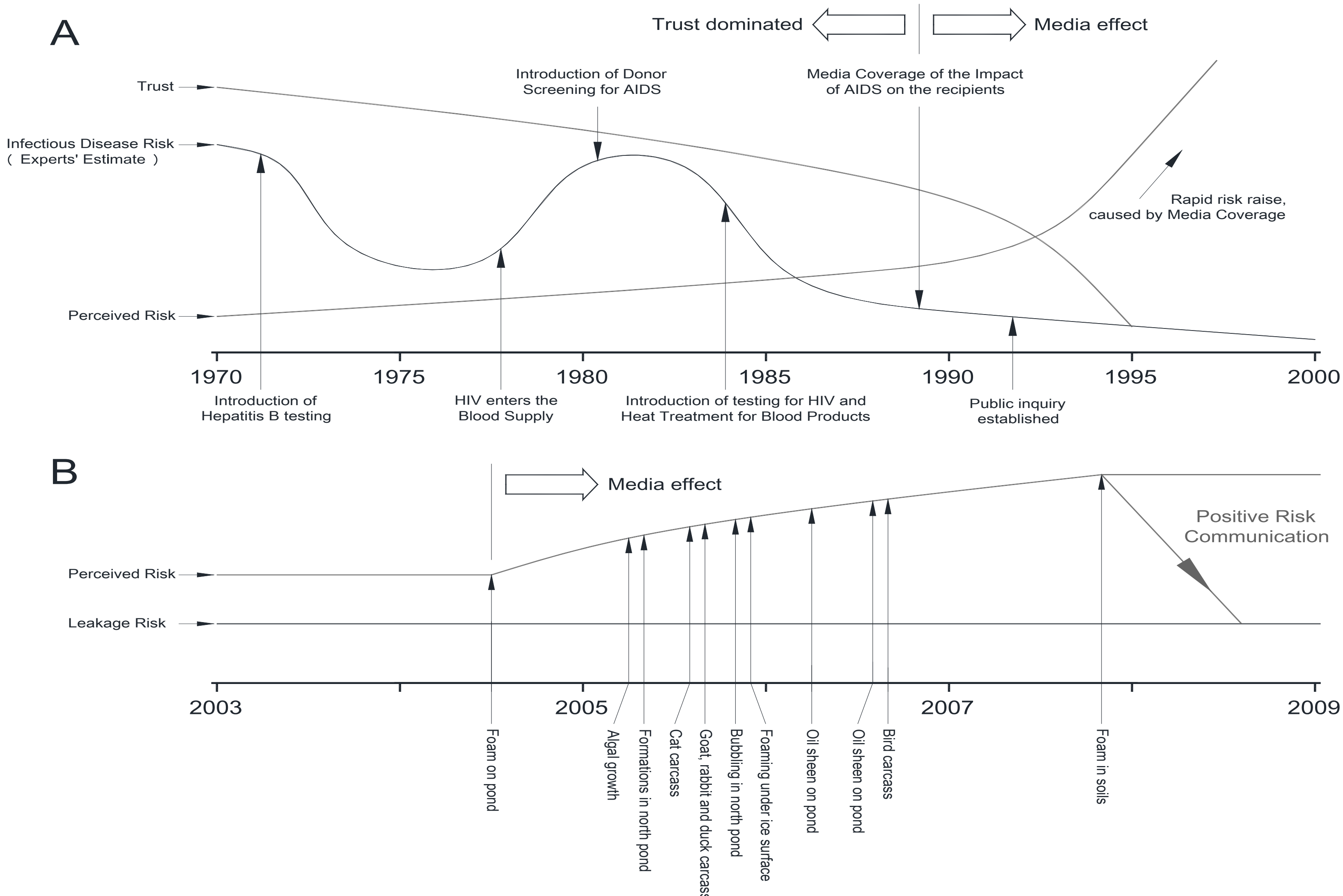


Figure 20. Media effect on risk perception, Section A is showing media effect for AIDS risk perception (courtesy of Penny Chan, from risk, media and stigma by Flynn, Slovic, and Kunreuther (2001), Chapter 14), and Section B is showing media effect for alleged signs of CO_2 leakage in Kerr property (extracted from

Robinson, 2011)

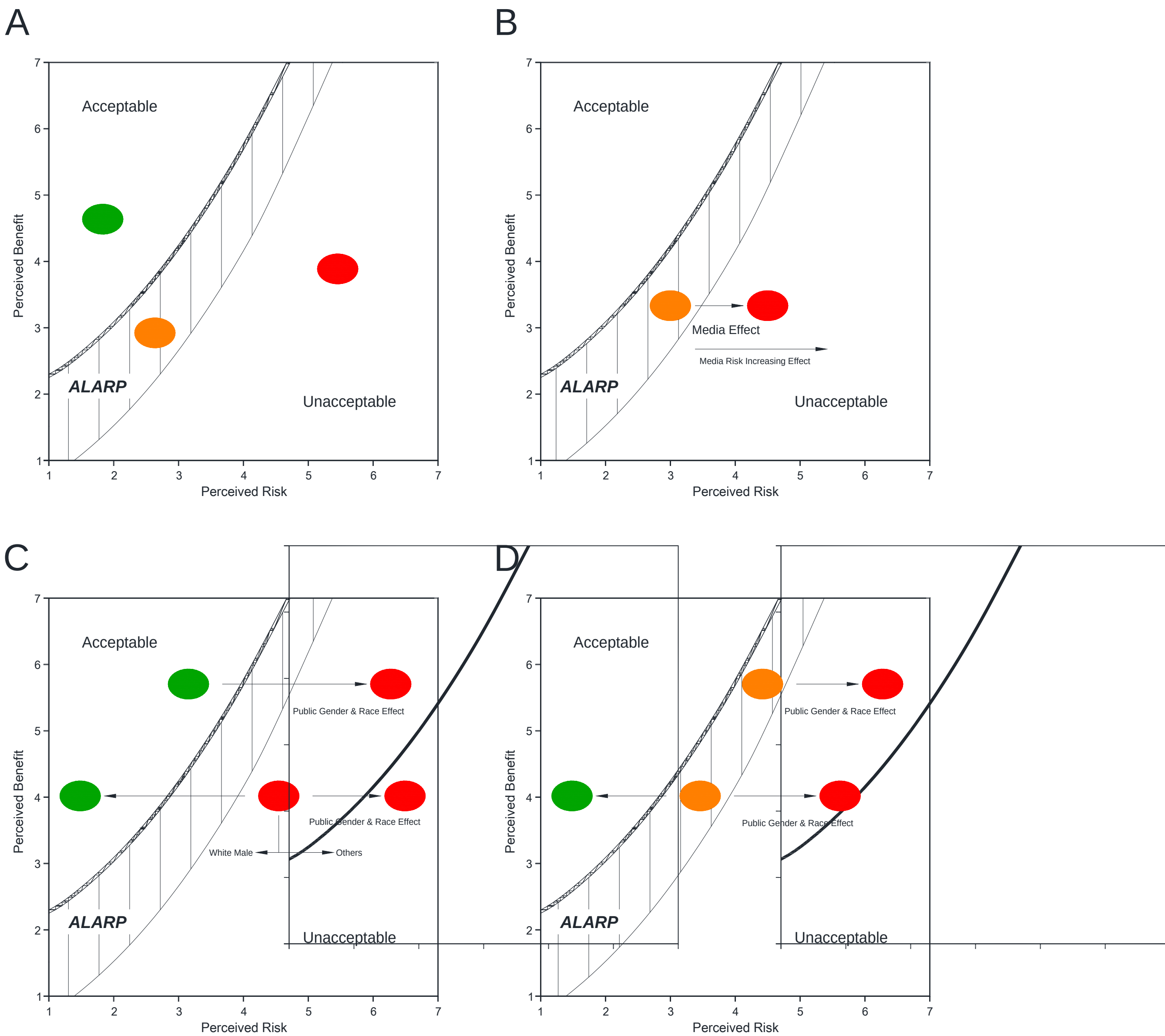


Figure 21. Proposed framework for acceptability evaluation and media effect and race and gender effect. Section A is showing proposed framework for acceptability evaluation; Section B is showing stigmatization causing by media; Section C is showing race and gender effect (specifically white male percentage difference amplification effect on risk perception); Section D is showing race and gender effect for cases in which technology risk and benefit before media amplification is in ALARP zone.

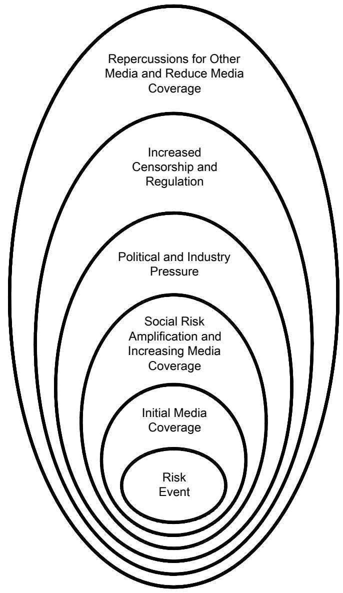


Figure 22. The risk social amplification of media coverage (Modified from Slovic et al., 1987)

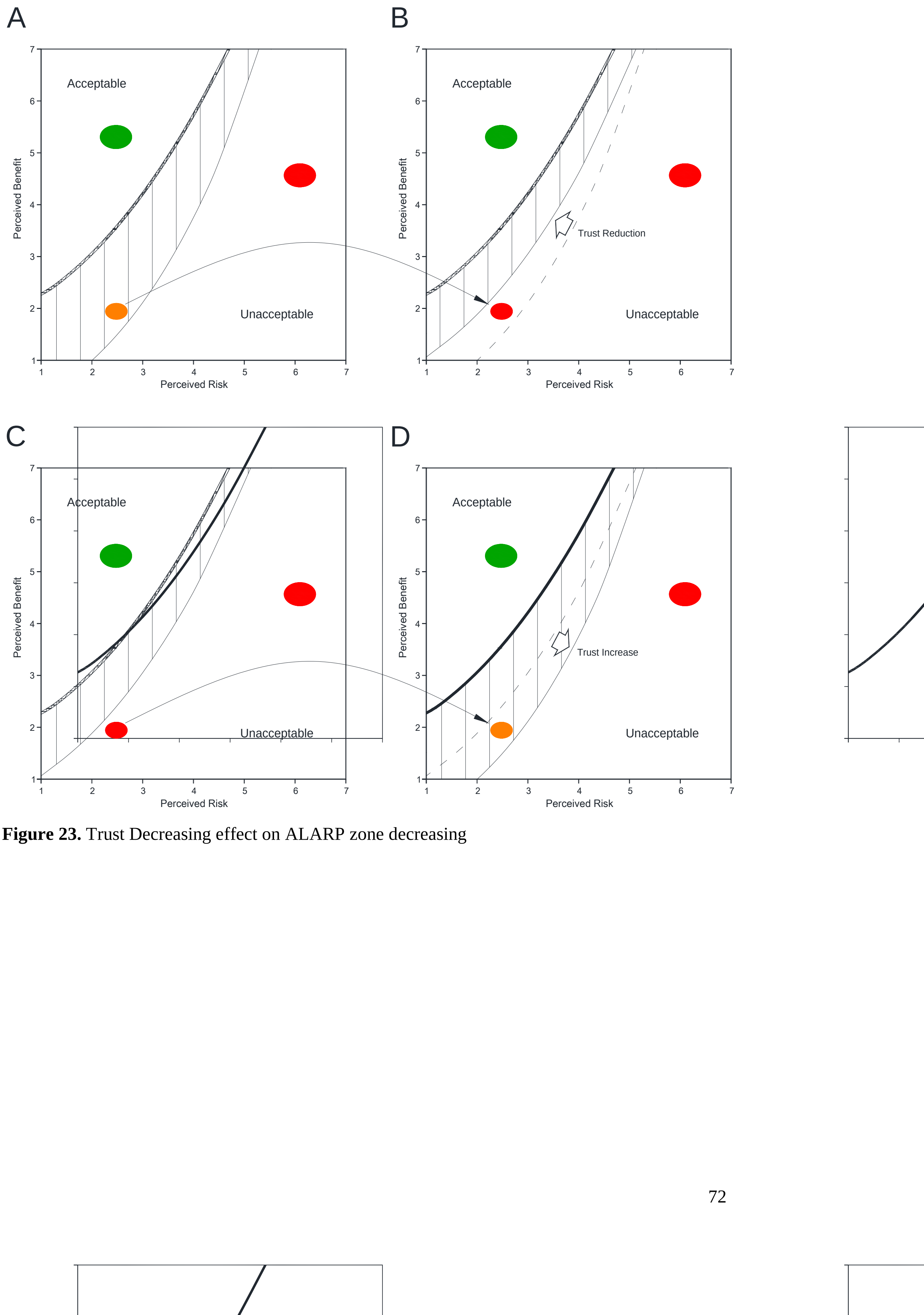


Figure 23. Trust Decreasing effect on ALARP zone decreasing

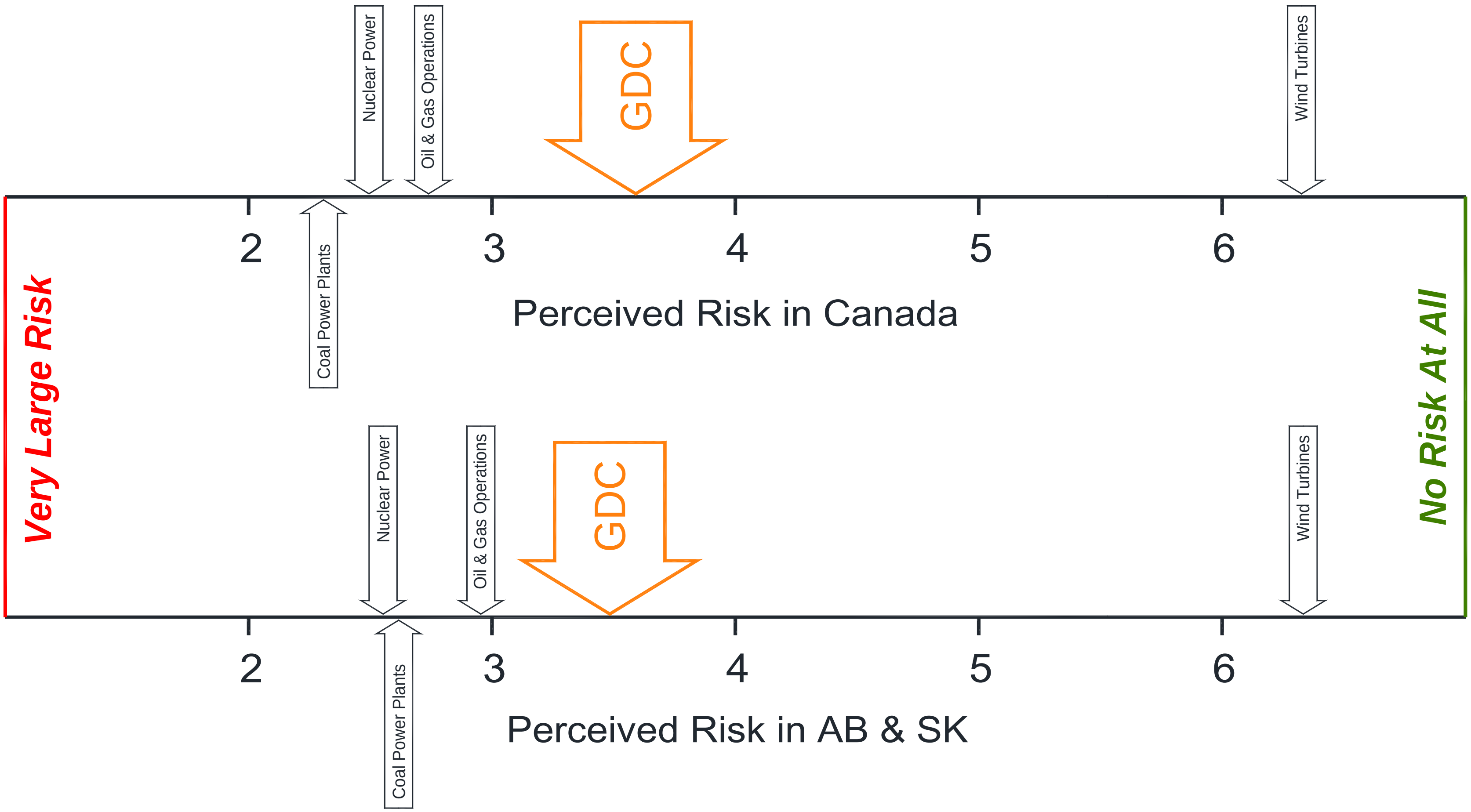


Figure 24. Perceived risk of GDC compared to other energy technologies in two different surveys first in Canada and second in Alberta and Saskatchewan (Sharp et al. 2005, 2006)

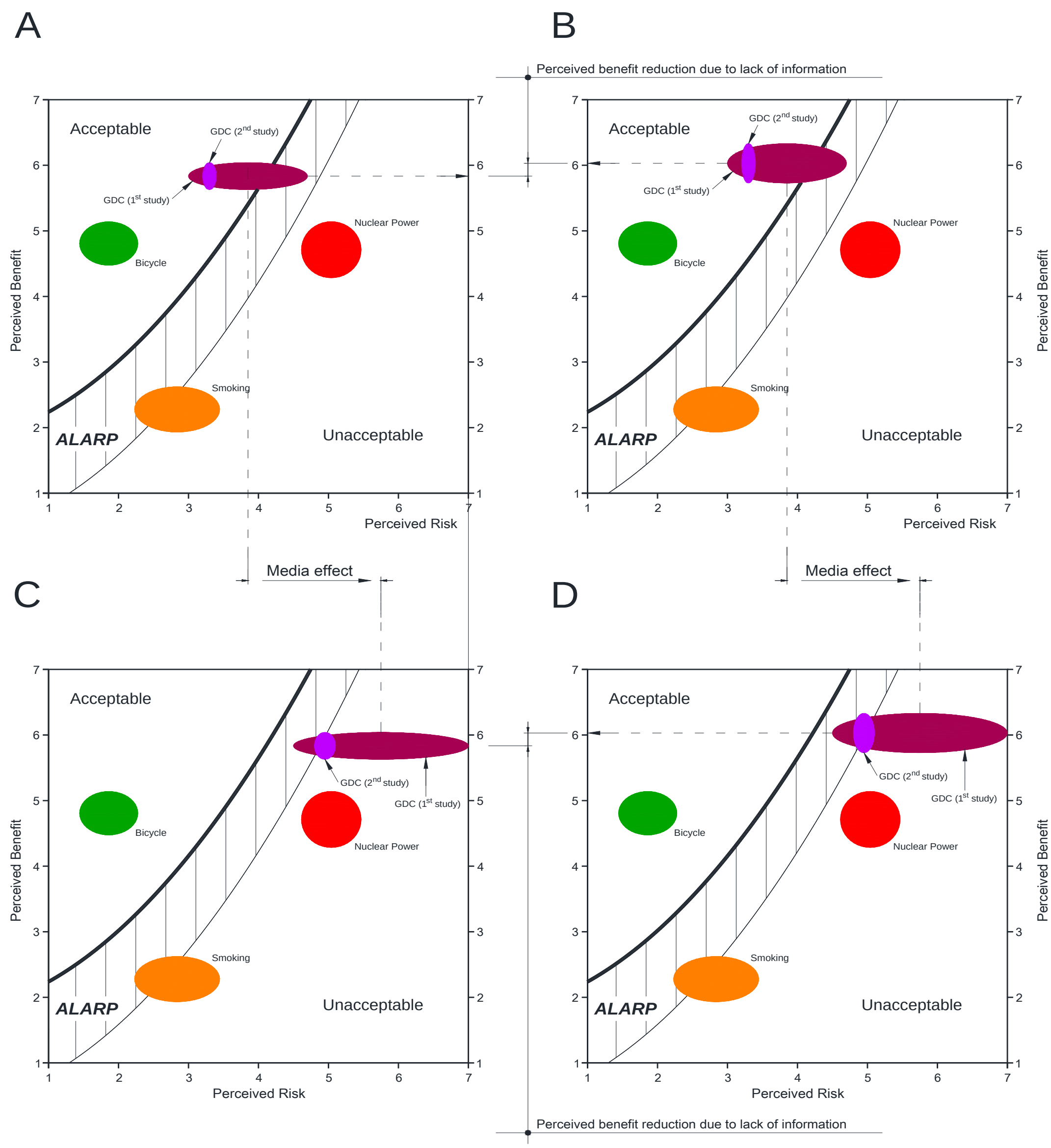


Figure 25. Evaluated perceived risk and perceived benefit of GDC. Section A is showing GDC condition before applying "Media Effect" for Weyburn project specific and perceived benefit evaluation before providing information for respondents; Section B is showing GDC condition before applying "Media Effect" for Weyburn project specific and perceived benefit evaluation after providing information for respondents; Section C is showing GDC condition considering "Stigmatization" (Media Effect) for Weyburn Project specific and perceived benefit evaluation before providing information for respondents, Section D is showing GDC condition considering "Stigmatization" (Media Effect) for Weyburn Project specific and perceived benefit evaluation after providing information for respondents.

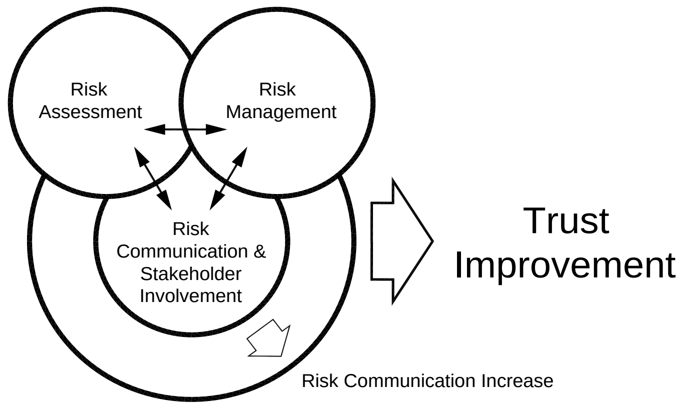


Figure 26. Trust improvement through transparency in risk communication

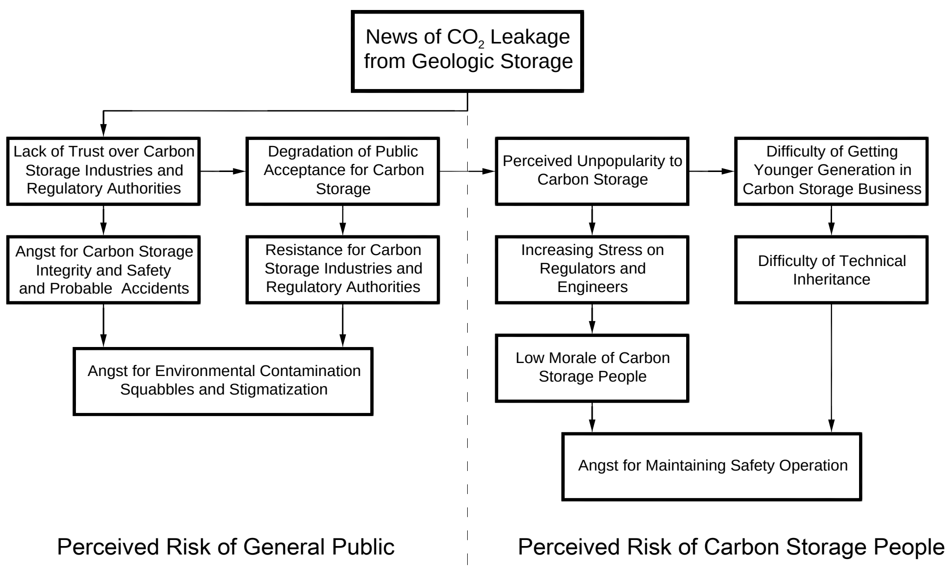


Figure 27. Contrasting perceived risk for carbon storage between general public and experts in carbon storage projects (modified for geologic storage projects from Slovic et al., 1987)

4. Long-Term Wellbore Integrity Index for Risk Assessments of CO_2 Geological Storage

Introduction

The sequestration of CO_2 is becoming more and more significant with passage of time, because of its simplicity and reliability. Geological formations, such as oil fields, coal beds, and aquifers, are likely to provide the first large scale opportunity for concentrated storage of CO_2. In some cases, it may even be accompanied by economic benefits such as enhanced oil recovery (EOR), and CO_2 enhanced coal bed methane (ECBM) projects. One of the major obstacles in geological storages is the risk of leakage from these reservoirs. Wellbores, faults, and fractures are generally considered the most important and most likely leakage pathways. Watson and Bachu (2009) and many other researchers have identified wellbores as a major leak pathway, particularly in mature sedimentary basins such as the Western Canadian Sedimentary Basin or mature projects such as Cenovus's Weyburn CO_2-EOR project that have high well densities. A commonly-held belief is that CO_2 injection wells in saline aquifer CO_2 injection projects will pose a lesser risk than abandoned wells which are mainly drilled and completed for oil production purposes. The potential rapid growth of CO_2 injection projects in Alberta and Saskatchewan requires that the leakage potential of abandoned wells be examined. In 2008, there were 31 wells used for CO_2 injection and 48 wells used for the disposal of produced acid gas in Alberta but only 22 wells were drilled specifically with the purpose of CO_2 and acid gas injection (Bachu and Watson, 2009). The drilling in the Weyburn Field started from 1956 (IEA GHG, 2006), and these wells are prior to the advent of regulations in 1994 regarding drilling and completion, these wells may be a major long-term leakage risk in Weyburn project. Although leakage from wellbores in the long-term is one of the more important components of risk assessment in CO_2 sequestration projects there is currently no accepted evaluation method for abandoned wellbore. In this research, a cause-effect approach is used to establish an index value for abandoned wells and this index is calibrated to leakage potential.

The current practice for zonal isolation evaluation is mostly related to gas reservoirs and acid gas (a mixture of H_2S and CO_2, with minor traces of hydrocarbons) disposal. Diagnostic testing is major method of zonal isolation evaluation in high-pressure gas reservoirs. These tests are mostly undertaken for sustainable annular pressure (SAP) or sustained casing pressure (SCP) calculation, which assess the sealing capacity along the cement-formation interface that is filled with cement. A successful test will require that the sustained pressure is greater than the reservoir pressure. In acid gas disposal formations, continuous measurement and monitoring is a requisite practice to confirm isolation. A commonly held belief is that both gas reservoirs and acid gas injection are identical to abandoned wells in CO_2 sequestration projects. But CO_2 sequestration projects are different since well life is much shorter in gas reservoirs and the area of injection is several orders of magnitude larger than in acid gas injection projects. So these cases are not suitable anomalies for wells in CO_2 sequestration projects. Also the sustainable annular pressure (SAP) and sustained casing pressure (SCP) cannot be considered as a suitable limit for CO_2 storage wells and even for gas reservoirs. As it is mentioned by Halliburton "25% to 30% of wells are affected by annular pressure problem and lack of zonal isolation, even in cases that sustained casing pressure (SCP) is higher than reservoir pressure" (Ravi and Hunter, 2008). In this research, by using the cause-effect approach, all the major properties affecting well failure in general term considering surface casing vent flow (SCVF) or gas migration (GM), casing failure (e.g. thread failure internal and external corrosion), tubing failure, packer failure, and zonal isolation failure (leakage through cement bonds) are collected in two main interaction matrix presented in Appendix D.

Methodology

An interaction matrix is a common design approach used in rock engineering for tunnel design and other rock engineering systems. An interaction matrix allows the cause-effect relationship between multiple parameters to be assessed. In this research, a wellbore interaction matrix was developed for use in a long-term wellbore leakage study. The proposed interaction matrix is presented in Appendix D.

4.1.1. Cause-Effect Method for Wellbore Index Evaluation

A cause-effect approach uses a square matrix for capturing the interactions between subjects, and forms the structure for coupled modelling and index evaluation. Matrices have been used as the means for assemblage of detached parameters effecting the same physics or final result by using the mathematical procedures that can be very complex in some cases. Although the cause-effect approach is not unique, by including the matrix as a structure for manipulating different parameters, it is very effective in identifying and highlighting the interactions between subjects which affect the final result. In this section, we introduce the cause-effect method. This method is presented within the wider context in 'Engineering rock mechanics an introduction to the principles' by Hudson et al. (1992). The cause-effect approach is shown in Figure 28 within the context of the full workflow used for wellbore index calculation.

A method of structuring different parameters in the cause-effect approach is gathered and processed in an 'interaction matrix' which is presented in Appendix D. The interaction matrix can contain any number of state variables. The interaction matrix was firstly presented in the rock engineering systems (RES) approach in Hudson (1992); Hudson and Harrison (2000). As it is illustrated in Figure 29, each row in the interaction matrix passing through a parameter describes the influence of the parameter on the system, which is termed ‘Cause’ due to the parameter; whilst each column describes the influence of the system on the parameter, which is termed ‘Effect’ on the parameter.

In the first step, based on the objective of CO_2 leakage potential assessment from abandoned wellbores in carbon sequestration projects two main sets of wellbore properties were defined as early time and long-term properties. The early time consisted of 8 factors (these 8 parameters are located along the diagonal of the matrix shown in Figure 30) for which 5 factors have been assumed to influence the final wellbores’ leakage potential index, and the long-term properties consisted of 16 factors (these 16 parameters are located along the diagonal of the matrix shown in Figure 31) for which 15 factors have been assumed to influence the final wellbores’ leakage potential index. The first set of parameters is mainly concerned with cementing and well construction issues with both happening before any injection and abandonment and in turn these are defined as early time properties. The second set of parameters was chosen to capture the long-term properties of formation, cement annulus and cement plugs. These properties can potentially be ameliorated by future remediation. Judgements on both sets of parameters are determined by expertise, available literatures and historical documents.

The second step is to evaluate the interactions of primary parameters influencing the CO_2 leakage potential from wellbores. An interaction matrix was established by placing the primary parameters in the leading diagonal of a square matrix which is called ‘interaction matrix’ and establishing the mutual interaction between primary properties in the off-diagonal boxes of the interaction matrix. For this research, the range of interactivity values varies from no interaction (or very low interaction) to critical interaction (or very high interaction). Based on the approach followed by Hudson (1992), the range of these interactivity values was categorized in five classes, which are scaled from 0 (no interaction) to 4 (critical interaction). The other studies such as Mazzoccola and Hudson (1996); Shang et al. (2000; 2003; 2004) used the same coding method.

Using the same approach adopted for the fault tree research discussed in Chapter 2, an expert opinion survey conducted at the 5th **PR**oject **I**ntegration and **S**ponsors **M**eeting (PRISM) provided an opportunity to quantify the interactivity values in the interaction matrix. ‘Cause’ is calculated from the sum of all coding’s in each row and ‘Effect’ is the sum of all coding’s in each column.

The third step involves calculating relative weighting for each parameter. In this step, the equation which is a function of the influence of each parameter on the system which is ‘Cause’, and the effect of other parameters on each parameter ‘Effect’ will be the contribution of each parameter to the overall assessment of CO_2 leakage. Equation 15 are the commonly used methods for calculating the contribution rate (weighting) for each case but in this research, an alternative form was adopted and is shown in Equation 16.

$$\text{Cont. Rate} = \frac{\text{Cause} + \text{Effect}}{2} \quad \text{or} \quad \text{Cont. Rate} = \text{Cause} + \text{Effect} \qquad 15$$

$$\text{Cont. Rate} = \text{Cause} + \frac{\text{Effect}}{2} \qquad 16$$

The reason for adopting a modified equation is described in the following section and it will be shown that the new equation will give better results for the wellbore index evaluation. Defining a rating code as a normalized contribution rate (Equation 17) means that rating codes will sum to 100%. The calculated weight factors for early time properties index and long-term properties index are presented in Figure 32.

$$\text{Rating Code} = \frac{\text{Cause}_i + \frac{\text{Effect}_i}{2}}{\sum_{i=1}^{n}\left(\text{Cause}_i + \frac{\text{Effect}_i}{2}\right)} \qquad 17$$

Since two sets of properties (early-time and long-term) are involved in the evaluation, techniques for combining these two sets is of interest. The Analytic Hierarchy Process (AHP) is used for scaling between the early time properties index, long-term properties index and cement top. The low cement top is evaluated in most of studies as the major cause of well integrity problems. It is worth noting that 63% of the wells leaking in Alberta acid gas and CO_2 injection projects are not fully cemented to the surface (Bachu and Watson, 2009). The weighting based on Analytic Hierarchy Process (AHP) is discussed in next section.

In the fourth step, the wellbore index value is evaluated. The weighting and evaluated properties codes to be incorporated are provided in Equation 18 for wellbore index evaluation:

$$\begin{aligned}\text{Wellbore Index} = \sum_{j=1}^{3}\text{RVV}_j \times \sum_{i=1}^{n} a_i\, p_i = \text{RVV}_{\text{early time}} \sum_{i=1}^{5} \text{early time weighting factors}_i \times p_i \\ + \text{RVV}_{\text{long term}} \sum_{j=1}^{15} \text{long term weighting factors}_j \times p_j \\ + \text{RVV}_{\text{cement top}} \times \text{cement top weighting factors} \times p\end{aligned} \qquad 18$$

where, i is different parameters, a_i is weighted ratio of factor i, and p_i is rating value of parameter i. The weighting factors are based on the analysis of the interaction matrix and the relative vector values are calculated by the AHP method, which will be discussed in section. The rating values for the main influential factors (1−5) are based on their degree of action for relative evaluation. The absence of a factor is coded as 1 assigning to ‘very low’, and if it is in ‘very good’ condition it is coded as 5. For example, if the expert judged that the casing condition was very poor; i.e. the corrosion had progressed through much of the casing body and connection seals and threads are corroded and lost their sealing ability, the very low value would be checked off in the questionnaire handed to experts for casing condition. The average values for each property based on experts' judgement are presented in Table 12.

The "Time Effect and Future Human Activities" and "Bottom Wellbore CO_2 Pressure" long-term effects properties are shown to be functions of time in Table 12 and vary from 5 to 1 and 1 to 5 for Time Effect and Bottom Wellbore CO_2 Pressure, respectively. It has been assumed that CO_2 Pressure will decrease with time and any effects due to the passage of time (the Time Effect) are increasing which will tend to reduce wellbore index over time. The final step of this evaluation will be wrapping up all these weights to the final index by using Equation 18. These results are presented in Table 13.

By considering cement top equal to 5 for 'cement top to the top of well head' the index for the wellbore sealing condition in the short-term will be equal to 75.08/100 and 74.93/100 for wellbore integrity at Weyburn anhydrite seal and Watrous seal location, respectively. These values are for assigned values for "time effect" and "bottom wellbore CO_2 pressure" condition at starting of abandonment. These values will be changed to 75.16/100 and 75.01/100 for long-term wellbore integrity at Weyburn anhydrite seal and Watrous seal location, respectively. As it can be seen the index is slightly decreasing which is a result of small weighting factor for "time effect" and "bottom wellbore CO_2 pressure" condition based on this survey. For deep cement top (which is severe case for cement top) the index will be decreased to 53.44/100 and 53.29/100 for long-term wellbore integrity at Weyburn Anhydrite Seal and Watrous Seal location, if the cement top value assigned equal to 1.

4.1.2. Weighting early time and long-term indexes using Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a mathematical technique for multicriteria decision-making, which was developed by Saaty (1980, 1990, 1994) and is often referred to as the Saaty method. In essence, AHP is used to construct a matrix expressing the relative values of a set of attributes. For the current effort to establish a wellbore integrity index, AHP will be used to assess the contribution that early time and long-term indices make. Experts were asked to assess the contribution of the different indices based on their judgment. Each of these judgments is assigned a number on a scale. One common scale (adapted from Saaty) is shown in Table 14. As mentioned earlier, it is easier to compare two things than to compare all the items in a list. For this component of the research, the questionnaire shown in Appendix H, I and J were presented to the experts in attendance at the 5th PRISM. The questionnaire is structured with a series of pairwise comparisons between the verbal probability phrases. Responses were entered into the overall preference matrix (OPM), shown in Table 15. It should be noted that the numbers in Table 15 are averages of the judgment of experts for each matrix cell. It is obvious that the lower part of the OPM, which is the inverse of the upper, can be ignored. The pairwise comparison values are calculated using the OPM. It must be noted that geometric averaging was used for populating the ranking values in the OPM matrixes.

The Relative Value Vector (RVV) is calculated using the OPM by normalizing the geometric average of each row of the OPM. The RVV values are calculated as: 0.37 (0.36), 0.36 (0.37) and 0.27 (0.27) for early time effect index, long time effect index and cement top, respectively. The values in parenthesis are RVV values calculated by normalizing the arithmetic average of each row of OPM.

AHP also evaluates the consistency of the decision maker by finding the Consistency Ratio (CR) parameter, and allows for the revision of responses. In this analysis, the CR parameter equals 0.063, well below the critical limit of 0.1. This indicates that the experts were consistent in their choices. These results are incorporated into the final index weighting factors.

Proposed simple proxies as a validation strategy

In order to validate the proposed wellbore index method the Finite Element Analysis (FEA) and elasticity theory were used. The leakage predictions from wellbores with different indexes are verified by comparing with leakage results from finite-element models and theoretical wellbore models. In this section a number of synthetic wellbores were analysed and the calculated trend of CO_2 leakage is compared with the wellbore integrity index value for that case. This analysis is not intended to calculate the CO_2 leakage probability from the wellbore integrity index, but it is mainly focused on the trend of reduction or increase of leakage probability versus proposed index variation.

4.1.3. Microannulus theoretical model and wellbore index validation

Microannulus between formation and cement annulus can be the result of cement shrinkage and or cement vertical stress reduction. Nishikawa and Wojtanowicz (2002) proposed a new model for vertical stress reduction evaluation. They believed that after cement placement cement fluid starts to dissipate by filtration driven by a hydrostatic overbalance. The resulting volume change causes cement pressure reduction as result of compressibility effect. This volume reduction causes downward movement of the cement slurry which in turn causes friction drag at the wellbore walls and results in an annular pressure decrease. This pressure reduction is transmitted upward from the zone of fluid loss to the surface. Their model is formulated as the following:

$$P_{Cement} = 0.052\rho_{eq}h + 2 \times 0.052\sum_{n=1}^{\infty}\frac{\left(\rho_{slurry} - \rho_{eq}\right)}{D_{boc}}\left[\frac{(-1)^{n+1}}{\alpha^2}\right]\sin(\alpha h)\ \exp\left(c^2\alpha^2 t\right) \qquad 19$$

where, c is cement compressibility which is equal to $(1-2\mu)/3E$ (1/psi), and D_{boc} is depth at bottom of cement (cm), h is depth (cm), t is time after pumping slurry (min), ρ_{eq} is equivalent density of normal formation pressure gradient (lbm/gal), ρ_{slurry} is density of cement slurry (lbm/gal) and α is constant defined as:

$$\alpha = \left(n\pi - \frac{\pi}{2}\right)\frac{1}{D_{boc}} \quad (20)$$

By substituting the range of properties for conventional cements a reduction of 30% to 40% is anticipated. Based on this assumption we can calculate the differential pressure from the time zero to infinite time value using Equation 21:

$$\Delta P_{Cement} = 0.052\rho_{slurry}\, h \times 0.4 \text{ (psi)} = 0.052\rho_{slurry}\, h \times 0.4/145 \text{ (MPa)} \quad (21)$$

The problem is illustrated in Figure 33, as it can be seen the microannulus will be happening if the formation displacement (u_{fi}) is less than cement annulus displacement (u_{co}). Cement annulus displacement (u_{co}) can be formulized from Sadd (2005) for thick cylinder as the following:

$$u_{co} = \frac{1+\nu_{cement}}{E_{cement}}\left[-\frac{r_{casing}^2 r_{bit}\left(p_{co}-p_{ci}\right)}{r_{bit}^2 - r_{casing}^2} + \left(1-2\nu_{cement}\right)\frac{r_{casing}^2 p_{ci} - r_{bit}^2 p_{co}}{r_{bit}^2 - r_{casing}^2} r_{bit}\right] \quad (22)$$

And internal radial displacement of the formation (u_{fi}), which is the same as the displacement of an infinitely long thick cylinder, is presented in Equation 23 from Sadd (2005).

$$u_{fi} = \frac{1+\nu_{formation}}{E_{formation}} p_{fi}\, r_{bit} \quad (23)$$

In Figure 34 the pressure superposition is illustrated for better understanding.

There are two assumptions in this model, first zero displacement at casing (u_{ci}) and differential vertical stress can be assumed equal to Equation 21. For first assumption we have:

$$u_{casing} = 0$$

$$u_{casing} = u_{ci} = \frac{1+\nu_{cement}}{E_{cement}}\left[-\frac{r_{casing}\, r_{bit}^2\left(p_{ao}-p_{ai}\right)}{r_{bit}^2 - r_{casing}^2} + \left(1-2\nu_{cement}\right)\frac{r_{casing}^2\, p_{ai} - r_{bit}^2\, p_{ao}}{r_{bit}^2 - r_{casing}^2} r_{casing}\right] = 0 \quad (24)$$

And for the second assumption, $\Delta\sigma_v$ is calculated assuming plain-strain condition. In turn $\Delta\sigma_v$ for plain-strain condition is:

$$\Delta\sigma_v = \Delta\sigma_z = 2\nu_{cement}\frac{r_{casing}^2\,\Delta p_{ai} - r_{bit}^2\,\Delta p_{ao}}{r_{bit}^2 - r_{casing}^2} = \Delta P_{cement} \text{ :from Equation 21} \quad (25)$$

It must be noted that because $\Delta\sigma_v$ is negative and compressive force consider to be negative, in turn $\Delta\sigma_v$ is equal to absolute value of ΔP_{cement}. By combining Equations 24 and 25 we can calculate the two unknown (Δp_{ai}) and (Δp_{ao}) as:

$$\Delta p_{ai} = \frac{\Delta P_{cement}}{2\nu_{cement}}\left(r_{bit}^{2} - r_{casing}^{2}\right) \times \frac{1}{r_{casing}^{2} - r_{bit}^{2}\frac{1}{2-2\nu_{cement}}\left(1+\left(1-2\nu_{cement}\right)\frac{r_{casing}^{2}}{r_{bit}^{2}}\right)} \qquad 26$$

$$\Delta p_{ao} = \Delta p_{ai}\ (\text{Eq.26}) \times \frac{1}{2-2\nu_{cement}}\left(1+\left(1-2\nu_{cement}\right)\frac{r_{casing}^{2}}{r_{bit}^{2}}\right) \qquad 27$$

Now assuming the interaction law between formation and the cement annulus, we can say $\Delta p_{ao} = \Delta p_{fi}$. So the formation of a microannulus is possible if the formation displacement is lower than cement annulus displacement, which indicates that:

$$u_{fi} - u_{co} - \text{shrinkage} \times (r_{bit} - r_{casing})\,(1+\nu_{cement}) < 0$$

$$\frac{1+\nu_{formation}}{E_{formation}} p_{fi}\, r_{bit} - \frac{1+\nu_{cement}}{E_{cement}}\left[-\frac{r_{casing}^{2}\, r_{bit}\,(p_{ao}-p_{ai})}{r_{bit}^{2} - r_{casing}^{2}} + (1-2\nu_{cement})\frac{r_{casing}^{2} p_{ai} - r_{bit}^{2} p_{ao}}{r_{bit}^{2} - r_{casing}^{2}} r_{bit}\right] - \text{shrinkage} \times (r_{bit} - r_{casing})(1+\nu_{cement}) < 0 \qquad 28$$

After theory identification we have to identify the formation and annulus properties. For formation elastic modulus considering it as the fractured rock mass the Hoek-Brown elastic modulus evaluation method is used. In this model the downgrading effect of fracturing is considered in elastic modulus evaluation equation. Based on Hoek et al. (2002) which they modified the Hoek and Brown (1998) equation, the elastic modulus of fractured rock will be calculated as the following equation for intact rock with uniaxial compressive strength (UCS) smaller than 100 MPa.

$$E_{Fractured\,Rock}(GPa) = \left(1-\frac{D}{2}\right)\sqrt{\frac{\sigma_{ci}}{100}}\,10^{\frac{GSI-10}{40}} = \sqrt{\frac{\sigma_{ci}}{100}}\,10^{\frac{GSI-10}{40}} \qquad 29$$

And for intact rock uniaxial compressive strength (UCS) larger than 100 MPa, Equation 30 is suggested by Hoek et al. (2002).

$$E_{Fractured\,Rock}(GPa) = \left(1-\frac{D}{2}\right)10^{\frac{GSI-10}{40}} = 10^{\frac{GSI-10}{40}} \qquad 30$$

where σ_{ci} is uniaxial compressive strength (UCS) of intact rock and D is the disturbance factor which varies from 0 for ‘undisturbed in-situ rock masses’ to 1 for ‘very disturbed rock masses’. This parameter is mainly for tunnelling and blasting, which may cause a large disturbance zone surrounding the tunnel. Whereas in oil well drilling which is considered highly controlled and less disturbing in comparison with blasting, the D value was assumed equal to 0 for this study. The Geological Strength Index (GSI) value was introduced by Hoek (1994), Hoek et al. (1992, 1998) and Hoek and Brown (1980, 1988) to provide a framework for estimating the reduction in rock mass strength and stiffness. GSI is used in the Hoek-Brown constitutive plastic model for capturing the level of fracturing in rock mass. The GSI value for different geological conditions is identified by field observations. Its evaluation is straightforward, and is based upon the visual impression of the rock structure, in terms of blockiness, and the surface condition of the discontinuities indicated by joint. In right side of Figure 35 the modified format of GSI value evaluation chart prepared by Hoek et al. (1998) is shown. Since the surface condition evaluation for formations one to two kilometres deep in the ground is hard or maybe impossible this chart is modified to the figure in the left side of Figure 35, based on rock intact strength instead of joints' surface condition. The evaluated GSI value for each fracture condition and rock intact strength is presented on top corner of each box.

Since the Hoek and Brown criterion is used extensively in anisotropic rocks, such as metamorphic and sedimentary formations that possess an inherent anisotropy due to foliation or bedding (Saroglou et al., 2004), it is not very common to use the Hoek and Brown criterion of Shale formations, but definitely is suitable for Anhydrite formations. Wherein for consistency the Hoek and Brown criterion is used for all kind of formations in this study. Since, Hoek and Brown (1980) explained that the value of m_i refers to intact rock specimens tested normal to bedding or foliation and will be significantly different if failure occurs along a weakness plane, such as foliation, cleavage or schistosity. It must be noted, that the rock strength test for index evaluation has to be tested normal to bedding or foliation.

