Assessment of the Conditions of Abandoned Wells in Potential CO2 Storage Reservoirs

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Master Thesis

Assessment of the Conditions of Abandoned Wells in Potential CO_2 Storage Reservoirs

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Abstract

This project is part of the larger REX-CO2 project, which assesses the re-usability of existing oil and gas wells in reservoirs targeted for CCS operations. It comes as a necessity to also assess the abandoned wells that will not be re-purposed, by assessing the risk they pose in terms of allowing the stored CO_2 to resurface across them, which is the focus of this work.

In order to assess these wells, a decision making framework was developed that will consider the main mechanisms that can lead to leakage across an abandoned wellbore. The objective is that this framework could be used by an operator of a prospective reservoir for a CCS project, prior to the start of the operations, in order to understand the risk associated with the abandoned wells present, and take decisions for remediation if necessary and possible. This framework considers three main aspects relevant for the formation of leakage paths. These are the effectiveness of the abandonment process itself, the chemical processes that can lead to the degradation of the isolation elements, and the mechanical processes that can lead to loss of integrity.

The framework consists of two main parts. The first is a qualitative analysis, based on a thorough literature review, assessment of experts and testing with case studies. This qualitative assessment consist of decision trees, formed by a series of questions which answers will dictate the final outcome that will reflect the state of the abandonment. The second part is a quantitative risk analysis. For this purpose "Bayesian Belief Networks" are used which is a probabilistic tool used for calculating the relative probability of a combination of factors. The BBNs are constructed and populated based on a thorough literature review including data on experimental results. In addition, geomechanical simulations were carried to populate these models. All this data was processed and converted into normal random distribution functions, which were used to infer the probabilities that would be included in the BBNs. The final outcome of the BBNs reflect the probability for leakage to occur.

Both the qualitative and quantitative parts of the framework are integrated together in order to obtain a complete analysis. The complete framework was tested with case studies based on real wells for which the abandonment states are known and reported by the operator, to observe how the outcome of the framework analysis matched the outcomes of the analysis performed by the operator.

With this study, a complete and systematic framework was developed that can be used to aid decision making for prospective CCS projects in the future. The framework is constructed such that it has the capacity to be improved and expanded in the future, to increase its consistency and broaden its applications. A series of potential improvements are also explained at the end of this report.

Furthermore, the framework can be used to challenge the current abandonment standards and assess what will have to be changed to adapt the current abandonment techniques so that they include CCS projects.

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The research, development and completion of this master thesis would not have been possible without the careful guidance of all my supervisors, Vedran Zikovic, Maartje Boon, Maartje Koning and Hadi Hajibeygi, that guided me during the long buy enjoyable process of putting this study together, by always making time to answer my questions, providing me with ideas and giving me feedback when necessary. This support is a very important part of successfully finishing this project. I also want to mention the support I got along the way from experts of different fields, which helped by providing me their expertise at different stages of this research. Finally I want to mention Kaj van der Valk who had the idea for this project and chose me to develop it and was also my supervisor for the beginning of the project.

Since this is the culmination of my master studies in the TU Delft I would like to thanks all my classmates and professors that made part of this experience and especially to my family and my partner who always encouraged me in the overwhelming moments.

Preface

The development of this thesis served as an integrative project to put together the different disciplines and skills that I acquired during my master track journey. Being a culmination of two years of work, from learning the basics of geology, modelling and technologies for geo-engineering to combining those disciplines for complex engineering applications. In this thesis paper, the use of knowledge and skills in the field of applied earth sciences were necessary in order to approach and solve the research question. This thesis, in particular, serves as a broad study into the factors relevant for assessing risk in real application related to geo-energy engineering. For this, a multi discipline approach was used, as in order to complete this project, different fields, including, well technology, geo-mechanics, chemistry and probability and statistics where combined. This project challenged me in its complexity and allowed me to learn new skills related to managing a project this broad and how to work with a vast array of subjects, also obtaining new knowledge in these specific subjects.

In this study I aim for the development of a framework that can assess the risk of formation of leakage paths in abandoned wellbores that will be placed in reservoirs targeted for CCS. This is done with the objective of increasing the feasibility of CCS projects in the future by preventing unforeseen leakages across these wells. For this I conducted an extensive literature review on well abandonment practices and the mechanisms that will form leakage paths across them. I later integrated this into the analysis together with probabilistic methods to form the risk assessment framework. I also thought it was important to test the framework with case studies in order to improve it and update it during the course of this project, until a final version was obtained. The future development of this framework into a well assessment tool could become useful for future CCS projects, where abandoned wells are an issue to be considered.

J. Mozas Maradiaga
Delft, July 2022

Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation

Due to the global rising emissions of greenhouse gases and their association with global warming, reducing these emissions has become a focal challenge society is facing. CO_2 capture and storage (CCS) is technique useful to reduce the total amount of emissions of CO_2 into the atmosphere. The 2022 IPCC report mentions CCS as one of the top 5 measures to halve CO_2 emissions before 2030 (IPCC, 2022). CCS consists of injecting CO_2 into a reservoir, trapping it permanently in the subsurface, storing it instead of releasing the CO_2 in the atmosphere. To do this, it is necessary to find an appropriate reservoir, with conditions that would allow for the CO_2 to be permanently trapped, without a possibility for resurfacing (Gasda et al, 2004). Figure 1 shows a schematic of a CCS project.

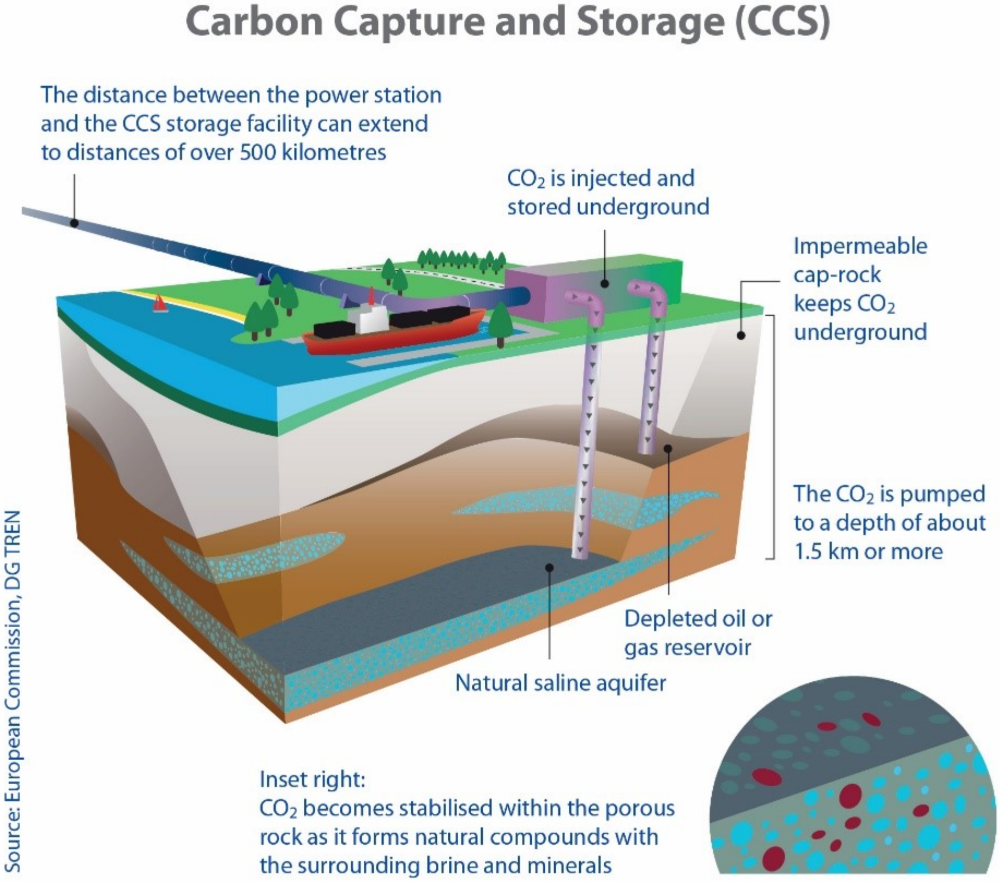


Figure 1: Schematic on CCS (European union science hub, retrieved 2021).

For CO_2 to be trapped it is required to store it in a appropriate reservoir with enough capacity to hold enough volume of CO_2 to justify the project. The reservoir rock also has to have good properties regarding its permeability, so that the CO_2 injection can be feasible. Lastly, it is also necessary that CO_2 will remain trapped in the subsurface, for this it is required that there is an effective sealing layer and a trapping mechanism. Generally an impermeable caprock will act as primary trapping mechanism, preventing the CO_2 to escape. Although the subsurface has a great capacity to store and keep the CO_2 trapped permanently, not everywhere will be suitable for this. Identifying the right fields and developing them can be costly, especially for a process that would not result in an economic gain, like CCS. This is why reservoirs that already have been used for oil and gas production and that have been depleted are being targeted as potential sites for CO_2 storage, like several reservoirs in the Dutch North Sea (Neele et al, 2013). The re-utilization of these reservoirs provide three advantages that will significantly reduce the cost:

- The reservoirs have proven to be able to store oil and gas safely, creating confidence in the capacity of the reservoir to maintain the stored CO_2.

- The reservoirs have already been extensively characterized, saving time and money into surveying and characterizing the reservoir.
- The reservoirs existing infrastructure used for oil and gas production could be reused, reducing costs on developing new infrastructure (Pawar et al, 2021a).

In the Netherlands, there exists a large capacity for storage in depleted offshore reservoirs (Neele et al, 2011). Even for these well characterized offshore reservoirs still uncertainties and factors that have to be assessed before injecting CO_2 into the reservoirs exists. One specific factor of concern regarding the re-utilization of these depleted reservoirs is the presence of abandoned oil and gas wells that were used for exploration, injection or production that are penetrating the caprock and reservoir. Some of these wells can be remediated and re-used for the injection of CO_2, while others will be left abandoned. For each of these wells, there will be a risk of leakage, especially for wells that have been abandoned and have become inaccessible (legacy wells), discarding the possibility for remediation and re-usage. Figure 2 shows a representation of how the spread of a CO_2 plume across the reservoir can result in leakage when crossing an abandoned well that is penetrating the caprock (Gasda et al, 2004).

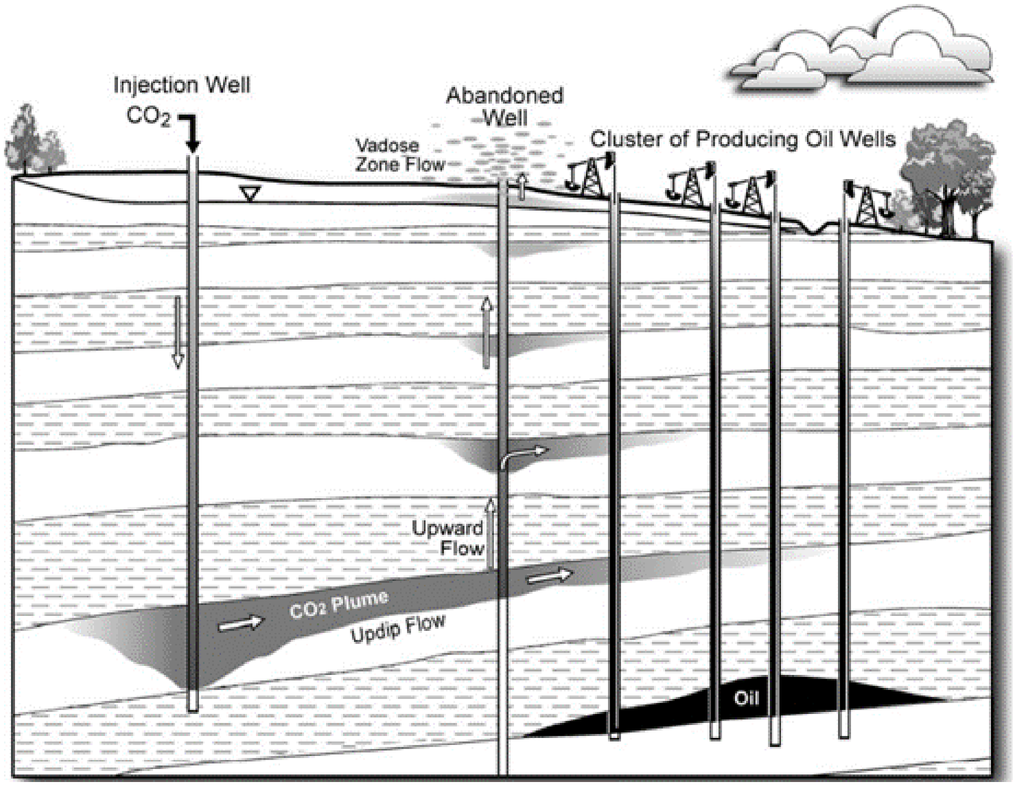


Figure 2: Schematic of leakage across abandoned well in a CCS reservoir, where the CO_2 is injected in the permeable layers (white) and it isolated by the caprock or impermeable layers (layers with grey lines). The abandoned wells can provide leakage points so that the CO_2 can scape the reservoir rock (Gasda et al, 2004).

The objective of the European research project REX-CO_2 is to develop a system to assess the re-usability of suspended or producing oil and gas wells for CO_2 injection. This project targets exclusively wells that will be re-used, however, does not consider wells that have been abandoned and will not be re-used. Depending on the conditions of the project and the conditions at which the wells have been abandoned there will be the possibility that they pose a significant risk of leakage. This will have to be assessed, especially when documentation on the state of these abandoned wells is missing or not complete enough to properly know their conditions. Currently, there is no system to assess these abandoned wells in terms of their abandonment conditions and the risk of leakage they present on a CCS project. Therefore, there is a necessity for the development of an assessment framework that can assess the conditions and the risk of leakage of abandoned wells in a systematic and effective way, including wells for which certain abandonment data is missing or highly uncertain.

In order to develop such an assessment framework, it is necessary to analyze the leakage through abandoned wells by taking into account all the different processes that will take place for this to occur. This includes having an in depth knowledge of the state of abandonment for wells and CCS reservoirs, but also understanding of geomechanics, chemistry and material properties. The inclusion of a broad range of disciplines into this project is required to cover all the relevant aspects. In order to incorporate all these factors into the risk analysis framework and to estimate risk, probabilistic tools will be used.

This report will explain the different stages of the development of the framework, consisting of two main parts. First a qualitative risk analysis, based on decision trees models that guide the user towards a final outcome based on a series of questions. Secondly, a quantitative risk analysis based on probabilistic methods. These two methods should complement each other, covering the short comings of each individual part, forming a single framework that uses both methods.

1.2 Approach

The objective of this analysis is to develop a framework to analyse the risk of leakage of abandoned wellbores in reservoirs re-used for CO_2 storage. To develop this framework it was first important to analyse the current, state of the art, abandonment techniques as well as the standards that rule the abandonment process and the main technical aspects that could lead to leakage. This gives the background necessary to develop a framework that considers all aspects of the process.

The need for such a framework comes from the fact that in reservoirs that will be re-used for CCS, where previously another projects of exploration or extraction took place, the abandonment wells are an unaddressed risk. While some of the wells can be re-used, some or most of them would not. Leaving these wells unaddressed can be problematic for a project, as this will result in an additional risk that can affect its overall feasibility. However, many wells are difficult or impossible to access and properly assess by tests, making it almost impossible to address the risk of each well, without significantly increasing the costs. Therefore, currently, the only possible way to assess abandoned wells is based on their abandonment reports left from the previous operator of the wells; which could be missing or have inaccurate or incomplete information. These factors make assessing abandoned wells, while very important, very challenging, as the processes leading to leakage can be very diverse and also complex, and most of the time there exists little evidence to make a proper assessment.

The objective of this framework is to address these challenges, by providing an effective way to assess wells, considering the whole spectrum of processes that can be relevant to leakage, and doing it in a way were the uncertainty can be incorporated into the analysis. While there is an abundance of studies and research on the specific topics relevant to the processes (studies on chemical degradation of cement, mechanical integrity of wellbore, etc) there is not a single systematic method to assess abandoned wells in CCS projects.

This framework looks into how can an abandoned well crossing a CCS reservoir be assessed, completely and consistently in a systematic way, regarding its risk of leakage.

This will have to be done in two parts, first by looking at what are the main factors affecting leakage across an abandoned wellbore in a CCS reservoir and secondly by analysing how these factors can be quantified and incorporated into a risk analysis. It is also necessary that this can be done for cases with large levels of uncertainty and missing data.

The framework will be designed to be used as a screening tool for decision making. This means that the framework will not go in depth into the analysis of a specific well, providing a precise and certain assessment of the state of a well, but instead will be able to easily assess a single or a group of wells in a reservoir. This approach was preferred as analysing a well in depth might become very challenging when there is a significant lack of data, which becomes even more of a problem when there is a large amount of abandoned wells in a reservoir that has to be assessed. As a decision making tool, it can provide a generic outlook for the user to decide the state of the well, and if further studies will be necessary for a particular well.

The framework will consist of two main parts, a qualitative part based on decision trees, and a quantitative part based on probabilistic methods for risk analysis. The objective is that these two parts function together as the framework for the leakage risk assessment. In this sense the quantitative part of the framework will be used to complement the outcomes of the qualitative part by supporting with a quantification of the estimated probability.

The first part of this report consists of the literature review and background information necessary to understand the processes of leakage across abandoned wells so that the framework can be developed. This is explained in chapter 2, first by explaining the current techniques used for abandonment of wells as well as the standards that regulate the abandonment. The second part of the chapter is about the potential leakage paths in an abandoned wellbore, which includes identification of the paths, and understating and classifying their potential causes. Three main categories are identified, being the processes related to the abandonment itself, the leakage paths formed by chemical degradation and the the leakage paths formed by loss of mechanical integrity.

Chapter 3 will explain in depth the development of the qualitative part of the framework, which is based on decision trees that will give the user a series of questions related to the abandonment conditions. The user will follow the flow chart, answering different questions about the state of the abandonment, the reservoir conditions and other factors. Depending on the different answers to the questions an outcome will be given, which will be a qualitative indication of the risk of leakage of the well. The choice of using the decision trees format comes from the system used for the REX-CO_2 framework, where decision trees are also used (Pawar & van der Valk, 2020). Three decision trees are developed based on the three potential causes for formation of leakage paths as explained in chapter 2 (abandonment process, chemical processes, and mechanical processes). This chapter also explains the main characteristics of the decision tree and how the assessment outcomes are obtained.

Chapter 4 will explain the development of the quantitative part of the framework. The quantitative analysis will be based on the use of 'Bayesian Belief Networks' (BBN). These are probabilistic tools that allow to calculate conditional probabilities in a graphical and straightforward way. These networks will be used to perform the quantitative risk analysis by calculation of the percentage probability of leakage occurring based on a set of conditions inputed by the user. A separate network will be used for different processes that can lead to leakage. This method is based on the current beta feature present in the REX-CO_2 for cement integrity prediction (Zikovic & van der Valk, 2021). This BBNs will be developed using the HUGIN expert software. In order to populate these networks, a literature review was performed in order to obtain experimental data. For the development of the BBNs related to the mechanical integrity a geomechanical model of an abandoned well was used, this was done in the DIANA FEA software.

In Chapter 5 the framework is applied to several case studies. This was done to test and validate the framework. In total three case studies were performed, obtaining different insights from each.

Lastly, chapter 6 consists of the main conclusions of the study based on the findings from the development of the framework and the results from the case studies. This also includes a list of recommendations for further studies and developments of the framework.

2 Abandonment practices and potential leakage paths

After the conclusion of any operation of extraction or injection from or into the subsurface, all the wells that have been used have to be properly closed and abandoned, to keep the environment and those around it safe from leakages and other environmental hazards. There are certain techniques and practices used to achieve a proper and successful abandonment. Well operators have to follow a certain set of rules or guidelines, to ensure that the abandonment is properly done and to ensure that the acceptance criteria are met (NOGEPA, 2021; Norsok, 2013). These rules and guidelines are defined in standards that can be international like the ISO standards or national like the NOGEPA nr. 45 standard from the Dutch mining regulations or the UK oil and gas integrity guidelines Issue 1 standard. In this section the main techniques used for well abandonment and also the standards that define the practices required for a proper abandonment will be explained, by reviewing a selection of international and national standards for well abandonment. This is important as it will give an indication of the current conditions of abandoned wells. This will be followed up by an analysis of the potential leakage paths that can form in an abandoned well as well as how they can form.

2.1 State of the art abandonment practices

When abandoning the well it is important to avoid any connection between the subsurface reservoirs and the surface. It is also important to separate different permeable intervals that might have the risk to be connected due to the presence of the well, to avoid flow from one reservoir to the other. For this, isolations have to be created between layers and between the shallowest reservoir and the surface (top isolation). The isolation comes from installing sealing barriers, commonly made from cement across the intervals of the wells. These isolation barriers are set to ''restore" the caprock, returning the reservoir back to its initial condition. Figure 3 shows a schematic for an abandonment concept showing sealing barrier placements (Oil and Gas UK, 2015).

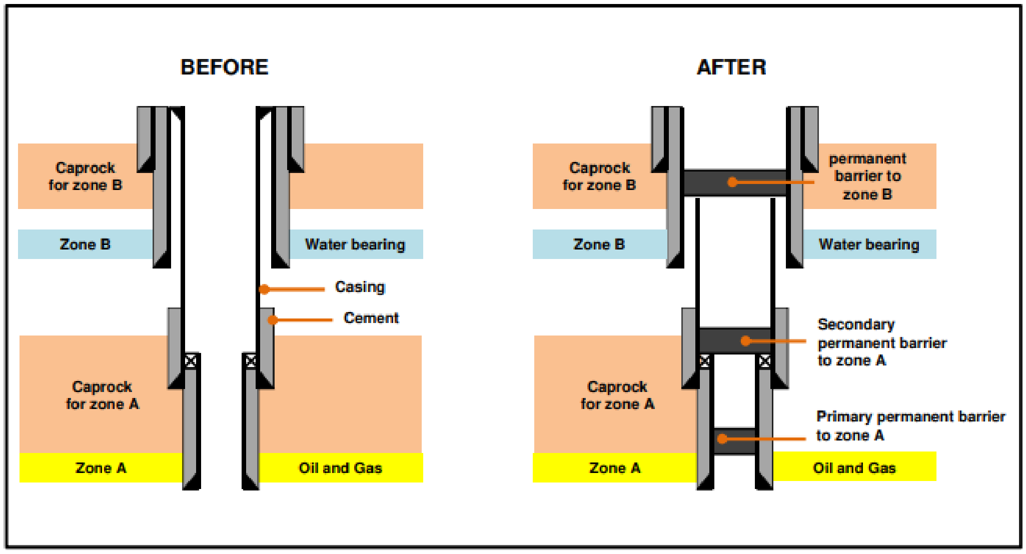


Figure 3: Schematic for well abandonment, showing barrier placements separating the lower oil and gas reservoir from the higher water-bearing reservoir and also separating both from the surface (Oil and Gas UK, 2015). This image shows two isolation barriers according the requirements of the Oil and Gas UK Well integrity guidelines standard, however not all standards require two barriers.

The material commonly used for these cement plugs is Portland cement, which has similar sealing properties to those of caprock (Oil and Gas UK, 2015), but other materials could be used. The importance is that the material has the appropriate characteristics for proper isolation. For this the material used for the plug has to have a very low permeability to prevent the migration of fluid. Furthermore, it has to be able to withstand, for a long time period, the pressure and temperature conditions of the reservoir, to avoid the formation of paths that will allow for fluid to flow across it. It is also necessary that the material is resilient to stress changes, that it does not corrode with fluids present in the well or reservoir and that it does not shrink after placement so that it can properly bond with the casing or caprock, avoiding the creation of fluid paths across the interfaces (Oil and Gas UK, 2009). The cement plug has to be of a certain thickness (normally specified by the standards) and has to cover the whole cross-sectional area of the wellbore. Cement is also used to plug the annulus between the casing and the rock interface. Figure 4 shows a schematic of a proper barrier conformed of a cement plug, explaining all the barrier elements that will form the isolation.

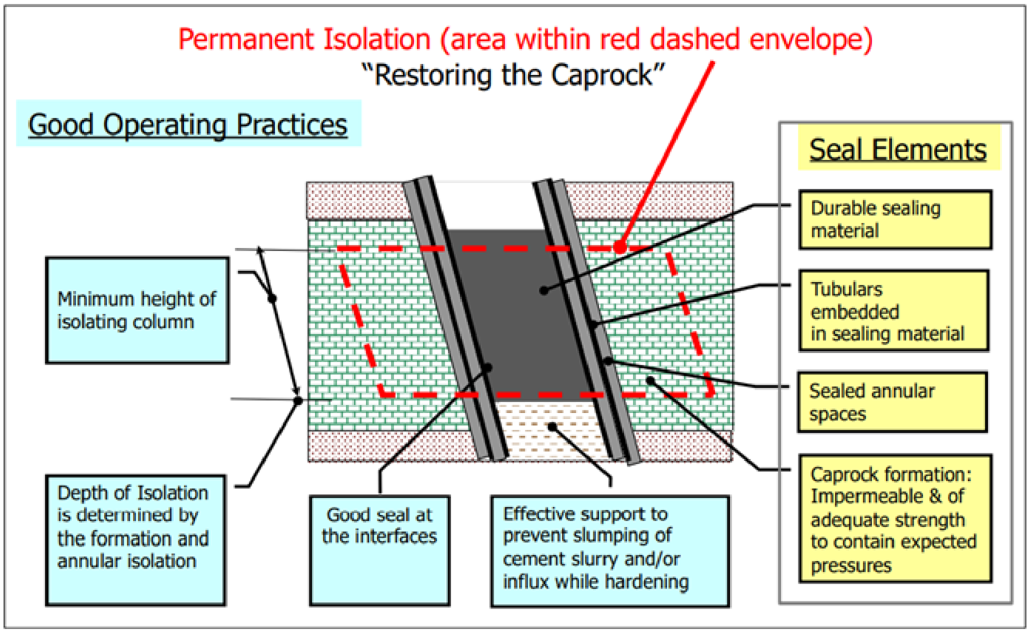


Figure 4: Schematic of cement barrier used for permanent isolation, with sealing elements (NOGEPA, 2021).

In combination with the cement, it is also possible to place a mechanical plug (cement retainers or bridge plugs) below the cement. The addition of these mechanical plugs is to reduce the amount of cement required by adding extra structure and to provide additional protection against formation pressure (NPC, 2011). These plugs generally have to be combined with cement since by itself it can corrode with the formation fluids.

The cement plug has to be placed in a position that it can separate the flow zones between each other and the surface, so the plug has to be placed above a certain zone of flow potential. Figure 5 of section 2.3 shows an example of how a typical plug looks like. The shallowest depth for the placement of the plug will be given by the formation strength, the formation pressure and the fluid gradient, so that the plug can withstand the maximum anticipated pressure of the zone with flow potential (NOGEPA, 2021).

Prior to the plugging, all the downhole equipment has to be removed. This includes tools, cables and anything that had been left in the well; following this, the wellbore is cleaned from any debris by the means of a suitable dense fluid (Benedictus et al, 2008). For the placement of the plug, the tubing is run down the well until the desired depth and then the cement is injected down the tubing; the tubing is then removed, and the cement will occupy its place, resulting in a solid layer of cement (NPC, 2011). To prevent cement slumping, there has to be a support which can be a mechanical plug, a packer, a previous cement column or other during the hardening of the cement slurry (NOGEPA, 2021). In order to place the annular cement, the cement is injected across the perforated part of the casing, It is also possible to reduce the number of interfaces present by performing a pancake plug (figure 6 of section 2.3). To do this, first the casing is milled out at the depth the plug will be installed (Benedictus et al, 2008).

The techniques described have been the common practice for well abandonment for many years and were designed without having CCS in mind. Despite small changes, the technologies used are the same since the 1970s. Proper well plugging and abandonment will prevent potential environmental damages and will reduce risks if a reservoir will be reused for EOR or CCS projects. The following section will explain the regulations set by a selection of international and national standards to ensure the proper abandonment of the wells.

2.2 Current standards and regulations

The main standards for well abandonment reviewed for this research are:

- Nogepa nr. 45 well decommissioning standard

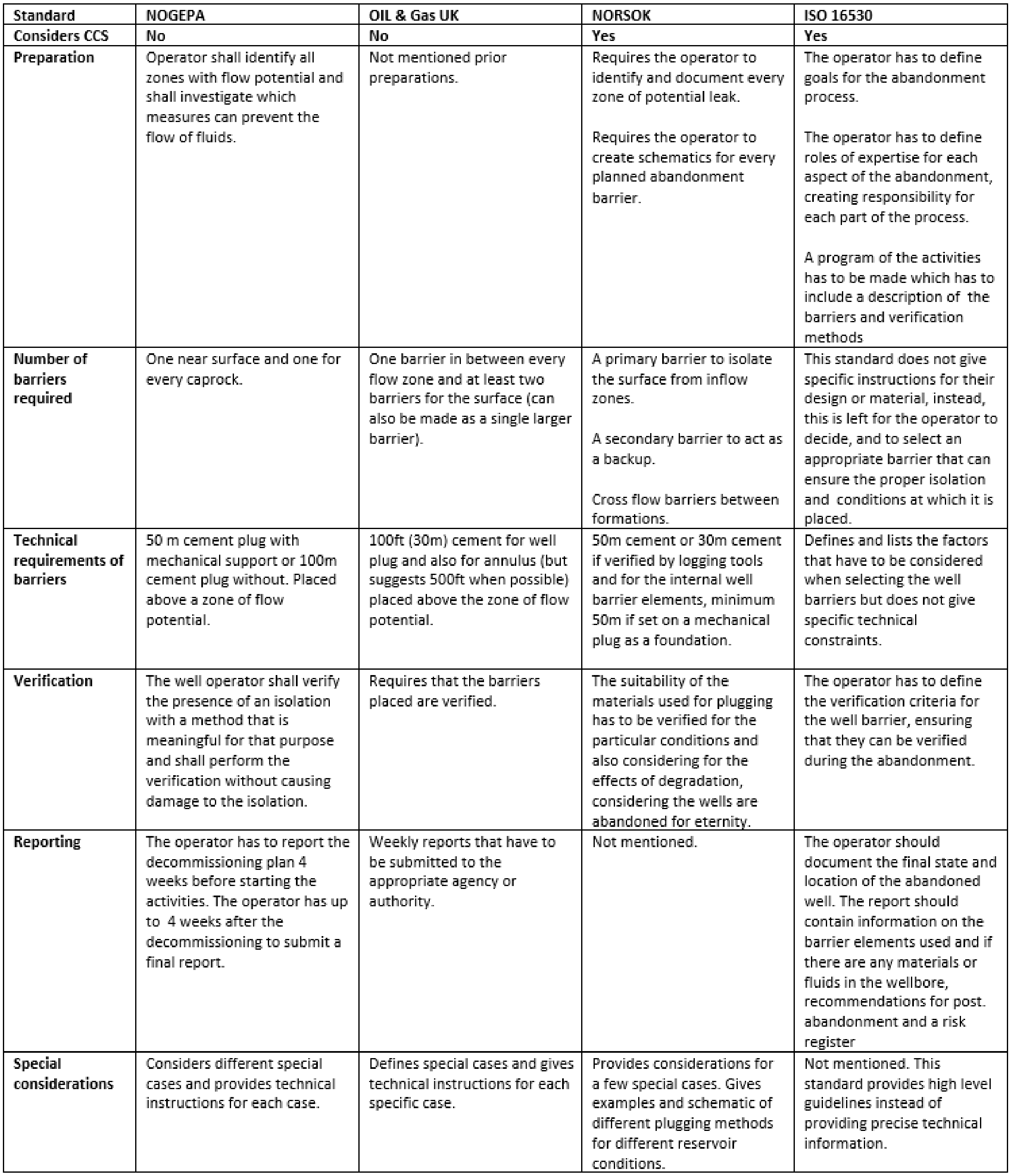
- ISO 16530
- Oil Gas UK Well integrity guidelines Issue 1
- NORSOK D-010
- ISO 27914

These standards (except for the ISO 27914) are general standards for setting the practices for well abandonment, but not particularly for CCS. The ISO 27914 standard is a standard specific for CCS projects but not specifically for well abandonment, although it does include a section for this part of the process. For this research the standard that will be used as the main reference will be the NOGEPA nr.45 standard since it will be the standard to which most wells in the Netherlands have been abandoned.

These regulations provide, in general, a high level description of what to be followed in order to ensure the proper decommissioning of the wells. They also provide technical details of the activities that will have to be done and how. Table 1 shows a comparison between the main points of each standard. In general, these standards have a lot in common. However there are some differences in the requirements, as can be seen in Table 1 (This does not include ISO 27914 since this standard is not specific for abandonment as mentioned above). In summary, the main points that these standards share are:

- Prior to abandonment, the operator has to identify all potential fluid paths across the wellbore.
- The isolation material has to have low permeability and be suitable for the conditions of the reservoir. It has to be placed above a high permeability zone and it has to be capable of withstanding the pressure conditions of the reservoir.
- There has to be at least one isolation plug between the surface and the flow zone and isolations separating flow intervals.
- Cement plugs have to have a thickness of 30m to 100m depending on the conditions and the standards and have to cover the whole cross sectional area of the wellbore.
- All materials inside the wellbore have to be removed prior to the decommissioning and all material near the surface has to be removed.
- Operators should verify the state of the plugging by performing integrity tests.
- The operator has to report to the appropriate agency or authority about the abandonment plan and processes. The content and scheduling of these reports vary for each standard.

Table 1: Main aspects of each standard considered for this study.



Standard	NOGEPA	OIL & Gas UK	NORSOK	ISO 16530
Considers CCS	No	No	Yes	Yes
Preparation	Operator shall identify all zones with flow potential and shall investigate which measures can prevent the flow of fluids.	Not mentioned prior preparations.	Requires the operator to identify and document every zone of potential leak. Requires the operator to create schematics for every planned abandonment barrier.	The operator has to define goals for the abandonment process. The operator has to define roles of expertise for each aspect of the abandonment, creating responsibility for each part of the process. A program of the activities has to be made which has to include a description of the barriers and verification methods
Number of barriers required	One near surface and one for every caprock.	One barrier in between every flow zone and at least two barriers for the surface (can also be made as a single larger barrier).	A primary barrier to isolate the surface from inflow zones. A secondary barrier to act as a backup. Cross flow barriers between formations.	This standard does not give specific instructions for their design or material, instead, this is left for the operator to decide, and to select an appropriate barrier that can ensure the proper isolation and conditions at which it is placed.
Technical requirements of barriers	50 m cement plug with mechanical support or 100m cement plug without. Placed above a zone of flow potential.	100ft (30m) cement for well plug and also for annulus (but suggests 500ft when possible) placed above the zone of flow potential.	50m cement or 30m cement if verified by logging tools and for the internal well barrier elements, minimum 50m if set on a mechanical plug as a foundation.	Defines and lists the factors that have to be considered when selecting the well barriers but does not give specific technical constraints.
Verification	The well operator shall verify the presence of an isolation with a method that is meaningful for that purpose and shall perform the verification without causing damage to the isolation.	Requires that the barriers placed are verified.	The suitability of the materials used for plugging has to be verified for the particular conditions and also considering for the effects of degradation, considering the wells are abandoned for eternity.	The operator has to define the verification criteria for the well barrier, ensuring that they can be verified during the abandonment.
Reporting	The operator has to report the decommissioning plan 4 weeks before starting the activities. The operator has up to 4 weeks after the decommissioning to submit a final report.	Weekly reports that have to be submitted to the appropriate agency or authority.	Not mentioned.	The operator should document the final state and location of the abandoned well. The report should contain information on the barrier elements used and if there are any materials or fluids in the wellbore, recommendations for post. abandonment and a risk register
Special considerations	Considers different special cases and provides technical instructions for each case.	Defines special cases and gives technical instructions for each specific case.	Provides considerations for a few special cases. Gives examples and schematic of different plugging methods for different reservoir conditions.	Not mentioned. This standard provides high level guidelines instead of providing precise technical information.

Appendix A shows a summary of the main individual standards and their main points.

2.3 Identification of leakage paths across abandoned wellbores

Abandoned legacy wells which penetrate reservoirs, form a potential leakage path for the reservoir fluids to resurface (Gasda et al, 2004). When performing the storage of CO_2 it is important to guarantee that the injected gas will remain trapped in the reservoir. When re-using depleted oil and gas reservoirs it is assumed that the trapping mechanisms that kept hydrocarbons in the reservoir will also keep the injected CO_2 trapped. However, because of the addition of these legacy wells, the risk of leakage significantly increases. These wells might not have been properly abandoned, resulting in fluid paths across them; or while they might have been properly abandoned given the conditions of a depleted reservoir, this does not guarantee that the techniques used will suffice when the reservoir conditions change when the injection of CO_2 starts.

