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CO2WELLS

Guideline for the risk management of existing wells at CO_2 geological storage sites

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Summary:

This document is a DNV guideline that describes a risk management framework for existing wells at CO_2 storage sites, both onshore and offshore. It supplements the DNV CO2QUALSTORE guideline [1] that was published in 2010 and is the final deliverable from the CO2WELLS Joint Industry Project (April 2010 to June 2011).

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TABLE OF CONTENTS

PREFACE

This guideline:

- describes a risk management framework for existing wells at potential CO_2 storage sites, both onshore and offshore;
- supplements the CO2QUALSTORE guideline [1] that was published in 2010;
- is the final deliverable from the CO2WELLS Joint Industry Project (April 2010 to June 2011);
- does not represent a standardized guidance for the design, operation and monitoring of new wells, although the qualification methodology described in Chapters 2 and 3 may be relevant to these activities;
- is intended to support the development of CO_2 geological storage projects up to the point of final investment decision, as shown in Figure 1;
- has a scope that includes, i) risk assessment of active and abandoned wells prior to storage site selection, and ii) qualification of existing wells for abandonment, conversion or continued use at the storage site selected.
- is consistent with current and emerging regulations for CO_2 geological storage and other supporting guidelines [2-28]

The value of this guideline for operators, regulators and third parties is shown in Table 1.

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Table 1: Value of this guideline for different users.

	Operator	Regulator	Third party
Guide implementation	X		
Support risk-based decision making	X		
Communicate industry practice	X	X	X
Support implementation of regulations	X	X	
Reference for verification	X	X	X
Support stakeholder communication	X	X	X

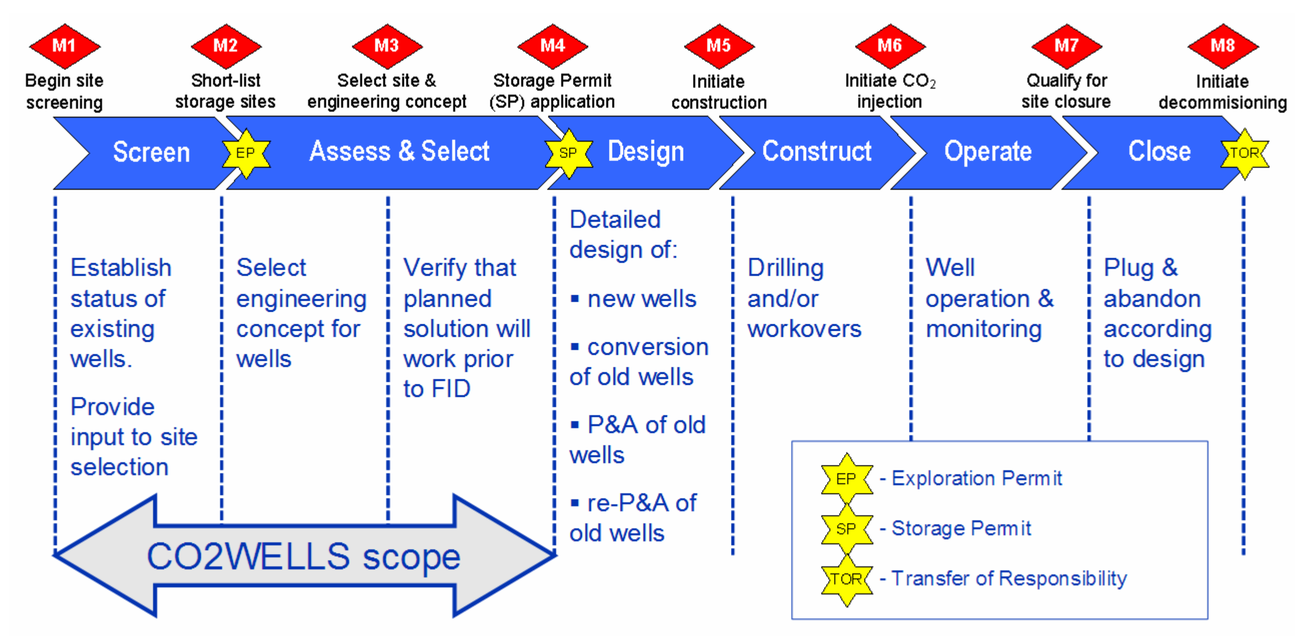

Figure 1: The scope of this guideline with respect to expected well engineering activities at each stage of a CO_2 storage project. Project stages (blue), milestones (red) and permits (yellow) are from the CO2QUALSTORE guideline [1].

1. INTRODUCTION

Carbon capture and storage (CCS) has been highlighted as one of the key technologies that can facilitate a transition to a more carbon neutral world. However, for carbon capture and storage to play a significant role in combating climate change, a significant number of commercial scale projects must be initiated around the world within the coming decades. To boost the deployment of CCS in a safe and sustainable way, there is a need for unified, recognized and publicly available guidelines that contribute to:

- proper selection and qualification of storage sites according to recognized procedures;
- efficient and harmonized implementation of legal and regulatory frameworks for carbon capture and storage;
- predictable technical, financial and regulatory operating conditions for operators, regulators and other stakeholders;
- a swift transition from research and demonstration scale projects to large scale carbon capture and storage by acceptance for a learning-by-doing approach where data is gathered during operation to validate storage performance and uncertainties are controlled through a risk-based verification and qualification process;
- use of current best engineering practice, best available technology and proper management of risk and uncertainties throughout the life of a carbon capture and storage project.

To support widespread implementation of carbon capture and storage, authorities and the public demand a robust, traceable and transparent approach to storage site selection that gives credibility to the proper management of risks. The development of acknowledged procedures for selection and management of storage sites for CO_2 geological storage should meet these demands and thus facilitate large scale deployment of carbon capture and storage.

The CO2QUALSTORE guideline [1] serves as a reference for how to qualify, manage and approve CO_2 geological storage sites and projects. This supplementary guideline provides further detail and consideration to well integrity at CO_2 geological storage sites. In the future, both guidelines will be combined and maintained as a single DNV Recommended Practice.

This CO2WELLS guideline is based on principles outlined in:

1) ISO31000 standard for risk management [2];
2) DNV Recommended Practice for Technology Qualification [21].

Technology qualification is defined as the process of providing the evidence that the technology in question will function within specific limits with an acceptable level of confidence. It may be applied to new technology in a new or familiar setting, or familiar technology applied in a new setting.

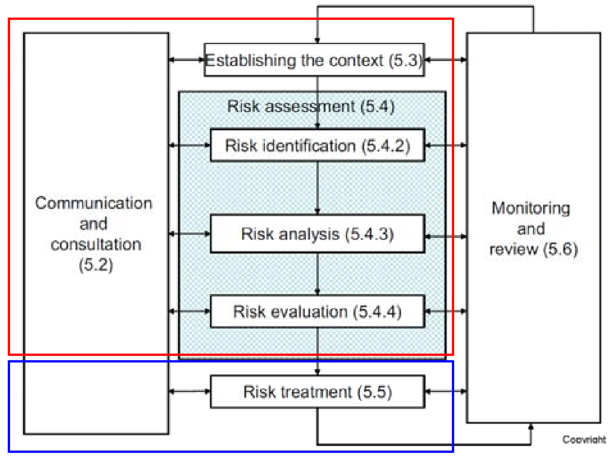

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Figure 2: Guideline scope with respect to the ISO31000 standard for risk management [2]. Red box: Chapter 2. Blue box: Chapters 3 and 4.

1.1. Qualification of wells

Existing wells at potential CO_2 storage locations are regarded as familiar technology exposed to a new environment and the qualification of such wells is referred to as Well Qualification in this document.

Chapter 2 describes a risk assessment process to establish the current status of existing wells at CO_2 geological storage sites and Chapters 3 and 4 describe a well qualification process that is designed to manage (treat) the assessed risks. The relationship between these chapters is illustrated in Figure 2 with respect to the ISO31000 standard for risk management [2]. The scope of Chapter 2 is highlighted in red and the scope of Chapters 3 and 4 is highlighted in blue. This distinction is repeated in Figure 3.

Well qualification should be performed by a team with expertise within the areas outline in Table 2. The qualifications of the respective personnel should be assessed by the facilitator of the qualification process.

This guideline covers the qualification of existing wells in a proposed storage site to verify that the planned solution is feasible as part of the FID and storage permit application process (Milestone M4 in the CO2QUALSTORE guideline [1]). This CO2WELLS guideline may also be used as a basis for new well qualification.

Table 2: Areas of expertise that a well qualification team should possess.

Discipline	Expertise/knowledge required
Well engineering	- procedures for drilling, construction and permanent abandonment of wells
Materials/ corrosion	- characteristics of materials in well construction and their susceptibility to corrosion
Cements	- chemical and physical properties of different cement types - interpretation of cement evaluation logs
Geochemistry	- geochemical interactions between injected or resident fluids, well materials, cements, rocks and fluids in the near wellbore environment
Geomechanics	- potential geomechanical impacts on well cements and the near wellbore environment that may stem from CO_2 storage operations
Well integrity	- well integrity management and CO_2 specific well integrity issues
Storage site characterization	- storage site characteristics - potential effects on the near-well environment if the site is or will be used for CO_2 geological storage (i.e., predicted changes in pressure, temperature and exposure to CO_2 or fluids charged with CO_2 or other constituents in the CO_2 stream).
HSE	- HSE management and requirements in applicable regulations

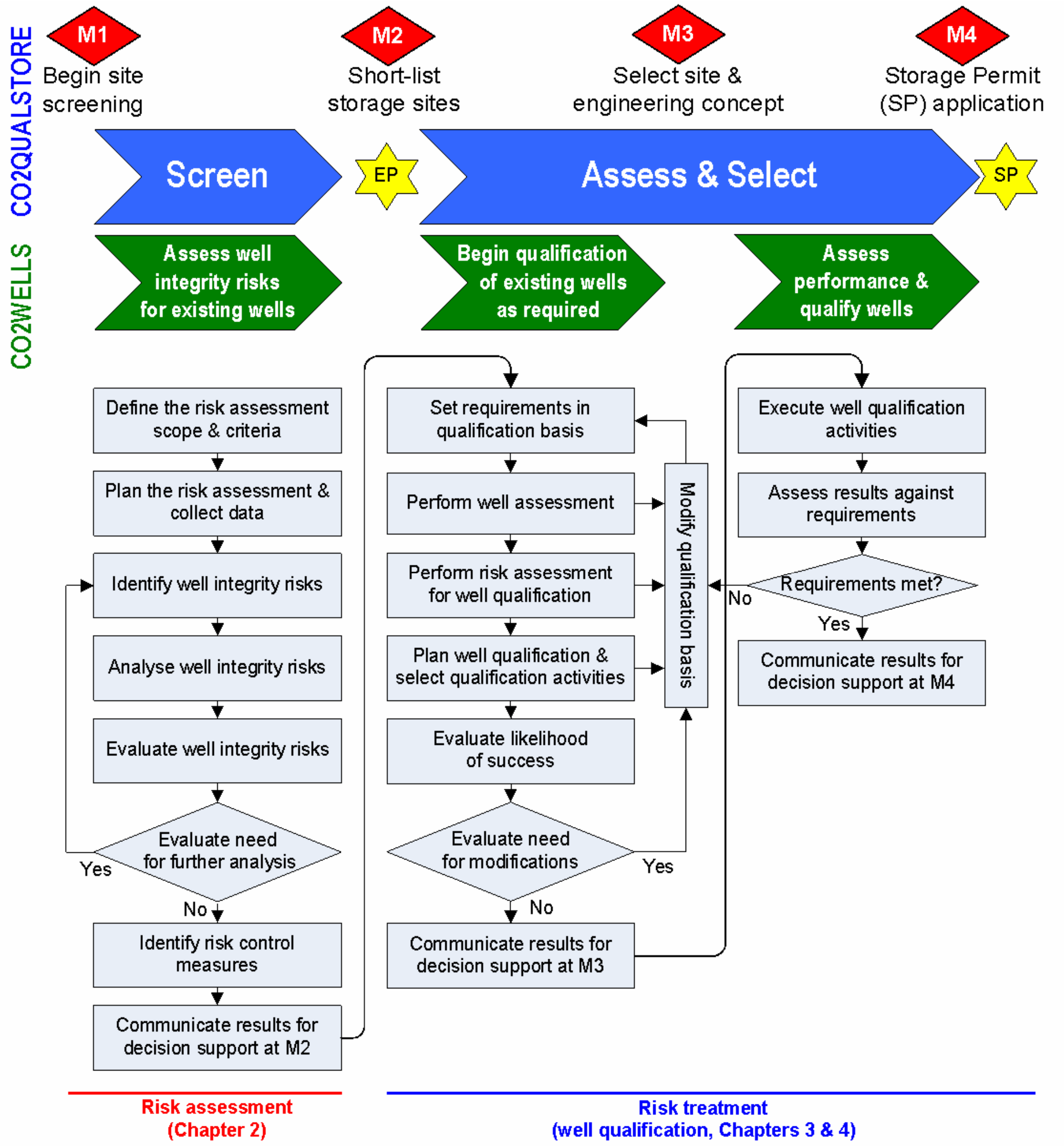

Figure 3: Flow diagram showing the structure of the CO2WELLS guidance. i) Red and blue areas refer to the ISO31000 framework in Figure 2. ii) Well qualification activities prior to M3 are designed to provide the basis for the engineering concept selection. iii) Well qualification activities prior to M4 are designed to provide the basis for the Storage Permit application. iv) Detailed design and well deployment are assumed to take place after M4 and are not included in this guideline.