In this study based on current available literatures the ranges for Young's Modulus, Poisson's Ratio, uniaxial compressive strength (UCS) and uniaxial tensile strength for different cement classes is gathered and analyzed for Weyburn wellbore cement. For Portland cements the uniaxial compressive strength (UCS) is correlated to porosity, and Roy et. al (1993) gathered the data to show this concept. Figure 36 is showing the trend-line calculated based on Roy et. al (1993). The equation for trend-line is as follows:

$$\mathrm{UCS}(10^3\,\mathrm{psi}) = 0.0057 \times [\phi(\%)]^2 - 0.7141 \times \phi(\%) + 22.754 \qquad 31$$

where ϕ is cement porosity in percentage and UCS in 10^3 psi unit. Chevron drilling reference series, volume seven (1990) suggests that the uniaxial compressive strength (UCS) is correlated to water-cement ratio (see Figure 37), the water ratio reduction will increase compressive strength. The water ratio reduction is usually used for increasing cement slurry density. This increased compressive strength makes cement more resistant to the effects of drilling fluid contamination which is considered as an advantage. Equation 32 provides the trend-line relationship shown in Figure 37:

$$\log_{10}[\mathrm{UCS}\,(\mathrm{psi})] = -4.31\,(w/c) + 5.37 \qquad 32$$

where w/c is the water-cement ratio.

Since the water-cement ratio for common cements is between 0.3 to 0.45 (see Figure 37), the UCS variation will be between to 19.0 to 82.7 MPa (2750 to 12000 psi), which is not in contradiction with the range of UCS values from Equation 31 for reasonable porosity values (0.18 to 0.42), which is ranging between 19.3 to 81.0 MPa (2800 to 11750 psi). As it can be seen the minimum value has 50 psi (2%) and maximum value has 1.7 MPa (250 psi) (2%). In this study Equation 31 was used for property evaluation and Equation 32 was used for validation.

The variation of cement elastic modulus is also studied in this research and variation of different cement classes Young's modulus was gathered and is presented in Figure 38. Cement Poisson's ratio varied between 0.15 to 0.2 for common wellbore cementing practices (Nelson et. al, 2006); 0.18 for a class "G" based slurry and 0.14 for a class "A" or "H" based slurry. For extreme cases, such as a foamed system, they may have Poisson's ratio of 0.09. Although some studies give the correlation between porosity and elastic modulus since they are specific on the project, which they are performed, it was decided not to use these correlations.

Now based on knowing the range of cement Young's Modulus and Poisson's ratio and also fracture effect on formation Young's Modulus, we can explore the proposed index capability in microannulus potential evaluation. Five cases have been explored and are tabulated in Table 17. The values in "categorized values" rows are assigned based on the property value condition in the possible range of property variation. For example, if the annular cement strength is assumed to be 82.74 MPa (12000 psi), and the cement strength varied from 27.58 to 82.74 MPa (4000 to 12000 psi) (see Table 16) then the annular cement strength is considered "very high" or categorized value estimated 5 based on possible range for cement strength. The "categorized values" will be used for index evaluation. For shrinkage evaluation the study by Backe et al. (1998, 1999) is referred which suggested the oil well cement volumetric shrinkage between 0.6 and 6% (see Table 16).

The microannulus model has been used for a depth of 1219 m which is somewhat near to Weyburn condition, and the bit radius and the casing inside radius are 5 cm and 4 cm, respectively. The model results are presented in Figure 39.

This version of the model is not very accurate. For case 5, a microannulus equal to 30 mm was computed, which is clearly unreasonable. The unreasonable values occur because the elasticity equations are only valid while the cement annulus and formation are in contact. After detachment, these equations are no longer valid. Although not predictive, the analytical approach is however useful as a proxy for the potential development of a microannulus and was used for the comparison of different cases. As shown in Figure 39, a higher normalized index is correlated with smaller potential microannulus.

4.1.4. *Cement plug leakage theoretical model and wellbore index validation*

Localization of softening damage around a cement plug, which can cause microannulus in case of a degraded casing, can be the major cause of the leakage. For the special case of the cement plug inside the cement annulus, it has been assumed no displacement occurs on the outer side of the cement annulus, (u_{ao}). This can only occur if the formation surrounding the cement annulus has infinite stiffness but it is assumed that a relatively high formation bulk modulus (in comparison to the cement) would reduce the displacement on the outer side of the cement annulus to a reasonably low value to satisfy the assumption made for this analysis.

The elastic solution for the radial displacements and the radial normal stresses at a point of radial coordinate is (Timoshenko and Goodier, 1970):

$$u = Ar + Dr^{-2} \tag{33}$$

$$\sigma_r = E\left(\frac{A}{1-2\nu} - \frac{2D}{1+\nu} r^{-3}\right) \tag{34}$$

where A and D are arbitrary constants to be found from the boundary conditions. E and ν are Young's modulus and Poisson's ratio, respectively. For the fixed outer annulus surface it is assumed that during localization, $\Delta u_{ao} = 0$ at r = R, and $\Delta p_{ao} = -\Delta p$ at r = a. From Equations 33 and 34 and applying these boundary conditions, the A and D constants are calculated as (Bazant and Cedolin, 2003):

$$A = -\frac{\Delta p}{E_{annulus}} \left[\frac{1}{1-2\nu_{annulus}} + \frac{2R^3}{(1+\nu_{annulus})a^3}\right]^{-1} \tag{35}$$

$$D = -AR^3 \tag{36}$$

By substituting A and D, the displacement at the inside annulus, Δp_{ai} ,will be:

$$\Delta p_{ai} = \frac{E_{annulus} \times a^2}{R^3 - a^3} \left[\frac{1}{1-2\nu_{annulus}} + \frac{2R^3}{(1+\nu_{annulus})a^3}\right] \Delta u \tag{37}$$

If the cement plug starts to soften, its elastic modulus starts to decrease; in special cases the plug elastic modulus is lower than the annulus elastic modulus these cases are also can be treated the same as plug elastic modulus softening; plug starts to expand with lower rate than annulus. The states of stress and strain are assumed to be uniform, and strain softening properties to be isotropic (Bazant and Cedolin, 2003). Assuming the uniform and hydrostatic pressure will cause strains to be equal to $\Delta\varepsilon_{plug} = \frac{\Delta u_{po}}{a} = \frac{\Delta u}{a}$ for $r < a$ and the stresses will be equal to $\Delta p_{po} = \frac{E_{plug}}{1-2\nu_{plug}} \Delta\varepsilon_{plug} = \frac{E_{plug}}{1-2\nu_{plug}} \frac{\Delta u}{a}$.

As shown in Figure 40, if there is no gap (or no micro-annulus), displacement at boundary of the annulus (Δu_{ai}) and plug (Δu_{po}) is equal. By assuming the same displacement at the boundary of the annulus and the plug, the interaction pressure will be equal to:

$$\Delta p = \Delta p_{po} - \Delta p_{ai} = \left\{ \frac{E_{plug}}{1-2\nu_{plug}} \frac{1}{a} - \frac{E_{annulus} \times a^2}{R^3 - a^3} \left[\frac{1}{1-2\nu_{annulus}} + \frac{2R^3}{(1+\nu_{annulus})a^3} \right] \right\} \Delta u \qquad 38$$

Yielding Δp to zero (0) means the starting point of a micro-annulus is at the boundary of the annulus and the plug. The Δp value can be considered as the leakage potential for the case of plug–annulus micro-annulus. The more positive Δp means the higher potential of micro-annulus in wellbore. For index evaluation based on this theory five cases have been explored with the results provided in Table 18. The values in “categorized values” rows are assigned based on the property value condition in the possible range of property variation (see Table 16). The “categorized values” will be used for index evaluation.

In this evaluation bit radius and casing inside radius are considered 5 cm and 4 cm, respectively. The proxy model results are presented in Figure 41. It can be said that this suggested proxy is not very accurate but it is informative and it is useful as a proxy for the potential development of plug–annulus micro-annulus. As shown in Figure 41 there is a trend between the indices and proxies results, although case 2 must be more problematic than case 1 because of lower index value, which is suggested vice versa by proxy model.

Discussion and conclusion

Well integrity in CO_2 storage field studies are in their early stage either in theoretical concept or in experience. In the case of old fields such as Weyburn where operation and well drilling were started from 1956 (IEA GHG, 2006) well integrity remains a critical issue for long term storage of CO_2 in this field. The debate for Weyburn well integrity intensifies when regulations will likely require that sealing is required for hundreds of wells for 100’s of years. Extensive monitoring and surveillance can help evaluate well integrity, but maintaining an operational monitoring system over long time frames is challenging. It is also important to know that surveillance options for some problems such as sustained casing pressures (SCP) appear to be limited. It must be noted some standard tests such as well pressure test can be a source of SCP problems. In case of problem recognition remediation is applied to problematic wells. Since remediation have positive effects but in some cases, such as injecting high density brine in the annulus in the Gulf of Mexico has limited or no success. Since CO_2 storage fields is new in industry the well sealability experience for abandoned wells in CO_2 geological storage projects is more for natural gas production wells which are not completely analogous to CO_2 storage sealed wells.

From this research, the most weighted properties are cement top, casing centralization, well cleaning, cement placement, production and injection well history, and cement volume reduction. Besides cement top the other five properties are early time effects and they are the major causes of sustained casing pressures (SCP). Sustained casing pressures (SCP) are the major result of integrity problem. Based on a study conducted by Sweatman (IEA GHG ,2006), 60% to 70% of wells in the Gulf of Mexico have SCP problems. Based on this study approximately 45% of the 14,927 operational wells in 2004 in the Gulf of Mexico had SCP problems and about 33% of the SCP problems were linked to the cementing process. It is instructive to test the ranking evaluation criteria developed in this research against these field results. The sum of properties which are related to cement are as follows:

$$\frac{\begin{pmatrix} w_{\text{Well Cleaning}} + w_{\text{Cement Placement}} + w_{\text{Cement Volume Reduction}} + w_{\text{Production and Injection Well History}} + \\ w_{\text{Annular Cement Porosity}} + w_{\text{Annular Cement Strength}} + w_{\text{Cement Plug Porosity}} \end{pmatrix}}{\text{Total Weight Value}} = \frac{5.94}{20} = 0.30 \qquad 39$$

where, w presents the cement properties weighting values. The 0.30 value from our ranking evaluation is in close agreement with 33% value Sweatman (IEA GHG ,2006) found in his study.

It is believed that gas flow through the cement matrix is the main cause of SCP. Gas flow problems are a result of gas flow through unset cement and shrinkage after completion. The shrinkage after completion is thought to be a major contributor (IEA GHG, 2006). In this study 'Cement Volume Reduction' with Index weighting of 0.72 is considered to be less important than 'Cement Placement' with Index weighting of 1.20 which contradicts the IEA GHG (2006) study conclusions.

For the Weyburn Project, data on failure modes for wells is limited and generally unavailable for this research. A tailored database of well characteristics for wells within the Weyburn Project is still under development and unavailable to test for possible relationships in well behaviour. Although most studies suggest that the main failure mode for wells is cement micro annulus leaks, the most important causes of cement micro annulus leaks are casing centralization, cement placement and cement volume reduction which are the main parameters in index evaluation based on index weighting values.

Overall as long as the supervised or unsupervised data mining study is not applied on available data from different carbon geological storage projects which experienced minor and major failures, the capability of suggested index cannot be confirmed. In future by increasing the data from different projects the developed index such as this study can be evaluated. Until then, the procedure for evaluation can be simple closed form calculations such as Section 4.1.3 and 4.1.4 or brief discussions based on past studies such as introduction of discussion or summary.

A lack of useful guides and regulations in oil industry can be managed by wellbore indices such as the index suggested in this study. A number of guides and regulations are in place in the Alberta, Saskatchewan and British Columbia oil industries to provide direction for wells constructed in CO_2 storage fields:

1. Alberta Energy Utilities Board (AEUB) Guide 8 (October 1997) provides guidance on the emplacement of surface casing to avoid contamination of near-surface resources, particularly water aquifers.
2. Alberta Energy Utilities Board (AEUB) Guide 51 (March 1994) provides guidance on injection and disposal wells. Inert and sour gas fall under AEUB Class III wells.
3. Alberta Energy Utilities Board (AEUB) Guide 65 (June 2000) provides guidance on the development of miscible enhanced oil recovery projects. It also contains requirements for the conversion of oil or gas fields to acid gas injection, with reference to Guide 51 for the development of the injection wells.
4. Alberta Energy Utilities Board (AEUB) Guide 20 (March 1996) provides minimum standards for well abandonment and the testing for natural gas leaks from the abandoned well.
5. Saskatchewan’s oil and gas conservation regulations form 1985 (with amendments through to 2000) provide minimum standards for the drilling, surface casing and well abandonment. This regulation is provided for the disposal of saltwater and other oilfield waste fluids.
6. Saskatchewan’s mineral industry environmental protection regulations (1996) provide some standards and recommendations for the development of a disposal facility.
7. The British Columbia drilling and production regulations discuss well completion requirements. Generally, the regulations are similar in nature to those of Alberta.

There is no specific regulation for CO_2 in Canada. The AEUB Guide 8 (October 1997) is not provided for acid injection or CO_2 Injection fields. Moreover volumes of CO_2 being injected significantly higher than the gas (H_2S) volume envisaged in AEUB Guide 51 (March 1994), AEUB Guide 65 (June 2000), AEUB Guide 20 (March 1996) and Saskatchewan’s oil and gas conservation regulations (1985). Saskatchewan’s oil and gas conservation regulations (1985) is the basis for developing regulations for storage of CO_2 in Alberta. But these regulation do not anticipate the need for storage of a large volume of contaminated fluid.

The Well abandonment configuration based on ERCB Directive 020 (Energy Resources Conservative Board (ERCB), 2007), Saskatchewan Regulation 172/66 (1966) and British Columbia Regulation 390 (2004) for wellbores which passing aquifer zone is illustrated in Figure 42. In Figure 42 the red colour identifies less strict standard and green colour identifies stricter standard. As it can be seen the ERCB Directive 020 is stricter than Saskatchewan Regulation 172/66 and British Columbia Regulation 390/2004. It must be mentioned that Well completion, maintenance and abandonment guideline (February, 2011) force permit holders to conduct abandonments and plugbacks in accordance with the ERCB Directive 20. Weyburn is located in Saskatchewan so the probability of leakage is much higher than a field located in Alberta and British Columbia, as a result of lower standards in this province. For future work, the suggested wellbore index can be used and evaluated in future projects, and effects of regional geology, pressure and fluid chemistry in the overlying saline aquifer and production, injection and/or pressure history (for existing wells) which is not discussed in this study should be considered.

This study attempted to explore the difficulties in wellbore integrity and the results are presented in wellbore integrity index value. The easiness of this approach made this index as very strong tool for feasibility studies in CO_2 sequestration projects in depleted reservoirs.

Table 12. Average decided values for each property based on experts' judgement

Early Time Effects	Casing Centralization	Well Cleaning	Cement Placement	Cement Volume Reduction	Production & Injection Well History
	2.83	**3.60**	**3.40**	**3.60**	**4.40**

Long-term Effects	Well Trajectory	Bounding Seal (Formation) Fluid Properties	Bounding Seal (Formation) In Situ Stress	Bounding Seal (Formation) Pressure	Bounding Seal (Formation) Strength	Bounding Seal (Formation) Permeability	Bounding Seal (Formation) Fracture Condition	Annular Cement Porosity	Annular Cement Strength Properties	Wellbore's Completion Fluids Chemical Properties	Cement Plug Porosity	Casing Condition	Time Effect & Future Human Activities	Injected CO_2 Gas Properties	Bottom Wellbore CO_2 Pressure
Anhydrite Seal	**4.40**	**3.00**	**2.40**	**3.00**	**3.83**	**4.44**	**2.38**	**3.38**	**3.00**	**3.00**	**3.20**	**2.80**	**F1(t)**	**3.00**	**$F_2(t)$**
Watrous Seal	**4.20**	**3.00**	**2.40**	**3.60**	**3.83**	**4.17**	**2.00**	**2.40**	**2.40**	**3.60**	**2.60**	**2.80**	**F1(t)**	**4.00**	**$F_2(t)$**

Table 13. Final Index weighting considering Equation 18

Casing Centralization	Well Cleaning	Cement Placement	Cement Volume Reduction	Production & Injection Well History	Well Trajectory	Bounding Seal (Formation) Fluid Properties	Bounding Seal (Formation) In Situ Stress	Bounding Seal (Formation) Pressure	Bounding Seal (Formation) Strength	Bounding Seal (Formation) Permeability	Bounding Seal (Formation) Fracture Condition	Annular Cement Porosity	Annular Cement Strength Properties	Wellbore's Completion Fluids Chemical Properties	Cement Plug Porosity	Casing Condition	Time Effect & Future Human Activities	Injected CO_2 Gas Properties	Bottom Wellbore CO_2 Pressure	Cement Top
2.68	**2.03**	**1.16**	**0.72**	**0.81**	**0.56**	**0.33**	**0.52**	**0.61**	**0.50**	**0.49**	**0.48**	**0.46**	**0.41**	**0.46**	**0.35**	**0.52**	**0.50**	**0.54**	**0.48**	**5.41**

Table 14. The Saaty rating scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favour one over the other
5	Much more important	Experience and judgment strongly favour one over the other
7	Very much more important	Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values	When compromise is needed

Table 15. Different indexes' contribution OPM (Overall Preference Matrix) evaluated based on experts' judgment

	Early Time Effect Index	Long Time Effect Index	Cement Top
Early Time Effect Index	1	1.35	1.05
Long Time Effect Index	0.74	1	1.74
Cement Top	0.96	0.57	1

Table 16. Possible variation of different properties used in formation-annulus microannulus (Section 4.1.3) and cement plug-annulus microannulus (Section 4.1.4)

Different System Properties	Strength or UCS value (MPa)	Elastic Modulus (GPa)	Poisson's Ratio (No unit)	Porosity (%)	Shrinkage Volume Reduction (%)
Annular cement	27.58 to 82.74	2.0 to 8.0	0.15	20 to 40	0.6 to 6
Plug cement	27.58 to 82.74	2.0 to 8.0	0.15	20 to 40	N/A
Bounding Seal (Formation)	N/A	N/A	0.3	N/A	N/A

Table 17. Different cases for formation-annulus micro-annulus

Different System Properties		Bounding Seal (Formation) Properties					Annular Cement Properties					
		Bounding Seal (Formation) Strength or UCS value (MPa)	Bounding Seal (Formation) Fracture Condition	Geological Strength Index (GSI) evaluated from Figure 35	Bounding Seal Elastic Modulus (GPa) from Eq. 29 and 30	Bounding Seal Poisson's Ratio	Annular Cement Porosity (%)	Annular Cement Strength (MPa)	Annular Cement Elastic Modulus (GPa)	Annular Cement Poisson's Ratio	Annular Annular Cement Slurry Density (lbm/gal)	Cement Shrinkage Volume Reduction (%)
Case 1	Property Values	Very High (100)	Very Low Fractured	85	74.99	0.3	20%	Very High (82.74)	8.0	0.15	16	0.6%
	Categorized Values	5.00	5.00	N/A	N/A	N/A	5.00	5.00	N/A	N/A	N/A	5.00
Case 2	Property Values	High (50)	Low Fractured	65	16.77	0.3	30%	Moderate (55.16)	6.0	0.15	16	0.6%
	Categorized Values	4.00	4.00	N/A	N/A	N/A	3.00	3.00	N/A	N/A	N/A	5.00
Case 3	Property Values	Moderate (25)	Moderate Fractured	45	3.75	0.3	40%	Very Low (27.58)	2.0	0.15	16	2%
	Categorized Values	3.00	3.00	N/A	N/A	N/A	1.00	1.00	N/A	N/A	N/A	3.00
Case 4	Property Values	Low (5)	High Fractured	25	0.53	0.3	30%	Moderate (55.16)	6.0	0.15	16	6%
	Categorized Values	2.00	2.00	N/A	N/A	N/A	3.00	3.00	N/A	N/A	N/A	1.00
Case 5	Property Values	Very Low (2)	Very High Fractured	10	0.14	0.3	40%	Very Low (27.58)	2.0	0.15	16	2%
	Categorized Values	1.00	1.00	N/A	N/A	N/A	1.00	1.00	N/A	N/A	N/A	3.00

Table 18. Different cases for plug–annulus micro-annulus

Different System Properties		Plug Cement Properties				Annular Cement Properties			
		Plug Cement Porosity (%)	Plug Cement Strength (MPa)	Plug Cement Elastic Modulus (GPa)	Plug Cement Poisson's Ratio	Annular Cement Porosity (%)	Annular Cement Strength (MPa)	Annular Cement Elastic Modulus (GPa)	Annular Cement Poisson's Ratio
Case 1	Property Values	Very Low (20%)	Very High (82.74)	8.0	0.15	Very Low (20%)	Very High (82.74)	8.0	0.15
	Categorized Values	5.00	5.00	N/A	N/A	5.00	5.00	N/A	N/A
Case 2	Property Values	Moderate (30%)	Moderate (55.16)	6.0	0.15	Very Low (20%)	Very High (82.74)	8.0	0.15
	Categorized Values	3.00	3.00	N/A	N/A	5.00	5.00	N/A	N/A
Case 3	Property Values	Moderate (30%)	Moderate (55.16)	6.0	0.15	Moderate (30%)	Moderate (55.16)	6.0	0.15
	Categorized Values	3.00	3.00	N/A	N/A	3.00	3.00	N/A	N/A
Case 4	Property Values	Moderate (30%)	Moderate (55.16)	6.0	0.15	Very High (40%)	Very Low (27.58)	2.0	0.15
	Categorized Values	3.00	3.00	N/A	N/A	1.00	1.00	N/A	N/A
Case 5	Property Values	Very High (40%)	Very Low (27.58)	2.0	0.15	Very High (40%)	Very Low (27.58)	2.0	0.15
	Categorized Values	1.00	1.00	N/A	N/A	1.00	1.00	N/A	N/A

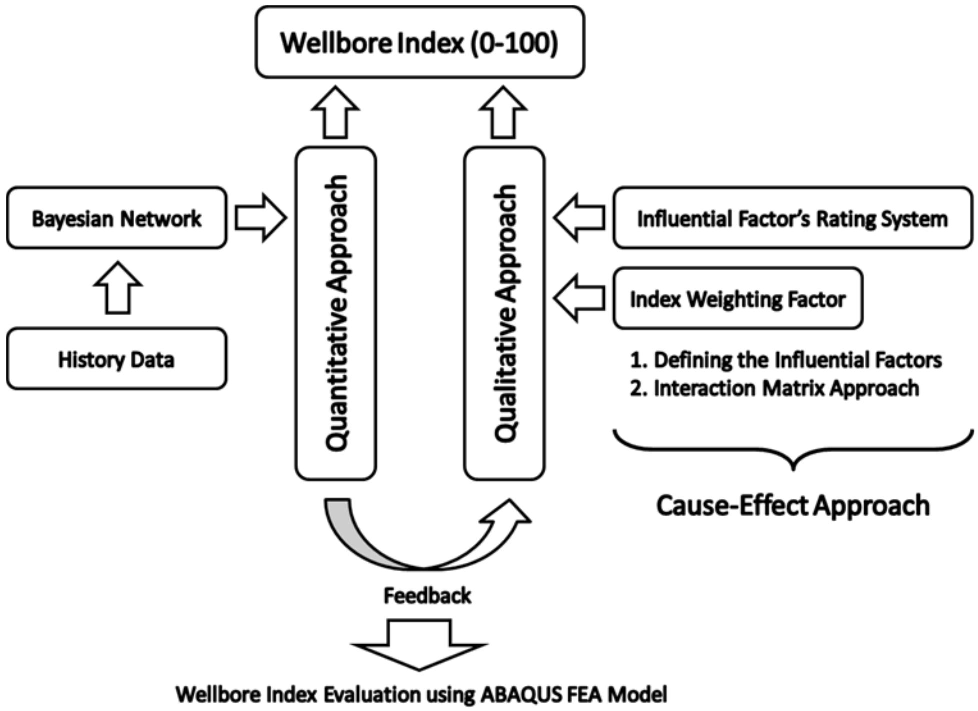


Figure 28. Elements of this study including the index evaluation major subcomponents and Bayesian network feedback and validation models for index evaluation.

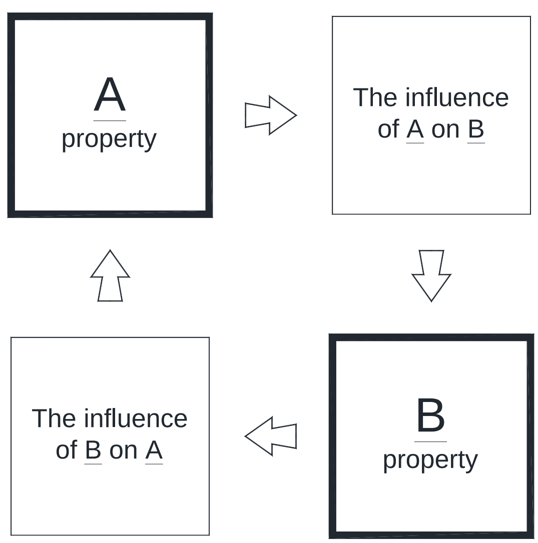


Figure 29. Cause-effect interaction matrix illustration and the positioning of the primary variables and their interactions (modified from Hudson and Harrison, 2000).

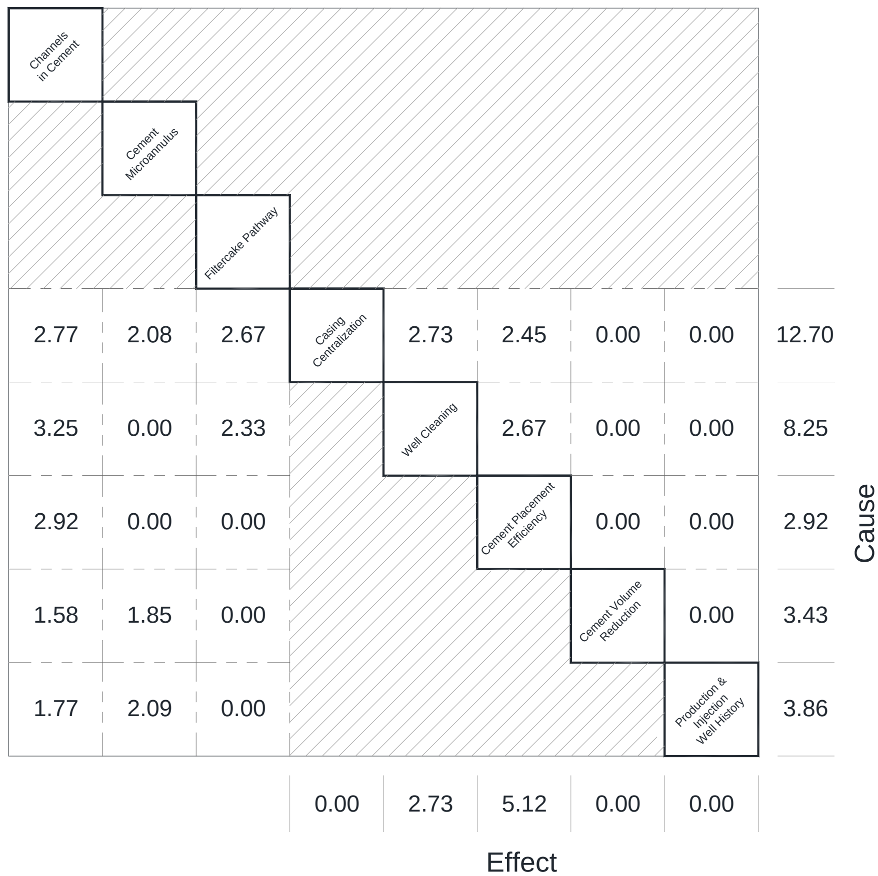
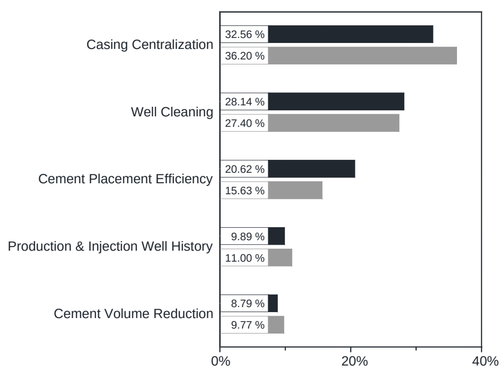


Figure 30. The 8 influential factors comprising one interaction matrix for early time properties (wellbore's construction) Index.

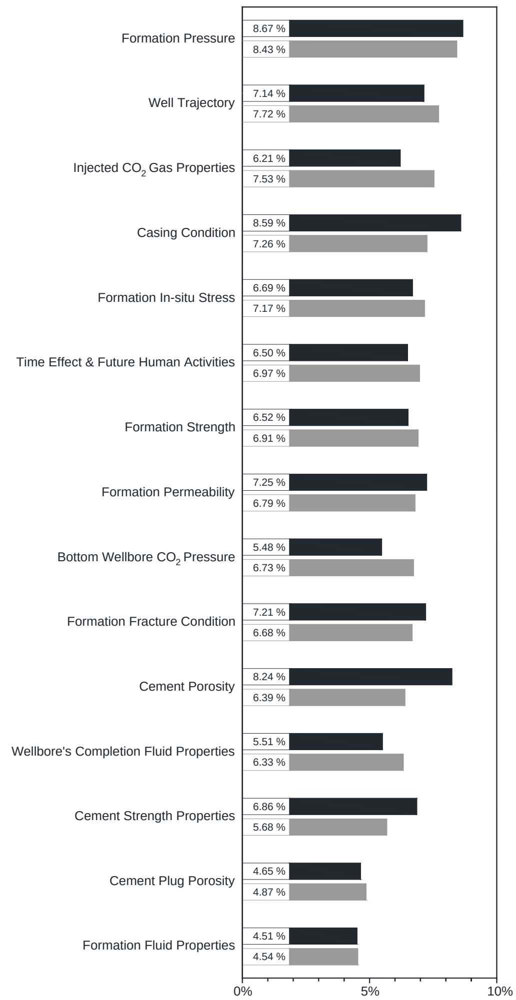
																Cause
CO_2 Leakage Fluid																
1.26	Well Trajectory	0.00	2.14	0.00	0.00	2.23	2.55	2.65	2.50	0.00	2.21	2.39	1.67	0.00	0.00	19.59
2.17	1.43	Formation Fluid Properties	0.00	0.00	0.00	2.15	1.41	1.55	0.00	0.00	0.00	1.56	0.00	0.00	0.00	10.26
2.18	1.52	0.00	Formation In-situ Stress	1.05	2.15	2.20	2.00	1.45	1.57	0.00	0.00	2.05	1.78	0.00	0.00	17.96
2.91	1.52	0.00	2.05	Formation Pressure	2.20	0.00	3.09	2.33	1.95	0.00	0.00	1.72	0.00	0.00	0.00	17.78
1.82	1.74	0.00	1.81	1.48	Formation Strength	2.29	1.68	1.86	1.50	0.00	0.00	1.81	1.00	0.00	0.00	16.98
2.50	1.87	0.00	0.00	2.23	0.00	Formation Perm	0.00	21.86	1.77	0.00	0.00	1.67	1.31	0.00	0.00	13.21
2.74	0.00	0.00	0.00	0.00	1.48	1.19	Formation Fracture Condition	2.50	1.91	0.00	0.00	1.56	1.31	0.00	0.00	12.69
2.09	0.00	0.00	0.00	1.14	0.00	0.00	0.00	Cement Porosity	1.94	0.00	0.00	1.44	0.00	0.00	0.00	6.61
2.22	0.00	0.00	0.00	2.13	0.00	0.00	0.00	1.63	Cement Strength Properties	0.00	0.00	1.81	0.00	0.00	0.00	7.79
2.14	0.00	1.55	0.00	1.87	0.00	1.47	1.50	3.15	1.50	Wellbore's Completion Fluid Properties	1.63	1.21	0.00	1.47	0.00	17.49
2.00	0.00	1.82	0.00	1.57	0.00	0.00	0.00	1.44	1.63	1.80	Cement Plug Porosity	1.50	0.00	0.00	0.00	11.75
2.86	0.00	0.00	0.00	2.50	0.00	0.00	0.00	2.50	0.00	0.00	1.61	Casing Condition	1.24	0.00	0.00	10.71
1.95	1.77	0.00	0.00	0.00	0.00	1.53	1.43	2.42	2.16	0.00	0.48	1.33	Time Effect & Future Human Activities	1.92	2.48	17.48
1.79	0.00	2.83	2.00	2.13	1.57	1.75	1.14	2.00	2.05	1.28	1.50	2.18	0.00	Injected CO_2 Gas Properties	0.00	22.21
2.30	0.00	2.13	1.63	1.87	2.50	1.87	2.23	0.00	0.00	2.13	0.00	2.45	1.00	0.00	Bottom Wellbore CO_2 Pressure	20.11
	9.86	8.32	9.62	17.96	9.90	16.67	17.03	27.34	20.49	5.21	7.43	24.69	9.30	3.40	2.48	

Effect

Figure 31. The 16 influential factors comprising one interaction matrix for long-term properties Index.



a. Cause-Effect Matrix calculated weight factors for early time properties Index



b. Cause-Effect Matrix calculated weight factors for long-term properties Index

Figure 32. Cause-Effect Matrix calculated weight factors for early time and long-term properties Index.

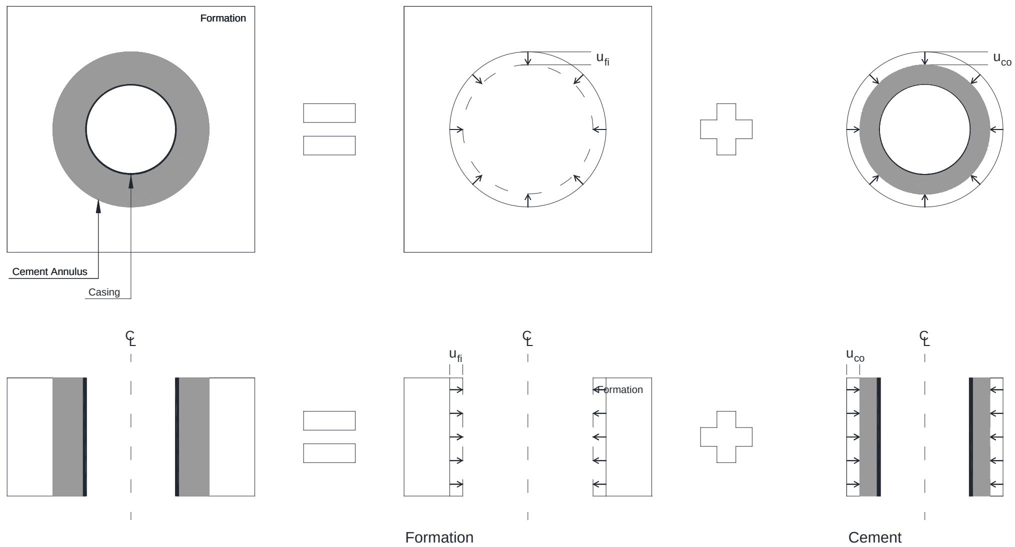


Figure 33. Displacement illustration for micro-annulus calculation

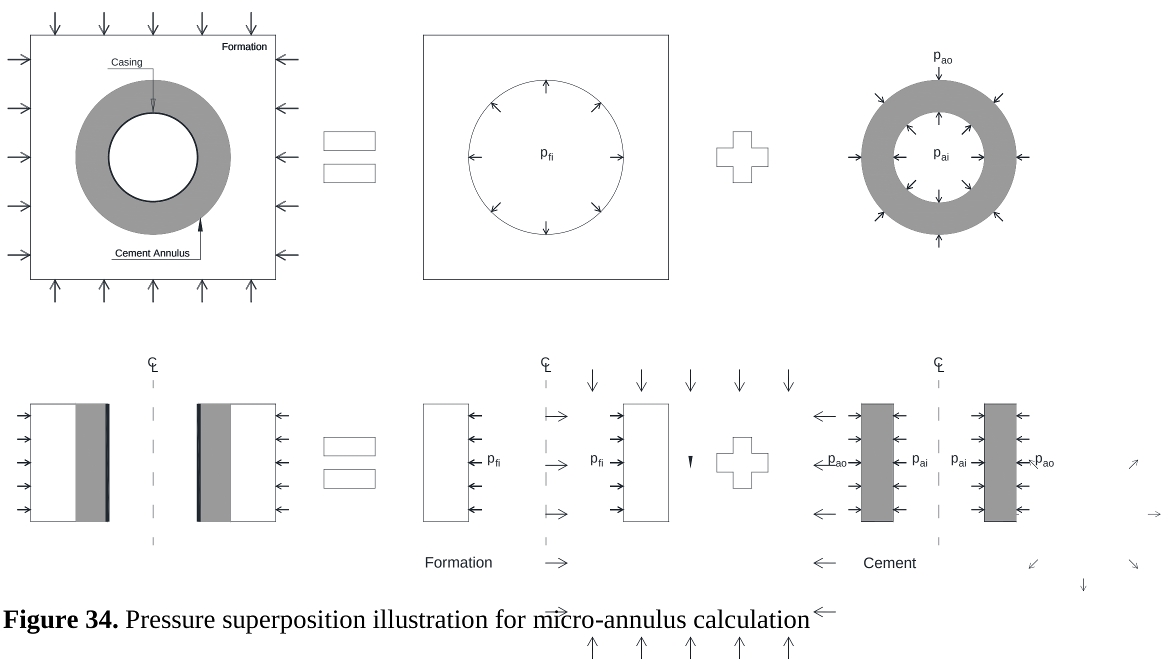


Figure 34. Pressure superposition illustration for micro-annulus calculation

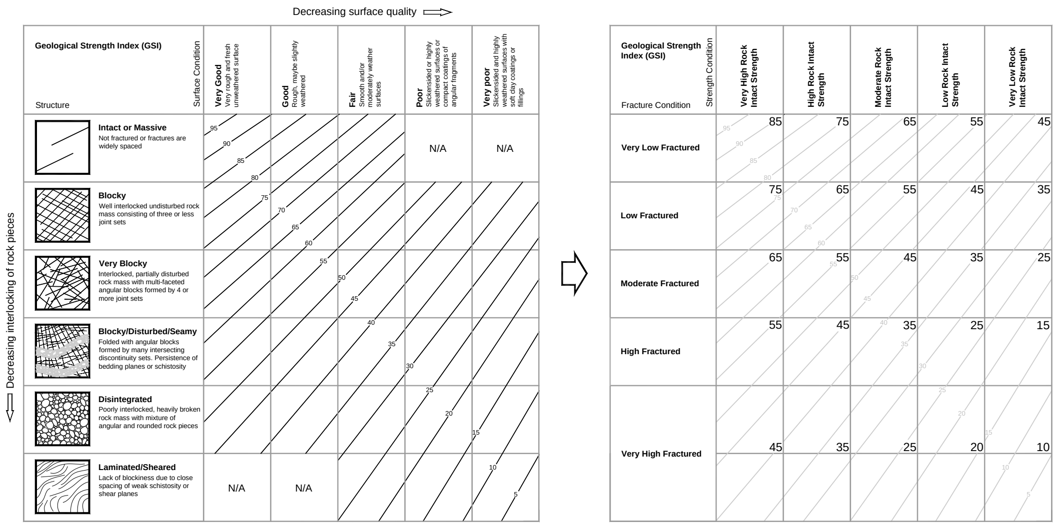


Figure 35. Characterisation of rock masses and GSI value evaluation on the basis of interlocking and joint alteration (modified form Hoek et al. (1998)). As it can be seen the GSI values which are used in this study are shown on the right side table for different rock fracture condition and rock strength

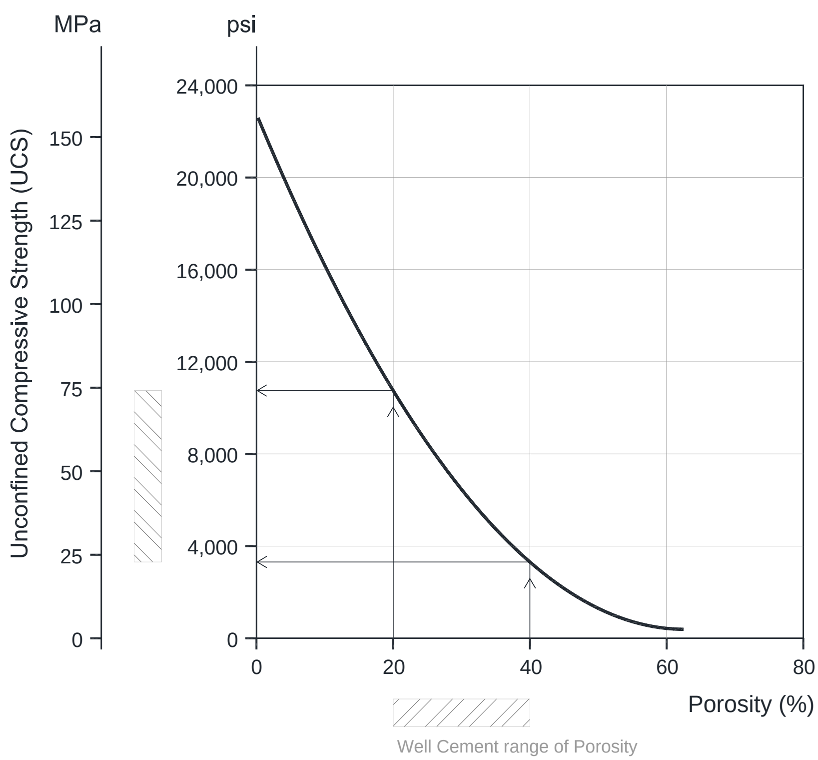


Figure 36. Uniaxial Compressive strength (UCS) versus porosity (Modified from Roy et al.,

1993)

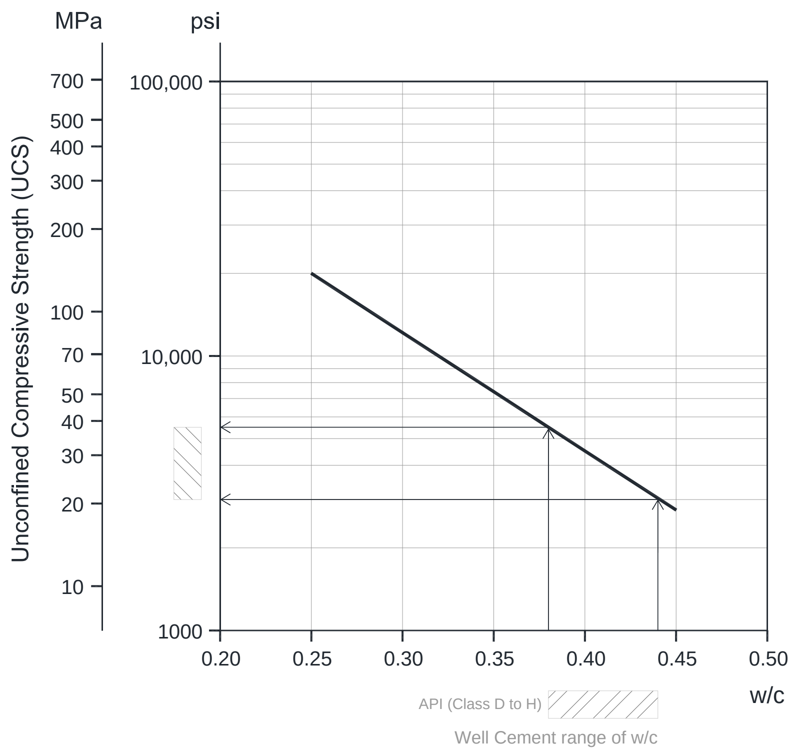


Figure 37. Uniaxial compressive strength (UCS) versus water ratio (Chevron drilling reference series, volume seven, 1990)

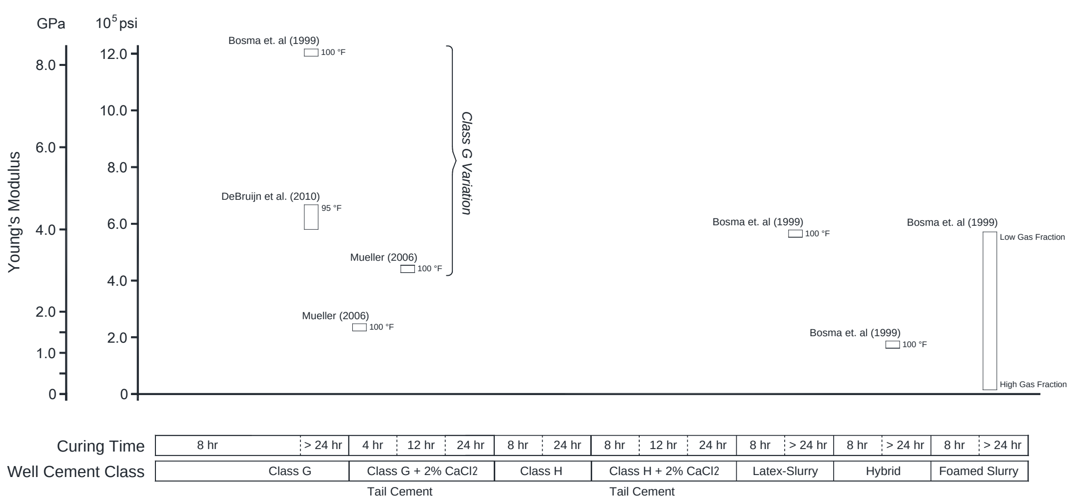


Figure 38. Variation of Young's Modulus for different wellbore cements

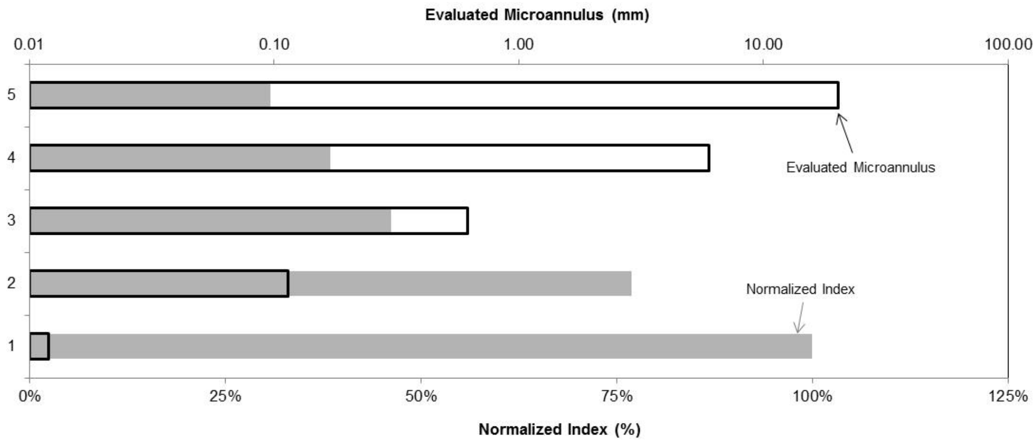


Figure 39. Five evaluated cases index and normalized index of Young's Modulus for different wellbore cements.