Leakage of CO_2 across an abandoned well can occur through different parts of the borehole. Figure 5 (Gasda et al, 2004) shows a schematic of the potential paths that would allow for the flow of reservoir fluid across the wellbore. While not detailing the causes that lead to these leakage paths it does give a good description of where the leakages can occur. This schematic shows a case where the well was abandoned with a cement plug and conserving its casing. There are other methods of abandonment, for example by removing the casing and performing a pancake plug, which will reduce the number of interfaces and potential flow paths.

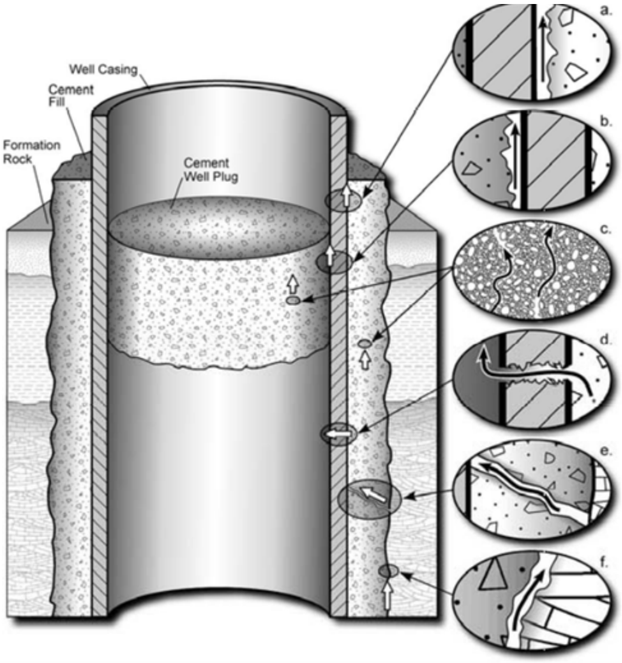


Figure 5: Potential paths for leakage of CO_2 to the surface: a) between the casing exterior and cement, b) between the casing interior and cement, c) across cement, d) across casing, e) across cement fractures and f) between cement and rock formation (Gasda et al, 2004).

As shown in the figure above, the main paths for flow can be summarized by:

- Flow paths in the interfaces between materials: cement-casing (exterior between annular cement and casing and interior between cement plug and casing) and cement-rock layer.
- Across the cement plug or the annular cement, by the formation of fractures or the degradation of the cement.
- Across casing, by damage and the formation of fractures.

Figure 6 shows how a pancake plug, placed by milling a section of the casing will result in less interfaces reducing the potential leakage paths.

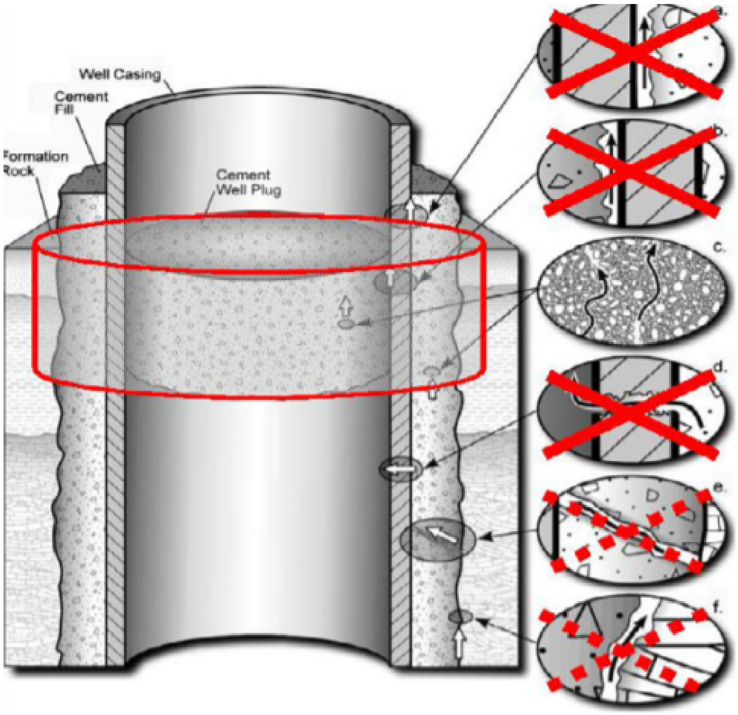


Figure 6: Leakage paths when placement with a pancake plug (adjusted from Seeberger & Hugonet, 2011).

In the next section, the causes that might lead to the formation of these leakage paths and the factors that will play a role will be explained.

2.4 Causes for formation of leakage paths

Several factors might lead to the formation of leakage paths. For this research, it is important to make a distinction between two types of flow paths.

- **Leakage paths before the start of CCS activities**: These are paths created during the plugging process or soon after. This occurs when the plugging process was not effective, resulting in improper isolation or the operator failed to consider important factors for the abandonment process or the well was abandoned before proper abandonment techniques were common. These paths will exist before the beginning of the CCS activities and are not related to any changes caused by the start of the operations. The operator is supposed to verify the conditions of the abandonment and report it, to make sure the abandonment is effective and provides proper isolation However, it is important to consider that there exists a risk of leakage. Especially in cases where there is no documentation or reporting about the wells abandonment process. This lack of data will increase the uncertainty and the risk that it pose will have to be considered in the assessment.
- **Leakages paths caused by the CCS activities**: At the time of the abandonment of the well the prospect of the re-utilization of the reservoir for CCS was not considered. Because of this, the plugging mechanisms used might not sustain the new conditions. Changes in pressure, temperature and the presence of new fluid, mainly CO_2, can lead to the formation of these leakage paths. Assuming that the well has been properly plugged, and properly abandoned to the conditions of the reservoir before its re-utilization for the CO_2 storage, once the CCS activities start, there are two main types of processes that can lead to the formation of leakage paths across the wellbore. These are by chemical or mechanical processes (Gasda et al, 2004):
  - **Chemical processes** will be related to the corrosion and degradation of the abandonment elements (cement, casing) as a result of the CO_2 rich environment. These processes will be affected by the materials themselves, the pressure and temperature conditions of the reservoir as well as the concentration of CO_2 and the presence of other contaminants (Akemu, 2011; Wei et al, 2015).

- **Mechanical processes** will be related to the mechanical integrity of the abandonment elements themselves and how they are affected by the changes in pressure and temperature when the reservoir is re-pressurized by the injection of CO_2. This will depend on the stress changes induced by pressure and temperature changes, the materials themselves and their elastic properties and mechanical strengths (Kermen & Meekes, 2013).

The main factors that will lead to the formation of leakage paths are summarized in figure 7. This will form the basis for the framework presented in this study for assessing abandoned wells, regarding their risk of leakage. Both the mechanical and chemical processes will be explained in more detailed in the following sections of this chapter

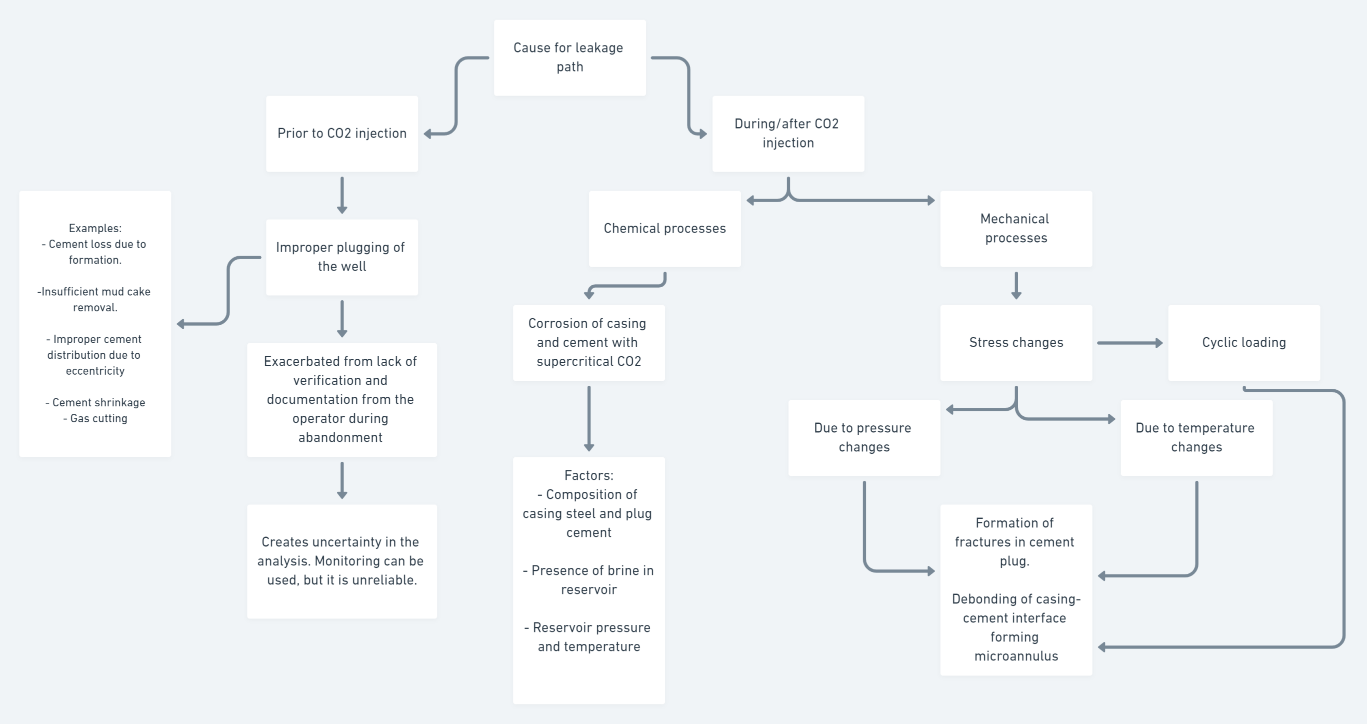


Figure 7: Schematic of main causes for leakage paths.

Despite identifying the different processes and mechanisms that can lead to the formation of leakage paths across the wellbore, it is not possible to know with confidence the conditions of the reservoirs or the wells. As mentioned before, there are a large number of factors that will end up causing CO_2 leakage, being it before or after the start of the CCS process. In many cases, it is not fully understood how these processes take place at reservoir conditions, since experiments can not always replicate this with precision or the data might be limited. In addition, the conditions at which wells have been abandoned might not have been fully documented, or the wells could have been abandoned a long time ago when the procedures for abandonment were different. This might lead to a lack of data and uncertainty that will make it difficult to impossible to assess the conditions of the wells. Because monitoring for the detection of leakages is not always a reliable option, when assessing the risk of leakage for the abandoned wells, this uncertainty has to be considered in the analysis.

2.5 Chemical processes

The components of the abandoned wellbore have the potential to corrode over time. This is due to the interaction between the wellbore materials and fluids in the reservoir. When wells are decommissioned, it is done in such a way that they would not experience significant corrosion overtime for the conditions at which the reservoir was abandoned. However, when the state of the reservoir is changed, due to the beginning of a CCS project, the well materials may corrode in the new reservoir conditions as a result of change in pressure, temperature and especially the change in composition due to the presence of CO_2 that will be injected. It is known that in certain circumstances CO_2 can be corrosive to the well components, and specialized materials have to be used when the concentrations of CO_2 are high, in order to avoid corrosion. The risk of corrosion has to be considered both for the cement in the well but also for the steel casing. Because these are two different materials that can potentially interact with CO_2, they have to be analysed separately. The chemical processes that can lead to the corrosion of the casing and degradation of the cement can lead to the formation of leakage paths across the isolation barriers. The rate at which degradation will affect the well materials is highly dependent on the conditions of the reservoir, and the materials used in the wellbore.

The two main causes that can lead to leakage due to chemical processes are explained in more detail in the following subsections.

2.5.1 Cement degradation

The main reaction that will affect the state of the cement (both annular cement and the cement plug) in a high CO_2 reservoir environment is the carbonation/bicarbonation reaction (Abid et al, 2015; Nygaard, 2010). This happens because the CO_2 in contact with Portland cement is not stable and will react with it (Nygaard, 2010). The first stage of the process is the reaction of the CO_2 gas with water, described by,

$$\mathrm{CO_2 + H_2O = HCO_3{}^- + H^+ = CO_3{}^{2-} + 2H^+} \tag{1}$$

Portland cement contains $Ca(OH)_2$ which will react with the $CO_3{}^{2-}$ formed in the previous reaction step as,

$$\mathrm{Ca(OH)_2 + CO_3{}^{2-} + 2H^+ = CaCO_3 + 2H_2O} \tag{2}$$

Where the final products are calcium carbonate and water. This first step of the reaction is referred as the carbonation reaction, and it does not directly corrode the cement in a way that will lead to the formation of leakage paths (Nygaard, 2010). Instead, it will alter the state of the cement, generally decreasing its porosity (and as an effect of this, its permeability) which makes the cement even more capable to isolate against CO_2 leakage. The issue that leads to cement degradation is by the continuation of the reaction; as long as there still is $Ca(OH)_2$ in the cement it will continue dissolving, lowering the pH of the brine. This will cause the CO_2 to react with the water, forming carbonic acid (H_2CO_3), which when dissolved, will form HCO_3^- ions. These ions will also react with the calcium carbonate, forming calcium (II) carbonate, that will dissolve out of the cement into the brine-CO_2 solution. Finally, at the cement surface calcium silicate hydrate from the cement will react with the carbonic acid to form calcium carbonate $CaCO_3$, as described by equation 3 (Nygaard, 2010).

$$\mathrm{3H_2CO_3 + Ca_3Si_2O_7 * 4H_2O = 3CaCO_3 + 2SiO_2 * H_2O + 3H_2O} \tag{3}$$

This final reaction (bi-carbonation) is the one that leads to the degradation of cement as it will increase its porosity and affect its integrity, providing the possibility of leakage paths forming, or by reducing the isolation capacity of the cement. Figure 8 shows the main reaction steps and the associated reaction zones.

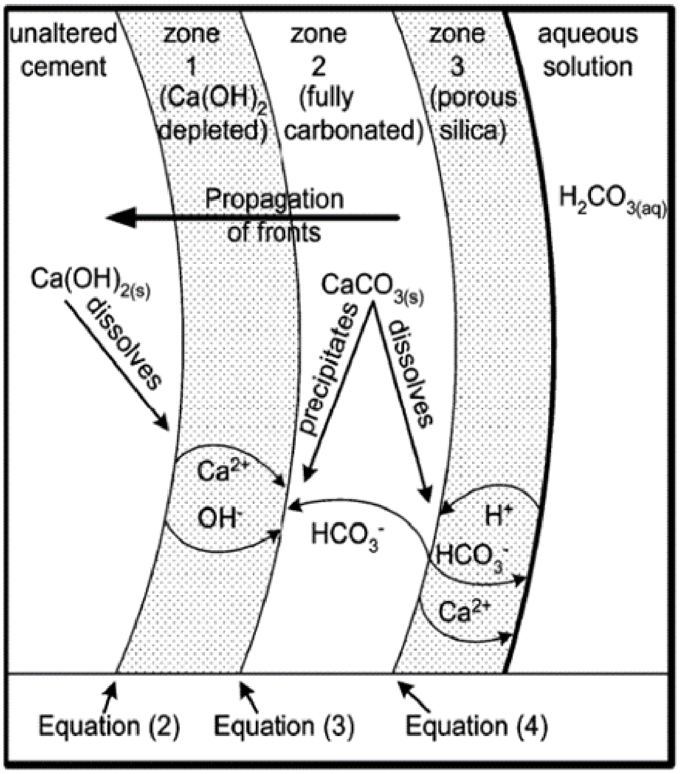


Figure 8: Representation of reaction zones of bi-carbonation reaction (klutchko et al, 2007; retrieved from Nygaard, 2010).

The objective of this part of the study is to analyse the main factors that will play a role in the rate of the bi-carbonation reaction, affecting the degradation rate and the final effect on the integrity of the cement as an isolation barrier.

Despite the main reaction affecting cement degradation in a high CO_2 reservoir environment is the bi-carbonation reaction, there are other reactions taking place that will affect the rate of cement degradation, in combination with the bi-carbination or independently; mainly redox reactions taking place by the presence of other contaminants like H_2S, NO_2 or others. The effect of these redox reactions will change the composition of the precipitate material when compared with the precipitate of only the bicarbonation reaction. However the effects on the changing of the rate of degradation are inconclusive, so this factors will be excluded of the analysis. (Carroll, 2016 ; Kutchko, 2009).

2.5.2 Casing corrosion

At high pressure and temperature environments, especially in the presence of high concentrations of CO_2, it is very likely that steel casings will experience a significant amount of corrosion. Generally, corrosion of the steel casings will occur due to the conversion of the Fe(s) present in steel to its aqueous form $Fe^{2+}_{(aq)}$. This reaction is facilitated by the presence of CO_2, as described by the redox reaction (Kahyarian et al, 2017),

$$Fe_{(s)} + CO_{2(g)} + H_2O_{(l)} \rightarrow Fe^{2+}_{(aq)} + CO^{2-}_{3(aq)} + H_{2(g)}. \tag{4}$$

This reaction represents the main process of casing corrosion, however, there are other associated reactions as part of the corrosion process. The reaction does not directly happen by the presence of CO_2 as it is not a directly corrosive component for the steel, however, it does increase the acidity of brine when a dissolution between water and the CO_2 occurs, which will lead to the formation of the corrosive solution to the steel surface. In particular for reservoirs, where the CO_2 will take a super critical state (SC CO_2), in order for the SC CO_2 to react with the wellbore elements so that degradation can occur, the CO_2 will have to be in contact with enough amounts of brine so that dissolution between the SC CO_2 and brine happens; dry SC CO_2 by itself does not corrode the casing. As with the cement plug it is important to analyse the effect that the corrosion will have on the formation of leakage paths, by also analysing the different factors that will play a role in the corrosion rate and its effect on the formation of leakage paths.

2.6 Mechanical processes

Mechanical processes that can affect the well integrity are related to the stress changes caused in the reservoir due to the CO_2 storage process. When the operations are ceased at the end of the hydrocarbon production, the reservoir is abandoned at certain conditions of pressure and temperature. Usually, the reservoir is abandoned with a much lower pressure than initially. Once the CO_2 injection starts, the pressure will now increase, and it might be re-pressurized back to initial conditions. The pressure changes will affect the stress state of the reservoir and the borehole, which can cause the formation of fractures, tensile cracks and shearing that will result in high permeable paths (Akemu et al, 2011). The failure mechanisms that can lead to the formation of leakage paths will depend on the total amount of stress that the wellbore elements will experience, be it by pressure changes or by thermal stresses. However, it will also depend on the material properties of the abandonment elements like the elastic properties of the cement and casing as well as the thermal properties and the strength of the materials in tension, compression and shearing. It is important to distinguish the failure criteria for the cement and casing since not all will lead to the formation of a continuous leakage path for CO_2. This section will consist of an analysis of the different method of how leakage paths will form by the effect of stress changes in the reservoir. For this, the main relevant failure modes will be explained and the conditions that can lead to their formation.

Failure modes

There are a number of ways in which the wellbore elements can fail. These have to be distinguished between the casing and the cement, as both elements behave differently as their mechanical properties will differ. However, it is necessary to consider that the casing will be completely embedded between the cement, by having the cement plug inside and the annular cement outside. Because of this the different failure possibilities for the casing (like buckling, shearing or burst failure) will not be relevant for the formation of leakage paths. This issues are generally of bigger concern in operational wells but not so much in abandoned wells. If any of this issues occur below or above the cement plug, this would still prevent a leakage path from the reservoir to the surface or other reservoirs in between. Because of this the focus of this analysis is on the integrity of the cement plug itself and on the possibility of debonding between the cement and casing or the cement and reservoir formation. Figure 9 shows the main failure modes for the cement in abandoned wells.

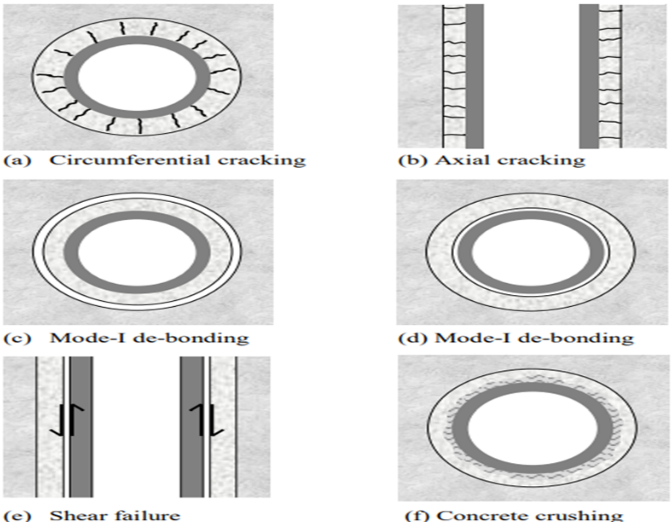


Figure 9: Failure modes for cement and debonding of interfaces (Schreppers, 2015).

a) Circumferential cracking caused by heating expansion, pressure loading or shrinkage.

b) Axial cracking of the cement caused by shrinkage in the cement where the cement is bonded to the steel casing and formation.

c) Debonding of the connection between cement and the formation, which may be a result of cement shrinkage.

d) Debonding of the connection between the cement and the casing, which may be a result of the casing cooling down.

e) Shear failure of the connection of cement and casing, which may occur at the intersection of well with depleting (compacting) and non-depleting formations.

f) Concrete crushing caused when the cement is exposed to strongly anisotropic far-field rock stresses, or when casing expands. Thermal or pressure expansion of the casing leads to a reduction of compressive stresses in the circumferential direction and an increase of compressive stresses in the radial direction.

Out of these failure modes, only modes a, c and d will provide a continuous leakage path for the CO_2 to cross the plug. This is because of how the orientations of the cracks form. If the cracks do not follow a direction along the plug that might connect top to bottom, they would not lead to loss of isolation. The other modes might be relevant when analysed in combination with the effects of chemical processes, as the loss of the integrity of the cement will have an effect on the chemical degradation, possibly increasing the rate by increasing the contact surface of the cement to the CO_2 rich brine. However, for this study, both processes will be considered in separate ways.

3 Qualitative approach

The qualitative framework is based on the decision tree format used by the REX-CO_2 tool (Pawar & van der Valk, 2020). The framework will be separated in three main decision trees. These three trees are based on the three main groups of processes that can lead to leakage, as explained in chapter 2. These are:

- **A-tree: Abandonment prior to CCS**: This refers to the state and condition of all the elements present in the wellbore post abandonment. Most of the wellbore elements would have to be removed from the well before abandonment, so it almost exclusively will refer to just the casing of the wellbore and the annular spaces and the abandonment elements (cement plug). This tree will assess that the right materials were used, that the methods used were adequate and that they were properly verified after their placement. As a guideline, the NOGEPA n. 45 standard will be used as a reference in order to act as a checklist for the most important points necessary for the abandonment. However, since this standard is not considered specifically for CCS, this tree is not limited by this standard. All requirements of the standard will be considered necessary. However to ensure proper abandonment under CCS conditions additional elements not directly linked to the standard might be considered. This will be based on literature and case studies. This tree contains two specific out of scope tracks. Out of scope is an outcome of the decision tree that is reserved for special cases, that deviate from the most common practices and are not frequently encountered when dealing with abandoned wells. These cases are:
    - Other completion elements left in the well that were supposed to be removed that affect the plugging and abandonment process or any casing issue that can prevent the placement of the plug. This is out of the scope, since each potential wellbore element would have to be verified and assessed in terms of how they would affect the abandonment.
    - Materials other than cement are used for the plug. This is considered out of scope because in most cases Portland cement is used for plugging, and rarely alternative materials are used. Incorporating every single potential material that could be used would not be practical, especially, since these cases will be rare. Because the NOGEPA nr.45 standard allows for the use of other materials as long as they provide the same sealing quality as cement, the materials used could be assessed separately and then the assessment could be continued with this tree.
- **B-tree: Post CCS chemical processes**: This refers to all the chemical interactions that can lead to the degradation of the wellbore materials. Because CO_2 is a highly corrosive gas, the CCS reservoir can become a corrosive environment to the wellbore elements. Next to the environmental factors that can lead to corrosion (pressure, temperature, composition) the material properties of the well elements will be considered.
- **C-tree: Post CCS mechanical processes**: This refers to the effect changes on the geomechanical state of the reservoir will have on the wellbore and how this can lead to leakage. Due to the injection of CO_2, pressure and temperature changes in the reservoir will lead to changes in the stress state of the reservoir, which can lead to deformation of the wellbore elements. This can cause fractures in the cement or debonding within the interfaces of the materials.

The following subsection will explain more in detail the components of these decision trees and how they are designed.

3.1 Decision trees design

Decision trees elements

The main structure of the decision trees is composed of different elements, which are:

- Sections: Individually referring to one specific area of interest within the wellbore, the reservoir or the processes performed (e.g. the cement plug, external factors). Each section will be composed of at least one element. Separating each tree in sections will allow for a better way to assign a risk rating for each tree, as a rating can be given per section and also to more clearly identify where or what might be causing the leakage (e.g. the main risk point was identified in the cement plug).
- Elements: Each element is a node to which different outcomes will be given depending on the answer. These are the main questions of the tree that will guide towards the next element and the different outcomes. Not necessarily for each element there will be different outcomes, some can simply be to redirect the flow to different elements.

- Flow direction lines: the main direction to follow for the flowchart, represented by arrows
- Outcomes: the different colour outcomes. These will come as a result of the different elements and will be used to give a rating for each section and for the whole tree.

Assessment of factors

The different factors that will play a role in the formation of leakage paths will be included in the tree as elements. These factors are not necessarily related to causes that would lead to the formation of leakage paths, but to the effects they would have and how these effects can be detected. Because the goal of this decision tree is to practically assess wells in terms of the risk of leakage, it is important that the elements included can be practically observed. The decision tree elements are classified by:

- Structural elements: Refers to the physical elements of the wellbores and their conditions(e.g. the presence and state of the casing, and cement plugs).
- Verifications or documentations: Refers to if a certain verification was performed (e.g. results of tests verifying the state of the cement, documentation of any issues).
- Processes: Refers to the performance of any process that is relevant to the formation of leakage paths (e.g. the cement plug placement process).
- Environmental/reservoir elements: Refers to the state of the reservoir or other environmental factors that will affect the process (e.g. reservoir pressure, reservoir brine composition).

While understanding the causes is of great importance to understanding the system, the decision trees will not be addressing the causes directly, for the most part. This is because once a well is abandoned, depending on the available data and information about it, it might not be possible to pinpoint the presence of leakage to a particular cause. This is why the decision trees for the qualitative assessment will focus on elements that will give evidence of the presence of leakage across the different well parts, by the means of verification, observations or test results. Also, important elements for the decision tree is the factors that will exacerbate the processes that might lead to a cause for leakage (for example, a higher reservoir temperature might increase the rate of the reaction of corrosion).

Risk rating outcomes

A-tree: Abandonment prior to CCS

The A tree ranks the risk of leakage in an abandoned well based on the quality of its abandonment process, the elements present and to a smaller extent reservoir factors. There are five outcomes of the flow chart of this decision tree (excluding out of scope);

Red: Main required abandonment features not present or not in condition, insufficient or not properly verified. This entails a high risk of leakage. A red ranking will be generally given when a main isolation element that is required by the standard and is essential for the isolation is missing so that there would not be effective isolation to prevent leakage.

Orange: Main required abandonment features present; however, they might not have been properly verified and there are a few key elements that might lead to leakage. This entails a moderate to high risk of leakage. Orange ratings will be usually given when there is a lack of proof that the elements present are effective, for example by not performing the verifications required, or when there are factors that might significantly increase the risk of leakage, for example, some environmental conditions that might not be ideal. An orange outcome might not indicate that leakage will for sure happen, because the main isolations will be there, but there is no proof that they are effective.

Yellow: Main required abandonment features present and verified, however, most ideal practices not followed or smaller factors might affect integrity. This entails a moderate to low risk of leakage. Yellow ratings will be usually given when the main elements are there and they are verified, but there might still be some factors that could slightly increase the risk of leakage, like not using the most ideal processes or some environmental factors that will have a minor effect.

Green: Main required abandonment features present and verified and most ideal practices followed. This entails a low risk of leakage. Green ratings will be usually given when all the necessary elements are present in the well, there is proof of their proper functioning as isolations and the conditions and practices do not favour leakage across the wellbore. This does not mean that there would not be leakage, but that the risk is low and nothing could have been done better to prevent it.

Grey: Not enough data or information to perform the assessment. When there is missing data it might be impossible to properly perform the assessment with confidence.

This colour rating reflects on the **Shall, Should, Could** compliance levels of the NOGEPA nr.45 standard, with elements having red outcomes relating to the shall requirements of the standard while elements with yellow or orange outcomes relating to should and could requirements for the most part (with the exception of some verification steps, which are shall requirements in the standard and lead to orange outcomes, as explained above).

The final outcome will be a weight of the different green, yellow, and orange outcomes for each element (since a red outcome will put an end to the flowchart). The flowchart is also divided into sections of the wellbore, with each section having a specific number of elements with their outcomes. These sections are based on the specific part of the wellbore that is being addressed by the elements (e.g. the casing, the cement plug, the annular cement). The rating will be given for each section, depending on the element outcome with the highest risk for that section. The overall risk rating will be given as the highest one of the different sections, addressing to what section it corresponds to, with exceptions if a section later on the tree will cover issues from up the tree (e.g. well-plugging process section results in an orange rating, while the abandonment verification section results in a green rating, which will cover the orange section).

B and C trees: Post CCS chemical and mechanical processes

The risk ratings of these trees are based on the same colour code ratings as with the A-tree. Despite this, the way the final outcome is obtained and the meaning of each individual colour outcome for each element will be different from the A tree. This is because the A-tree elements are based on the presence of different structures and their verification, so the outcomes were distinctively binary (e.g. either there is a barrier present or there is not, the importance of this barrier will result in a risk rating outcome). The B and C trees on the other hand are based on the chemical and mechanical processes that could lead to the formations of leakage paths respectively. Elements in these trees might not necessarily be related to specific binary outcomes, but instead, in most cases, they will be related to factors that might increase the likelihood of leakage happening (e.g. certain reservoir conditions might accelerate the rate of the corrosion reaction of well elements). This will result in much fewer elements having a red outcome, especially for the B-tree. This also will require a different method to weigh in all the individual outcomes towards an overall outcome of the flowchart. For example, several yellow outcomes in the B-tree can add up to a risk level higher than yellow (e.g. the reservoir temperature favours corrosion, the wellbore casing is not of corrosion-resistant material and there are contaminants that will increase the reaction rate will result in a relatively high risk of leakage, even though all those specific outcomes individually will not indicate a high-risk level). In this way, a decision tree flowchart is limited for these two trees, as it is not the most suitable method to deal with elements that might have outcomes that cannot be accurately represented in a binary way. Following up, on the next stages of the project, modelling and probabilistic analysis will be implemented in order to more accurately represent the outcomes, by quantifying the different factors in order to obtain a final estimation. As a preparation for that, these tree outcomes will be given like in the case of the A-tree, for each of the different sections. The colours now represent how critically the different factors will have an effect on the risk of leakage. Unlike the A tree, a specific cut off between orange and yellow cannot be defined, as for the most part the exact effects of each outcome is variable depending on the different factors magnitudes and these might be difficult to assess without delving into quantifications of these parameters. Regardless of this, these trees provide a preliminary risk analysis with all the relevant elements that will later be the basis for the probabilistic risk assessment.

3.2 Decision trees format and factors

Figure 10 shows a small sample of one of the decision trees, showing the flow from question to question. Tables 2 to 4 shows the sections and elements of the decision trees. Appendix B shows the three complete decision trees, accompanied by an explanation of each element.

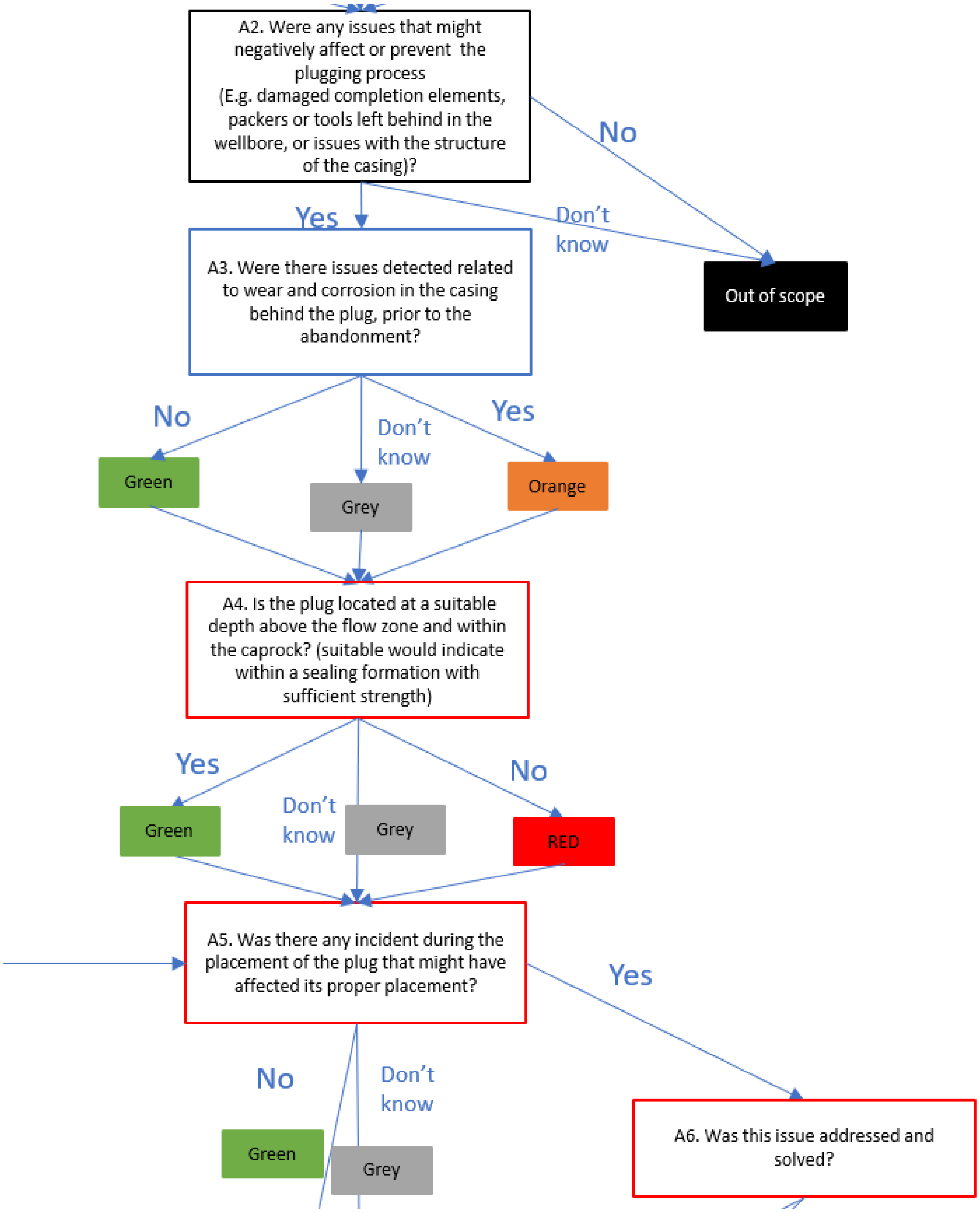
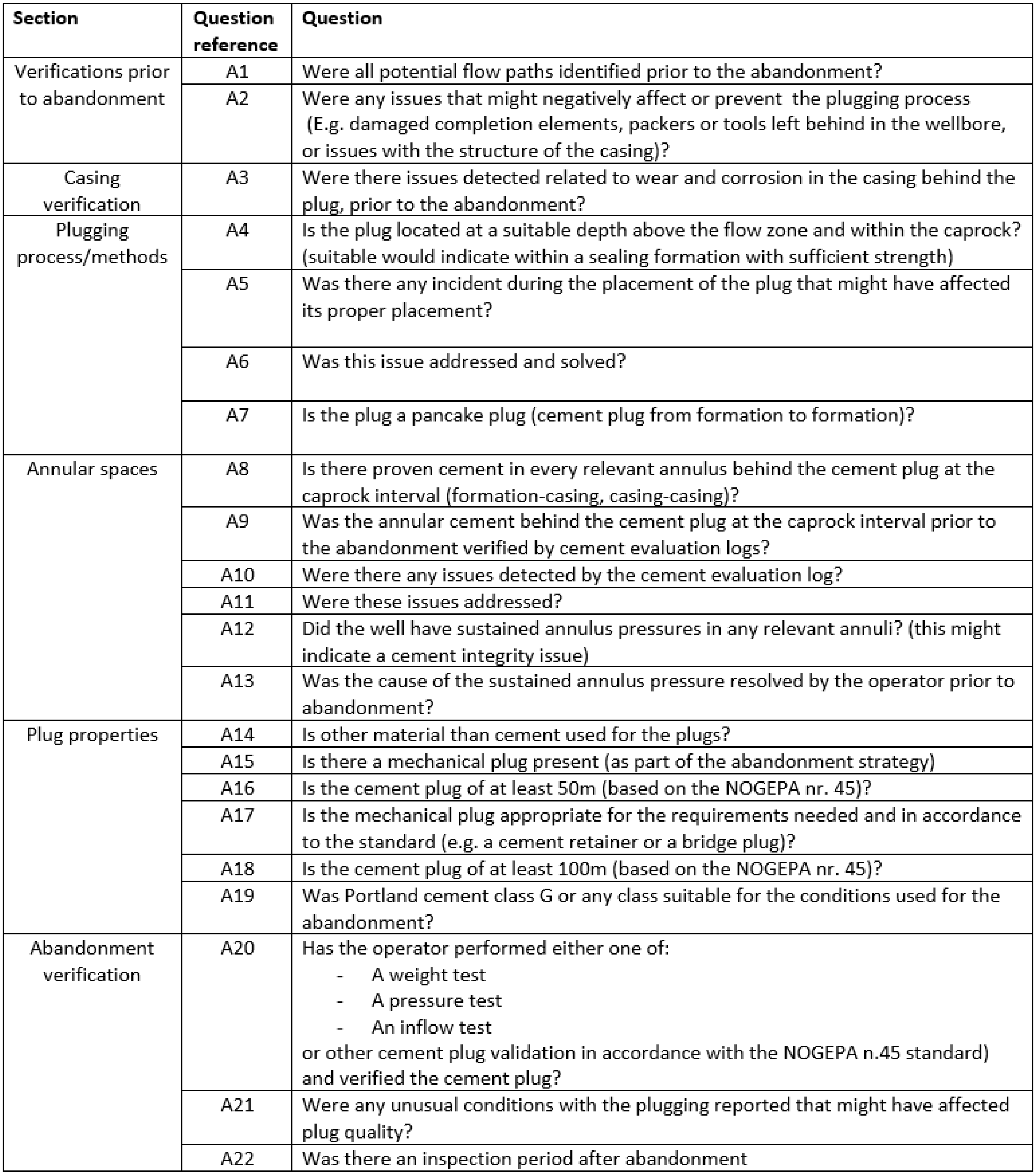


Figure 10: Sample of the A-tree. showing the structure and flow chart.