2. ASSESS WELL INTEGRITY RISKS FOR EXISTING WELLS

The workflow steps in this chapter are illustrated in Figure 3. They are designed to facilitate the short-listing of candidate storage sites at milestone M2 in Figure 3.

Note: well integrity risks include both:
1. existing inherent risks without CO_2 storage;
2. additional risks caused by CO_2 storage;

where 2) is a function of the likelihood of:
a) a well being exposed to the effects of CO_2 storage (reservoir dynamics);
b) well integrity failure in the event of such exposure.

The likelihood of a) will be a function of the CO_2 storage volume that is defined for a given storage site and used to estimate capacity in the screen stage of [1] and is not discussed further in this guideline. The likelihood of b) is discussed here in detail with respect to the direct effects on the near-well environment if the site is or will be used for CO_2 geological storage. This includes:

a. predicted effects of changes in pressure;

b. predicted effects of temperature changes;

c. predicted effects of exposure to CO_2 or fluids charged with CO_2 or other constituents in the CO_2 stream.

Where the term *CO_2* is used in the guideline, it assumes that carbon dioxide is pressurized; may or may not contain water; exists either as a liquid, super critical fluid or a gas; and also includes carbon dioxide dissolved in water contained in the reservoir.

Predicted effects of changes in pressure may extend beyond the area of legal control of a project developer in which case a mitigation plan may have to be put in place.

A number of co-components may typically be associated with industrial CO_2 streams, such as those listed below. The well qualification issues related to these are not specifically addressed in this guideline, but may be handled by the same qualification methodology:
- Cracking and fouling associated with H_2S either present in the injection stream or released in the geological formation by CO_2.
- Nitrogen and Argon; these are non-condensable and will alter the vaporization and condensation properties of the CO_2 stream.
- Oxygen; this may increase corrosion rates.
- Hydrogen; this may limit materials of construction.
- Trace components, such as seal oil from compressors.

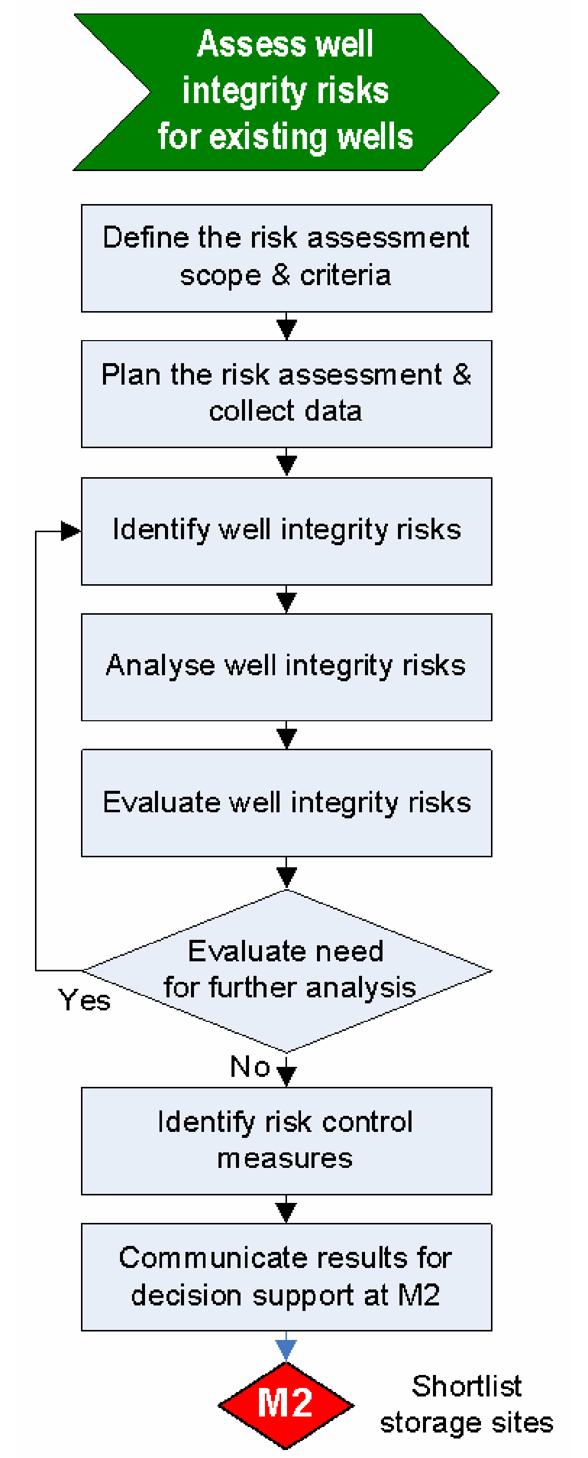

Figure 4: Guideline steps in Chapter 2. Modified from Figure 3.

2.1. Define the risk assessment scope & risk criteria

2.1.1. Objective

The purpose of this step is to develop the context for the risk assessment and to define risk criteria that will be used for evaluation of well integrity risks. The deliverables from this step are:
- risk assessment scope;

- list of risk criteria.

2.1.2. Define risk assessment scope

The context and scope of this specialist risk assessment should be defined by the more general risk assessment step in Section 2.5 of [1]. The latter should assess risks to the capacity, injectivity and containment of candidate storage sites, where well integrity represents one type of risk to storage containment.

This step should involve:
- defining the goals and objectives of the well integrity risk assessment;
- defining responsibilities for and within the risk assessment process;
- defining the specific inclusions and exclusions;
- defining the risk assessment in terms of time and location;
- defining the relationship between the risk assessment process and the overall development of the CO_2 geological storage project;
- defining the risk assessment methodologies;
- identifying and specifying the decisions that have to be made prior to milestone M2;

2.1.3. Defining risk criteria

Risk criteria for evaluating the significance of well integrity risks need to be defined by the project developer. The risk criteria should reflect the objectives and context for the risk assessment. Adequate consideration should be given to the time and resources available, stakeholder views and risk perceptions, and the applicable legal and regulatory requirements. The risk criteria chosen should be continuously reviewed.

Prior to specifying risk criteria, the categories for which risks will be evaluated shall be defined. These include:
- human health and safety;
- environmental protection;
- legal and regulatory compliance;
- cost;
- project schedule;
- reputation;
- well integrity (functional) performance.

The following points should be considered when defining risk criteria for well integrity assessments:
- the categories of risk for the CO_2 geological storage project established in the ‘screening basis’ step of [1];
- the nature and type of causes and consequences that can occur and how they will be measured;
- how likelihood will be defined (for example qualitatively or as a quantitative probability);
- the timeframe of interest;
- how the level of risk is to be determined;
- the level at which the risk becomes acceptable or tolerable;
- whether combinations of multiple risks should be taken into account and, if so, how and which combinations should be considered (for example leakage pathways composed of multiple failures).

In order for the risk criteria to be adequate to support a storage site selection decision they should:
- be suitable for decisions regarding risk reducing measures to levels as low as reasonably practicable;
- be suitable for communication;
- be unambiguous in their formulation;
- not favour any particular concept solution explicitly nor implicitly through the way in which risk is expressed.

In addition, risk criteria for CO_2 leakage rates related to existing wells should be consistent with the overall storage site containment criteria established in Section 2.1 (‘Screening basis’) of [1].

Note: Temporal, spatial, volumetric and rate limits for CO_2 leakage should be finite and quantifiable to allow for effective risk management.

2.2. Plan the risk assessment & collect data

2.2.1. Objective

The objectives of this step are to plan the schedule, budget and deliverables for the risk assessment and begin data collection. The deliverables from this step are:
- well integrity risk assessment plan;
- well data and condition assessment.

2.2.2. Plan the risk assessment

The project developer should exhibit a clear understanding of how the criteria defined in the previous step will be used to differentiate and rank the potential storage sites at milestone M2.

The assessment plan should include a plan for data collection and take into account the availability of data, the number of wells, the regulatory environment, the age of the wells in the area and possibly the potential presence of unidentified wells that penetrate the storage volume.

2.2.3. Data collection and well condition assessment

The data collection is to establish an accurate picture of each individual well’s current mechanical condition and integrity within the geological formations.

Each well to be assessed should be described in as much detail as possible by drawings, text, data or other relevant documents. This should include production and intervention history and directional coordinates within the storage site. Missing information, ambiguous data and other uncertainties should be highlighted.

Examples of the type of data that should be collected are shown in Table 3 together with examples of the information that may be derived from each.

Table 3: Examples of relevant data and information that may be derived from each.

Data type	Information derived
Well schematics	- as built construction
Drilling reports including drilling fluid reports	- well construction - quality of execution - problem areas - wear points
Open hole log information including calliper logs	- geological formation and hole condition prior to setting casing
Cement evaluation logs	- cement position - cement quality
Cement placement information including centralizer program	- cement position - cement quality
Cement design and related laboratory reports	- mechanical and chemical properties of cement
Well completion logs	- tubular connection and jewellery depths - condition of the above
Dates of spudding, workovers, plugging and abandonment (P&A);	- age of equipment - history of the well
Description of materials and cements used	- mechanical and chemical properties
Results of mechanical integrity tests performed on the well	- geological formation strength - cement quality
Annulus pressure/fluid sampling	- integrity of casing and well barriers - seal leak rates
Visual inspection of the sealed top of the abandoned wellbore with possible bubble tests	- integrity of the abandonment
Records of leak tests performed before abandonment	- integrity of the abandonment
Other information such as the presence or absence of sustained casing pressure	- integrity of casing and well barriers
List of operators (drilling operator, well operator, logging operator, etc.)	- sources of further information
Track record of relevant regulatory changes regarding drilling and abandonment practices	- gaps with respect to current regulations
Geomechanical history of the field including subsidence	- stress/strain/shear history of the well
Industrial history of the area including drilling, injection, production and mining	- history of external factors on the well
Records of temperature and pressure and composition of formation fluids over time	- Reservoir history - Wellbore chemical exposure history

2.3. Identify well integrity risks

2.3.1. Objective

The purpose of this step is to create a comprehensive register of well integrity risks and provide specialist input to Section 2.5 (‘Identification and assessment of risks and uncertainties’) of [1]. The deliverable from this step is a list of well integrity risks.

2.3.2. Methodology

Risk identification is the process of finding, recognizing and describing risks. The scope of the risk identification discussed in this document consists of:

> “identification of failure modes that individually or in combination have potential to cause loss of well integrity, and have significant negative impact on one of the identified elements of concern”

Failure modes are defined as the observed manner of failure, where failure is in turn defined as the termination of the ability of an item to perform its required (specified) function

Risk identification can involve historical data, theoretical analysis, informed and expert opinions and stakeholder’s needs. Consideration should be given to the quality, reliability and applicability of the data collected.

Risks may be internal or external to the well. This system should be analysed in terms of sub-systems, such as well barriers, in order to facilitate risk identification. A system for identification of possible failure modes should be established and described.

Risks should be registered and handled by the use of appropriate lists throughout the risk assessment process. It is important to keep track of all changes and assumptions and this may be best achieved through use of a database. Appendix C provides a template for a list that may be used as the basis for such a database.

Qualified personnel should be used to identify potential risks and each person’s relevant qualification should be documented. The number of people involved and their range of experience should be determined by the size and complexity of the well that is being analysed. The risk identification should be undertaken by personnel, or groups of personnel who are knowledgeable about the design, operation and maintenance of the well under consideration. In particular, all disciplines listed in Table 2 should be covered by the personnel involved.

The system to be used can be based on traditional failure modes, effect and criticality analysis methods outlined in [23,24]; by individuals or in group work. To check the thoroughness of the risk identification process, the group may consult the generic checklist of failure modes for wells as presented in Appendix B.

2.3.3. Comparing storage sites with large numbers of existing wells

Risk identification should be carried out on a well by well basis unless the large number of existing wells involved makes this approach untenable during an initial risk assessment. In such a case the risk identification process may be made more efficient by grouping wells into high risk and low risk categories based on some screening criteria. Appendix D provides an example of such an approach to categorising and collectively assessing abandoned wells to support the screening stage risk assessment process.

If the risk contribution from a group of wells has initially been collectively assessed based on a few indicative parameters, then the detail and rigour of the assessment of the risk contribution from wells at prospective storage sites may need to be increased in a possible iterative fashion until confidence has been established that the relevant risk criteria have been met. This iterative approach is represented by the feedback arrow on the left hand side of Figure 4.

2.4. Analyse well integrity risks

2.4.1. Objective

The objective of the risk analysis is to determine the level of risk for each failure mode by analyzing its consequence and likelihood. The deliverable from this step is a list of risk analysis findings.

2.4.2. Methodology

Risk analysis involves consideration of the consequences of failure modes and the likelihood of these to occur. Classes of likelihood and classes reflecting the consequence severity should be defined in the case of a qualitative assessment. Based on these definitions a risk matrix shall also be defined showing fully acceptable combinations ("low risk") and unacceptable combinations ("high risk") as well as intermediate combinations ("medium risk") of likelihood and consequence classes. See Figure 5 for an example of such a matrix.