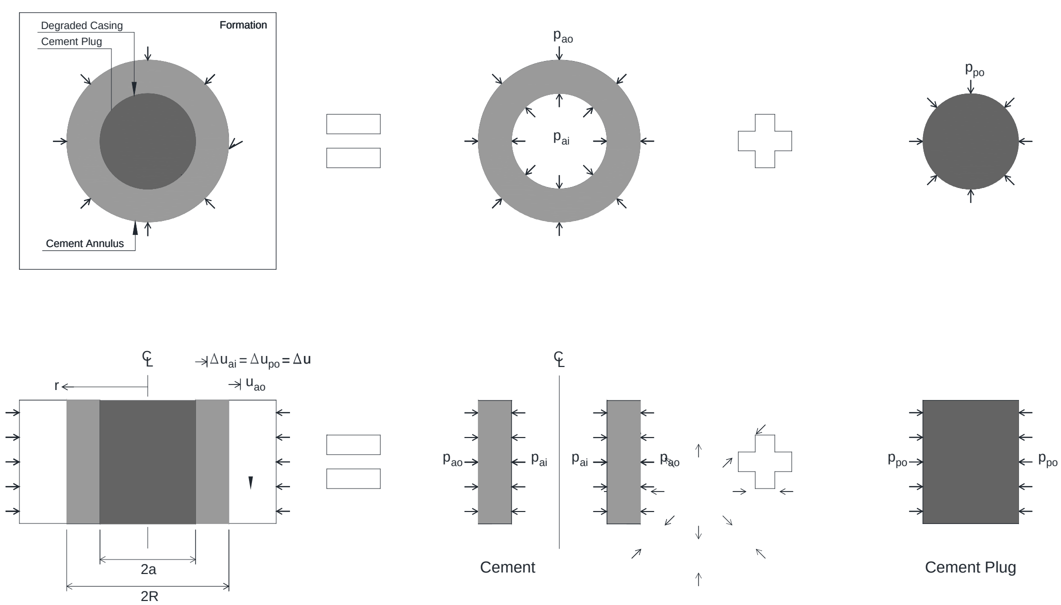


Figure 40. Localization of strain which causing microannulus between cement annulus and cement plug illustration

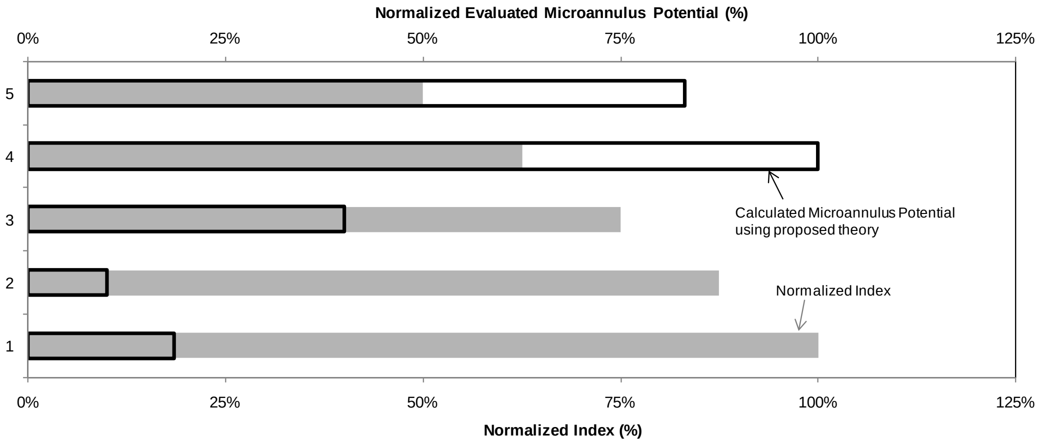
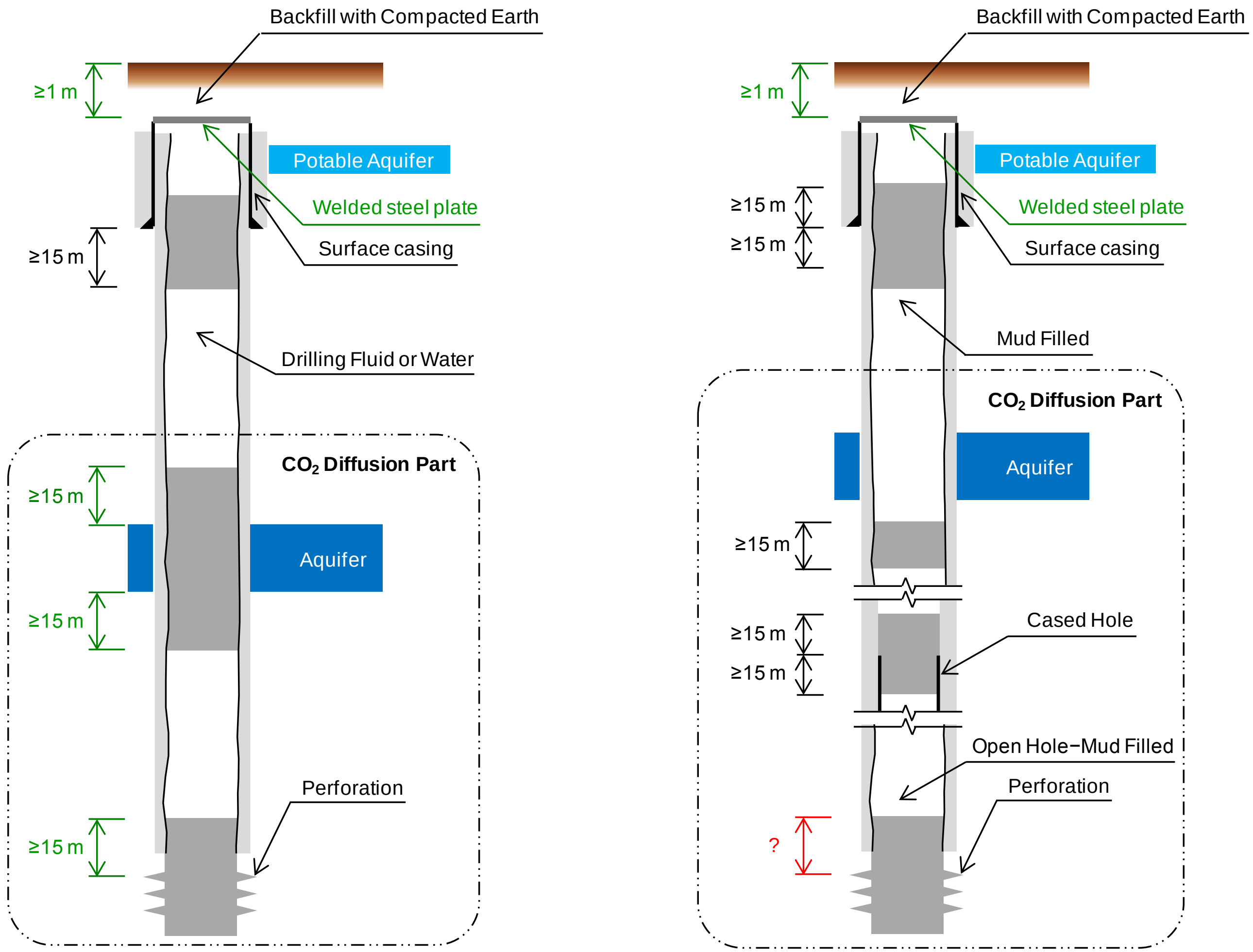


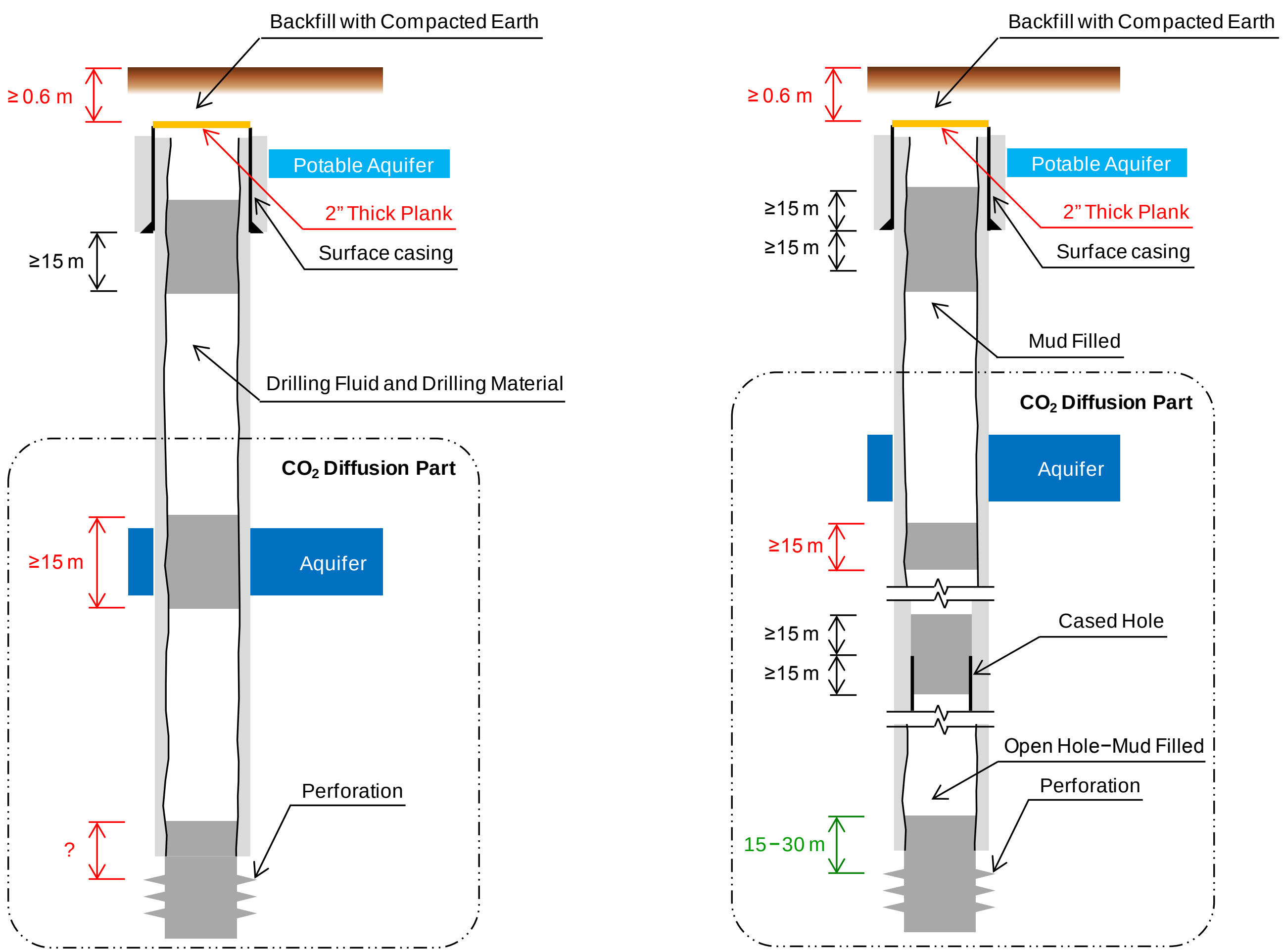
Figure 41. Calculated indexes and normalized evaluated plug–annulus microannulus potential for five different cases



Energy Resources Conservative Board (ERCB) Directive 020, 2007

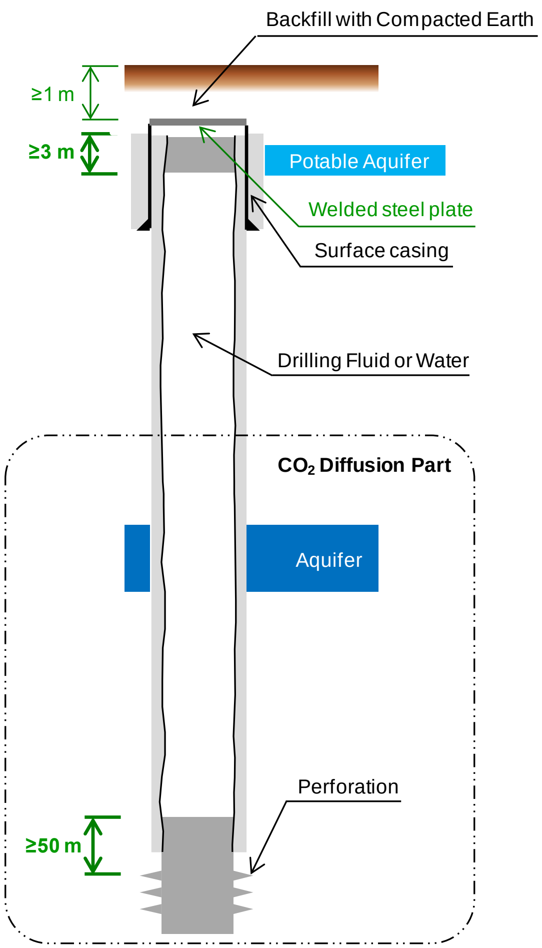
a. Open-hole well abandonment configuration

b. Cased-hole well abandonment configuration

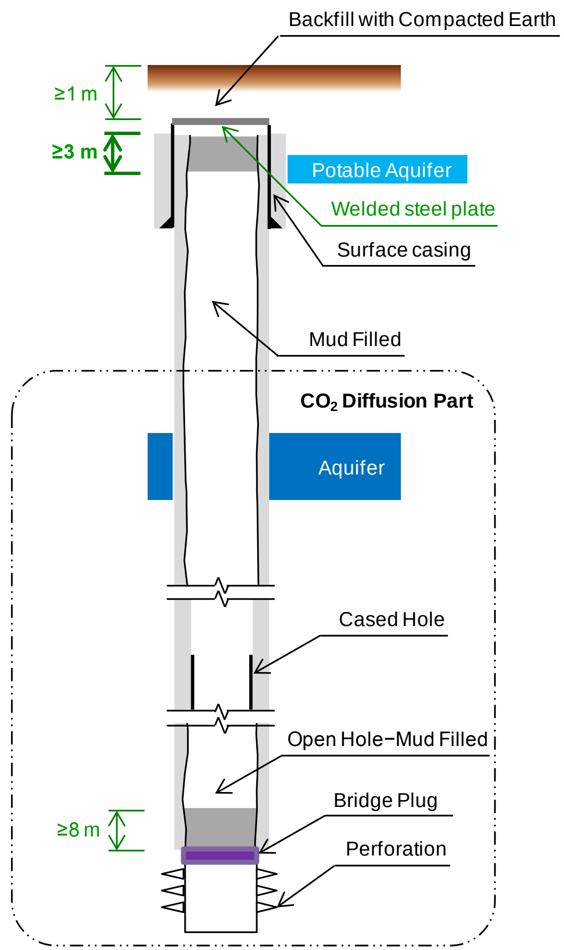


Saskatchewan Regulation 172/66, 1966

c. Open-hole well abandonment configuration



d. Cased-hole well abandonment configuration



British Columbia Regulation 390/2004

e. Open-hole well abandonment configuration **f.** Cased-hole well abandonment configuration

Figure 42. Well abandonment configuration for wellbores which passing aquifer zone, dimensions in green identifying more strict standard and dimensions in red identifying less strict standard.

5. Fuzzy Set and Evidence Theory in BowTie Risk Assessment Approach

Introduction

In this chapter, the BowTie framework, which can accommodate multiple outcomes and simultaneous multiple failure events, is used as the risk assessment approach to couple different aspects such as cost, capital loss, CO_2 leakage rate and duration, CO_2 leakage rate reduction related to each barrier, and etc.; and finally severity evaluation of long-term risk of Weyburn carbon dioxide storage project. This chapter presents the development of a semi-quantitative risk assessment framework for CO_2 geological storage projects based on the BowTie approach. This framework will be developed by incorporating fuzzy logic theory in the BowTie method, by using linguistic methods to combine different issues of risk such as: leakage flux, leakage duration and likelihood of leakage. The method developed in chapter 2 will be used in this chapter for BowTie framework. The challenge in this section will be the barriers and how to apply fuzzy logic and evidence theory to barriers.

Methodology

The proposed framework for this study is presented in Figure 58. In this section the suggested process from questionnaire inputs (see Figure 46) to final results is illustrated. As it shown, the first stage is the fuzzified likelihood (see Figure 60) is processed through the left side of the BowTie (illustrated in Figure 44) is passes through a main knot and goes into the consequence side and then is presented firstly in fuzzified format (see Figure 61) and secondly in defuzzified format (see Figure 63). The process of defuzzification from Figure 61 into Figure 63 is presented in Figure 62. As it is presented in Figure 62 the center of gravity of fuzzified risk values for each belief value is evaluated, the collection of these COGs are resulting the defuzzified risk value-belief graph. Then the Gaussian probability function is fitted into defuzzified risk value-belief data to show the results in Gaussian bell function for better estimate of risk varation. The belief values discussed in this section are calculated based on evidence theory. The evidence theory was applied to the input of different experts for evaluation of degree of agreement on each risk value. Evidence theory or the Dempster-Shafer method is discussed in Section 5.1.3. In this study in parallel the fuzzy risk values and the belief values for the various risk compounds in air and water were specified and analysed through the mathematical suggested method suggested in following section. . In this study the MATLAB software (MATLAB®) is used for programing and the data processing is conducted in Microsoft Excel. Then the resulted vectors from Microsoft Excel are processed in MATLAB software (MATLAB®).

5.1.1. Basic concepts of BowTie Diagram

The BowTie approach, originally devised for safety management systems, is based on the swiss cheese model developed by British psychologist James T. Reason in 1990 (Reason, 1997). The

BowTie has become popular as a structured method to assess risk where a qualitative approach is not possible or desirable. The value of the BowTie diagram is that it is simple and easy for the non-specialist to understand, and it provides a unified structure for incident analysis. The idea is a simple one of combining the causes (fault tree) and the consequences (event tree). When the fault tree is drawn on the left hand side and the event tree is drawn on the right hand side with the hazard drawn as a "knot" in the middle of the diagram, it looks a bit like a BowTie, as shown in Figure 43. To produce a BowTie diagram, the following elements must be defined as:

- Event to be prevented.
- Threats that could cause the event to occur.
- Consequences of the event occurring.
- Controls to prevent the event occurring.
- Controls to mitigate against the consequences.

Barriers controlling the prevention of hazard are generally called preventing barriers, and barriers controlling the mitigation of hazard are called compensator barriers.

The BowTie method offers many attributes of the Hazard and Operability (HAZOP) PHA method (Philley 2006). The BowTie method can accommodate multiple outcomes and simultaneous multiple failure events making it possible to assimilate an accident scenario to a sequence of events and a sequence of barriers that are mitigating these events. The term barrier encompasses a wide range of preventative measures such as guards, personal protective equipment, natural preventative, and failsafe systems. However, barriers need not be physical objects but could include preventative measures such as working procedures, training, supervision, space, time, emergency plans and management and organisational controls such as design and safety reviews and risk assessments.

In this research, the left-hand side of the BowTie diagram (the fault tree) will be referred to as the Failure Block Diagram (FBD) and is illustrated in Figure 44. In the FBD, the indices for wellbore and caprock can be used as the First Failure Block. As noted in Figure 44, there are four methods incorporated into this risk analysis. From the left side of the BowTie diagram the first applied technique is cause-effect technique, which is used for the index evaluation. The cause-effect technique and index evaluation was discussed in 4 but is reviewed briefly for completeness. The second technique is Analytic Hierarchy Process (AHP) technique (described in Appendix A), which is used for weighting the branches both on the left side (for weighting between wellbore and caprock leakage likelihood) and the right side (for weighting between different leakage paths such as leakage in air, leakage in ground water and leakage in drinking water). The questionnaire in Appendix H is used for pairwise comparison between different paths and for the leakage likelihood. The third technique is the mitigation barriers approach which is discussed subsequently in Section 5.1.4. The fourth technique is a consequence evaluation approach which is discussed in Section 5.1.7. The fuzzy logic and Dempster-Shafer theory are the main processors that are passing through the BowTie diagram. The fuzzy logic and Dempster-Shafer calculation methods have been modified to fit these techniques.

In this risk analysis the likelihood of the top event with high leakage is evaluated in the left hand side of the BowTie diagram and the consequence of this high leakage is evaluated in the right hand side. By combining both sides the risk is calculated versus the belief based on the inputs from the experts in both the PRISM #3 and #5 meetings. In the future studies the wellbore and caprock indexes can be used for the leakage-likelihood graph instead of big event likelihood, and this can be an open research for future studies.

The probability calculation of the block diagram shown on the left hand side of the BowTie diagram (Figure 44) is illustrated in Figure 45. The computation concept in Figure **45** is a combination of the bridge part (through block 3) being valid or invalid. For the valid part the connecting line is applied instead of the block 3 and for the invalid part no connection is applied instead of the block 3. For considering the probability of failure in block 3 the probability of failure at block 3 is multiplied by the first case (connected circuit) and the inverse of the probability of failure at block 3 is termed the second case (unconnected circuit) (Kuo and Zuo, 2003).

5.1.2. Fuzzy sets theory and its use in block diagram analysis

Fuzzy logic provides a language with syntax to translate qualitative knowledge into numerical reasoning. It is easy to use, and fuzzy mathematics is developed in understandable terms, with the unique ability to consider verbal assessments (e.g. “likely”, “not likely” for probability evaluation and “low”, “high” and “moderate” for leakage flux rate) mathematically. The significance of fuzzy variables is that they facilitate gradual transition between states and consequently are capable of expressing and dealing with uncertainties of observation and measurement. Both fuzzy set theory and probability theory are mathematical frameworks for characterizing uncertainties. Since the 1960s, these frameworks have been used to formalize different types of uncertainties, but the fuzzy set theory and fuzzy logic have been applied more successfully in risk assessments than have the more recent possibility theory (Dubois and Parade, 1988), and Dempster-Shafer theory (DST) (Dempster,1968; Shafer, 1976). Section 2.2.2 describes the concepts and mathematical functions related to fuzzy logic that will be applied with the BowTie approach. For the BowTie application of fuzzy theory, the triangle, trapezoid and Gaussian membership functions, as illustrated in Figure 46 were used to determine grades of membership. This provides an opportunity to assess the sensitivity of BowTie structure outcomes against the assumptions of the membership function. In fuzzy logic analysis and fuzzy sets theory, verbal statements such as ‘high’ or ‘very low’ are used to introduce degrees of belief, which is very similar to the verbal categories in membership functions, as shown in Figure 46. The triangular membership function has been chosen for these analyses because of computational efficiency in comparison with exponential or other more complex membership functions. The Gaussian and Trapezoid membership functions are only considered for sensitivity studies.

Section 2.2.2 outlines the application of Boolean algebra in the fault tree approach and this also is adopted for the BowTie approach. Fuzzy calculations in the fault tree section (or fault block diagram for this study) of the BowTie structure are illustrated in Figure 47.

In this research, for fuzzy calculations in block diagram for blocks connected to one gate in parallel, which is similar to :OR" function as "max" function, and linearly connected blocks which is similar to "AND" function considered as $\min$ function in the fuzzy sets theory. The max and min functions can be defined as 'union' and 'intersection', and were shown in Equations 2and 3.

As it can be seen in Figure 45 instead of the "OR" and "AND" functions, the inverse function is also needed for fault block diagram modelling. The inverse function can be defined as a 'complement' and it is formulated as:

$$\mu_{\bar{A}} = 1 - \mu_A(x) \qquad 40$$

The inverse function is illustrated in Figure 49, and the min and max functions are illustrated in Figure 48. In this study, the Block Diagram on the left hand side of the BowTie diagram is responsible for likelihood evaluation. The likelihood versus degree of belief is evaluated at the "knot" point of the BowTie diagram. For likelihood evaluations, both fuzzy logic and the Dempster-Shafer theory act as compilers for the Block Diagram presented in Figure 44. As mentioned in Section 5.1.3 the bridge structure in Figure 45 is converted to the illustration presented in Figure 50. The mathematical calculations are completed using Equations 2, 3 and 40 are also illustrated in Figure 48 and Figure 49.

5.1.3. Block Diagram Evidence Processing Method

In this research, 'evidence theory' is responsible for capturing the uncertainty in the experts' opinions recorded in the questionnaires given to the BowTie diagram. The likelihood is calculated versus degree of belief at the knot point of the BowTie diagram using the 'Evidence Theory'. The evidence theory employed in this research is based on Dempster-Shafer theory (DST). The Dempster-Shafer theory (DST) of evidence, also known as the theory of belief functions, is a generalization of the Bayesian theory of subjective probability which was first described by Dempster (1968) and extended by Shafer (1976). The degree of belief may or may not have the mathematical property of probability, whereas the Bayesian theory requires probabilities for each failure. This makes the D-S theory more flexible in qualitative risk analysis problems, as was described in Section 2.2.7.

As discussed previously in Section 2.2.7, there are two parts to a solution using evidence theory: 1) obtaining degrees of belief for a question from subjective probabilities for a related question, and 2) using appropriate mathematical rules to combine such degrees of belief when they are based on independent pieces of evidence. In this research, degrees of belief are processed based on experts' inputs for different wellbore index inputs. Caprock index was not calculated, since wellbore is anticipated to be much more prone to failure in comparison. The cumulative probability of the calculated index was used as the "degree of belief" on the inputs from experts. The second part (the mathematical process) is implemented through the Guth (1991) method, which was developed to infer fault tree rationales (Boolean algebra) and rule-based expert systems. Guth used the Truth tables for "AND" and "OR" gate functions to found the mathematical function for "AND" and "OR" gates, as:

$$\mathrm{AND}\{m(A),m(B)\}=\mathrm{Bel}_A\otimes\mathrm{Bel}_B=m\left(\mathrm{Bel}_A^L\times\mathrm{Bel}_B^L,\mathrm{Bel}_A^U\times\mathrm{Bel}_B^U\right) \quad 41$$

$$\mathrm{OR}\{m(A),m(B)\}=\mathrm{Bel}_A\oplus\mathrm{Bel}_B=m\left(1-\left(1-\mathrm{Bel}_A^L\right)\left(1-\mathrm{Bel}_B^L\right),1-\left(1-\mathrm{Bel}_A^U\right)\left(1-\mathrm{Bel}_B^U\right)\right) \quad 42$$

where Bel^L and Bel^U are degree of belief and degree of plausibility, respectively. The Bel^L and Bel^U are basically the lower/upper bound of each failure, and are the topic of many probabilistic studies. To utilize the failure block diagram, the Guth theory is a suitable technique but needs to be modified to accommodate the Bridge structure (i.e., the Aquifer Exchange path on the left hand side of the BowTie structure). Figure 45 illustrates the logic developed based on Guth theory and shows both the "connected" and "unconnected" states or circuits for the Bridge. The resulting value from these circuit calculations (i.e. connected or unconnected) is multiplied to the Block 3 belief values and belief inverse value, respectively. Finally the fuzzy results assigned to each belief value and represented in a 3D graph illustrated in Figure 60. In Figure 60 the evaluated fuzzy likelihood resulting from wellbore and caprock indices (which will be discussed in Section 5.1.6) is presented. Evidence theory helps better decision making on the inputs from different experts. In the next step of the analysis, the right side of BowTie, which is the consequence side of the BowTie, will be evaluated. The final stage of analysis involves combining the left and right sides to compute a final risk value, as shown in Figure 61 and Figure 63. The process of defuzzification from Figure 61 into Figure 63 is presented in Figure 62. As it is presented in Figure 62 the center of gravity (COG) of fuzzified risk values for each belief value is evaluated, the collection of these COGs are resulting the defuzzified risk value-belief graph. As the following the migration barriers and escalators will be discussed (Section 5.1.4 and 5.1.5) and consequence evaluation and its combination with likelihood will be discussed in Section 5.1.7.

5.1.4. BowTie Mitigation Barriers Modelling

In the BowTie diagram the barriers on the left side (fault tree) are called 'preventions' because they are preventing the failure to cause big event and the barriers on the right side (event tree) are called 'mitigations' because they are decreasing the big event effects on humans, animals and plants. 'Prevention barriers' are placed to reduce the 'likelihood' of the hazardous event from occurring, and the 'mitigation barriers' are put in place to avoid or minimise escalation of the event into a larger consequence or consequence reduction.

The ‘prevention barriers’ are considered as wellbores and seals (i.e., caprock and upper seals), which are generally viewed as the barriers to leakage of CO_2 to the ground surface. Consequently, the ‘prevention barriers’ in the BowTie are represented by wellbore and caprock indexes which act as proxies for the assessment of the potential for CO_2 leakage from reservoir to an aquifer and to the atmosphere (air). The wellbore and caprock indices are discussed in Sections 5.1.2, 5.1.3 and 5.1.6. The mitigation barriers effect on likelihood reduction is considered as their main role and the fuzzy logic IF-THEN approach is suggested for modeling the likelihood reduction. The IF-THEN rules are provided in Figure 53 and are evaluated using a stochastic method called ‘Markov Chain model’. The term ‘Markov Chain model’, named after the mathematician Andrei Markov, originally referred exclusively to mathematical models in which the future state of a system depends only on its current state, not on its past history. The main focus for the application of the Markov Chain model was to determine the steady-state solution of the “closed-loop” system, which is from the failure to mitigation process. Although the aquifer system may not be restored to its fully functional state, which relates primarily to the water chemistry prior to any CO_2 leakage, the ‘Markov model’ is used for creating a fuzzy rules table because it was the most suitable method for dealing with determining the long-term average reliability. The mitigation may happen frequently for some of the failures and the average system failure rate over a finite time period can be computed by a Markov steady-state analysis. Equation 43 is a core equation in this modeling and provides the curves in grey color in Figure 53.

$$\text{Not Functioning Likelihood} = \frac{\text{MTTR}}{\text{MTTF} + \text{MTTR}} = \frac{\text{Failure Likelihood}}{\text{Failure Likelihood} + \text{Mitigation Likelihood}} \qquad 43$$

Equation 43 is calculated based on Markov Chain process as illustrated in Figure 52. In Figure 52, the 1 and 0 are signs for functioning and failed state, respectively. Transition from state 0 to state 1 means that the component is repaired (Rausand and Høyland, 2004).

The matrix chart on the right side in Figure 53 provides the IF-THEN rules’ statements which will be used to formulate the conditional statements that comprise fuzzy logic. The bottom row (the “x” variable) is considered as ‘Failure Likelihood’ and the left column (the “y” variable) is considered as ‘Mitigation Likelihood’. The IF-THEN rules’ results are evaluated inside of this table. For example, for ‘Failure Likelihood’ equal to *Low* and ‘Mitigation Likelihood’ equal to *High* results in a *Moderate* final failure probability. This IF-THEN rule also can be defined as:

$$\text{IF } (x = \text{Low}) \text{ AND } (y = \text{High}) \text{ THEN } (z = \text{Moderate}) \qquad 44$$

In fuzzy texts, the “if” part of the rule is called the *antecedent*, and the “then” part of the rule is called the *consequent*. As it can be seen the linguistic values such as ‘Low’ and ‘High’ are defined in IF-THEN rules’ statements instead of mathematical expressions.

5.1.5. BowTie Escalator and Escalator Controller Modelling

Barriers are provided in the BowTie structure to represent project elements that provide protection against events that threaten the integrity of the project. However, the barriers may decay because of the ‘inadequate measurement, monitoring and Verification (MMV) (sometimes called “measurement, maintenance and verification” and as well as “monitoring, mitigation, and verification”)’ or may fail due to ‘Vandalism or CO_2 Erosion’. These barriers’ decay/failure mode are called ‘Escalators’ or ‘Escalation factors’ in the BowTie structure. If the escalator is identified then it may be required to provide a secondary barrier to prevent the decay/failure mode. These secondary barriers, which reinforce primary barriers, are named ‘Escalator Controllers’. In other words, ‘Escalators cause an increase in risk due to loss of barriers and ‘Escalator Controllers’ are put in place to manage conditions that may lead to the appearance of an ‘Escalator’.

The relative position of an ‘Escalator’ and ‘Escalator Controller’ within a BowTie diagram is illustrated in Figure 54. If there are no barriers (including escalator and escalator controller) the occurrence of the *threats* will result in the *Top Event* - the probability of a *Top Event* is equal to probability of a *Threat*. If a barrier is put in place the resultant probability will be equal to $P_{Top\ Event\ Failure} \times P_{Barrier}$. An *escalator* acts as risk trigger so ($1- P_{Escalator}$) or inverse of *escalator probability* will be multiplied to *barrier probability*. In the same manner because an *escalator controller* acts as risk stopper the $P_{Escalator\ Controller}$ expression will be multiplied to *barrier probability*. This branch of the BowTie along with the probability expressions are illustrated in Figure 54 the final probability of the *Top Event* is expressed in Equation 45:

$$P_{Event} = P_{Failure} \times P_{Barrier} \times \left(1 - P_{Applied\ Escalator}\right) = P_{Failure} \times P_{Barrier} \times \left\lfloor P_{Escalator} \times \left(1 - P_{Escalator Controller}\right)\right\rfloor \qquad 45$$

Equation 45 can be converted to fuzzy set and evidence theory format in Equations 46 and 47, respectively.

$$P_{Event} = \min\left(\mu_{Failure}(x),\ \mu_{Barrier}(x),\ \mu_{Escalator}(x),\ \text{inverse}\left\lfloor \mu_{Escalator\ Controller}(x)\right\rfloor\right) \qquad 46$$

$$P_{Event} = Bel_{Failure} \otimes Bel_{Barrier} \otimes \left\lfloor Bel_{Escalator} \otimes \left(1 - Bel_{Escalator\ Controller}\right)\right\rfloor \qquad 47$$

In this study wellbore and caprock indices were used instead of common block barriers in the BowTie structure but ‘Escalator’ and ‘Escalator Controller’ blocks can still be used to represent external impacts on wellbores and/or caprock such as vandalism.

5.1.6. Wellbore Index Evaluation

As mentioned in Section 5.1.1 the barriers in the BowTie approach were evaluated using indexes for wellbore and caprock computed based on qualitative analysis on the wellbores and seals systems. In this research the method suggested in Chapter 4 was used for wellbore index evaluations and the following provides a brief description of procedure. In this approach the wellbore index is evaluated in Equation 48:

$$\begin{aligned} \text{Wellbore Index} = \sum_{j=1}^{3} RVV_j \times \sum_{i=1}^{n} a_i\, p_i = RVV_{early\,time} \sum_{i=1}^{5} \text{early time weighting factors}_i \times p_i \\ + RVV_{long\,term} \sum_{j=1}^{15} \text{long term weighting factors}_j \times p_j \\ + RVV_{cement\,top} \times \text{cement top weighting factors} \times p \end{aligned} \qquad 48$$

where, i is different parameters, a_i is weighted ratio of factor i, and p_i is rating value of parameter i. The weighting factors are based on the analysis of the interaction matrix and RVV values are calculated by the AHP method. The rating values for the main influential factors (1-5) are based on their degree of action for relative evaluation. The absence of a factor is coded as 1 which is assigned 'very low', and for a factor rated being in very good condition, it is coded as 5. For example, if an expert judged that the casing condition as very poor; i.e. corrosion was judged to have affected much of the casing body, connection seals and threads were corroded and lost their sealing ability, a "very low" value is checked off for casing condition in questionnaire presented to the experts.

Using the inputs from the expert questionnaire populated during the 5th PRISM of the Weyburn Project, the average values chosen for each property based on experts' judgement are presented in Table 12 . The final step of this evaluation involves integrating all these judgements or "weighting factors" into one final index by using Equation 48. These results are presented in Table 20.

The average index for wellbore sealing condition in the short-term was computed to be 75.08/100 or 0.751. For wellbore integrity over the anhydrite and Watrous seal location, the average index was computed as 74.93/100 or 0.749. These values are for assigned values of Time Effect and Bottom Wellbore CO_2 Pressure condition at the start of abandonment. These values become 75.16/100 and 75.01/100 for long-term wellbore integrity at Weyburn anhydrite seal and Watrous seal location, respectively. These indices slightly increase as a result of the small weighting factor for Time Effect and Bottom Wellbore CO_2 Pressure condition based on outcomes from this questionnaire.

For the case where the cement (in the annulus) top is deep, which is classified as a severe case for depth to cement top, the index decreases to 53.44/100 and 53.29/100 for long-term wellbore integrity at Weyburn anhydrite seal and Watrous seal location. The variation in the wellbore index, as defined by the degree of belief, is used for the block diagram analysis. The inputs for the wellbore index are illustrated in Figure 55. The variation was small because of minimum number of experts that completed this section of the questionnaire. The illustration in Figure 55 is produced by fuzzification from wellbore indexes to the triangle membership function by using categorization shown in Figure 46. In fuzzification each wellbore index value represents a number of membership triangles with different weighting values. It should be noted that while triangular membership functions were chosen for this research, trapezoid or gaussian membership functions could be used. The weighting values should sum to 1. If the membership functions are not designed properly, the sum may not quite be equal to one but as long as the value is very near to unity the final results will not be affected enormously.

For fuzzy calculations, values in the analysis have to be fuzzified to be processed. In this research, belief values are also assigned to different fuzzified values (or wellbore index, as shown in Figure 55) which is evaluated from a number of experts considering different weighting values based on their expertise. The belief function represents agreement on different aspects. The belief value can be defined as a cumulative probability which undertaking experts with higher weighting values as number of experts equal to its weighting value, e.g. if the expert weighting value is equal to 2 he will considered as 2 persons instead of one in cumulative probability calculation. The belief evaluation provides an opportunity to assess the final agreement of respondents to the final risk values. In Figure 55, the fuzzified failure likelihood variation versus degree of belief is also presented parallel to the fuzzified wellbore index, and as it can be seen in this study the relation between wellbore index and failure likelihood is assumed to be linear. In some technologies, such as the pipeline industry (Muhlbauer, 2004), the risk index will be calibrated with failure field data and after calibration failure probability can be calculated for each case based on its evaluated risk index. The same procedure can be used for membership function design and the redesign of the categorization ranges assigned to the membership functions for wellbore index and failure likelihood.

The index method presented in this study has the capability to capture many of the common remediation processes, such as squeeze cementing and plug cementing. Since most wellbore remediation "barriers" have an effect on the wellbore properties; e.g. the squeeze cement can reduce cement fracturing and also reduce cement porosity; the effect of remediation barriers will be applied inside the index by changing the index value and so no controlling barrier is required to represent wellbore failures. If a barrier such as bridge plugs is deployed in the wellbore, which cannot be captured inside the wellbore index, the controlling barrier seems to be necessary as it is mentioned in Section 5.1.4.

5.1.7. Consequence Evaluation and Final Risk Evaluation Process

Final phase of this study is risk evaluation. In all risk assessments the risk is combination of consequence and likelihood, which can be combined to result a risk value. In this research, the risk matrix, as provided in Table 21, is used to combine likelihood and consequence. The final risk evaluation involves the combination of consequence, which is evaluated on the right side of the BowTie structure, and the likelihood, which is evaluated on the left side of the BowTie structure. There are three major processes to be performed before finalizing the consequence evaluation, as noted in Figure 44. The likelihood resulting at the knot point, i.e., CO_2 Leakage from wellbores or final seal in this study, will pass through all the branches on the left side of the BowTie (Event Tree section) without any modification unless there is no mitigation barrier. If any mitigation barrier is active in any branch, the likelihood of failure will decrease using the fuzzy logic IF-THEN rules based on mitigation barrier effectiveness (see Section 5.1.4). The consequence of each hazard must be evaluated at the end of each branch. The fuzzified consequence value and fuzzified likelihood value at each branch will be converted to the fuzzified risk value using fuzzy logic IF-THEN rules based on the risk matrix (Table 21). The final total risk value is computed by combining all fuzzified risk values generated for each branch considering the weighting factors along each branch, which have been evaluated using the AHP method. The following section discusses the mathematical process of consequence evaluation and finalized risk evaluation process.

For consequence evaluation, different aspects of the location of CO_2 leakage are considered. The consequence or severity is considered as two separate factors. First factor (Factor 1) is a combination of 6 components such as: Release Severity, CO_2 Sensibility, Impact Rate, Alert Ability, Controllability, and Transportation System Capability. Factor 1 focusses on the ability to alert and transport public people and their belongings from the leakage area. Second factor (Factor 2) is a combination of 5 components such as: “capital loss”, “barrier cost”, “voluntariness”, “known to expose”, and “future sciences’ effects”. This factor focuses on voluntariness and capital loss of the failure. Voluntariness in this factor basically means how people are voluntarily taking the risk of living in the area of the leakage or surrounding the area of the leakage. Capital loss in this factor covers human loss, cattle loss and costs exposed to public because of losing their crops.

The survey was completed with the same experts who were asked for the AHP analysis and index evaluation. For this survey, the experts were asked two sets of questions: 1) one for the Weyburn Project as the specific carbon geological storage and 2) one for the consequence for the nuclear waste repository leakage. For consequence evaluation, the fuzzy max function with the same weighting factor for all the components was chosen as the mathematical process for the evaluation. The defuzzified values for different components of factor 1 and factor 2 based on survey data are presented in the Figure 56. It must be mentioned that low values are assigned for high voluntariness, good transportation, good alert ability, rapid sensing the failure, and high knowledge to expose, since these parameters are lowering the final consequence. The data presented in Figure 56 are illustrated in the consequence severity matrix (see Figure 57). In Figure 57 the big black dot represents the consequence associated with the nuclear waste repository leakage scenario, and smaller white dots represents different hazard components of Weyburn carbon geological storage leakage scenario. The nuclear waste repository leakage consequence is considered as the most severe hazard and it is presented for comparison. And it is asked from experts in form of questionnaire for consequence evaluation to proof this concept. But as it can be seen in Figure 57 the consequence evaluated for the Weyburn carbon geological storage leakage scenario is very much the same as nuclear waste repository leakage scenario and somewhat more severe than nuclear waste repository leakage scenario. And both scenarios are not showing very sever consequence as a results of failure. Usually engineers and people dealing with technology are less conservative and have lower consequence understanding from the technology related failures, maybe it is what embedded in these consequence evaluation results.

The fuzzified values from Factor 1 and Factor 2, which were presented in the consequence severity matrix (see Figure 57), are combined using the fuzzy logic IF-THEN rules based on consequence severity matrix in Figure 57. For example, IF factor 1 is ‘High’ and factor 2 is ‘Low’, THEN consequence will be ‘Low’.

For risk evaluation at each branch, consequence and likelihood values must be computed at each branch. As illustrated in Figure 58, the fuzzified likelihood value that is calculated at the knot point will be exactly the same at each branch if no mitigation barrier is implied. If there is a mitigation barrier the modified fuzzified likelihood (see Section 5.1.4) using IF-THEN fuzzy logic based on Figure 53 will be used at each branch. Then the fuzzified consequence value evaluated based on consequence severity matrix using Factor 1 and Factor 2 (see Figure 57) will be used for risk evaluation. Then the fuzzified values from consequence (see Figure 57) and likelihood (see Figure 60) are combined using the fuzzy logic IF-THEN rules based on Table 21. The Table 21 is a risk matrix suggested by the Shell, which presents the consequence versus likelihood for different risk categories. The risk matrix is the most common approach for a qualitative risk assessment when dealing with linguistic values of consequence and likelihood. For better understanding different evaluated fuzzified likelihood results in a 3D configuration for different membership functions (triangle, trapezoid and Gaussian) at the knot point is presented and final fuzzified risk values for these fuzzified likelihood inputs is evaluated.

Finally, as shown in Figure 58, evaluated fuzzified risk values from each branch are combined using the Analytic Hierarchy Process (AHP) weighting factor. The final results shown in Figure 61 considered all branches combined consequence versus degree of belief; the branches are combined by their respective weighting factor evaluated from the AHP method. In fuzzy language the combination is processed using the max function considering different AHP weighting factor. The Analytic Hierarchy Process (AHP) is also used for weighting both sides of the BowTie structure. On the left side the degree of importance of failures is explored, but on the right side degree of importance of consequences is explored. The mathematics and calculation techniques of the AHP are briefly explained in Appendix A, but in essence, AHP method is used to construct a matrix expressing the relative values of a set of attributes. A potential application based on the present research would be a comparison of different suggested CO_2 leakage paths for the right side of the BowTie structure and a comparison of different suggested consequences for the left side of the BowTie structure. For example, experts are asked to choose whether air contamination, in relation to ground water contamination, is ‘very much more severe’, rather ‘more severe’, ‘as severe’, and so on, down to ‘very much less severe’. Each of these judgments is assigned a number on a scale. One common scale (adapted from Saaty) is shown in Table 22.

Saaty (1972) argues that a decision maker naturally finds it easier to compare two things than to compare all the items in a list. That is why in AHP, experts are asked to make pairwise comparisons between verbal phrases. Questionnaire shown in Appendix H, presented to the experts with a series of pairwise comparisons between the verbal probability phrases. Responses were analyzed and the results for each branch are shown in Figure 59. AHP also evaluates the consistency of the decision maker by finding the Consistency Ratio (CR) parameter, and allows for the revision of responses.

The AHP procedure is very advantageous in this study, allowing experts to consider consequence branches weighting evaluation based on different site condition. For example, if CO_2 geological storage is launched in middle of desert such as In Salah CO_2 storage project, Algeria, the human toxicities from leakage in air would likely result in weighting factors that are much smaller than plant death from leakage in ground water, because a lack of population close to the geological storage decreases risks to humans. In contradiction to this example, the experts would likely weigh higher values the human toxicities in projects which taking place near large population centers.