Table 2: Questions of the A-tree and each associated section.



Section	Question reference	Question
Verifications prior to abandonment	A1	Were all potential flow paths identified prior to the abandonment?
	A2	Were any issues that might negatively affect or prevent the plugging process (E.g. damaged completion elements, packers or tools left behind in the wellbore, or issues with the structure of the casing)?
Casing verification	A3	Were there issues detected related to wear and corrosion in the casing behind the plug, prior to the abandonment?
Plugging process/methods	A4	Is the plug located at a suitable depth above the flow zone and within the caprock? (suitable would indicate within a sealing formation with sufficient strength)
	A5	Was there any incident during the placement of the plug that might have affected its proper placement?
	A6	Was this issue addressed and solved?
	A7	Is the plug a pancake plug (cement plug from formation to formation)?
Annular spaces	A8	Is there proven cement in every relevant annulus behind the cement plug at the caprock interval (formation-casing, casing-casing)?
	A9	Was the annular cement behind the cement plug at the caprock interval prior to the abandonment verified by cement evaluation logs?
	A10	Were there any issues detected by the cement evaluation log?
	A11	Were these issues addressed?
	A12	Did the well have sustained annulus pressures in any relevant annuli? (this might indicate a cement integrity issue)
	A13	Was the cause of the sustained annulus pressure resolved by the operator prior to abandonment?
Plug properties	A14	Is other material than cement used for the plugs?
	A15	Is there a mechanical plug present (as part of the abandonment strategy)
	A16	Is the cement plug of at least 50m (based on the NOGEPA nr. 45)?
	A17	Is the mechanical plug appropriate for the requirements needed and in accordance to the standard (e.g. a cement retainer or a bridge plug)?
	A18	Is the cement plug of at least 100m (based on the NOGEPA nr. 45)?
	A19	Was Portland cement class G or any class suitable for the conditions used for the abandonment?
Abandonment verification	A20	Has the operator performed either one of: - A weight test - A pressure test - An inflow test or other cement plug validation in accordance with the NOGEPA n.45 standard) and verified the cement plug?
	A21	Were any unusual conditions with the plugging reported that might have affected plug quality?
	A22	Was there an inspection period after abandonment

Table 3: Questions of the B-tree and each associated section.

Section	Question reference	Question
External environmental factors	B1	Is there brine present in the reservoir that might come in contact with the abandoned well?
	B2	Is the brine in the reservoir initially saturated (a higher saturation results in less capacity for the brine to react with cement)?
	B3	Is the initial pH of the brine (before CO_2 injection) low due to the presence of contaminants (E.g. O_2, SO_2, H_2S, NO_2)?
	B4	Is the temperature of the reservoir above 90℃?
	B5	Is the pressure of the reservoir after re-injection above 450 bar?
CO_2 injection	B6	Is the pH of the brine below 1.5? (caused by dissolution of CO_2 and/or other contaminants)
Cement plug	B7	Is the current well cement in the plug and the annulus mixed with a pozzolan additive (e.g. Silica flour, fly/glass/volcanic ash) on proportions of over 40%?

Table 4: Questions of the C-tree and each associated section.

Section	Question reference	Question
Cement properties	C1	Will the cement used for plugging and annulus maintain integrity under the predicted temperature change? (depending on thermal coefficients of cement and magnitude of temperature change)?
	C2	Will the cement used for plugging the annulus maintain integrity under the predicted load profiles during its anticipated operational life?
	C3	Is the expected stress change due to the injection of CO2 higher than the strength between the cement-casing bond, breaking the integrity of this bond?
	C4	Is the expected stress change due to the injection of CO2 higher than the strength between the cement-formation bond, breaking the integrity of this bond?
	C5	Are the isolation elements (cement and casing) be expected to maintain their integrity for the new reservoir conditions for eternity (or as specified by standards)?

4 Quantitative methods

The quantitative part of the network uses Bayesian Belief Networks as a probabilistic tool. This section explores the development of the BBNs. Each network will be explained in detail. This will be separated in three sections, based on the methods used to design the networks. This will be the "prior to CCS network", "chemical processes" and "mechanical processes". Except the 'prior to CCS' network, each section will consists of several networks, each addressing a specific aspect that can lead to leakage.

4.1 Explanation of Bayesian Belief Networks

In order to perform the risk analysis, it was opted to use Bayesian Belief Networks (BBNs) as a probabilistic tool. This section will go in depth in what are BBNs, the concept behind them and on how they can be used for this particular project.

A Bayesian network (BN) is a model that represents the relation of different 'events' or 'nodes' in terms of the relative probability of these elements. Basically, a BN is used whenever there is a model of factors where there is some level of uncertainty. The BN is represented by a network of nodes that are connected by direct links, figure 11 shows an example of a simple BBN. These nodes represent variables which can take discrete or continuous states. The links between the 'nodes' or 'variables' indicate what sort of relation this nodes have with each other. A node is said to be a parent node if there is a link coming from this node pointing towards another node. A node without a parent node will have a marginal probability table, which for discrete nodes, it consists of a probability distribution over the states of the variable that it parents. If a node does have parents, the node will consist of a conditional probability table (CPT). Each element of this CPT will represent the conditional probability of the node having a specific state, given the specific configuration of the state of the parent node. Overall, a BN is a graphical way to represent the conditional probability between the states of different variables, mapping the relation between them. The two elements of a BN are the network itself, which represents the relation between the variables and the CPTs, which define the conditional probability between these events (HUGIN GUI, 2022).

Formally, as written in the HUGIN guider user interface, a BN is defined as:

"A Bayesian network is a pair (G,P), where G=(V,E) is a directed acyclic graph (DAG) over a finite set of nodes (or vertices), V, interconnected by directed links (or edges), E, and P is a set of (conditional) probability distributions. The network has the following property:

Each node representing a variable A with parent nodes representing variables $B1, B2, \ldots, Bn(i.e., Bi, ßA$ *for each* $i = 1, \ldots, n)$ *is assigned a conditional probability table (CPT) representing* $P(A|B1, B2, \ldots, Bn)$.

The nodes represent random variables, and the links represent probabilistic dependences between variables. These dependences are quantified through a set of conditional probability tables (CPTs): Each variable is assigned a CPT of the variable given its parents. For variables without parents, this is an unconditional (also called a marginal) distribution"(HUGIN GUI. 2022).

BNs are useful as they are a way of inferring the relative probability of an event, given the state of a prior. This is based on Bayes theorem, which uses a mathematical formula to determine the conditional probability of an event, based on a previous outcome. Bayes theorem is represented by formula 5

$$P(A \mid B)P(B) = P(B \mid A)P(A) \tag{5}$$

Where: $P(A \mid B)$ is the probability of A given B

$P(B)$ is the probability of B occurring

$P(B \mid A)$ is the probability of B given A

$P(A)$ is the probability of A

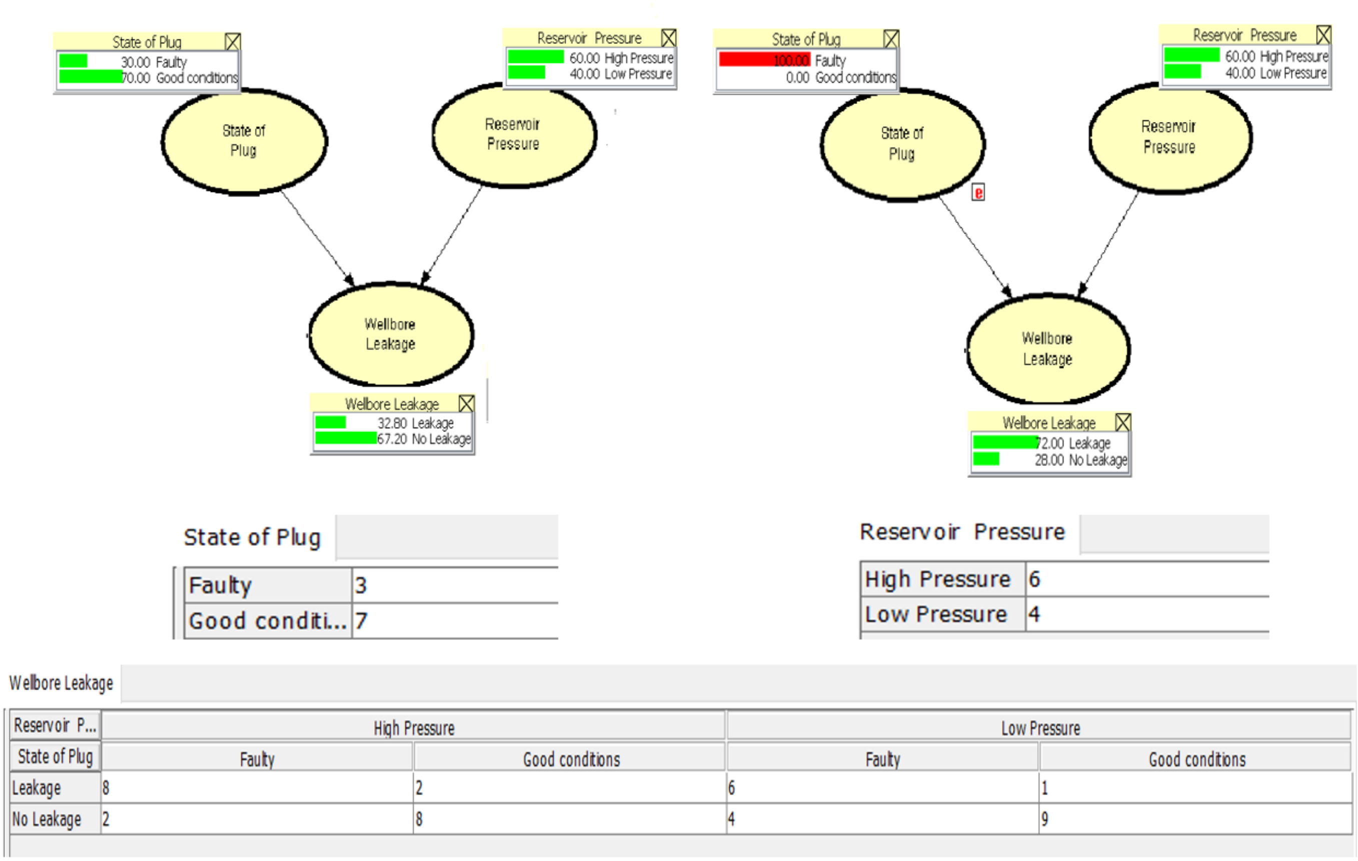
$P(B)$ is the probability of B

The Bayesian network is applying this formula between the events present in the network, where the values of the probabilities themselves are defined in the CPTs.

A Bayesian 'belief' network (BBN) refers to a BN that is populated by the criteria or observations of an expert. In this case there will be some fundament of the chosen probabilities in the CPTs. In the case of this project, the networks used will be BBNs because the CPTs are populated with probabilities based on literature studies, experiments and results from modelling.

The advantage of using BBNs for this risk analysis is that they are very useful when working with uncertainty and lack of data. While data can be incorporated into the model to be used as evidence for a given state or probability, the model can still estimate the probability of an event occurring without evidence as long as the relative probabilities of the states are defined.

Figure 11 shows an easy example to understand more in depth the use of BBNs by the use of a relevant problem.



State of Plug

Faulty	3
Good conditi...	7

Reservoir Pressure

High Pressure	6
Low Pressure	4

Wellbore Leakage

Reservoir P...	High Pressure		Low Pressure	
State of Plug	Faulty	Good conditions	Faulty	Good conditions
Leakage	8	2	6	1
No Leakage	2	8	4	9

Figure 11: Hypothetical example on how BBNs can be used to estimate risk in abandoned wells with the networks and the respective tables. The top left picture shows an example without evidence, and the top right shows an example with evidence (represented by the red line on the state of the plug monitor window). The bottom tables represent the CPTs associated with each respective node.

This example represents the risk of leakage through a wellbore occurring based on two factors, the state of the plug and the reservoir pressure (with this two elements acting as parent nodes to the wellbore leakage node, indicated by the direction of the arrow). Each of the nodes have two possible states, which each state having a probability, which is filled in for each of the parents nodes. By filling the CPTs, the model will calculate the probabilities of the states of the 'wellbore leakage' node based on the probabilities of the parent node. If evidence is included, in this case, assuming that it is known that the plug will be faulty, this data can be included in the model and the probabilities will be recalculated. This shows the power of this tool in working with cases where uncertainty and lack of data are common (which is common when dealing with abandoned wells), as a result can be obtained regardless.

Apart from this advantage BBNs also provide a simple and straight forward graphical method to calculate relative probabilities, and can easily represent and approximate very complex systems in a simpler way using probabilities. On the other hand, the main disadvantage of using BBNs is the need for ‘expert’ information or data to fill the tables. This might require a lot of data as well as a deep understanding, depending on the complexity of the system that needs to be modelled. In this case, models with a large amount of relevant factors might become easily to complex to model with BBNs.

For this project, several BBNs will be used to model the risk of several aspects that can lead to leakage. The exact process for the construction and population of these BBNs will be explained in the chapter of each respective process.

There are some assumptions that have to be made before using these BBNs for the process:

- All the elements included in the BBNs have to be independent of each other, or if not their relation will have to be indicated by arrows between the nodes.
- All factors specified will be consider as discrete variables, this means that they will be composed of discrete states. If continuous variables are included they will have to be discretized to be included in the model.

Apart from these simple assumptions, there are also other specific assumptions for each of the individual networks developed, which will be explained in the relevant sections.

4.2 Abandonment prior to CCS BBN

The first network is based on the A-tree. This network is different from the other ones as it does not focus on a specific process, but instead it translates the decision tree into a BBN format. Because of this, this network will not be populated as the other trees will, where extensive literature, modelling and data processing were involved. Instead, the outcomes will be considered binary, based on observations or evidence from the available data. Figure 12 shows the main network that represents the A-tree.

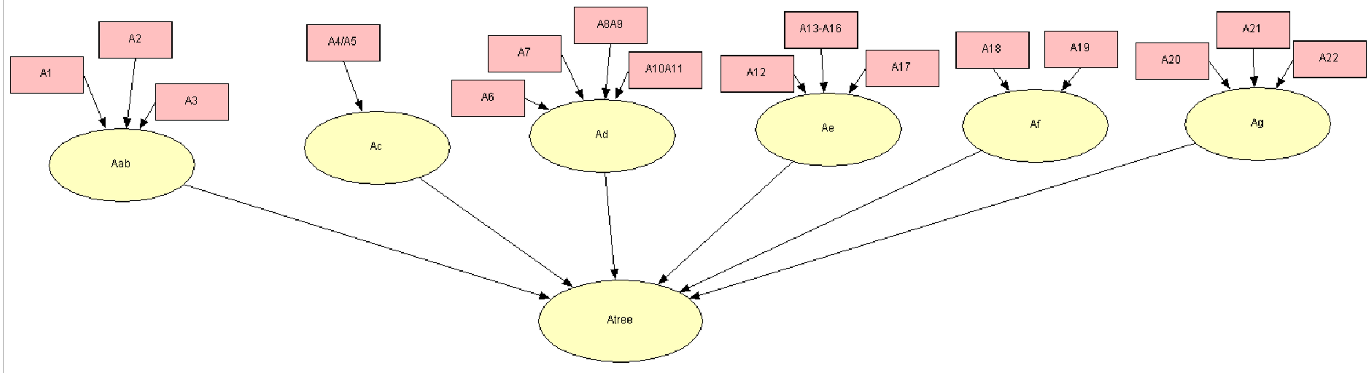


Figure 12: A-tree represented as a BBN. Each evidence node represents a question with the same branching options as the qualitative tree; the decision boxes represent each section of the tree, which outcomes depend on the evidence nodes that parent each section.

While having the format of a BBN, this tree does not function very differently than the qualitative decision, as the decision nodes will be formed of two outcomes each with a probability of 50% (with some exceptions). the user should follow each question following the same flow as the tree. When an outcome is unknown, it has to be left vague, representing the ’don’t know’ outcome of the decision tree by leaving the outcome of the BBN as a fifty-fifty probability for each outcome. The verification questions will be an exception to this, where instead of having two outcomes some will have three outcomes representing the "passed the verification", "failed the verification" and "verification not performed". If it is not known that a verification was performed this can be left vague, giving a 33% probability for each possible state.

The final outcomes of the sections will also represent the color rating of the qualitative tree. Outcomes that would be red will result in a ’failure’ rating for the network, this applies to most elements that are absolutely required for a proper abandonment. Most elements to relate on verifications or minor elements that are recommended but not required will not indicate a failed ranking directly, but instead increase the probability of ’failure’ by a fixed amount, to represent the orange and yellow outcomes.

Apart from the "pass" or "failure" outcomes, there will also be an "out of scope" outcome as with the qualitative tree. This is relevant for 2 questions (A2 and A12). Due to the way the the model considers the "out of scope" outcome, as it should over-power the other outcomes if it is selected, it will result in an over-representation of this outcome in the final probability. Because of this, it is very important that both these questions are answered in this network. If these questions are left on a 50/50 state, then the probability of the out of scope outcome will be higher than what it really should be.

Because of the BBN format, some of the branching questions of the qualitative tree had to be combined into a single evidence node, this is the case of the questions relating to the state of the plug (A13 to A17) where in the BBN this questions are represented by only one node. This will require the user to first answer all the questions as they are indicated in the qualitative tree, before selecting the relevant state in the BBN.

While the BBN functions the same way as the qualitative tree, using this format has some advantages. The main advantage of using this format is the possibility of obtaining a final numerical outcome of probability that weights the results of all the other outcomes, specially in cases where the result is not 100% "pass" or "failure". While this numerical result is only an indication, it can be useful to the user at the time of making decisions on how to deal with an specific well. The other main advantage is that, if there is a lot of missing data, the qualitative tree will most likely result in a grey outcome, which might not be very useful for the user. The BBN will still be able to give a numerical result as it will do the calculations considering the 50/50 states. While this will carry a lot of uncertainty due to the missing data, the user could still use the probability result as an indication for decision making, as long as the uncertainty is considered.

4.3 Chemical BBNs development

The probabilistic risk analysis will be based on data from a literature review of relevant experimental results. The process for the determination of the risk of leakage giving the reservoir and abandonment conditions will be done by identifying the main factors that will play a role in the process and assessing their impact. For this, a literature review was performed in order to obtain data from several experiments, that will be compiled and processed so that it can be included in the probabilistic models. Prior to performing the assessment the assumptions required for each of the respective processes will be explained, as both processes, cement degradation and casing corrosion will be analysed separately. The main general steps that will be followed for both analysis will be:

- Analysis of the main factors involved in the process.
- Development of the logic behind the probabilistic model based on Bayesian belief networks.
- Compilation of relevant experiments from literature where the experimental conditions and measured rate of corrosion/degradation are well defined.
- Data analysis: compiling of measured rates, creating relations where possible on rate change with change of a relevant factor.
- Defining the variations, either specified for a specific experiment or estimated from analysing results for same conditions.
- Running Monte Carlo with the analysed data to sample how many iterations will be required for the analysis .
- Processing of the data: mean rate and variation for a specific condition to create the histograms based on truncated normal random distributions.
- Infer probability from random normal distribution function to fill into the BBNs, populating the model.

In order to estimate the risk of the formation of leakage paths from cement degradation and casing corrosion, by the means of a probabilistic analysis, the following assumptions are necessary:

- The starting conditions are based on intact cement and casing, that has not been previously degraded or which integrity was not affected by mechanical processes.
- Assume that the cement plug and annular cement were properly set and are properly bonded to the casing or formation surfaces.

- Assume that the casing was properly placed and it is properly bonded to the cement.
- The curing conditions of the cement are considered optimal for the required abandonment and the effect of different curing conditions would not be considered on the reaction rates.
- The cement plug is assumed to be of 50m as minimally required by the NOGEPA nro. 45 standard.
- The degradation will take place over 1000 years (as this is what is practically considered for ‘eternity’ based on several standards) and formation of leakage path will be considered if the 50m of cement will have been corroded over this period of time. In the case of the casing, it will require that 50m of casing contiguous to the cement plug are corroded.
- Processes will be considered independent of time (a rate of reaction for an experiment performed in a few days will be considered the same for 1000 years), however, experiments performed over very short time frames will be discarded as these might not be representative.
- Degradation is based only on bi-carbonation reaction (other reaction mechanisms are neglected).
- The continuous factors will be discretized in order to be included in the analysis (for example temperature and pressure). The ranges chosen for the discretization were based on significant thresholds that would affect the process significantly or based on the availability of experimental data for the selected ranges.

4.3.1 Cement degradation BBN

The factors to be included in the Bayesian belief network were selected by assessing the main factors that affect the rate of cement degradation. This was based on a thorough literature review on experimental data and on experts revision. From this assessment the network developed is represented by figure 13, where the factors were chosen based on their impact on the rate, while factors with smaller impacts were discarded, like the curing conditions or the effects of other impurities.

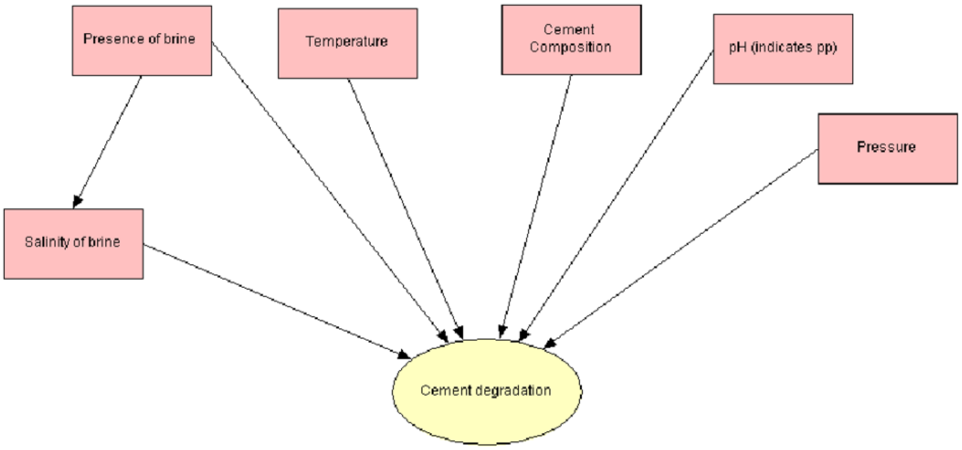


Figure 13: Cement degradation BBN.

Each of the elements included represent factors that impact the reaction and that will affect the rate of the reaction significantly. These factors are:

- **Presence of CO_2 saturated brine in contact with the cement**: Dry CO_2 does not corrode cement or corrosion rates are small enough to be negligible. Significant cement degradation will only occur in an environment where both brine and CO_2 are present.
- **Initial salinity of the Brine**: Refers to the capacity of the brine to dissolve the cement in the bicarbonation reaction. The closer to pure water the more cement can be dissolved and the higher the rate of reaction (based on chemical equilibrium concept).

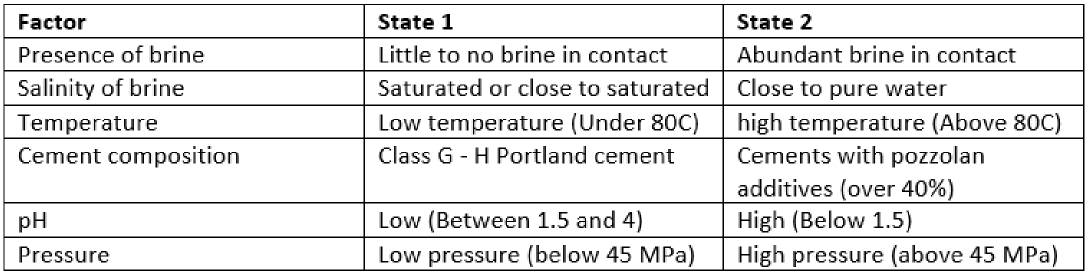
- **Temperature**: A higher temperature will increase the rate of the bi-carbonation reaction due to it providing a higher activation energy for the reaction.
- **pH**: The most significant change in pH is related to the partial pressure (p.p.) of the CO_2 phase (higher p.p. will make solution more acidic. The lower the pH the faster the rate of the bi-carbonation reaction (the presence of other contaminants dissolved in the brine will also affect the pH, although in a smaller capacity).
- **Cement type**: Cements with pozzolan additives (silica flour, fly ash) degrade significantly faster than pure cements (this element considers cements with 40% or higher amounts of pozzolan additives).
- **Pressure**: Higher pressure increases the reaction rate linearly by decreasing the threshold of activation energy for the reaction to occur

With these states, the distribution of the probabilities in the final BBN is present in figure 16

In order to populate this model, a series of experimental results from literature were compiled, with the data assessed and processed so that the results and findings obtained from these experiments could be incorporated into the probabilistic model. Table 7 in appendix C summarises the main experiments that were used for the population of the model.

Each of the factors present in the BBN is discretized into two states. Table 5 shows the values taken for each state. The values of the states were chosen such that they were the most representative of the expected conditions for abandoned wells, but also represent critical points were these factors will have a significant effect on the process. As described by the assumptions sections, this is also based on the available experimental data, therefore the states used for the values are limited to the available data from the experiments.

Table 5: Possible states for each evidence node of the BBN.



Factor	State 1	State 2
Presence of brine	Little to no brine in contact	Abundant brine in contact
Salinity of brine	Saturated or close to saturated	Close to pure water
Temperature	Low temperature (Under 80C)	high temperature (Above 80C)
Cement composition	Class G - H Portland cement	Cements with pozzolan additives (over 40%)
pH	Low (Between 1.5 and 4)	High (Below 1.5)
Pressure	Low pressure (below 45 MPa)	High pressure (above 45 MPa)

The data of these experiments was processed by creating random normal distributions from the ranges defined in the experiments, and by creating relations between the variation of the selected factors with the corrosion rates. For example, if an experiments for certain conditions report a range for the rate of the reaction, this range is used to create the random normal distribution function. In order to create the distributions first a Monte Carlo simulation was performed for each case, in order to validate the amount of iterations that would be required for the distributions. The amount of iterations chosen was for 1000 iterations which was validated by the Monte Carlo distribution, shown in figure 14.

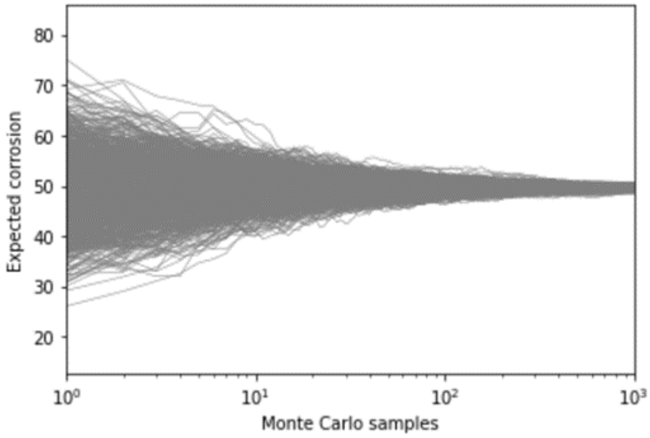
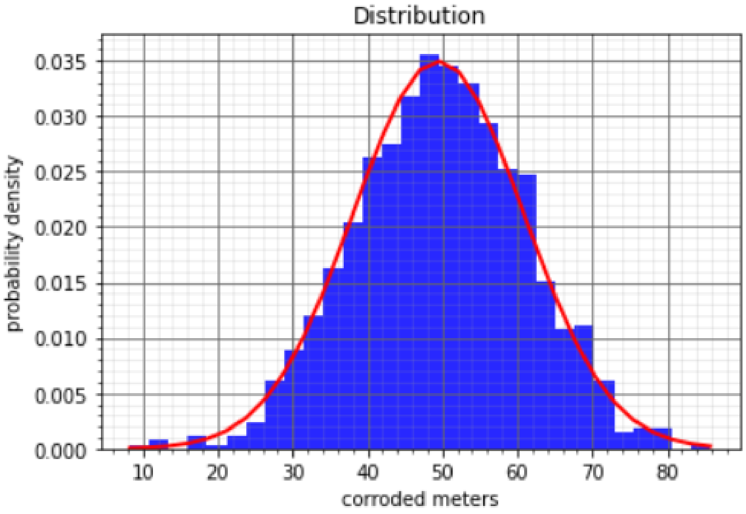


Figure 14: Monte Carlo simulation results, showing the values converging after 1000 simulations are performed.

Figure 15 shows an example of one of the many distributions developed for the analysis, where the histogram approximates the random normal distribution function. From distribution function the probability of the total cement corroded being 50 meters can be inferred. These inferred probabilities were later used for the population of the conditional probability tables (CPTs) for the BBNs.



Factor	**State 1**	**State 2**
Presence of brine	Little to no brine in contact	**Abundant brine in contact**
Salinity of brine	Saturated or close to saturated	**Close to pure water**
Temperature	Low temperature (Under 80C)	**high temperature (Above 80C)**
Cement composition	Class G - H Portland cement	**Cements with pozzolan additives (over 40%)**
pH	**Low (Between 1.5 and 4)**	High (Below 1.5)
Pressure	Low pressure (below 45 MPa)	**High pressure (above 45 MPa)**

Figure 15: Example of one of the distributions developed for the estimation of the probabilities. The histogram is represented in blue and it shows the distribution of the results of the 1000 simulations. The red line represents the random normal distribution obtained from the data. This distribution is for the specific set of conditions defined in the table below, where the probability that 50m of cement will degrade after 1000 years is 50%. This was repeated for every possible combination of states, to obtain the data to fill the CPT for the BBN.

Results

Figure 16 shows the final BBN for the cement degradation. The right side shows the different factors with their monitor windows showing the different states they can take. The left hand side shows the list of this factors with the states and their respective probabilities, with the probability of the cement degradation being displayed on the top.

From the obtained network it was possible to obtain insights into the impact of the different factors in the overall process. This is explained in more detail in the general conclusions in section 4.3.3.

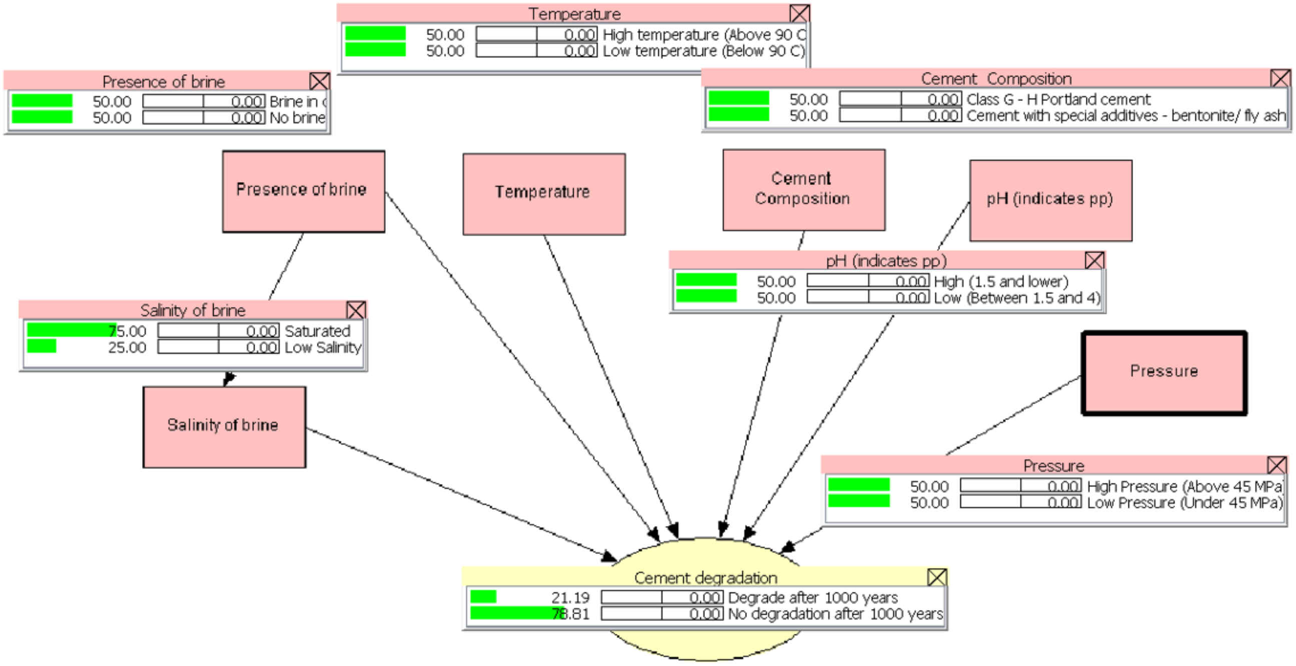


Figure 16: Cement degradation BBN with monitor windows and states.

4.3.2 Casing corrosion BBN

The same process explained for the cement corrosion was used for the population of this BBN. From this assessment the network developed is represented by figure 17, where the factors were chosen based on their impact on the rate, while factors with smaller impacts were discarded.

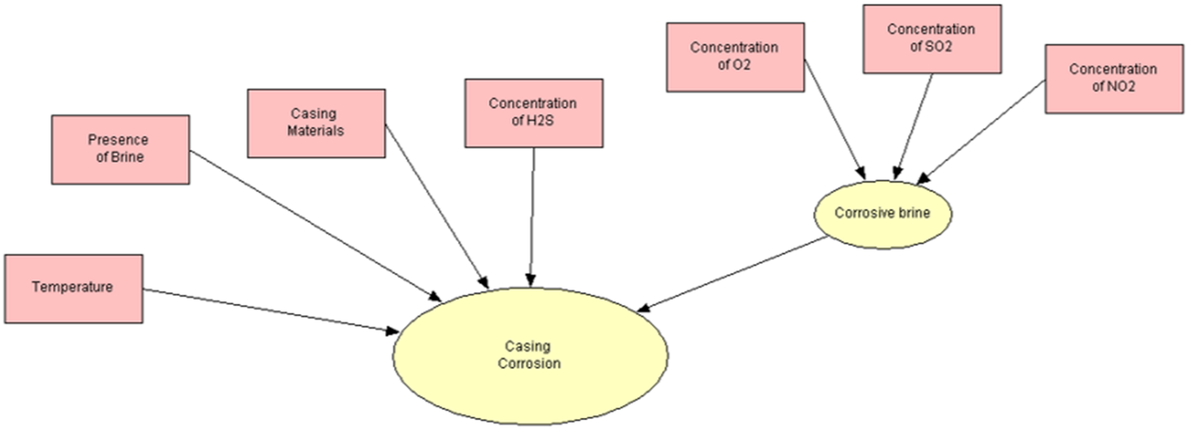


Figure 17: Casing corrosion BBN.

Each of the elements included represent factors that will be involved in the reaction and that will affect the rate of the reaction significantly.