All relevant failure modes should be assigned a likelihood class and consequence class based on documented reliability or expert judgments. In the latter case uncertainties shall be reflected by selecting conservative classes.

A qualitative risk analysis method may be most practical during storage site screening (prior to milestone M2) due to a general lack of quantitative information about the wells under investigation. In such a case two approaches to determining the likelihood and consequence of risks are relevant:

- engineering judgment;
- statistical evidence from testing and field experience.

Risk analysis can be based on failure modes, effect and criticality analysis as defined in Section 2.3.2. See Appendix C for an example of a log sheet that may be used during such an analysis.

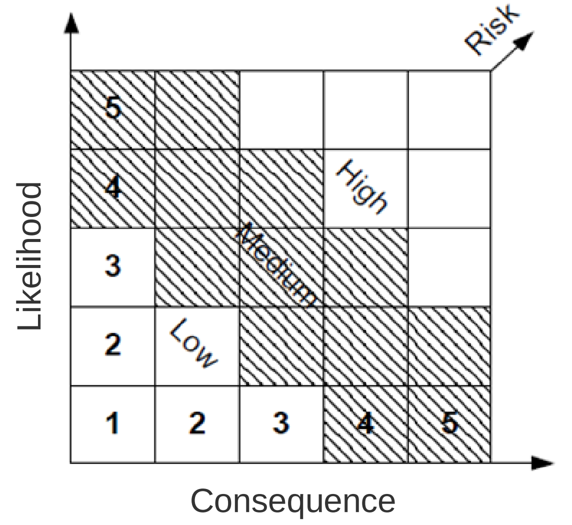

Figure 5: Risk matrix

A likelihood based on engineering judgement will in some form be based on statistical evidence through experience. It is hence of importance that this is done by qualified personnel. The number of people involved and their range of experience should be determined by the size and complexity of the well that is being analysed. Risk analysis should be undertaken by personnel, or groups of personnel, who are knowledgeable about the design, operation and maintenance of the well under consideration.

In the case that statistical evidence from testing or field experience is available then quantitative estimates of probability and consequence may be determined. Uncertainty in the estimates should be handled according to *ISO/IEC Guide 98, Guide to the expression of uncertainty in measurement [25]*.

Risks may usefully be grouped into categories according to the nature of their consequences, such as those described in ISO 17776 [26]:

1) people;
2) environment;
3) assets;
4) reputation.

2.4.3. Classes of consequence

Examples of consequence classes within each category are given in Table 4 and described below.

With regard to consequence analysis on 'people', this examines the potential harm to individuals from injuries and fatalities attributable to the identified hazards.

Consequence analysis for the environment should examine any potential local effects on the ecosystem and the overall impact of greenhouse gas (GHG) storage, such as:

- no effect on the net GHG benefit of the storage site;
- insignificant effect on the net GHG benefit of the storage site;
- noticeable reduction in the net GHG benefit of the storage site;
- net GHG benefit of the storage site cancelled out.

The consequence impact analysis for assets should examine:

- individual wells;
- well inventory;
- reservoir;
- associated facilities;
- nearby infrastructure/environment;
- natural resources including, but not restricted to, freshwater, oil & gas, coal, geothermal and minerals.

Reputation analysis is generally as a result of the worst consequence from the other categories and is not generally analysed *per se*.

Table 4: Example of consequence categories and classes that may be considered during risk analysis. Modified from ISO 17776 [26].

	Consequence category			
Class	**People**	**Assets**	**Environ-ment**	**Reputation**
0	Zero injury	Zero damage	Zero effect	Zero impact
1	Slight injury	Slight damage	Slight effect	Slight impact
2	Minor injury	Minor damage	Minor Effect	Limited impact
3	Major injury	Local damage	Local effect	Considerable impact
4	Single fatality	Major damage	Major effect	Major national impact
5	Multiple fatalities	Extensive damage	Massive effect	Major international impact

2.4.4. Classes of likelihood

Example likelihood classes are given in Table 5. These classes make use of historical data in the upstream oil and gas industry to give an indication of the degree of likelihood that a particular failure mode may occur within a specified time frame. This is found necessary because CO_2 geological storage is a relatively new industry.

The following examples of likelihood classes that may be used for a particular failure mode are based on whether or not it has occurred;

- in the upstream oil and gas industry;
- in the operating company in question;
- several times a year in the operating company in question;
- several times a year in the location in question.

Table 5: Example of likelihood classes that may be considered during risk analysis (Section 2.4). Modified from ISO 17776 [26].

Class	***Likelihood***
0	Has occurred in industry
1	Has occurred in operating company
2	Has occurred several times a year in operating company
3	Has occurred several times a year in location

2.5. Evaluate well integrity risks

2.5.1. Objective

Risk evaluation should assist in making decisions about which wells would require risk control measures and what the total risk control requirements would be for each storage site. The deliverable from this step is a list of risk evaluation findings.

2.5.2. Methodology

Risk evaluation should compare the level of risk found for each well during the analysis in Section 2.4 with the risk criteria established in Section 2.1.

Table 6 gives an indication of risk tolerability in general terms based on the consequence categories and likelihood classes from Section 2.4, but matrices specific to the activity under consideration should be prepared and used. Tolerable limits should be defined and set that are in line with company, regulatory and societal expectations. The table developed for each project should clearly identify what is not acceptable, and where risk is acceptable and managed for continuous improvement.

The adjusted matrix should govern identification and prioritization of potential risk control options, with focus on the highest risk.

Failure modes with medium and high risk should be investigated further in the event that a well is selected for further development and are defined as failure modes of concern. Failure modes with low risk can be concluded based on a qualitative assessment made by qualified personnel. Failure modes with low risk should not be deleted from the list of possible failure modes.

The second stage of risk evaluation should group the findings for each well into an overall evaluation for each storage site. This storage site level evaluation should then form the basis for comparing the well integrity risks at each storage site in the short-listing process at milestone M2.

If a storage site is subsequently chosen for development then risk control measures, such as well qualification, should be based on the findings of this risk evaluation.

Table 6: Example of risk matrix and consequence categories that may be considered during risk analysis (Section 2.4). Modified from ISO 17776 [26].

Consequence category					***Likelihood***			
Class	**People**	**Assets**	**Environment**	**Reputation**	Has occurred in industry	Has occurred in operating company	Occurred several times a year in operating company	Occurred several times a year in location
0	Zero injury	Zero damage	Zero effect	Zero impact	**Acceptable: manage for continued improvement**			
1	Slight injury	Slight damage	Slight effect	Slight impact				
2	Minor injury	Minor damage	Minor Effect	Limited impact			▨	▨
3	Major injury	Local damage	Local effect	Considerable impact		▨	▨ **Unacceptable: identify risk control measures**	▨
4	Single fatality	Major damage	Major effect	Major national impact	▨	▨	▨	▨
5	Multiple fatalities	Extensive damage	Massive effect	Major international impact	▨	▨	▨	▨

Note: Table 6 gives an indication of risk tolerability in general terms, but matrices specific to the activity under consideration should be prepared and used.

2.6. Evaluate need for further analysis

In some circumstances the risk evaluation may lead to a decision to undertake further risk analysis. This may be particularly relevant at storage sites with a large number of existing wells, which require an iterative approach to risk analysis (see 2.3.3). The deliverables from this step are:

- plan for additional data acquisition and/or analysis if required;
- decision to proceed to identification of risk control measures.

2.7. Identify risk control measures

2.7.1. Objective

The objective of this step is to identify measures for controlling unacceptable risks in the event that a given storage site is selected for development. The deliverable from this step is:

- list of risk control measures.

2.7.2. Risk control measures identification

This activity should be repeated in greater detail between milestones M2 and M3 if a storage site is selected, but the intention at this stage is to identify the need for risk control measures that can be compared across candidate storage sites.

Risk control measures should be selected on a well by well basis in order for each well to meet the criteria established in Section 2.1. The following order of preference should apply:

- avoiding the risk;
- removing the risk source;
- reducing the likelihood;
- reducing the consequences;
- sharing the risk with another party or parties;
- retaining the risk by informed decision.

Risk control measures for well integrity may include the following:

- re-designing the CO_2 storage site and/or injection strategy to remove or reduce the risk source;
- well intervention to remove the risk source by repairing, strengthening or replacing specific components in the well;
- monitoring of well barriers to identify emerging risks.

2.8. Communicate results for decision support at M2

2.8.1. Objective

The milestone M2 is designed to filter out storage sites that are not suitable for long term geological storage of the intended volumes of CO_2. This step shall establish the level of confidence in the integrity of the existing wells at each candidate storage site and thereby contribute to this filtering process.

A comparison of the overall risk control requirements for existing wells at each storage site shall be generated in order to fulfill the criteria that were established in Section 2.1. The deliverable from this step is:

- well screening report describing the overall risk picture for existing wells at each CO_2 geological storage site under consideration.

This deliverable should then be able to support the decision to commit budget and resources for the Assess & Select stage in [1].

2.8.2. Coordination with CO2QUALSTORE

The findings of the well integrity risk assessment should be included in the 'Screening report' described in Section 2.6 of the CO2QUALSTORE guideline [1].

Table 7: Summary of the activities and deliverables for the assessment of well integrity risks for existing wells.

Assess well integrity risks for existing wells	
Activities	**Deliverables**
Define the risk assessment scope & criteria (Section 2.1)	
Establish the context for the risk assessment	Risk assessment scope
Develop criteria to be used for well integrity evaluation	List of risk criteria
Plan the risk assessment & collect data (Section 2.2)	
Define schedule, budget and deliverables for the risk assessment	Well integrity risk assessment plan
Describe each well to the maximum extent possible and assess condition	Well data and condition assessment
Identify well integrity risks (Section 2.3)	
Identify well integrity risks	List of well integrity risks
Analyse well integrity risks (Section 2.4)	
Perform analyses of risks identified in the previous step. Identify likelihood and consequence classes.	Risk analysis report
Evaluate well integrity risks (Section 2.5)	
Evaluate acceptability of the risks to assist with decision making.	Risk evaluation report
Evaluate need for further analysis (Section 2.6)	
Decide whether additional data collection and/or risk analysis are required	Plan for additional data acquisition and/or analysis, if required Decision to proceed to identification of risk control measures
Identify risk control measures (Section 2.7)	
Identify risk control measures	List of risk control measures
Communicate results for decision support at M2 (Section 2.8)	
Prepare report describing the overall risk picture for existing wells at each CO_2 geological storage site under consideration	Well integrity risk component of CO2QUALSTORE Screening report
M2: Short-list storage sites	
Main question: Is there an adequate level of certainty that further well integrity assessment will provide confidence that at least one of the nominated storage sites is suitable for long term geological storage of the intended volumes of CO_2? ***Decision:*** Commit budget and resources for the Assess & Select stage	

3. BEGIN QUALIFICATION OF EXISTING WELLS AS REQUIRED

Well qualification should be applied to all types of existing wells that may be exposed to the effects of CO_2 storage:

1. Plugged and abandoned wells that should continue to provide formation fluid containment;
2. active wells that should be plugged and abandoned prior to CO_2 storage operations;
3. active wells that should retain their original function during CO_2 storage operations before final plugging and abandonment;
4. active wells that should have a modified function during CO_2 storage operations before final plugging and abandonment.

The workflow steps that are specific to this chapter are shown in Figure 6. A generic representation of the life cycle of an existing well is shown in Figure 7.

Well qualification uses the output from the risk assessment in Chapter 2 as input to establish the current status of each well. Risks to future performance and reliability are then identified and reduced in a systematic manner by targeted qualification activities such as testing and analysis. Uncertainty is addressed in an explicit manner and future monitoring of wells may be used as a means to trigger specified risk reduction measures as required in the future.

The steps in the well qualification process are illustrated in Figure 3. Feedback loops between the steps imply that the process is iterative in nature, considering that modification of specifications, function of the well and/or intervention may be needed, and will trigger full or partial iterations of the overall process in order for the well to be qualified.

The well qualification process is divided into two stages that are designed to meet the needs of the CO2QUALSTORE milestones at M3 and M4 in Figure 3. This distinction is for guidance only.

The result of well qualification is a statement and documentation of fitness for purpose that define margins against specified failure modes or margins towards specified performance targets. The qualification results can be used:

- as an acceptance for implementation of an existing well to a carbon capture and storage application;
- for comparison between solutions for a given well;
- as input in the evaluation of the reliability of a CO_2 geological storage site that the well may be part of;
- as an assurance of well integrity.