The belief evaluation process is identical to fuzzy evaluation process in many aspects. For the left side of the BowTie diagram (block diagram) the evidence calculation methodology was provided in Section 5.1.3. The likelihood value versus belief is evaluated at each branch based on this methodology. The belief value for consequence evaluation is based on the collection of the experts' inputs. The final belief value corresponding to a fuzzified risk is evaluated using the Monte Carlo method over likelihood versus belief data and consequence versus belief data. The final result of this analysis is a 3-D graph shown in Figure 61. This graph has three axes, the Belief (agreement) axis, the Fuzzy Variable axis (or in this study, the Risk Qualitative values axis), and the z-axis showing the fuzzy dominating factor for each risk value. In this figure, the fuzzy variable defines the "Very Low" to "Very High" risk definition, and Degree of Belief is defined by the agreement of the audience over each final part of output.

For a better understanding, a defuzzified graph from data shown in Figure 61 is presented in Figure 63 (for triangular membership function). Put simply, defuzzification is converting fuzzy set confidences into fuzzy numbers, and defuzzification is the reverse. Defuzzification makes it possible to present outputs in fuzzy numbers for better decision-making. Most experts surveyed agreed that defuzzified data are more meaningful output for the user. Fuzzy control engineers have many different ways of defuzzification, but it is usually possible to use quite simple methods. The center of gravity (COG) was used in this study since it is simple and commonly used in current practice. The process of defuzzification from Figure 61 into Figure 63 is presented in Figure 62. As it is presented in Figure 62 the center of gravity of fuzzified risk values for each belief value is evaluated, the collection of these COGs are resulting the defuzzified risk value-belief graph. Then the Gaussian probability function is fitted into defuzzified risk value-belief data to show the results in Gaussian bell function for better estimate of risk varation.

It is clearly much easier to make decisions based on a defuzzified graph. Based on Figure 63 for 50% belief, the fuzzified CO_2 leakage risk equals:

$$X = \left\{ \frac{0.0}{\text{VeryLow}}, \frac{0.12}{\text{Low}}, \frac{0.88}{\text{Medium}}, \frac{0.0}{\text{High}}, \frac{0.00}{\text{VeryHigh}} \right\} \quad 49$$

where X shows the dominating factor for each fuzzy variable on 75% agreement. The X value corresponds to the mean fuzzy value in Figure 61. However, in most risk assessments, regulators wish to see the degree of agreement on each risk value, and most prefer to see the range of risk based on different percentiles. The shaded zone boundaries represent audience agreement based on 12.5% probability and 87.5% probability. It should be noted that the nearest fuzzy values (4.6 and 4.8) are chosen to represent 12.5% and 87.5% probability. The risk value of the Weyburn Project is evaluated as "medium" for 75% percentile interval. A classification of "moderate" or "medium" means that based on the Weyburn's wellbores quality evaluation from the questionnaire inputs from the experts in both the PRISM #3 and #5 meetings, the evaluated risk is in the range of "medium". "Medium" can be considered the same risk as "smoking" (based on the results in Section 3).

Discussion and conclusion

The definition of risk can affect policy debates, the allocation of resources towards safety measures, and the distribution of political power in society. Society can direct capital such that it reduces general public risk. The objective of this study was to develop a methodology for incorporating subjective risk evaluation procedures into the "BowTie", which included fuzzy logic, belief theory and AHP, to the Weyburn geological storage project site. A proposed methodology structured around the BowTie diagram, using fuzzy logic and Dempster-Shafer methods as compilers for adapting the opinions of experts to the system. A wellbore integrity index was also included in the BowTie diagram that is useful in future studies as a robust method for considering indices for caprock and wellbore in the BowTie diagram and potentially, any other risk structure. The ease of the index approach provides a very strong tool for feasibility studies in CO_2 sequestration projects in depleted reservoirs. Currently, the lack of multiple field project data sets leaves qualitative risk assessment based on the linguistic input of experts as the only possible and justifiable method.

This methodology was applied to the Weyburn project, using the expert panel in 5^{th} PRISM. This study cannot be considered as full field risk assessment of the Weyburn project, due to limitations for expert to be involved in all aspect of this research, validation with other CO_2 storage projects. Ultimately, risk and belief are combined to assign different belief values to different evaluations of calculated risk values. The risk value of the Weyburn Project is evaluated as "medium" for 75% percentile interval, as it is shown in Figure 63. This result shows that the "medium" risk value will be resulted considering the inputs from experts considering all leakage pathways included in suggested "BowTie structure" (see Figure 3) and wellbore index evaluation. The 75% percentile interval can be a reasonable range and can be accepted agreement range for this methodology. The 75% percentile interval suggestion can be on conservative side if the expert panel is not well defined and the methodology is not well presented to the panel, since experts mostly stays on the conservative side if they are not well confident on methodology or risk associated questions.

This methodology can be used in future for sub-surface geological CO_2 storage field risk assessment. Future validation and feedbacks from different geological storage projects can build up consistency and reliance on this methodology.

Table 19. Average decided values for each property based on experts' judgement

Early Time Effects	Casing Centralization	Well Cleaning	Cement Placement	Cement Volume Reduction	Production & Injection Well History
	2.83	**3.60**	**3.40**	**3.60**	**4.40**

Long-term Effects	Well Trajectory	Bounding Seal (Formation) Fluid Properties	Bounding Seal (Formation) Insitu Stress	Bounding Seal (Formation) Pressure	Bounding Seal (Formation) Strength	Bounding Seal (Formation) Permeability	Bounding Seal (Formation) Fracture Condition	Annular Cement Porosity	Annular Cement Strength Properties	Wellbore's Completion Fluids Chemical Properties	Cement Plug Porosity	Casing Condition	Time Effect & Future Human Activities	Injected CO_2 Gas Properties	Bottom Wellbore CO_2 Pressure
Anhydrite Seal	**4.40**	**3.00**	**2.40**	**3.00**	**3.83**	**4.44**	**2.38**	**3.38**	**3.00**	**3.00**	**3.20**	**2.80**	**F1(t)**	**3.00**	**$F_2(t)$**
Watrous Seal	**4.20**	**3.00**	**2.40**	**3.60**	**3.83**	**4.17**	**2.00**	**2.40**	**2.40**	**3.60**	**2.60**	**2.80**	**F1(t)**	**4.00**	**$F_2(t)$**

Table 20. Final Index weighting considered in Equation 48

Casing Centralization	Well Cleaning	Cement Placement	Cement Volume Reduction	Production & Injection Well History	Well Trajectory	Bounding Seal (Formation) Fluid Properties	Bounding Seal (Formation) Insitu Stress	Bounding Seal (Formation) Pressure	Bounding Seal (Formation) Strength	Bounding Seal (Formation) Permeability	Bounding Seal (Formation) Fracture Condition	Annular Cement Porosity	Annular Cement Strength Properties	Wellbore's Completion Fluids Chemical Properties	Cement Plug Porosity	Casing Condition	Time Effect & Future Human Activities	Injected CO_2 Gas Properties	Bottom Wellbore CO_2 Pressure	Cement Top
2.68	**2.03**	**1.16**	**0.72**	**0.81**	**0.56**	**0.33**	**0.52**	**0.61**	**0.50**	**0.49**	**0.48**	**0.46**	**0.41**	**0.46**	**0.35**	**0.52**	**0.50**	**0.54**	**0.48**	**5.41**

Table 21. The risk matrix suggested by Shell used for final risk value evaluation

Consequence Linguistic Value						
	VH	M	M	H	VH	VH
	H	L	M	M	H	VH
	M	L	L	M	M	H
	L	VL	L	L	M	M
	VL	VL	VL	L	L	M
Risk Evaluation		**VL**	**L**	**M**	**H**	**VH**
		Likelihood Linguistic Value				

Table 22. The Saaty rating scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favour one over the other
5	Much more important	Experience and judgment strongly favour one over the other
7	Very much more important	Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values	When compromise is needed

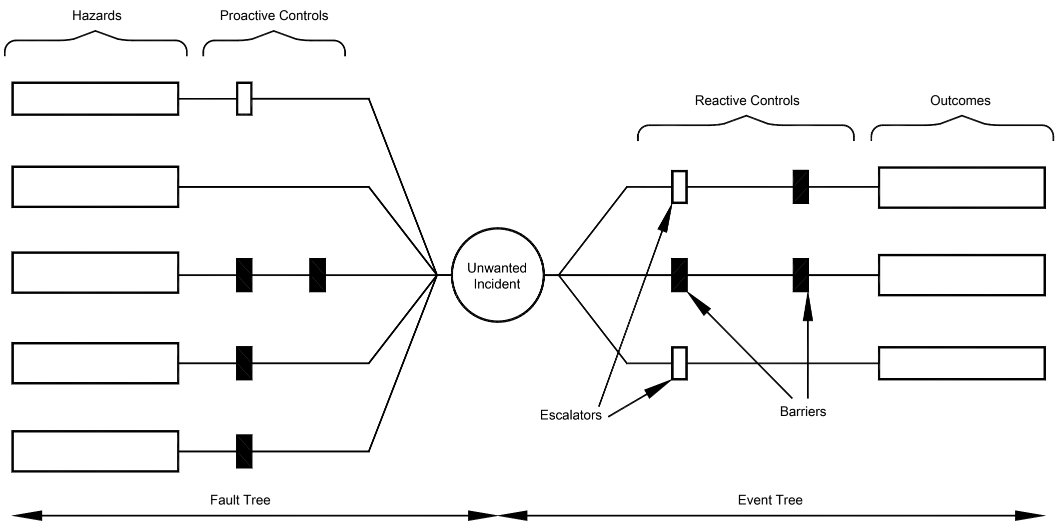


Figure 43. BowTie general diagram

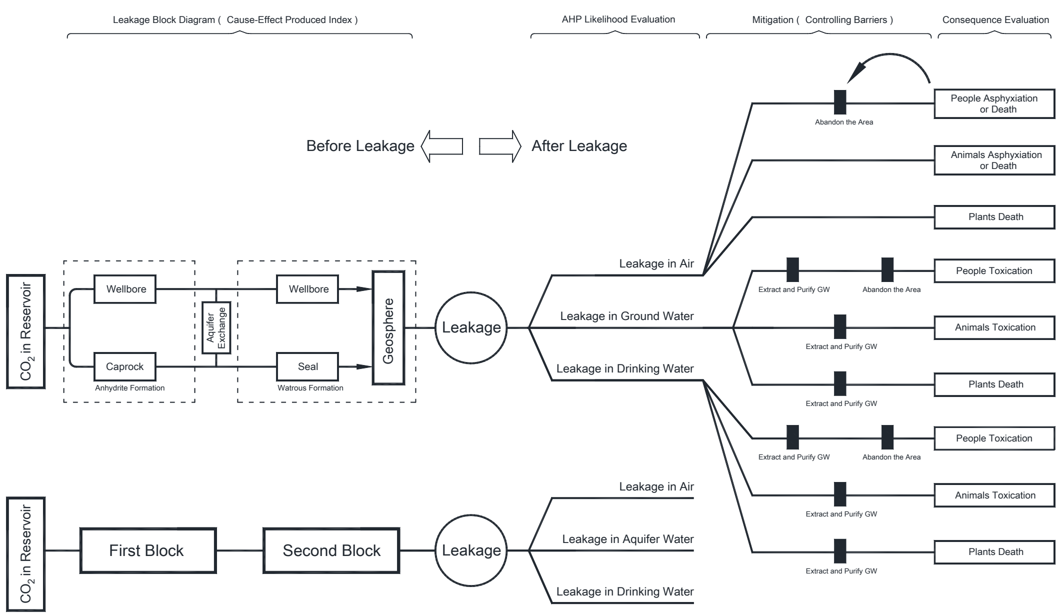


Figure 44. Proposed Failure Block Diagram (FBD) for CO_2 contamination risk. In this figure Elements of this study including the index evaluation major subcomponents and Bayesian network feedback and validation models for index evaluation are also shown

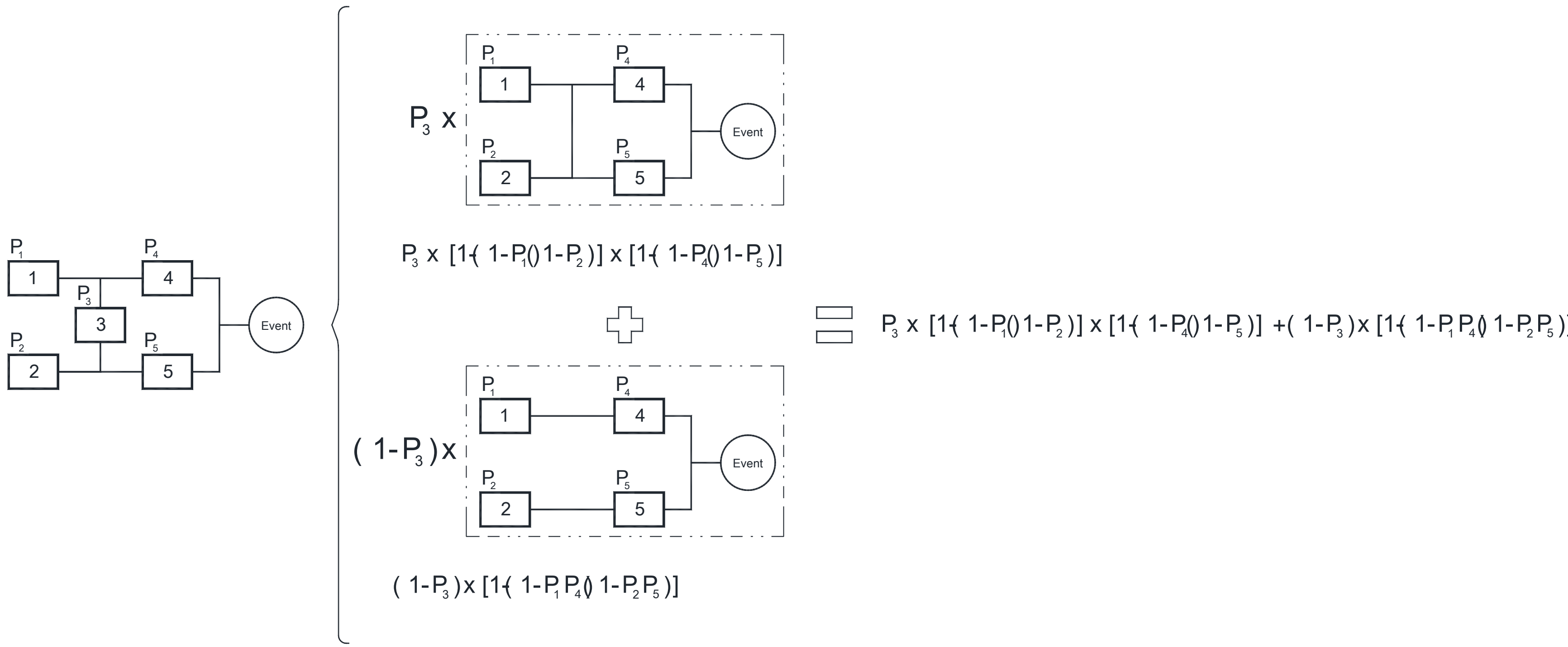


Figure 45. Bridge structure in block diagram and its probability calculation

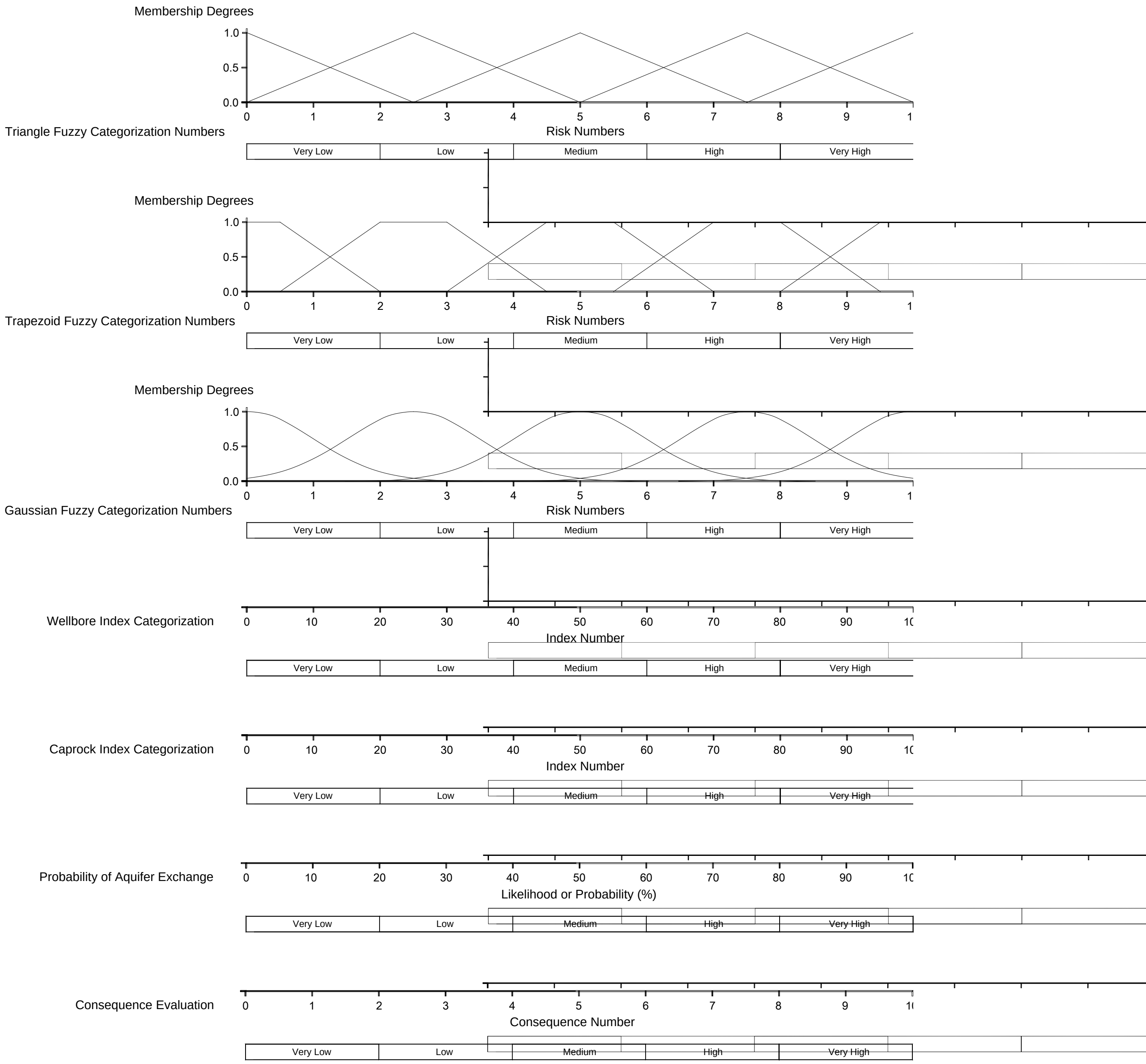


Figure 46. Proposed fuzzy membership functions for this study. In this study Triangle, Trapezoid and Gaussian membership functions are used in the fuzzy logic analysis

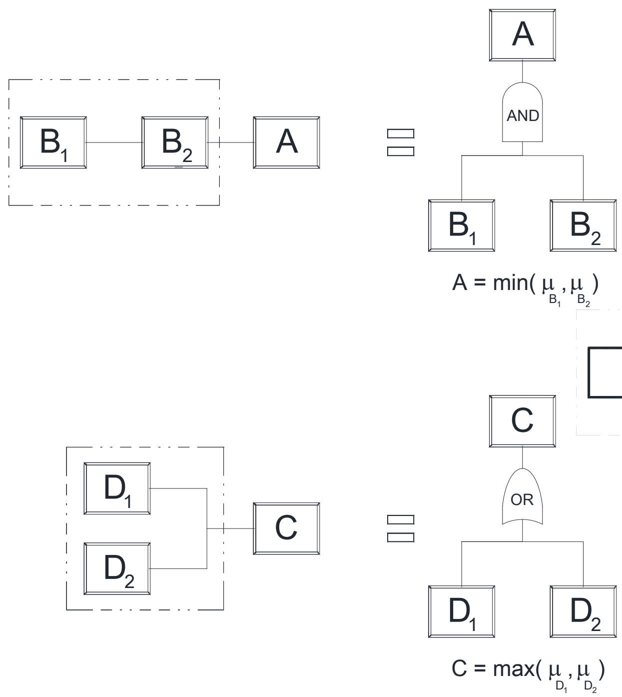


Figure 47. Fuzzy calculations in block diagram for blocks connected to one gate which is similar to ***OR Function*** as ***max Function***, and linearly connected blocks which is similar to ***AND Function*** considered as ***min Function*** in the fuzzy sets theory

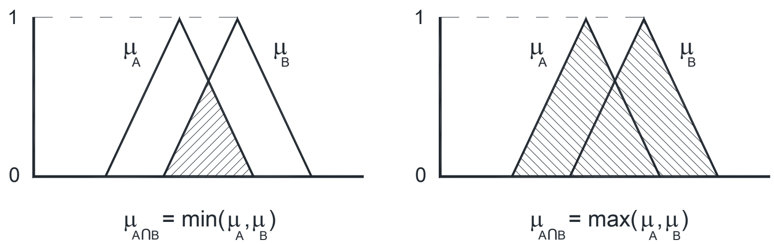


Figure 48. Illustration of ***min Function*** and ***max Function*** in fuzzy sets theory

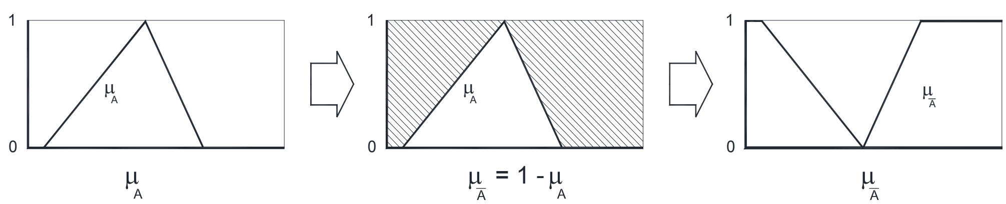


Figure 49. Illustration of ***inverse Function*** in fuzzy sets theory

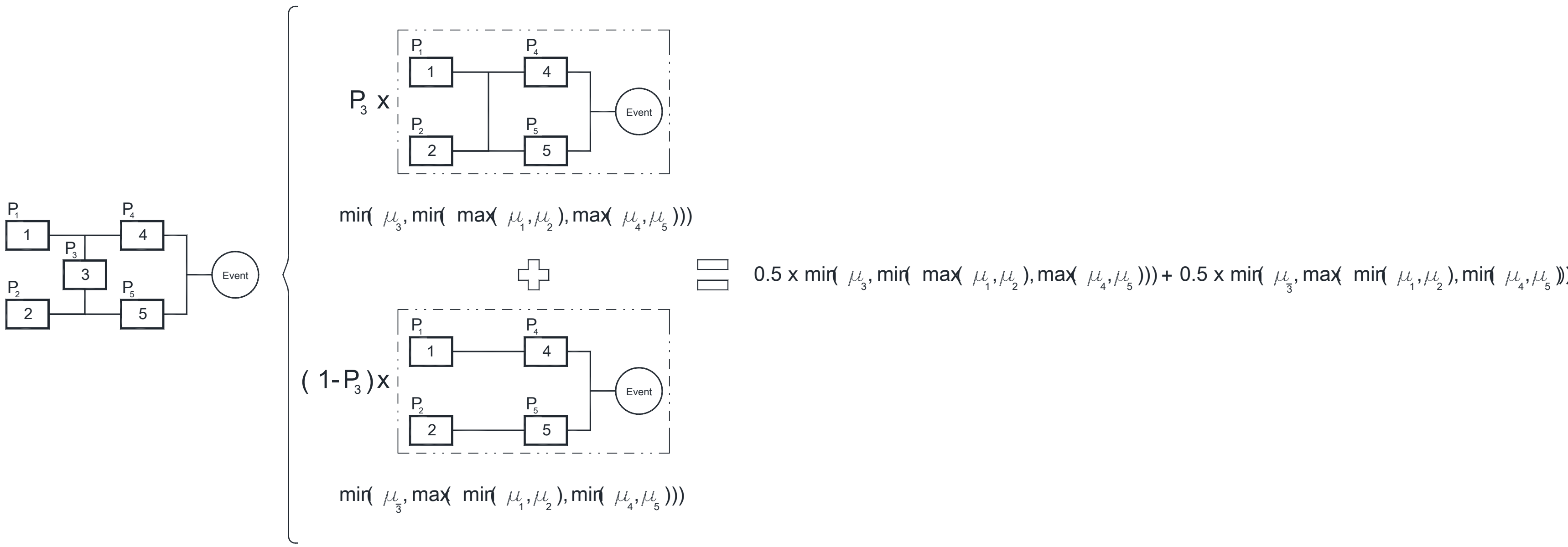


Figure 50. Suggested method for the fuzzy set process in the bridge structure

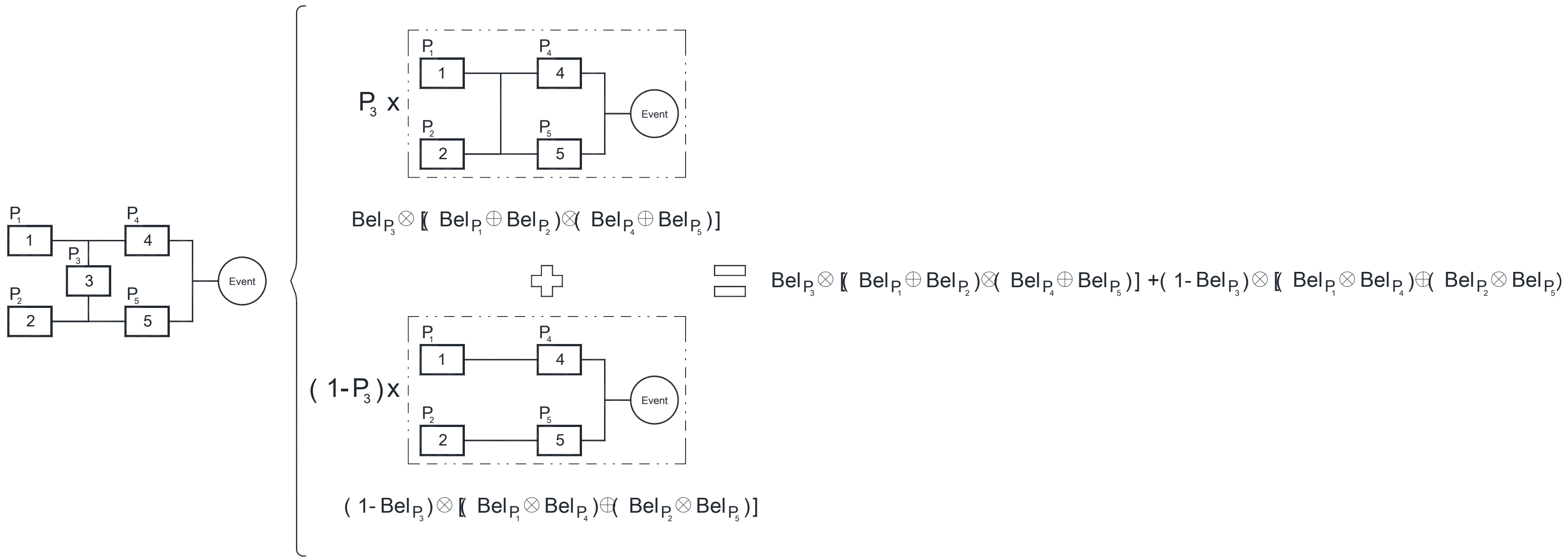


Figure 51. Suggested Guth (1988) method application to Bridge structure

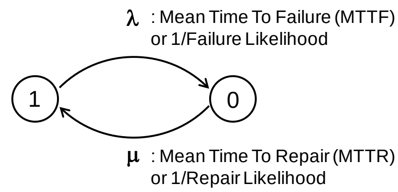


Figure 52. State transition diagram for a single component for a failure repair cycle

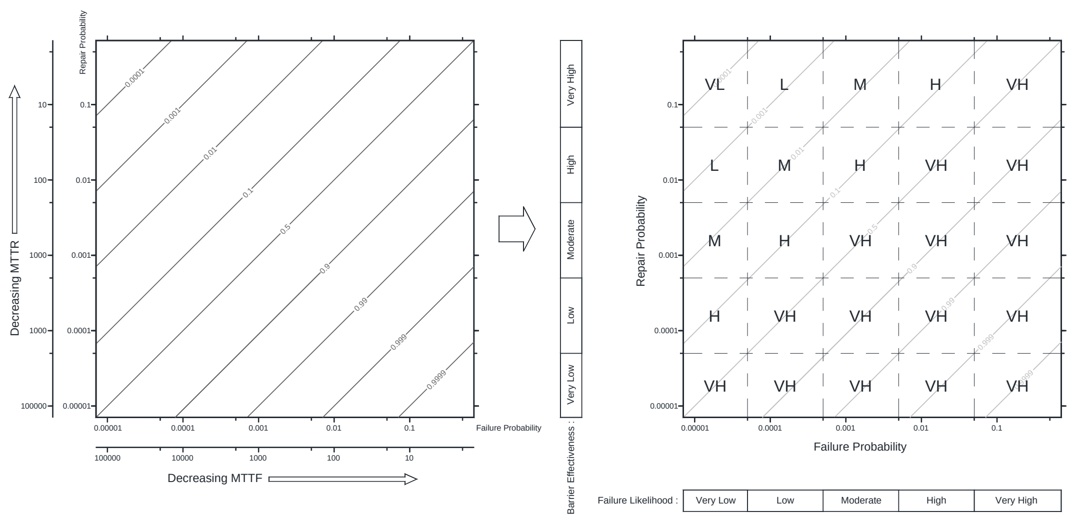


Figure 53. IF-THEN approach suggested for modelling the likelihood reduction by inserting the mitigation barriers

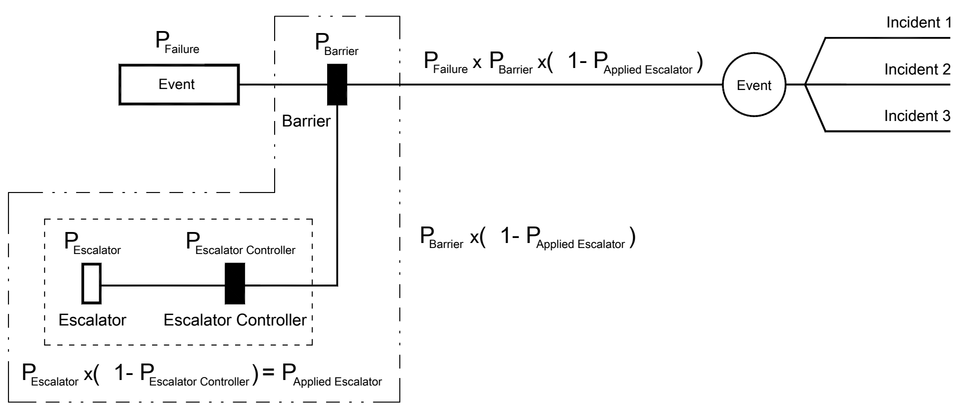


Figure 54. Escalator and Escalator Controller effects in Top Event probability

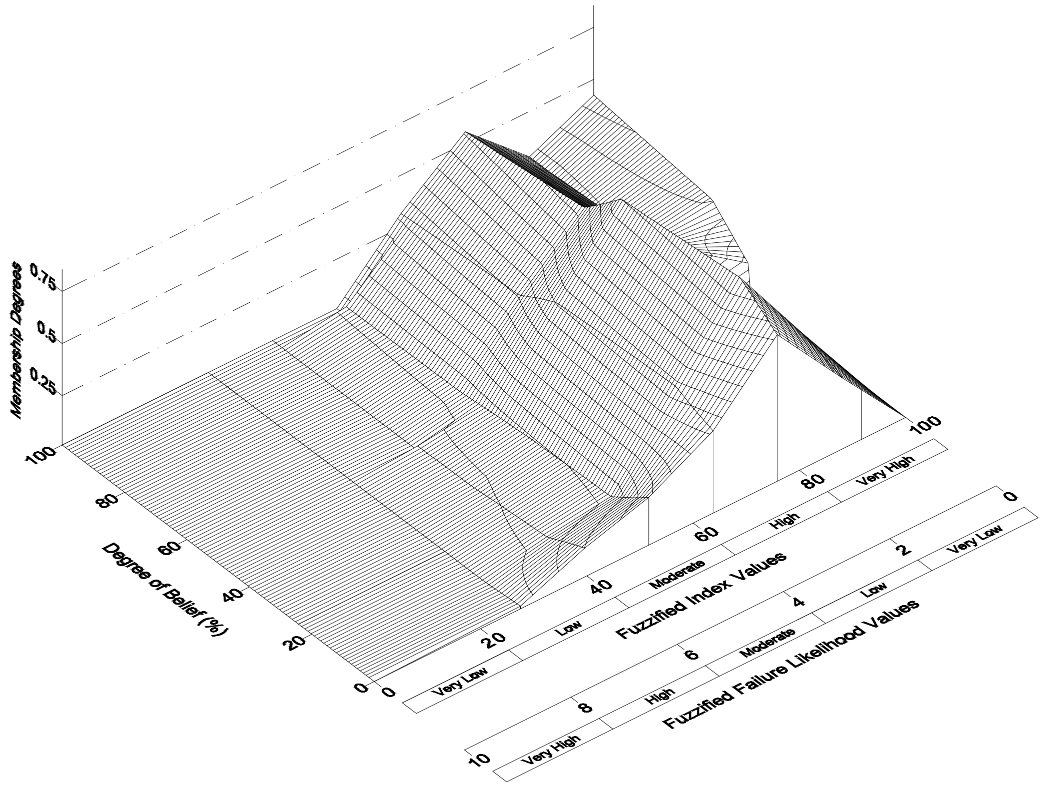


Figure 55. Fuzzified wellbore index and fuzzified likelihood variation versus degree of belief

Consequence Severity		Air: Human	Air: Cattle	Air: Plants	Ground Water: Human	Ground Water: Cattle	Ground Water: Plants	Potable Water: Human	Potable Water: Cattle	Potable Water: Plants	Nuclear Waste Repository
Factor 1	Release Severity	1.50	1.50	1.50	2.40	2.40	2.40	2.40	2.40	2.40	2.80
Factor 1	Sensibility	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.10
Factor 1	Impact Rate	1.40	1.50	1.70	1.40	1.50	1.70	1.40	1.50	1.70	2.20
Factor 1	Alert Ability	2.60	2.60	5.00	3.20	3.20	5.00	3.20	3.20	5.00	2.20
Factor 1	Controllability	2.10	2.10	2.10	2.30	2.30	2.30	2.30	2.30	2.30	2.30
Factor 1	Transportation System	2.00	2.70	5.00	2.00	2.70	5.00	2.00	2.70	5.00	1.90
Factor 2	Capital Loss	1.80	1.90	1.00	2.00	2.00	2.80	2.00	2.00	2.80	1.50
Factor 2	Barrier Cost	2.90	2.90	2.90	3.20	3.20	3.20	3.20	3.20	3.20	4.00
Factor 2	Voluntariness	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.00
Factor 2	Known to Expose	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.40
Factor 2	Future Sciences	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.30

Figure 56. Defuzzified Factor 1 and Factor 2 components which causing Consequence Severity

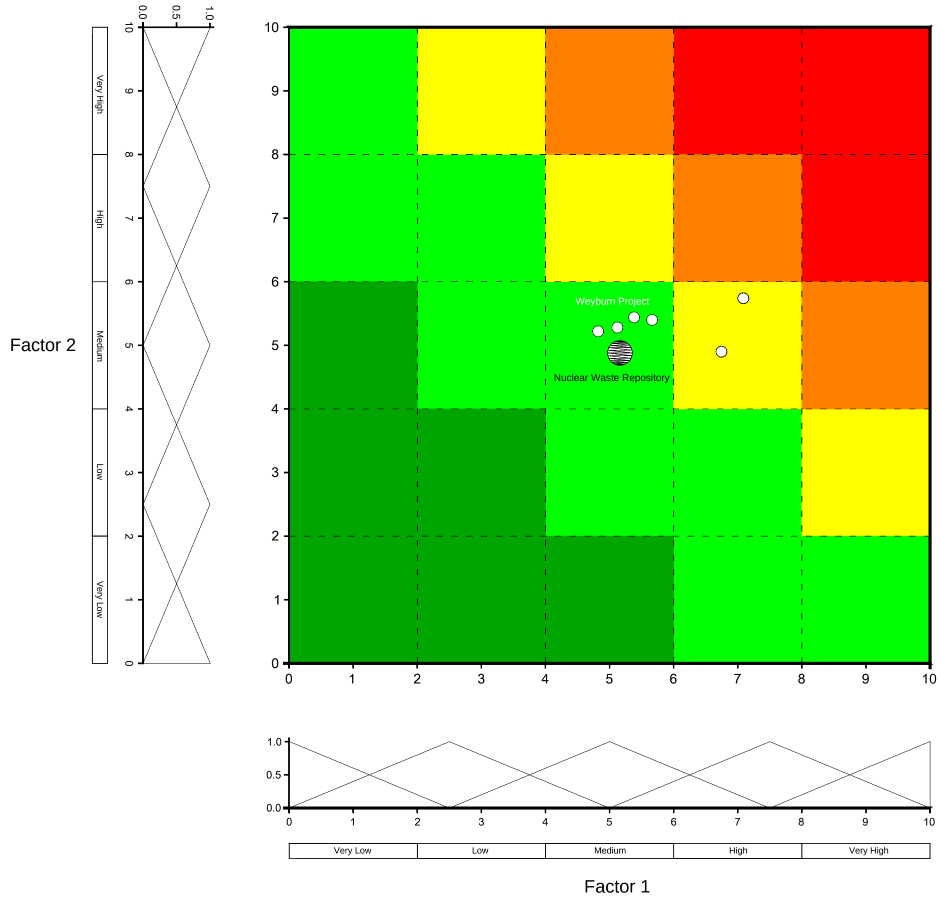


Figure 57. Illustration of average defuzzified Factor 1 and Factor 2 for Weyburn carbon geological storage survey and its comparison with nuclear waste repository leakage survey

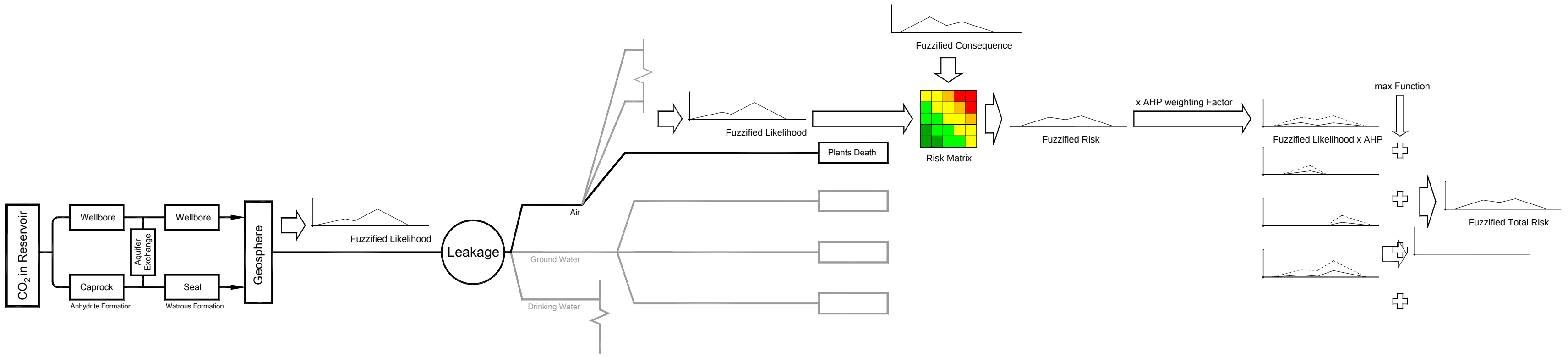


Figure 58. The flowchart which presenting the framework in this study

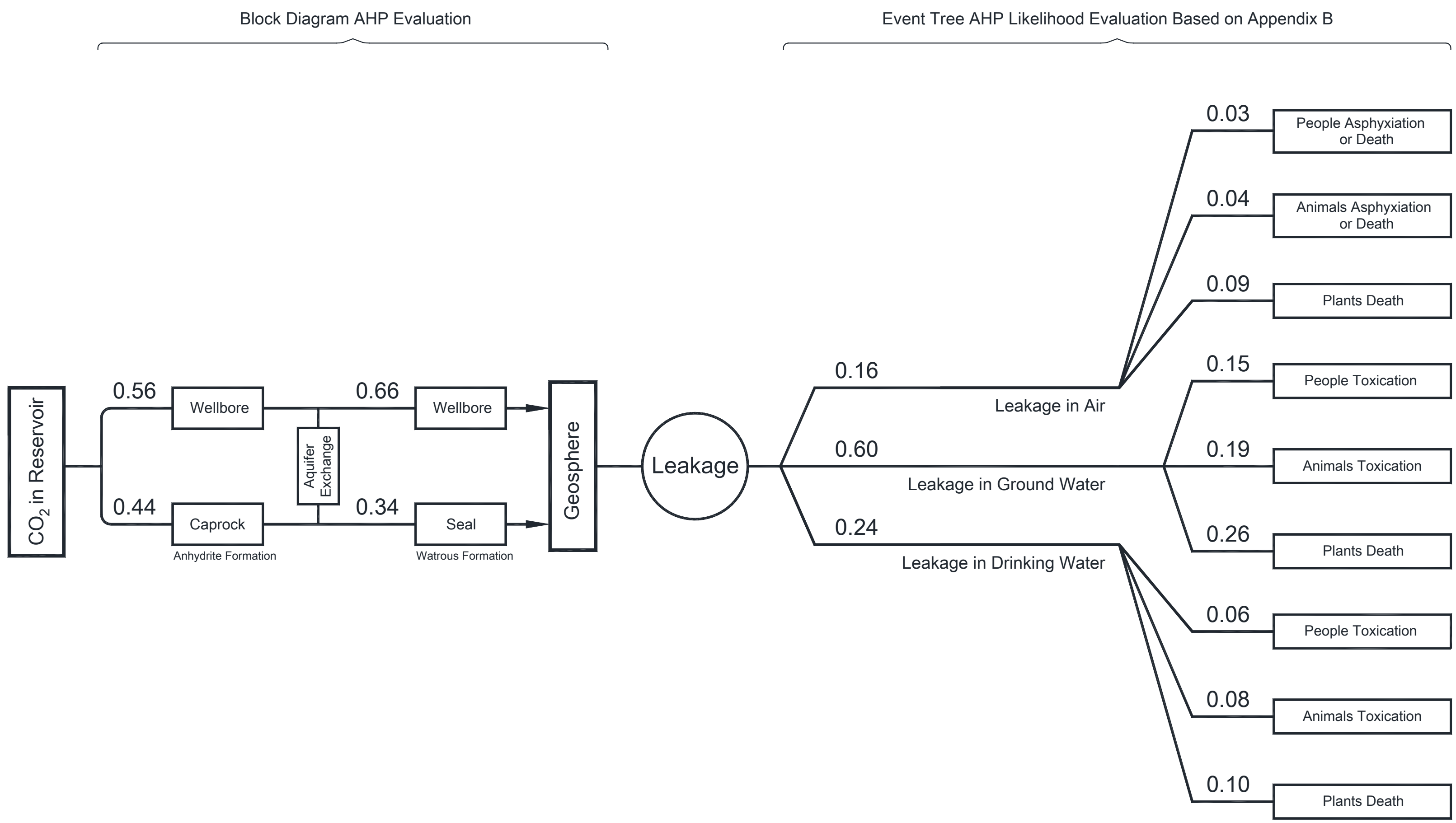
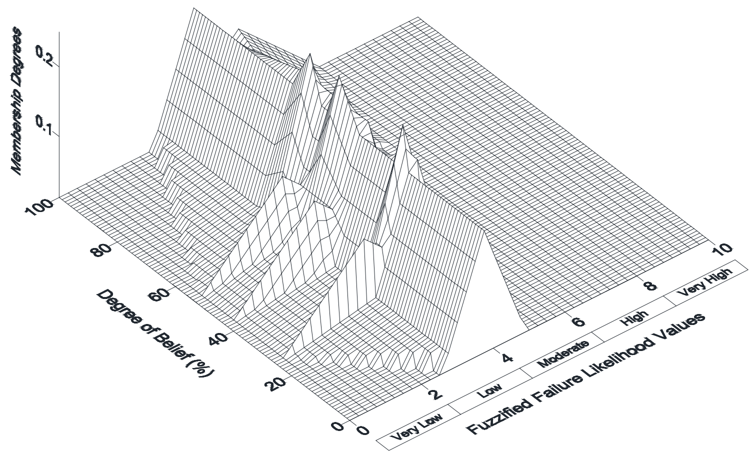
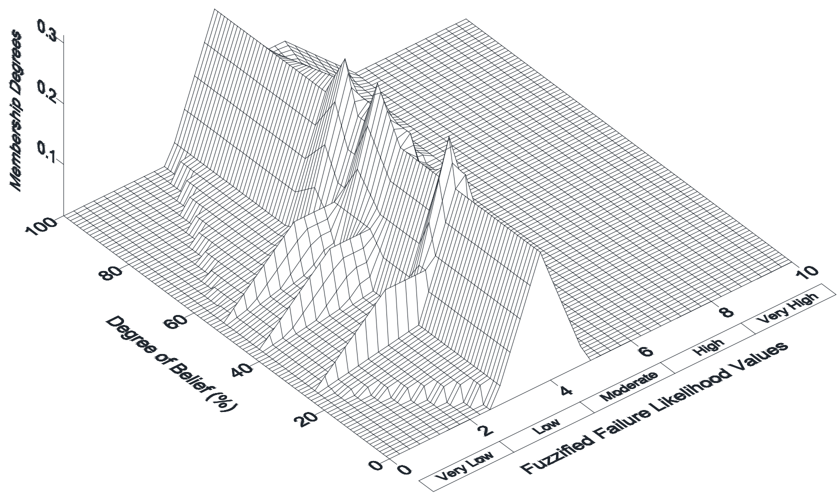