- **Presence of brine**: As with the cement degradation, in order for significant corrosion to occur the sc CO_2 has to be in the presence of abundant water for degradation to occur. Only in a high water environment the sc CO_2 will corrode the casing
- **Composition of brine and presence of O_2, SO_2 and NO_2**: The presence of contaminants will significantly

affect the corrosion rate of the CO_2 brine mixture as this contaminants can make the solution more acidic or provide extra pathways for the corrosion reaction to occur.

- **Steel type (carbon steel or stainless steel)**: The different possible materials used for the casing will have different resistances to corrosion.
- **Concentration of H_2S**: H_2S is also a highly corrosive contaminant that can be present in the reservoir, together with the CO_2. The presence of this contaminant will also increase the rate of corrosion.
- **Temperature**: A higher temperature will also affect the corrosion rate by increasing the rate of the corrosion reaction.

In order to populate this model, a series of experiments were compiled, with the data assessed and processed so that the results and findings obtained from these experiments could be incorporated into the probabilistic model. Table 8 in appendix C summarises some of the main experiments that were finally used for the population of the model. The data was compiled from Wei et al (2015) which presents a compilation of data from relevant experiments.

As with the cement degradation data analysis, relations were developed from this data in order to create histograms based on normal random distributions, also using a Monte Carlo assessment to validate the amount of simulations performed.

Results

From the analysis made based on the experimental results, it was observed that in not a single case the casing would corrode 50m, or near to that amount in the span of 1000 years. This leads to a probability of corrosion of 0 for all cases, indicating that there is no risk of the whole length of the casing degrading to form a continuous leakage path. This is a result of the very low corrosion rates for all cases, where the maximum expected corrosion was of 12.6m average after 1000 years. This distribution of results rends the population of the BBN redundant, as the final outcome will be the same for every possible state.

4.3.3 Conclusion and recommendations

Cement degradation

The BBN obtained for the risk of cement degradation due to CO_2 can be used as a screening and decision making tool for assessing the risk of the formation of leakage paths across the cement plug. From the analysis used for the construction of the tool, the impact each of the factors will have on the overall process was also analyzed. The factors are listed here from highest to lowest impact:

- Presence of CO_2 saturated brine in contact with the cement
- Initial salinity of the Brine
- Temperature
- pH
- Cement type
- Pressure

Casing corrosion

With this analysis, it was confirmed that the corrosion of the casing, in terms of the abandonment is not the main threat towards the formation of a leakage path, instead the degradation of the cement is, as this will degrade quicker, also altering its properties making it more permeable. Casing corrosion might become an issue for operating wells, where there exist the possibility of the casing corroding across the whole of its thickness causing integrity issues in the wellbore affecting operations. However, for abandoned wells, if the casing corrodes radially across its thickness, this would not be a significant issue since the casing is embedded in between cement and this would not lead to a continuous leakage path.

Despite of this, it is important to consider that this analysis is limited by intact casings that have been properly placed, and that have at least 50m of contiguous cement along it. However, this might not be always the case since it is possible the casing has been damaged prior or the plug was not properly placed inside the casing, this might facilitate the creation of leakage paths, specially if there is a shorter length of cement across it.

General Conclusions

While this BBN can be useful for a well screening tool, significant improvements can be made in its developments so that it can be more precise and also expand its applications. The main recommendations for future developments would be:

- Perform relevant experiments in reservoir conditions (by placing cement samples and in high temperature and high pressure vessels) to obtain more realistic results and also increase the availability of data. While an abundance of relevant experiments were considered in the analysis there are still gaps in data that could be filled with extra experiments or simulations, especially considering that some of the experiments analysed do not closely replicate the expected environmental conditions.
- The ranges selected are limited for two states. Adding an extra state for each of the factors of the BBN could significantly increase its application, especially for cases were the selected states might not be representative. This would be especially important for the continuous variables. Adding extra states does however increase the complexity in the development of the BBN and will also require more data to be utilized.
- While the factors included are the most influential for the degradation of cement, there are other factors that, while having smaller effects, can be significant in the overall process. The main factors that could be explored further and included are the presence of other contaminants and the initial curing conditions.
- While the standards define the minimum cement plug as 50m, it will not always be the case that cement plugs will be exactly this length. The BBN as it stands cannot assess wells with plugs smaller or bigger than this, limiting its application. A solution for this would be to replicate BBNs for other length ranges using the same available data. Another option that would require more rework would be to realize a continuous BBN, however, this would require a significantly larger amount of data.

4.3.4 Impact of different cement plug lengths

Next to analyzing the cement degradation for a plug length of 50m, the cement degradation BBN was also developed considering a plug length of 30m. This was done to reflect the requirement based on the Oil Gas UK Well integrity guidelines, which specifies a minimum plug length of 100ft (approximatly 30m) with the combination of a mechanical plug. The objective of developing this BBN is to compare the risk outcome of using different plug lengths. Because the lengths of the plugs in the standard are chosen in an arbitrary way, this analysis is useful in determining an ideal plug length. By verifying the probability of corrosion for different lengths, it can be observed how much the probability will change with length. With this, the cost to benefit ratio of increasing the plug length could be assessed. If this is done several times, it could be calibrated so that an ideal plug length is chosen, using the least amount of cement possible while still obtaining a low risk of leakage.

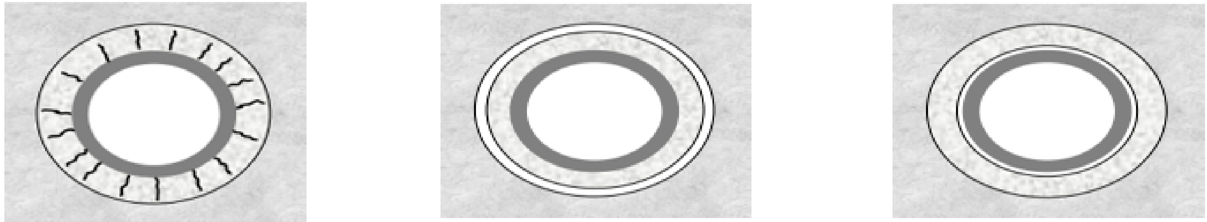
Table 6 shows the results of the BBNs for the cement degradation with both plug lengths. The first comparison is done considering a case with no evidence, leaving all the states vague. This shows a probability of failure for the 50m plug of 21% compared to a probability of 31% for the 30m plug. This indicated that a 40% reduction in cement length will increase the probability of leakage by 10%. The second comparison is done assuming there is brine in the reservoir that will come in contact with the cement plug. As explained previously, degradation will only take place when this condition is met, so it is important to consider how the risk changes in this case. For the 50m length plug the probability of failure will be of 42% and for the 30m plug it will be of 62.5%. In this case we see a 20% increase for the different plug lengths.

Table 6: Probabilities of failure for the 50m and 30m cement plug BBNs with and without brine in contact

	50 m plug	30 m plug
No brine	**21%**	**31%**
Brine	**42%**	**62.5%**

4.4 Mechanical BBNs

For this assessment three BBNs were developed, analysing the failure mechanisms a, c and d, shown in figure 18 in order to estimate the risk of a leakage path forming, by considering the stresses involved as well as the material and reservoir properties.



(a) Circumferential cracking **(c) Mode-I de-bonding** **(d) Mode-I de-bonding**

Figure 18: Failure modes relevant for this study

The factors to be included in the Bayesian belief networks were selected by assessing the main factors that affect the formation of leakage path by either of the three relevant processes. This was based on a thorough literature review on experimental data and on experts revision, and was also validated by the results of the geomechanical model, where the effect of the different factors was assessed. In order to develop this probabilistic risk analysis some general assumptions were required:

- The factors included in the BBNs will always be discrete, consisting of two states. For this, continuous parameters were discretized in order to fit into the model. The values selected for the different states of the parameters are based on typical values for the materials and for the expected conditions at different ends of the spectrum.
- The analysis are made assuming intact cement and casing initially, and will not consider the added effect of chemical processes
- It is assumed that the BBNs will be useful to representing generic cases and might not be able to assess wells with uncommon conditions like wells using special casing alloys or other materials instead of cement.
- It is assumed that the factors included in the BBNs are considered to be the most important for each specific process, there are other factors that will play a smaller role, however this will be neglected. While more factors can be included in the BBNs, the gain in precision does not justify the increase in complexity for the BBN, specially considering the larger processing requirements of the geomechanical model.
- Because the initial state of the stress in the cement after curing is unknown, this value will have to be assumed (Mogadham & Orlic , 2021). For this analysis the initial state of stress of the cement plug is assumed to be equal to hydrostatic pressure of the reservoir.
- For the cases of debonding, generally there is always a certain amount of debonding estimated for the geomechanical model, however, a small amount of debonding will not lead to a significant amount of flow of CO_2. Debonding will be considered only when it passes the threshold for which it will lead to significant leakage, which for this study will be considered as 1e-5 m (Lyons, 2010), although this value depends on the driving pressure across the micro-annulus. This also applies for the width of the circumferential cracking.
- All the factors included should be considered independent of each other, if they are not, this should be indicated by a connection between the factors. The exception is in the "cement failure BBN" where the Poisson's ratio and

Young modules are not completely independent however there is no connection for these factors in the BBN, this is due to the fact that the dependency between this two factors could not be quantified. This should only present a problem in the case where one of the two factors is known, where an inference of the value o the other could be made. There will not be a difference in the case both are known or both are unknown.

Debonding cement formation

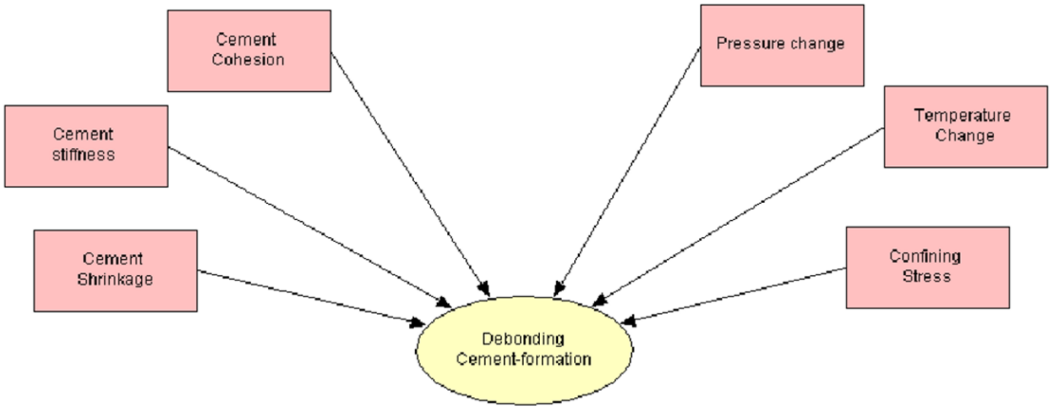


Figure 19: Cement formation debonding BBN, where the main factors are represented by the pink nodes. The factors included in this BBN are the cement shrinkage, cement stiffness, cement cohesion, pressure change, temperature change and the confining stress.

Debonding will occur when there is a separation between the annular cement and the formation. The driving force for the debonding is the effective tensile radial stress, and it will cause the debonding when this stress exceeds the strength between the cement and formation bond (Meng et al, 2021). The factors that will be included in the BBN are those that are either related to the strength of the bond in itself and the capability of the materials to deform or on the amount of stress that the bond will experience.

Debonding cement-casing

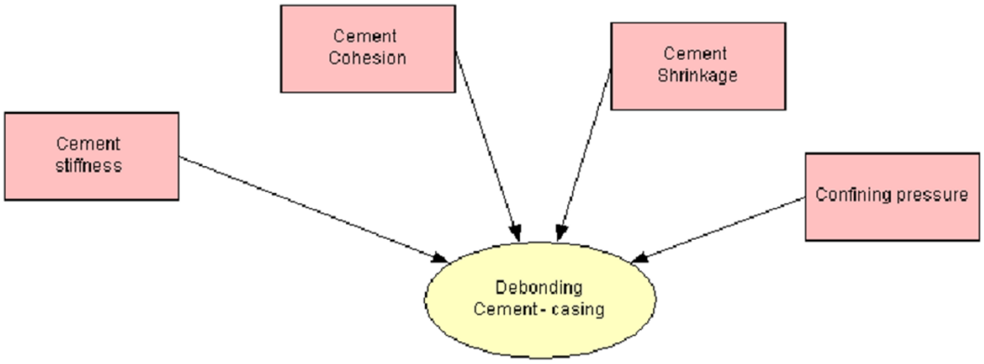


Figure 20: Cement casingn debonding BBN, where the main factors are represented by the pink nodes. The factors included in this BBN are the cement shrinkage, cement cohesion, cement stiffness and the confining pressure.

The debonding between the cement and the casing is similar to that of the debonding between cement and formation. However, in general, it is expected that the debonding of the casing-cement is less likely to happen than that of cement and formation. This is mostly the case because thermal effects will have a smaller impact on the debonding as the steel casing can more easily accommodate deformations caused by changes in temperature; because of the relatively higher thermal expansion coefficient of the casing (Torsæter et al, 2015). This means that the main drivers for the debonding are the cement properties itself, especially the shrinkage of the cement. In general, there will be an expected difference between the debonding of the annular cement and the cement plug, due to how the bonding is affected by being on a convex or concave surface, however, this effect tends to be small and will be neglected for this analysis (Torsæter et al, 2015).

Cement failure (circumferential cracking)

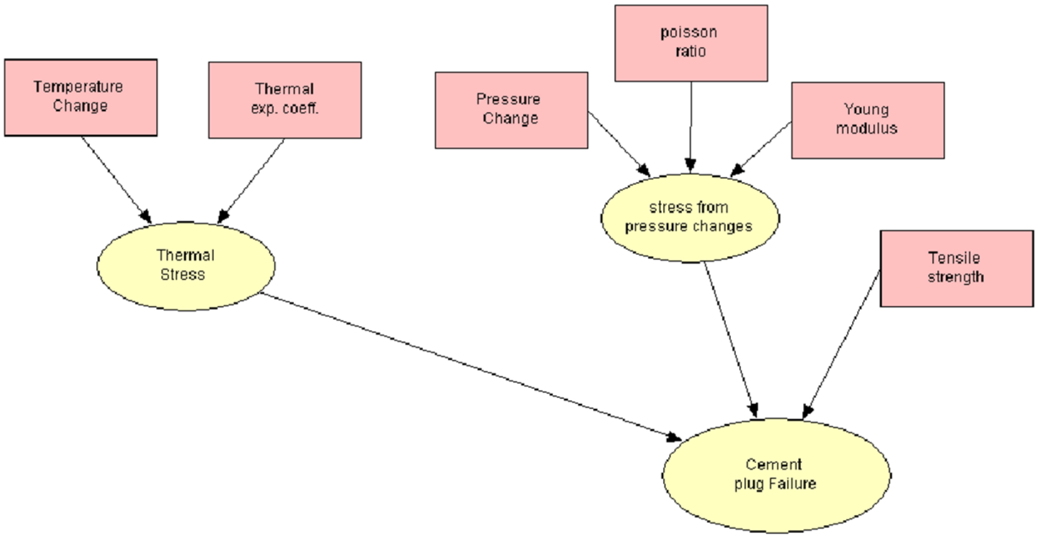


Figure 21: Cement failure BBN, where the main factors are represented by the pink nodes. The factors included are the temperature change, thermal expansion coefficient, the pressure change, Poisson's ratio, Young modulus and the tensile strength of the cement.

Cement plug failure as it relates to circumferential cracking can be caused when the effective tangential stress becomes tensile and exceeds the tensile strength (Meng et al, 2021). The tensile stress is controlled by a combination of the thermal stresses and the stresses induced from pressure change. The magnitude of the stresses is controlled by the magnitude of the pressure and temperature change but also of the elastic and thermal properties of the materials involved.

4.4.1 Methodology

A geomechanical model was developed using the DIANA FEA software with the objective of generate the data used to populate the BBNs. The details of this model are presented in appendix D.

Processing of Diana data

Since every element in the BBNs consist of two states, the amount of simulations required to populate each of the BBNs is 2^n, with n being the amount of elements. The different simulations will be done by varying the parameters defined in table 10, alternating between the two possible states. For each simulation, the DIANA model will be run for 1000 iterations, in order to obtain the distribution for each of the results. The 1000 runs is validated by a Monte Carlo simulation with this model (Brunner et al, 2019). The results obtained are they downloaded directly as spreadsheets. The results are obtained as distributions of the displacements in a certain element of the wellbrore. By selecting the direction relative to the axis, and the locations of the nodes it can be selected what is the relevant data for the analysis, selecting the displacement data for the relevant failure mechanisms as shown in figure 18. Results are then saved and the data of displacement is then processed in excel to obtain means and standard deviations for each case. After the data from the model is processed and the ranges are obtained, the populations of the BBNs follow the same steps as explained for the chemical BBNs. The cases are then compiled and for each possible set of states, and histograms are developed for the data for each specific case, based on the mean and standard deviation. From this, the normal random distribution functions are created, that are used to estimate the risk of debonding for each case. The probability of each case is then filled in for each element of the CPTs for the BBNs.

Debonding cement-formation Results

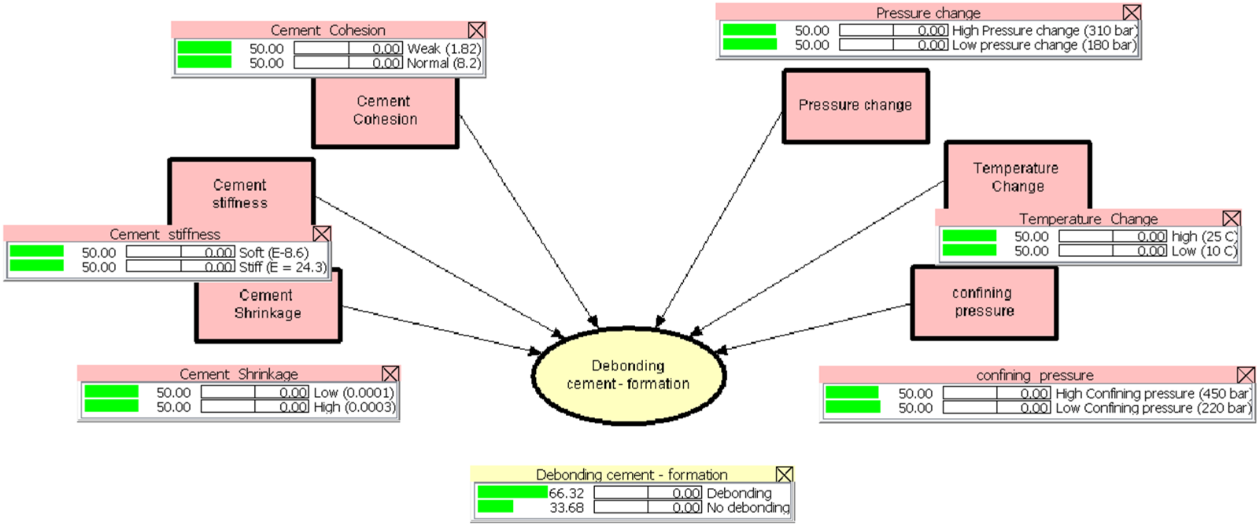


Figure 22: Cement formation debonding BBN with monitor windows and states.

From the obtained results it was observed that the impact of each factor on the final outcome is (from the highest impact to the lowest):

- Cement shrinkage
- Cement stiffness
- Cement cohesion
- Pressure change
- Temperature change
- Confining pressure

Overall, the debonding was controlled for the most part by the properties of the cement, in particular the cement shrinkage. Cements with higher shrinkage coefficients will lead to a higher tensile stress in the surface, pulling the cement away from the bond, increasing the amount of debonding. By itself, the temperature and pressure change have a small impact as well.

Debonding cement-casing results

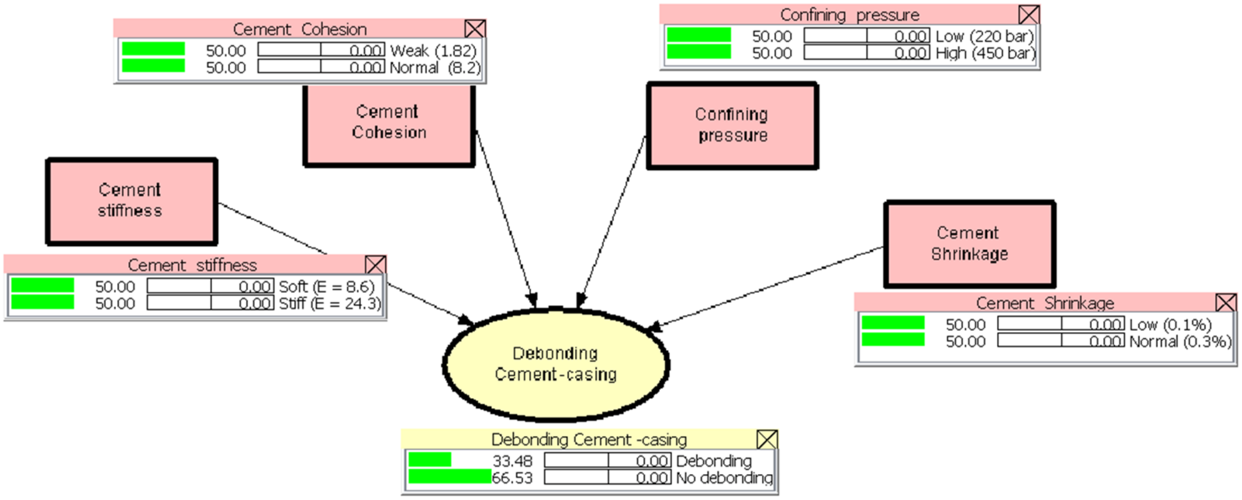


Figure 23: Cement casing debonding BBN with monitor windowns and states.

From the obtained results it was observed that the impact of each factor on the final outcome is (from the highest impact to the lowest):

- Cement shrinkage
- Cement stiffness
- Cement cohesion
- Confining pressure

Like with the debonding of the cement-formation, the most relevant factors are related to the cement properties. In this case the temperature and pressure changes are even less relevant, due to the ability of the casing to deform together with the cement, and the impact was considered so low that it was excluded from the analysis. The casing properties are also excluded, because regardless of the capacity of different casing materials to deform, steel will always be more ductile than cement, meaning that in general it will accommodate the deformation. In this case the cement shrinkage is even more relevant than in the case of the cement-formation BBN.

Cement failure results

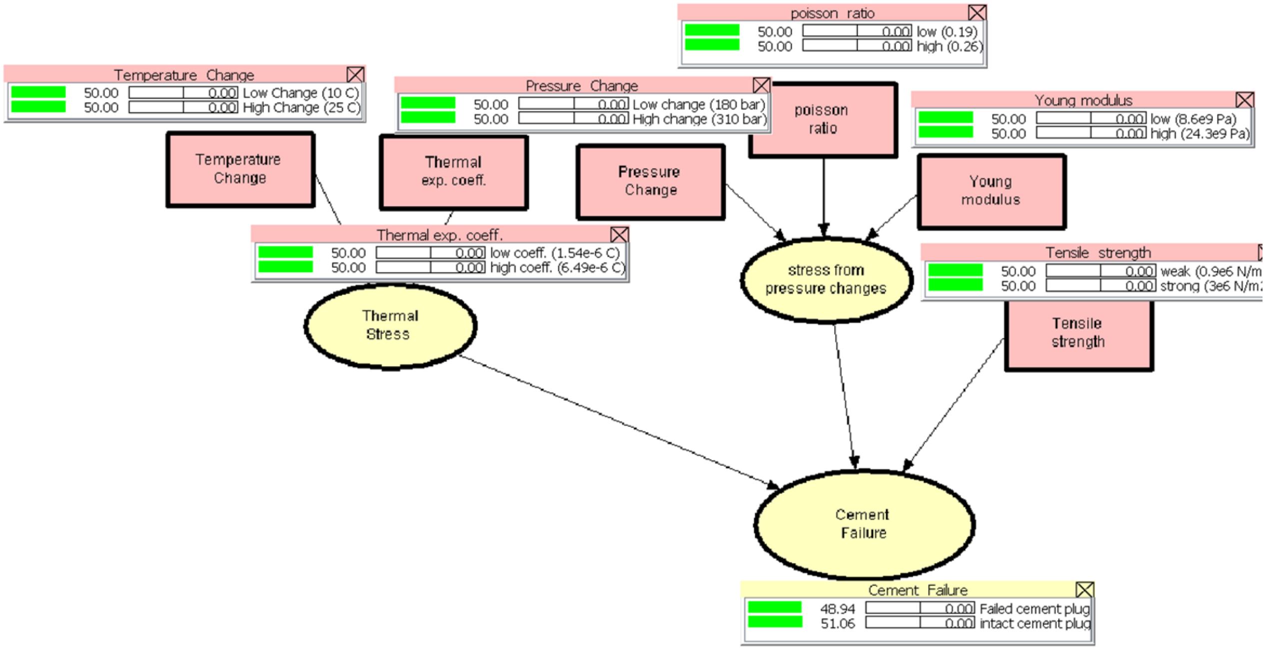


Figure 24: Cement failure BBN with monitor windows and states.

For the formation of the circumferential cracks, the impact of the thermal stress and stress from pressure changes was similar. The main factor that will determine if leakage paths will form is the tensile stress, as it will allow the cement to resist the failure. However, even a high tensile stress will be insufficient to resist the combined effects of high thermal stress and large pressure changes.

4.4.2 Conclusions and recommendations

The BBNs obtained for the risk of formation of leakage paths caused by mechanical processes can be useful in screening wells based on the available information. Specially, as it applies to the risk of debonding which is the most likely cause of leakage. There are however several recommendations that can be made to increase accuracy of the analysis, and to expand its applications:

- As mentioned above the, initial state of stress of the cement plug once it sets has to be assumed because this is not known. Extra experiments at reservoir conditions should be performed in order to quantify this and include it in the analysis.
- Shrinkage is the most relevant factor in the debonding process. However shrinkage usually is hard to predict for cements once they set down the well. As a result, the user of the BBN may not have the proper information to fill this element of the network, leading to a larger uncertainty.
- The ranges selected are limited for two states. Adding an extra state for each of the factors of the BBN could significantly increase its application, especially for cases were the selected states might not be representative. This would be especially important for the continuous variables. Adding extra states does however increase the complexity in the development of the BBN and will also require more data to be utilized.
- While the factors included are the most influential for each specific BBN, there are other factors that, while having smaller effects, can be significant in the overall process.
- This analysis is performed assuming that the cement and casing are intact and properly placed. This does not consider the combined effects of chemical degradation.

- Specifically for the cement-formation debonding, the properties of the formation are not included. This is not a very relevant factor unless the formation is composed of a very ductile rock which will have an impact on the debonding process, as the debonding will be less likely if the rock can easily deform with the cement.

5 Case Studies

An important part for the development of the framework was to use case studies to test and validate the framework at different parts of its development. For the case studies, wells were chosen for which the abandonment conditions where reported by the operator, as required by the standards of each specific country where the wells were located. Furthermore, the wells selected for the case studies were all different in their conditions to ensure to have a broader representation of wells in the analysis. Three different case studies were analyzed. The objective is to perform the analysis using the framework and assess the obtained results by comparing it to the assessment from the operators. By doing this during the development, the framework can be corrected and improved based on the assessment performed. Finally, at the end of the development the case studies are useful to validate the framework and to draw conclusions of its performance as a screening tool.

5.1 Porthos P18-02 well

The P18-02 well is an abandoned well in the P18 reservoir located in the North Sea, offshore of the Netherlands. The P18 is a depleted gas reservoir that is being targeted as a potential site for CCS and was discovered by the P18-02 exploration well in 1989 (Vandeweijer et al, 2011). The site was operated by TAQA energy B.V. and was producing since 1993. The reservoir consists of Triassic sandstones and it is bounded by a set of NW-SE normal faults; the sealing layer is composed of impermeable siltstones, claystones, dolomites and evaporites (Vandeweijer et al, 2011).

Part of the planning for the development of the field for storage use is assessing the conditions of the abandoned wells. This is interesting because the well P18-02 will have to be re-abandoned since it does not meet the requirements to ensure that it is properly isolated. This can be done because the well is still accessible.

In order to use this well to test the decision trees, the well abandonment reports from the initial operator will be used as well as reports from the operators of the new CCS project, as those consider more in depth the conditions of the reservoirs after the injection of CO_2, which is needed for the B and C trees. Figure 25 shows a schematic of the well after abandonment and figure 26 details the abandonment barriers. Here it is mentioned the integrity issue related to the secondary barrier elements as there is an issue with the 7" liner cement as observed by the results of the CBL.

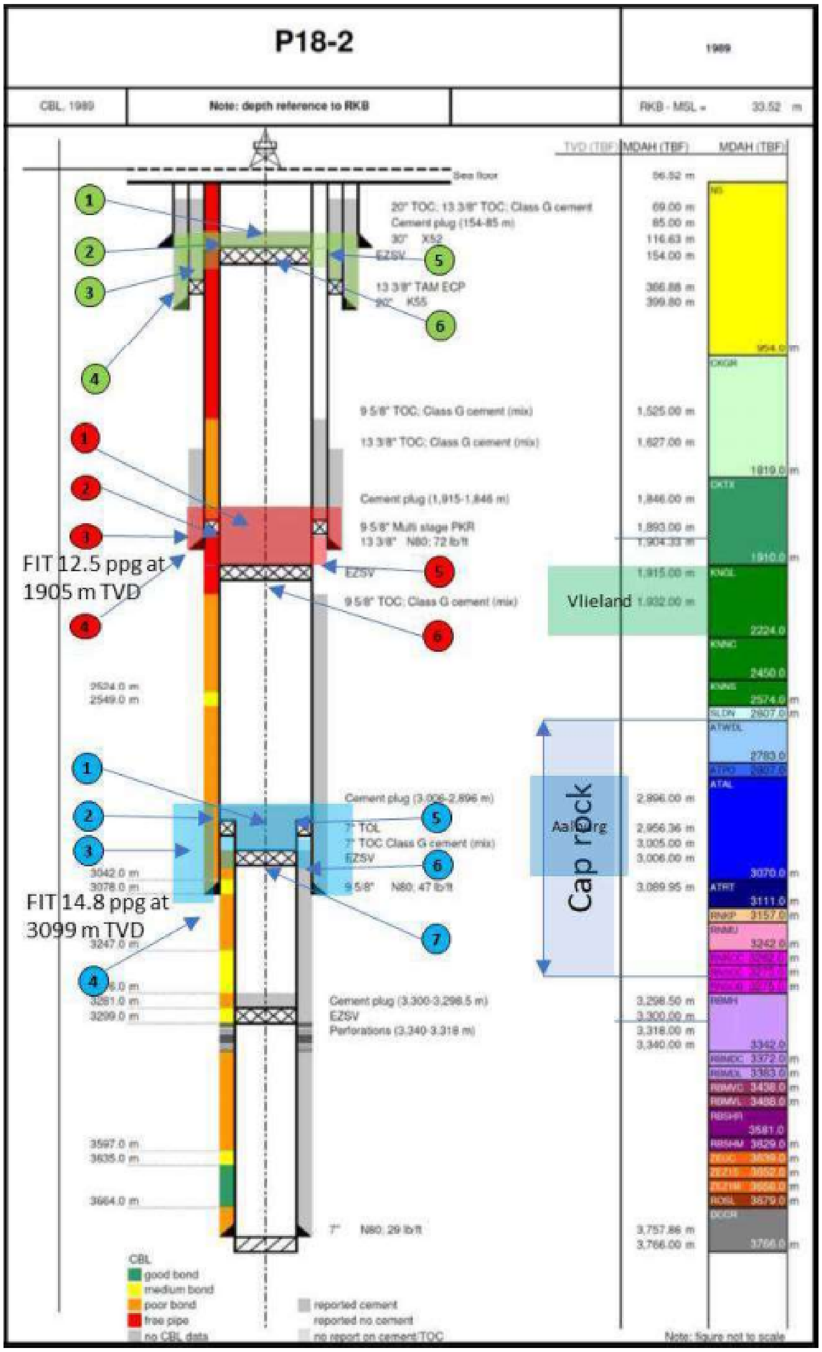
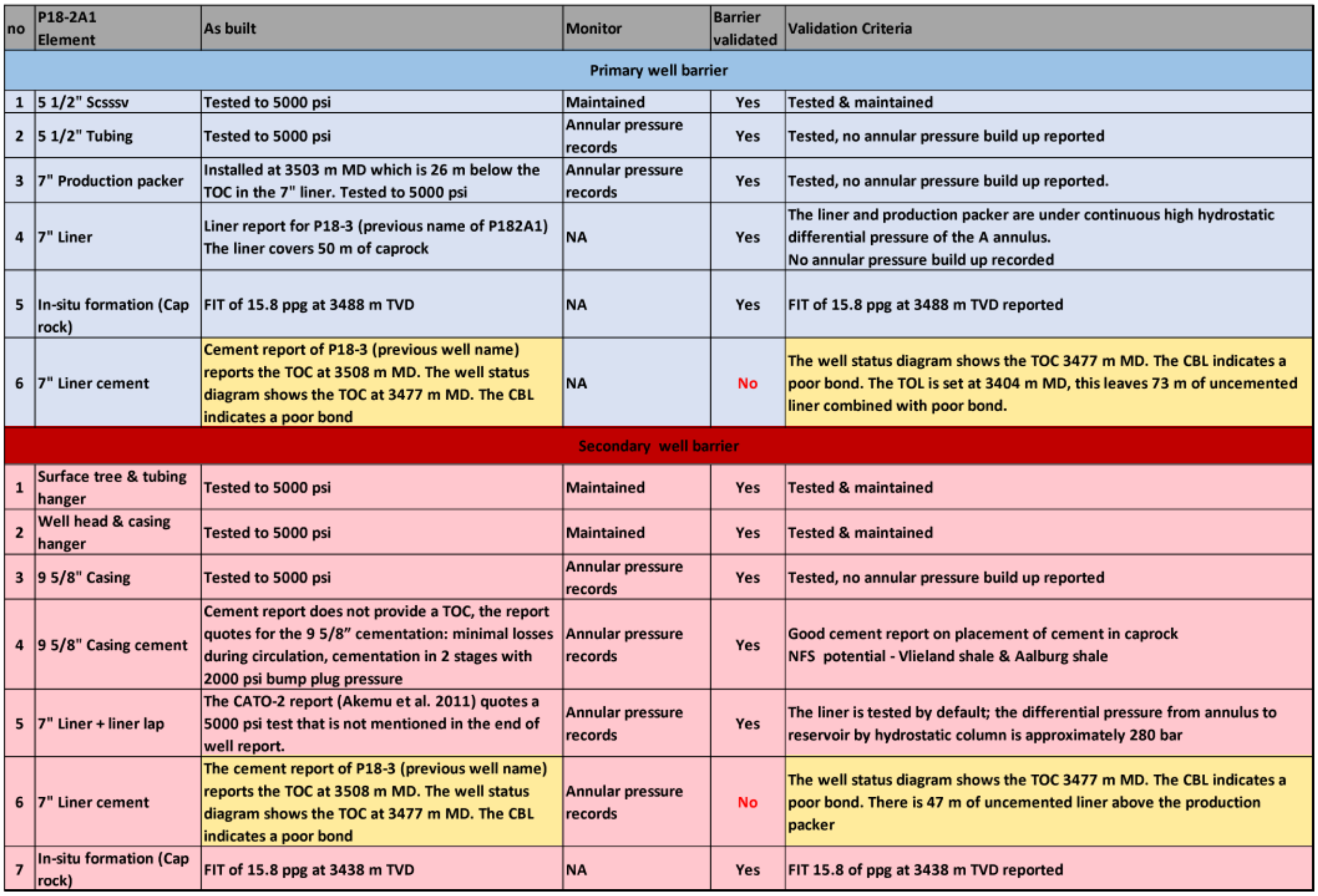


Figure 25: Well P18-02 schematic (Neele et al, 2019).



no	P18-2A1 Element	As built	Monitor	Barrier validated	Validation Criteria
Primary well barrier					
1	5 1/2" Scsssv	Tested to 5000 psi	Maintained	Yes	Tested & maintained
2	5 1/2" Tubing	Tested to 5000 psi	Annular pressure records	Yes	Tested, no annular pressure build up reported
3	7" Production packer	Installed at 3503 m MD which is 26 m below the TOC in the 7" liner. Tested to 5000 psi	Annular pressure records	Yes	Tested, no annular pressure build up reported.
4	7" Liner	Liner report for P18-3 (previous name of P182A1) The liner covers 50 m of caprock	NA	Yes	The liner and production packer are under continuous high hydrostatic differential pressure of the A annulus. No annular pressure build up recorded
5	In-situ formation (Cap rock)	FIT of 15.8 ppg at 3488 m TVD	NA	Yes	FIT of 15.8 ppg at 3488 m TVD reported
6	7" Liner cement	Cement report of P18-3 (previous well name) reports the TOC at 3508 m MD. The well status diagram shows the TOC at 3477 m MD. The CBL indicates a poor bond	NA	No	The well status diagram shows the TOC 3477 m MD. The CBL indicates a poor bond. The TOL is set at 3404 m MD, this leaves 73 m of uncemented liner combined with poor bond.
Secondary well barrier					
1	Surface tree & tubing hanger	Tested to 5000 psi	Maintained	Yes	Tested & maintained
2	Well head & casing hanger	Tested to 5000 psi	Maintained	Yes	Tested & maintained
3	9 5/8" Casing	Tested to 5000 psi	Annular pressure records	Yes	Tested, no annular pressure build up reported
4	9 5/8" Casing cement	Cement report does not provide a TOC, the report quotes for the 9 5/8" cementation: minimal losses during circulation, cementation in 2 stages with 2000 psi bump plug pressure	Annular pressure records	Yes	Good cement report on placement of cement in caprock NFS potential - Vlieland shale & Aalburg shale
5	7" Liner + liner lap	The CATO-2 report (Akemu et al. 2011) quotes a 5000 psi test that is not mentioned in the end of well report.	Annular pressure records	Yes	The liner is tested by default; the differential pressure from annulus to reservoir by hydrostatic column is approximately 280 bar
6	7" Liner cement	The cement report of P18-3 (previous well name) reports the TOC at 3508 m MD. The well status diagram shows the TOC at 3477 m MD. The CBL indicates a poor bond	Annular pressure records	No	The well status diagram shows the TOC 3477 m MD. The CBL indicates a poor bond. There is 47 m of uncemented liner above the production packer
7	In-situ formation (Cap rock)	FIT of 15.8 ppg at 3438 m TVD	NA	Yes	FIT 15.8 of ppg at 3438 m TVD reported

Figure 26: Table of well integrity barriers and their states (Neele et al, 2019).