The following principles should apply to well qualification:

a) a qualification strategy should be developed to bring a well from its current state to a defined target state or to assess the present condition of the well;
b) specifications and requirements should be clearly defined, quantified and documented;
c) the performance margins and the margins to failure should be established based on recognised methods;
d) failure modes that are not identified may pose a risk to the successful implementation of the well. This residual risk is managed by ensuring the relevant competencies are used (see Table 2) and by challenging the critical assumptions during the course of qualification;
e) the qualification process should be based on a systematic, risk based approach and performed by a qualification team possessing all required competencies;
f) when service experience is used as proof of fulfilment of the specifications, then evidence of that experience should be collated and validated;
g) the work should be documented and traceable;
h) an iterative approach is recommended when uncertainties are very large;
i) the typical quality assurance system for drilling, completing, and plugging and abandonment

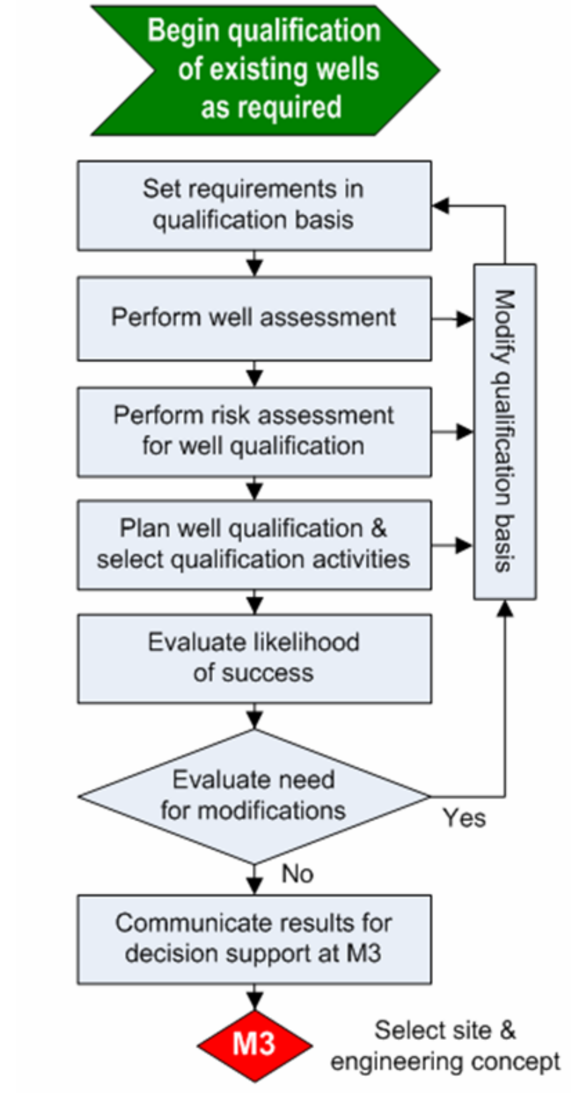

Figure 6: Guideline steps in Chapter 3. Modified from Figure 3.

(workover) a well is an integral part of the qualification process.

3.1. Set requirements in qualification basis

3.1.1. Objective

The qualification of the well should be based on specified performance limits, boundary conditions and interfacing requirements defined in the qualification basis. The objective of the following subsections is to define a basis for the qualification process, detailing the requirements for the information describing the well and its required functions. The qualification basis shall serve as input, defining the limits, to the qualification activities. The well qualification basis should consist of:
- well current status (see Section 2.2.3)
- well performance requirements;
- well specification (functional and technical);
- well critical parameters list.

The deliverables from this step are:
- list of well performance requirements;
- well specification;
- well critical parameters list.

3.1.2. Well performance requirements

The qualification basis should:
- define how the well will be used;
- define the environment that it is intended for;
- specify well function;
- specify requirements such as acceptance criteria, performance expectations and qualification targets.

This includes the performance requirements throughout the extended lifetime of the well. Through qualification steps, these requirements should be fulfilled.

The qualification basis should describe current well state and the target well state that should be achieved through qualification process. The target should be specified as a set of quantifiable requirements to be met to show attainment of the target state. These may be reliability requirements related to selected functions. Performance requirements could be, for example sustained annulus pressure limits, completion string leak rate limits, wear/corrosion tolerances within the completion string and casing corrosion rate limits.

The well performance requirements should reflect the storage site selection criteria, such as those that may have been specified in the site selection basis (Section 3.2 of [1]). These requirements should be consistent with project specific thresholds for acceptance or tolerable risk, as defined in the project risk register.

3.1.3. Well specification

The well specification should be described as completely and unambiguously as possible through text, drawings, reports and other relevant documents. It is important that the well integrity criteria are stated and that all relevant interfaces are clearly defined. The specification should identify all phases of the well's life and all relevant main parameters.

The specification may include, for example:
- well description, schematic and formation boundaries and lithology types along the well;
- functional requirements;
- authority requirements;
- health, safety and environmental requirements;
- well integrity criteria;
- operation and maintenance, monitoring and abandonment principles;
- completion and interfacing with surface facilities.

The specification and functional requirements should be quantitative and complete. In case quantitative measures are not available for some of the requirements (for example, no cement evaluation log available) the qualification can be carried out for a best estimate, but as soon as the target requirements can be quantified they should be entered into the well qualification basis and the implication of these new values should evaluated.

3.1.4. Critical parameters list

The purpose of the critical parameters list is to document the vital governing parameters for the well. Hence, at the conclusion of the well qualification process, the boundary limits for the parameters and items given in the critical parameters list will represent the qualified limits or operating envelope within which the well is considered qualified.

The governing parameters must be determined for critical failure mechanisms. The critical parameters list should specify such governing parameters, and include their limits/boundaries within the scope of the qualification. Further, this list should also specify the main concerns and uncertainties with the given parameters.

The critical parameters should be established in the initial phase of the well qualification process. The parameters and their limits may change as the qualification progresses or as more modifications of the well planned, and hence may need updating as necessary throughout the various iterations of the qualification.

3.2. Perform well assessment

3.2.1. Objective

Assess the well so as to focus the effort where the related uncertainty for adverse consequence is most significant. In addition assess maintenance, condition monitoring and possible modifications effects.

Input to the well assessment comes from the qualification basis, and the output is a list of the CO_2 geological storage related components in the concept and the main challenges and uncertainties.

The well assessment should include the following steps:

- breaking down the well into manageable components;
- assessment of the well components with respect to CO_2 geological storage implications (well classification);
- identification of the main challenges and uncertainties.

The deliverables from this step are:

- list of well components related to CO_2 geological storage;
- list of main uncertainties and challenges related to new well function.

3.2.2. Well breakdown into components

In order to fully understand the CO_2 well implications, the well should be subdivided into distinct and manageable components for analysis. Examples of well components can be found in Table 11 in Appendix B.

3.2.3. Well component classification

Well components may be classified so as to focus the qualification effort where the related uncertainty for adverse consequence is most significant.

Well component classification is a qualitative process that should make use of a failure mechanism (such as corrosion) that is common to the components in question. In the case of corrosion then the well components should be classified according to the corrosion resistance of their materials and their degree of expected exposure to a corrosive environment. An example of such a rating system is shown in Table 8.

In Table 8 the term 'technical uncertainty' relates to the potential incompatibility or poor performance of components, whereas the term 'technical challenges' relates to components of known incompatibility with CO_2 and where performance can be modelled.

In examining the well components it may be beneficial to group them into sub-systems (such as the lower completion) prior to performing the classification. A well component or sub-system rated as Class 1 is proven to be of no particular concern for this application with any technical uncertainties where proven methods for qualification, tests, calculations and analysis can be used to document margins.

It is important not to overlook the components falling into this category; they should be handled through the regular design process.

A well component or sub-system rated as between Class 2 to Class 3 has an increased degree of technical uncertainty. Components falling into these classes should be qualified according to the work process described in this guideline. Components falling into Class 4 likely require modification and thus the well assessment step may be used as an early screening tool for such requirements (Refer to Section 3.6).

Table 8: Example classification system for the corrosion resistance of well components.

		Corrosion resistance		
		High	Medium	Low
Exposure to CO_2 corrosion	Low	1	2	3
	Medium	2	3	4
	High	3	4	4

Where:
Class 1 represents no technical uncertainties;
Class 2 represents new technical uncertainties;
Class 3 represents new technical challenges;
Class 4 represents demanding technical challenges.

The defined classification ratings make it possible to distinguish between combinations of CO_2 exposure and CO_2 corrosion resistant components, and focus on the areas of concern.

3.2.4. Identification of main challenges and uncertainties

The main challenges and uncertainties related to the CO_2 geological storage well aspects should be identified as part of the well assessment. For demanding well conversions it is recommended that the main challenges and uncertainties are identified by carrying out a high level hazard identification study (HAZID).

3.3. Perform risk assessment for well qualification

3.3.1. Objective

This risk assessment is additional to that described in Chapter 2. It has the objective to analyse well integrity risks in more detail and in relation to the future function of the well, which may not have been known prior to milestone M2. The risk assessment method used represents a further iteration and specialization of the ISO31000 standard [2].

The objective of this step is to identify all relevant failure modes of concern with underlying failure mechanisms for each well and assess the associated risks. This assessment should make use of the following inputs:

- the output from the screening risk assessment (Chapter 2);
- the qualification basis (Section 3.1);
- Critical parameters list (Section 3.1.4);
- the list of components developed in the well assessment (Section 3.2).

This step should be coordinated with the data collection and risk assessment steps in the Assess & Select stage of [1] (Sections 3.4 and 3.5 of CO2QUALSTORE guideline).

The deliverable from this step is:

- failure mode register containing identified failure modes and failure mechanisms ranked according to their risk level.

3.3.2. Risk identification

See Section 2.3 for a method description. In addition this activity should take into account Phases II, III and IV of the well service life from Figure 7. A generic list of failure modes and failure mechanisms for wells is given in Appendix B. The list gives a generic overview of internal failure modes, in addition external failure modes such as faulting, geomechanical effects on the well resulting pressure changes in reservoir, etc. should be considered. The risk assessment should incorporate failure modes and their underlying failure mechanisms related to operational history and future service.

3.3.3. Special considerations for well integrity under exposure to CO_2

1) Corrosion of carbon steel pipe and degradation of cement: the dominating failure mechanism related to long term exposure to CO_2 or CO_2 saturated formation fluids is anticipated to be corrosion of carbon steel pipe and degradation of cement. The probability of failure modes resulting from these failure mechanisms will depend on the corrosion and degradation rates that are assumed. It is understood that international research and development work continues to reach an industry consensus on how to predict these rates in a reliable manner.
2) Elastomers: routinely used as sealing elements and can be found in surface and downhole valves, packers and downhole seals. CO_2 presents additional challenges to elastomer design. Elastomers should resist explosive decompression (rapid gas-decompression) and be qualified appropriately (refer to, for example NORSOK M-710 [28]). Elastomer performance and properties change with time and they should be avoided as part of the primary abandonment barrier design.
CO_2 as a refrigerant: designers should be aware of the refrigerant properties of carbon dioxide. Pressure drops which cause a phase change will drop temperatures significantly. Materials of construction should ensure that toughness of metals and flexibility of elastomers (durometer) are maintained for both normal and abnormal flow conditions. Low temperatures can also freeze annulus fluids and cause additional tubing contraction, for example unstable flow regime down the tubing in low pressure reservoirs. The temperature range could therefore be greater than normally experienced in a conventional oil and gas injection well and may cause considerable growth/contraction and additional loads on the well.
3) Blow-down considerations: blow-down of CO_2 in liquid or super critical phase is a challenge. In addition to the low temperatures, dry ice can form which may land locally and create hazards, or in extreme cases cause erosion of the vent pipework. Design of wireline and coiled tubing systems and operations should take this into consideration, for example by displacing the CO_2 with nitrogen

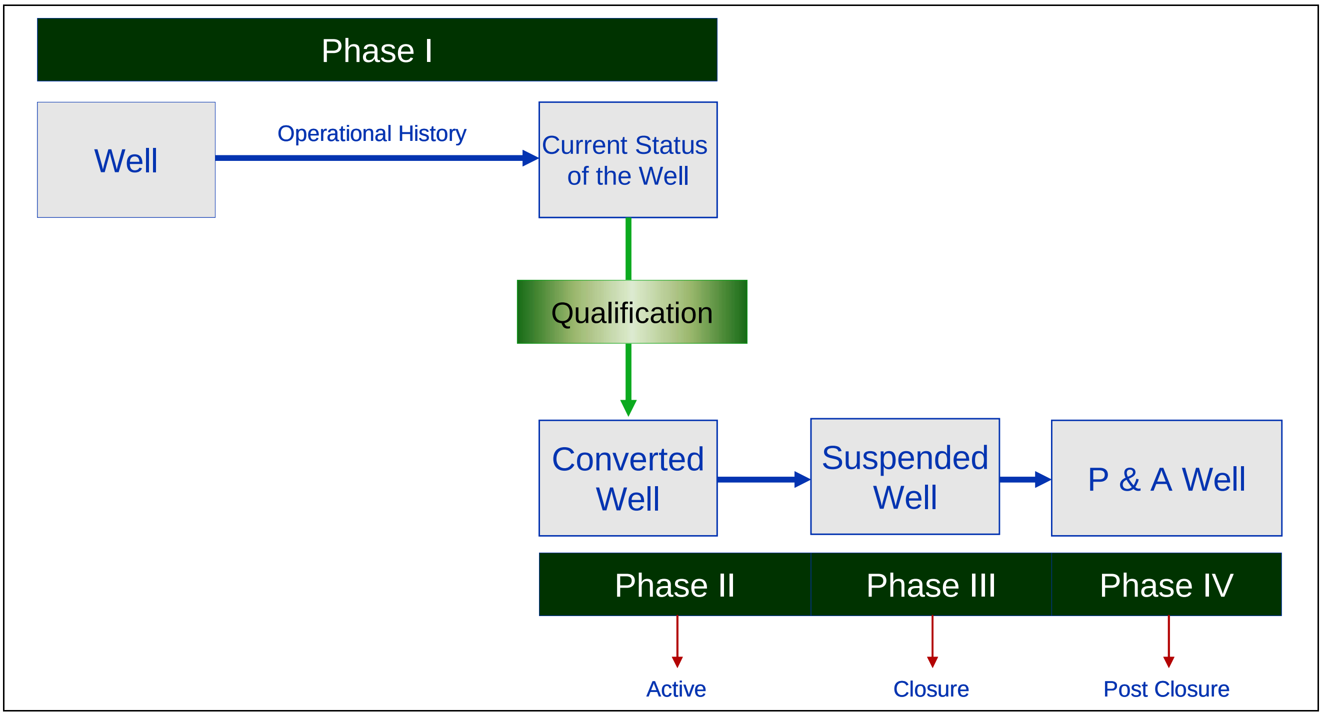

Figure 7: Life cycle for a well before and after qualification for CO_2 exposure

4) before depressurisation. This operational need also exists with downhole safety valve testing and this may be the dimensioning case for surface pressure control equipment.
5) Annulus management: the qualification process should examine the management of the annulus condition during the injection phase to detect well integrity problems early and prevent corrosion of casing and tubing. Condition monitoring of the annulus during the injection phase could include pressure monitoring, measurement of top-up volumes, sampling of annulus fluids, and pressure-volume measurements.