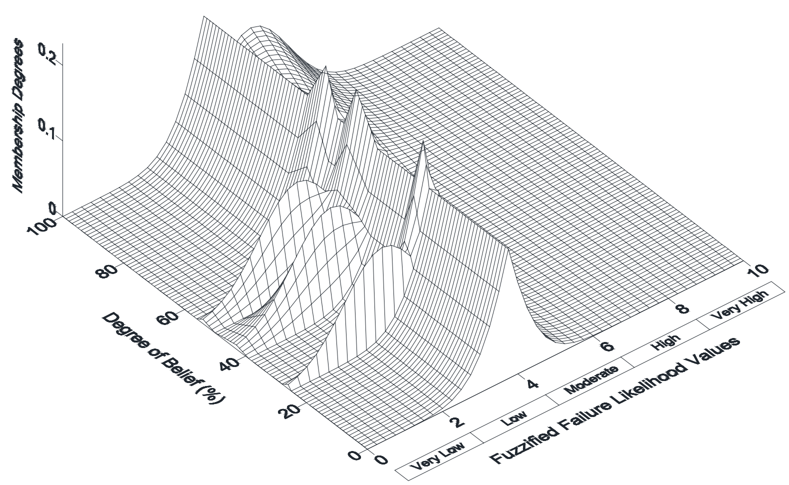
Figure 59. AHP results for different branches in block diagram and event tree in BowTie structure



a. Evaluated fuzzified likelihood results using Triangle membership function



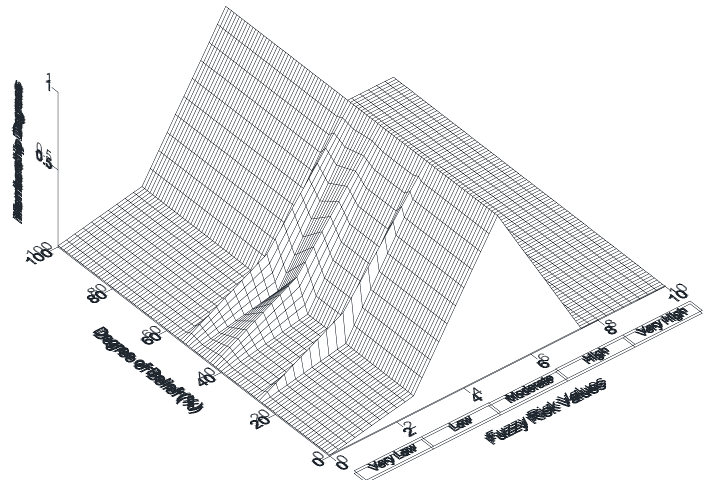
b. Evaluated fuzzified likelihood results using Trapezoid membership function



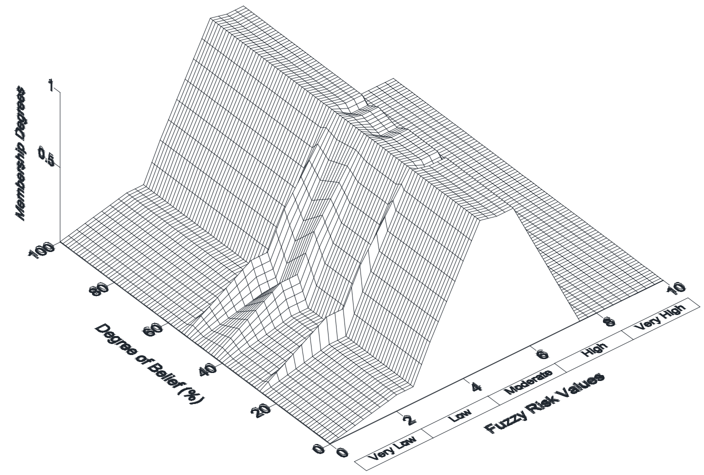
c. Evaluated fuzzified likelihood results using Gaussian membership function

Figure 60. Evaluated fuzzified likelihood results in 3D configuration, in this figure the fuzzy likelihood variable are defining the very low to very high likelihood definition and degree of belief is defining the agreement of audience over each final part of output. In this figure different

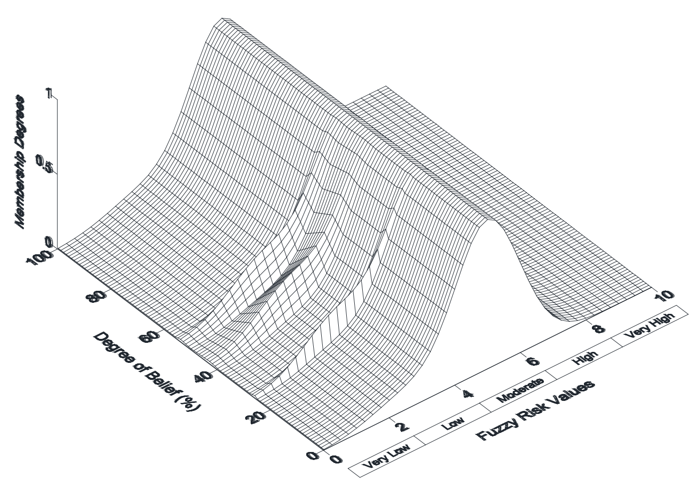
membership functions is studied



a. Evaluated fuzzified risk results of survey using Triangle membership function



b. Evaluated fuzzified risk results of survey using Trapezoid membership function



c. Evaluated fuzzified risk results of survey using Gaussian membership function

Figure 61. Final evaluated fuzzified risk results for this study, in this figure the fuzzy risk variable are defining the very low to very high risk definition and degree of belief is defining the agreement of audience over each final part of output. In this figure different membership functions is studied

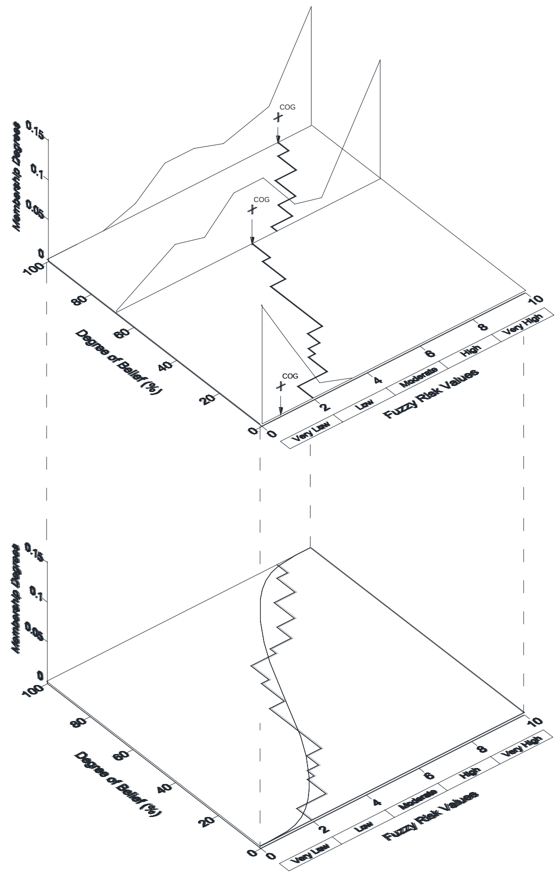
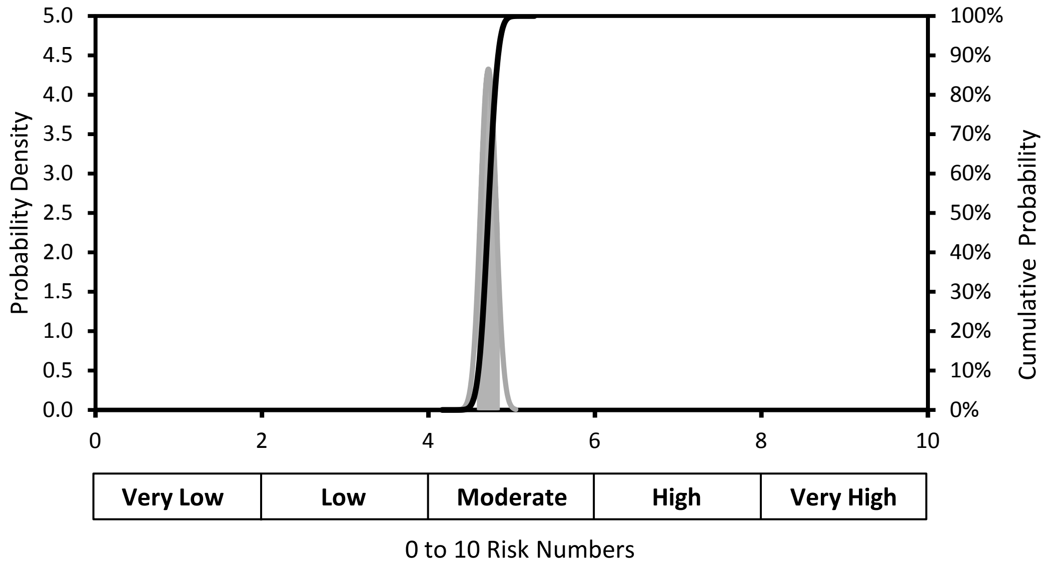
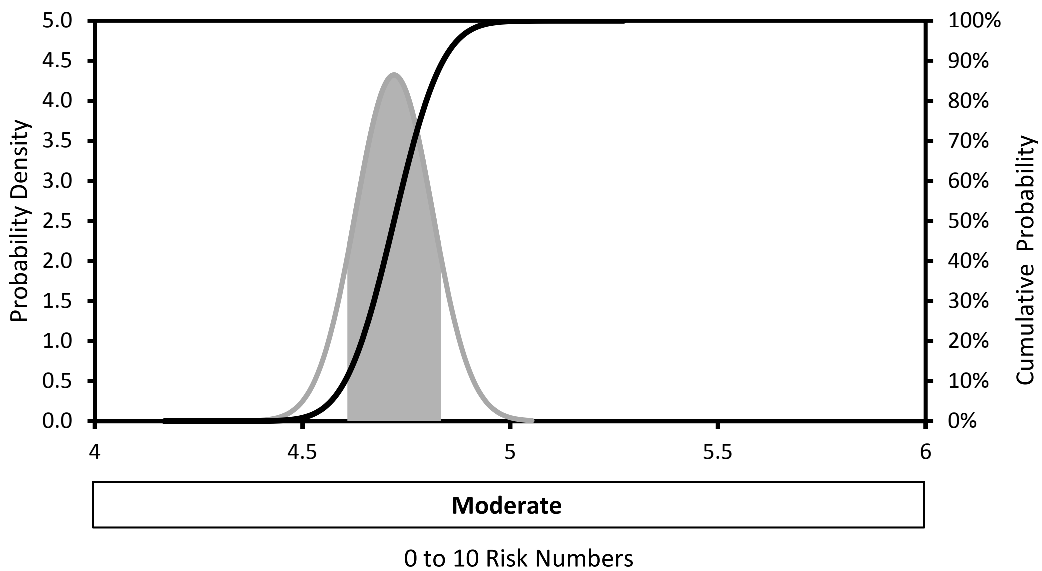


Figure 62. Illustration of defuzzification process of data in Figure 61 into Figure 63.



a. Probability Density and Cumulative Probability illustration for evaluated defuzzified risk for triangle membership function



b. Probability Density and Cumulative Probability illustration for evaluated defuzzified risk for triangle membership function in the smaller range of risk values for clarification

Figure 63. Final evaluated risk results of survey after defuzzification, the boundaries of audience agreement based on 12.5% probability and 87.5% probability is shown, it must be noted that the nearest meaningful fuzzy values 4.6 and 4.8 are chosen as 12.5% and 87.5% probability, the range of 4.6 to 4.8 covers the 75% of total probability

6. Conclusions and Recommendations

The research reported in this thesis successfully lead to the development of a methodology for incorporating subjective risk evaluation procedures into the BowTie risk assessment approach and was applied to the Weyburn Project. The subjective risk evaluation procedures included belief estimates for expert judgements, based on the Dempster-Shafer theory and expert judgement on risk levels (both likelihood and severity) using fuzzy logic theory. Ultimately, risk and belief were combined to assign different belief values to different evaluations of calculated risk values. In summary:

- a risk value of the Weyburn Project was evaluated as Low to Medium for 50% percentile interval;
- tools were developed for handling different aspects of the experts opinion consideration in BowTie and Fault Tree models;
- methods were developed for handling wellbore leakage probability by using wellbore index;
- A BowTie diagram and Fault Tree were structured around the specifics for Weyburn geological storage;
- Fuzzy logic theory and Dempster-Shafer methods were successfully implemented as compilers for adapting the opinions of experts; and
- development of an acceptability limit for carbon geological storage projects that considered media and trust effects on after leakage scenario.

Directions for Future Work

Although some potential directions for generalizing and improving upon the results were presented in this thesis, other relevant issues are discussed below as suggestions for future research that will build upon this methodology developed in this thesis and move us closer towards finding a general solution for the geological storage risk assessment.

- It is likely that the optimal solution to the experts' opinion evaluation problem is not unique. But an analytical solution such as Dempster-Shafer theory is necessary to characterize all variety of answers from different experts. To this end, it is useful to approach different analytical solution for better variety capturing.
- Developing the caprock index using the cause-effect method.
- In some cases, the future mitigation on left side of the BowTie has to be considered which in this analysis is briefly discussed. This difficulty can be partially overcome by extending the ideas presented in Section 5.1.4.
- Programming the Web based software, which captures expert's opinion through web provided questionnaires.

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Appendix A: Variation of acidity on pH scale with CO_2 concentration

For water contamination, the variation of acidity on the pH scale is deemed to represent the Severity Categorization of CO_2 concentration in water contamination. The acidity of the soil, or more precisely the acidity of the soil solution, is very important because soil solution carries nutrients such as nitrogen (N), potassium (K), and phosphorus (P) that plants need in specific amounts to grow, thrive, and fight off disease. If the pH of the soil solution is increased above 5.5, nitrogen (in the form of nitrate) is made available to plants. Phosphorus, on the other hand, is available to plants when soil pH is between 6.0 and 7.0. In acidic soils, plants are more likely to take up toxic metals and some plants eventually die of toxicity (poisoning). Humans and animals are also sensitive to the acidity of the water they consume. pH less than 5.5 could severely affect humans and animals, and is considered dangerous in the long term. The addition of CO_2 to water initially leads to an increase in the amount of dissolved CO_2. The dissolved CO_2 reacts with water to form carbonic acid. Carbonic acid dissociates to form bicarbonate ions, which can further dissociate into carbonate ions. The net effect of dissolving anthropogenic CO_2 in water is the removal of carbonate ions and the production of bicarbonate ions, with a lowering of pH.

We can write the dissolution of CO_2 gas in water as:

$$CO_2(g) + H_2O = H_2CO_3^o \tag{A.1}$$

Based on Henry's law, at 25^{o}C, the amount of dissolved gaseous carbon dioxide is calculated as:

$$K_{CO_2} = \frac{\left[H_2CO_3^o\right]}{P_{CO_2}} = 10^{-1.47} \tag{A.2}$$

The first dissociation step of carbonic acid is written as:

$$H_2CO_3^o = H^+ + HCO_3^- \tag{A.3}$$

The second dissociation step of carbonic acid (production of carbonate anion from bicarbonate anion) is written as:

$$HCO_3^- = H^+ + CO_3^{2-} \tag{A.4}$$

The equilibrium expression for the second dissociation at 25^{o}C is as follows:

$$K_2 = \frac{\left[H^+\right]\left[CO_3^{2-}\right]}{\left[HCO_3^-\right]} = 10^{-10.33} \tag{A.5}$$

By combining equation (A.2) and (A.5); and eliminating the result would be:

$$\left[H^+\right] = \frac{\left(K_{CO_2}K_1\right)P_{CO_2}}{\left[HCO_3^-\right]} \Rightarrow \log\left(\left[H^+\right]\right) = \log\left(\frac{\left(K_{CO_2}K_1\right)P_{CO_2}}{\left[HCO_3^-\right]}\right) \Rightarrow -pH = \log\left(P_{CO_2}\right) + \log\left(\frac{K_{CO_2}K_1}{\left[HCO_3^-\right]}\right) \tag{A.6}$$

It should be noted that K_1 and K_2 are functions of temperature. If the log form is recast to consider the activity coefficient, the result is:

$$\log\left(P_{CO_2}\right) = -pH + \log\left(\frac{\gamma_{HCO_3^-}\left(mHCO_3^-\right)}{K_{CO_2}K_1}\right) \quad (A.7)$$

The bicarbonate activity coefficient ranges between 0.4 to 0.9, and the total alkalinity (HCO_3) is practically constant at 2.80±0.04 mM, regardless of pH. The product of $K_{CO_2}K_1$ is nearly constant at ($10^{-1.47}\times10^{-6.35} = 10^{-7.82}$) $10^{-7.82}$. Based on these calculations, the range of variation of acidity on the pH scale with CO_2 concentration is calculated for pure water as shown in Figure 7. The equation A.7 is presented in Figure 7 by dashed boundaries. In Figure 7 for converting The CO_2 partial pressure (P_{CO_2}) to CO_2 Concentration the following equation can be used:

$$P_{CO_2} = \text{number of } CO_2 \text{ mole in the gas phase} \times P = \frac{\text{mole\% } CO_2 \text{ in the gas phase}}{100} \times P \quad (A.8)$$

where P is air pressure which equal to 1 atm.

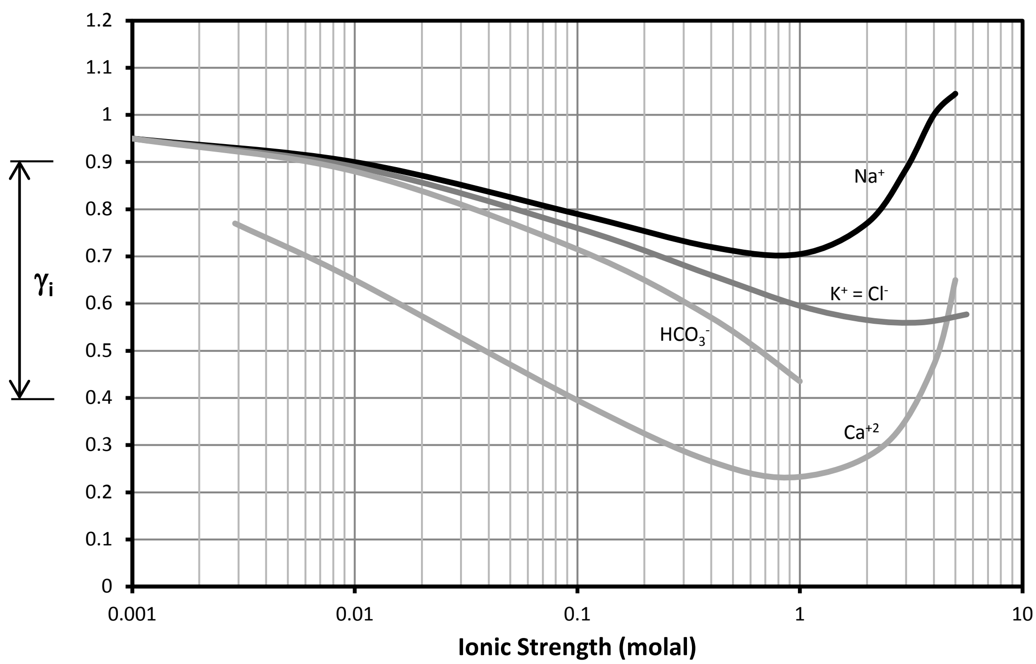


Figure A.1. Ion activity coefficients computed from mean salt data assuming the MacInnes convention (modified from Langmuir, 1997)

Most reservoirs below depths of a few hundred metres are saline to some extent. The salinity of water decreases the solubility of CO_2 in that water. For example, the solubility of CO_2 in water containing 3% salinity is approximately 85% of that in pure water (Enick and Klara, 1990).

In Figure 7, the variation of acidity on the pH scale with CO_2 concentration is illustrated by comparing data from the IEA Greenhouse Gas R&D Programme (2000) and from Lake Nyos (Nojiri et al., 1993). It should be noted that the IEA data (2000) are based on theoretical calculations, and the data reported by Nishikawa et al. (1992) for ocean sequestration and that reported by Nojiri et al. (1993) are experimental. The shift between these two sets of data can be caused due to differences between Lake Nyos temperatures and ocean sequestration data.

Appendix B: Risk Acceptance Evaluation – Environment Evaluation (QUESTIONNAIRE 1)

1. Choose the country that you consider to have levels of media freedom and media accessibility (such as newspaper, TV, and radio) most similar to those in Canada .

Former Soviet Union	Hungary	Norway	Poland	United States or France
☐	☐	☐	☐	☐

2. Select the best answer for each question.

SPECIFIC ELEMENTS

Oil Companies Conducting CCS

KNOWLEDGE AND EXPERTISE

What is your perception of the degree of knowledge and expertise of people working in petroleum companies conducting CCS?

Very Basic	Basic	Limited	Moderate	Familiar	Expert	Very Expert
☐	☐	☐	☐	☐	☐	☐

OPENNESS AND HONESTY

What is your perception of the degree of honesty of high-ranking staff of petroleum companies conducting CCS?

Very Dishonest	Dishonest	Limited	Moderate	Good	Honest	Very Honest
☐	☐	☐	☐	☐	☐	☐

CONCERN AND CARE

What is your perception of the degree of care practiced by the staff of petroleum companies conducting CCS?

Very Careless	Careless	Limited	Moderate	Watchful	Careful	Very Careful
☐	☐	☐	☐	☐	☐	☐

Regulatory Bodies

KNOWLEDGE AND EXPERTISE

What is your perception of the degree of knowledge and expertise of people working in regulatory bodies regulating CCS?

Very Basic	Basic	Limited	Moderate	Familiar	Expert	Very Expert
☐	☐	☐	☐	☐	☐	☐

OPENNESS AND HONESTY

What is your perception of the degree of honesty of people working in regulatory bodies regulating CCS?

Very Dishonest	Dishonest	Limited	Moderate	Good	Open	Very Open
☐	☐	☐	☐	☐	☐	☐

CONCERN AND CARE

What is your perception of the degree of care practiced by people working in regulatory bodies regulating CCS?

Very Careless	Careless	Limited	Moderate	Watchful	Careful	Very Careful
☐	☐	☐	☐	☐	☐	☐

Appendix C: Carbon leakage pathways severity comparison questionnaire

Place a check sign in places that implies your expression of relation between A and B, which are different index in wellbore integrity (Early Time Index and Long Time Index). In this part you are assigning the higher weighting factor to more important index property of the wellbore. In simpler way you are saying which cement property is more important early age properties (such as: gel strength, centralization, cement expansion, ...) or long term properties portion (such as: formation strength, cement plug porosity, insitu formation stresses, ...).

	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
Verbal Expression A						✓												Verbal Expression B

Placing a check sign to the left of equal indicates that verbal expression A implies a higher probability of occurrence than B

Placing a check sign to the right of equal indicates that verbal expression B implies a higher probability of occurrence than A

	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
Early Time Effect Index																		Long Time Effect Index
Cement Top																		Early Time Effect Index
Cement Top																		Long Time Effect Index

Appendix D: Interaction Matrix for early time and long-term sets of properties

For better depiction and pictures' clarification the long-term sets of properties interaction matrix is split in four parts presented in four different pages. The page orders are presented in Figure G.1.

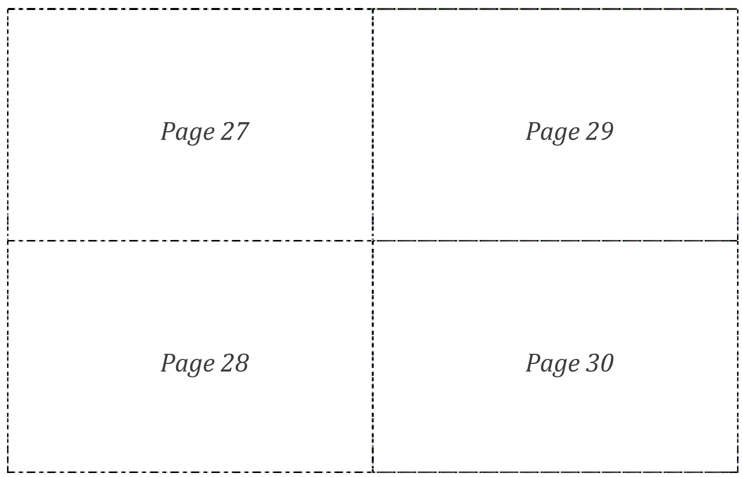
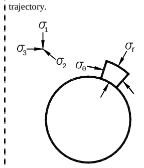
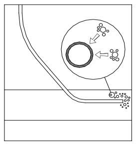
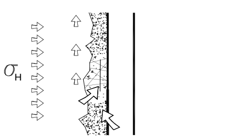
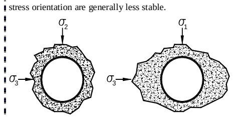
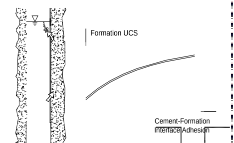
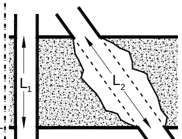
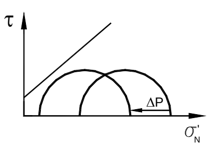
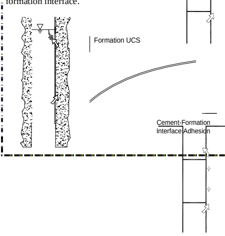
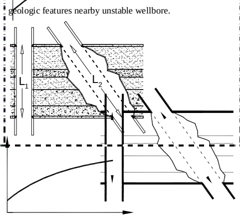
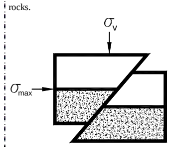
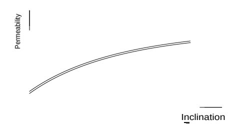
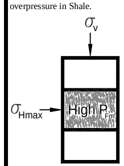
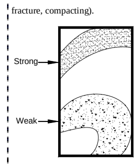
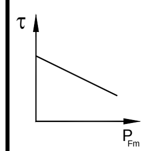
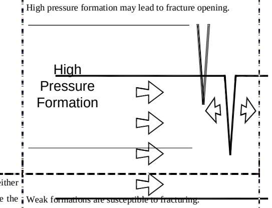
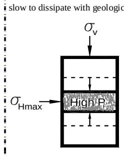
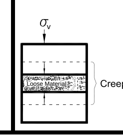
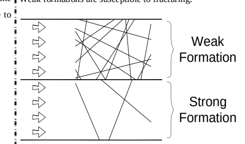


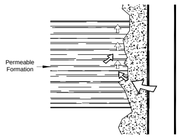
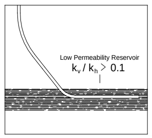
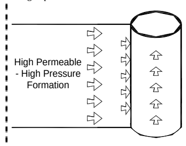
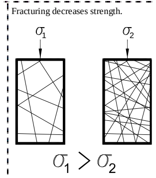
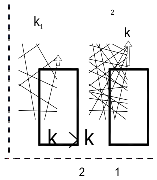
Figure G.1. Interaction Matrix for long-term sets of properties split pattern in the following pages

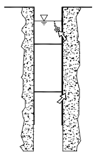
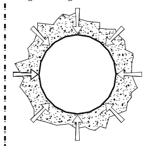
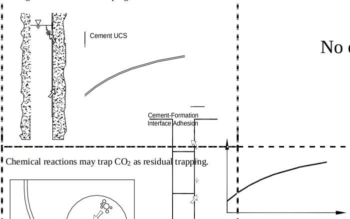
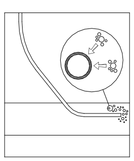
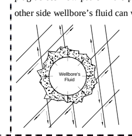
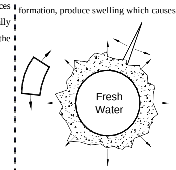
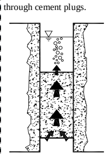
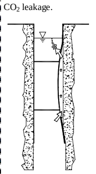
Channels in Cement (Mud Channels or Free-Fluid Channels or Bypassed Lead Cement Slurry) and High Perm Cement (or Gas Channels)							
	Cement Microannulus						
		Filtercake Pathway (Dehydrated Filtercake)					
1. A large angular channel of bypassed mud in the narrow part of the annulus is very common in the uncentralized casings.	**1.** Uncentralized casing may cause higher Poisson's effect on thicker part of uncentralized casing which is causing microannulus in most of cemented casings.	**1.** A thick filtercake or dehydrated trapped mud (usually in washouts) is very common on the narrow side of an eccentric annulus.	**Casing Centralization**	**1.** A large angular channel of bypassed mud in the narrow part of the annulus is very common in the uncentralized casings. **2.** A thick filtercake or dehydrated trapped mud (usually in washouts) is very common on the narrow side of an eccentric annulus.	**1.** The preflushing and washing is not taking place in the narrow part of the annulus in the uncentralized casings (A standoff of about 75% is acceptable).	No effect	No effect
1. Regardless of the properties of the cement placed in the annulus, a continuous mud channel or free fluid channel between two permeable zones will favour fluid migration.	No effect	**1.** Thick and strong filtercake cannot be easily washed and may cause migration path.		**Well Cleaning (Mud Removal Factor (MRF))**	**1.** High concentration of $CaCl_2$ and Ca(OH) in mud filtercake have a strong gelling and accelerating effect on cement slurries. **2.** Thin and slicken filtercake can be easily washed and helps good cement placement. **3.** OBMs produce thick filtercake which is hard to wash. **4.** Invert emulsions contain emulsifiers and oil-wetting surfactants that cover all polar surfaces. The emulsifiers in the mud may adsorb on the cement grains, inhibiting hydration.	No effect	No effect
1. Low-density cement systems with high water-to-cement ratios might exhibit fairly high perm (0.5 to 5.0 mD). **2.** Gelation and Bridging owing to fluid loss could restrict the transmission of hydrostatic pressure which may results gas channels. **3.** High Filtration causes a decrease in the height of the hydrostatic column which results gas channels more susceptible. **4.** High Filtration causes Fluid Loss .which may create space within the cement matrix that gas can occupy.	No effect	No effect			**Cement Placement Efficiency (High Fluid Loss and Low Gel Strength)**	No effect	No effect
1. Chemical shrinkage of cement causes a decrease in the height of the hydrostatic column which causes gas channels more susceptible.	**1.** Chemical shrinkage of cement causes a Microannulus between cement and casing (and between cement and formation).	No effect				**Cement Volume Reduction**	No effect

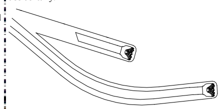
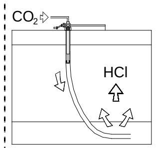
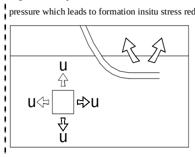
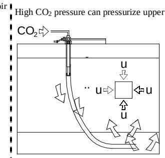
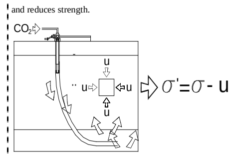
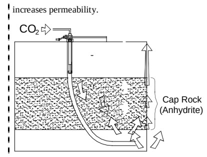
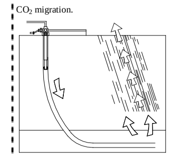
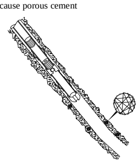
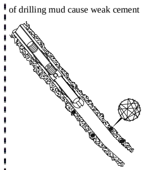
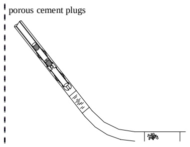
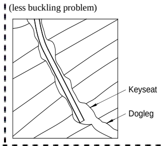
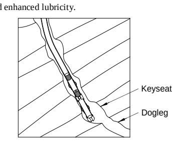
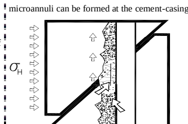
1. High reduction and increase in temperature is applying high stresses to the cement sheath which is causing fracturing in cement sheath. This is very common in CO_2 and steam injectors.	**1.** A well temperature decreases and inside well pressure decrease will result in the casing a casing diameter reduction which will result in microannulus in between cement and casing. The well temperature and inside well pressure reduction is common in CO_2 injector wells and also abandoned wells and wells with closed casing (at the end of cement job).	No effect					**Production & Injection Well History**

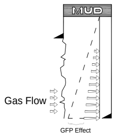
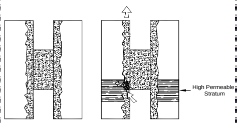
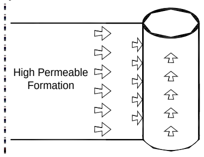
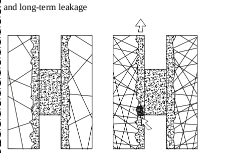
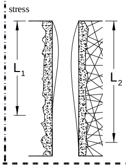
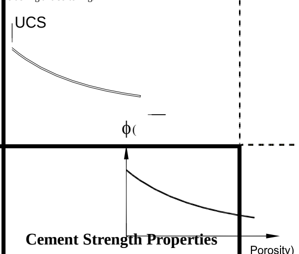
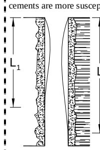
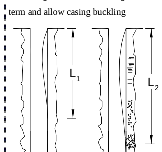
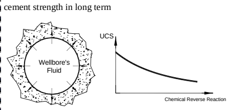
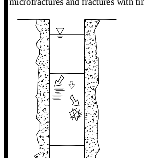
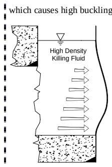
CO_2 Leakage Flux			
CO_2 leakage flux is higher in vertical wellbores and CO_2 leakage pathway is shorter in vertical wells. Also poor cementing and mud cleaning which is usually happening in inclined wells are creating extra pathways.	**Well Trajectory**	No effect	Near Wellbore stress concentration affected by well trajectory. 
Chemical reactions may trap CO_2 as residual trapping. 	Horizontal wells are mostly drilled in EOR project with low oil content.	**Formation (Bounding Seal) Fluid Properties**	No effect
High insitu stresses in formation may degrade bonding between cement and formation and accelerates CO_2 leakage through cement-formation interface. 	In some cases deviated wells are drilled for accommodating the high insitu stress formations and anisotropic stress conditions. Wells drilled normal to maximum principle stress orientation are generally less stable. 	No effect	**Formation (Bounding Seal) Insitu Stress**
Formation pressure increasing accelerates CO_2 leakage through formation and cement-formation interface. 	Length of well in unstable over-pressured formations increases for high angle wells. 	No effect	Mean effective stress reduced in overpressure formations. 
Formation strength impacts cement and formation bonding strength which mitigates CO_2 leakage through cement-formation interface. 	Inclined wellbores are less stable in rocks with anisotropic strength (e.g. fissile Shale). Also sidetracking operation is applied for bypassing an unstable wellbore and exploring geologic features nearby unstable wellbore. 	No effect	Limiting insitu stress set by the shear strength of the weakest rocks. 

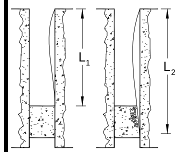
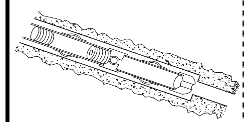
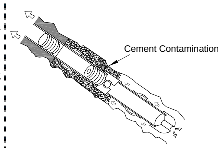
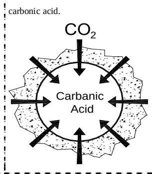
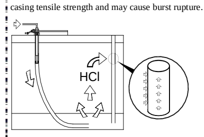
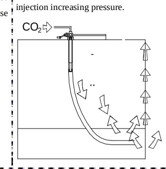
No effect	No effect	Horizontal wells increase the global permeability of formation. 	Good Well Trajectory choice will reduce fracturing around the wellbore.
No effect	No effect	Precipitation of solid particles in the formation fluid can decrease the effective permeability of the formation in the near-wellbore region. Also low viscous fluids as oil has lower relative permeability comparing to low viscous fluids as water.	Precipitation of solid particles in the formation fluid can seal fractures in the near-wellbore region.
Active tectonic stresses can generate and maintain overpressure in Shale. 	Rock strength affected by current and paleo-stresses (e.g., fracture, compacting). 	Increasing insitu stress decreases void ratio which decreases permeability.	Formations in tectonic zones and zone with high horizontal stresses are susceptible to fracturing.
Formation (Bounding Seal) Pressure	Overpressured formations have lower effective shear strength. 	No effect	High pressure formation may lead to fracture opening. 
Weak compacting shale can create overpressures that are slow to dissipate with geologic time. 	**Formation (Bounding Seal) Strength**	Loose material are susceptible to creep which may either increase or decrease the degree of sealing and therefore the potential for the region immediately around the borehole to act as a migration pathway for CO_2. 	Weak formations are susceptible to fracturing. 

Permeable formations are susceptible to CO_2 leakage through formation and cement-formation interface. 	Horizontal wells are mostly drilled in low permeability formation, and heterogeneous carbonate reservoirs. 	No effect	No effect	Formation pressure acts as external pressure on casing and lining in permeable zones. 	No effect	**Formation (Bounding Seal) Permeability**	No effect
Fractured formations are susceptible to more CO_2 Leakage.	No effect	No effect	No effect	No effect	Fracturing decreases strength. 	Formation fracturing may lead to permeability increasing. 	**Formation (Bounding Seal) Fracture Condition**

Cement porosity increasing accelerates CO_2 leakage through cement. 	No effect	No effect	No effect	Cement porosity impacts formation external pressure on casing and lining. 	No effect	No effect	No effect
Cement strength impacts cement bonding strength and cement and plug adhesion which mitigates CO_2 leakage through cement and cement-plug interface. 	No effect	No effect	No effect	No effect	No effect	No effect	No effect
Chemical reactions may trap CO_2 as residual trapping. 	No effect	Chemical reactions between the drilling fluid and the formation fluid can precipitate solids that plug pore spaces.	No effect	No effect	No effect	Chemical reactions between the drilling fluid and the formation rock can precipitate solids that plug pore spaces and also solid particles from the drilling fluid can physically plug across flow-paths in the porous formation. Also on the other side wellbore's fluid can wash the filled fractures. 	Fresh water contact with certain clay minerals in the formation, produce swelling which causes fracturing. 
Cement plug porosity increasing accelerates CO_2 leakage through cement plugs. 	No effect	Cement will be degraded by high concentrations of sulphate, chloride, and magnesium ions in the formation fluid.	No effect	No effect	No effect	No effect	No effect
Poor casing centralization creates channelling which causes CO_2 leakage. 	No effect	No effect	No effect	No effect	No effect	No effect	No effect

Work-over operations may degrade cement and plugs and accelerate CO_2 leakage.	Sidetracking operation may be done intentionally in inaccessible wellbores due to an irretrievable fish or junk in the hole or in a collapsed wellbores or may occur accidentally. 	No effect	No effect	No effect	No effect	Excessive pressure in squeeze cementing and plug cementing may force filtrate into the formation and decreases formation permeability, and also a higher pump rate in cement job increases the quality of cement-formation bond.	Excessive pressure in squeeze cementing and plug cementing creates hydraulic fracturing.
Salinity decreases CO_2 solubility and reduces solubility trapping and also reducing in temperature hydrates CO_2 and decreases gas gradient.	No effect	CO_2 injection increases the formation fluid acidity and reduces reservoir fluid pH.	CO_2 injection cools down the formation which causes insitu stress reduction in formation and caprock.	CO_2 injection pressurize reservoir which can cause over-pressurizing the formation.	CO_2 injection cools down the formation which causes effective stress reduction in formation and caprock leading to formation strength reduction.	H_2S and HCl dissolve carbonate and anhydrite, and increases permeability, and also CO2 injection increases fluid viscosity that increases global formation permeability.	Some earth tremors may be caused by injection, and also insitu stress decreasing caused by injection pressure and reduced temperature may widen fractures.
Higher CO_2 reservoirs are susceptible to higher CO_2 leakage flux.	No effect	High CO_2 content in CO_2 reservoir can reduce pH aquifers' fluid. 	Higher CO_2 pressure in reservoir decreases reservoir pressure which leads to formation insitu stress reduction. 	High CO_2 pressure can pressurize upper formations. 	Higher CO_2 pressure in reservoir can increase pore pressure and reduces strength. 	Carbonic acid dissolves carbonate and anhydrite, and increases permeability. 	Fractured regions around wellbore provide flow paths for CO_2 migration. 
Difficult cementing in horizontal wells and poor placement of drilling mud cause porous cement 	Difficult cementing in horizontal wells and poor placement of drilling mud cause weak cement 	No effect	Difficult plug cementing in horizontal and inclined wells and poor placement of drilling mud mostly cause weak and porous cement plugs 	Casing string not easily fit through the curved sections as dogleg. Dogleg severity impacts on casing bending stresses. Also deviation angle increasing decreases buckling length (less buckling problem) 	Doglegs and deviated wells reduce access and encumber inspection and remediation process. Also high angle wells may need enhanced lubricity. 	No effect	No effect
Precipitation of solid particles in the invading formation fluid can plug wellbore cement pore spaces	No effect	No effect	No effect	Larger buoyancy in formation with high density fluid decreases axial stress in casing which causes less buckling and rupture problems	No effect	No effect	No effect
High tectonic forces can cause cracking and degradation of cements which decrease cement strength	High tectonic forces can cause cracking and degradation of cements which increase cement permeability and also large microannuli can be formed at the cement-casing interface 	No effect	No effect	High horizontal stress in formation may cause casing collapse	High horizontal stresses force usage of high density muds which may cause hydraulic fracturing in soft upper or lower formations	No effect	No effect

Over-pressure formations because of high gas flow potential (GFP) are susceptible to gas flow and long-term leakage through cement 	Over-pressure formations because of high gas flow potential (GFP) are susceptible to gas flow in gelation period which cause cement to be porous and weak	No effect	No effect	Over-pressure formation may cause casing collapse and under-pressure may cause burst failure. Also formation pressure act as external pressure on casing	No effect	No effect	No effect
No effect	High strength formation with higher Young' Modulus produce higher confining stress over cement which will cause higher cement sheath strength and also make cement less susceptible to cracking.	No effect	No effect	Effective restraint in strong formations limits ballooning and reduces buckling length which reduces casing axial stress. Also formation with plastic behaviour (salt) applied higher external pressure on casing and strong formations limit tectonic forces on casings	High strength formations let usage of low density muds and less number of centralizers	No effect	No effect
Volume reduction because of fluid loss in gelation period is plausible in permeable formation which causes channelling and long-term leakage 	Volume reduction because of fluid loss in gelation period is plausible in permeable formation which may cause weak cementing	No effect	No effect	High external pressures on casing are susceptible in high permeable zones 	In permeable formation contractors increase the number of cement sacks or use iron slugs to reduce permeability	No effect	No effect
Volume reduction because of fluid loss in gelation period is plausible in fractured formation which causes channelling and long-term leakage 	Volume reduction because of fluid loss in gelation period is plausible in fractured formation which may cause weak cementing	No effect	No effect	Effective restraint in unfractured formation limits ballooning and reduces buckling length which reduces casing axial stress 	In fractured formation contractors increase the number of cement sacks or use iron slugs to reduce permeability	No effect	No effect
Cement Porosity	Porous cements are susceptible to low strength, and also high porosity results of high shrinkage usually happens with cracking and softening. 	No effect	No effect	Casings in porous cements because of low stiffness in these cements are more susceptible to buckling and corkscrewing. 	No effect	No effect	No effect
Stronger cements are susceptible to low porosity, and also gas percolation in gelation period which cause channelling in cements with high static gel strength (SGS) is less probable.	**Cement Strength Properties**	No effect	No effect	Casings are applied to less external pressure in good cementing and also low strength cement may decay in long term and allow casing buckling 	No effect	No effect	No effect
Drilling mud may be bypassed behind a casing or a liner when pumping cement into the casing or wellbore annular region. This mud-contaminated cement might not set up and might not isolate zones satisfactorily.	Wellbore's chemical reactions with cement decreases the cement strength in long term 	**Wellbore's Completion Fluids Properties**	Chemical reactions may develop increasing number of microfractures and fractures with time 	High density completion fluid applies higher axial stress which causes high buckling stresses and rupture 	No effect	Carbonate, and anhydrite dissolution and reaction with carbonic acid increase diffusion passage	No effect

Fractured rocks are susceptible to low ductility.	Fracture susceptibility decreases ductility.	Microfractures and fractures in saturated zones increase chemical reactions with making more space for reaction.	**Cement Plug Porosity**	Non-porous and intact cement plugs can act as supporter in reducing buckling length 	No effect	No effect	No effect
Improper spacer position creates channels and high porous zones in cement.	No effect	No effect	Casing helical and s-shape buckling produces significant error in placement of plugs and evaluation of plugs location which can cause unsealed layers and channelling in plugs.	**Casing Condition**	Larger casing diameter leads to easier and faster hole cleaning and plugging and pumping. 	No effect	No effect
Poor displacement of mud during cement placement can bypass a continuous channel of drilling fluid traversing the annulus. Also microannuli at the cement's interfaces can form as a result of thermal or pressure fluctuation during cementing operation.	Poor cement placement causes fluid-cement contamination which reduces the cement's strength. 	No effect	Vandalism may cause plug failure.	Pressures higher than casing burst strength in integrity test and squeeze cementing lead to casing rupture. Also pre-tensioning of the casing, using centralization, and pick up application before landing can reduce buckling danger.	**Time Effect & Future Human Activities**	CO_2 capture process and resources carbon dioxide produces from effects on injected gas properties.	Time duration will increase trapping mechanisms which will reduce CO_2 pressure in Carbon Storage
Attack of high partial pressures of CO_2, low pH causes degrading and corrosion of liner.	Input of high concentrations of CO_2 degrade borehole linings with time	H_2S dissolved in wellbore fluid produced Sulphuric Acid and the CO_2 solubility in formation water decreases as salinity increase	Input of high concentrations of CO_2 degrades borehole plugs with time. Also reduced temperature caused by injection applies thermal stresses.	H_2S present in impure CO_2 accelerates corrosion of metal casing. Also increasing in casing axial load caused by pumping of liquid CO_2 can be critical.	No effect	**Injected CO_2 Gas Properties (Purity and Temperature)**	No effect
No effect	No effect	Increasing CO_2 content in reservoir may increase insitu carbonic acid. 	No effect	Carbonic acid accelerates casing corrosion, and decrease casing life time. Also tubing leak in injection time decrease casing tensile strength and may cause burst rupture. 	CO_2 leakage decreases reservoir pressure may lead to injection increasing pressure. 	No effect	**Bottom Wellbore CO_2 Pressure**

Appendix E: AHP Evaluation for Event Tree Branches – Leakage Paths Ranking Evaluation Questionnaire

Place a check sign in place that implies your expression of relation between two given consequences severity in Weyburn Project.