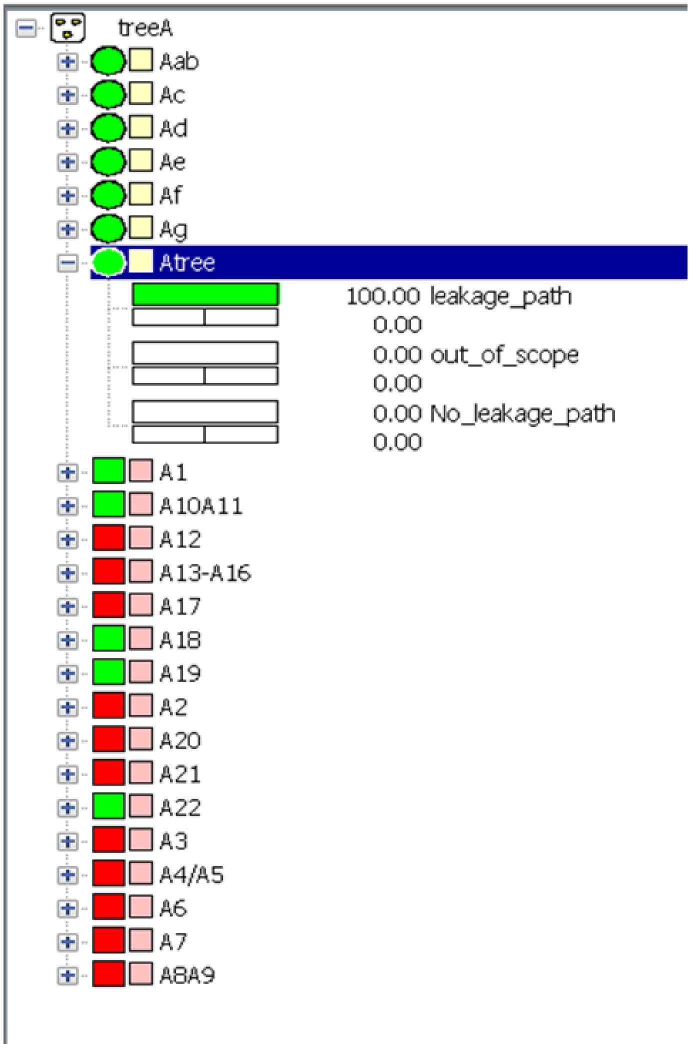
5.1.1 A-tree

The results from the A tree can be observed in figure 27. For this tree, the individual outcomes of each element are displayed on the right while the outcome for each section is on the left. The assessment from the well operator concluded that the well will have to be re-abandoned since there were issues observed with the annular cement (as indicated in figure 26 for secondary well barriers). This is seen in the A-tree results, where the annular spaces section got a red rating, considering the lack of cement in the annular space. Because this is a critical necessity to fully achieve isolation, this will give an overall outcome of red for this tree.

Sections	Elements	Outcomes
▨ Prior to abandonment	A1	▨
	A2	yes
🟩 Casing verification	A3	🟩
🟩 Plugging process/method	A4	🟩
	A5	🟩
	A6	\
	A7	no
🟥 Annular spaces	A8	🟥
	A9	yes
	A10	yes
	A11	🟥
	A12	🟩
	A13	\
	A14	no
🟩 Plug properties	A15	yes
	A16	🟩
	A17	🟩
	A18	\
	A19	🟩
▨ Abandonment verification	A20	🟩
	A21	🟩
	A22	▨

Figure 27: Qualitative A-tree results. The green outcomes indicate that the most ideal practices or conditions are followed and the red outcome indicates that a main requirement is missing. Grey outcomes are given when there is missing information. In this case there are no yellow or orange outcomes.

This outcome is also consistent with the outcome of the A-tree BBN, where a probability of 100% leakage is given due to the outcome of question A7. This reflects the results obtained from the qualitative decision tree and the analysis performed by the operator.

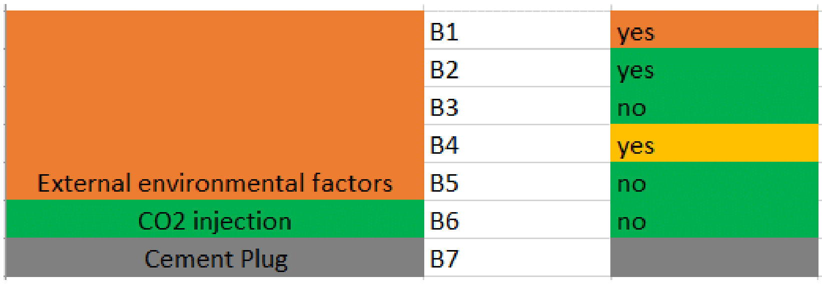


treeA
Aab
Ac
Ad
Ae
Af
Ag
Atree
100.00 leakage_path
0.00
0.00 out_of_scope
0.00
0.00 No_leakage_path
0.00
🟩 A1
🟩 A10A11
🟥 A12
🟥 A13-A16
🟥 A17
🟩 A18
🟩 A19
🟥 A2
🟥 A20
🟥 A21
🟩 A22
🟥 A3
🟥 A4/A5
🟥 A6
🟥 A7
🟥 A8A9

Figure 28: Results from A-tree BBN analysis as displayed in the HUGIN software. The questions that are answered are represented with the red boxes while those that are left vague are represented in green (this would be the grey outcomes in the qualitative tree).

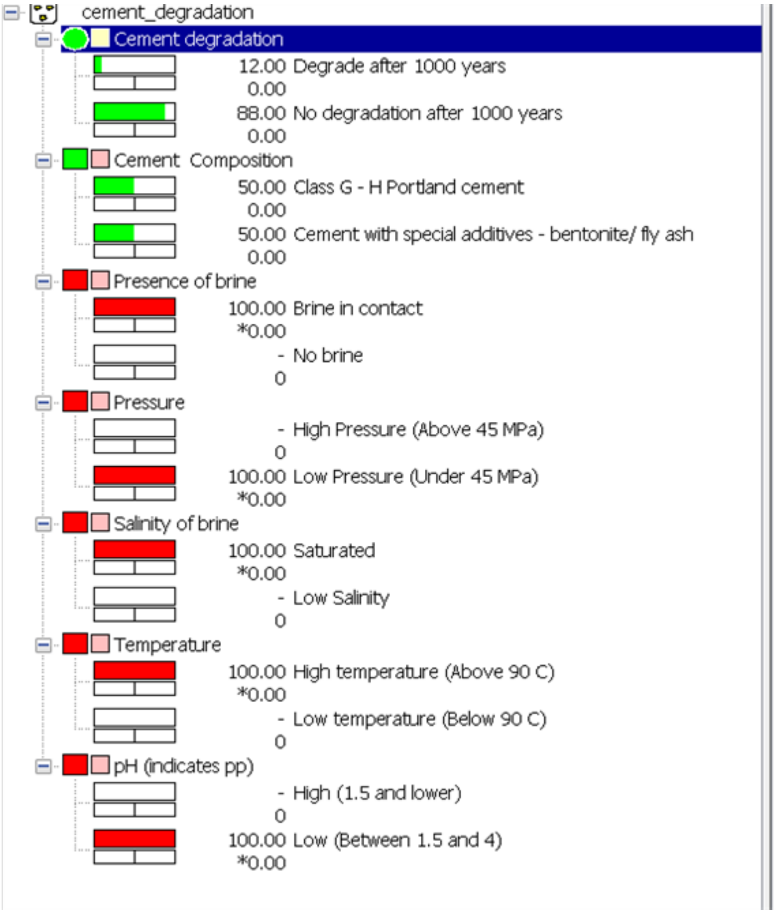
5.1.2 B-tree

No major issues were observed in the B-tree as shown in figure 29, which is consistent with what the operator concluded as they expect only 12m of cement corrosion after 10000 years as mentioned in the project report (Vandeweijer et al, 2011). The operator performed a geochemical analysis, which will be enough to provide all the data required for the risk analysis and to fill the BBN. The operator also assumed, based on the geochemical analysis that there are no concerns related to chemical degradation on the abandonment elements. The only uncertainty is related to the composition of the cement, which is not reported. The orange rating is given for the first question " *B1. Is there brine present in the reservoir that might come in contact with the abandoned well?*" as there will be brine in contact with the well, facilitating the degradation. In general, if brine is not in contact with the wellbore elements, no degradation will occur (or at least the effect after 1000 years will not be significant). However, the other conditions are favourable to prevent degradation of the cement, so it is unlikely the whole plug will completely degrade. From the BBN shown in figure 30 it is estimated a 12% probability of the cement degrading completely after 1000 years. This has a significant discrepancy with the analysis of the operator, as it only predicts 12m of degradation after 10000 years, which will lead to a probability of full degradation close to 0, since the rate of degradation is so small. This discrepancy is likely caused by the node left ambiguous (grey) (related to the cement composition) and also by the error margin of the analysis. Regardless of this, both outcomes are consistent with each other, showing that degradation is not expected, even if the magnitudes differ. For this case it can be observed how the BBN for cement degradation complements the qualitative analysis.



External environmental factors	B1	🟧 yes
	B2	🟩 yes
	B3	🟩 no
	B4	🟨 yes
	B5	🟩 no
CO2 injection	B6	🟩 no
Cement Plug	B7	

Figure 29: Results from qualitative B-tree. The green outcomes indicate that the most ideal practices or conditions are followed, the yellow outcomes which would indicate a minor issue with the abandonment, the orange outcome indicates a lack of verification or a relatively important issue was encountered. Grey outcomes are given when there is missing information. In this case there are no red outcomes which would indicate a critical issue with the abandonment.

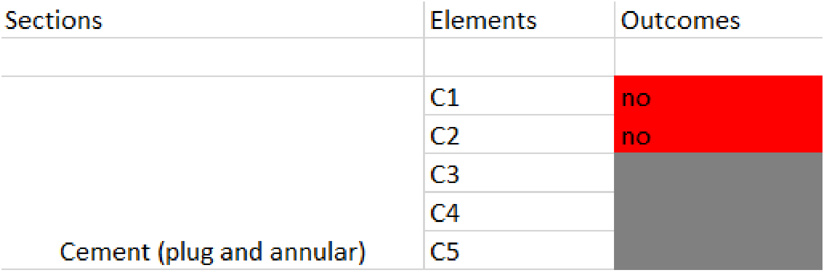


```
cement_degradation
  Cement degradation
      12.00 Degrade after 1000 years
       0.00
      88.00 No degradation after 1000 years
       0.00
  Cement Composition
      50.00 Class G - H Portland cement
       0.00
      50.00 Cement with special additives - bentonite/ fly ash
       0.00
  Presence of brine
     100.00 Brine in contact
      *0.00
          - No brine
          0
  Pressure
          - High Pressure (Above 45 MPa)
          0
     100.00 Low Pressure (Under 45 MPa)
      *0.00
  Salinity of brine
     100.00 Saturated
      *0.00
          - Low Salinity
          0
  Temperature
     100.00 High temperature (Above 90 C)
      *0.00
          - Low temperature (Below 90 C)
          0
  pH (indicates pp)
          - High (1.5 and lower)
          0
     100.00 Low (Between 1.5 and 4)
      *0.00
```

Figure 30: Results from cement degradation BBN, where a probability of complete degradation of 12% is estimated, with one unknown factor.

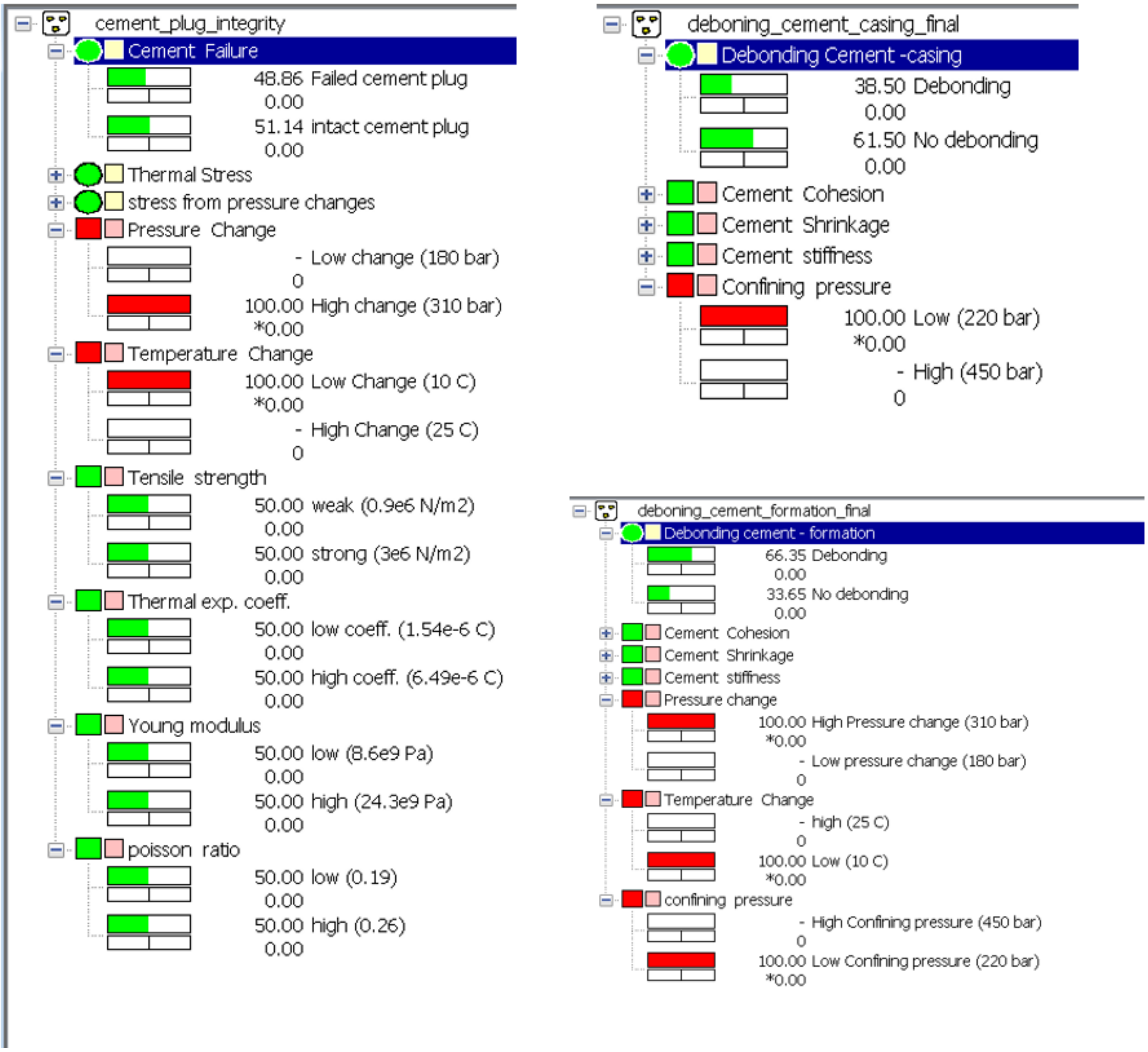
5.1.3 C-tree

The operator does not report the specific characteristics of the cement required for the C-tree analysis, which are the thermal and elastic properties of the cement. This makes it impossible to accurately fill the BBNs as these elements are the most critical elements in predicting cement failure and debonding. This results in the BBNs having too large of an uncertainty to be useful. The operator does, however, give its own prediction based on their evaluation of the cement used. The cement is described as being of 'poor quality' and it is predicted to not be able to act as an effective seal for the required duration. This information was used to fill in the qualitative decision tree shown in figure 31, which will have a negative outcome based on the operators analysis. Overall, the C-tree BBN (shown in figure 32) analysis is inconclusive for this well based on the lack of available relevant data.



Sections	Elements	Outcomes
	C1	no
	C2	no
	C3	▨
	C4	▨
Cement (plug and annular)	C5	▨

Figure 31: Results from qualitative C-tree. The green outcomes indicate that the most ideal practices or conditions are followed, the orange outcome indicates a lack of verification or a relatively important issue was encountered and the red outcome indicates that a main requirement is missing. Grey outcomes are given when there is missing information. In this case there are no yellow outcomes which would indicate a minor issue with the abandonment.



```
cement_plug_integrity
  Cement Failure
    48.86 Failed cement plug
    0.00
    51.14 intact cement plug
    0.00
  Thermal Stress
  stress from pressure changes
  Pressure Change
    - Low change (180 bar)
    0
    100.00 High change (310 bar)
    *0.00
  Temperature Change
    100.00 Low Change (10 C)
    *0.00
    - High Change (25 C)
    0
  Tensile strength
    50.00 weak (0.9e6 N/m2)
    0.00
    50.00 strong (3e6 N/m2)
    0.00
  Thermal exp. coeff.
    50.00 low coeff. (1.54e-6 C)
    0.00
    50.00 high coeff. (6.49e-6 C)
    0.00
  Young modulus
    50.00 low (8.6e9 Pa)
    0.00
    50.00 high (24.3e9 Pa)
    0.00
  poisson ratio
    50.00 low (0.19)
    0.00
    50.00 high (0.26)
    0.00

deboning_cement_casing_final
  Debonding Cement -casing
    38.50 Debonding
    0.00
    61.50 No debonding
    0.00
  Cement Cohesion
  Cement Shrinkage
  Cement stiffness
  Confining pressure
    100.00 Low (220 bar)
    *0.00
    - High (450 bar)
    0

deboning_cement_formation_final
  Debonding cement - formation
    66.35 Debonding
    0.00
    33.65 No debonding
    0.00
  Cement Cohesion
  Cement Shrinkage
  Cement stiffness
  Pressure change
    100.00 High Pressure change (310 bar)
    *0.00
    - Low pressure change (180 bar)
    0
  Temperature Change
    - high (25 C)
    0
    100.00 Low (10 C)
    *0.00
  confining pressure
    - High Confining pressure (450 bar)
    0
    100.00 Low Confining pressure (220 bar)
    *0.00
```

Figure 32: Results from cement plug integrity BBN (left), debonding cement-casing BBN (top right) and debonding cement-formation (bottom right). Although an outcome is given , the uncertainty is too high for it to be reliable due to the lack of information for all three BBNs.

5.2 Peterhead 14/29a-5 well

The Peterhead project is a UK based CCS project taking place in the Goldeneye reservoir, in the North sea. The project documentation contains extensive knowledge of the abandoned wells present in the reservoir. While no issues were detected in most of the wells, there are two that have been considered as potential leakage points, not because of particular abandonment issues but because these wells are in contact with the gas-bearing layer. Another interesting fact about these wells is that they have not been abandoned following the NOGEPA nr. 45 standard, so it will provide the opportunity to test the framework with a well outside of the standard, to see how it hold-ups for other abandonment conditions. One of these wells, the 14/29a-5 was used to test the framework. This well counts two cement plugs acting as barriers. Figure 33 shows a schematic of the abandonment of the well.

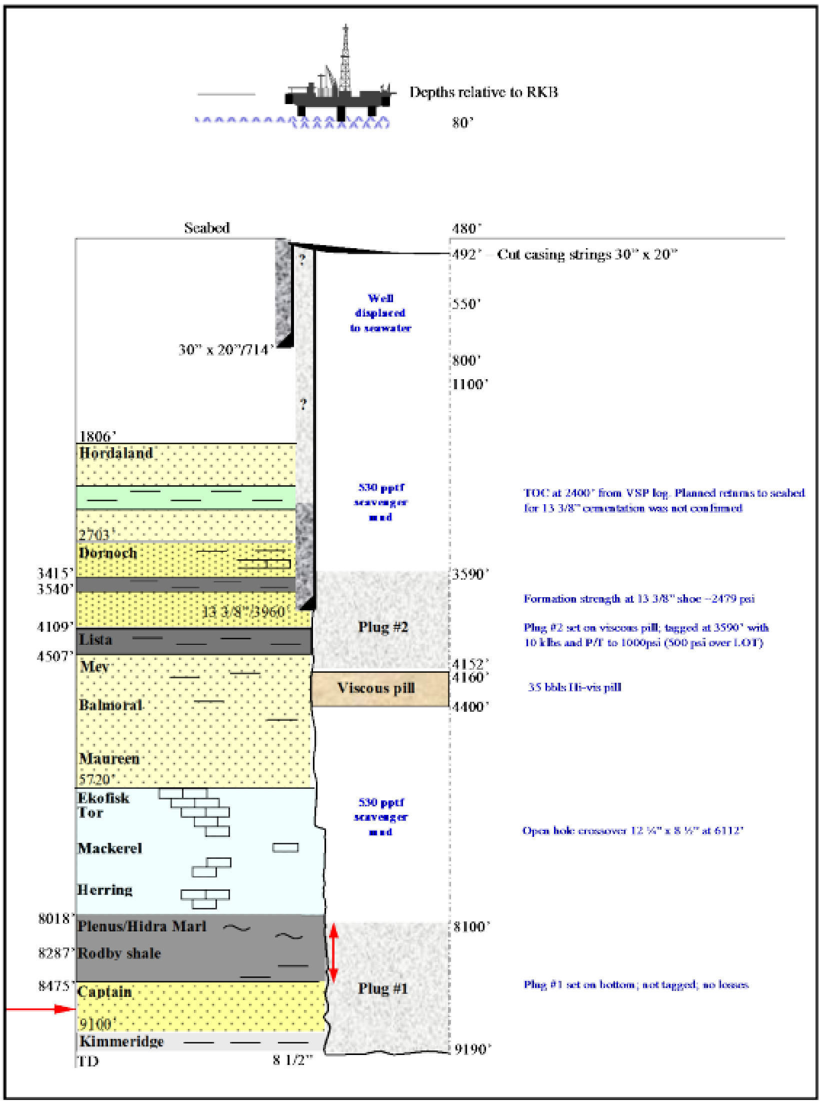


Figure 33: 14/29a-5 well abandonment schematic (Shell UK limited, 2014).

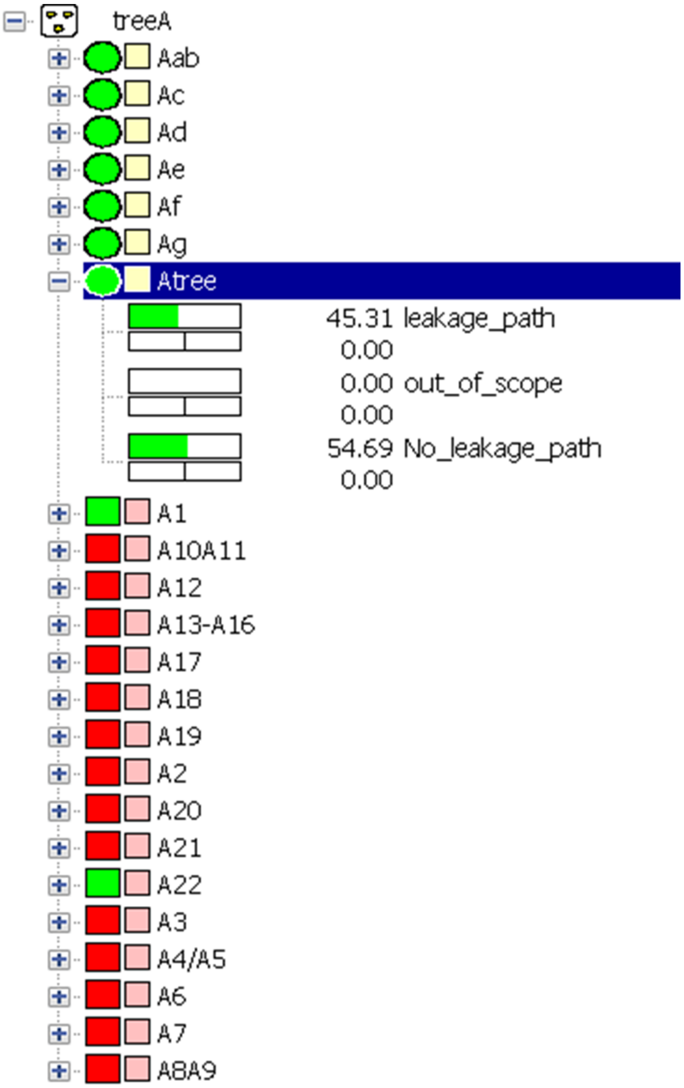
5.2.1 A-tree

The outcomes of the qualitative tree are shown in figure 34. The results are consistent with the low risk of leakage specified by the operator. While not being abandoned under the NOGEPA nr. 45 standard, the resulting abandonment does fit the criteria for a safe abandonment plan with low risk of leakage. The only issue detected is the lack of verification of the barrier, however, there exist another barrier closer to the surface that was verified. The operator reports that there is no leakage concern and that the well is properly abandoned, matching the outcome of the qualitative A-tree.

Sections	Elements	Outcomes
Prior to abandonment	A1	⬛
	A2	yes
Casing verification	A3	🟩
	A4	🟩
	A5	🟩
	A6	\
Plugging process/method	A7	🟩 yes
	A8	\
	A9	\
	A10	\
	A11	\
	A12	\
Annular spaces	A13	\
	A14	no
	A15	no
	A16	\
	A17	\
	A18	🟩
Plug properties	A19	🟩
Abandonment verification	A20	🟧
	A21	🟩
	A22	⬛

Figure 34: Qualitative A-tree results. The green outcomes indicate that the most ideal practices or conditions are followed, the orange outcome indicates a lack of verification or a relatively important issue was encountered. Grey outcomes are given when there is missing information. In this case there are no red or yellow outcomes.

The results of the A-tree BBN are shown in figure 35. While the qualitative analysis matches the outcome of the operator, the result from the A-tree BBN over represents the risk of leakage, predicting a 45.3% probability of leakage happening. The relatively high leakage risk compared to the qualitative analysis is due in part to the 'grey' outcomes in question A1 and A22, which are left vague in the BBN, and the orange outcome in question A20 related to the lack of verification. In this case it can be observed how this BBN can over represent the failure state, specially when critical elements (those that in the qualitative tree would lead to red outcomes) are left vague due to lack of data.

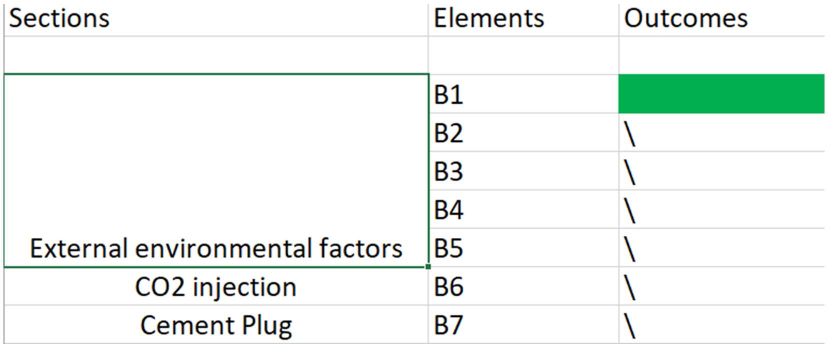


treeA
Aab
Ac
Ad
Ae
Af
Ag
Atree
45.31 leakage_path
0.00
0.00 out_of_scope
0.00
54.69 No_leakage_path
0.00
A1
A10A11
A12
A13-A16
A17
A18
A19
A2
A20
A21
A22
A3
A4/A5
A6
A7
A8A9

Figure 35: A-tree BBN results, showing a risk of leakage path formation of 45.3%, which is higher than expected considering the outcome of the qualitative tree and the analysis of the operator.

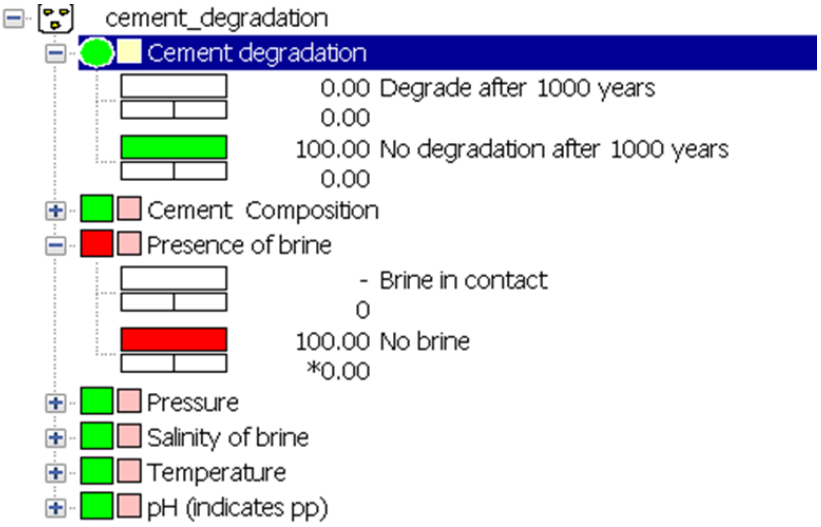
5.2.2 B-tree

The qualitative B-tree outcomes are shown in figure 36 and the BBN results are shown in figure 5.2.2. Both resulted in a low risk of a leakage path forming. The B-tree is easily resolved since the operator analysis predict that there will be no significant amounts of brine in contact with the wellbore elements. Without a brine – CO_2 mixture the degradation of the cement will be too slow to be of any significance, to the point that the other exacerbating factors (which are described by the other questions of the decision tree) are not relevant. This is also the case for the BBN, where the risk of leakage is very small due to the outcome of the question related to the presence of brine in contact with the wellbore. In this case however, it has to be mentioned that the BBN cannot be directly applied, since the plug is longer than 50m in this case.



Sections	Elements	Outcomes
External environmental factors	B1	🟩
	B2	\
	B3	\
	B4	\
	B5	\
CO2 injection	B6	\
Cement Plug	B7	\

Figure 36: Qualitative B-tree results. A green outcome in the first question makes following with the analysis unnecessary. This is because when there is not abundant brine in contact with the well, no significant degradation will occur.



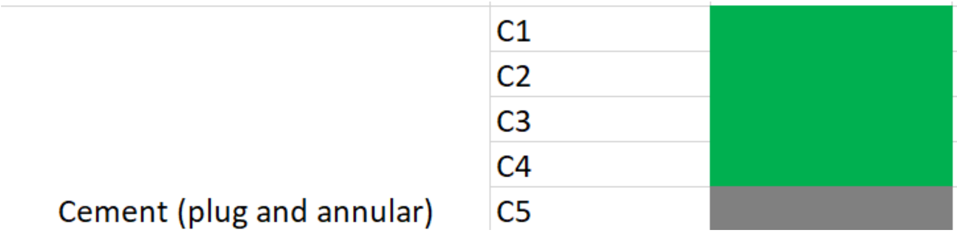
cement_degradation
Cement degradation
0.00 Degrade after 1000 years
0.00
100.00 No degradation after 1000 years
0.00
Cement Composition
Presence of brine
- Brine in contact
0
100.00 No brine
*0.00
Pressure
Salinity of brine
Temperature
pH (indicates pp)

Figure 37: B-tree BBN results, showing no risk of a leakage path forming.

5.2.3 C-tree

In order to analyse the mechanical integrity of the abandonment elements, the operator performed a geomechanical analysis using the DIANA FEA software, which was also used for the development of the BBNs for this project. The results obtained from the operator are enough to answer the questions of the qualitative decision tree, which predicts that the well will conserve its integrity for all elements. The outcomes of the qualitative C-tree are shown in figure 38. Because the operator does not describe the time frame for which the conditions of the wellbore will still be positive, question C7 is left as unknown.

Because the values used for the DIANA model are not reported it becomes impossible to fill in the BBNs relevant for the analysis. The only property described is the cement shrinkage, which is described to be low, and the reservoir pressure and temperature, which play smaller roles. The lack of data makes the outcomes for the BBNs unreliable, however, the final outcome from the qualitative tree can be used instead. The outcomes for the BBNs are shown in figure 39.



	C1	🟩
	C2	🟩
	C3	🟩
	C4	🟩
Cement (plug and annular)	C5	▒

Figure 38: Qualitative C-tree results. For this tree all outcomes are green, based on the predictions of the operator after performing geomechanical simulations with the DIANA FEA software. The only unanswered question is related to the time frame of the abandonment.

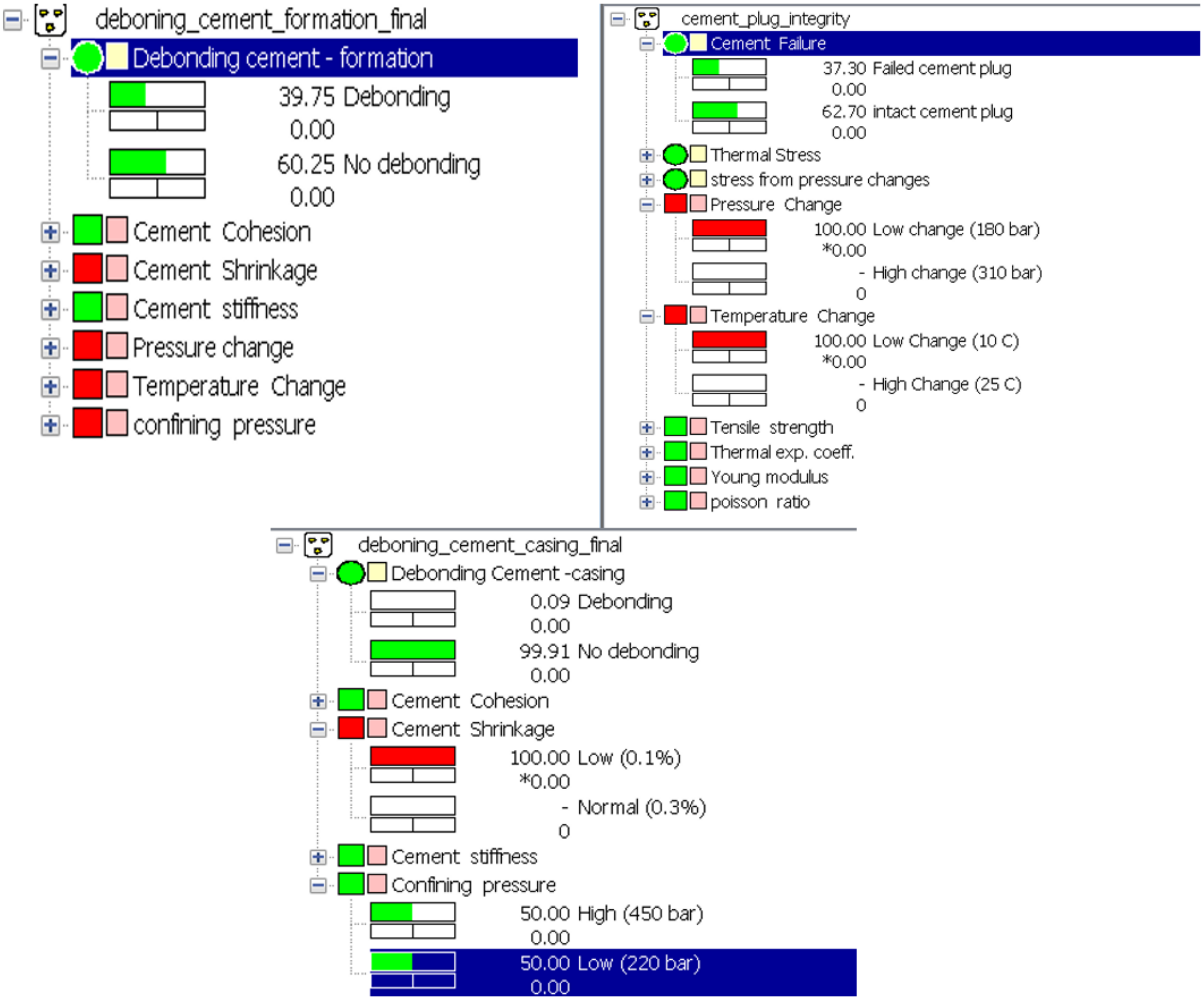


Figure 39: Results from cement plug integrity BBN (left), debonding cement-casing BBN (top right) and debonding cement-formation (bottom right). Although an outcome is given , the uncertainty is too high for it to be reliable due to the lack of information for all three BBNs.