3.3.4. Risk analysis

See Section 2.4 for a method description. A greater emphasis should be placed on using quantitative measures of probability and consequence where this is supported by the data that is available.

3.3.5. Risk evaluation

The input and output for this step are specific to well qualification, but the methodology used is similar to that described in Section 2.5. Risk ranking should be used to focus qualification effort where the benefits are greatest. The risk classification scheme has to be adapted to fit the case considered, but in general failure modes with medium and high risk are considered critical and should be covered by the well qualification plan (Section 3.4). Failure modes with low risk can be concluded based on a qualitative assessment made by qualified personnel. Failure modes with low risk should not be deleted from the list of possible failure modes.

The risk estimates should be updated during the qualification process, utilising qualification evidence and information from mitigating actions, which is made available through the qualification process.

A system for tracking of each failure mode and failure mechanism should be established. The purpose of this system is to document the initial risk assessment and allow updating and verifying the risks as the qualification proceeds while maintaining full traceability back to each failure mode and mechanism.

This system should include:
- all identified failure modes and mechanisms;
- a probability estimate for each failure mode to occur;
- the basis for the probability estimate tracing documentation revisions and implementation of mitigating actions;
- the degree of CO_2 implications to which the failure mode relates (class 2 to 4) in order to focus on the important components.

3.4. Plan well qualification & select qualification activities

3.4.1. Objective

The objective of this step is to develop a well qualification plan that provides the evidence needed to manage the critical failure modes identified in Section 3.3. The selected qualification activities should be specified in the well qualification plan in sufficient detail to enable execution. These activities should provide evidence that can be used to document compliance with the requirements specified in the well qualification basis. The qualification activities should be traceable back to the failure mode register developed during the risk assessment step. The reasoning relating the pieces of evidence to the failure mode should be presented.

The well qualification plan should be coordinated with the storage site selection plan described in Section 3.3 of [1].

The deliverable from this step is:
- well qualification plan.

3.4.2. Methodology

The well qualification plan should reflect the iterative nature of the overall qualification process, seeking to reduce the largest risks first. It is recommended that an overall internal milestone plan for the entire qualification is defined to achieve this.

Development of the well qualification plan includes:
- high level planning to implement the overall qualification process;
- analysis and selection of qualification activities to provide the evidence needed for each failure mode;
- development of the reasoning that connects the evidence produced by the qualification activities to the requirements set in the qualification basis.
- develop detailed specifications of the qualification activities.

The detailed specifications of qualification activities should explicitly specify:
- the evidence to be produced by each qualification activity;
- the failure modes each piece of evidence relates to;
- the reasoning that relates the pieces of evidence to the failure modes;
- the reasoning that relates the evidence to the requirements specified in the qualification basis;
- success criteria for this evidence to be successful in meeting the requirements.

The well qualification plan should be revised as necessary.

3.4.3. Selection of qualification activities

Qualification activities should be specified in order to build up evidence so that the identified failure modes will not occur with a sufficient margin. The result of the qualification activities shall verify that the requirements stated in the qualification basis have been met.

If a quantitative reliability target is stated in the qualification basis, then a quantitative reliability method is required to document fulfilment of the target, for example, by determination of a lifetime probability density distribution for the relevant failure modes.

For each failure mode of concern, it should be determined if the failure mechanisms can be modelled by recognised and generally accepted methods. Then a detailed plan for the qualification activities can be established, for example, by use of existing standards or industry practices.

The following methods can be used, separately or in combination, to provide qualification evidence:

- failure mode avoidance, such as operational procedures or design changes;
- analysis or engineering judgement of previous documented experience with similar equipment and operating conditions;
- analytical methods such as handbook solutions, methods from existing standards, empirical correlations or mathematical formulas;
- numerical methods, such as process simulation models, computational fluid dynamics, finite element modelling, coupled geomechanical and reservoir simulation modelling, corrosion models, etc.;
- experimental methods, scale model testing, identification or verification of critical parameters and their sensitivities.

3.5. Evaluate likelihood of success

3.5.1. Objective

The objective of this step is to give a reliable indication of the likelihood of completing the remaining qualification program successfully. This is intended to give a basis for the decision to proceed with the analysis and testing phase (qualification activities).

The success evaluation may be carried out at various levels of sophistication depending on the needs for information into decision process and accessibility to input parameters.

The deliverable from this step is:

- likelihood of success evaluation.

3.5.2. Evaluate likelihood of successful qualification

The evaluation will normally be assessed on a qualitative basis with respect to technical challenges and the available time for qualification, hence the term likelihood is used. In the case where a quantitative estimate is calculated, this should be referred to as the probability of success.

A more sophisticated and informative assessment of the total probability of success for the whole qualification may be carried out in order to give the probability of success as function of time. Such an assessment requires that a qualification execution plan, that includes all qualification activities, is prepared and that both the probability of a successful outcome for each activity, and the uncertainty in the durations are estimated.

An economic assessment of the qualification activities may be carried out following the same principles, where the time parameter is replaced by costs. This requires that cost estimates with uncertainties are estimated for each qualification activity.

In the event that further development of a storage site is anticipated then a project developer should consider initiating baseline monitoring of existing wells at the earliest possible opportunity. See Section 3.6 of [1].

During the risk evaluation, the degradation rate should be considered. For example, the existing casing may be sufficient for CO_2 injection service for a certain number of years at which point is should be abandoned.

The qualification activities may consist of qualitative and quantitative methods, analysis and testing. A typical qualification program may include a combination of the following activities:

- material corrosion resistance, historical data, corrosion prediction models, testing;
- capturing field history, quantitative/ qualitative evaluation of failure history of wells in a field with similar wells and exposure;
- assess documented industry practice with the specific well components;
- CO_2 degradation and migration prediction modelling.

3.6. Evaluate need for modifications

In this step, the need for further modifications is evaluated against the likelihood of success of each qualification activity. Modifications of the well and /or the qualification basis should be considered where the likelihood of successful qualification is low and/or the associated time and cost are high.

If the likelihood of success is unacceptable and required modifications are excessively costly, the well might not be considered for further qualification and the storage site containing such well might be eliminated from the list of potential storage sites at milestone M3.

The deliverable from this step is:

- the decision to proceed to performance assessment & well qualification or to modify the qualification basis.

3.7. Modify qualification basis

3.7.1. Objective

The objective of this step is to modify the qualification basis when found necessary or beneficial for the

successful completion of the well qualification process in Section 3.6. The effects of such modifications must be evaluated to avoid invalidating the qualification of the converted well. The deliverable from this step is:
- modified qualification basis.

3.7.2. Modifications

Modification to the well qualification basis should have a defined purpose, such as:
- removal of a failure mode;
- reduction of the probability of occurrence or consequence of failure mode to an acceptable level;
- reduction of the total well cost;
- increasing confidence;
- change of well function.

Any modifications to the well qualification basis imply that the well qualification steps need to be updated. The update may range from a limited update of parameters or risk data to major re-design of the well. In either case documentation is required in order to maintain traceability of the process.

3.8. Communicate results for decision support at M3

The main question at this stage of the overall CO_2 storage project may be to establish which combination of storage site and well engineering concept represents the most cost-effective solution for CO_2 storage.

The answer to this question will then be able to support the decision to commit budget and resources for preparation of the CO_2 storage permit application.

The likelihood of well qualification success and/or the need for further modifications may be a crucial element in answering the question above and should be included in the overall evaluation of the maturity of a storage site in order to be able to answer this question. This is discussed further in Section 3.7 of the CO2QUALSTORE guideline [1].

The deliverable from this step is:
- initial well qualification report describing the likelihood of successful qualification and required qualification activities to be performed.

Table 9: Summary of the activities and deliverables for the beginning of qualification of existing wells as required.

Begin qualification of existing wells as required	
Activities	**Deliverables**
Set requirements in qualification basis (Section 3.1)	
Identify performance requirements for the wells in question	List of performance requirements
Describe well specification as completely as possible	Well specification (functional and technical)
Establish well critical parameters list	Well critical parameters list
Perform well assessment (Section 3.2)	
Divide well into manageable components in order to assess which components of the well may be affected by CO_2 geological storage activities	List of CO_2 geological storage related components
Identify the key challenges and uncertainties related to new well function	List of main challenges and uncertainties
Perform risk assessment for well qualification (Section 3.3)	
Identify relevant failure modes of concern with associated failure mechanisms for the CO_2 well	Failure mode register containing identified failure modes of concern and failure mechanisms
Rank failure modes based on their risk (combination of probability and consequence)	Updated failure mode register with failure modes ranked according to the risk level
Plan well qualification & select qualification activities (Section 3.4)	
Develop well qualification plan	Well qualification plan
Evaluate likelihood of success (Section 3.5)	
Evaluate likelihood of completing qualification program successfully	Likelihood of success evaluation
Evaluate need for modifications (Section 3.6)	
Evaluate need for modifications	Decision to proceed to performance assessment & well qualification or to modification of qualification basis
Modify qualification basis (Section 3.7)	
Modify qualification basis if needed	Modified qualification basis
Communicate results for decision support at M3 (Section 3.8)	
Prepare report supporting decision on the selected CO_2 geological storage site	Assess & Select report
M3: Select storage site &engineering concept	
Main question: Which combination of storage site and well engineering concept represents the most cost-effective solution for CO_2 storage?	
Decision: Commit budget and resources for preparation of the CO_2 storage permit application	

4. ASSESS PERFORMANCE & QUALIFY WELLS

4.1. Execute well qualification activities

4.1.1. Objective

The objective of this step is to carry out the well qualification plan from Section 3.4. This involves:
- execution of the qualification activities;
- failure mode detection;
- collection and documentation of data;
- ensuring traceability of data.

The deliverable from this step is:
- traceable documentation of qualification activities execution.

The workflow steps that are specific to this chapter are shown in Figure 8.

4.1.2. Execution of the qualification activities

The activities specified in the qualification plan should be executed according to industry recognised specifications. The assumptions and conditions assumed as basis for the qualification activities that need to be fulfilled by the qualified component should be documented.

4.1.3. Failure mode detection

Failure modes detected during execution of the qualification activities (quality control qualification test, acceptance tests or later operations) should be recorded and documented. The documentation should include the date detected, the description of the failure mode, other observation and the identity of the originator.

When a failure mode is detected in the qualification process, the occurrence of the failure mode should be evaluated with regard to the three following cases:
1. will occur within the expected frequency of occurrence according to the analysis;
2. will occur with a higher frequency;
3. has not been considered.

In case 2 the basic assumption for the frequency of occurrence should be re-evaluated. This re-evaluation should include implications for any models used. In case 3 there should be an evaluation stating if the failure mode is an artefact that need not be considered or if it was missed and must be included in the qualification.

4.1.4. Collection and documentation of data

The documented evidence from the execution of the qualification activities should enable the performance assessment step to be carried out. The failure mode register from Section 3.3 should be used to follow up the data collection and the qualification of the well.