	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
Verbal Expression A						✓												Verbal Expression B

Placing a check sign to the left of equal indicates that verbal expression A implies a higher probability of occurrence than B

Placing a check sign to the right of equal indicates that verbal expression B implies a higher probability of occurrence than A

		Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
Leakage Paths	Leakage in Air																		Leakage in Ground Water
	Leakage in Air																		Leakage in Drinking Water
	Leakage in Ground Water																		Leakage in Drinking Water
Leakage in Air (Risk Potentials)	People Asphyxiation or Death																		Plants Death
	People Asphyxiation or Death																		Animals Asphyxiation or Death
	Animals Asphyxiation or Death																		Plants Death
Leakage in Ground Water (Risk Potentials)	People Toxication																		Plants Death
	People Toxication																		Animals Toxication
	Animals Toxication																		Plants Death
Leakage in Potable Water (Risk Potentials)	People Toxication																		Plants Death
	People Toxication																		Animals Toxication
	Animals Toxication																		Plants Death

Appendix F: Opinions of the Expert Committee for Implementing a Risk Assessment on Weyburn CO_2-EOR Storage – How Much Safe is Weyburn CO_2-EOR Storage?

The final objective of this research is to develop a framework for risk assessment of CO2 geological storage projects. This objective will be achieved by using BowTie method as a framework for CO2 geological storage system, and using Fuzzy Logic theory and Dempster-Shafer theory to combine different issues of risk producers as: leakage flux, leakage duration and likelihood of leakage. The inputs in this study will be collected from opinions of experts plan. This questionnaire is important part in this study.

This questionnaire takes approximately 20 minutes to complete. Confidentiality is of utmost importance to us. Neither your identity nor your personal answers will be revealed in any manner.

Initial Benchmarking

Only answer one of the choices. Choose the nearest choice which fit you.

3. I am considering myself as ....

- **a.** NGO
- **b.** Industry
- **c.** Academia
- **d.** Government

4. I consider myself expert in ....

- **a.** Well Completion
- **b.** Caprock Integrity
- **c.** Monitoring
- **d.** Risk Assessment
- **e.** Reservoir Engineering
- **f.** Production
- **g.** Drilling
- **h.** Stimulation
- **i.** Others

5. I agree that CCS can play an important role in Reducing Canada's GHG Emission

- **a.** Strongly Agree
- **b.** Agree
- **c.** Disagree
- **d.** Strongly Disagree

Risk Acceptance Evaluation – Environment Evaluation

6. Choose the more similar country in the matter of Media Freedom and Media (such as Newspaper, TV, and radio) accessibility in the whole country to Canada.

Former Soviet Union	Hungary	Norway	Poland	United States or France
☐	☐	☐	☐	☐

7. Select your best answer for each question which is asked.

	SPECIFIC ELEMENTS						
Oil Companies Conducting CCS	KNOWLEDGE AND EXPERTISE What is your assessment over the degree of knowledge and expertise of people working in petroleum companies conducting CCS?						
	So Amateur ☐	Amateur ☐	Low ☐	Moderate ☐	Limited ☐	Expert ☐	Very Expert ☐
	OPENNESS AND HONESTY How much honest do you feel that people in high positions working in petroleum companies conducting CCS are?						
	So Dishonest ☐	Dishonest ☐	Low ☐	Moderate ☐	Limited ☐	Open ☐	Very Open ☐
	CONCERN AND CARE How much careful do you feel that people working in petroleum companies conducting CCS are?						
	So Careless ☐	Careless ☐	Low ☐	Moderate ☐	Limited ☐	Careful ☐	Very Careful ☐

Regulatory Bodies	KNOWLEDGE AND EXPERTISE What is your assessment over the degree of knowledge and expertise of people working in regulatory bodies regulating CCS?						
	So Amateur ☐	Amateur ☐	Low ☐	Moderate ☐	Limited ☐	Expert ☐	Very Expert ☐
	OPENNESS AND HONESTY How much honest and open do you feel that people working in regulatory bodies regulating CCS are?						
	So Dishonest ☐	Dishonest ☐	Low ☐	Moderate ☐	Limited ☐	Open ☐	Very Open ☐
	CONCERN AND CARE How much careful do you feel that people working in regulatory bodies regulating CCS are?						
	So Careless ☐	Careless ☐	Low ☐	Moderate ☐	Limited ☐	Careful ☐	Very Careful ☐

Circle your best answer to the following questions:

8. How you categorized your familiarity with details of Weyburn project?

- **a.** Very Low
- **b.** Low
- **c.** Moderate
- **d.** High
- **e.** Very High

9. By knowing that there are 37,680 wells in Alberta at the end of 2006. Can you guess "How many wells in Alberta are leaking?"

- **a.** Less than 500
- **b.** 500 - 1000
- **c.** 1000 - 2500
- **d.** 2500 - 5000
- **e.** 5000 - 10000
- **f.** Over 10000

10. What is the Absolute Permeability of intact cement with porosity of 10%?

- **a.** Less than 0.000005 μD
- **b.** 0.000005 - 0.0005 μD
- **c.** 0.0005 - 0.05 μD
- **d.** 0.05 – 5.0 μD
- **e.** 5 - 500 μD
- **f.** 500 μD - 5000 μD

11. What is the common good cement porosity?

- **a.** Less than 5%
- **b.** 5% - 10%
- **c.** 10% - 20%
- **d.** 20% - 30%
- **e.** 30% - 40%

12. What is the porosity of unfractured shale caprock?

- **a.** Less than 1%
- **b.** 1% - 5%
- **c.** 5% - 10%
- **d.** 10% - 20%
- **e.** Over 20%

Risk Assessment Evaluation - Failure Mechanisms Ranking Evaluation

13. Place a check sign in place that implies your expression of relation between A and B, which are different failure mechanism indicating the risk occurrence.

	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
A						✓												B

Placing a check sign to the left of equal indicates that verbal expression A implies a higher probability of occurrence than B

Placing a check sign to the right of equal indicates that verbal expression B implies a higher probability of occurrence than A

		Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
Biosphere	Air Contamination																		Water Contamination
Geosphere	Pipeline Failure																		Wellbores Leakage
	Pipeline Failure																		Fault Leakage
	Pipeline Failure																		Caprock Leakage
	Pipeline Failure																		Dissolved CO_2 Escapes in GW
	Wellbores Leakage																		Fault Leakage
	Wellbores Leakage																		Caprock Leakage
	Wellbores Leakage																		Dissolved CO_2 Escapes in GW
	Fault Leakage																		Caprock Leakage
	Fault Leakage																		Dissolved CO_2 Escapes in GW
	Caprock Leakage																		Dissolved CO_2 Escapes in GW
Caprock	Diffusion Through Caprock																		Microseismicity Caused by Injection
	Diffusion Through Caprock																		Hydraulic Pressure Opens Fracture
	Diffusion Through Caprock																		Erosion of Caprock (Chemical Reaction)
	Microseismicity Caused by Injection																		Hydraulic Pressure Opens Fracture
	Microseismicity Caused by Injection																		Erosion of Caprock (Chemical Reaction)
	Hydraulic Pressure Opens Fracture																		Erosion of Caprock (Chemical Reaction)
Wellbore	Cement and Casing																		Cement and Rock
	Cement and Casing																		Through Cement Plugs
	Cement and Casing																		Through Cement
	Cement and Rock																		Through Cement Plugs
	Cement and Rock																		Through Cement
	Through Cement Plugs																		Through Cement

14. Fill table 1a, 1b and 1c for ***Weyburn EOR project specific*** according to ranges shown in figure 1. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to questions asked in table 1.

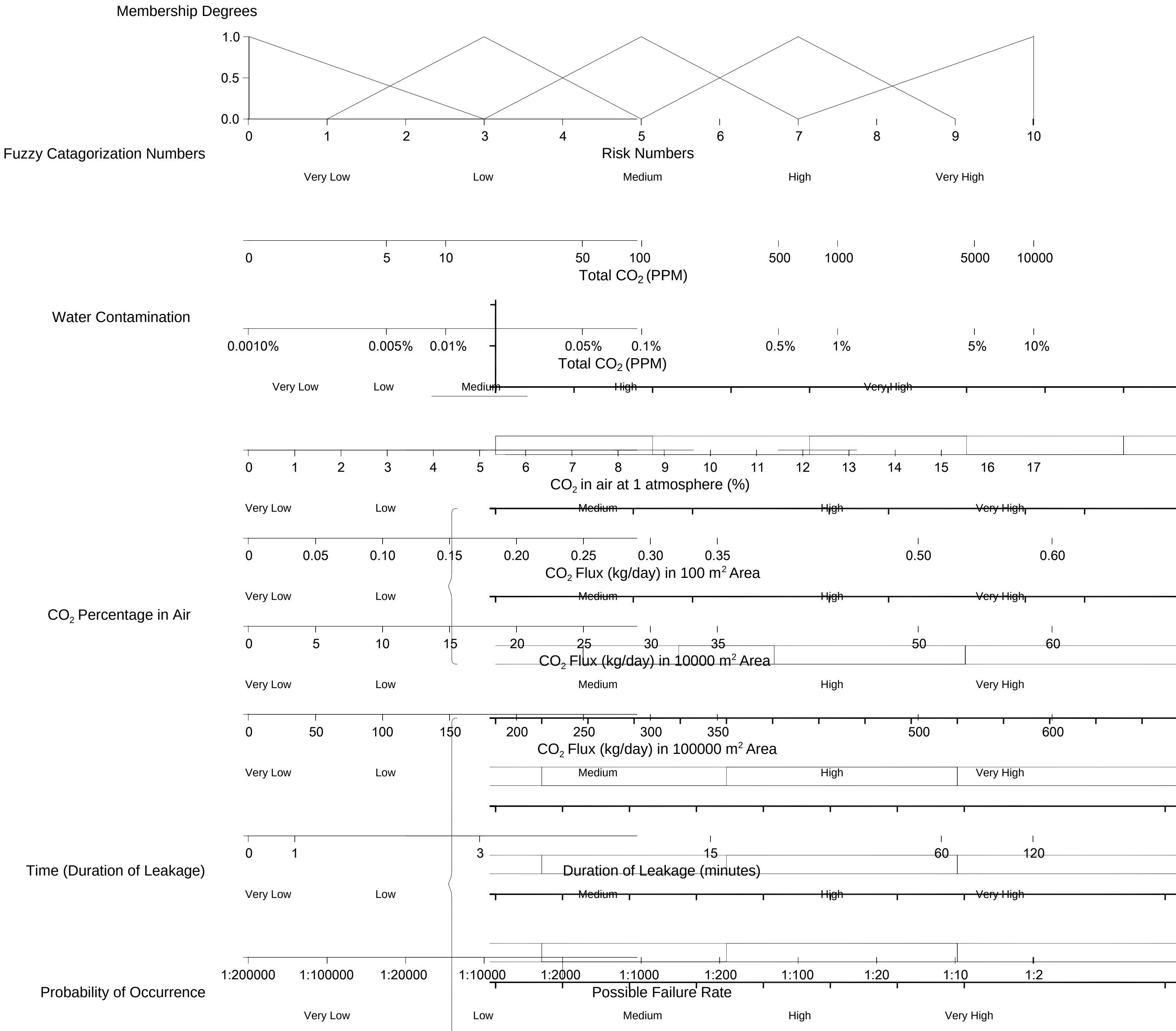


Figure 1. Categories for different experts' opinion for CO_2 Concentration and Duration and Probability

Table 1a. Experts' Evaluation for Different Failure's Incidents (Wellbore and Fault related Incidents)

	Leakage Incidents	Expert's Evaluation				
Wellbore Leakage Incidents	Mechanism of Leakage Between Cement and Casing	**How Likely is this mechanism to occur?**				
		Very Low □	Low □	Moderate □	High □	Very High □
		If it occurs, what would be the expected CO_2 Flux rate?				
		Very Low □	Low □	Moderate □	High □	Very High □
		If it occurs, what would be the expected Duration of Leakage?				
		Very Low □	Low □	Moderate □	High □	Very High □
	Mechanism of Leakage Between Cement and Formation	**How Likely is this mechanism to occur?**				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected CO_2 Flux rate?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected Duration of Leakage?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
	Mechanism of Leakage through Cement Plugs	**How Likely is this mechanism to occur?**				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected CO_2 Flux rate?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected Duration of Leakage?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
	Mechanism of Leakage through Cement (Diffusion and Pressure Induced Leakage)	**How Likely is this mechanism to occur?**				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected CO_2 Flux rate?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected Duration of Leakage?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
	Mechanism of Fault Leakage	**How Likely is this mechanism to occur?**				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected CO_2 Flux rate?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected Duration of Leakage?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □

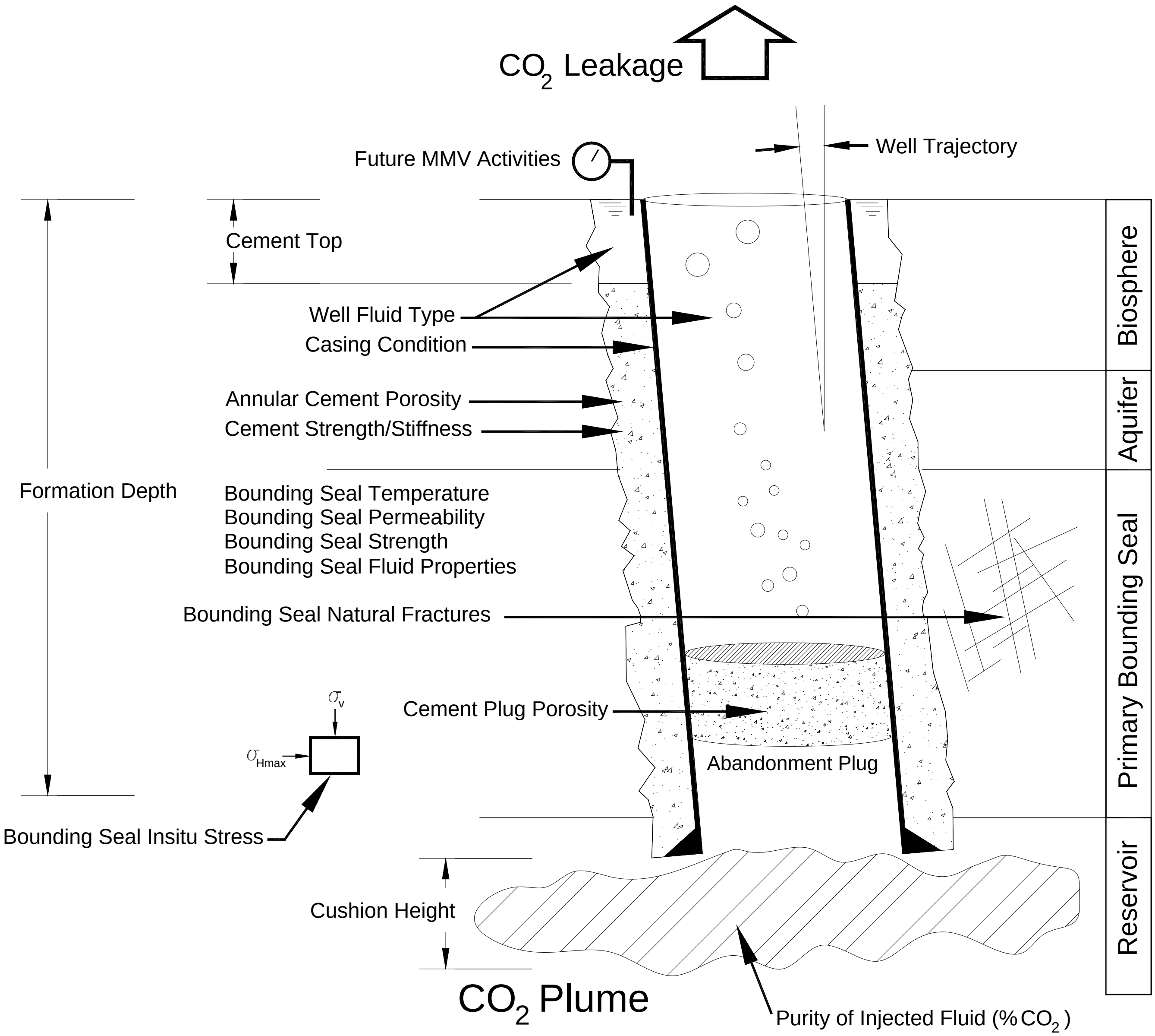
Table 1b. Experts' Evaluation for Different Failure's Incidents (Caprock related Incidents)

	Escalators	Expert's Evaluation				
Caprock Leakage Incidents	Diffusion through Caprock	**How Likely is this mechanism to occur?**				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected CO_2 Flux rate?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected Duration of Leakage?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
	Microseismicity Caused by Injection Opens Fractures	**How Likely is this mechanism to occur?**				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected CO_2 Flux rate?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected Duration of Leakage?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
	Hydraulic Pressure Opens Fracture	**How Likely is this mechanism to occur?**				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected CO_2 Flux rate?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected Duration of Leakage?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
	Erosion of Caprock due to Chemical Reaction with CO_2	**How Likely is this mechanism to occur?**				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected CO_2 Flux rate?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected Duration of Leakage?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
Pipeline Failure		**How Likely is this mechanism to occur?**				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected CO_2 Flux rate?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □
		If it occurs, what would be the expected Duration of Leakage?				
		Very Low □	Very Low □	Very Low □	Very Low □	Very Low □

Table 1c. Experts' Evaluation for Different Failure's Incidents for Water Contamination

	Different Failure Incident	Experts Evaluation for Water Contamination resulted from CO_2 Leakage				
Caprock Leakage	Diffusion through Caprock	Very Low □	Low □	Moderate □	High □	Very High □
	Microseismicity Caused by Injection Opens Fractures	Very Low □	Low □	Moderate □	High □	Very High □
	Hydraulic Pressure Opens Fracture	Very Low □	Low □	Moderate □	High □	Very High □
	Erosion of Caprock due to Chemical Reaction with CO_2	Very Low □	Low □	Moderate □	High □	Very High □
Wellbore Leakage	Leakage Between Cement and Casing	Very Low □	Low □	Moderate □	High □	Very High □
	Leakage Between Cement and Formation	Very Low □	Low □	Moderate □	High □	Very High □
	Leakage through Cement Plugs	Very Low □	Low □	Moderate □	High □	Very High □
	Leakage through Cement	Very Low □	Low □	Moderate □	High □	Very High □
Mechanism of Fault Leakage		Very Low □	Low □	Moderate □	High □	Very High □

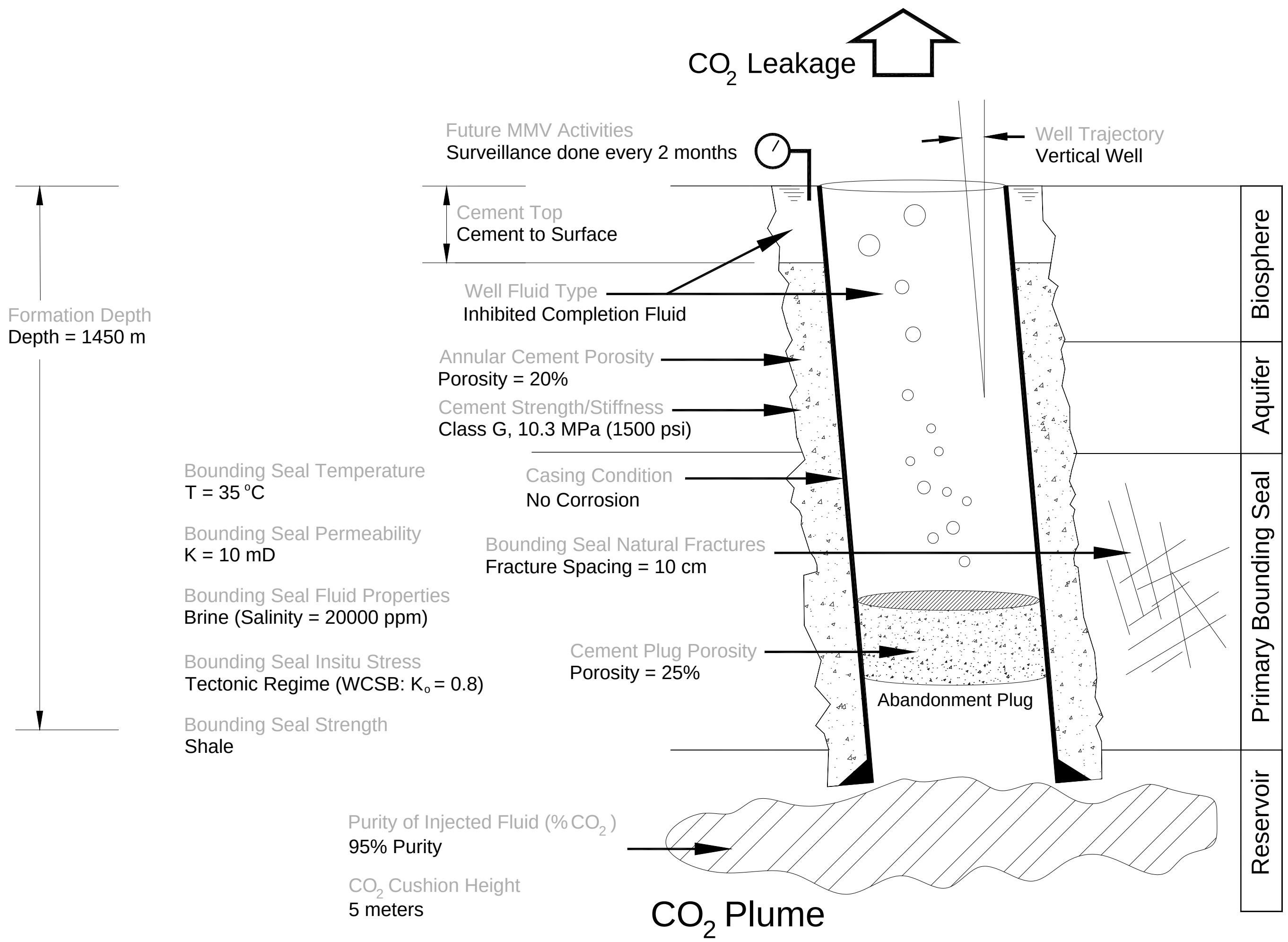
15. In following table evaluate the Importance of each well system property in Long-Term Well Integrity. In other word by choosing linguistic words as Very Low, Low, Medium, High and Very High use your judgment to evaluate the role of each component of wellbore integrity in long term.



The following table is given for your evaluation over the Importance of each well property in Long-Term Well Integrity.

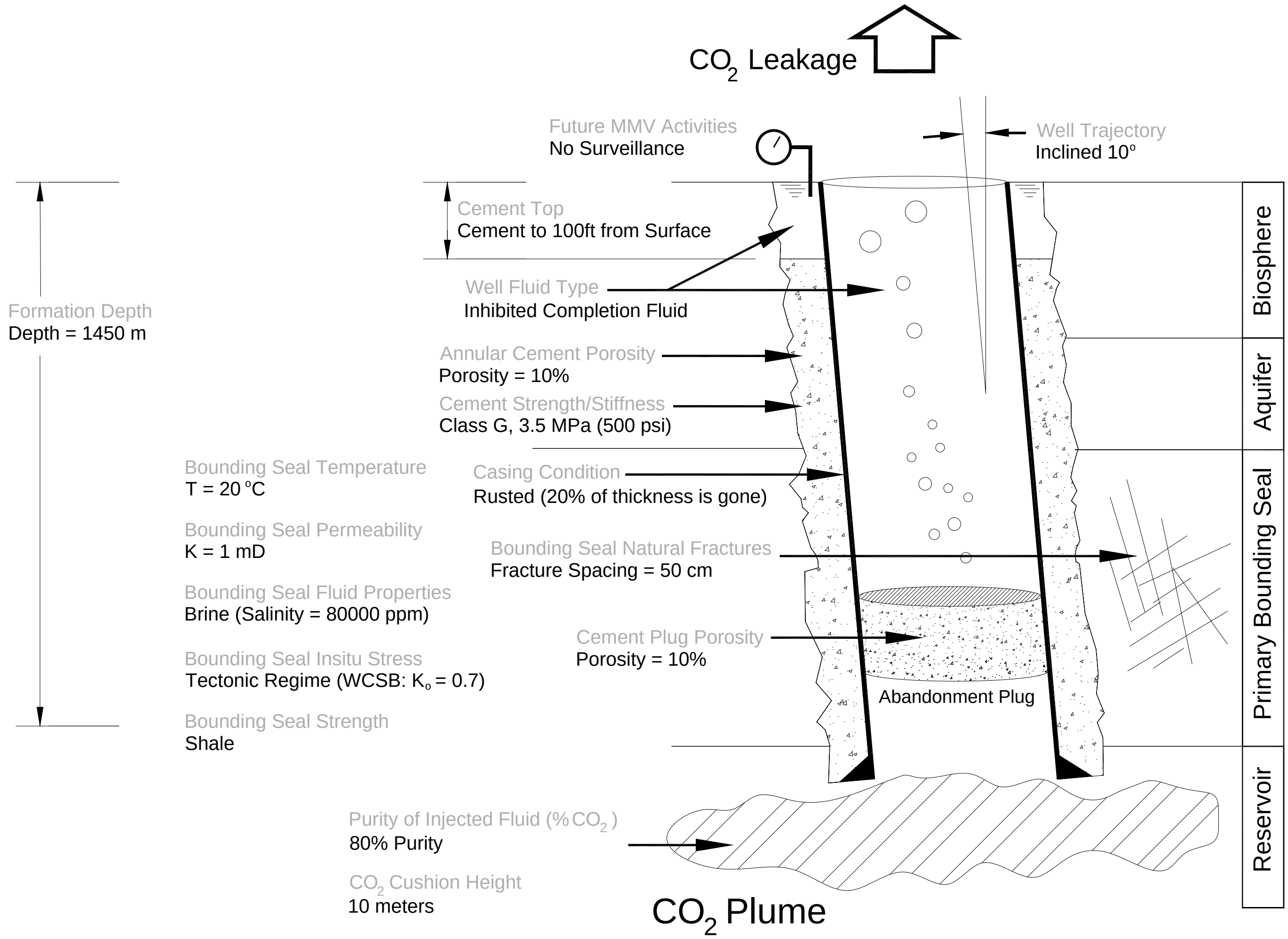
Well System Properties	**Importance of Variable for Long-Term Well Integrity**				
Well Trajectory	Very Low □	Low □	Moderate □	High □	Very High □
Formation Depth (Reservoir Depth)	Very Low □	Low □	Moderate □	High □	Very High □
Cement Top	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal Fluid Properties	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal In Situ Stress	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal Strength	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal Permeability	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal Natural Fractures	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal Temperature	Very Low □	Low □	Moderate □	High □	Very High □
Annular Cement Porosity	Very Low □	Low □	Moderate □	High □	Very High □
Cement Strength Properties	Very Low □	Low □	Moderate □	High □	Very High □
Wellbore's Fluids Chemical Properties	Very Low □	Low □	Moderate □	High □	Very High □
Cement Plug Porosity	Very Low □	Low □	Moderate □	High □	Very High □
Casing Condition	Very Low □	Low □	Moderate □	High □	Very High □
Future MMV Activities	Very Low □	Low □	Moderate □	High □	Very High □
CO_2 Cushion Height (Buoyancy)	Very Low □	Low □	Moderate □	High □	Very High □
Purity of Injected Fluids (CO_2)	Very Low □	Low □	Moderate □	High □	Very High □

Case A1: Select your evaluated CO_2 leakage likelihood for the following wellbore scenario based on given data in following figure. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to this question.



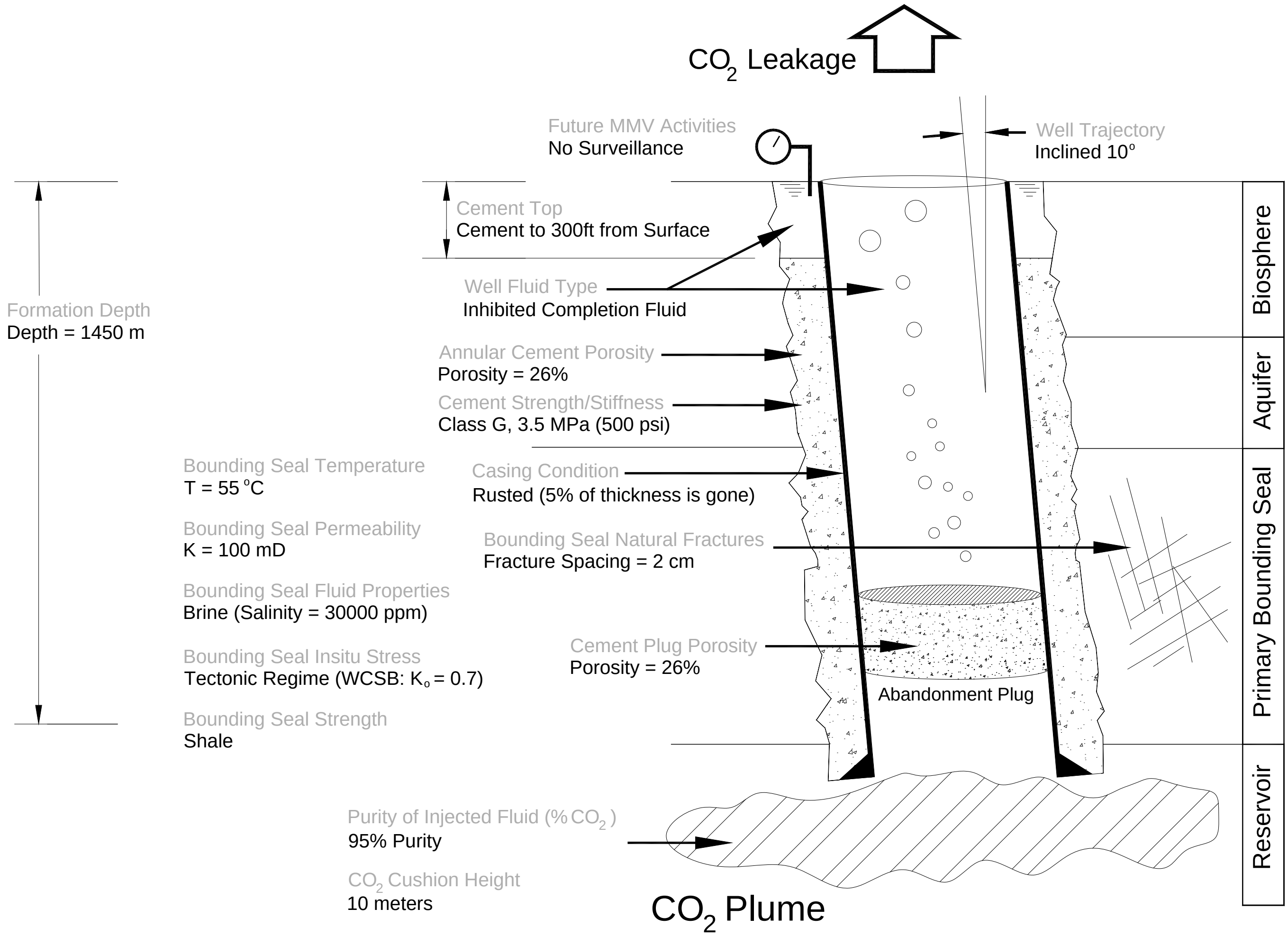
Likelihood of CO_2 Leakage from Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

Case A2: Select your evaluated CO_2 leakage likelihood for the following wellbore scenario based on given data in following figure. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to this question.



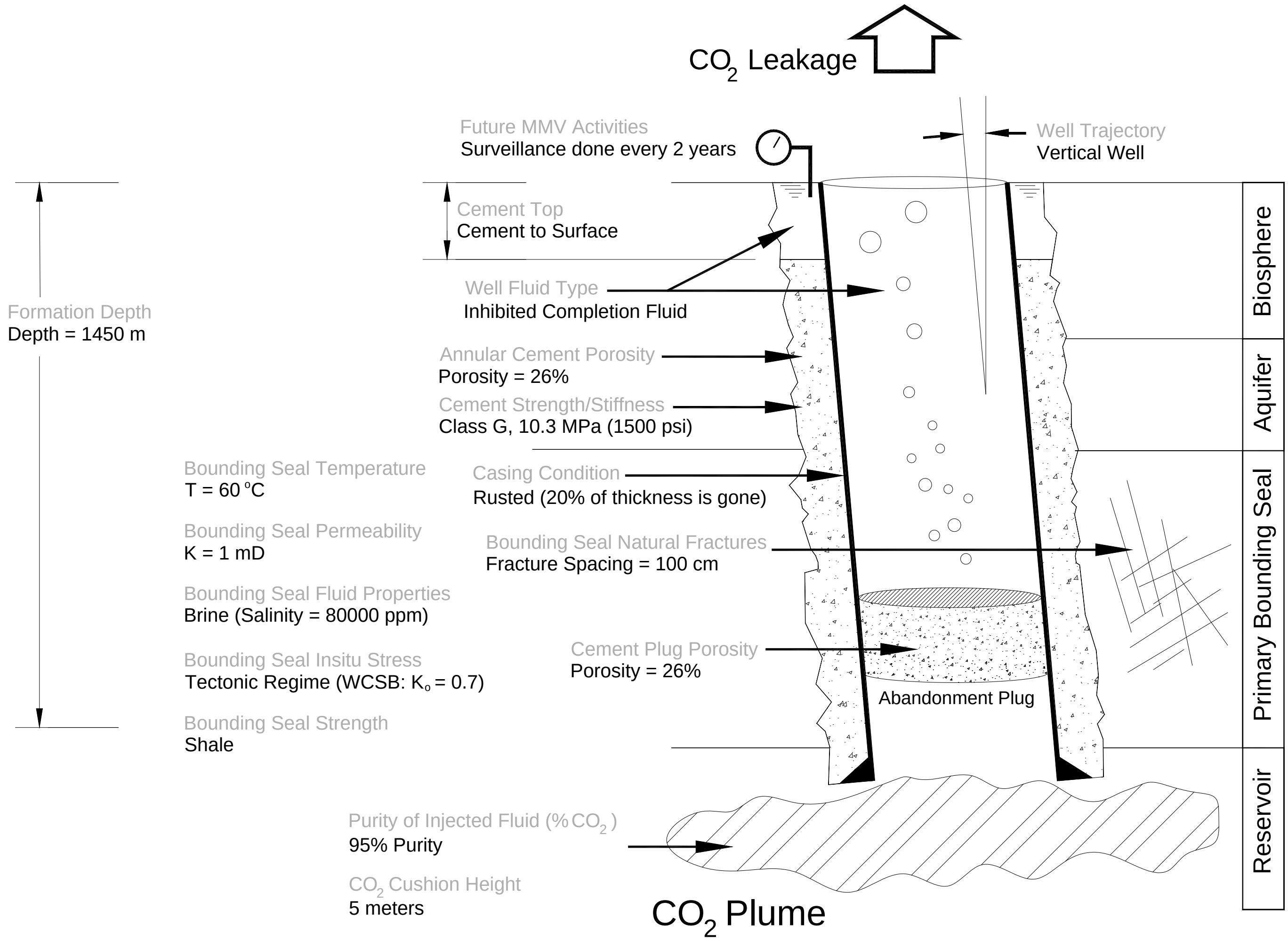
Likelihood of CO_2 Leakage from Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

Case A3: Select your evaluated CO_2 leakage likelihood for the following wellbore scenario based on given data in following figure. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to this question.



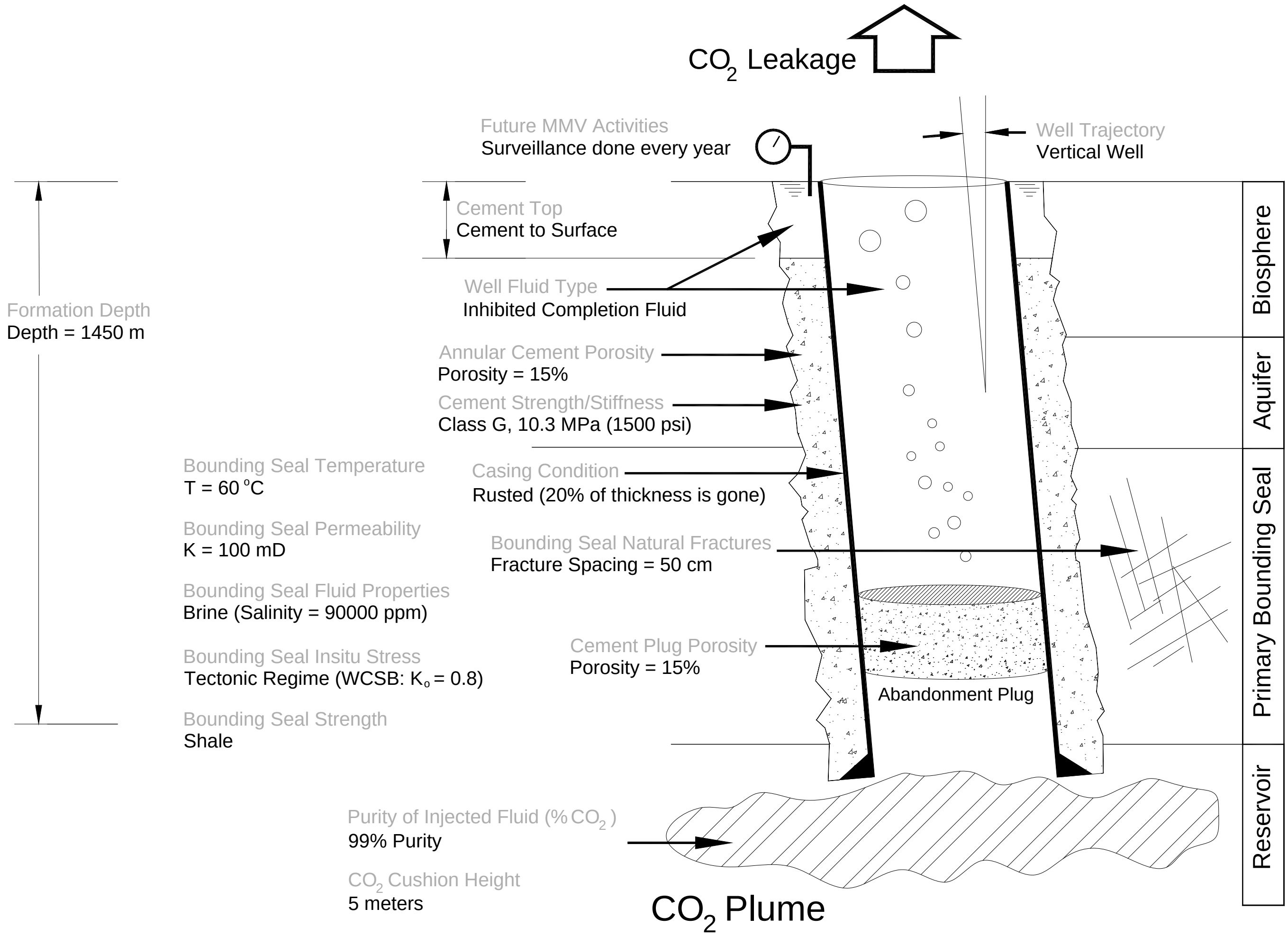
Likelihood of CO_2 Leakage from Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

Case A4: Select your evaluated CO_2 leakage likelihood for the following wellbore scenario based on given data in following figure. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to this question.



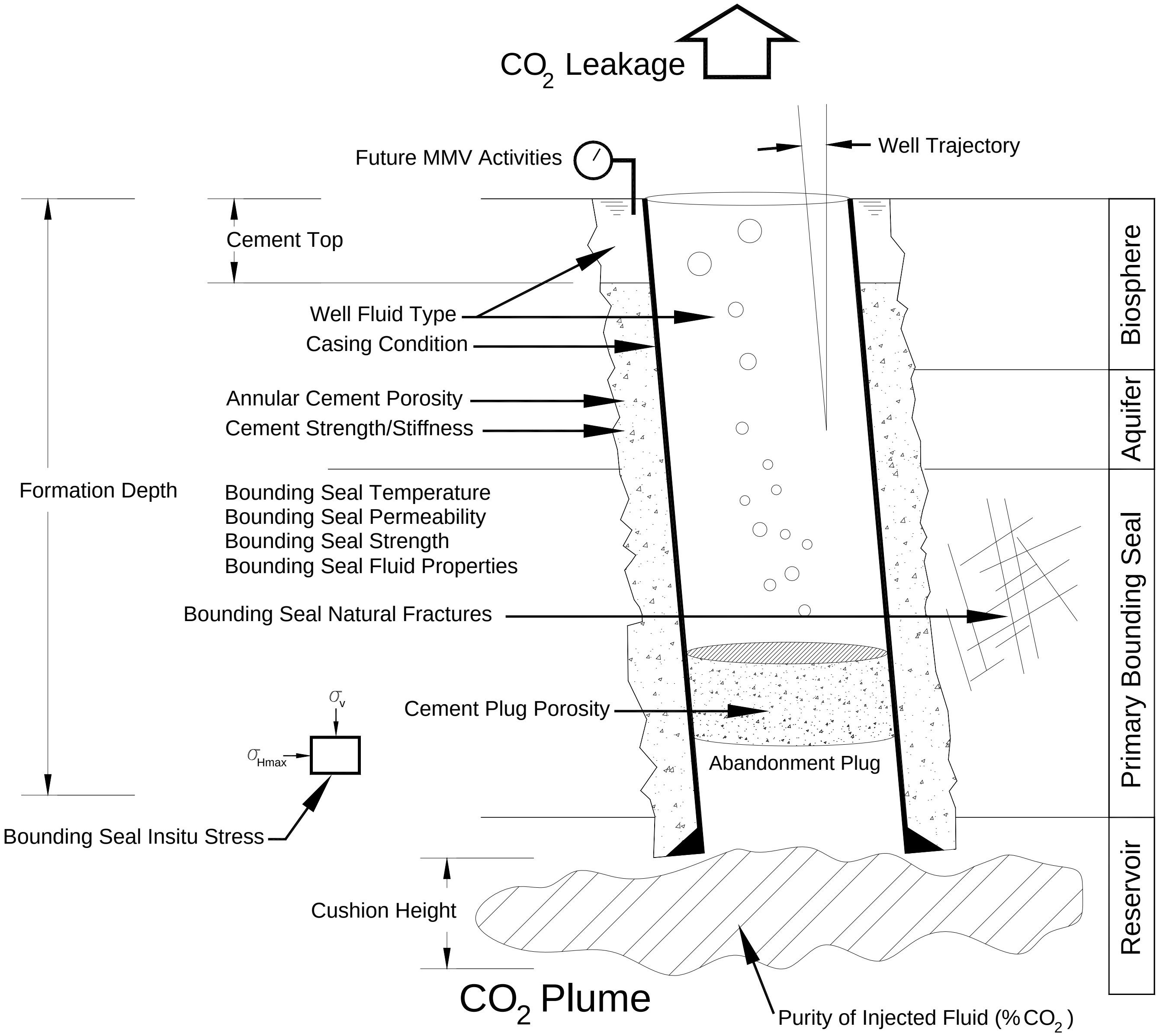
Likelihood of CO_2 Leakage from Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

Case A5: Select your evaluated CO_2 leakage likelihood for the following wellbore scenario based on given data in following figure. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to this question.



Likelihood of CO_2 Leakage from Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

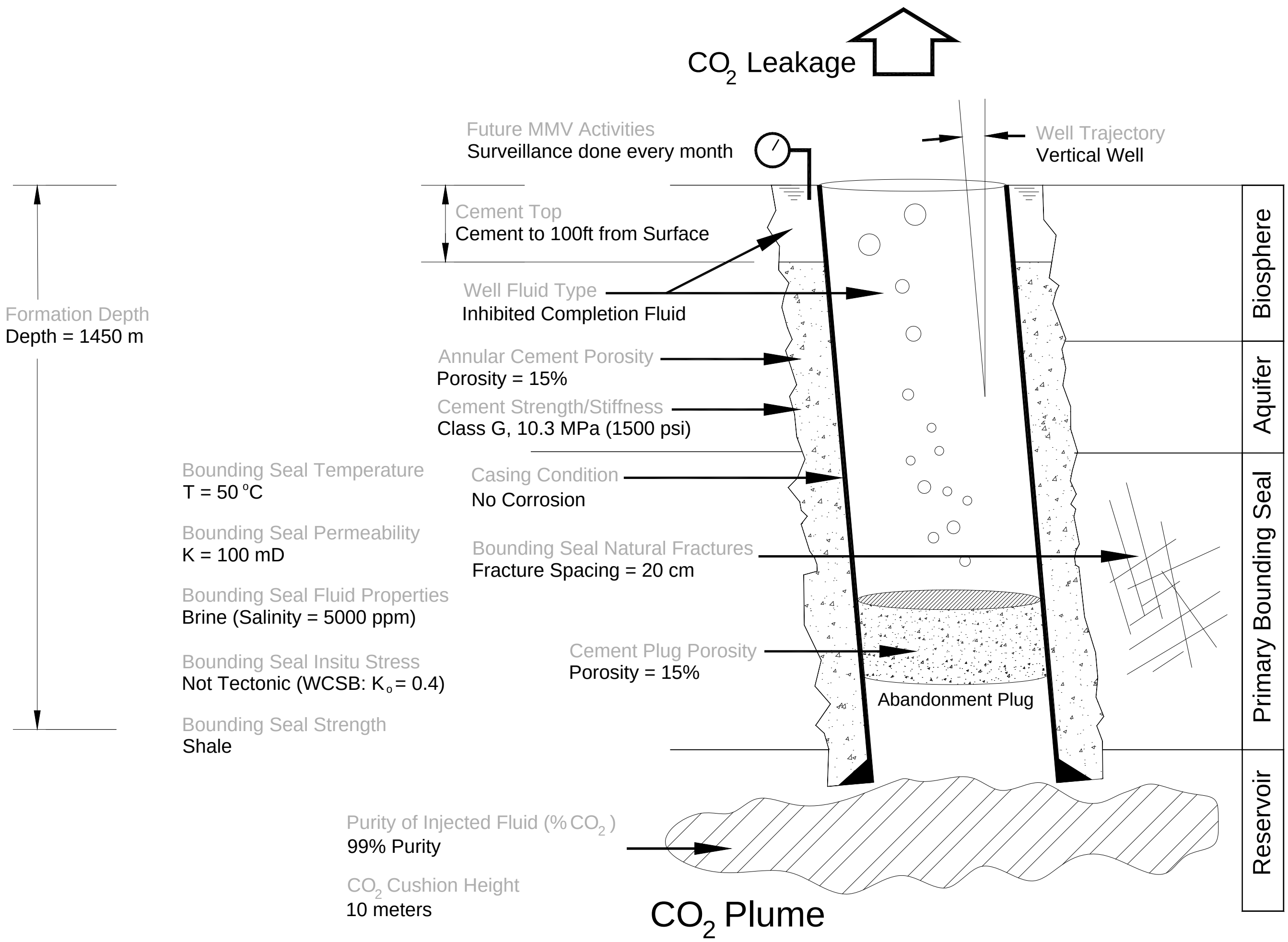
16. In following table evaluate the Importance of each well system property in Long-Term Well Integrity. In other word by choosing linguistic words as Very Low, Low, Medium, High and Very High use your judgment to evaluate the role of each component of wellbore integrity in long term.



