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Carbon dioxide capture, transportation and geological storage — Geological storage

Capture, transport et stockage géologique du dioxyde de carbone — Stockage géologique

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 265, *Carbon dioxide capture, transportation, and geological storage*.

Introduction

Geological storage of carbon dioxide (CO_2) is recognized as a key technology for abatement of CO_2 emissions to the atmosphere or ocean and is an essential component in the process of carbon dioxide capture and storage (CCS)[1]. The objective of this document is to provide recommendations for the safe and effective storage of CO_2 in subsurface geologic formations through all phases of a storage project life cycle (see Figure 1). While CCS is a nascent industry, this document is supported by a wide range of operational experiences in pilot to commercial scale carbon dioxide storage projects that have used methods and technologies mostly developed and widely deployed by the oil and gas industry including CO_2-enhanced oil recovery (EOR). This document applies to injection of CO_2 into geologic units for the sole purpose of storage and does not apply to CO_2 injection for hydrocarbon recovery, or storage of CO_2 that occurs in association with carbon dioxide enhanced hydrocarbon recovery. [ISO 29716 is in development to address carbon dioxide storage using enhanced oil recovery (CO_2-EOR)]. This document is supplemented by recommended practice manuals for CO_2 storage and numerous standards and technical recommendations developed for the oil and gas industry. [See Bibliography for selected references (References [1] to [12])].

Carbon dioxide capture, transportation and geological storage — Geological storage

1 Scope

This document

a) establishes requirements and recommendations for the geological storage of CO_2 streams, the purpose of which is to promote commercial, safe, long-term containment of carbon dioxide in a way that minimizes risk to the environment, natural resources, and human health,

b) is applicable for both onshore and offshore geological storage within permeable and porous geological strata including hydrocarbon reservoirs where a CO_2 stream is not being injected for the purpose of hydrocarbon production or for storage in association with CO_2-EOR,

c) includes activities associated with site screening and selection, characterization, design and development, operation of storage sites, and preparation for site closure,

d) recognizes that site selection and management are unique for each project and that intrinsic technical risk and uncertainty will be dealt with on a site-specific basis,

e) acknowledges that permitting and approval by regulatory authorities will be required throughout the project life cycle, including the closure period, although the permitting process is not included in this document,

f) provides requirements and recommendations for the development of management systems, community and other stakeholder engagement, risk assessment, risk management and risk communication,

g) does not apply to, modify, interpret, or supersede any national or international regulations, treaties, protocols or instruments otherwise applicable to the activities addressed in this document, and

h) does not apply to or modify any property rights or interests in the surface or the subsurface (including mineral rights), or any pre-existing commercial contract or arrangement relating to such property.

The life cycle of a CO_2 geological storage project covers all aspects, periods, and stages of the project, from those that lead to the start of the project (including site screening, selection, characterization, assessment, engineering, permitting, and construction), through the start of injection and proceeding through subsequent operations until cessation of injection and culminating in the post-injection period, which includes a closure period. Figure 1 illustrates the limits of this document.

NOTE 1 This document does not address any post-closure period or specify post-closure period requirements.

This document does not apply to

— the post-closure period,

— injection of CO_2 for enhancing production of hydrocarbons or for storage associated with CO_2-EOR,

— disposal of other acid gases except as considered part of the CO_2 stream,

— disposal of waste and other matter added for purpose of disposal,

— CO_2 injection and storage in coal, basalt, shale and salt caverns, or

— underground storage using any form of buried container.

NOTE 2 This document may not be suitable for research projects, for example, those with a primary objective to test technologies or methods of monitoring.

NOTE 3 The closure period in this document does overlap with the post-closure phase of the EU regulatory definition. This document, however, is not concerned with transfer of liability.

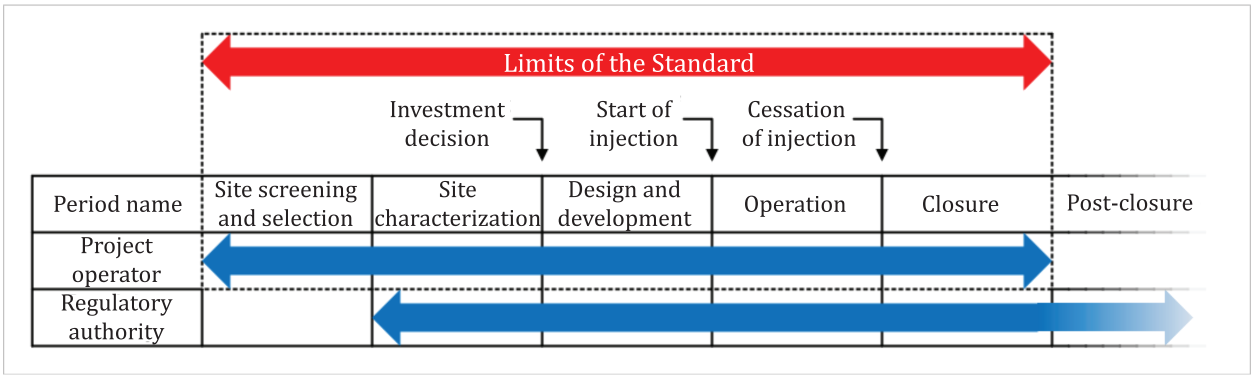

Figure 1 — Entities involved in the storage project life cycle

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1
abandonment
process and procedures used to permanently end the operation of a well