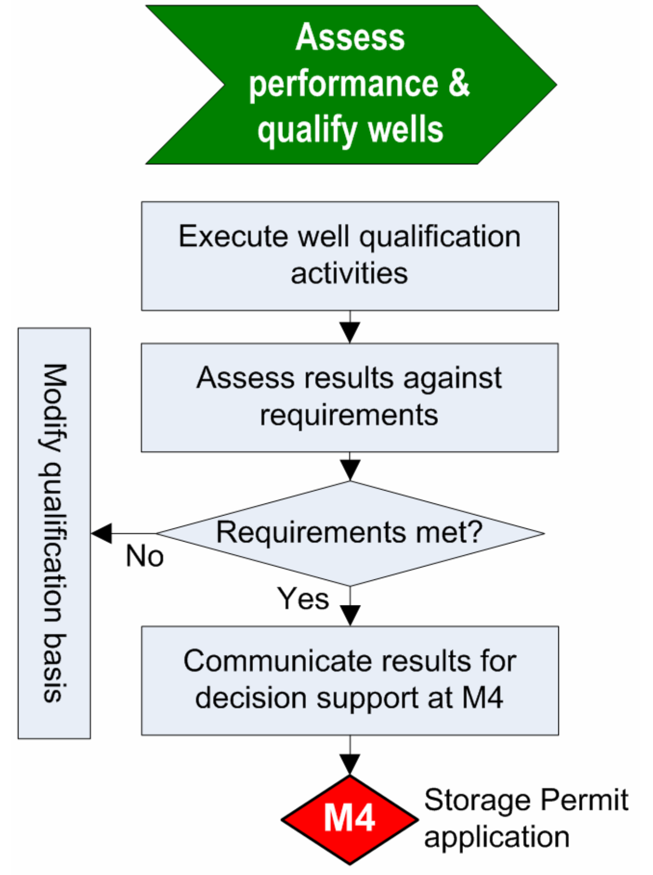

Figure 8: Guideline steps in Chapter 4. Refer to Figure 3 for the full context of these steps. 'Requirements met? - No' branch recycles to the pre-M3 workflow.

4.1.5. Ensuring traceability of data

In order to ensure traceability of data, an "audit trail" should be provided for the qualification process. The data should be organized in such a manner that there is a clear link between the steps of the qualification process, from the qualification basis to performance assessment. It should be possible to trace the threads that have been identified, how they have been addressed (test, analysis, previous experience, etc.), what evidence has been developed (test and analysis reports), and how that evidence meets requirements in the well qualification basis.

This provides opportunity for independent review of the qualification conclusions and will enable reuse of evidence in future projects, for example qualification of other wells or the same wells for a different use.

4.2. Assess results against requirements

4.2.1. Objective

The objective of this phase is to decide whether or not the well qualification has been successful by assessing the available evidence against the requirements specified in the well qualification basis.

The output of this step comprises the reasoning linking the available evidence to the failure modes and the requirements in the well qualification basis as well as the conclusions following this reasoning regarding fulfilment of the requirements. If the assessment concludes that some requirements are not met, risk control options (modifications to the well) and further qualification activities can be identified. This can include tightening of the operating envelope for the technology or enhanced inspection, workover and intervention strategies to meet the requirements based on the existing evidence. If none of these are feasible, the well cannot be qualified against the well qualification basis.

Performance assessments can also be performed at defined point during operation to confirm that the operations are within the assumptions for qualification stated in the Qualification Basis.

The deliverables from this step are:
- conclusion on whether qualification program has been reached;
- decision to proceed to storage permit application or to modification of qualification basis.

4.2.2. Methodology

Key steps of the performance assessment are to:
- interpret the evidence to account for simplifications and assumptions made when the evidence was generated and limitations and approximations in the methods used;
- confirm that the qualification activities have been carried out and that the risk criteria have been met. A key part of this confirmation is to carry out a gap analysis to ensure that the qualification evidence for each identified failure mode meets the specified risk criteria;
- perform a sensitivity analysis of relevant parameter effects;
- assess the confidence that has been built in the qualification evidence through the qualification activities. This should consider the extent to which test specifications have independently reviewed and test witnessed by an independent party.
- compare the failure probability or performance margin for each identified failure mode of concern with the requirements in the qualification basis. Evidence should be propagated from individual technology components to the requirements specified for the entire system covered by the qualification.

The assessment findings may be represented as safe service envelopes such that a wider range of operating conditions is covered than those specified in the well qualification basis. This can greatly simplify qualification for modified operating conditions.

4.3. Requirements met?

Depending on the findings of the previous step the project developer should decide on the need to modify the qualification basis in Section 3.1.

4.4. Communicate results for decision support at M4

The main question at this stage of the project may be to determine if the planned well engineering concept will work and if there is there enough documented evidence of this to support the storage permit application.

The answer to this question should be based on the findings of the well qualification process and the deliverable from this step is:
- a report documenting that the functional requirements and target reliability as stated in the qualification basis are met. This shall be done by confirming that the qualification activities have been carried out, and that the acceptance criteria for the analyses and testing have been met.

In addition to supporting the decision above, the results of well qualification should also be used as input to components of the overall CO_2 Storage Development Plan for a storage site, including (see Section 3.10 of [1]):
- Characterization Report;
- Injection and Operating Plan;
- Environmental Impact Assessment;
- Contingency Plan;
- Monitoring, Verification, Accounting and Reporting Plan.

Note that the Injection and Operating Plan includes a tentative site closure plan with a description of the planned abandonment procedure for wells within the storage site.

The success or failure of well qualification should also be documented in the CO2QUALSTORE step to ‘Evaluate overall compliance with regulations and qualification goals’ described in Section 3.11 of [1].

Table 10: Summary of the activities and deliverables for the assessment of performance & well qualification.

Assess performance & qualify wells	
Activities	**Deliverables**
Execute well qualification activities (Section 4.1)	
Carry out qualification activities prescribed in the well qualification plan	Traceable documentation of qualification activities execution
Assess results against requirements (Section 4.2)	
Assess results of qualification program against requirements specified in the well qualification basis	Conclusion on whether qualification program has been reached at the time of assessment
Requirements met? (Section 4.3)	
Evaluate whether the requirements stated in qualification basis are met	Decision to proceed to storage permit application or to modification of qualification basis
Communicate results for decision support at M4 (Section 4.4)	
Prepare report supporting storage permit application	Report supporting storage permit application
M4: Storage Permit (SP) application	
Main question: Will planned well engineering concept work? Is there enough documented evidence to support the storage permit application? ***Decision:*** Apply for a CO_2 storage permit	

APPENDICES

A. TERMS AND NOMENCLATURE

To enhance consistency with other proposed guidelines and regulatory frameworks, the guideline attempts to use well established terms. However, when different regions have adopted different linguistic terms, we have either selected the term found to be most appropriate, or adopted a neutral term and attempted to clarify how this term corresponds to other analogous terms that have been used in other relevant documents.

Abbreviations

CCS	Carbon Capture and Storage
EP	Exploration Permit
FME(C)A	Failure Modes, Effect (and Criticality) Analysis
GHG	Greenhouse Gas
HAZID	Hazard Identification Study
HSE	Health, Safety and Environment
JIP	Joint Industry Project
NACE	The National Association of Corrosion Engineers
P&A	Plug and Abandon
SCSSV	Surface Controlled Subsurface Safety Valve
SP	Storage Permit
TOR	Transfer of Responsibility

Definition of terms

Cement plug: a volume of cement slurry placed in the wellbore, which once in a solid state functions as a well barrier.

Consequence: Outcome of an *event* affecting objectives. An event can lead to a range of consequences. A consequence can be certain or uncertain and can have positive and negative effects on objectives. Consequences can be expressed qualitatively or quantitatively. Initial consequences can escalate through knock-on effects (from [3]).

Contingency Plan (CP): Plan to implement corrective measures if a significant irregularity occurs. The corrective measures should be prioritized and ranked according to the assessed cost-effectiveness of their risk/uncertainty reducing effect. In addition, the CP should document that conceivable significant irregularities can be adequately controlled, and express the project developer's commitment to implement appropriate contingency measures if necessary. The CP corresponds to the plan to implement corrective measures, which should be included in the storage permit application according to the EU CCS Directive.

CO_2 Geological Storage: Injection accompanied by storage of CO_2 streams in underground geological formations.

CO2QUALSTORE guideline: Guideline for Selection and Qualification of Sites and Projects for CO_2 Geological Storage [1] developed by DNV in collaboration with industry partners of CO2QUALSTORE project.

Corrective measures: Measures taken to correct (remediate) significant irregularities or to prevent or stop leakages of CO_2 from the storage volume.

Event: Occurrence or change of a particular set of circumstances. An event can be one or more occurrences and can have several causes. An event can sometimes be referred to as an incident or accident (from [3]).

Exploration permit: Written decision authorizing exploration, and specifying the conditions under which it may take place, issued by competent authority.

Failure: Termination of the ability of an item to perform the required (specified) function (from [21]).

Failure cause: The circumstances during design, manufacturing or use which have induced or activated a failure mechanism. The basic reason(s) for a failure

Failure likelihood: the qualitative *likelihood* of failure occurring within a specified time period. See also *failure probability*.

Failure mechanism: The physical, chemical or other process which leads to, or has led to, a *failure* (from [21]).

Failure mode: The observed manner of *failure* (on a specified level) (from [21]).

Failure probability: The quantitative *probability* of failure occurring within a specified time period (from [21]). See also *failure likelihood.*

Failure risk: The qualitative *likelihood* or quantitative *probability* of an accident or unplanned event occurring, considered in conjunction with the potential consequences of such a *failure*. In quantitative terms, risk is the quantified probability of a defined failure mode times its quantified consequence (from [22]).

Hazard: Source of potential harm. Can be a *risk source* (from [3]). In the context of well integrity a hazard is referred to as a failure mode,

Hazard Identification Study (HAZID): A structured review technique with the purpose of identifying all significant hazards associated with the particular activity or operation under consideration.

Leakage: Any measurable release of CO_2 from the storage volume arising as a result of project activity.

Level of risk: Magnitude of a risk or a combination of risk, expressed in terms of the combination of consequences and their likelihood (from [3]).

Likelihood: Chance of something happening expressed either qualitatively or quantitatively and described using general terms or mathematically, such as a *probability* or a frequency over a given time period (from [3]).

May: Verbal form used to indicate a course of action permissible within the limits of the standard.

Migration: Movement of CO_2 within storage volume.

Monitoring: Measurement and surveillance activities necessary for ensuring safe and reliable operation of a CO_2 geological storage project (storage integrity), and for estimating emission reductions. Monitoring activities covers the following three categories:

- injection operation at wellhead(s);
- storage reservoir and potential leakage pathways;
- surface and atmosphere or seafloor and water column;
- baseline conditions;
- condition of the well bore.

Operation: Sequence of planning and execution tasks that are carried out to complete a specific activity.

Qualification: See *technology qualification* or *well qualification*.

Performance target: Target level of risk/uncertainty reduction achieved through implementation of a defined safeguard, or range of safeguards. Performance targets should be defined prior to project approval and be agreed by the project developer and the regulator. Provisional performance targets for storage site closure should be defined prior to project approval. These performance targets represent the provisional post-closure plan which should be included in the storage permit application according to the EU CCS Directive.

Permanent abandonment: Well status, where the well or part of the well, will be plugged and abandoned permanently, and with the intention of never being used or re-entered again.

Permit area: Surface area beneath which a project developer is permitted to store CO_2 (storage permit), or explore the potential for CO_2 geological storage (exploration permit).

Plug: See *Cement plug*.

Plugging: Operation of securing a well by installing required well barriers.

Post-closure: Period after transfer of responsibility to the competent authority.

Probability: Measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty (from [3]).

Procedure: Series of steps that describes the execution of a task or piece of work.

Project developer: Any natural or legal, private or public person who operates or controls the CO_2 geological storage site or to whom decisive economic power over the technical functioning of the storage site has been delegated according to national legislation.

Regulator: Relevant competent national authority and/or international regulatory body.

Reliability: The ability of an item to perform a required function under a given conditions for a given time interval (from [21]).

Risk: Effect of *uncertainty* on objectives. Risk is often expressed in terms of a combination of the *consequences* of an event and the associated *likelihood* of occurrence (from [3]). See also *Failure risk*.

Risk analysis: Process to comprehend the nature of *risk* and to determine the *level of risk* (from [3]).

Risk assessment: Overall process of *risk identification*, *risk analysis* and *risk evaluation* (from [3]).

Risk criteria: Terms of reference against which the significance of a risk is evaluated (from [3]).

Risk evaluation: Process of comparing the results of *risk analysis* with *risk criteria* to determine whether the risk and/or its magnitude is acceptable or tolerable. Risk evaluation assists in decisions about risk control measures.

Risk identification: Process of finding, recognizing and describing *risks*. Risk identification involves the identification of risk sources, events, their causes and their potential consequences. Risk identification can involve historical data, monitoring data, theoretical analysis, informed and expert opinions and stakeholder's needs (from [3]).

Risk control measures (for risks to well integrity): Those measures taken to reduce the risks to the *well integrity* by:

- reduction in the probability of failure
- mitigation of the consequences of failure (based on [22]).

Risk source: Element which alone or in combination has the intrinsic potential to give rise to risk. A risk source can be tangible or intangible (from [3]).

Safeguard: Preventive or corrective measure to avoid risks developing into incidents, or mitigate their effects. A safeguard may also aim to reduce uncertainty associated with the probability and consequence of a potential hazardous feature, event or process.

Should: Verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required.

Site closure: Closure and abandonment of a storage site, including plugging and abandonment of all unplugged wells within the permit area (e.g., that have been used for monitoring after cessation of injection), and the decommissioning of all associated surface or subsurface facilities. **NB!** Site closure is here defined differently from the EU CCS Directive [5], where it is defined as cessation of CO_2 injection.