The following table is given for your evaluation over the Importance of each well property in Long-Term Well Integrity.

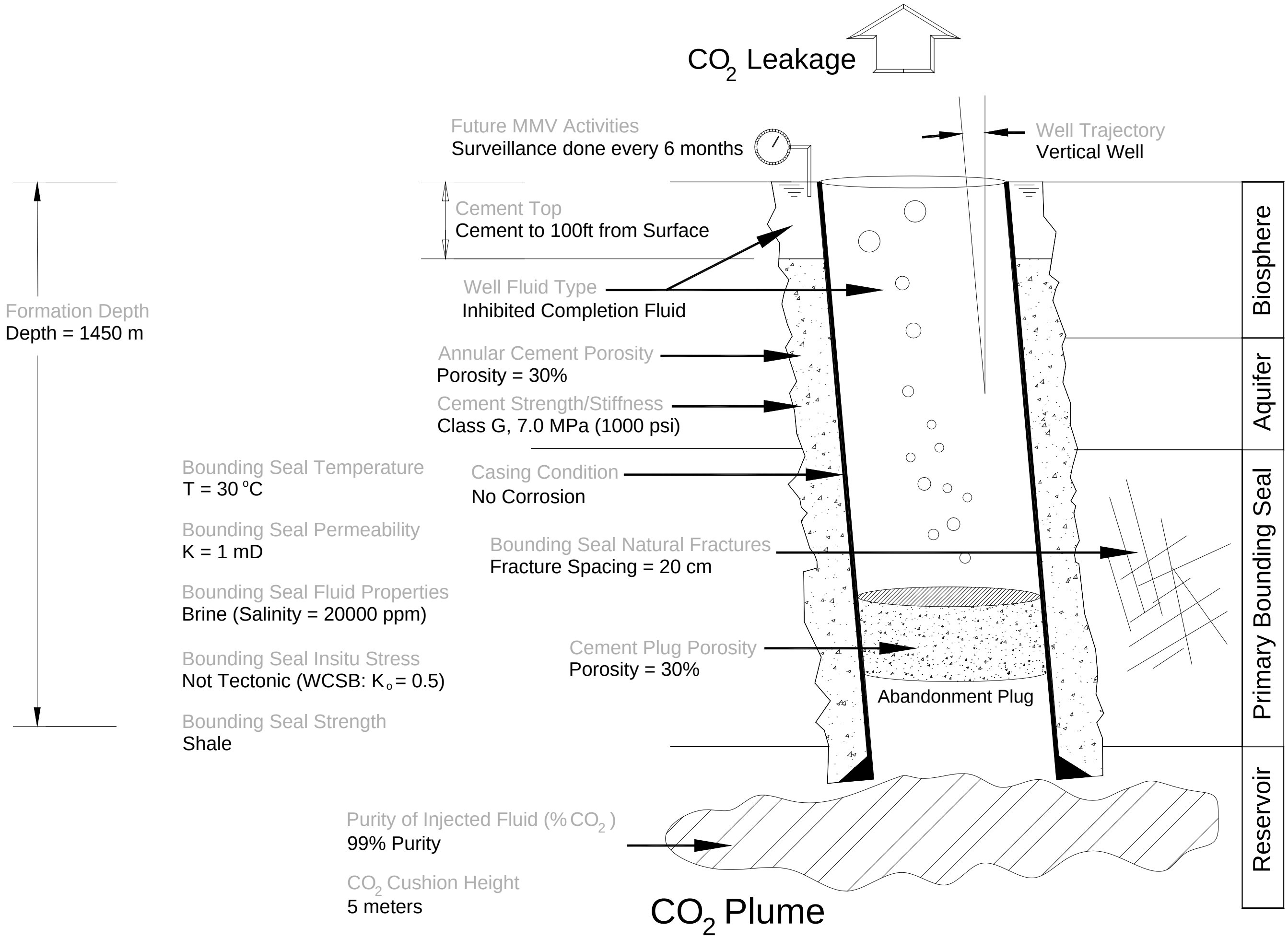
Well System Properties	**Importance of Variable for Long-Term Well Integrity**				
Well Trajectory	Very Low □	Low □	Moderate □	High □	Very High □
Formation Depth (Reservoir Depth)	Very Low □	Low □	Moderate □	High □	Very High □
Cement Top	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal Fluid Properties	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal In Situ Stress	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal Strength	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal Permeability	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal Natural Fractures	Very Low □	Low □	Moderate □	High □	Very High □
Bounding Seal Temperature	Very Low □	Low □	Moderate □	High □	Very High □
Annular Cement Porosity	Very Low □	Low □	Moderate □	High □	Very High □
Cement Strength Properties	Very Low □	Low □	Moderate □	High □	Very High □
Wellbore's Fluids Chemical Properties	Very Low □	Low □	Moderate □	High □	Very High □
Cement Plug Porosity	Very Low □	Low □	Moderate □	High □	Very High □
Casing Condition	Very Low □	Low □	Moderate □	High □	Very High □
Future MMV Activities	Very Low □	Low □	Moderate □	High □	Very High □
CO_2 Cushion Height (Buoyancy)	Very Low □	Low □	Moderate □	High □	Very High □
Purity of Injected Fluids (CO_2)	Very Low □	Low □	Moderate □	High □	Very High □

Case B1: Select your evaluated CO_2 leakage likelihood for the following wellbore scenario based on given data in following figure. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to this question.



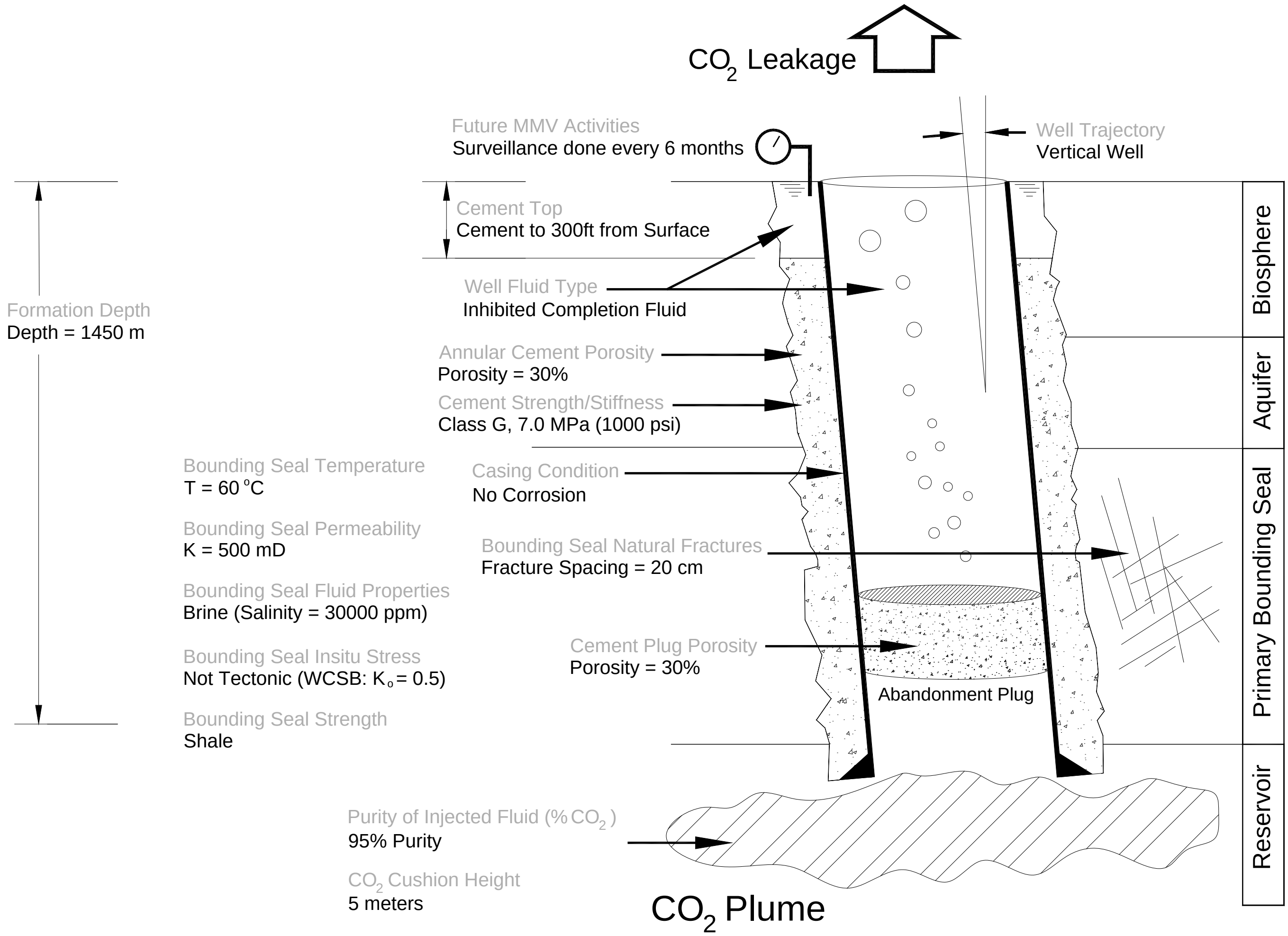
Likelihood of CO_2 Leakage from Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

Case B2: Select your evaluated CO_2 leakage likelihood for the following wellbore scenario based on given data in following figure. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to this question.



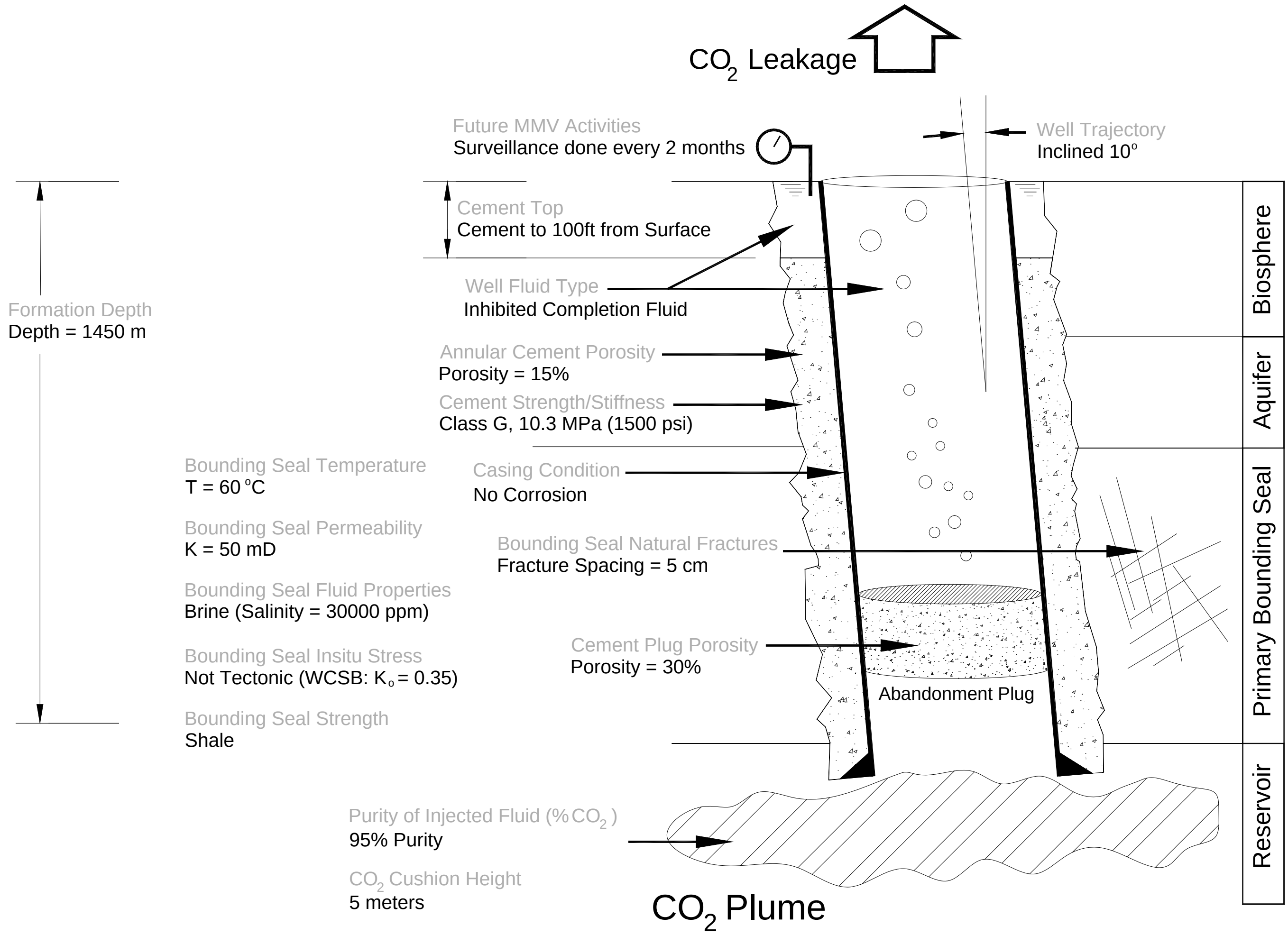
Likelihood of CO_2 Leakage from Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

Case B3: Select your evaluated CO_2 leakage likelihood for the following wellbore scenario based on given data in following figure. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to this question.



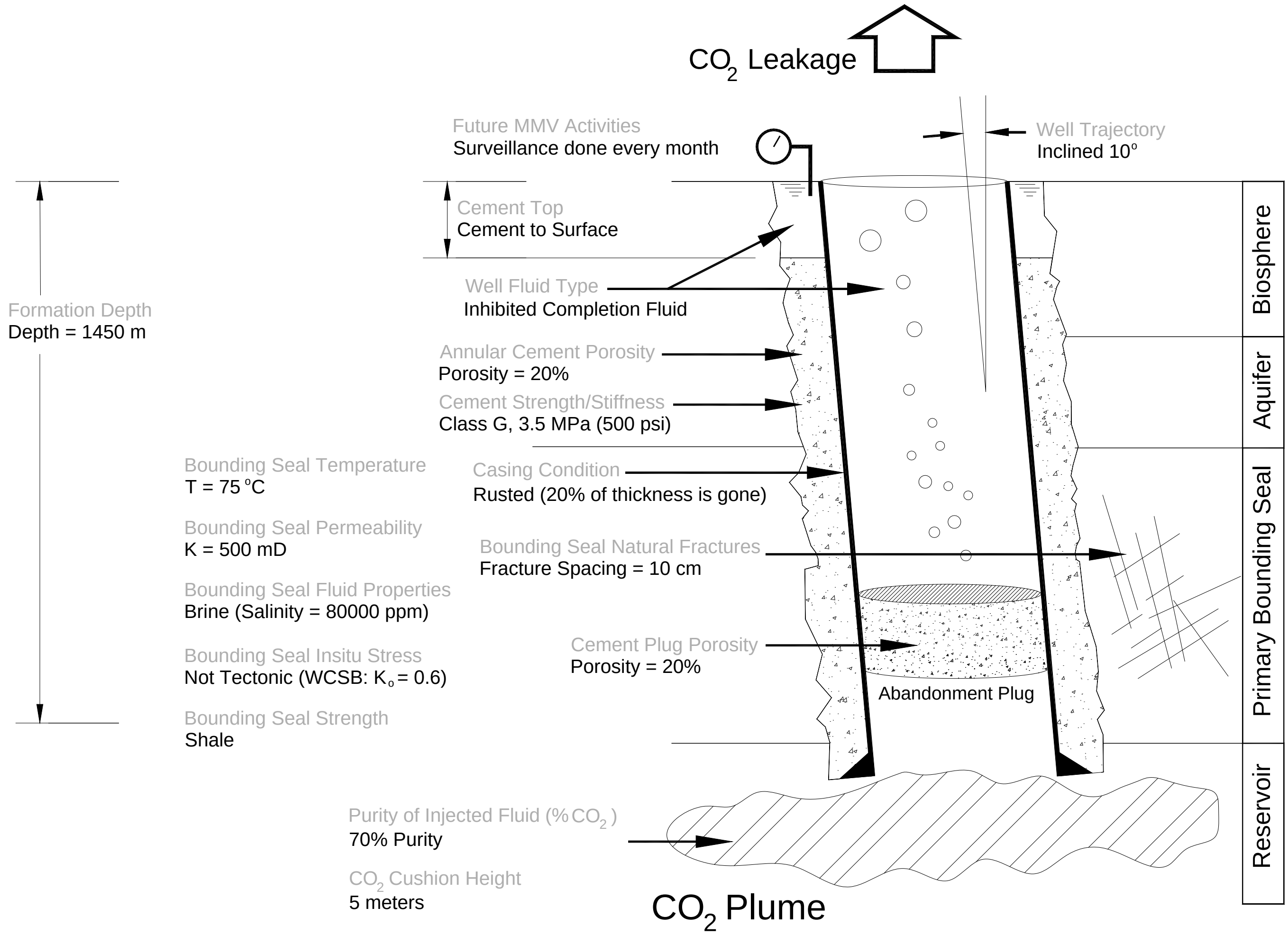
Likelihood of CO_2 Leakage from Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

Case B4: Select your evaluated CO_2 leakage likelihood for the following wellbore scenario based on given data in following figure. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to this question.



Likelihood of CO_2 Leakage from Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

Case B5: Select your evaluated CO_2 leakage likelihood for the following wellbore scenario based on given data in following figure. For your answers choose linguistic words as Very Low, Low, Medium, High and Very High. Use your best judgment regarding to this question.



Likelihood of CO_2 Leakage from Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

Appendix G: Early time and long-term properties evaluation

1. The following table is given to the experts for their evaluation over the condition of each well property in Long-Term Well Integrity.

	Well System Properties	Weyburn Condition for this Property				
	Casing Centralization	Very Poor □	Poor □	Moderate □	Good □	Very Good □
	Well Cleaning	Very Poor □	Poor □	Moderate □	Good □	Very Good □
	Cement Placement Efficiency	Very Poor □	Poor □	Moderate □	Good □	Very Good □
	Cement Volume Reduction	Very Poor □	Poor □	Moderate □	Good □	Very Good □
	Production & Injection Well History	Very Poor □	Poor □	Moderate □	Good □	Very Good □
Wellbore Condition at Weyburn (Midale) Reservoir	Well Trajectory	45° □	30° □	15° □	5° □	Vertical □
	Bounding Seal Fluid Properties	Oil □	Potable □	Low Salinity □	Saline □	High Salinity □
	Bounding Seal Insitu Stress	Very Low □	Low □	Moderate □	High □	Very High □
	Bounding Seal (Formation) Pressure	Very Low □	Low □	Moderate □	High □	Very High □
	Bounding Seal Strength	Very Low □	Low □	Moderate □	High □	Very High □
	Bounding Seal Permeability	Very Low □	Low □	Moderate □	High □	Very High □
	Bounding Seal Natural Fractures Condition	Negligible □	Very Small □	Blocky □	Fractured □	Jointed □
	Annular Cement Porosity	Very Low □	Low □	Moderate □	High □	Very High □
	Annular Cement Strength Properties	Very Low □	Low □	Moderate □	High □	Very High □
	Wellbore's Fluids Chemical Properties	Very Poor □	Poor □	Moderate □	Good □	Very Good □
	Cement Plug Porosity	Very Low □	Low □	Moderate □	High □	Very High □
	Casing Condition	Very Poor □	Poor □	Moderate □	Good □	Very Good □
	Purity of Injected Fluids (CO_2)	Pure CO_2 □	Not Pure □	Moderate □	Low H_2S □	High H_2S □

	Well System Properties	Weyburn Condition for this Property				
Wellbore Condition at Watrous Seal	Well Trajectory	45° □	30° □	15° □	5° □	Vertical □
	Bounding Seal Fluid Properties	Oil □	Potable □	Low Salinity □	Saline □	High Salinity □
	Bounding Seal Insitu Stress	Very Low □	Low □	Moderate □	High □	Very High □
	Bounding Seal (Formation) Pressure	Very Low □	Low □	Moderate □	High □	Very High □
	Bounding Seal Strength	Very Low □	Low □	Moderate □	High □	Very High □
	Bounding Seal Permeability	Very Low □	Low □	Moderate □	High □	Very High □
	Bounding Seal Natural Fractures Condition	Negligible □	Very Small □	Blocky □	Fractured □	Jointed □
	Annular Cement Porosity	Very Low □	Low □	Moderate □	High □	Very High □
	Annular Cement Strength Properties	Very Low □	Low □	Moderate □	High □	Very High □
	Wellbore's Fluids Chemical Properties	Very Poor □	Poor □	Moderate □	Good □	Very Good □
	Cement Plug Porosity	Very Low □	Low □	Moderate □	High □	Very High □
	Casing Condition	Very Poor □	Poor □	Moderate □	Good □	Very Good □
	Purity of Injected Fluids (CO_2)	Pure CO_2 □	Not Pure □	Moderate □	Low H_2S □	High H_2S □

Appendix H: Cause-Effect Evaluation – Wellbore Integrity Evaluation

2. In this part of questionnaire you will answer the effect of any parameters involved in wellbore integrity evaluation on other parameter. The results of this evaluation will be used to evaluate final wellbore index.

Expert's Cause-Effect Matrix Evaluation for long time Properties effect on Wellbore Long term Integrity

1. Well Trajectory effect on CO_2 Leakage Flux

CO_2 leakage flux is higher in vertical wellbores.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

2. Formation (Bounding Seal) Fluid Properties effect on CO_2 Leakage Flux

Chemical reactions may trap CO_2 as residual trapping.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

3. Formation (Bounding Seal) Insitu Stress effect on CO_2 Leakage Flux

High insitu stresses in formation (bounding seal) may degrade bonding between cement and formation (bounding seal) and accelerates CO_2 leakage through cement-formation interface.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

4. Formation (Bounding Seal) Pressure effect on CO_2 Leakage Flux

Formation (Bounding Seal) pressure increasing accelerates CO_2 leakage through Formation (Bounding Seal) and cement-formation interface.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

5. Formation (Bounding Seal) Strength effect on CO_2 Leakage Flux

Formation (Bounding Seal) strength impacts cement and formation (bounding seal) bonding strength which mitigates CO_2 leakage through cement-formation interface.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

6. Formation (Bounding Seal) Permeability effect on CO_2 Leakage Flux

Permeable formations (bounding seals) are susceptible to CO_2 leakage through Formation (Bounding Seal) and cement-formation interface.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

7. Formation (Bounding Seal) Fracture Condition effect on CO_2 Leakage Flux

Fractured formations (bounding seals) are susceptible to more CO_2 Leakage.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

8. Formation (Bounding Seal) Fluid Properties effect on Well Trajectory

Horizontal wells are mostly drilled in EOR project with low oil content.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

9. Formation (Bounding Seal) Insitu Stress effect on Well Trajectory

In some cases deviated wells are drilled for accommodating the high insitu stress formations (bounding seals) and anisotropic stress conditions. Wells drilled normal to maximum principle stress orientation are generally less stable.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

10. Formation (Bounding Seal) Pressure effect on Well Trajectory

Mean effective stress reduced in overpressure Formation (Bounding Seal) s

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

11. Formation (Bounding Seal) Strength effect on Well Trajectory

Inclined wellbores are less stable in rocks with anisotropic strength (e.g. fissile shales). Also sidetracking operation is applied for bypassing an unstable wellbore and exploring geologic features nearby unstable wellbore.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

12. Formation (Bounding Seal) Permeability effect on Well Trajectory

Horizontal wells are mostly drilled in low permeability Formation (Bounding Seal) , and heterogeneous carbonate reservoirs.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

13. Well Trajectory effect on Formation (Bounding Seal) Insitu Stress

Near Wellbore stress concentration affected by well trajectory.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

14. Formation (Bounding Seal) Pressure effect on Formation (Bounding Seal) Insitu Stress

Mean effective stress reduced in overpressure Formation (Bounding Seal) s.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

15. Formation (Bounding Seal) Strength effect on Formation (Bounding Seal) Insitu Stress

Weak compacting shales can create overpressures that are slow to dissipate with geologic time.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

16. Formation (Bounding Seal) Permeability effect on Formation (Bounding Seal) Insitu Stress

Formation (Bounding Seal) pressure acts as external pressure on casing and lining in permeable zones.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

17. Formation (Bounding Seal) Insitu Stress effect on Formation (Bounding Seal) Pressure

Active tectonic stresses can generate and maintain overpressure in shale.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

18. Formation (Bounding Seal) Strength effect on Formation (Bounding Seal) Pressure

Weak compacting shales can create overpressures that are slow to dissipate with geologic time.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

19. Formation (Bounding Seal) Permeability effect on Formation (Bounding Seal) Pressure

Formation (Bounding Seal) pressure acts as external pressure on casing and lining in permeable zones.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

20. Formation (Bounding Seal) Insitu Stress effect on Formation (Bounding Seal) Strength

Rock strength affected by current and paleo-stresses (e.g., fracture, compacting).

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

21. Formation (Bounding Seal) Pressure effect on Formation (Bounding Seal) Strength

Overpressured formations (bounding seals) have lower effective shear strength.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

22. Formation (Bounding Seal) Fracture Condition effect on Formation (Bounding Seal) Strength

Fracturing decreases strength.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

23. Well Trajectory effect on Formation (Bounding Seal) Permeability

Horizontal wells increase the global permeability of Formation (Bounding Seal) .

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

24. Formation (Bounding Seal) Fluid Properties effect on Formation (Bounding Seal) Permeability

Precipitation of solid particles in the Formation (Bounding Seal) fluid can decrease the effective permeability of the Formation (Bounding Seal) in the near-wellbore region. Also low viscous fluids as oil has lower relative permeability comparing to low viscous fluids as water.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

25. Formation (Bounding Seal) Insitu Stress effect on Formation (Bounding Seal) Permeability

Increasing insitu stress decreases void ratio which decreases permeability.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

26. Formation (Bounding Seal) Strength effect on Formation (Bounding Seal) Permeability

Loose material are susceptible to creep which may either increase or decrease the degree of sealing and therefore the potential for the region immediately around the borehole to act as a migration pathway for CO_2.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

27. Formation (Bounding Seal) Fracture Condition effect on Formation (Bounding Seal) Permeability

Formation (Bounding Seal) fracturing may lead to permeability increasing.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

28. Formation (Bounding Seal) Permeability effect on Formation (Bounding Seal) Fracture Condition

Good Well Trajectory choice will reduce fracturing around the wellbore.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

29. Formation (Bounding Seal) (Bounding Seal) Fluid Properties effect on Formation (Bounding Seal) Fracture Condition

Precipitation of solid particles in the formation (bounding seal) fluid can seal fractures in the near-wellbore region.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

30. Formation (Bounding Seal) Insitu Stress effect on Formation (Bounding Seal) Fracture Condition

Formations (Bounding Seal) in tectonic zones and zone with high horizontal stresses are susceptible to fracturing.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

31. Formation (Bounding Seal) Pressure effect on Formation (Bounding Seal) Fracture Condition

High pressure Formations (Bounding Seals) may lead to fracture opening.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

32. Formation (Bounding Seal) Strength effect on Formation (Bounding Seal) Fracture Condition

Weak Formations (Bounding Seals) are susceptible to fracturing.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

33. Cement Porosity effect on CO_2 Leakage Flux

Cement porosity increasing accelerates CO_2 leakage through cement.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

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34. Cement Strength Properties effect on CO_2 Leakage Flux

Cement strength impacts cement bonding strength and cement and plug adhesion which mitigates CO_2 leakage through cement and cement-plug interface.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

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35. Wellbore's Completion Fluids Properties effect on CO_2 Leakage Flux

Chemical reactions may trap CO_2 as residual trapping.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

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36. Cement Plug Porosity effect on CO_2 Leakage Flux

Cement plug porosity increasing accelerates CO_2 leakage through cement plugs.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

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37. Casing Condition effect on CO_2 Leakage Flux

Poor casing centralization creates channeling which causes CO_2 leakage.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

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38. Time Effect & Future Human Activities effect on CO_2 Leakage Flux

Work-over operations may degrade cement and plugs and accelerate CO_2 leakage.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

39. Injected CO_2 Gas Properties (Purity and Temperature) effect on CO_2 Leakage Flux

Salinity decreases CO_2 solubility and reduces solubility trapping and also reducing in temperature hydrates CO_2 and decreases gas gradient.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

40. Bottom Wellbore CO_2 Pressure effect on CO_2 Leakage Flux

Higher CO_2 reservoirs are susceptible to higher CO_2 leakage flux.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

41. Time Effect & Future Human Activities effect on Well Trajectory

Sidetracking operation may be done intentionally in inaccessible wellbores due to an irretrievable fish or junk in the hole or in a collapsed wellbores or may occur accidentally.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

42. Wellbore's Completion Fluids Properties effect on Formation (Bounding Seal) Fluid Properties

Chemical reactions between the drilling fluid and the Formation (Bounding Seal) fluid can precipitate solids that plug pore spaces.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

43. Cement Plug Porosity effect on Formation (Bounding Seal) Fluid Properties

Cement will be degraded by high concentrations of sulphate, chloride, and magnesium ions in the Formation (Bounding Seal) fluid.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

44. Injected CO_2 Gas Properties (Purity and Temperature) effect on Formation (Bounding Seal) Fluid Properties

CO_2 injection increases the Formation (Bounding Seal) fluid acidity and reduce reservoir fluid pH.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

45. Bottom Wellbore CO_2 Pressure effect on Formation (Bounding Seal) Fluid Properties

High CO_2 content in CO_2 reservoir can reduce pH aquifers' fluid.

Very Low or No Effect ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

46. Injected CO_2 Gas Properties (Purity and Temperature) effect on Formation (Bounding Seal) Insitu Stress

CO_2 injection cool down the Formation (Bounding Seal) which cause insitu stress reduction in Formation (Bounding Seal) and caprock.

Very Low or No Effect ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

47. Bottom Wellbore CO_2 Pressure effect on Formation (Bounding Seal) Insitu Stress

Higher CO_2 pressure in reservoir decreases reservoir pressure which leads to Formation (Bounding Seal) insitu stress reduction.

Very Low or No Effect ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

48. Cement Porosity effect on Formation (Bounding Seal) Pressure

Cement porosity impacts Formation (Bounding Seal) external pressure on casing and lining.

Very Low or No Effect ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

49. Injected CO_2 Gas Properties (Purity and Temperature) effect on Formation (Bounding Seal) Pressure

CO_2 injection pressurize reservoir which can cause over-pressurizing the Formation (Bounding Seal) .

Very Low or No Effect ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

50. Bottom Wellbore CO_2 Pressure effect on Formation (Bounding Seal) Pressure

High CO_2 pressure can pressurize upper Formation (Bounding Seal) s.

Very Low or No Effect ☐	Low ☐	Moderate ☐	High ☐	Very High ☐

51. Injected CO_2 Gas Properties (Purity and Temperature) effect on Formation (Bounding Seal) Strength

CO_2 injection cool down the Formation (Bounding Seal) which cause effective stress reduction in Formation (Bounding Seal) and caprock leading to Formation (Bounding Seal) strength reduction.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

52. Bottom Wellbore CO_2 Pressure effect on Formation (Bounding Seal) Strength

Higher CO_2 pressure in reservoir can increase pore pressure and reduces strength.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

53. Wellbore's Completion Fluids Properties effect on Formation (Bounding Seal) Permeability

Chemical reactions between the drilling fluid and the Formation (Bounding Seal) rock can precipitate solids that plug pore spaces and also solid particles from the drilling fluid can physically plug across flow-paths in the porous Formation (Bounding Seal) . Also on the other side wellbore's fluid can wash the filled fractures.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

54. Time Effect & Future Human Activities effect on Formation (Bounding Seal) Permeability

Excessive pressure in squeeze cementing and plug cementing may force filtrate into the Formation (Bounding Seal) and decreases Formation (Bounding Seal) permeability, and also a higher pump rate in cement job increases the quality of cement-Formation (Bounding Seal) bond.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

55. Injected CO_2 Gas Properties (Purity and Temperature) effect on Formation (Bounding Seal) Permeability

H_2S and HCl dissolves carbonate and anhydrite, and increases permeability, and also CO_2 injection increases fluid viscosity that increases global Formation (Bounding Seal) permeability.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

56. Bottom Wellbore CO_2 Pressure effect on Formation (Bounding Seal) Permeability

Carbonic acid dissolves carbonate and anhydrite, and increases permeability.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

57. Wellbore's Completion Fluids Properties effect on Formation (Bounding Seal) Fracture Condition

Fresh water contact with certain clay minerals in the Formation (Bounding Seal) , produce swelling which causes fracturing.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

58. Time Effect & Future Human Activities effect on Formation (Bounding Seal) Fracture Condition

Excessive pressure in squeeze cementing and plug cementing creates hydraulic fracturing.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

59. Injected CO_2 Gas Properties (Purity and Temperature) effect on Formation (Bounding Seal) Fracture Condition

Some earth tremors may be caused by injection, and also insitu stress decreasing caused by injection pressure and reduced temperature may widen fractures.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

60. Bottom Wellbore CO_2 Pressure effect on Formation (Bounding Seal) Fracture Condition

Fractured regions around wellbore provide flow paths for CO_2 migration.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

61. Well Trajectory effect on Cement Porosity

Difficult cementing in horizontal wells and poor placement of drilling mud cause porous cement.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

62. Formation (Bounding Seal) Fluid Properties effect on Cement Porosity

Precipitation of solid particles in the invading Formation (Bounding Seal) fluid can plug wellbore cement pore spaces.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

63. Formation (Bounding Seal) Insitu Stress effect on Cement Porosity

High tectonic forces can cause cracking and degradation of cements which decrease cement strength.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

64. Formation (Bounding Seal) Pressure effect on Cement Porosity

Over-pressure Formations (Bounding Seals) because of high gas flow potential (GFP) are susceptible to gas flow and long-term leakage through cement.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

65. Formation (Bounding Seal) Permeability effect on Cement Porosity

Volume reduction because of fluid loss in gelation period is plausible in permeable Formation (Bounding Seal) which causes channeling and long-term leakage.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

66. Formation (Bounding Seal) Fracture Condition effect on Cement Porosity

Volume reduction because of fluid loss in gelation period is plausible in fractured Formation (Bounding Seal) which causes channeling and long-term leakage.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

67. Well Trajectory effect on Cement Strength Properties

Difficult cementing in horizontal wells and poor placement of drilling mud cause weak cement.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

68. Formation (Bounding Seal) Insitu Stress effect on Cement Strength Properties

High tectonic forces can cause cracking and degradation of cements which increase cement permeability and also large micro-annuli can be formed at the cement-casing interface.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

69. Formation (Bounding Seal) Pressure effect on Cement Strength Properties

Over-pressure formations (bounding seals) because of high gas flow potential (GFP) are susceptible to gas flow in gelation period which cause cement to be porous and weak.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

70. Formation (Bounding Seal) Strength effect on Cement Strength Properties

High strength Formation (Bounding Seal) with higher Young' Modulus produce higher confining stress over cement which will cause higher cement sheath strength and also make cement less susceptible to cracking.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

71. Formation (Bounding Seal) Permeability effect on Cement Strength Properties

Volume reduction because of fluid loss in gelation period is plausible in permeable Formation (Bounding Seal) which may cause weak cementing.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

72. Formation (Bounding Seal) Fracture Condition effect on Cement Strength Properties

Volume reduction because of fluid loss in gelation period is plausible in fractured Formation (Bounding Seal) which may cause weak cementing.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

73. Well Trajectory effect on Cement Plug Porosity

Difficult plug cementing in horizontal and inclined wells and poor placement of drilling mud mostly causes weak and porous cement plugs.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

74. Well Trajectory effect on Casing Condition

Casing string not easily fit through the curved sections as dogleg. Dogleg severity impacts on casing bending stresses. Also deviation angle increasing decreases buckling length (less buckling problem).

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

75. Formation (Bounding Seal) Fluid Properties effect on Casing Condition

Larger buoyancy in Formation (Bounding Seal) with high density fluid decreases axial stress in casing which causes less buckling and rupture problems.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

76. Formation (Bounding Seal) Insitu Stress effect on Casing Condition

High horizontal stress in Formation (Bounding Seal) may cause casing collapse.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

77. Formation (Bounding Seal) Pressure effect on Casing Condition

Over-pressure Formation (Bounding Seal) may cause casing collapse and under-pressure may cause burst failure. Also Formation (Bounding Seal) pressure act as external pressure on casing.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

78. Formation (Bounding Seal) Strength effect on Casing Condition

Effective restraint in strong formations (bounding seals) limits ballooning and reduces buckling length which reduces casing axial stress. Also formation (bounding seal) with plastic behavior (salt) applied higher external pressure on casing and strong formations (bounding seals) limit tectonic forces on casings.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

79. Formation (Bounding Seal) Permeability effect on Casing Condition

High external pressures on casing are susceptible in high permeable zones.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

80. Formation (Bounding Seal) Fracture Condition effect on Casing Condition

Effective restraint in unfractured Formation (Bounding Seal) limits ballooning and reduces buckling length which reduces casing axial stress.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

81. Well Trajectory effect on Time Effect & Future Human Activities

Doglegs and deviated wells reduce access and encumber inspection and remediation process. Also high angle wells may need enhanced lubricity.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

82. Formation (Bounding Seal) Insitu Stress effect on Time Effect & Future Human Activities

High horizontal stresses force usage of high density muds which may cause hydraulic fracturing in soft upper or lower Formation (Bounding Seal) s.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

83. Formation (Bounding Seal) Strength effect on Time Effect & Future Human Activities

High strength formations (bounding seals) let usage of low density muds and less number of centralizers.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

84. Formation (Bounding Seal) Permeability effect on Time Effect & Future Human Activities

In permeable formation (bounding seal) contractors increase the number of cement sacks or use iron slugs to reduce permeability.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

85. Formation (Bounding Seal) Fracture Condition effect on Time Effect & Future Human Activities

In fractured formation (bounding seal) contractors increase the number of cement sacks or use iron slugs to reduce permeability.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

86. Cement Strength Properties effect on Cement Porosity

Stronger cements are susceptible to low porosity, and also gas percolation in gelation period which cause channeling in cements with high static gel strength (SGS) is less probable.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

87. Wellbore's Completion Fluids Properties effect on Cement Porosity

Drilling mud may be bypassed behind a casing or a liner when pumping cement into the casing or wellbore annular region. This mud-contaminated cement might not set up and might not isolate zones satisfactorily.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

88. Cement Plug Porosity effect on Cement Porosity

Fractured rocks are susceptible to low ductility.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

89. Casing Condition effect on Cement Porosity

Improper spacer position creates channels and high porous zones in cement.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

90. Time Effect & Future Human Activities effect on Cement Porosity

Poor displacement of mud during cement placement can bypass a continuous channel of drilling fluid traversing the annulus. Also microannulus at the cement's interfaces can form as a result of thermal or pressure fluctuation during cementing operation.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

91. Injected CO_2 Gas Properties (Purity and Temperature) effect on Cement Porosity

Attack of high partial pressures of CO_2, low pH causes degrading and corrosion of liner.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

92. Cement Porosity Properties effect on Cement Strength Properties

Porous cements are susceptible to low strength, and also high porosity results of high shrinkage usually happens with cracking and softening.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

93. Wellbore's Completion Fluids Properties effect on Cement Strength Properties

Wellbore's chemical reactions with cement decreases the cement strength in long term.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

94. Cement Plug Porosity effect on Cement Strength Properties

Fracture susceptibility decreases ductility.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

95. Time Effect & Future Human Activities effect on Cement Strength Properties

Poor cement placement causes fluid-cement contamination which reduces the cement's strength.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

96. Injected CO_2 Gas Properties (Purity and Temperature) effect on Cement Strength Properties

Input of high concentrations of CO2 degrade borehole linings with time.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

97. Cement Plug Porosity effect on Wellbore's Completion Fluids Properties

Microfractures and fractures in saturated zones increase chemical reactions with making more space for reaction.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

98. Injected CO_2 Gas Properties (Purity and Temperature) effect on Wellbore's Completion Fluids Properties

H_2S dissolved in wellbore fluid produced Sulfuric Acid and the CO_2 solubility in Formation (Bounding Seal) water decreases as salinity increase.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

99. Bottom Wellbore CO_2 Pressure effect on Wellbore's Completion Fluids Properties

Increasing CO_2 content in reservoir may increase insitu carbonic acid.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

100. Wellbore's Completion Fluids Properties effect on Cement Plug Porosity

Chemical reactions may develop increasing number of micro-fractures and fractures with time.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

101. Casing Condition effect on Cement Plug Porosity

Casing helical and s-shape buckling produces significant error in placement of plugs and evaluation of plugs location which can cause unsealed layers and channeling in plugs.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

102. Time Effect & Future Human Activities effect on Cement Plug Porosity

Vandalism may cause plug failure.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

103. Injected CO_2 Gas Properties (Purity and Temperature) effect on Cement Plug Porosity

Input of high concentrations of CO_2 degrades borehole plugs with time. Also reduced temperature caused by injection applies thermal stresses.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

104.Cement Porosity effect on Casing Condition

Casings in porous cements because of low stiffness in these cements are more susceptible to buckling and corkscrewing.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

105.Cement Strength Properties effect on Casing Condition

Casings are applied to less external pressure in good cementing and also low strength cement may decay in long term and allow casing buckling.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

106. Wellbore's Completion Fluids Properties effect on Casing Condition

High density completion fluid applies higher axial stress which causes high buckling stresses and rupture.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

107. Cement Plug Porosity effect on Casing Condition

Non-porous and intact cement plugs can act as supporter in reducing buckling length.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

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108. Time Effect & Future Human Activities effect on Casing Condition

Pressures higher than casing burst strength in integrity test and squeeze cementing lead to casing rupture. Also pre-tensioning of the casing, using centralization, and pick up application before landing can reduce buckling danger.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

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109. Injected CO_2 Gas Properties (Purity and Temperature) effect on Casing Condition

H_2S present in impure CO_2 accelerates corrosion of metal casing. Also increasing in casing axial load caused by pumping of liquid CO_2 can be critical.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

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110. Bottom Wellbore CO_2 Pressure effect on Casing Condition

Carbonic acid accelerates casing corrosion, and decrease casing life time. Also tubing leak in injection time decrease casing tensile strength and may cause burst rupture.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

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111. Casing Condition effect on Time Effect & Future Human Activities

Larger casing diameter leads to easier and faster hole cleaning and plugging and pumping.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

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112. Bottom Wellbore CO_2 Pressure effect on Time Effect & Future Human Activities

CO_2 leakage decreases reservoir pressure may lead to injection increasing pressure.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

113. Wellbore's Completion Fluids Properties effect on Injected CO_2 Gas Properties (Purity and Temperature)

Carbonate, and anhydrite dissolution and reaction with carbonic acid increase diffusion passage.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

114. Time Effect & Future Human Activities effect on Injected CO_2 Gas Properties (Purity and Temperature)

CO_2 capture process and resources carbon dioxide produces from effects on injected gas properties.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

115. Time Effect & Future Human Activities effect on Bottom Wellbore CO_2 Pressure

Time duration will increase trapping mechanisms which will reduce CO_2 pressure in Carbon Storage.

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

Appendix I: Questionnaire for Early time effect on Long-Term Well Integrity Evaluation

For experts decision clarification the early time Cause-Effect Matrix is prepared in this part. In this study it is considered that the wellbore leakage is a dominating failure in long-term geological carbon storage. This cause-effect matrix is presented in page 5.

Experts can elaborate or discussed boxes in following empty part. You can suggest your effect on box itself or subscript the box area and write your decision in following part.

Appendix J: Cause-Effect Evaluation – Wellbore Integrity Evaluation

3. In this part of questionnaire you will answer the effect of any parameters involved in wellbore integrity evaluation on other parameter. The results of this evaluation will be used to evaluate final wellbore index.

Expert's Cause-Effect Matrix Evaluation for Early time Properties effect on Wellbore Long term Integrity

116. Casing Centralization effect on Channels in Cement & High Perm Cement

A large angular channel of bypassed mud in the narrow part of the annulus is very common in the uncentralized casings.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

117. Well Cleaning effect on Channels in Cement & High Perm Cement

Regardless of the properties of the cement placed in the annulus, a continuous mud channel or free fluid channel between two permeable zones will favor fluid migration.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

118. Cement Placement Efficiency effect on Channels in Cement & High Perm Cement

- ✓ *Low-density cement systems with high water-to-cement ratios might exhibit fairly high perm (0.5 to 5.0 mD).*
- ✓ *Gelation and Bridging owing to fluid loss could restrict the transmission of hydrostatic pressure which may results gas channels.*
- ✓ *High Filtration causes a decrease in the height of the hydrostatic column which results gas channels more susceptible.*
- ✓ *High Filtration causes Fluid Loss .which may create space within the cement matrix that gas can occupy.*

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

119. Cement Volume Reduction effect on Channels in Cement & High Perm Cement

Chemical shrinkage of cement causes a decrease in the height of the hydrostatic column which causes gas channels more susceptible.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

120. Production & Injection Well History effect on Channels in Cement & High Perm Cement

High reduction and increase in temperature is applying high stresses to the cement sheath which is causing fracturing in cement sheath. This is very common in CO_2 and steam injectors.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

121. Casing Centralization effect on Cement Microannulus

Uncentralized casing may cause higher Poisson's effect on thicker part of uncentralized casing which is causing microannulus in most of cemented casings.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

122. Cement Volume Reduction effect on Cement Microannulus

Chemical shrinkage of cement causes a Microannulus between cement and casing (and between cement and formation).