Note 1 to entry: Well abandonment is designed to eliminate the physical hazard of the well (the hole in the ground), eliminate a pathway for migration of contamination, and prevent changes in the hydrogeologic system, such as the changes in hydraulic head and the mixing of formation fluids between hydraulically distinct strata.

3.2
acceptable risk
risk (3.39) borne by the *project operator* (3.33) and others, having regard to legal obligations and management policies

3.3
area of review
geographical area(s) of a *storage project* (3.56), or part of it, designated for assessment of the extent to which a storage project, or part of it, could affect life and human health, the environment, competitive development of other resources, or infrastructure

Note 1 to entry: The delineation of an area of review defines the outer perimeters on the land surface or seabed and water surface within which assessments will be conducted as may be required by regulatory authorities.

3.4
baseline
reference basis for comparison against which project performance is monitored or measured

3.5
biosphere
realm of living organisms including the atmosphere, on the ground surface and in soils, in oceans and seas, in surface waters such as rivers and lakes, and in the subsurface above the *storage complex* (3.54)

3.6
carbon dioxide (CO_2) plume
region within geologic strata where CO_2 is present in free phase

3.7
carbon dioxide (CO_2) stream
stream consisting overwhelmingly of carbon dioxide

Note 1 to entry: The stream is a fluid mixture that may include any incidental associated substances derived from the source materials or the capture process and any substances added to the stream to enable or improve the injection process and/or trace substances added to assist in CO_2 migration detection.

3.8
casing
pipe material placed inside a drilled hole to prevent the surrounding strata from collapsing into the hole

Note 1 to entry: There are many acceptable variations on casing design but typical types of casing in most injection wells are:

a) surface casing, i.e. the outermost casing that extends from the surface to the base of the lowermost *protected groundwater* (3.37);

b) intermediate casing is one or more strings of casing installed between the surface and long-string casing for various design reasons;

c) long-string casing, which extends from the surface to or through protected groundwater to the bottom of the well.

3.9
casing shoe
reinforcing steel collar that is screwed onto the bottom joint of the *casing* (3.8) to prevent abrasion or distortion of the casing when it is forced past obstructions on the wall of the borehole

3.10
closure period
period between the cessation of injection and the demonstration of compliance with the criteria for *site closure* (3.52)

3.11
containment
retention of CO_2 and formation fluids within a *storage complex* (3.54)

3.12
corrective action
action taken to correct material irregularities or to contain breaches in order to prevent or minimize damage to, or release of CO_2 from, a *storage complex* (3.54)

Note 1 to entry: Corrective actions are implemented after an irregularity has occurred to help prevent or minimize damage.

3.13
decommission
take an engineered system or component out of service, render it inoperative, dismantle and decontaminate it

3.14
element of concern
valued element or objective for which *risk* (3.39) is evaluated and managed

3.15
elevated pressure zone
zone within a *storage complex* (3.54) where there is sufficient pressure to cause flow of formation fluids through a pathway from the *storage unit(s)* (3.59) to outside the storage complex into economic resources, *protected groundwater* (3.37), or the *biosphere* (3.5)

3.16
event
material occurrence or change in a particular set of circumstances

3.17
geological storage
long-term *containment* (3.11) of *CO2 streams* (3.7) in subsurface geological formations

Note 1 to entry: Long-term means the minimum period necessary for CO_2 geological storage to be considered an effective and environmentally safe climate change mitigation option.

Note 2 to entry: The term "sequestration" has been used by a number of countries and organizations instead of "storage" (e.g. the international "Carbon Sequestration Leadership Forum"). The two terms are considered to be synonymous, and only "storage" is used in this document.

Note 3 to entry: Within the context of this document, geological storage

a) is applicable to permeable and porous strata that do not contain *protected groundwater* (3.37),

b) is applicable to nonproducing hydrocarbon reservoirs, and

c) does not apply to

   1) CO_2 injection and storage in unmineable coal beds, basalt formations, shales, and salt caverns,

   2) CO_2 injection and storage in any formations containing producible hydrocarbons, and

   3) underground storage in materials involving the use of any form of man-made containers.