Storage integrity: Storage refers to a process for retaining captured CO_2 within a defined storage volume and its integrity refers to the technical, operational or organizational solutions which contribute to reduce the risk of leakage of CO_2.

Storage permit: A written decision authorizing CO_2 geological storage within a prescribed storage volume by a CO_2 geological storage project developer, and specifying the conditions under which it may take place, issued by the competent authority.

Storage site: Defined volume area within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities.

Storage volume: Collection of geological storage and barrier formations that contribute to provide secure long-term CO_2 geological storage. The storage volume includes the target storage formation and any secondary containment formations, i.e., shallower permeable geological formations that may contain CO_2 that has migrated from the target storage formation.

Laterally the storage volume will be bounded by the lateral boundaries of the permit area, or by the contours of the lateral seal. Analogous terms used in the EU CCS Directive and the proposed underground injection control (UIC) regulations for CCS in the US are storage complex and area of review, respectively.

Surface casing: First casing on which a BOP is installed.

Technology Qualification: Process of providing the evidence that the technology will function reliably within specific limits with an acceptable level of confidence. Qualification thus differs from certification and verification, which confirm that the technology complies with specified codes and procedures.

Transfer of Responsibility (ToR): Transfer of all rights and obligations associated with a storage site to a designated authority. Transfer of responsibility will normally be granted when the obligations in the site closure permit has been met with an adequate level of confidence.

Uncertainty: The state, even partial, of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood (from [3]).

Verification: Quality assurance process of determining compliance with a regulation, code, standard, or specification, or process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model. Verification is also used for comparison and evaluation of predicted and measured performance of a project in terms of, e.g., safety and environment, and/or CO_2 emission reduction at various stages throughout the project life. For CO_2 geological storage it is anticipated that verification will be done by the operator, competent authority and/or an independent third party.

Well barrier: Envelope of one or several dependent components preventing fluids or gases from flowing unintentionally from the formation, into another formation or to surface.

Well component: Individual pieces of equipment which are joined together as part of the well construction.

Well control: Collective expression for all measures that can be applied to prevent uncontrolled release of wellbore effluents to the external environment or uncontrolled underground flow.

Well integrity: The ability of the well to perform its required function effectively and efficiently whilst safeguarding life and environment. The required function of suspended and abandoned wells is to maintain zonal isolation.

Well intervention: Any operation carried out on a well during, or at the end of its productive life, that alters the state of the well and/or well geometry, provides well diagnostics or manages the production of the well.

Well qualification: The process of providing the evidence that a well will function reliably within specified operational limits with an acceptable level of confidence.

Well qualification activity: Activity aiming at providing evidence that a risk is adequately addressed (testing, analysis, documenting previous experience, developing operational procedures, etc).

Well qualification plan: The qualification activities specified with the purpose of generating qualification evidence and the logical dependencies between the individual pieces of qualification evidence.

Wellbore: The physical hole that makes up the well. It can be cased, open, or a combination of both. Open means open for fluid migration laterally between the wellbore and surrounding formations. Cased means closing of the wellbore to avoid such migration.

B. GENERIC FAILURE MODES FOR WELL INTEGRITY UNDER EXPOSURE TO CO_2

Generic check list of failure modes and failure mechanisms for wells under exposure to CO_2 can be found in Table 11. Some of these are illustrated in Figure 9:

a) between cement and outside of casing;
b) between cement and inside of casing;
c) through the cement;
d) through the casing,
e) through fractures in cement,
f) between cement and formation,

Also (from [30]):

- through completion equipment (packers, plugs, safety valves),
- through tubing hangers.

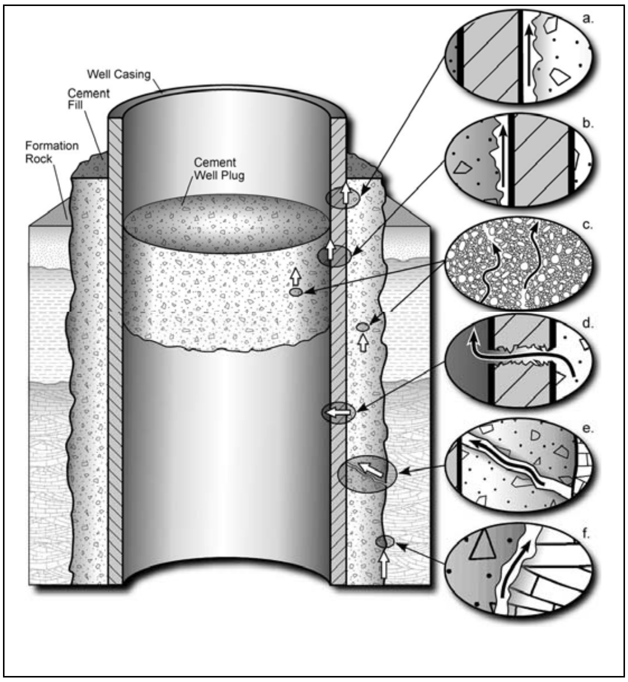

Figure 9: Schematics of possible leakage pathways along a well (from [31]).

Table 11: Generic check list of failure modes and failure mechanisms for wells (including active, suspended and P&A) under exposure to CO_2.

No.	Well Component	Failure mode	Failure mechanism
1	**Well**		
1.01	Any part of the well	Misjudgement of status	- Missing critical data - Poor data
2	**Upper Completion**		
2.01	Production packer (including seal assemblies)	Material yields or cracks	- Materials of construction lose their mechanical strength and begin to yield (hot), or brittle fracture if subjected to very cold conditions; - Materials on construction do not have capacity to resist pressure forces.
2.02		Material degradation	- Compatibility with CO_2 and other trace products in fluid stream; - Degradation under chemical stimulus; - H_2S cracking (corrosion) (Consider if H_2 is likely).
2.03		Unreliable material performance	- Explosive decompression; - Improper hardness at all conditions; - Degradation under chemical stimulus or under production fluid conditions.
2.04		Slipping	- Thermal expansion (or contraction) of tubing places additional load on locking mechanism; - Locks attempt to hold on to a worn or corroded casing wall; - Unstable well flow cycles material to fatigue failure
2.05	Tubing and jewellery	Material degradation	- Corrosion from fluids or from annulus souring; - Erosion (high flow rates, wireline intervention, tubing movement).

No.	Well Component	Failure mode	Failure mechanism
2.06		Material yields (cracks)	- Pressure and temperature causes metal to yield; - Unstable flow causes fatigue; - Improper tubing movement causes buckling or necking.
2.07		Tools stuck downhole	- Tubing and liner not in gauge.
2.08	Completion String Couplings	Material degradation	- Corrosion from fluids or from annulus souring; - Erosion (high flow rates, wireline intervention, tubing movement).
2.09		Material yields (cracks)	- Pressure and temperature causes metal to yield; - Unstable flow causes fatigue; - Improper tubing movement causes buckling or necking.
2.10		Seal fails	- Improper coupling connection used for CO_2 service (no metal to metal); - Improper assembly of coupling; coupling damaged before or during make-up; - Coupling backs off; - Corrosion cell within coupling threads; - Couplings back-off during running (rotation).
2.11	SCSSV	Material degradation	- Corrosion from fluids; - Erosion (wireline intervention, high flow rates); - Elastomer explosive decompression; - Elastomer degradation under fluids; - Elastomer hardness poor under certain conditions
2.12		Material yields (cracks)	Materials on construction do not have capacity to resist pressure forces or remain ductile at certain temperatures;
2.13		Control line failure	- Control line blockage; - Control line disconnects from coupling; - Control line breaks owing to fatigue; - Control line is eroded by rubbing;
2.14	Wellhead & Christmas Tree	Material degradation, or Unreliable material performance	- Explosive decompression; - Improper hardness at all conditions; - Degradation under chemical stimulus; - Degradation under production fluid conditions
2.15		Material yields (cracks)	- Materials of construction loose their mechanical strength and begin to yield (hot), or - Brittle fracture if subjected to very cold conditions; - Materials on construction do not have capacity to resist pressure forces
2.17		Corrosion of metal from inside	- Thinning of pressure envelope owing to corrosion; - Embrittlement if H_2S is present and not to NACE standard
2.18		Cracks from Cathodic protection; Corrosion from the environment; Loss of containment	- Hydrogen embrittlement; - External corrosion
2.19		Stress from piping on tree	- Piping and tree movements place unacceptable stress on wellhead; - "Water Hammer"
2.20		Stress from well supporting structure and environment	- Structural events and tree movements place unacceptable stress on wellhead
3	**Lower Completion**		
3.01	Open hole - uncased	CO_2 is not injected in the zone of interest	- Thief zone

No.	Well Component	Failure mode	Failure mechanism
3.02	Sand control	Equipment failures	- Materials incompatibility, - Deterioration of equipment, - Mechanical failures of equipment
3.03	Stimulation	Fracture of cap rock	- Hydraulic fracture job
4	**Casing/Liner/Cement**		
4.01	Casing/Liner	Material Degrades	- Corrosion from annulus fluids (aerobic or anaerobic); - Corrosion from reservoir fluids; (only for the production string) - Embrittlement from sour annulus
4.02		Material yields (cracks)	- Materials on construction do not have capacity to resist pressure forces or remain ductile at certain temperatures; (this only applies to the strings that actually see the CO_2)
4.03		Tools stuck downhole	- Tubing and liner not in gauge
4.04	Connections	Material degradation	- Corrosion from annulus fluids (aerobic or anaerobic); - Corrosion from reservoir fluids; - Embrittlement from sour (H_2S) annulus
4.05		Material yields (cracks)	- Materials of construction do not have capacity to resist pressure forces or remain ductile at certain temperatures; - Drilling dog-leg adds additional stress; - Local stress associated with rock movements place excessive stress load on casing causing collapse. Rock movement may be caused by one or more of the following: i) compaction in overburden related to changes in reservoir rock; ii) gas seepage through overburden; iii) reactivation of faults or new faults in overburden affecting well path.
4.06		Seal fails	- Coupling incorrectly installed; - Rock movement stresses pull couplings apart (axial) or collapse (pressure); - Coupling backs off during running (rotation)
4.07	Conductor	Corrosion of surface conductor onshore and platform wells	Collapse under weight
4.08		Hydraulic damage of foundation soils around surface conductor	Collapse under weight
4.09	Cement	Leak behind casing	- CO_2 degradation of cement; - H_2S degradation of cement; - Magnesium chloride degradation; - Thermal cracking and/or de-bonding (micro-annulus between cement and casing) due to Joule-Thomson effect during injection into e.g.. Depleted gas reservoir; - Pre-existing channels in cement; Pre-existing mirco-annulus between casing and cement.
4.10		Cracked cement and casing and/or debonding	- Different relative movement along wellbore due to subsidence of reservoir and/or expansion due to injection (e.g. "shear, kink, collapse") Ref geomechanical effects e.g. Ekofisk
4.11		Poor cement job	- Centralisers
4.12		Damaged cement across reservoir interval	- Pressure tests (higher pressures) - Temperature and pressure cycling - Acids, chelators, stimulation
5	**Annuli**		
5.01		Frozen well	- Leak to annulus: - Cold fluid entering tubing

No.	Well Component	Failure mode	Failure mechanism
6	**Injection system**		
6.01		Unintended phase change in the wellbore	- Both gas and dense phase CO_2 present in the wellbore
6.02		Equipment failures	- Pipeline specs inconsistent with materials specs of well
6.03		Tubing shocks	- Fluctuations due to start up (phase transition)

C. EXAMPLE OF A RISK ANALYSIS AND EVALUATION LOG SHEET

Table 12: Example of a risk analysis and evaluation log sheet

ID	Failure mode	Well info	Indicators of sufficient well integrity under exposure to CO_2	Indicators of insufficient well integrity under exposure to CO_2	Risk category			Comments
					Cons.	Likelihood.	Risk	
1	**Surface casing cement**							
	Cement bond with formation	G class cement	Generally G class cement is compatible with all formations encountered	No indication of good centralization	4	3	🟨	
	Cement degradation caused by CO_2		In case cement is in place, properly centralized and properly bonded cement degradation is not an issue.	Class G cement was not intended for CO_2 corrosive environment.	3	1	🟩	
2	**Surface casing**							
	Casing condition under exposure to CO_2	Grade: Weight: Steel type: Wall thickness:		In the event that the casing is exposed to a corrosive CO_2 environment because of cement deterioration, the carbon steel is expected to corrode rapidly.	5	5	🟥	
3	**Top cement plug**							
	Verification of top cement plug	The plug was not tested		There has been no sufficient verification of the barrier	4	5	🟥	

ID: for documentation purposes each failure mode should be numbered.

Failure mode: all failure modes and uncertainties should be identified and documented.

Well info: well information related to specific failure modes should be specified.

Indicators of sufficient well integrity under exposure to CO_2: indicators of sufficient well integrity should be identified and documented.

Indicators of insufficient well integrity under exposure to CO_2: indicators of insufficient well integrity should be identified and documented.

Consequence: the consequence identified according to principles given in Section 2.4.2.

Likelihood: the likelihood identified according to principles given in Section 2.4.2.

Risk: the risk classification should follow the principles given in Section 2.5.