5.3 GDF Suez D15-A105

The D15-A105 well is located in the North Sea and it is operated by GDF Suez. It was completed in 2012 and it is producing gas. The plans for abandonment are detailed in the completion report of the well, however, there is not a report with the specifics of the abandonment. This results in a severe lack of data for this well, especially as it relates to the B and C trees. Figure 40 shows a schematic of the abandonment as described by the operator.

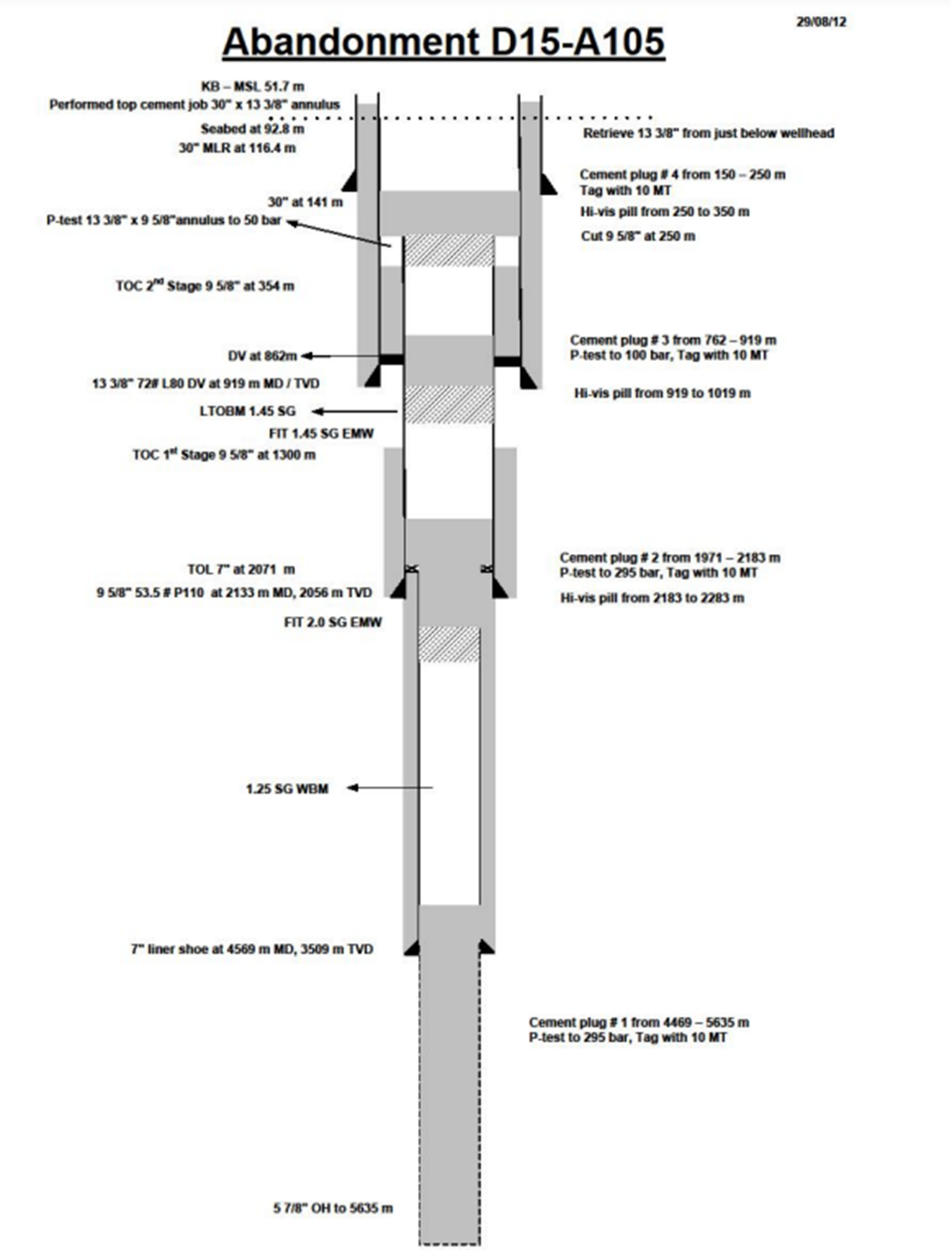
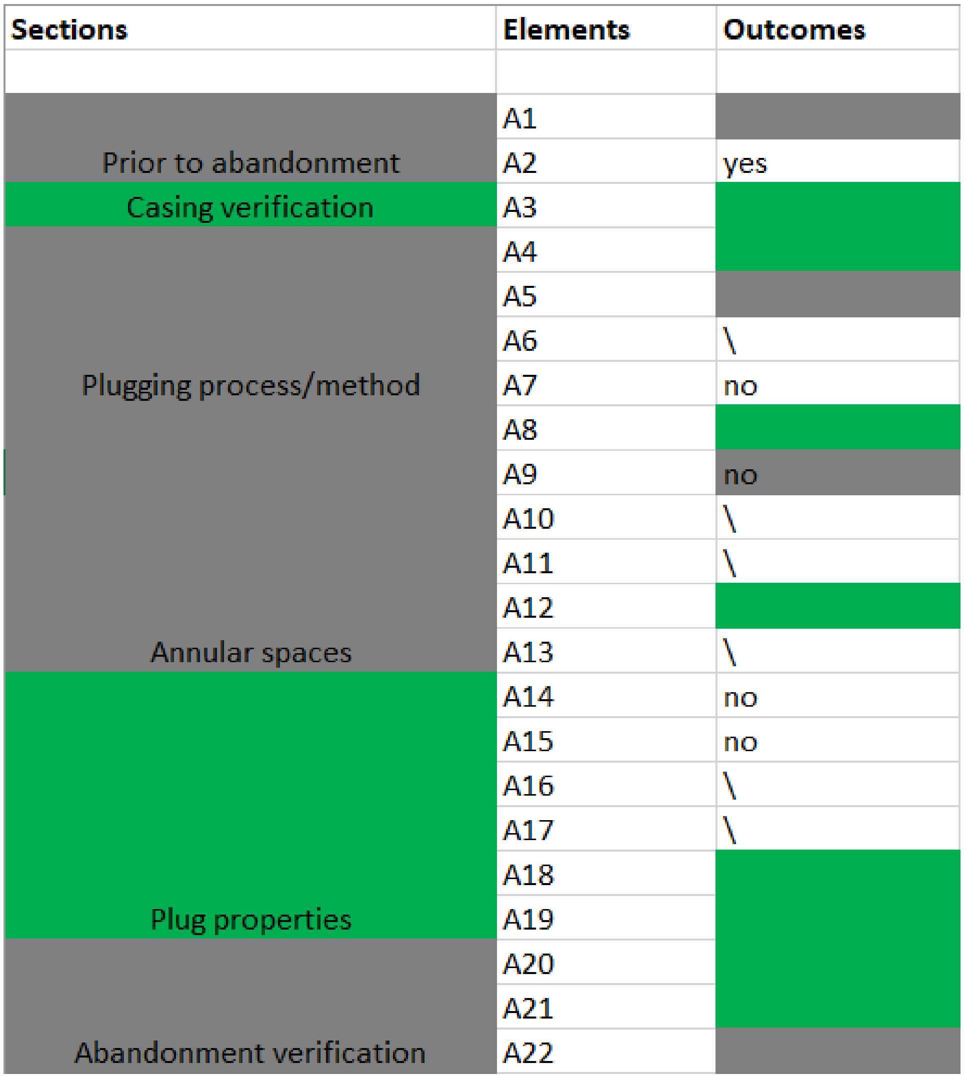


Figure 40: Abandonment scheme described by the operator, which consists of three cement plugs placed without a mechanical plug.

5.3.1 A-tree

The result from the A-tree can be observed in figure 41. The operator does not mention any specific issues with the abandonment and considers that it should be sufficient for the current conditions of the reservoir at the moment of the abandonment. From the A-tree analysis no major issues are observed, as all the critical elements for a proper abandonment are present. The biggest fault observed is in a lack of verification of the cement by performing cement bond logs, which will result in a grey rating. Apart from this, there is a lack of data, with a few of the points missing; while most of this are minor requirements they still hold some weight as they relate to verifications and the abandonment process.



Sections	Elements	Outcomes
Prior to abandonment	A1	▨
	A2	yes
Casing verification	A3	🟩
Plugging process/method	A4	🟩
	A5	▨
	A6	\
	A7	no
Annular spaces	A8	🟩
	A9	no ▨
	A10	\
	A11	\
	A12	🟩
	A13	\
Plug properties	A14	no
	A15	no
	A16	\
	A17	\
	A18	🟩
	A19	🟩
Abandonment verification	A20	🟩
	A21	🟩
	A22	▨

Figure 41: Qualitative A-tree results. The green outcomes indicate that the most ideal practices or conditions are followed. Grey outcomes are given when there is missing information. In this case there are no red, orange or yellow outcomes.

Figure 42 shows the result from the BBN representing tree-A. The outcome of this network shows a probability of failure of 85%, despite there not being any specific mayor issues with the abandonment. The reason why the rating is so high has to do with the unanswered questions related to the missing data (the operator does not report on the verifications made). The way this network calculates probability, it over estimates the risk of failure, because if critical elements are missing, the failure rate given is of 100%. Because of the missing data in this case. This case shows the limitations of using the BBN format in cases where the uncertainty is high.

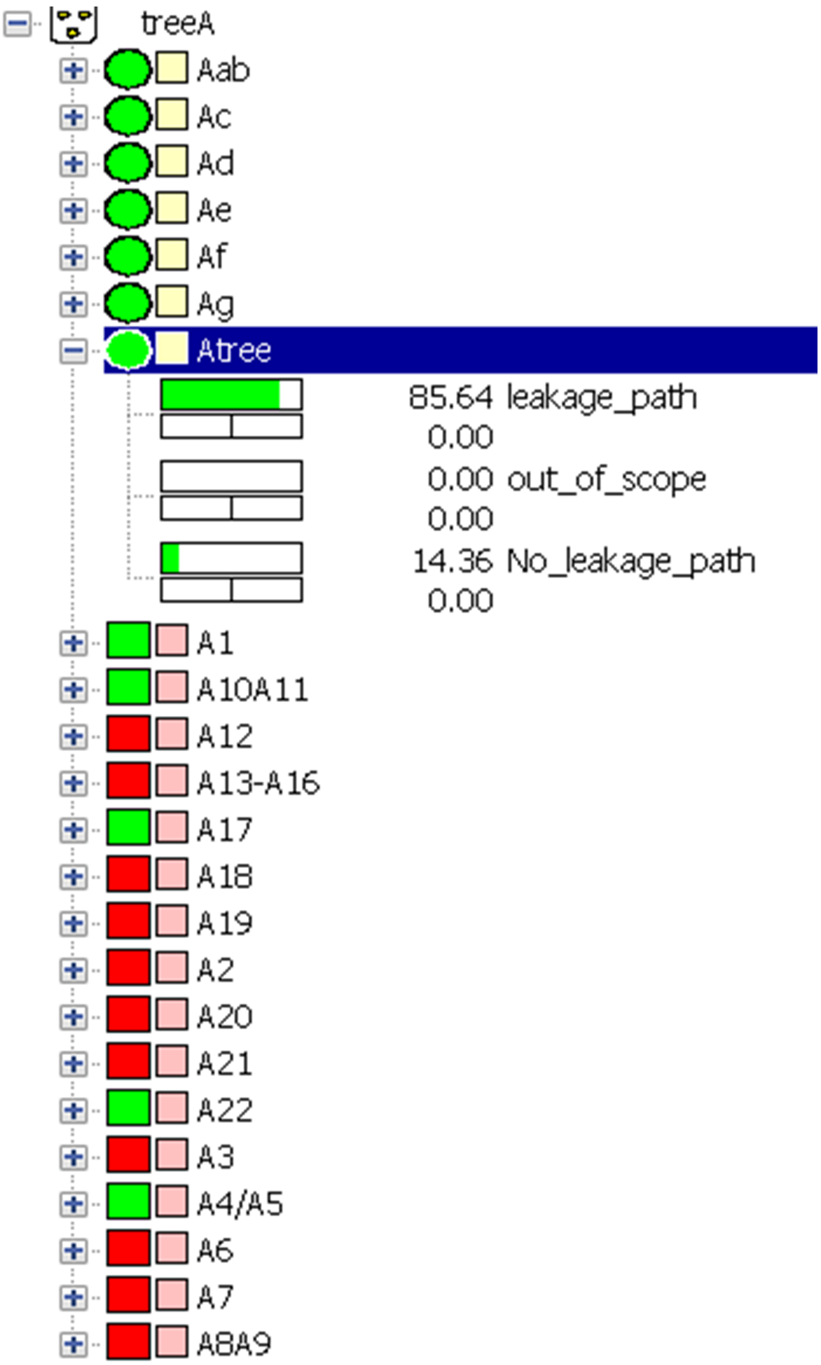


Figure 42: Results from BBN representing the A-tree, with an estimate probability of failure of 86%.

5.3.2 B and C trees

A full analysis of the B and C tree is not possible for this well, as the operator does not report the required data that will be necessary for the analysis. For the B-tree, there is no information about the chemical composition of the brine. The only data relevant is the fact that there will be brine present in contact with the plug (inferred from depth of plug and the depth of the water contact), the pressure and temperature. Because of these conditions, the risk of degradation should be considered and further investigation of the chemical conditions of the reservoir is required.

For the C-tree there is no cement data available, with makes it impossible to properly predict its mechanical stability for the reservoir conditions. The missing data results in the B and C trees not being useful for this analysis, which indicates the limitations of the framework for these situations. It does also, showcases the limitations of the current standards of abandonment. The abandonment is not performed considering CCS, as it is not required by the current standards, so all the data reported is what relates to the current abandonment conditions, and not for future CCS requirements. This means that in general the A-tree will be most likely be possible to be fully complete with enough data to do a proper analysis, while this might not be the case for the B and C trees. If this wants to be avoided a good measure would be to start reporting relevant information for the re-utilization considering CCS, which would only have to include the chemical composition of the brine of the reservoir and the elastic and thermal properties of the cement used.

6 Conclusion and Recommendations

6.1 Conclusions

In this study, a decision making framework was developed to assess abandoned wells in terms of their abandonment conditions and the risk of leakage they present on a CCS project. The objective of this decision framework is to have a consistent, and systematic method to assess the risk of leakage across abandoned wellbores in CCS reservoirs. The methodology for developing such a framework consisted of a thorough literature review in order to review all the necessary factors that will have to be included in the analysis, as well as additional simulations to obtain additional data. With all the factors incorporated, two separate assessment methods were developed. First, a qualitative part that functions as a group of decision trees with a series of questions that have to be answered in order to obtain a qualitative probability of leakage based on the answer for each specific question. The second method is a probabilistic model based on "Bayesian Belief Networks", which will estimate the quantitative probability of a leakage path being formed based on the conditions of the abandonment and environment. The quantitative part is based on the same decision trees as the qualitative part. Both methods were tested with a series of case studies to test and improve the framework on real cases. The P-18 well case study served as the validation case, as it was also evaluated by the experts. The case studies allowed to observe the big picture of the main features of the framework, how it can be used and its strengths and insights. Overall the main conclusions related to the framework itself are:

- The framework works better when both parts are used together. Depending on the data available, it is up to the criteria of the user to define which analysis is more appropriate for each case.
- The framework should be used as a screening tool, to quickly scan wells to aid decision making. It does not replace a complete engineering analysis, however it can indicate when one is necessary.
- One of the biggest advantages of the framework is that it looks at the overall condition of a well, and it also serves as a complete check list of the main factors that should be considered when evaluating the risk of leakage of a well.
- Because of the probability approach it can be useful for analyzing a high density of abandoned well in a single reservoir, specially if there is overlap in the characteristics of the wells.
- The framework is intended to be used by operators that have sufficient data from the well, reservoir and abandonment procedure prior to the start of a new CCS project.
- The framework is very sensitive to the data availability. If certain data is missing, the uncertainty in the analysis will be large, and it might be impossible to draw acceptable outcomes.
- There are some specific conclusions related about the main factors that contribute to the formation of leakage paths. For the chemical degradation of cement the most important parameter is the presence of abundant brine in contact with the cement. For the mechanical processes the main factor that can lead to debonding is the shrinkage factor of the cement.

Another important finding of developing this framework was the insight gained in the current practices for abandonment, the standards, and how it is reported. This study shows that the current abandonment norms can be challenged. Specially considering the growing popularity of CCS, abandonment practices should adapt to consider the possibility of the re-utilization of a reservoir for CCS. In summary, the main conclusions for the analysis are:

- There is a frequent lack of information related to the cement properties reported in the abandonment reports which is critical information for predicting the risk of a leakage path forming for a specific process. Factors that should be reported are the elastic parameters, shrinkage and thermal properties, as they are critical in predicting the mechanical behaviour of the cement. Another important cement property that should be reported is the percentage of additives (generally pozzolan mixtures) that are mixed with the cement slurry, as they will affect the rate of degradation of the cement.
- In general, standards for abandonment do not apply for CCS projects, the standards should be updated to consider the specifics necessities of CCS.
- The current standards as they are have proven that they can be acceptable for CCS projects. Generally, if the abandonment is properly done, the risk of leakage of the well should be relatively low. However, if the conditions are not favorable (for example in very corrosive environment) then current abandonment standards will not suffice. Implementing small adjustments to the standards could significantly reduce the risk of leakage for abandoned wells in CCS projects. Some main points to be modified or added could be:

  - Consider the use of expansive cements to reduce loss of integrity in the cement-casing and cement-formation boundaries.
  - Limit the amount of pozzolan additives to be added in the cement mixture.
  - Report on the pressure and temperature changes caused by the injection of CO_2 and determine the magnitude that is acceptable for the integrity of the cement, casing and isolation elements.
  - Consider using cements that are resistant to the degradation by CO_2 or other materials that do not degrade in this conditions.

- Some standards arbitrarily define eternity as 1000 years. This should be updated, by considering the different time-scales for the trapping mechanisms for CO_2 in a reservoir (residual, solubility and mineral trapping for example). Evaluating percentage amounts of CO_2 that will be permanently trapped after certain amount of years can lead to a better, more useful time frame to consider for the duration of the effective abandonment.

6.2 Recommendations for future developments

The framework developed in this study provides a base for estimating risk of formation of leakage paths. However, as it stands at the end of this study, it is still limited in its applications. Some important considerations were made in order to expand the applications of the framework, improve its results and make it more user friendly. The main improvement points are:

- The framework only considers the different processes independently. The combined chemical and mechanical effects were not included in the analysis due to the added complexity it adds, as it will also require extra experiments and modelling to be able to perform it. In order to improve the model for the future this should be included.

- The quantitative analysis was done using discrete BBNs. This means that the variables included will have to be discretized if they are continuous. Using discrete variables will approximate a continuous property into a few discrete states. This limits the accuracy of the analysis if the real parameter does not fall exactly in any of the states define. Using continuous BBNs will allow to improve the accuracy of the obtained results as they can include the values in between, although they require more data to populate.

- In order to populate the BBN related to the chemical processes, the data was obtained from experimental results reported in literature. This limits the amount of data available and also its quality. Performing extra experiments with consistent conditions that can better represent the system accurately will be preferred.

- In order to populate the BBNs related to the mechanical processes, the data was obtained from the results of the DIANA FEA geomechanical model. For this a generic well was modelled to obtained the data for the population of the BBNs. This is limited as it might not be representative for different types of wells with other conditions. Developing similar models with other conditions will be positive to be able to perform the analysis for a broader assortment of wells. Also, while the model is validated by experimental data, performing extra experiments, specially as they related to the cement properties and shrinkage will be necessary to properly characterize the cement properties at the down well conditions.

- If it is opted to continue using discrete BBNs, adding extra states will increase the capacity of the BBNs to model more specific cases and to obtain more accurate results. This will however, require a larger amount of data, and it will also significantly increase the complexity of the BBNs.

- The BBNs and decision trees are done based on the NOGEPA nr. 45 standard from the Netherlands. The framework could be modified and expanded to fit for other standards, in order to broaden its applications.

- The framework applies for the most typical abandonment standards, and generally does not apply to specific techniques or materials that might not be the most common. In order to broaden the framework, a larger range of materials for the plug (for example expansive cements or bentonite), casings (non steel casings or corrosive resistant alloys for example) could be considered.

- This framework could be expanded and integrated by the means of an interface that could turn this framework into a tool for risk analysis.

- Lastly, at the moment this framework is specifically designed to estimate the risk of formation of leakage paths. This is not the only factor that will lead to leakage. In order to CO_2 to escape from the subsurface there has to be a path but also a driving force (pressure difference, diffusion or other mechanisms). In order to have a complete risk analysis this should be included too.

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A Appendix; International standards

A.1 NOGEPA nr. 45 (The Netherlands)

The current mining regulation in the Netherlands sets the regulations required for the abandonment and decommissioning of wells. The NOGEPA Industry Standard no. 45 provides the standards and practices required to meet the conditions set by the mining regulation, setting the guidelines for the proper decommissioning of wells (NOGEPA, 2019), following each article stated by the mining regulation. This regulation makes the operator responsible for the proper decommissioning of the wells. The most important points stated in this standard are:

- This regulation applies exclusively for wells used for the exploration of hydrocarbons from the subsurface, excluding wells used for CCS or other activities.
- Requires the operator, before the start of the abandonment to identify all potential leak paths and how to remediate then.
- The isolation has to be durable, effective and there has to be an isolation barrier across every caprock and also a top isolation barrier near the surface. The isolations across the caprocks have to be able to withstand the pressure of the reservoir and have to be placed in locations above zones with flow potential. For the near surface isolation, it has to extend across the full cross section of the well and annular spaces. Regarding the top isolation, there are differentiations between offshore and on land wells.
- The isolation should consist of cement of at least 100m or 50m if it is combined with a mechanical or solid support. If the caprock thickness is smaller than 50m then a shorter cement barrier can be used. Other suitable materials can be used for exceptional cases. This not only applies to the cement plugs but also for the annular cement, which have to follow the same strict conditions of cement placement and also verification.
- All cables and well materials have to be removed, as well as all well material near the surface.
- The operator has to verify the isolation without causing damage to the isolation. Methods suggested for the verification are:
    - Weight test
    - Pressure test
    - Inflow test
- The fluids remaining in the well cannot cause more than minimal damage to the isolations or have a pressure gradient that exceeds the formation gradient in the zones with flow potential.
- The operator has to report the plan for the decommissioning four weeks before the start of the activity. For weeks after the activities have ceased a final report of the decommissioning has to be submitted.

A.2 ISO 16530 (International)

This international standard provides a set of high level indications that complement the local regulations of where it is applied. It defines well abandonment as the final activity performed, where the permanent barriers will be established for the wellbore isolation. The main points stated in this standard are:

- The well operator should define goals for the well abandonment activities with should include.
    - Prevention of fluid scape to environment
    - Prevention of fluid flow across formations/zones
    - Prevention of contamination of aquifers
    - Isolation of hazardous materials that can remain in the wellbore
    - Specific legal requirements
- Requires proper expertise from the side of the operator in order to properly execute the abandonment plans. The roles and responsibilities have to be well defined.
- A program of the activities has to be made. This has to include the plans for the well barriers and for their verification.

- Defines the factors that have to be considered when selecting the well barriers, which include:
    - Identification of potential sources of flow that can exist at the time of well abandonment.
    - Potential future flow sources due to reservoir re-pressurization.
    - Depletion of a reservoir leading to potential for cross-flow to other distinct zones.
    - Identification of potential leak paths.
    - Options to establish permanent barriers to potential leak paths at abandonment.
    - Capability to verify annulus cement isolation effectiveness (initially and prior to abandonment).
    - Capability to access well sections for placement of permanent barriers.
    - Formation compaction.
    - Seismic and tectonic forces.
    - Temperature.
    - Chemical and biological regimes that can exist.
- Regarding the selection of well barriers, this standard does not give specific instructions of their design or material, instead this is left for the operator to decide, and to select an appropriate barrier that can ensure the proper isolation and retain the integrity and the specific conditions at which it is placed. The barriers have to create isolation for:
    - Hydrocarbon zones;
    - Over-pressured water zones
    - Injection fluids
    - Shallow aquifers
    - Hazardous materials left in the wellbore
- The operator has to define the verification criteria for the well barrier, ensuring that they can be verified during the abandonment.
- Requires the operator to perform a risk analysis which includes the identification of all the threats, mitigations and requirements to comply with local regulatory requirements.
- The operator should document the final state and location of the abandoned well. The report should contain information on the barrier elements used and if there are any materials or fluids in the wellbore, recommendations for post abandonment and a risk register.

A.3 Norsok D-010 (Norway)

The objective of this standard is to define the best practices for the establishment of the well barriers, ensuring safety in the process. Primarily the objective of the barriers is to create isolation of any permeable formation. The main points in this standard are:

- Requires well barrier schematics for every well activity and operation
- Requires identification and documentation of all flow zones
- The design basis has to consider
    - Well configuration (depths of formations, inflow zones, well materials and design properties)
    - Information of the subsoil and reservoir properties (stratigraphy, fluids present, pressure)
    - Logs and data from the cementing operations
    - Well barrier elements and their conditions
    - Specific well conditions
- Defines the requirements that have to be considered for the well barrier elements, and the factors that will pose a risk. These are considered for cement or other alternative materials.

- Defines abandonment requirements for suspended wells, temporally abandoned wells and permanently abandoned wells.
- The permanent wells have to be abandoned with an eternal perspective, meaning that the barriers placed have to withstand the effect of any chemical or geological processes over time.
- Provides specific requirements for the barriers, which includes:
  - A primary barrier: to isolate zones of inflow to the surface or seabed, which has to be placed at a depth where the formation integrity can withstand the below pressure
  - Secondary well barrier: as a backup to the primary well barrier
  - Crossflow well barrier: to prevent flow between formations
  - Open hole to surface well barrier: to permanently isolate flow conduits from exposed formations after casings are cut and retrieved.
  - Permanent barriers have to extend across the full cross section of the well, including annuli.
- The suitability of the materials used for plugging has to be verified for the particular conditions and also considering the effects of degradation.
- The remaining well materials, including control lines and cables, have to be removed.
- Defines conditions that have to be met for the external well barrier elements (50m cement or 30m cement if verified by logging) and for the internal well barrier elements (minimum 50m if set on a mechanical plug as a foundation.
- The wellhead and casings near surface have to be removed up to an appropriate depth.
- The operator should assess the design and operational risks, related to well and reservoir conditions.
- Provides examples for different plugging techniques and configurations. Also provides decision trees for the assessment of best practices for different circumstances.

A.4 Oil and Gas UK Well integrity guidelines issue 1

This standard provides the minimum criteria guidelines that the operators have to take when abandoning a well, in order to ensure the proper isolation of formation fluids within the reservoir to the surface. This standard applies both for onshore and offshore wells, and it is the responsibility of the operator to assess each well on an individual basis in consideration of its conditions. The main points in the standard are:

- Defines the required properties of the materials used for the abandonment, which have to have the following characteristics:
  - Very low permeability, to prevent flow
  - Long term integrity
  - No shrinking, to avoid fluid flow across interfaces
  - Ductile and non-brittle material, that can accommodate for stress changes in the reservoir.
  - Resistance to downhole fluids and gases
  - Able to bond to casing or formation where it is placed
  - Have to be placed by a proper technique to ensure its proper placement
- Requires verification of barriers after installation whether they are made from cement or alternative materials
- There has to be at least one barrier to separate each permeable zone and there have to be at least two barriers to separate the surface to a hydrocarbon bearing permeable zone or an overpressured water bearing layer. Exceptions can be made to replace the two barriers with a single one that has the same effect.
- The first barrier has to be set above the highest point of potential inflow and it should be lapped by annular cement. The second barrier has to be set up as a backup to the first barrier, making sure the formation fraction pressure is above the internal pressure.

- The barrier has to be at a cement column of at least 100ft (approximately 30m), although where possible 500ft (150m) barriers should be placed. For the first barrier, its top has to be at least 100ft above the highest point of flow potential. Also requires to have a cement barrier of at least 100ft in the annulus (when applicable).
- Distinguishes differences for plugging for open hole wells and cased holes, providing indications for each case.
- Every barrier has to be verified regarding its sealing capacity and placement. The verification has to be done for the cement plug and the casing cement.
- Abandonment operations have to be reported weekly and submitted to the appropriate authority or agency.

A.5 ISO 27914 (International)

This standard differs from the others mentioned before because it is exclusive to CCS. While not specifically for well abandonment, it does provide some guidelines on well integrity and abandonment that can be considered for CCS.

Section 7.6.2 of the standard provides a guideline for the evaluation of the conditions of abandoned wells. This includes the identification of these wells across the storage and shallower layers and their type (exploration, production, injecting, suspended or abandoned). The operator should evaluate their characteristics and conditions and their potential for leakage, evaluate plugging records and determine the chemical composition of the materials that might come in contact with CO_2.

It is also stated that before the storage process wells have to be inspected by cement integrity logs, casing inspections and pressure testing the casing without damaging the cement or cement casing bond. Legacy wells have to be evaluated by their records and history and assessed on their risk of leakage. If there is not enough documentation to assess the well, its impacts have to be considered by a risk analysis.

Regarding closure, the operator has to demonstrate that there are no detectable leakages and that the storage site is understood in such a way that it is sufficient to assess its future evolution, regarding the CO_2 plume migration, pressure states and changes of formation fluid. The operator is responsible for the development of a closure plan, which has to be developed prior to the start of injection and has to be regularly updated.

B Appendix: Decision trees and explanations

B.1 A-tree: Abandonment verification prior to CCS (based on NOGEPA n.45 standard)

A1. Were all potential flow paths identified prior to the abandonment?

It is specified by the NOGEPA nr.45 that prior to the abandonment process, the operator shall identify all zones with flow potential and investigate which measures will prevent the flow of fluids and gasses to or from rocks outside the zone or to the surface (article 8.5.1.2). This is necessary to know the placement location and number of isolations required (NOGEPA, 2021); if this is not performed the element will provide a red risk rating as there would not be guaranteed that all potential flow paths were considered.

A2. Were any issues that might negatively affect or prevent the plugging process (E.g. damaged completion elements, packers or tools left behind in the wellbore, or issues with the structure of the casing)?

There are some specific issues that can affect the abandonment process, by impeding the placement of a plug, in this case the operator will have to use alternative methods to plug the well. This might happen if the casing is affected or if there are tools or elements left behind in the wellbore. Before abandoning the well all retrievable elements should be removed from the wellbore. This should leave the well only with the casing string and the annular cement. In the case these elements will not be removed, each of these elements will have to be assessed, which is out of the scope of this assessment framework, as the majority of wells should be abandoned after removing all the elements, and a special assessment will have to be made when this would not be the case (a separate branch could be developed particularly for completion elements for wells where these would not be removed).

A3. Were there issues detected related to wear and corrosion in the casing (exclusive for issues that can affect the abandonment of the well)?

Casing integrity is important to ensure that the casing will provide proper isolation. Degradation of the casing leading to loss of integrity can happen due to wear of the casing caused by drilling or corrosion due to the casing coming in contact with a corrosive reservoir gas (Lin et al, 2016). Other forms of damage might come from insufficient centralization or any damaging occurrence during operations. To ensure that the casing is effective in isolating the interior of the well from the exterior, it should be verified by the operator before or during the abandonment process. To verify the integrity of the casing it can be done with pressure tests across the casing (Graves, 2018). A failure to verify this would lead to an orange risk rating for this element, as an isolating barrier will be present however there would not be proof of its integrity.

A4: Is the plug located at a suitable depth above the flow zone and within the caprock (suitable would indicate within a sealing formation with sufficient strength)?

Based on the NOGEPA n. 45 standard, there are specific conditions required for the cement plug for the abandonment of the well. The cement plug also has to be placed above a flow zone, to ensure that it will effectively act as a seal to the flow zone (NOGEPA, 2021).

A5: Was there any incident during the placement of the plug that might have affected its proper placement?

A6. Was this issue addressed and solved?

If there is documentation of any issue occurring during the abandonment process this might have led to the possibility that the plugging was not effective. The operator must address and resolve the issue. In the case this was not done, this element will give an orange rating.

A7: Is the plug a pancake plug (cement plug from formation to formation)?

This element refers to the method used for the plugging, which is either done by placing the cement plug directly inside the casing of the well or by milling out the casing in the section the cement will be placed, this is called a pancake plug). Pancake plugs have the advantage that, by removing the casing, it reduces the number of interfaces (cement-casing interface in the exterior and interior). Since one of the potential leakage paths is across the interfaces this reduces the probability of leakage by reducing the number of methods through with fluids can leak from the reservoir across the well (Seeberger & Hugonet, 2011).

A8: Is there proven cement in every relevant annulus behind the cement plug at the caprock interval (formation-casing, casing-casing)?

To ensure that the well is properly isolated from the environment, the space between the casing and caprock has to be cemented, this would be done to restore the isolation surrounding the caprock. Evidence for this would come from reports from the operator for the well completion and also tests of the annular cement. This element is of great importance since it is the only barrier to prevent flow across the annulus, so its omission will certainly result in a leakage path. If there is no annular cement across the caprock, this element will result in a red risk rating, as there would not be a barrier for leakage in the annular space.

A9: Was the annular cement behind the cement plug at the caprock interval prior to the abandonment verified by cement evaluation logs?

A10: Were there any issues detected by the cement evaluation log?

A11: Were the issues addressed and solved?

Cement bond logs or cement evaluation logs indicate the state of the cement bond behind the casing (Kyi & Goh, 2015). These logs are generally done by using ultrasonic signals inside the casing to estimate the acoustic impedance of the cement behind the pipe (Kyi & Goh, 2015). This will indicate the state of the cement bond and its quality and if any remediation will be necessary. If the operator of the well performed this verification before the abandonment and the bond quality has been verified as sufficient, the risk of leakage across the annular cement will be low. Not having performed a cement bond log would result in an orange rating as there would not be evidence that this will provide proper isolation. A cement evaluation log can be used to detect damage in the annular cement resulting from:

- Improper placement of annular cement due to impurities: One of the factors that will play a role in the proper placement of the cement in the annulus across the caprock is the presence of impurities in the annular space before cementing. These impurities might be any debris from the drilling of the well but might also come from leftover mud. Before the cementing the space has to be properly cleaned, removing any leftover mud or contaminant. This is done by circulating a fluid across the spaces where cement will be injected. If there are any mud or particles left in the annulus this will impede the proper cementing of the annular space, by forming porous conduits as the cement sets (Bittleston et al, 2002)
- Cement shrinkage in annulus: If the cement in the annulus shrinks after it has set, there will be debonding between the interfaces with the casing or the rock. This will result in the formation of a micro annulus that could allow flow. Cement shrinkage is independent of the amount of water in the mixture and cement is expected to shrink between 1.2% to 2.6% of its volume in the first 48hs of it being placed (Justnes et al, 1995). Cement shrinkage is associated with a decrease in the hydrostatic pressure of the cement column as it hydrates. If this falls below the pore pressure of the gas-bearing formation, then it will lead to gas migration across the annulus (Lyomov et al, 1997).
- in contact with formation due to insufficient centralization: Particularly for horizontal wells or wells with high deviation angles, there is an increased risk of decentralization of the casing (Sabins, 1990). To prevent this, centralizers are used, however, this can still lead to decentralization of the casing if these tools are not properly calibrated or in some conditions they might not be sufficient (Sabins, 1990). A casing that is not properly centralized can come in contact with the formation, leading to damage of the casing, or creating the inability to properly perform the cementing.

A12: Did the well have sustained annulus pressures in any relevant annuli (this might indicate a cement integrity issue)?

A13: Was the cause of the sustained annulus pressure addressed and resolved by the operator before abandonment?

If before abandonment the operator has detected some pressure on one of the annuli, this indicates a leak. If this was the case it is important that the operator dealt with it and addressed the source of the leak, especially if fluids were detected in the annular space (Wellcem.com, 2021).

If the operator has not addressed this before abandonment, then there exists a high risk of leakage, since there is a strong indication for a breach in the well, granting a red risk rating.

A14: Is other material than cement used for the plugs?