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

123. Production & Injection Well History effect on Cement Microannulus

A well temperature decreases and inside well pressure decrease will result in the casing a casing diameter reduction which will result in microannulus in between cement and casing. The well temperature and inside well pressure reduction is common in CO_2 injector wells and also abandoned wells and wells with closed casing (at the end of cement job).

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

124. Casing Centralization effect on Filtercake Pathway

A thick filtercake or dehydrated trapped mud (usually in washouts) is very common on the narrow side of an eccentric annulus.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

125. Well Cleaning effect on Filtercake Pathway

Thick and strong filtercake cannot be easily washed and may cause migration path.

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

126. Casing Centralization effect on Well Cleaning

- ✓ *A large angular channel of bypassed mud in the narrow part of the annulus is very common in the uncentralized casings.*
- ✓ *A thick filtercake or dehydrated trapped mud (usually in washouts) is very common on the narrow side of an eccentric annulus.*

Very Low or No Effect ☐ Low ☐ Moderate ☐ High ☐ Very High ☐

127. Casing Centralization effect on Cement Placement Efficiency

The preflushing and washing is not taking place in the narrow part of the annulus in the uncentralized casings (A standoff of about 75% is acceptable).

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

128. Well Cleaning effect on Cement Placement Efficiency

- ✓ *High concentration of $CaCl_2$ and Ca(OH) in mud filtercake have a strong gelling and accelerating effect on cement slurries.*
- ✓ *Thin and slicken filtercake can be easily washed and helps good cement placement.*
- ✓ *OBMs produce thick filtercake which is hard to wash.*
- ✓ *Invert emulsions contain emulsifiers and oil-wetting surfactants that cover all polar surfaces. The emulsifiers in the mud may adsorb on the cement grains, inhibiting hydration.*

Very Low or No Effect ☐ | Low ☐ | Moderate ☐ | High ☐ | Very High ☐

Appendix K: Risk Assessment Evaluation - Failure Mechanisms Ranking Evaluation

4. Place a check sign in place that implies your expression of relation between A and B, which are different index in wellbore integrity (Early Time Index and Long Time Index). In this part you are assigning the higher weighting factor to more important index property of the wellbore. In simpler way you are saying which cement property is more important early age properties (such as: gel strength, centralization, cement expansion , ...) or long term properties portion (such as: formation strength, cement plug porosity, insitu formation stresses, ...).

	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
A						✓												B

Placing a check sign to the left of equal indicates that verbal expression A implies a higher probability of occurrence than B

Placing a check sign to the right of equal indicates that verbal expression B implies a higher probability of occurrence than A

	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
Early Time Effect Index																		Long Time Effect Index
Cement Top																		Early Time Effect Index
Cement Top																		Long Time Effect Index

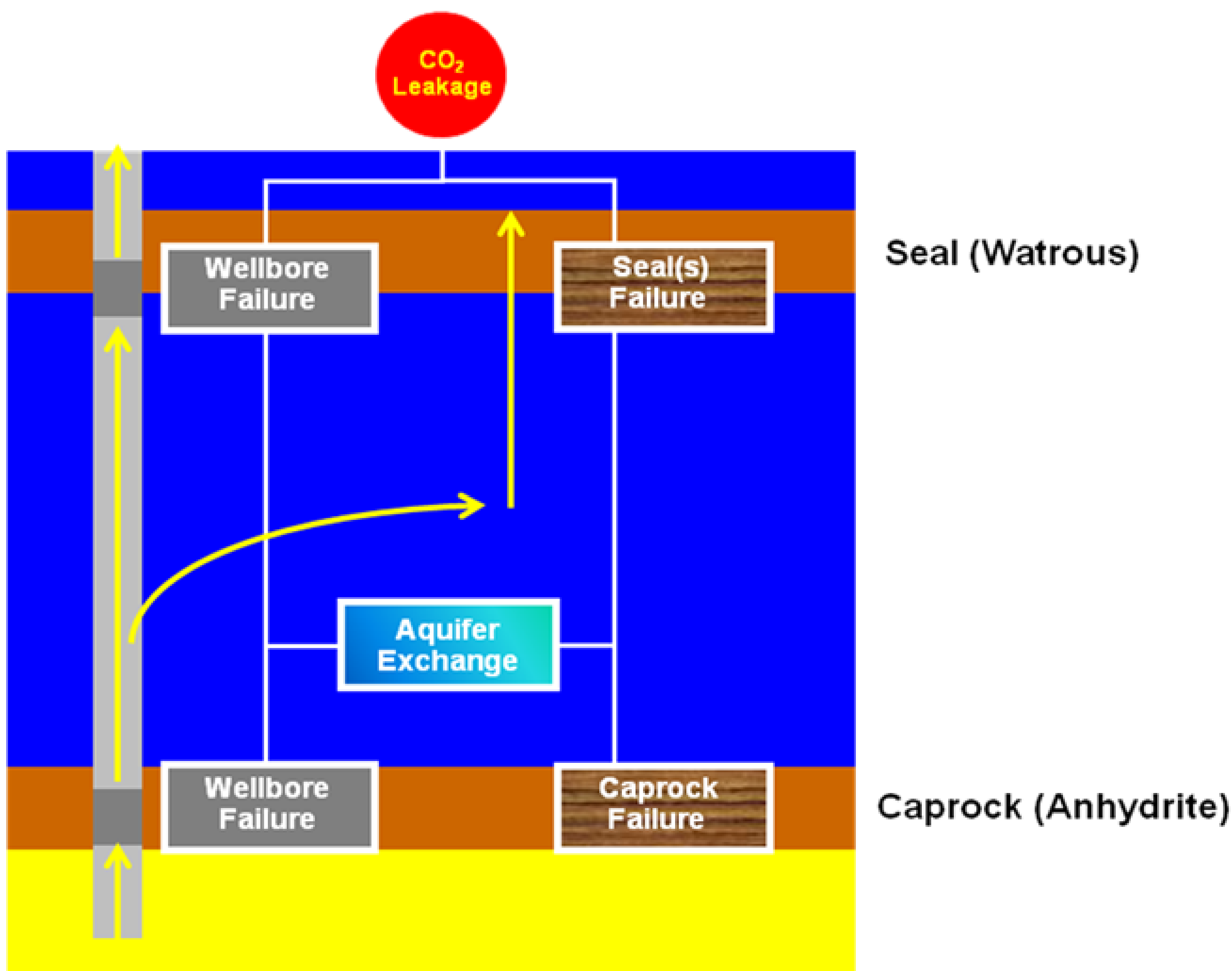
5. The following table is given for your evaluation over the condition of each well property in Long-Term Well Integrity.

	Well System Properties	Weyburn Field Condition for this Property				
	Casing Centralization	Very Poor ☐	Poor ☐	Moderate ☐	Good ☐	Very Good ☐
	Well Cleaning	Very Poor ☐	Poor ☐	Moderate ☐	Good ☐	Very Good ☐
	Cement Placement Efficiency	Very Poor ☐	Poor ☐	Moderate ☐	Good ☐	Very Good ☐
	Cement Volume Reduction	Very Poor ☐	Poor ☐	Moderate ☐	Good ☐	Very Good ☐
	Production & Injection Well History	Very Poor ☐	Poor ☐	Moderate ☐	Good ☐	Very Good ☐
Wellbore Condition at Weyburn (Midale) Reservoir	Well Trajectory	45^o ☐	30^o ☐	15^o ☐	5^o ☐	Vertical ☐
	Bounding Seal Fluid Properties	Oil ☐	Potable ☐	Low Salinity ☐	Saline ☐	High Salinity ☐
	Bounding Seal Insitu Stress	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
	Bounding Seal (Formation) Pressure	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
	Bounding Seal Strength	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
	Bounding Seal Permeability	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
	Bounding Seal Fracture Condition	Negligible ☐	Very Small ☐	Blocky ☐	Fractured ☐	Jointed ☐
	Annular Cement Porosity	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
	Annular Cement Strength Properties	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
	Wellbore's Fluids Chemical Properties	Very Poor ☐	Poor ☐	Moderate ☐	Good ☐	Very Good ☐
	Cement Plug Porosity	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
	Casing Condition	Very Poor ☐	Poor ☐	Moderate ☐	Good ☐	Very Good ☐
	Injected CO_2 Gas Properties	Pure CO_2 ☐	Not Pure ☐	Moderate ☐	Low H_2S ☐	High H_2S ☐

	Well System Properties	Weyburn Field Condition for this Property				
Wellbore Condition at Watrous Seal	Well Trajectory	45° ☐	30° ☐	15° ☐	5° ☐	Vertical ☐
	Bounding Seal Fluid Properties	Oil ☐	Potable ☐	Low Salinity ☐	Saline ☐	High Salinity ☐
	Bounding Seal Insitu Stress	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
	Bounding Seal (Formation) Pressure	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
	Bounding Seal Strength	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
	Bounding Seal Permeability	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
	Bounding Seal Fracture Condition	Negligible ☐	Very Small ☐	Blocky ☐	Fractured ☐	Jointed ☐
	Annular Cement Porosity	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
	Annular Cement Strength Properties	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
	Wellbore's Fluids Chemical Properties	Very Poor ☐	Poor ☐	Moderate ☐	Good ☐	Very Good ☐
	Cement Plug Porosity	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
	Casing Condition	Very Poor ☐	Poor ☐	Moderate ☐	Good ☐	Very Good ☐
	Injected CO_2 Gas Properties	Pure CO_2 ☐	Not Pure ☐	Moderate ☐	Low H_2S ☐	High H_2S ☐

6. The following table is given for your evaluation over different seal failure likelihood evaluation for different seal failure in Weyburn Project. The results of this part will be used for evaluation with results from the index method.

Seal Name		Likelihood of Failure in Weyburn Field				
Wellbores	Well System on top of reservoir	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
	Well System on top of reservoir	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Seals	Anhydrite Caprock	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
	Watrous Seal (Formation)	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
	Exchange between the seal and Wellbore	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐



7. The following table is given for the consequence evaluation over different failures. Consider these answers with respect to Weyburn Project.

Consequence Parameters	Evaluation of the Parameter in Weyburn Field				
Release Severity (Leakage in the Air) How big can be the leakage rate in the air?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Release Severity (Leakage in the Groundwater or Potable Water) How big can be the leakage rate in the ground water?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
CO_2 Sensibility How probable is that people sense the CO_2 (smell or taste it)?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Impact Rate (Humans) How fast the CO_2 will start causing death or nausea for the people?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Impact Rate (Cattle) How fast the CO_2 will start causing death for the cattle?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Impact Rate (Plants) How fast the CO_2 will start causing death for the plants?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Alert Ability (Leakage in the Air) How good is the MMV or other sensors to alert the leakage? (For the leakage in the air)	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Alert Ability (Leakage in the Groundwater or Potable Water) How good is the MMV or other sensors to alert the leakage? (For the leakage in the Groundwater or Potable Water)	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Controllability (Leakage in the Air) How controllable is the CO_2 in the Weyburn Project with current practice?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Controllability (Leakage in the Groundwater or Potable Water) How controllable is the CO_2 in the Weyburn Project with current practice?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Transportation System Capability (Humans) How fast people can evacuate the area?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Transportation System Capability (Cattle) How fast people can take their cattle from the area?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐

Capital Loss (Leakage in the Air, Humans) How many persons are living in the area? How many persons will get affected?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Capital Loss (Leakage in the Air, Cattle) How many cattle are in the area? How many cattle will get affected?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Capital Loss **(Leakage in the Potable Water and Ground Water, Humans)** How many persons are living in the area? How many persons will get affected?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Capital Loss **(Leakage in the Potable Water and Ground Water, Cattle)** How many cattle are in the area? How many cattle will get affected?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Capital Loss **(Leakage in the Potable Water and Ground Water)** How big is the agriculture in the area?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Barrier Cost (Leakage in the Air) How much money must be spent to stop the leakage in the air?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Barrier Cost **(Leakage in the Potable Water and Ground Water)** How much money must be spent to stop the leakage in the groundwater?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Voluntariness How voluntary people are taking the risk of living next to the Weyburn Project?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Known to Expose How much people are aware that their are living next to the Weyburn Project?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Future Sciences' Effects How much you think that future sciences will decrease the risk of the leakage from the Weyburn Project?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐

8. The following table is given for the consequence evaluation. In this part you asking the same answers you did for the Weyburn Project for the nuclear waste repository leakage. This nuclear waste repository leakage is assumed as highest consequence possible.

Consequence Parameters	Evaluation of the Parameter in Weyburn Field				
Release Severity (Leakage in the Groundwater) How big can be the leakage rate in the ground water?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Leakage Sensibility How probable is that people sense the nuclear rays? *The answer is obviously very low, but it is embedded for the completeness of the questionnaire.*	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Impact Rate (on Humans) How fast the nuclear rays will start causing problem for the people?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Alert Ability (Leakage in the Air) How good is alert ability in nuclear repository areas?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Controllability How controllable is the nuclear leakage with current practice?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Transportation System Capability (Humans) How fast people can evacuate the area?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Capital Loss (Humans) How many persons are living in the area? How many persons will get affected?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Barrier Cost (Leakage in the Air) How much money must be spent to stop the leakage?	Very Low ☐	Low ☐	Moderate ☐	High ☐	Very High ☐
Voluntariness How voluntary people are taking the risk of living next to the nuclear repository?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Known to Expose How much people are aware that their are living next to the nuclear repository?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐
Future Sciences' Effects How much you think that future sciences will decrease the risk of the leakage from the nuclear repository?	Very High ☐	High ☐	Moderate ☐	Low ☐	Very Low ☐

Appendix L: Consequence Evaluation – Leakage Paths Ranking Evaluation

1. Place a check sign in place that implies your expression of relation between two given consequences severity in Weyburn Project.

	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
A						✓												B

Placing a check sign to the left of equal indicates that verbal expression A implies a higher probability of occurrence than B

Placing a check sign to the right of equal indicates that verbal expression B implies a higher probability of occurrence than A

		Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
Leakage Paths	Leakage in Air																		Leakage in Ground Water
	Leakage in Air																		Leakage in Drinking Water
	Leakage in Ground Water																		Leakage in Drinking Water
Leakage iin Air (Risk Potentials)	People Asphyxiation or Death																		Plants Death
	People Asphyxiation or Death																		Animals Asphyxiation or Death
	Animals Asphyxiation or Death																		Plants Death
Leakage in Ground Water (Risk Potentials)	People Toxication																		Plants Death
	People Toxication																		Animals Toxication
	Animals Toxication																		Plants Death
Leakage in Potable Water (Risk Potentials)	People Toxication																		Plants Death
	People Toxication																		Animals Toxication
	Animals Toxication																		Plants Death

Appendix M: Matlab File Regarding Section 2 (Fuzzified Fault Tree)

```
%% Fault Tree and DT and FL Method

% Mazda Irani

% Discussion: Limitation of 3 Branches

clc
clear

%% Input form Experts
% Assume we ask 4 experts:

% Number of Experts are 4
%%%%%%%%%%%%%%%%%%%%%%%%%%
Number_of_Experts = 37;
% 39 but 38 : 23 & 35 is out

% Experts Ranking
%%%%%%%%%%%%%%%%%%%%%%%%%%
%        1      2     3      4     5    6     7     8    9     10
11  12    13   14    15     16     17    18     19    20     21
22    23+1       25    26    27     28    29    30     31     32
33    34    35+1    37    38   39
Rank = [2.166, 1.9, 2.366, 2.032, 1.6, 2.5, 2.166, 2.1, 2.266,
1.9, 1.4, 1.9, 1.7, 2.35, 1.50, 1.332, 2.800, 2.10, 1.60, 1.533,
1.266, 1.466, 1.800, 1.700, 1.400, 2.166, 1.866, 1.00, 1.500,
2.100, 1.766, 2.00, 2.40, 2.000, 2.100, 2.10, 2.1];

Total_Rank = sum(Rank);

%% Experts Decision:

% Example
% For Branch 1:
% First Expert Risk Value: Medium (3)
% Second Expert Risk Value: High (4)
% Third Expert Risk Value: Very Low (1)
% Fourth Expert Risk Value: Low (2)
% 5 Branches for Fault Tree
%%%%%%%%%%%%%%%%%%%%%%%%%%

Exl_Exp_Decision = [3, 3, 3, 1, 1, 2, 2, 1, 3, 2, 3, 3, 1, 1, 2,
2, 1, 2;
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2, 1, 3;
```

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2, 1, 3;
2, 1, 3;
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2, 1, 4;
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1, 1, 1;
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1, 1, 1;
1, 1, 1;
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3, 1, 1;
                    3, 3, 2, 3, 1, 1, 3, 1, 3, 3, 3, 1, 2, 1, 1,
3, 1, 3;
                    1, 1, 1, 1, 2, 1, 1, 1, 2, 1, 1, 1, 1, 1, 1,
1, 1, 2];


Experts_Decision = Exl_Exp_Decision';

%% Input for Fault Tree

% Assume we have 5 Branches in our Fault Tree.

% Number of Branches are 3
%%%%%%%%%%%%%%%%%%%%%%%%%%
Number_of_Branches = 18;

% Branches Ranking AHP
%%%%%%%%%%%%%%%%%%%%%%%%%%
AHP_Rank = [0.046, 0.038, 0.027, 0.021, 0.011, 0.015, 0.03,
0.013, 0.068, 0.106, 0.087, 0.063, 0.049, 0.038, 0.052, 0.104,
0.045, 0.144];

AHP_Total_Rank = sum(AHP_Rank);



%% Membership Functions Definition

% We range our Risk Number Ranking 0 to 10
x = 0:0.5:10;

% We assumed Triangle Membership Functions for our case
mf_Very_Low = trimf(x,[0 0 2.5]);
mf_Low = trimf(x,[0 2.5 5]);
mf_Medium = trimf(x,[2.5 5 7.5]);
mf_High = trimf(x,[5 7.5 10]);
mf_Very_High = trimf(x,[7.5 10 10]);


%% Loop for Evaluation

n = 0;
MFF_Final = sparse ( 100, 21 );
Center =  sparse ( 5^Number_of_Branches, 1 );
```

```
% a, b, c, d, f are number of loops because of branches, each one
for different loop
n1 =  2;
n2 =  2;  %3; =2
n3 =  2;  %3;
n4 =  2;  %1;
n5 =  1;  %1;
n6 =  2;  %3;
n7 =  2;  %1;
n8 =  2;  %1;
n9 =  2;  %5;
n10 = 2;  %5;
n11 = 2;  %4;
n12 = 3;  %3;
n13 = 2;  %3;
n14 = 2;  %3;
n15 = 4;  %2;
n16 = 2;  %5;
n17 = 2;  %3;
n18 = 2;  %5;

Step = 0;

%% Number of FOR must be changed

for a1 = 1 : n1 : 5
    for a2 = 1 : n2 : 5
        for a3 = 1 : n3 : 5

            Step = Step + 1

        for a4 = 1 : n4 : 5
        for a5 = 1 : n5 : 5
        for a6 = 1 : n6 : 5
        for a7 = 1 : n7 : 5
        for a8 = 1 : n8 : 5
        for a9 = 1 : n9 : 5
        for a10 = 1 : n10 : 5
        for a11 = 1 : n11 : 5
        for a12 = 1 : n12 : 5
        for a13 = 1 : n13 : 5
        for a14 = 1 : n14 : 5
        for a15 = 1 : n15 : 5
        for a16 = 1 : n16 : 5
        for a17 = 1 : n17 : 5
        for a18 = 1 : n18 : 5

        Branches = [a1, a2, a3, a4, a5, a6, a7, a8, a9, a10, a11,
a12, a13, a14, a15, a16, a17, a18];

        MFF = trimf(x,[-1 -1 -1]);

% Fuzzy Set Coupling for fuzyy sets

%% Fuzzy Evaluation
```

```
for i = 1 : Number_of_Branches
     if Branches(i) == 1
     MF = (AHP_Rank(i)/AHP_Total_Rank)*mf_Very_Low;
       elseif Branches(i) == 2
          MF = (AHP_Rank(i)/AHP_Total_Rank)*mf_Low;
          elseif Branches(i) == 3
          MF = (AHP_Rank(i)/AHP_Total_Rank)*mf_Medium;
              elseif Branches(i) == 4
              MF = (AHP_Rank(i)/AHP_Total_Rank)*mf_High;
     else
     MF = (AHP_Rank(i)/AHP_Total_Rank)*mf_Very_High;
     end
     MFF = max(MF,MFF);
end

Belief1 = 0;
Belief2 = 0;
Belief3 = 0;
Belief4 = 0;
Belief5 = 0;
Belief6 = 0;
Belief7 = 0;
Belief8 = 0;
Belief9 = 0;
Belief10 = 0;
Belief11 = 0;
Belief12 = 0;
Belief13 = 0;
Belief14 = 0;
Belief15 = 0;
Belief16 = 0;
Belief17 = 0;
Belief18 = 0;

for k = 1 : Number_of_Experts
    if Branches(1) >= Experts_Decision(1, k)
    Belief1 = Belief1+1;
    end
    if Branches(2) >= Experts_Decision(2, k)
    Belief2 = Belief2+1;
    end
    if Branches(3) >= Experts_Decision(3, k)
    Belief3 = Belief3+1;
    end
    if Branches(4) >= Experts_Decision(4, k)
    Belief4 = Belief4+1;
    end
    if Branches(5) >= Experts_Decision(5, k)
    Belief5 = Belief5+1;
    end
    if Branches(6) >= Experts_Decision(6, k)
    Belief6 = Belief6+1;
    end
    if Branches(7) >= Experts_Decision(7, k)
    Belief7 = Belief7+1;
```

```
            end
            if Branches(8) >= Experts_Decision(8, k)
            Belief8 = Belief8+1;
            end
            if Branches(9) >= Experts_Decision(9, k)
            Belief9 = Belief9+1;
            end
            if Branches(10) >= Experts_Decision(10, k)
            Belief10 = Belief10+1;
            end
            if Branches(11) >= Experts_Decision(11, k)
            Belief11 = Belief11+1;
            end
            if Branches(12) >= Experts_Decision(12, k)
            Belief12 = Belief12+1;
            end
            if Branches(13) >= Experts_Decision(13, k)
            Belief13 = Belief13+1;
            end
            if Branches(14) >= Experts_Decision(14, k)
            Belief14 = Belief14+1;
            end
            if Branches(15) >= Experts_Decision(15, k)
            Belief15 = Belief15+1;
            end
            if Branches(16) >= Experts_Decision(16, k)
            Belief16 = Belief16+1;
            end
            if Branches(17) >= Experts_Decision(17, k)
            Belief17 = Belief17+1;
            end
            if Branches(18) >= Experts_Decision(18, k)
            Belief18 = Belief18+1;
            end
        end

Belief = ( 1 - (1-Belief1/Number_of_Experts) )*( 1 - (1-
Belief2/Number_of_Experts) )...
        *( 1 - (1-Belief3/Number_of_Experts) )*( 1 - (1-
Belief4/Number_of_Experts) )...
        *( 1 - (1-Belief5/Number_of_Experts) )*( 1 - (1-
Belief6/Number_of_Experts) )...
        *( 1 - (1-Belief7/Number_of_Experts) )*( 1 - (1-
Belief8/Number_of_Experts) )...
        *( 1 - (1-Belief9/Number_of_Experts) )*( 1 - (1-
Belief10/Number_of_Experts) )...
        *( 1 - (1-Belief11/Number_of_Experts) )*( 1 - (1-
Belief12/Number_of_Experts) )...
        *( 1 - (1-Belief13/Number_of_Experts) )*( 1 - (1-
Belief14/Number_of_Experts) )...
        *( 1 - (1-Belief15/Number_of_Experts) )*( 1 - (1-
Belief16/Number_of_Experts) )...
        *( 1 - (1-Belief17/Number_of_Experts) )*( 1 - (1-
Belief18/Number_of_Experts) );
```

```
n = fix(Belief*100) + 1;  % For more Precision we consider .1%
for Belief Variation

Center1 = defuzz(x,MFF,'centroid');
Center2 = max(Center(n,1), 0);

  if Center2 == 0
         Center(n,1) = Center1;
         MFF_Final(n,:) = MFF;
  elseif  Center1 <= Center2
         Center(n,1) = Center1;
         MFF_Final(n,:) = MFF;
  end

%% Centroid
% Centroid defuzzification returns the center of area under the
curve. If you
% think of the area as a plate of equal density, the centroid is
the point along
% the x axis about which this shape would balance.


% Fuzzy Coupled data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        end
        end
        end
        end
        end
        end
        end
        end
        end
        end
        end
        end
        end
        end
        end
    end
  end
end


%% Plot Section
Z=MFF_Final;
figure
surface(Z);
view ( -25, 60 );
title ( 'Solution to the Dempster-Shafer and Fuzzy Logic Problem'
)


mm = 0;
jj = 0;
```

```
for h = 1 : 11
    if Center(h,1) > 0
      for j = 1 : (h - jj)
         mm = mm + 1;
         CDFCenter(mm,1) = Center(h,1);
      end
      jj = h;
    end
end

% Average and Variance
miu = mean(CDFCenter);
s = std(CDFCenter);

figure
cdfplot(CDFCenter)
p = cdf('Normal',0:0.5:10,miu,s);
hold on
plot(x,p,'-')
hold off
title ( 'Defuzified Answer for Dempster-Shafer and Fuzzy Logic
Problem' )
xlabel('0 to 10 Risk Numbers')
ylabel('Belief or Agreement Percentage')

figure
hist(CDFCenter,12)

figure
h = normplot(CDFCenter);

figure
p = capaplot(CDFCenter,[2.5 5]);
```

Appendix N: Matlab File Regarding Section 5 (Consequence Evaluation)

```
%% Consequence Evaluation

% Mazda Irani


clc
clear

%% Input form Experts Consequence

Factor1 = [ 2.41;
            2.56;
            3.37;
            2.69;
            2.83;
            3.54;
            2.69;
            2.83;
            3.54];

Factor2 = [ 2.61;
            2.64;
            2.45;
            2.72;
            2.70;
            2.87;
            2.72;
            2.70;
            2.87];

AHP     = [ 0.03, 0.04, 0.09, 0.15, 0.19, 0.26, 0.06, 0.08,
0.10];


   Input_F1F2 = horzcat(Factor1, Factor2);   % Horizontally
concatenate Factor1 and Factor2


   Consequence_mat = readfis('Consequence_matrix');
   Consequence  = evalfis(Input_F1F2, Consequence_mat);


   Final_Consequence  = AHP * Consequence  % Value calculated
1.6242
```

Appendix O: Matlab File Regarding Section 5 (Likelihood Evaluation)

```
%% BowTie and DT and FL Method

% Mazda Irani

% Discussion: Limitation of 3 Branches

clc
clear

%% Input form Experts
% Assume we ask 5 experts:

% Number of Data which is Experts in this case
Number_of_Data_Wellbore    = 5;
Number_of_Data_Caprock     = 3;
Number_of_Data_Transition  = 3;

Number_of_Data_Consequence = 3;

Number_of_Branches         = 9;

%% Experts Decision:

% Example
% For Branch 1:
% First Expert Risk Value: Medium (3)
% Second Expert Risk Value: High (4)
% Third Expert Risk Value: Very Low (1)
% Fourth Expert Risk Value: Low (2)


%% AHP evaluation

AHP_Well_1    = 1; % 0.56;
AHP_Well_2    = 1; % 0.66;
AHP_Caprock_1 = 1; % 0.44;
AHP_Caprock_2 = 1; % 0.34;


AHP_Branches  = [0.03
                 0.04
                 0.09
                 0.15
                 0.19
                 0.26
                 0.06
                 0.08
                 0.10];


%% Fuzzified Wellbore Index
```

```
Fuzzified_Wellbore       = [ 0         0.7416    0.2584         0
0
                             0         0.8844    0.1156         0
0
                             0.1724    0.8276         0         0
0
                             0.3545    0.6455         0         0
0
                             0.4251    0.5749         0         0
0];

Wellbore_Belief_1      = [ 0;
                           0.125;
                           0.5;
                           0.625;
                           1];

Wellbore_Belief_2      = [ 0;
                           0.125;
                           0.5;
                           0.625;
                           1];

%% Fuzzified Caprock Index

Fuzzified_Caprock        = [ 0.2500    0.7500     0         0
0
                             0         1          0         0
0
                             0         0.7500     0.2500    0
0];

Caprock_Belief_1       = [ 0;
                           0.5;
                           1];

Caprock_Belief_2       = [ 0;
                           0.5;
                           1];



%% Fuzzified Transition

Fuzzified_Transition     = [ 0    0.2500    0.7500         0
0
                             0         0         1         0
0
                             0         0    0.7500    0.2500
0];

Transition_Belief       = [0;
                           0.5;
                           1];
```

```
%% Input for BowTie



%% Membership Functions Definition

% We range our Risk Number Ranking 0 to 10
x = 0:0.25:10;

% We assumed Triangle Membership Functions for our case
mf_Very_Low = trimf(x,[0 0 2.5]);
mf_Low = trimf(x,[0 2.5 5]);
mf_Medium = trimf(x,[2.5 5 7.5]);
mf_High = trimf(x,[5 7.5 10]);
mf_Very_High = trimf(x,[7.5 10 10]);


%% Loop for Evaluation

n = 0;
MFF_Final = sparse ( 100, 41 );


% Number of Blocks in BowTie Structure ??????????
Number_of_Blocks = 5;%%% was 1

% a, b, c, d, f are number of blocks

for a = 1 : Number_of_Data_Wellbore
      for b = 1 : Number_of_Data_Caprock
            for c = 1 : Number_of_Data_Transition


% Fuzzy Set Coupling for fuzyy sets

%% Fuzzy Evaluation

       MFF = trimf(x,[-1 -1 -1]);


       Wellbore1 = trimf(x,[-1 -1 -1]);

       for i = 1 : 5
            if i == 1
              MF_W = Fuzzified_Wellbore(a,1)*mf_Very_Low;
              elseif i == 2
                 MF_W = Fuzzified_Wellbore(a,2)*mf_Low;
                 elseif i == 3
                    MF_W = Fuzzified_Wellbore(a,3)*mf_Medium;
                    elseif i == 4
                       MF_W = Fuzzified_Wellbore(a,4)*mf_High;
```

```
      else
        MF_W = Fuzzified_Wellbore(a,5)*mf_Very_High;
      end

      Wellbore = max(MF_W,Wellbore1);

    end

    Wellbore1 = AHP_Well_1 * Wellbore;
    Wellbore2 = AHP_Well_2 * Wellbore;

%%

    Caprock = trimf(x,[-1 -1 -1]);

    for i = 1 : 5
      if i == 1
        MF_C = Fuzzified_Caprock(b,1)*mf_Very_Low;
        elseif i == 2
           MF_C = Fuzzified_Caprock(b,2)*mf_Low;
           elseif i == 3
              MF_C = Fuzzified_Caprock(b,3)*mf_Medium;
               elseif i == 4
                  MF_C = Fuzzified_Caprock(b,4)*mf_High;
      else
        MF_C = Fuzzified_Caprock(b,5)*mf_Very_High;
      end

      Caprock = max(MF_C,Caprock);

    end


    Caprock1 = AHP_Caprock_1 * Caprock;
    Caprock2 = AHP_Caprock_2 * Caprock;


%%

    Transition = trimf(x,[-1 -1 -1]);

    for i = 1 : 5
      if i == 1
        MF_T = Fuzzified_Transition(c,1)*mf_Very_Low;
        elseif i == 2
           MF_T = Fuzzified_Transition(c,2)*mf_Low;
           elseif i == 3
              MF_T = Fuzzified_Transition(c,3)*mf_Medium;
               elseif i == 4
                  MF_T = Fuzzified_Transition(c,4)*mf_High;
      else
        MF_T = Fuzzified_Transition(c,5)*mf_Very_High;
      end
```

```
            Transition = max(MF_T,Transition);

       end



%%  Fuzzy Evaluation

       Likelihood = 0.5 * min(Transition, min(
max(Wellbore1,Caprock1), max(Wellbore2,Caprock2))) +  0.5 *
min(1-Transition, max( min(Wellbore1,Caprock1),
min(Wellbore2,Caprock2)));
%      MFF = 0.5 * min(Transition, min( max(Wellbore1,Caprock1),
max(Wellbore2,Caprock2))) +  0.5 * min(Transition_Inverse, max(
min(Wellbore1,Caprock1), min(Wellbore2,Caprock2)));

%%
            B1 = Wellbore_Belief_1(a,1);
            B2 = Caprock_Belief_1(b,1);
            B3 = Transition_Belief(c,1);
            B4 = Wellbore_Belief_2(a,1);
            B5 = Caprock_Belief_2(b,1);

            Belief_Likelihood = B3 * ( (1-(1-B1)*(1-B2)) * (1-(1-
B4)*(1-B5)) ) +  (1-B3) * ( 1 - (1-B1*B4)*(1-B2*B5) ) ;

   for d = 1 : Number_of_Data_Consequence
          for e = 1 : Number_of_Branches
              % Branches of Consequence

            n = fix(Belief_Likelihood * 100) + 1;  % For more
Precision we consider .1% for Belief Variation


%% Risk Matrix Evaluation

         %   a = readfis('risk_matrix');
         %   evalfis([1 2], a)

            MFF_Final(n,:) = Likelihood;


                  end
            end
      end
end
end  % added

%% Plot Section
Z=MFF_Final;
figure
surface(Z);
view ( -25, 60 );
```

```
title ( 'Solution to the Dempster-Shafer and Fuzzy Logic Problem'
)
```

Appendix P: Matlab File Regarding Section 5 (Risk Evaluation)

```
%% Fault Tree and DT and FL Method

% Mazda Irani

% Discussion: Limitation of 3 Branches

clc
clear


%% Input form Experts Consequence

Factor1 = [ 2.41;
            2.56;
            3.37;
            2.69;
            2.83;
            3.54;
            2.69;
            2.83;
            3.54];

Factor2 = [ 2.61;
            2.64;
            2.45;
            2.72;
            2.70;
            2.87;
            2.72;
            2.70;
            2.87];

   AHP   = [ 0.03, 0.04, 0.09, 0.15, 0.19, 0.26, 0.06, 0.08,
0.10];


   Input_F1F2 = horzcat(Factor1, Factor2);   % Horizontally
concatenate Factor1 and Factor2

   Consequence_mat = readfis('Consequence_matrix');
   Consequence  = evalfis(Input_F1F2, Consequence_mat);

   Final_Consequence  = AHP * Consequence;


%% Input form Experts
% Assume we ask 5 experts:

% Number of Data which is Experts in this case
Number_of_Data_Wellbore    = 5;
```

```
Number_of_Data_Caprock     = 3;
Number_of_Data_Transition  = 3;

Number_of_Data_Consequence = 3;

Number_of_Branches         = 9;

%% Experts Decision:

% Example
% For Branch 1:
% First Expert Risk Value: Medium (3)
% Second Expert Risk Value: High (4)
% Third Expert Risk Value: Very Low (1)
% Fourth Expert Risk Value: Low (2)


%% AHP evaluation

AHP_Well_1    = 1; % 0.56;
AHP_Well_2    = 1; % 0.66;
AHP_Caprock_1 = 1; % 0.44;
AHP_Caprock_2 = 1; % 0.34;


AHP_Branches  = [0.03
                 0.04
                 0.09
                 0.15
                 0.19
                 0.26
                 0.06
                 0.08
                 0.10];


%% Fuzzified Wellbore Index
Fuzzified_Wellbore      = [ 0         0.7416    0.2584         0
0
                            0         0.8844    0.1156         0
0
                            0.1724    0.8276         0         0
0
                            0.3545    0.6455         0         0
0
                            0.4251    0.5749         0         0
0];

Wellbore_Belief_1     = [ 0;
                          0.125;
                          0.5;
                          0.625;
                          1];
```

```
Wellbore_Belief_2      = [ 0;
                           0.125;
                           0.5;
                           0.625;
                           1];

%% Fuzzified Caprock Index

Fuzzified_Caprock        = [ 0.2500    0.7500     0          0
0
                             0         1          0          0
0
                             0         0.7500     0.2500     0
0];

Caprock_Belief_1       = [ 0;
                           0.5;
                           1];

Caprock_Belief_2       = [ 0;
                           0.5;
                           1];



%% Fuzzified Transition

Fuzzified_Transition     = [ 0    0.2500    0.7500         0
0
                             0         0         1         0
0
                             0         0    0.7500    0.2500
0];

Transition_Belief       = [0;
                           0.5;
                           1];


%% Input for BowTie



%% Membership Functions Definition

% We range our Risk Number Ranking 0 to 10
x = 0:0.25:10;

% We assumed Triangle Membership Functions for our case
mf_Very_Low = trimf(x,[0 0 2.5]);
mf_Low = trimf(x,[0 2.5 5]);
mf_Medium = trimf(x,[2.5 5 7.5]);
mf_High = trimf(x,[5 7.5 10]);
mf_Very_High = trimf(x,[7.5 10 10]);
```

```
%% Loop for Evaluation

n = 0;
MFF_Final = sparse ( 101, 41 ); % 100 or 101
Center =  zeros ( 101, 1 ); % Changed By Mazda


% Number of Blocks in BowTie Structure ??????????
Number_of_Blocks = 5;%%% was 1

% a, b, c, d, f are number of blocks

for a = 1 : Number_of_Data_Wellbore
      for b = 1 : Number_of_Data_Caprock
            for c = 1 : Number_of_Data_Transition


% Fuzzy Set Coupling for fuzyy sets

%% Fuzzy Evaluation

       MFF = trimf(x,[-1 -1 -1]);


       Wellbore1 = trimf(x,[-1 -1 -1]);

       for i = 1 : 5
            if i == 1
              MF_W = Fuzzified_Wellbore(a,1)*mf_Very_Low;
              elseif i == 2
                 MF_W = Fuzzified_Wellbore(a,2)*mf_Low;
                 elseif i == 3
                    MF_W = Fuzzified_Wellbore(a,3)*mf_Medium;
                    elseif i == 4
                       MF_W = Fuzzified_Wellbore(a,4)*mf_High;
            else
              MF_W = Fuzzified_Wellbore(a,5)*mf_Very_High;
            end

            Wellbore = max(MF_W,Wellbore1);

       end

       Wellbore1 = AHP_Well_1 * Wellbore;
       Wellbore2 = AHP_Well_2 * Wellbore;

%%

       Caprock = trimf(x,[-1 -1 -1]);

       for i = 1 : 5
```

```matlab
          if i == 1
            MF_C = Fuzzified_Caprock(b,1)*mf_Very_Low;
            elseif i == 2
               MF_C = Fuzzified_Caprock(b,2)*mf_Low;
               elseif i == 3
                  MF_C = Fuzzified_Caprock(b,3)*mf_Medium;
                   elseif i == 4
                      MF_C = Fuzzified_Caprock(b,4)*mf_High;
          else
            MF_C = Fuzzified_Caprock(b,5)*mf_Very_High;
          end

          Caprock = max(MF_C,Caprock);

     end


     Caprock1 = AHP_Caprock_1 * Caprock;
     Caprock2 = AHP_Caprock_2 * Caprock;



%%

     Transition = trimf(x,[-1 -1 -1]);

     for i = 1 : 5
          if i == 1
            MF_T = Fuzzified_Transition(c,1)*mf_Very_Low;
            elseif i == 2
               MF_T = Fuzzified_Transition(c,2)*mf_Low;
               elseif i == 3
                  MF_T = Fuzzified_Transition(c,3)*mf_Medium;
                   elseif i == 4
                      MF_T = Fuzzified_Transition(c,4)*mf_High;
          else
            MF_T = Fuzzified_Transition(c,5)*mf_Very_High;
          end

          Transition = max(MF_T,Transition);

     end



%%  Fuzzy Evaluation

       Likelihood = 0.5 * min(Transition, min(
max(Wellbore1,Caprock1), max(Wellbore2,Caprock2))) +  0.5 *
min(1-Transition, max( min(Wellbore1,Caprock1),
min(Wellbore2,Caprock2)));
%      MFF = 0.5 * min(Transition, min( max(Wellbore1,Caprock1),
max(Wellbore2,Caprock2))) +  0.5 * min(Transition_Inverse, max(
min(Wellbore1,Caprock1), min(Wellbore2,Caprock2)));
```

```
%%
            B1 = Wellbore_Belief_1(a,1);
            B2 = Caprock_Belief_1(b,1);
            B3 = Transition_Belief(c,1);
            B4 = Wellbore_Belief_2(a,1);
            B5 = Caprock_Belief_2(b,1);

            Belief_Likelihood = B3 * ( (1-(1-B1)*(1-B2)) * (1-(1-
B4)*(1-B5)) ) +  (1-B3) * ( 1 - (1-B1*B4)*(1-B2*B5) ) ;



            %% Focus on Here


%% Consequence + Likelihood

            n = fix(Belief_Likelihood * 100) + 1;  % For more
Precision we consider .1% for Belief Variation


%% Risk Matrix Evaluation

% consequence evaluation
            consequence = Final_Consequence; %from upper section




%% Centroid Deffuzification
% Centroid defuzzification returns the center of area under the
curve. If you
% think of the area as a plate of equal density, the centroid is
the point along
% the x axis about which this shape would balance.

            defuzz_likelihood = defuzz(x,Likelihood,'centroid');

%% Risk  Evaluation
%
            e = ones(size(Likelihood,2),1);
            Consequence_Mat = Final_Consequence*e;

            risk_mat = readfis('Final_risk_matrix');

            Likelihood_Quality = 0 : 5/(size(Likelihood,2)-1) :
5;

            Input_Risk = horzcat(Likelihood_Quality',
Consequence_Mat);   % Horizontally concatenate Likelihood and
Final_Consequence

            Risk = evalfis(Input_Risk, risk_mat);
```

```
membership = [0       0       1.25;
              0       1.25    2.50;
              1.25    2.50    3.75;
              2.50    3.75    5.00;
              3.75    5.00    5.00];



for i = 1 : size(Likelihood,2)

    if and( Risk(i) <= membership(1,2), Risk(i) >
membership(1,1)) == 1
       M11 = (Risk(i) - membership(1,1)) / (
membership(1,2)- membership(1,1));
    else
       M11 = 0;
    end

    if and( Risk(i) <= membership(1,3), Risk(i) >
membership(1,2)) == 1
       M12 = 1-(Risk(i) - membership(1,2)) / (
membership(1,3)- membership(1,2));
    else
       M12 = 0;
    end

    M1 = M11 + M12;
%%
    if and( Risk(i) <= membership(2,2), Risk(i) >
membership(2,1)) == 1
       M21 = (Risk(i) - membership(2,1)) / (
membership(2,2)- membership(2,1));
    else
       M21 = 0;
    end

    if and( Risk(i) <= membership(2,3), Risk(i) >
membership(2,2)) == 1
       M22 = 1-(Risk(i) - membership(2,2)) / (
membership(2,3)- membership(2,2));
    else
       M22 = 0;
    end

    M2 = M21 + M22;
%%
    if and( Risk(i) <= membership(3,2), Risk(i) >
membership(3,1)) == 1
       M31 = (Risk(i) - membership(3,1)) / (
membership(3,2)- membership(3,1));
    else
       M31 = 0;
    end
```

```
        if and( Risk(i) <= membership(3,3), Risk(i) >
membership(3,2)) == 1
            M32 = 1-(Risk(i) - membership(3,2)) / (
membership(3,3)- membership(3,2));
        else
            M32 = 0;
        end

        M3 = M31 + M32;
%%
        if and( Risk(i) <= membership(4,2), Risk(i) >
membership(4,1)) == 1
            M41 = (Risk(i) - membership(4,1)) / (
membership(4,2)- membership(4,1));
        else
            M41 = 0;
        end

        if and( Risk(i) <= membership(4,3), Risk(i) >
membership(4,2)) == 1
            M42 = 1-(Risk(i) - membership(4,2)) / (
membership(4,3)- membership(4,2));
        else
            M42 = 0;
        end

        M4 = M41 + M42;
%%
        if and( Risk(i) <= membership(5,2), Risk(i) >
membership(5,1)) == 1
            M51 = (Risk(i) - membership(5,1)) / (
membership(5,2)- membership(5,1));
        else
            M51 = 0;
        end

        if and( Risk(i) <= membership(5,3), Risk(i) >
membership(5,2)) == 1
            M52 = 1-(Risk(i) - membership(5,2)) / (
membership(5,3)- membership(5,2));
        else
            M52 = 0;
        end

        M5 = M51 + M52;


      Fuzzified_Risk(i,:) =  ( M1 * mf_Very_Low +  M2 * mf_Low +
M3 * mf_Medium  +  M4 * mf_High +  M5 * mf_Very_High ) ;


     end
```

```
     Risk_Matrix =  Likelihood  *  Fuzzified_Risk ;  % This is
just for 1 Belief value


%    MFF =  quatnormalize( Risk_Matrix ) * length ( Risk_Matrix
);
     MFF =  Risk_Matrix * 1/ max( Risk_Matrix );


     Center1 = defuzz(x,MFF,'centroid');
     Center2 = max(Center(n,1), 0);

    if Center2 == 0
        Center(n,1) = Center1;
        MFF_Final(n,:) = MFF;
    elseif  Center1 >= Center2   %% Changed by Mazda
        Center(n,1) = Center1;
        MFF_Final(n,:) = MFF;
    end


  %   MFF_Final(n,:) = Risk_Matrix;


                 end
           end
     end




%% Plot Section
Z=MFF_Final;
figure
surface(Z);
view ( -25, 60 );
title ( 'Solution to the Dempster-Shafer and Fuzzy Logic Problem'
)



mm = 0;
jj = 0;
for h = 1 : 101  %%% Changed Mazda
    if Center(h,1) > 0
      for j = 1 : (h - jj)
         mm = mm + 1;
         CDFCenter(mm,1) = Center(h,1);
      end
      jj = h;
    end
end

% Average and Variance
miu = mean(CDFCenter);
```

```
s = std(CDFCenter);

figure
hist(CDFCenter,12)

figure
hist(CDFCenter,100)

figure
h = normplot(CDFCenter);

figure
p = capaplot(CDFCenter,[4.25 6.75]);

figure
p = capaplot(CDFCenter,[4.0 7.0]);


figure
cdfplot(CDFCenter)
p = cdf('Normal',0:0.25:10,miu,s);
hold on
plot(x,p,'-')
hold off
title ( 'Defuzified Answer for Dempster-Shafer and Fuzzy Logic
Problem' )
xlabel('0 to 10 Risk Numbers')
ylabel('Belief or Agreement Percentage')
```