Risk category:

- L = Low
- M = Medium
- H = High

Risk category is automatically calculated based on the consequence and likelihood categories.

Comments: additional comments needed to understand the information given.

D. COMPARING STORAGE SITES WITH LARGE NUMBERS OF EXISTING WELLS

This Appendix provides supplementary information to Section 2.3.3.

The integrity of abandoned wells is typically uncertain and costly to ascertain. Mature (onshore) hydrocarbon fields may contain tens to hundreds of such wells. Well integrity risk assessment of such fields prior to M2 should be iterative to deal with the high level of uncertainty.

A first-pass risk identification activity may be made more efficient by grouping wells into categories based on the amount of information available about their condition. Further categorisation will depend on the nature and amount of information available. For a detailed discussion refer to *T. L. Watson and S. Bachu paper on Identification of Wells with High* CO_2*-Leakage Potential in Mature Oil Fields Developed for* CO_2*-Enhanced Oil Recovery [29]*.

Figure 10 shows an example categorisation system for a storage site (or sites) where the following information is assumed to be available for a significant proportion of the abandoned wells (optimistic case):

- the number of well barriers above CO_2 storage interval;
- the cement quality of barriers (including design, placement and verification).

The four categories are defined as follows:

Category 0) insufficient information to determine well integrity based on these criteria;

Category 1) wells with an absence of barriers or poor cement quality on the barriers present;

Category 2) wells with adequate proven cement quality for one barrier;

Category 3) wells with adequate proven cement quality on two or more barriers.

The terms *insufficient*, *poor*, *adequate* and *proven* used here form the basis of the assessment and should be defined on a case by case basis as a function of the risk criteria specified in Section 2.1.3.

Category 0

Wells that do not have the minimum level of information required to describe the presence and condition of cement barriers. Such information may be derived from, for example:

- well completion report;
- production history;
- type of well and date of completion;
- applicable regulations of the time.

Categories 1-3

The well barriers above the CO_2 storage interval should be identified. In an abandoned well a barrier typically comprises either a solid cement plug in contact with the inner wall of the well casing and cement between the casing and the rock formation, or, if the casing is (partially) removed, by a so-called pancake plug, i.e., a cement plug filling the entire space enclosed by the rock formation in a portion of the wellbore trajectory.

For CO_2 geological storage it is recommended that abandoned wells that penetrate a target formation for CO_2 storage has at least two barriers above the target storage formation. Furthermore, if part of the casing may be exposed to CO_2 and the annulus between the casing and cement may provide a pathway for leakage of CO_2 or formation fluid to escape from the storage complex, then it is recommended that the abandonment should include a pancake plug. However, the latter recommendation is not reflected in the categorisation described here.

An example of well barriers is shown in Figure 11. If a cement plug is placed inside the casing, then the well barrier comprises of the envelope consisting of the cement plug, the casing and the cement in the annulus outside the casing. Two independent barriers mean that the same well component is not part of the well barrier envelope for both barriers. For instance, if two well barrier envelopes include the same casing so that corrosion of the casing or de-bonding of the casing and cement is enough to cause failure of both well barriers, then the barriers are not independent.

‘Proven cement quality’ during a first-pass identification of risks should mean that the requirements in applicable regulations and standards have been met and/or that a positive cement evaluation log is documented.

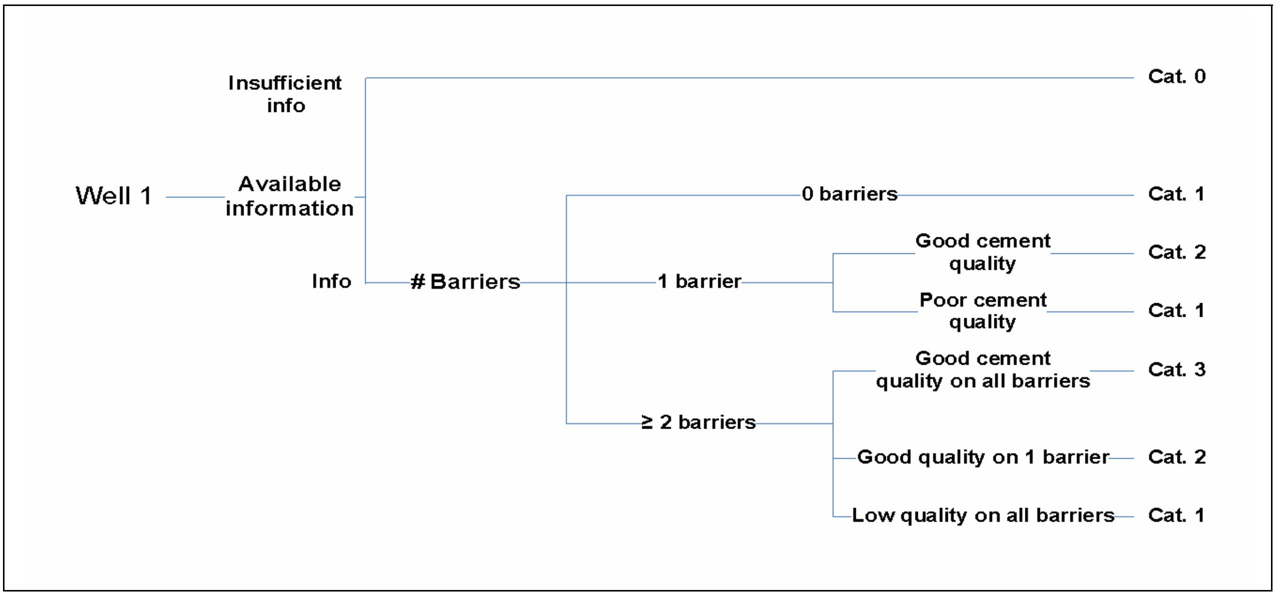

Figure 10: Example system for the categorisation of abandoned wells into four classes.

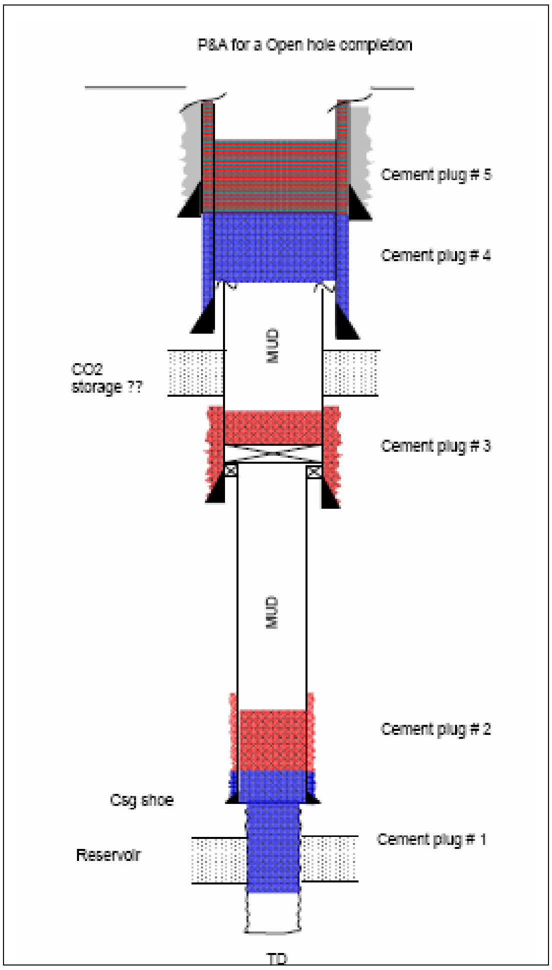

Figure 11: Example of cement barriers for a plugged and abandoned open-hole completion. From [20].

References

1. CO2QUALSTORE Guideline for Selection and Qualification of Sites and Projects for CO_2 Geological Storage. 2010. Oslo: DNV. Report No.: 2009-1425. www.dnv.com/co2qualstore
2. *ISO 31000, Risk Management – Principles and guidelines*, first edition. 2009. Geneva: ISO. www.iso.org
3. *ISO Guide 73 - Risk management vocabulary*, first edition. 2009. Geneva: ISO. www.iso.org
4. Metz, B., Davidson, O., de Coninck H.C., Loos, M. and Meyer L.A. eds. 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Cambridge, UK, New York, USA: Cambridge University Press.
5. Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide. 2009. Brussels: Commission of the European Communities.
6. Federal Requirements Under the Underground Injection Control Program for Carbon Dioxide Geologic Sequestration Wells Proposed Rule. 2008. Washington D.C.: U.S. Environmental Protection Agency.
7. Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. eds. 2006. *IPCC Guidelines for National Greenhouse Gas Inventories*. Japan: IGES.
8. Offshore Petroleum Amendment (Greenhouse Gas Storage) Bill. 2008. Canberra: The Parliament of the Commonwealth of Australia, House of Representatives.
9. Regulatory Framework for Industrial Greenhouse Gas Emissions. 2008. Ottawa: Government of Canada.
10. OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations. 2007. London: OSPAR Commission. OSPAR 07/24/1-E, Annex 7.
11. OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic, Annex II and III. 2007. London: OSPAR Commission.
12. Legal Aspects of Storing CO_2 – Update and Recommendations. 2007. Paris: OECD/IEA. www.iea.org/publications
13. Developing Monitoring, Reporting And Verification Guidelines For CO_2 Capture and Storage under The EU ETS. Report No. COAL R277 DTI/Pub URN 05/583. 2005. London: ERM and DNV.
14. Røed-Larsen, T., Flach, T. and Uzzell, J. 2009. Verification and Accreditation Schemes for Climate Change Activities: A Review of Existing National and International Requirements for Verification of Greenhouse Gas Reductions / Removals and Accreditation of Independent Verifiers. Implications for Long-Term Carbon Sequestration. *Geophysical monograph* **183**: 281-291.
15. Anderson, J., de Coninck, H., Curnow, P., Flach, T., Reiner, D., Richardson, P., Shackley, S., Upham, P., Sigurthorsson, G. 2007. The ACCSEPT Project – Summary of the Main Findings and Key Recommendations. Final report. Oslo: DNV. www.accsept.org
16. CCS Guidelines: Guidelines for Carbon Dioxide Capture, Transport, and Storage. 2008. Washington DC: World Resources Institute (WRI). www.wri.org/publication/ccs-guidelines
17. Kaldi, J.G. and Gibson-Poole C.M. 2008. *Storage Capacity Estimation, Site Selection and Characterization for CO_2 Storage Projects.* Canberra: CO2CRC. www.co2crc.com.au
18. Directive 2007/589/EC of the European Parliament and of the Council establishing guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC. 2007. Brussels: Commission of the European Communities.
19. *NORSOK Standard Z-013 - Risk and Emergency Preparedness Analysis*, Rev 2. 2001. Oslo: Standards Norway. www.standard.no/en/sectors/Petroleum
20. *NORSOK Standard D-010 - Well integrity in drilling and well operations*, Rev 3. 2004. Oslo: Standards Norway. www.standard.no/en/sectors/Petroleum
21. *RP-A203, Qualification Procedures for New Technology*. 2001. Oslo: DNV. http://exchange.dnv.com:6389/dynaweb/offshore/rp-a203
22. *OSS-401, Technology Qualification Management*. 2006. Oslo: DNV. http://exchange.dnv.com:6389/dynaweb/offshore/oss-401
23. BS 5760-5, *Reliability of systems, equipment and components. Guide to failure modes effects and criticality analysis (FMEA and FMECA).* 1991.
24. IEC-60300, *Dependability management.* 1993.
25. ISO/IEC Guide 98, *Guide to the expression of uncertainty in measurement.* 1993.
26. ISO 17776, *Petroleum and natural gas industries – Offshore production installations – Guidelines on tools and techniques for hazard identification and risk assessment*, First edition. 2000.
27. BS: IEC61882, *Hazard and operability studies (HAZOP studies)*- Application Guide. 2002.
28. *NORSOK Standard M-710, Qualification of non-metallic sealing materials and manufactures*, Rev 2. 2001.
29. Watson, T.L., Bachu, S. 2008. Identification of Wells with high CO_2-Leakage Potential in Mature

Oil Fields Developed for CO_2-Enhanced Oil Recovery. SPE/DOE Symposium on Improved Oil Recovery, 20-23 April 2008, Tulsa, Oklahoma, USA. 112924-MS.

30. Vignes, B., Enoksen, A.M., Ovesen, M. 2010. CO_2 Injection and Storage – Qualification of Well Barriers in Adjacent Wells. Offshore Technology Conference, 3-6 May 2010, Houston, Texas, USA.

31. Celia, M.A., Bachu, S., Nordbotten, J.M., Kavetski, D., Gasda, S.E. 2005. Modeling Critical Leakage Pathways in a Risk Assessment Framework: Representation of Abandoned Wells, Paper presented at Fourth Annual Conference on Carbon Capture and Sequestration DOE/NETL.

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DNV assists its customers in managing risk by providing three categories of service: classification, certification and consultancy. Since establishment as an independent foundation in 1864, DNV has become an internationally recognised provider of technical and managerial consultancy services and one of the world's leading classification societies. This means continuously developing new approaches to health, safety, quality and environmental management, so businesses can run smoothly in a world full of surprises.

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