Cement is the most common material in use for the abandonment plugs of well. The NOGEPA nr. 45 standard allows other suitable materials to be used as long as they provide similar isolation properties. Since options for other materials can be vast, and considering only a small part of abandoned wells will use these alternatives, assessing these alternatives will be left out of the scope of this assessment tree.

A15: Is there a mechanical plug present (as part of the abandonment strategy)?

The NOGEPA nr. 45 states that a cement plug can be placed along with a mechanical plug, altering the conditions of the length of cement required. So if there is a mechanical plug the cement plug has to be of at least 50m, but if there is no cement plug then it should be of at least 100m (NOGEPA, 2021).

A16: Is the cement plug of at least 50m(based on the NOGEPA nr. 45)?

Based on NOGEPA n.45 standards if the cement plug is placed together with a mechanical plug it has to be at least 50m in length (NOGEPA, 2021).

A17: Is the mechanical plug appropriate for the requirements needed and in accordance with the standard?

Two of the most common mechanical plugs are cement retainers and bridge plugs. Out of these elements it has been observed that cement retainers tend to be one of the most reliable kinds of mechanical plugs in terms of their ability to not degrade in the present to CO_2 and to lead to leakage across it (Watson & Bachu, 2009) based on statistical data, observed from a sample-based in the Alberta Basin. Bridge plugs on the other hand are considered one of the most likely types of mechanical plugs to fail and to lead to the flow of CO_2 across them. It is estimated that over 10% of bridge plugs will fail over a time frame between 5 to 30 years when placed under CO_2 conditions. This is observed from statistical data based on samples taken from the Alberta basin. The reason for the higher failure rates is due to the rapid degradation of the elastomers used, as well as the metal when in contact with CO_2 (Watson & Bachu, 2009). Despite the higher failure rate, based on the NOGEPA nr. 45 standard, the mechanical plugs are not considered isolation elements by themselves and are supposed to act as a way to properly retain the cement as it sets, so the different mechanical plugs should not affect the final abandonment as long as they serve this initial purpose.

A18: Is the cement plug of at least 100m of good cement (based on the NOGEPA nr. 45)?

Based on NOGEPA n.45 standards if the cement plug is not placed with a mechanical plug it has to be of at least 100m length of good cement (NOGEPA, 2021).

A19: Was Portland cement class G or any class suitable for the conditions used for the abandonment?

The main type of cement used for abandonment and completion is Portland cement. There are different types of Portland cement, based on composition, but they all have similar properties regarding their sealing capabilities. Portland cement is classified by API classes from A to J depending on their most ideal use in terms of placement depth, temperature, pressure and resistance to sulphate corrosion (Khalifeh & Saasen, 2020). The cement type used must be in accordance with the conditions of the reservoir.

A20: Has the operator performed either one of:

- **A weight test**
- **A pressure test**
- **An inflow test**

(or other cement plug validation in accordance with the NOGEPA n.45 standard) and verified the cement plug?

The NOGEPA nr. 45 standard specifies three tests, of each at least one should be performed after the plugging to verify the integrity of the internal cement column. These tests have to be performed without damaging the integrity of the cement. Performing at least one of these tests will confirm the state of the plug. The tests are:

Weight test: Confirms that the pumped cement has hardened, applying a load of 10MT

Pressure test: Confirms no leakages are present when applying a 5000 kPa pressure for at least 15 minutes.

Inflow test: Confirms there would not be fluid ingress, but it is not reliable in depleted reservoirs

(NOGEPA, 2021).

A21: Were any unusual conditions with the plugging reported that might have affected plug quality?

If there is documentation of any issue or any unusual condition occurring during the abandonment or with the plug itself after it was installed this should be documented and addressed by the operator, especially if this is something that could lead to the possibility that the plug is not effective. The operator must address and resolve the issue. In the case this was not done, this element will give a yellow rating.

A22: Was there an inspection period after abandonment?

While there is not a specific requirement for an inspection period after the placement of the plug by the NOGEPA n. 45 standard, it might still be useful to have an inspection period. This is a requirement for other local standards, to have an inspection period of 5 days after the plug was placed, to ensure that the cement was set properly before completely closing the wellbore. During this period the plug is checked for a static-fluid level or other indication of plug leakage (Watson & Bachu, 2009). Not having an inspection period will result in a yellow risk rating.

B.2 B-tree: Chemical processes post CCS

B1: Is there brine present in the reservoir that might come in contact with the abandoned well?

Out of the factors that can accelerate the rate of chemical corrosion both of the cement plug and of the steel casing the most is the presence of brine in contact with the CO_2 and the wellbore elements. Diffusion based chemical degradation in general is a relatively slow process, and it might take up to 10000 years to observe a few meters of cement corroded (Akemu et al, 2011) when the corrosion is caused by dry supercritical CO_2. Similar corrosion rates are expected when there is a small amount of water relative to the amount of CO_2 present, showing also small rates of corrosion. This is because most of the water will dissolve in the supercritical CO_2 and there would not be any free liquid in the system anymore (Wei et al, 2015). The high corrosion rates will be present when the water phase is abundant enough for the supercritical CO_2 to dissolve in it. Experimental results show a change in the rate of corrosion from 0.4mm/year with water-saturated CO_2 to 20mm/year with CO_2-saturated water (Wei et al, 2015) while these specific rates are also dependent on other conditions like pressure, temperature, the material of the wellbore elements and the presence of other minerals in the brine, there is a measured increase of corrosion rate by a factor of 50 when there is enough water for the supercritical CO_2 to dissolve in it. Figure 1 shows the comparison of the results obtained from different studies.

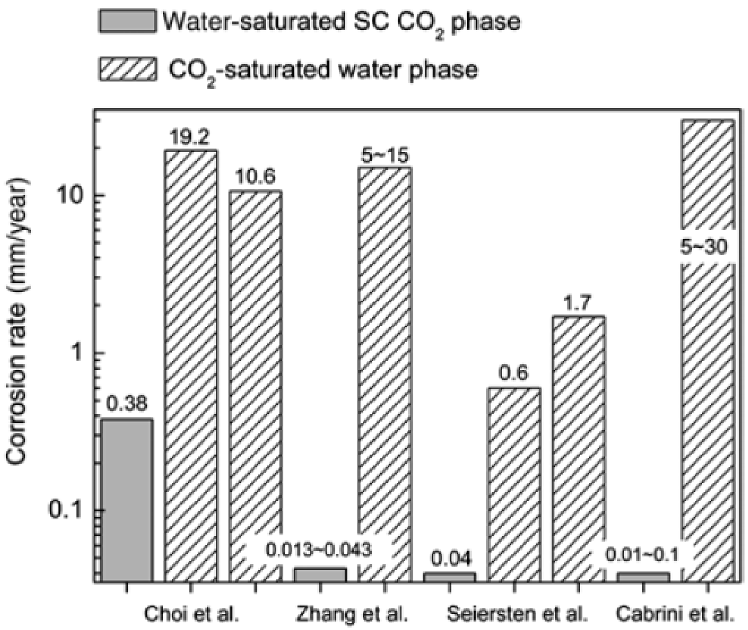


Figure 43: Experimental result comparison for the difference in corrosion rates with water-saturated supercritical CO_2 phase and CO_2 saturated water phase.

B2. Is the brine in the reservoir initially saturated (a higher saturation results in less capacity for the brine to react with cement)?

At a higher brine saturation, the brine will become less corrosive to the cement. This is due to the fact that part of the bi-carbonation reaction is the dissolution of some of the cement compounds in the brine. Due to chemical equilibrium if the brine is already saturated, then it will have a lower capacity to dissolve more molecules.

B3: Is the initial pH of the brine (before CO_2 injection) low due to the presence of contaminants (E.g. O_2, SO_2, H_2S, NO_2)?

The presence of impurities in the brine can affect the rate of corrosion. The effect of these impurities also depends on the conditions of the CO_2:

O_2: Oxygen resulted in an increase in corrosion for water-saturated supercritical CO_2 environments. The effects are observed with a composition of 3% - 4% O_2 and did not increase with increasing concentrations. When O_2 is present it prevents the formation of a protective layer that reduces corrosion. Other experiments measured an increase between 50% to 120% when O_2 is added at different concentrations (around 100ppm), and rates of 17mm/year were measured for the steel casing (Wei et al, 2015).

SO_2: It is observed that a 1% concentration of SO_2 will have significant effects on the rate of corrosion of the steel casing in all circumstances. The effect will vary for other factors, but a 1% increase in SO_2 can increase the corrosion rate up to a factor of 15 (Wei et al, 2015).

NO_2: The presence of this contaminant will also significantly affect the corrosion rate of the steel casing. The presence of a 100ppm concentration of NO_2 could increase the rate of corrosion from 4.6mm/year to 11.6mm/year (Wei et al, 2015).

H_2S: If the concentration of H_2S is too high, the elements used for the wellbore will have to be able to sustain the effects of this component and not corrode in its presence. If the wellbore elements are not verified for these conditions then there will be risk of leakage paths forming due to corrosion (ISO, 2017.)

Overall, for these three impurities, it was observed that for supercritical CO_2 and water environments the rate of corrosion will significantly increase in their presence. They will also have an effect when there is a limited amount of water (not enough to saturate the supercritical CO_2) but the effect will be smaller. While the effects were higher for carbon steels, the corrosion was also higher in stainless steel casings.

B4: Is the temperature of the reservoir above 90 °C?

In the case of the cement, it was observed in most experiments that the rate of reaction increases with temperature, as the reaction resulting in corrosion will be faster at higher temperatures. A significant increase in reaction rate is observed around 90C, however, this varies slightly with the type of cement (Abid et al, 2015).

B5: Is the pressure of the reservoir after re-injection above 450 bar?

At a higher pressure the reaction rate also becomes faster, due to a reduction of the activation energy require to start the reaction. Generally, the corrosion rate will increase linearly with a pressure increase (Abid et al, 2015).

B6: Is the pH of the brine below 1.5 (caused by dissolution of CO_2 and/or other contaminants)?

The more acidic the brine the quicker the reaction will occur, as the cement becomes even more unstable in an acidic environment. The main cause for the decrease of the pH is by the dissolution of the CO_2 in the brine. The higher the partial pressure of the CO_2 the more it will dissolve and decrease the pH Abid et al, 2015). The presence of other solid contaminants dissolve can also have an effect on the pH, but in general the impact will be much smaller.

B7: Is the current well cement in the plug and the annulus mixed with a pozzolan additive (e.g. Silica flour, fly/glass/volcanic ash) on proportions of over 40%?

Pozzolan additives are added to the cement mixtures to decrease costs. However, these additives do decrease the stability of the cement in contact with the acidic brine, accelerating the reaction if they are present in large proportions (Carroll et al, 2016).

B.3 C-tree: Mechanical processes post CCS

C1: Will the cement used for plugging and annulus maintain integrity under the predicted temperature change? (depending on thermal coefficients of cement and magnitude of temperature change)?

C2: Will the cement used for plugging the annulus maintain integrity under the predicted load profiles during its anticipated operational life?

During pressurization of the reservoir, the pressure increase reduces the compressive effects and the reservoir uncompaction increases the compressive stress, resulting in opposing effects. These stress changes can lead to the cement failing if the magnitudes are large enough and depending on the properties of the cement, however, the cement plugs are most likely to fail under tensile stress, caused by the pressurization. A higher tensile strength, a lower young modulus, a higher Poisson ratio will lead to a cement plug less likely to fail. The effect of the thermal coefficient will be relative to the formation thermal coefficient, where a thermal higher coefficient for the cement plug than the formation is preferred (Mainguy et al, 2007). Compressional stress will be less likely to cause any sort of failure of the cement, due to the cement high compressional strength, but extensional stresses are likely to lead to failure due to the lower tensile strength of cement, forming both horizontal and vertical cracks along with the cement (Mohammed et al, 2019). The development of fractures or annular pathways in the cement plug and also annular cement will result in an increase of its permeability and lead to the formation of flow paths (Benedictus et al, 2009).

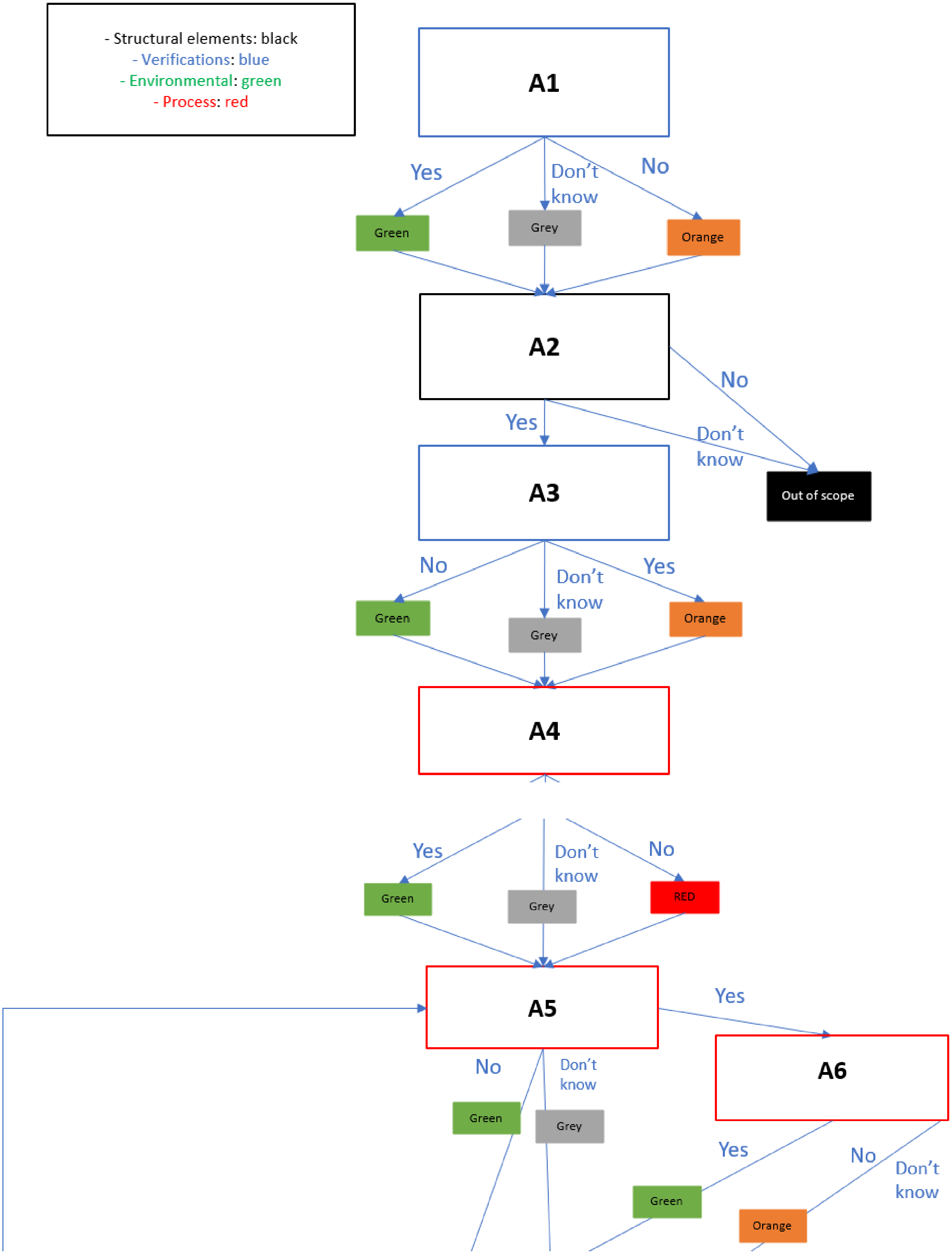
C3. Is the expected stress change due to the injection of CO_2 higher than the strength between the cement-casing bond, breaking the integrity of this bond?

C4. Is the expected stress change due to the injection of CO_2 higher than the strength between the cement-formation bond, breaking the integrity of this bond?

One of the most common mechanisms for leakage across the wellbore is across the interfaces between the cement and casing (either internally or externally) and the cement and formation. This would happen when micro annuli are formed, and it is continuous across the interface, allowing for CO_2 to leak across it. This would be a result of debonding between the two materials on the surface. This might happen for issues during the cement placement, but can also be triggered by stress changes in the wellbore due to CCS. Stress changes might lead to the casing and cement to deform, however, due to their different material properties they will deform differently. Because the casing will be surrounded with cement, it cannot freely deform, which might lead to the debonding between the cement and casing (Kermen & Meekes, 2013). Also, axial loading of casing due to reservoir decompaction caused by pressurization will result in additional stress on the wellbore. This might even cause the formation to lift up, resulting in vertical strains and stresses in the casing. Due to the casing being locked in place by the cement and formation, it might not be able to deform to accommodate this stress, which can lead to failure in the bond between casing and cement, forming micro annuli at the interface (Kermen & Meekes, 2013). The strength of the bond has to be assessed, and it has to be considered if it will be able to withstand the conditions of the reservoir.

C5. Are the isolation elements (cement and casing) be expected to maintain their integrity for the new reservoir conditions for eternity (1000 years)?

Some of the abandonment standards dictate that the abandonment will have to be effective for eternity; these standards also arbitrarily define eternity as 1000 years. Because of this, it is necessary that the abandonment conditions are effective and provide proper isolation for this span of time.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- Verifications: blue
- Environmental: green
- Process: red
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Out of scope
A3
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Don't know
Yes
Green
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A4
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A6
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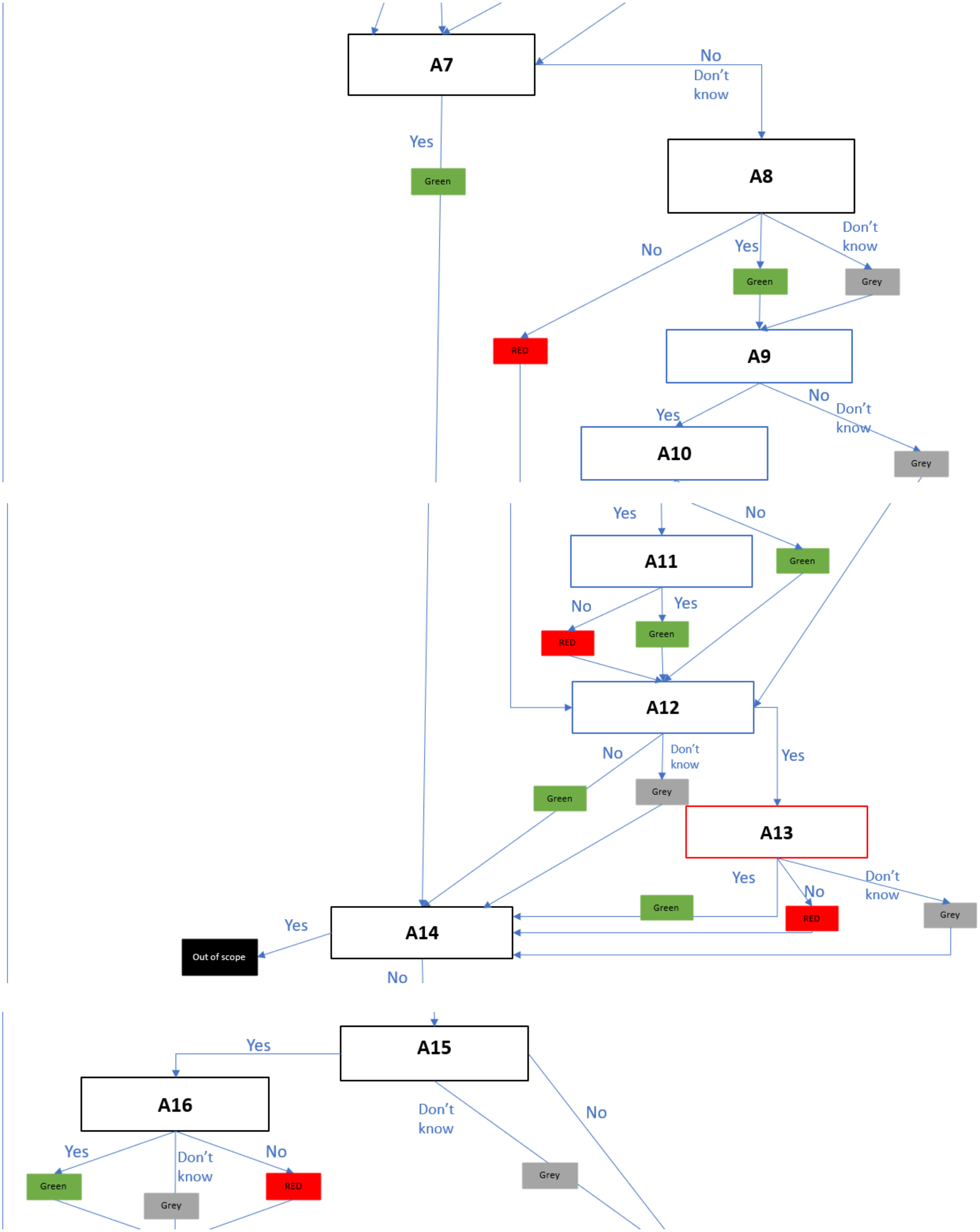
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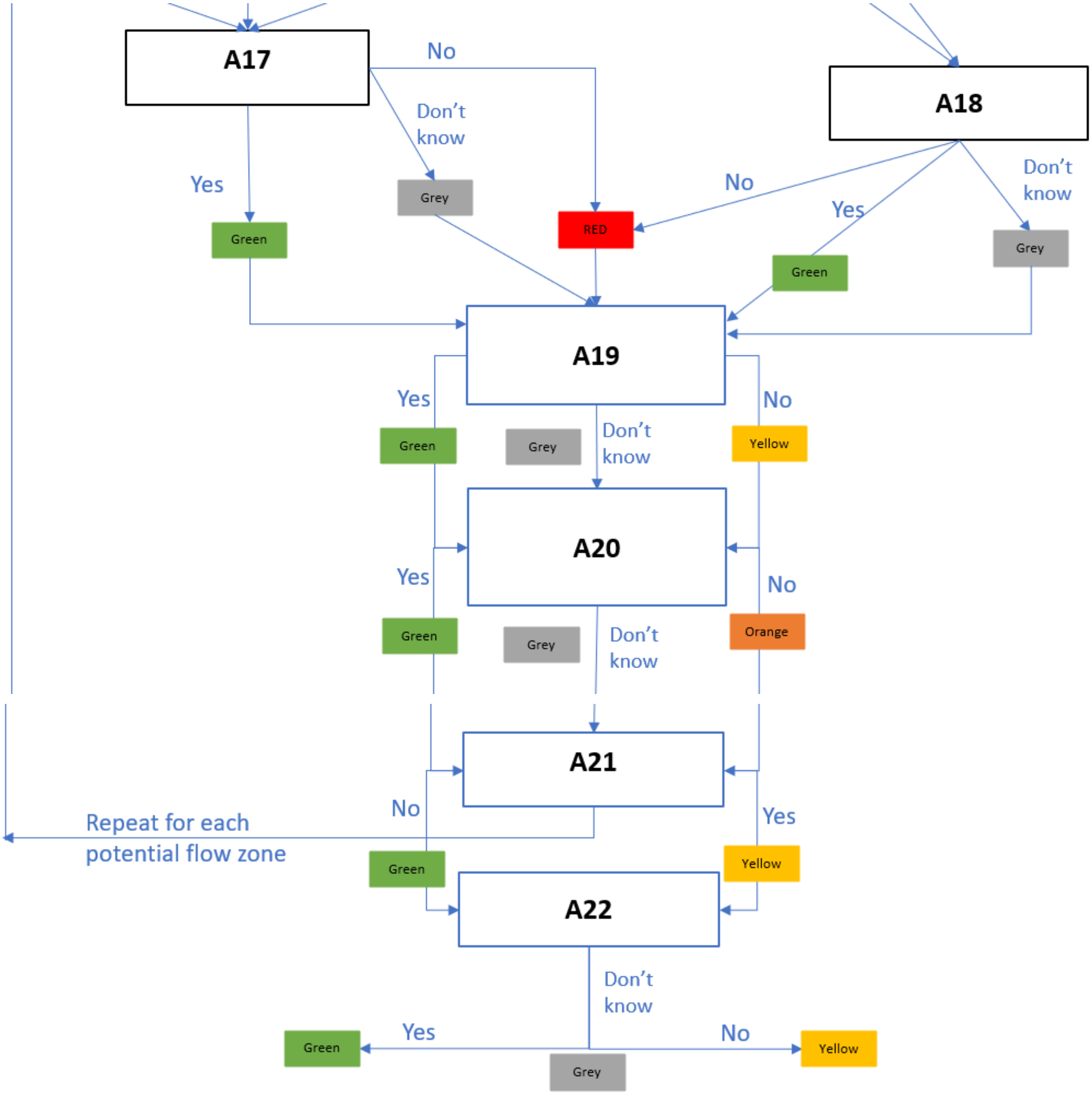
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Yellow
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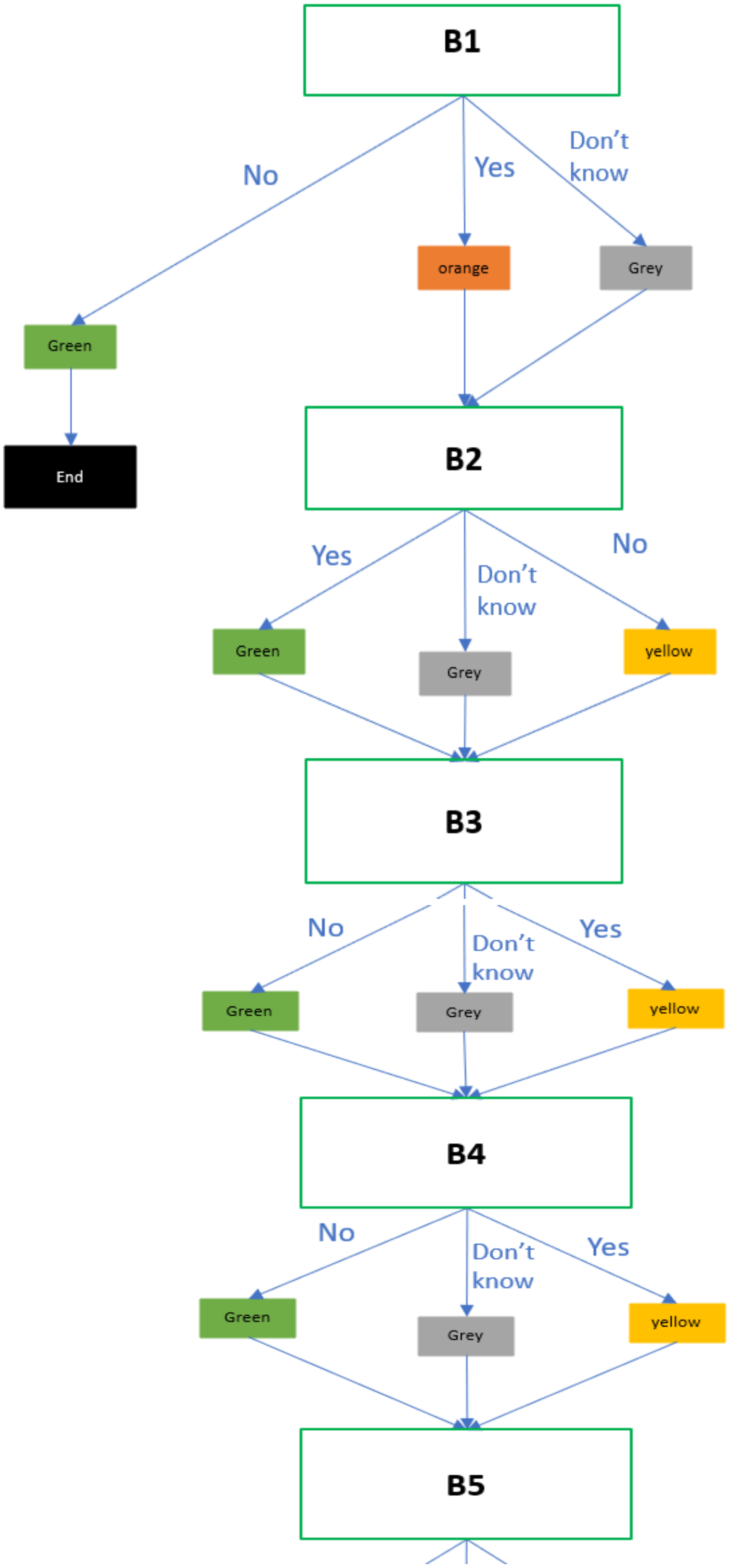
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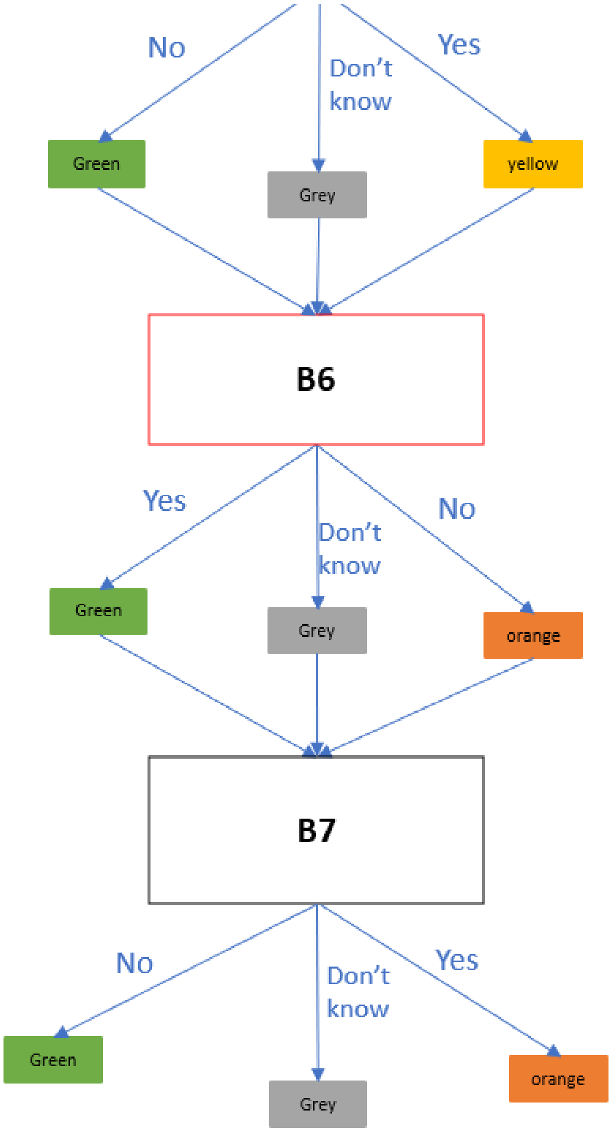
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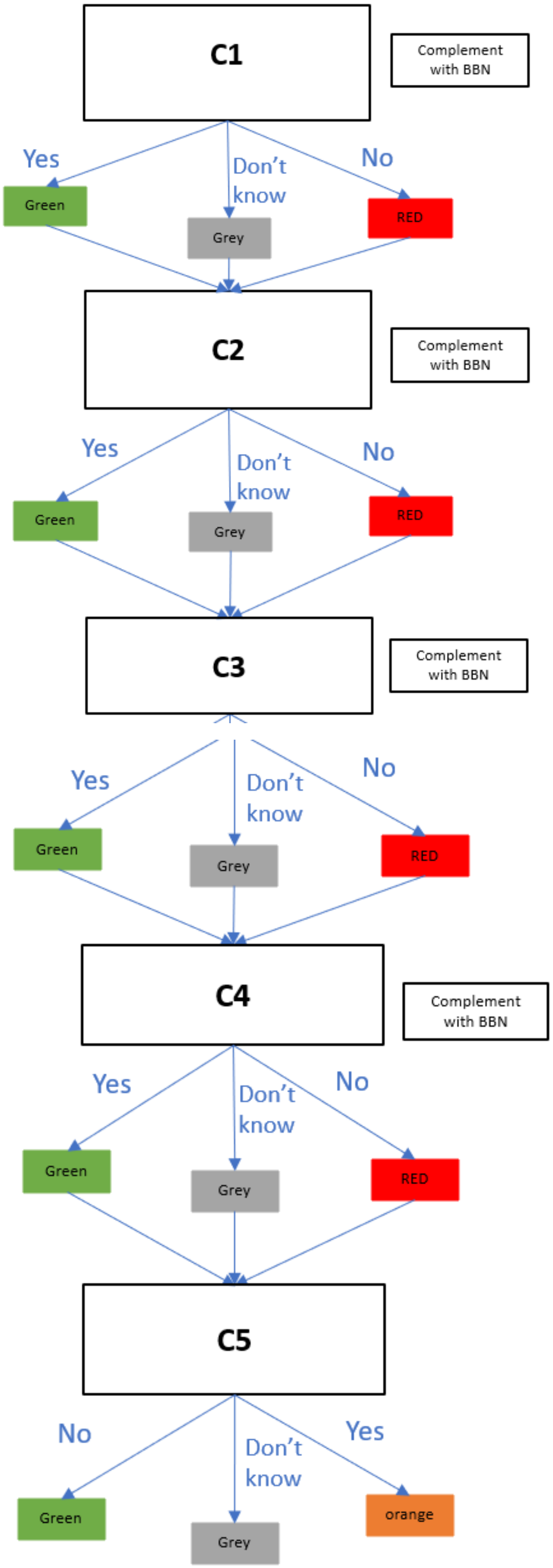
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No
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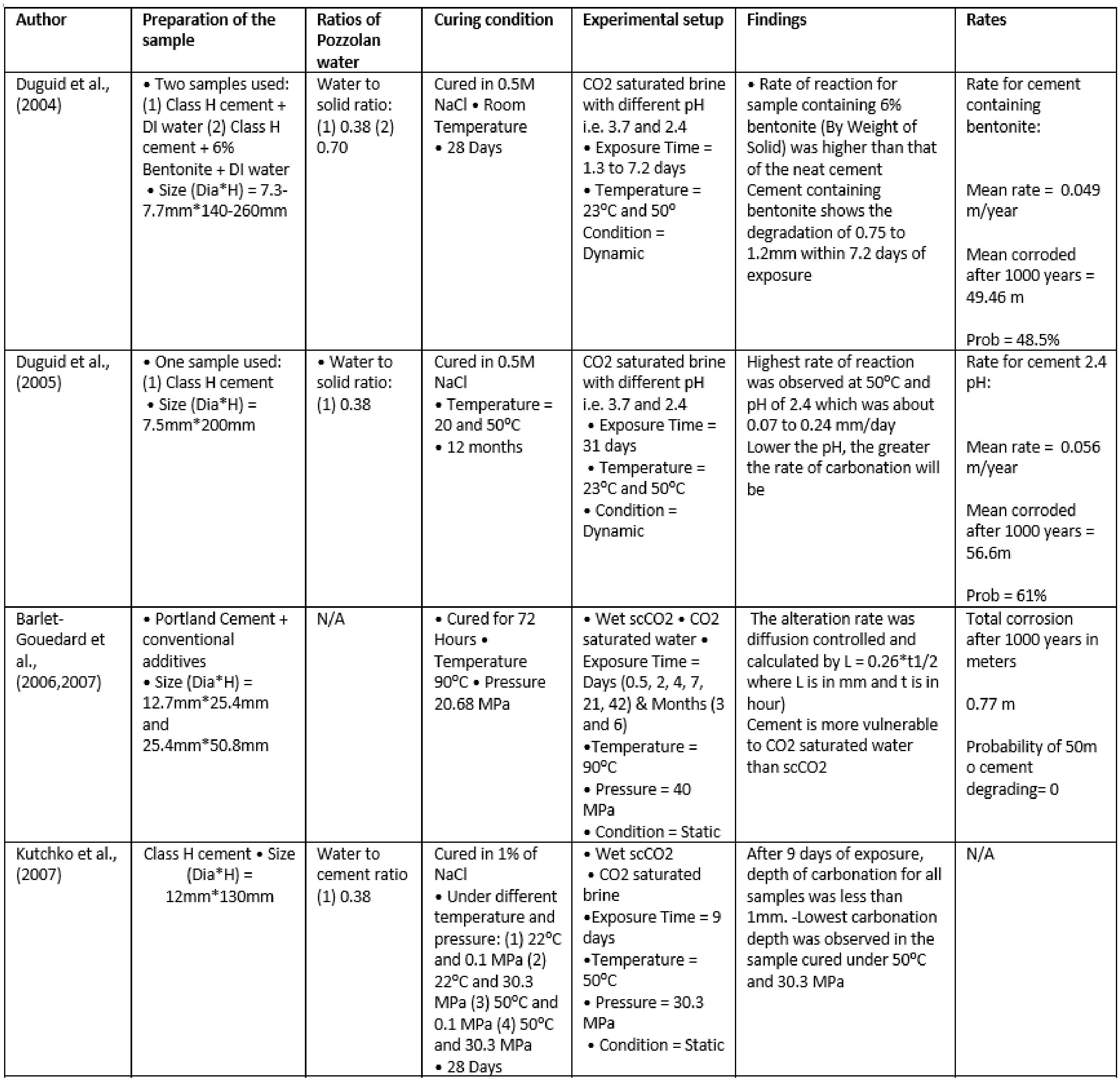
Grey
RED
C4
Complement with BBN
Yes
Don't know
No
Green
Grey
RED
C5
No
Don't know
Yes
Green
Grey
orange

C Appendix: Experimental data

Table 7 shows the experiments related to cement degradation. These were mostly compiled from Abid et al (2015). Table 8 shows the experiemntal data for the casing corrosion. These are mostly compiled from Wei et al (2015).

Table 7: Cement degradation experimental data

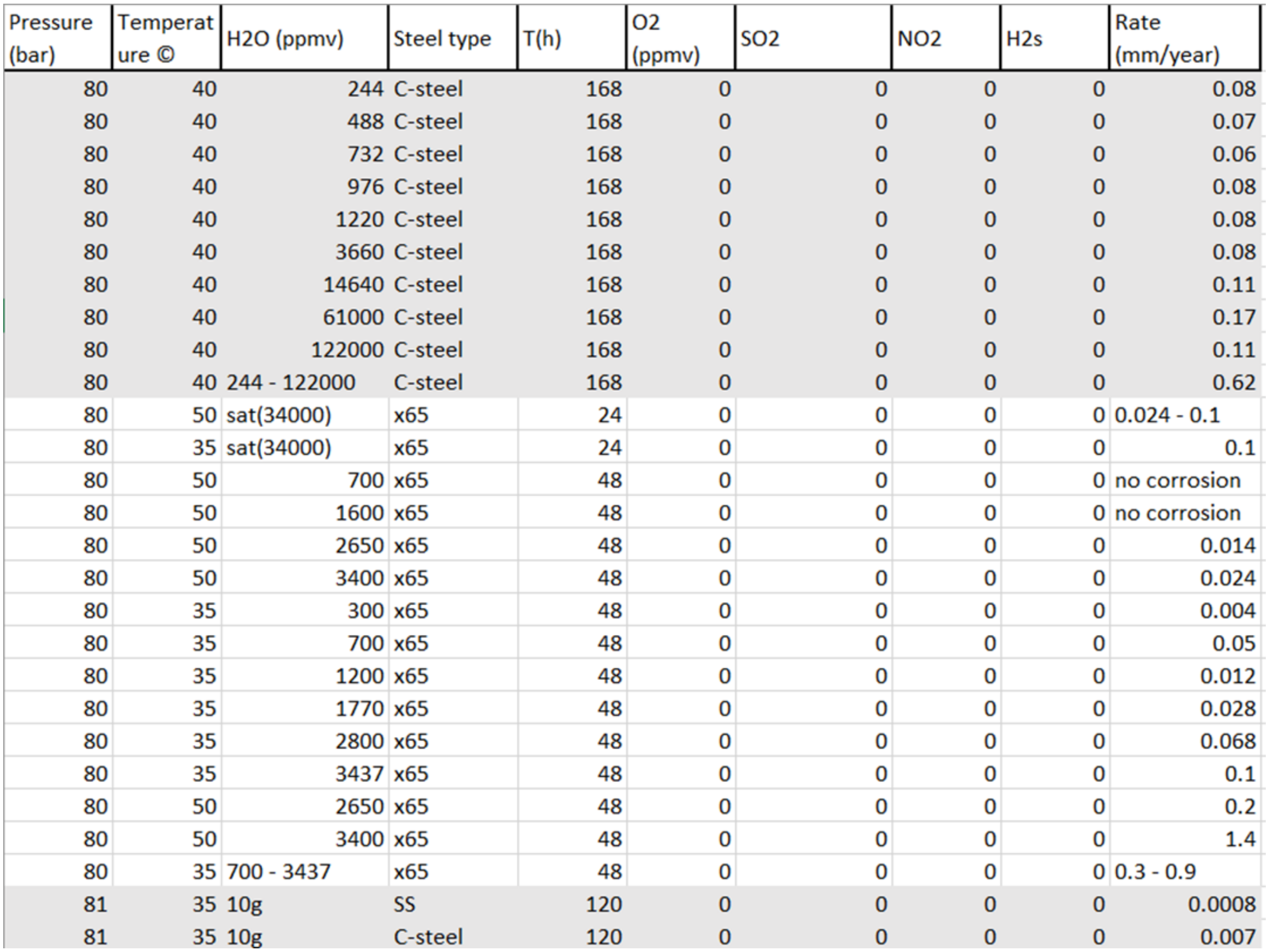


Author	Preparation of the sample	Ratios of Pozzolan water	Curing condition	Experimental setup	Findings	Rates
Duguid et al., (2004)	• Two samples used: (1) Class H cement + DI water (2) Class H cement + 6% Bentonite + DI water • Size (Dia*H) = 7.3-7.7mm*140-260mm	Water to solid ratio: (1) 0.38 (2) 0.70	Cured in 0.5M NaCl • Room Temperature • 28 Days	CO2 saturated brine with different pH i.e. 3.7 and 2.4 • Exposure Time = 1.3 to 7.2 days • Temperature = 23°C and 50° Condition = Dynamic	• Rate of reaction for sample containing 6% bentonite (By Weight of Solid) was higher than that of the neat cement Cement containing bentonite shows the degradation of 0.75 to 1.2mm within 7.2 days of exposure	Rate for cement containing bentonite: Mean rate = 0.049 m/year Mean corroded after 1000 years = 49.46 m Prob = 48.5%
Duguid et al., (2005)	• One sample used: (1) Class H cement • Size (Dia*H) = 7.5mm*200mm	• Water to solid ratio: (1) 0.38	Cured in 0.5M NaCl • Temperature = 20 and 50°C • 12 months	CO2 saturated brine with different pH i.e. 3.7 and 2.4 • Exposure Time = 31 days • Temperature = 23°C and 50°C • Condition = Dynamic	Highest rate of reaction was observed at 50°C and pH of 2.4 which was about 0.07 to 0.24 mm/day Lower the pH, the greater the rate of carbonation will be	Rate for cement 2.4 pH: Mean rate = 0.056 m/year Mean corroded after 1000 years = 56.6m Prob = 61%
Barlet-Gouedard et al., (2006,2007)	• Portland Cement + conventional additives • Size (Dia*H) = 12.7mm*25.4mm and 25.4mm*50.8mm	N/A	• Cured for 72 Hours • Temperature 90°C • Pressure 20.68 MPa	• Wet scCO2 • CO2 saturated water • Exposure Time = Days (0.5, 2, 4, 7, 21, 42) & Months (3 and 6) •Temperature = 90°C • Pressure = 40 MPa • Condition = Static	The alteration rate was diffusion controlled and calculated by L = 0.26*t1/2 where L is in mm and t is in hour) Cement is more vulnerable to CO2 saturated water than scCO2	Total corrosion after 1000 years in meters 0.77 m Probability of 50m o cement degrading= 0
Kutchko et al., (2007)	Class H cement • Size (Dia*H) = 12mm*130mm	Water to cement ratio (1) 0.38	Cured in 1% of NaCl • Under different temperature and pressure: (1) 22°C and 0.1 MPa (2) 22°C and 30.3 MPa (3) 50°C and 0.1 MPa (4) 50°C and 30.3 MPa • 28 Days	• Wet scCO2 • CO2 saturated brine •Exposure Time = 9 days •Temperature = 50°C • Pressure = 30.3 MPa • Condition = Static	After 9 days of exposure, depth of carbonation for all samples was less than 1mm. -Lowest carbonation depth was observed in the sample cured under 50°C and 30.3 MPa	N/A

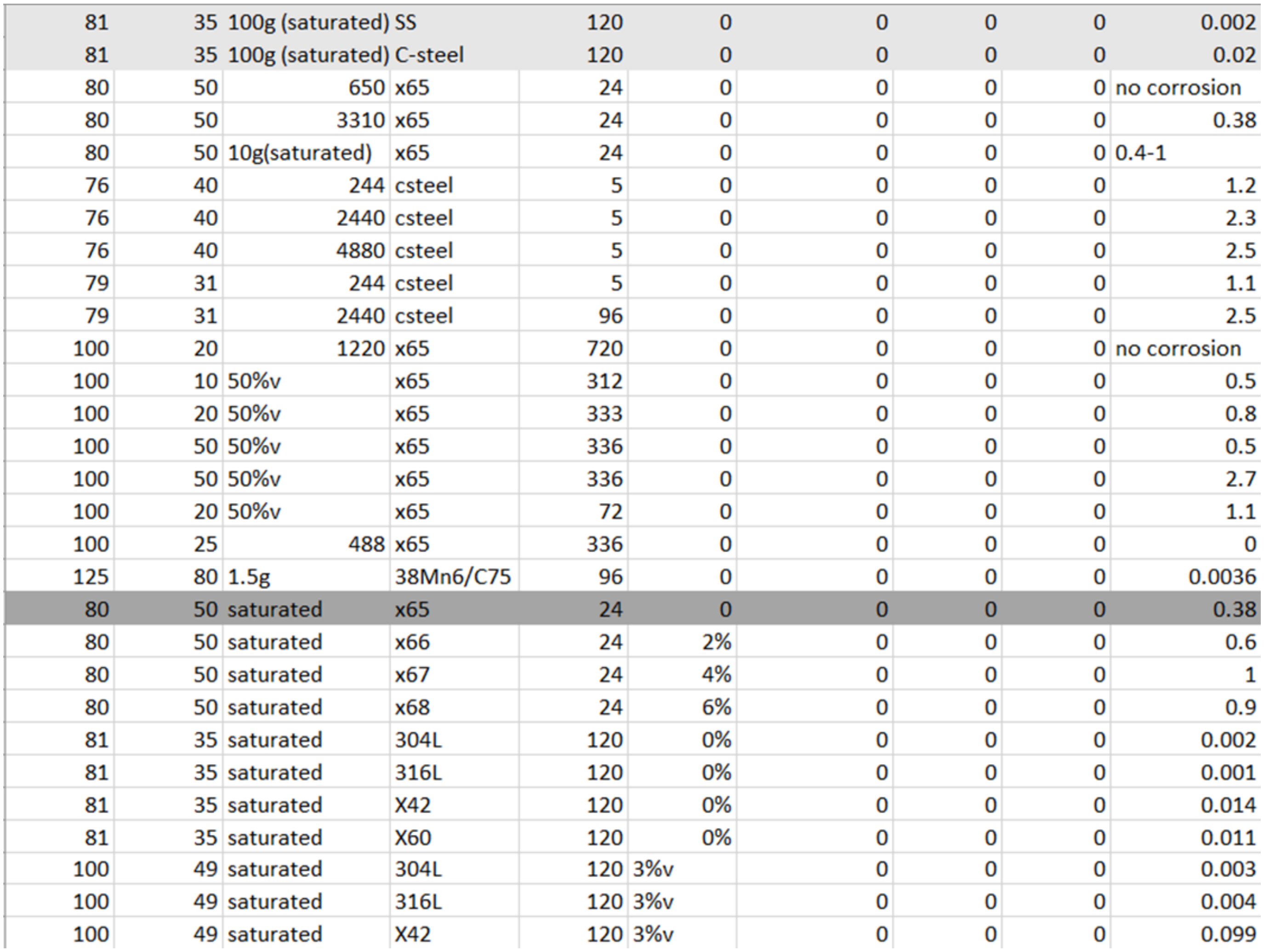
Kutchko et al., (2008)	• Class H cement • Size (Dia*H) = 12mm*130mm	• Water to cement ratio (1) 0.38	Cured in 1% of NaCl • Temperature = 50°C • Pressure = 30.3 MPa • 28 Days	• Wet scCO2 • CO2 saturated brine • Exposure Time = up to 12 months • Temperature = 50°C • Pressure = 30.3 MPa • Condition = Static	• For the samples presented in the scCO2, reaction was diffusion controlled and the depth of carbonation was given as L = 0.016*t1\2 (where L is in mm and t is in days). Carbonation propagation was complex for the sample exposed to CO2 saturated brine, and an empirical formula was developed to estimate the depth of carbonation i.e., L = 0.09ln (t) + 0.17	Total corrosion after 1000 years in meters Case 1: 0.096m Case 2: 0.013m Probability of 50m o cement degrading= 0 for both cases
Barlet-Gouedard et al., (2009)	• Portland Cement + conventional additive • Size (Dia*H) = 12.7mm*25.4mm and 25.4mm*50.8mm	N/A	Cured for 72 Hours • Temperature = 90°C • Pressure = 20.68 MPa	Wet scCO2 • CO2 saturated brine • Exposure Time = 2 days • Temperature = 90°C • Pressure = 20.68 MPa • Condition = Static	Propagation\alteration rate decreases in CO2 saturated brine compared to CO2 saturated in fresh water (i.e., 200μm a	Total degradation after 1000 years: 35m Probability of full cement plug corrosion: 7%
Pratt et al., (2009)	Portland cement • Size (Dia*H) = 7.5mm*200mm	N/A	Cured for 1 month at 100% RH and at room temperature	Wet scCO2 • Exposure Time = 84 days • Temperature = 50°C • Pressure = 10 MPa • Condition = Static	Carbonation depth of the sample was around 200μm and different zones of reactions were reported	Total degradation after 1000 years: 0.87 Probability of full cement plug corrosion: 0
Santra et al., (2009)	Cement with varying quantity of silica fumes and fly • Size (Dia*H) = 25.4mm*63.5mm	Varying quantity of silica fume and fly ash • For fly ash samples, w/s were (0.45 and 0.46) • For silica fume, w/s ratio varied from 0.45 to 0.58, depending upon the quantity of silica fume added	Cured in water • Pressure = 14 MPa • Temperature = 93°C • 15 Days	CO2 saturated water • Exposure time = 15 and 90 days • Temperature = 93°C • Pressure = 14 MPa • Condition = Static	Increasing the amount of silica fume (Ca/Si ratio of 0.47) did not improve the cement resistance. Neat sample had a penetration depth of 7mm, while that of others was up to 10mm. Partial carbonation of Pozzolanic cement did not lead to any loss of mechanical integrity	Low rate: Total degradation after 1000 years: 28.4m Probability of full cement plug corrosion: 1% High rate: Total degradation after 1000 years: 44.6 Probability of full cement plug corrosion: 27%

Duguid and Scherer, (2010)	Two samples used: (1) Class H cement + DI water (2) Class H cement + 6% Bentonite + DI water • Size (Dia*H) = 7.5mm*200mm	Water to solid ratio (1) 0.38 (2) 0.70	Cured in 0.5M NaCl • Temperature = 20 or 50°C • 12 months	CO2 saturated brine with different pH i.e. 3.7, 2.4 and 5 • Temperature = 50°C • Exposure Time: 26 Days • Condition: Dynamic	No carbonation was reported in the sample placed in the pH 5 solution	N/A
Garnier et al., (2010)	• Two samples used: (1) Neat class G cement (2) Class G + Silica Flour • Size(Dia*H) = 20mm*40mm	Silica flour added 40% BWOC	Cured at different condition: • First sample: Pressure = Atmospheric Temperature = 90°C 28 Days • Second Sample: For first 10 days: Pressure = 20.7 MPa Temperature = 140°C For rest 18 days: Pressure = Atmospheric Temperature = 90°C	For both samples: CO2 saturated water Pressure = 8 MPa Condition = static • First Sample: Exposure time = 7, 36, 65 and 90 days Temperature = 90°C • Second Sample: Exposure time = 4, 12, 21, 31, 55, 88 days Temperature = 140°C	Rate of alteration was 4mm after 65 days of exposure for sample No. 1 (Diffusion controlled event) Progress of carbonation front was 0.2 mm/day for the sample No.2 (reaction controlled event)	Total degradation after 1000 years: 91.3m Probability of full cement plug corrosion: 99.5%%
Duguid et al., (2011)	Two sample used: (1 and 2) Class H cement casted in hole of 25mm Dia of sandstone and limestone cylinder 55mm in height	Water to cement ratio (1 and 2) 0.38	Cured in 0.5M NaCl • Temperature = 20 or 50°C • 7 months	CO2 saturated brine with different pH i.e. from 3 to 7 • Temperature = 50°C • Exposure Time: 1, 2, 3, 6 and 12 months • Condition: Dynamic	Sample exposed to sandstone environment had a visual degradation of 0.577mm after 6 months No degradation was recorded for the sample placed in the limestone environment	Total degradation after 1000 years: 1m Probability of full cement plug corrosion: 1%
Zhang and Talman (2014)	Three samples used: (1) Neat Class G cement (2) Class G cement + Fly Ash + 2 %Bentonite (3) Class C cement + Fly Ash + 2% Bentonite + 1% Sodium Metasiliate (lightweight cement)	Poz mix ratio, cement to ash: (2) 59:41 (3) 59:41 •Water to solid ratio: (1) 0.44 (2) 0.554 (3) 1.130	• Cured in 0.5M NaCl • Temperature = 53°C • Pressure = 10 MPa • 25 Days	• CO2 saturated brine • Exposure Time = 3, 7, 14, 28 and 84 days • Temperature = 53°C • Pressure = 10 MPa • Condition = Static	Pozzolanic mix sample was fully carbonated after 28 days but durability of the cement was remained unchanged Lightweight cement totally lost its durability and fully carbonated within 7 days while its permeability increased from 0.16 to 1.1mD after 84 days of carbonation	N/A
Sauki and Irawan (2010)	Class G oilwell cement were mixed (35 seconds on Waring Blender at high speed) with fresh water at a water-to-cement ratio of 0.44 by using Model 7000 Constant Speed Mixer according to API Recommended Practice 10B-2	N/A	Cured at constant pressure (140 bar) and constant temperature(40C) After 8 hours curing period, the samples were demolded and washed to remove the grease from their surface	Cement Autoclave was used to expose cement core samples (1.5in-D x 2in-L) after curing with supercritical CO2 under two situations: wet supercritical CO2 and CO2-saturated brine. The CO2 experiments were performed under static condition. This condition was considered as a realistic simulation of the CO2-exposure conditions at the formation/ cement sheath interface.	A slight increase in depth of penetration was clearly observed at the rim of sample by using BSE-SEM image as early as 24hours of CO2 attack as shown in APPENDIX [III]. Sample exposed at 1200 C showed greater depth of penetration after 120-hours of attack up to 0.78 mm whereas sample exposed at 400 C had smaller depth of penetration that was up to 0.55mm deep after 120hours of CO2 attack.	Low rate: Total degradation after 1000 years: 40.15m Probability of full cement plug corrosion: 19.8% High rate: Total degradation after 1000 years: 66.43 Probability of full cement plug corrosion: 72%

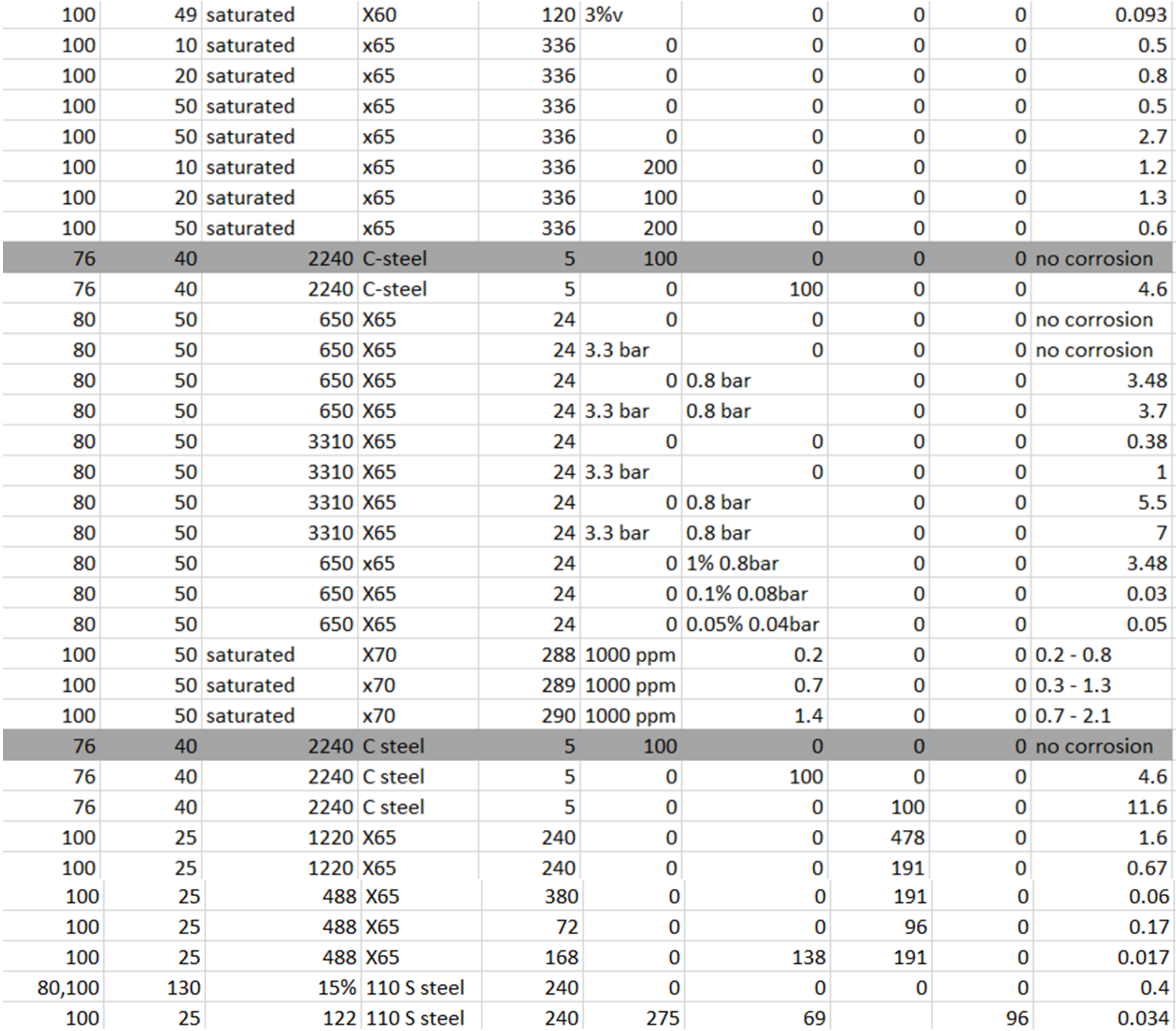
Table 8: Casing corrosion data



Pressure (bar)	Temperature ©	H2O (ppmv)	Steel type	T(h)	O2 (ppmv)	SO2	NO2	H2s	Rate (mm/year)
80	40	244	C-steel	168	0	0	0	0	0.08
80	40	488	C-steel	168	0	0	0	0	0.07
80	40	732	C-steel	168	0	0	0	0	0.06
80	40	976	C-steel	168	0	0	0	0	0.08
80	40	1220	C-steel	168	0	0	0	0	0.08
80	40	3660	C-steel	168	0	0	0	0	0.08
80	40	14640	C-steel	168	0	0	0	0	0.11
80	40	61000	C-steel	168	0	0	0	0	0.17
80	40	122000	C-steel	168	0	0	0	0	0.11
80	40	244 - 122000	C-steel	168	0	0	0	0	0.62
80	50	sat(34000)	x65	24	0	0	0	0	0.024 - 0.1
80	35	sat(34000)	x65	24	0	0	0	0	0.1
80	50	700	x65	48	0	0	0	0	no corrosion
80	50	1600	x65	48	0	0	0	0	no corrosion
80	50	2650	x65	48	0	0	0	0	0.014
80	50	3400	x65	48	0	0	0	0	0.024
80	35	300	x65	48	0	0	0	0	0.004
80	35	700	x65	48	0	0	0	0	0.05
80	35	1200	x65	48	0	0	0	0	0.012
80	35	1770	x65	48	0	0	0	0	0.028
80	35	2800	x65	48	0	0	0	0	0.068
80	35	3437	x65	48	0	0	0	0	0.1
80	50	2650	x65	48	0	0	0	0	0.2
80	50	3400	x65	48	0	0	0	0	1.4
80	35	700 - 3437	x65	48	0	0	0	0	0.3 - 0.9
81	35	10g	SS	120	0	0	0	0	0.0008
81	35	10g	C-steel	120	0	0	0	0	0.007



81	35	100g (saturated)	SS	120	0	0	0	0	0.002
81	35	100g (saturated)	C-steel	120	0	0	0	0	0.02
80	50	650	x65	24	0	0	0	0	no corrosion
80	50	3310	x65	24	0	0	0	0	0.38
80	50	10g(saturated)	x65	24	0	0	0	0	0.4-1
76	40	244	csteel	5	0	0	0	0	1.2
76	40	2440	csteel	5	0	0	0	0	2.3
76	40	4880	csteel	5	0	0	0	0	2.5
79	31	244	csteel	5	0	0	0	0	1.1
79	31	2440	csteel	96	0	0	0	0	2.5
100	20	1220	x65	720	0	0	0	0	no corrosion
100	10	50%v	x65	312	0	0	0	0	0.5
100	20	50%v	x65	333	0	0	0	0	0.8
100	50	50%v	x65	336	0	0	0	0	0.5
100	50	50%v	x65	336	0	0	0	0	2.7
100	20	50%v	x65	72	0	0	0	0	1.1
100	25	488	x65	336	0	0	0	0	0
125	80	1.5g	38Mn6/C75	96	0	0	0	0	0.0036
80	50	saturated	x65	24	0	0	0	0	0.38
80	50	saturated	x66	24	2%	0	0	0	0.6
80	50	saturated	x67	24	4%	0	0	0	1
80	50	saturated	x68	24	6%	0	0	0	0.9
81	35	saturated	304L	120	0%	0	0	0	0.002
81	35	saturated	316L	120	0%	0	0	0	0.001
81	35	saturated	X42	120	0%	0	0	0	0.014
81	35	saturated	X60	120	0%	0	0	0	0.011
100	49	saturated	304L	120	3%v	0	0	0	0.003
100	49	saturated	316L	120	3%v	0	0	0	0.004
100	49	saturated	X42	120	3%v	0	0	0	0.099



100	49	saturated	X60	120	3%v	0	0	0	0.093
100	10	saturated	x65	336	0	0	0	0	0.5
100	20	saturated	x65	336	0	0	0	0	0.8
100	50	saturated	x65	336	0	0	0	0	0.5
100	50	saturated	x65	336	0	0	0	0	2.7
100	10	saturated	x65	336	200	0	0	0	1.2
100	20	saturated	x65	336	100	0	0	0	1.3
100	50	saturated	x65	336	200	0	0	0	0.6
76	40	2240	C-steel	5	100	0	0	0	no corrosion
76	40	2240	C-steel	5	0	100	0	0	4.6
80	50	650	X65	24	0	0	0	0	no corrosion
80	50	650	X65	24	3.3 bar	0	0	0	no corrosion
80	50	650	X65	24	0	0.8 bar	0	0	3.48
80	50	650	X65	24	3.3 bar	0.8 bar	0	0	3.7
80	50	3310	X65	24	0	0	0	0	0.38
80	50	3310	X65	24	3.3 bar	0	0	0	1
80	50	3310	X65	24	0	0.8 bar	0	0	5.5
80	50	3310	X65	24	3.3 bar	0.8 bar	0	0	7
80	50	650	x65	24	0	1% 0.8bar	0	0	3.48
80	50	650	X65	24	0	0.1% 0.08bar	0	0	0.03
80	50	650	X65	24	0	0.05% 0.04bar	0	0	0.05
100	50	saturated	X70	288	1000 ppm	0.2	0	0	0.2 - 0.8
100	50	saturated	x70	289	1000 ppm	0.7	0	0	0.3 - 1.3
100	50	saturated	x70	290	1000 ppm	1.4	0	0	0.7 - 2.1
76	40	2240	C steel	5	100	0	0	0	no corrosion
76	40	2240	C steel	5	0	100	0	0	4.6
76	40	2240	C steel	5	0	0	100	0	11.6
100	25	1220	X65	240	0	0	478	0	1.6
100	25	1220	X65	240	0	0	191	0	0.67
100	25	488	X65	380	0	0	191	0	0.06
100	25	488	X65	72	0	0	96	0	0.17
100	25	488	X65	168	0	138	191	0	0.017
80,100	130	15%	110 S steel	240	0	0	0	0	0.4
100	25	122	110 S steel	240	275	69		96	0.034

D Appendix: Geo-mechanical model

In order to populate the BBN, data was obtained by performing geomechanical simulations based on the finite element analysis software DIANA FEA. The model consist of a 2D mesh that represents the wellbore system with the casing, cement and formation as distinct materials. The model is modelled as a 2D radial geometry system as shown in figure 44, where the formation is represented in orange, cement in gray and casing in blue.

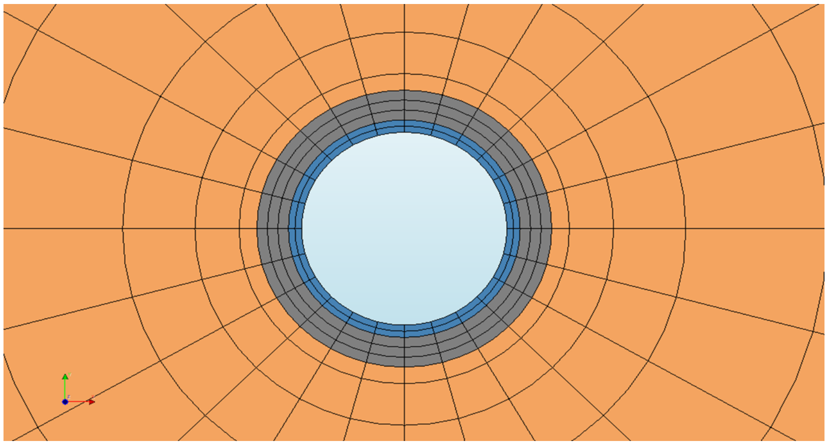


Figure 44: Main mesh of geomechanical model, where the orange grid blocks represent the formation, the grey represent the annular cement and the blue represent the casing.

Table 9 showcases some of the technical details of the mesh defined in the model

Table 9: Data about mesh of model

Total formation diameter	15.55m
Formation total elements	216
Annular cement diameter	0.311m
Annular cement thickness	0.0333m
Annular cement total blocks	72
Casing diameter	0.2444m
Casing thickness	0.01385m
Casing total blocks	48
Cement-formation interface element	Boundary element (24)
Cement-casing interface element	Boundary element (24)

The objective is to define the material properties of the different elements as well as the reservoir conditions. The different parameters involved will be defined as fixed deterministic parameters, varied deterministic parameters and stochastic parameters. The stochastic parameters will be the ones that are included in the BBNs and are the ones that will change for different simulations. The values for these parameters will be inputted and changed for every simulation required to populate the BBN.

D.1 Assumptions

In order to develop this model some assumptions are necessary:

- Initially the cement is intact and perfectly bonded.
- Cements are not expanding.
- Small/negligible pore pressure changes in rock formation (compressive rock failure of the formation is not expected to take place).

- Creep or other time dependant material properties are not considered (except cement shrinkage due to hydration).
- Heat flux only by convection.
- The time step is iterative, based on adaptive time increments, which are defined by the software.

D.2 Material and interface properties

The different materials included are modelled by different elastic criteria, which are:

Formation – Mohr-Coulomb failure criteria

The Mohr-Coulomb model assumes that the rock will behave as linear elastic material until the deviatoric stress reaches a critical value. In case of the Mohr-Coulomb model the critical deviatoric stress is defined as the difference between minimum and maximum principal stress. Material parameters for the Mohr-Coulomb model are the Young's modulus and Poisson ratio, as well as the cohesion and friction angle.

Casing – Von mises elasto-plastic material model

Standard von Mises elasto-plastic material model can be assumed. Von Mises criteria states that irreversible deformations will occur when a critical deviatoric stress is reached

Cement - Mohr-Coulomb elasto-plastic model with multi-directional fixed crack model.

The material model is a combination of the multi-directional fixed crack model and the Mohr-Coulomb elasto-plastic model where shrinkage can be defined as a function of time for the concrete.

Interfaces

Described as zero volume elements composed of nodes with displacement degrees of freedom. Relative displacement can be related to stresses in the interface-elements. A discrete crack model, where the interface will crack when the normal-stress in the interface reaches the defined tensile strength

D.3 Boundary conditions

A very important step in the development of the model is the definition of the boundary conditions. These will change for each different step of the development phases, but they will start as three fixed temperature boundaries at:

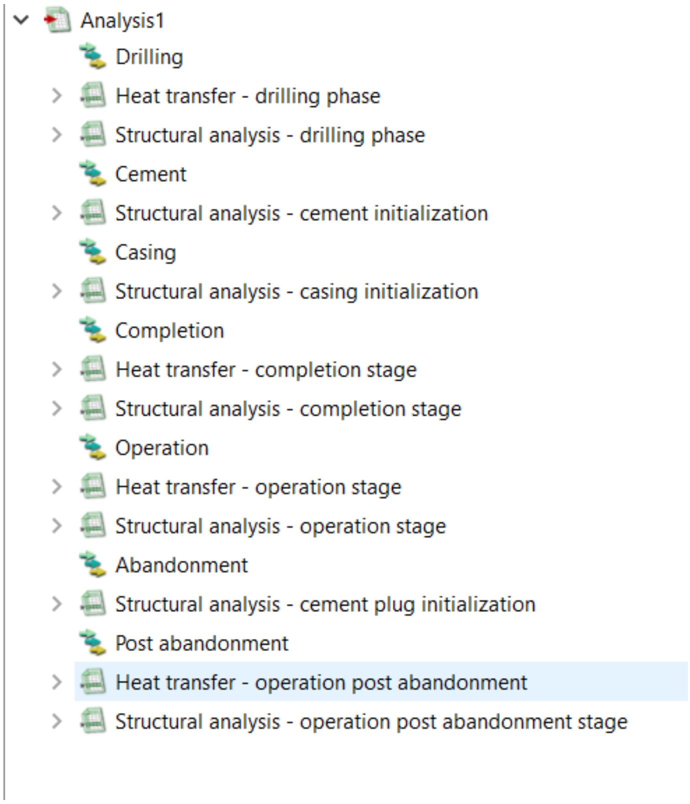
- Formation edge: formation temperature
- Borehole wall (interface cement-formation): initially as drilling fluid temperature at wall
- Inner casing: Operational temperature

For the post-abandonment phase, which is the phase of interest for the analysis, the boundary conditions will be:

- Formation edge: formation temperature.
- Borehole wall: mixed boundary condition (prescribed fixed flux, considering end temperature of last step.
- Inner casing: mixed boundary condition (prescribed fixed flux, considering end temperature of last step, convection at the boundary).

D.4 Development stages

Lastly, it is important to define the different phases of the analysis. The phases represent the different stages of the history of the well from the drilling, the operations and the abandonment and post abandonment. This represents the whole loading history of the elements present in the model. Figure 45 shows the development stages of this particular model. The different stages will define the initiation of the different elements present, as well as adapting the boundary conditions and changes in the evaluation models.



Analysis1

Drilling

Heat transfer - drilling phase

Structural analysis - drilling phase

Cement

Structural analysis - cement initialization

Casing

Structural analysis - casing initialization

Completion

Heat transfer - completion stage

Structural analysis - completion stage

Operation

Heat transfer - operation stage

Structural analysis - operation stage

Abandonment

Structural analysis - cement plug initialization

Post abandonment

Heat transfer - operation post abandonment

Structural analysis - operation post abandonment stage

Figure 45: Development stages of geomechanical model

D.5 Model inputs

After defining the model, it is necessary to define the material properties of the casing, cement and formation. As explained above, the values chosen will be varied for different simulations, obtaining the distribution of the results that will be used to populate the BBNs. The ranges of the properties for the materials are reservoir were chosen based on extensive literature review on different materials properties from relevant articles, manuals, standards and specifications from engineering and cementing companies (API Specification 5CT, 2006; Arularasi et al., 2021; Bu et al., 2017; Dellinger Poursaee, 2016; Ichim et al., 2018; Liu et al., 2013; Mohd Zulkarnain, 2015; MatWeb, 2022). Table 10 shows the values chosen for the two states of the variable parameters.

Table 10: Variable parameter values introduced in model

	min	Std min	max	Std max
Young modulus (e9 Pa)	8.6	0.324	24.3	3.43
Poisson ratio	0.194	0.00114	0.26	0.0234
Tensile strength (Mpa)	0.91	0.24	2.04	0.47
Cohesion (Kg/cm2)	1.82 (w/b = 0.9)	0.48	8.2 (w/b = 0.3)	0.84
Thermal ex. Coeff (e-6 C-1)	1.54	0.67	6.49	1.8
shrinkage	0.0001	30%	0.0003	30%
Stiffness (related to young modulus)	E =8.6	0.324	E = 24.3	3.43
Pressure change	180	30	310	50
pressure	220	30	450	50
Temperature change	10	2	25	5

D.6 Validation

It is important to note that this model has been validated by laboratory experiments. The methodsfor validation are described by Moghadam et al (2020).