3.18
geosphere
solid earth below the ground surface and bottom of rivers and other bodies of water on land, and below the sea bottom offshore

3.19
injectivity
rate and pressure at which fluids can be pumped into the *storage unit* (3.59) without fracturing the storage unit

3.20
leakage
unintended release of fluid out of a pre-defined *containment* (3.11)

Note 1 to entry: In this document, the pre-defined containment is the *storage complex* (3.54).

3.21
legacy well
pre-existing well within the *area of review* (3.3) of a CO_2 *storage project* (3.56) that was drilled for a different purpose than CO_2 injection or *monitoring* (3.27) of the respective CO_2 storage project

3.22
likelihood
chance of something happening, expressed qualitatively or quantitatively and described using general terms or mathematically, e.g. by specifying a probability or frequency of occurrence over a given period

3.23
liner
casing (3.8) string that does not extend to the surface

3.24
management of change
procedure used when making a change to the process equipment or operating procedures to detail changes made and to document steps taken to inform and train operating personnel and relevant stakeholders on process changes

3.25
mechanical integrity
mechanical condition of a well, such that engineered components maintain their original dimensions and functions, solid geological materials are kept out of the wellbore, and fluids including CO_2 are prevented from uncontrolled flow into, out of, along, or across the wellbore, cement sheath, annulus, *casing* (3.8), *tubing* (3.62), and/or *packers* (3.30)

3.26
mechanical integrity test
MIT
test performed on a well to confirm that it maintains internal or external *mechanical integrity* (3.25)

Note 1 to entry: MITs are a means of measuring the adequacy of the construction of a well and a way to detect problems within the well system.

3.27
monitoring
continuous or repeated checking, supervising, critically observing, measuring or determining the status of a system to identify change from *baseline* (3.4) or variance from an expected performance level

Note 1 to entry: In case of *geological storage* (3.17), monitoring is not restricted to the technical infrastructure of an operator. It also includes the wider surroundings of the surface and/or subsurface *storage site* (3.58).

3.28
operational period
period enduring from CO_2 stream first entering the wellhead for storage until injection ceases

3.29
overburden
geological material overlying an area or geological formation of interest in the subsurface

3.30
packer
mechanical device that seals the outside of *tubing* (3.62) to the inside of *casing* (3.8), isolating an annular space

3.31
post-closure period
period that begins after the demonstration of compliance with the criteria for *site closure* (3.52)

Note 1 to entry: In some countries, demonstration of compliance may need approval from a third party.

3.32
primary seal
continuous geological unit (known in reservoir engineering as caprock and in hydrogeology as aquitard or aquiclude) above a *storage unit* (3.59) that is part of a *storage complex* (3.54) and effectively restricts migration of fluids out of the storage unit and *leakage* (3.20) out of the storage complex

3.33
project operator
entity that is legally responsible for the CO_2 *storage project* (3.56)

3.34
project organization
project operator (3.33) and any subcontractor or other person or organization acting under the project operator's control or on behalf of the project operator

3.35
project personnel
person or persons employed by any member of the *project organization* (3.34)

3.36
project stakeholder
individual, group of individuals, or organization whose interests are or could be affected by a *storage project* (3.56)

Note 1 to entry: Stakeholders can include decision makers, employees, shareholders, academia, insurance companies, banks, community residents, suppliers, customers, non-governmental organizations, governments, regulators, labour unions, and other individuals or groups.

3.37
protected groundwater
water found beneath the water table in fully saturated soils and geologic formations that is used for human consumption, agricultural, or industrial uses or is protected from contamination by legislation or regulation

3.38
regulatory authority
entity that has legal authority to permit, approve, or otherwise authorize the siting, construction, testing, operation, *monitoring* (3.27), modification, plugging, or closure of a *geological storage* (3.17) site, well, unit, complex, or project and monitors compliance with the terms of the permit, approval, or authorization

3.39
risk
effect of uncertainty on project objectives [e.g. on performance metrics for an *element of concern* (3.14)], expressed in terms of the severity of consequences (negative impacts) of an *event* (3.16) and the associated *likelihood* (3.22) of their occurrence

Note 1 to entry: An effect is a deviation from the expected and can be either positive or negative.

Note 2 to entry: Objectives can have different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process).

3.40
risk analysis
process for understanding the nature and level of *risk* (3.39)

3.41
risk assessment
overall process of *risk identification* (3.45), *risk analysis* (3.40), and *risk evaluation* (3.43)

3.42
risk control
measure whose purpose is to reduce a specific *risk* (3.39) or avoid escalation of risk

3.43
risk evaluation
process of comparing the results of a *risk analysis* (3.40) with *risk evaluation criteria* (3.44) to determine whether the *risk* (3.39), its magnitude, or both are acceptable or treatment is required to reduce the risk

3.44
risk evaluation criteria
terms of reference against which the significance of *risk* (3.39) is evaluated

3.45
risk identification
process of finding, recognizing, and describing *risk* (3.39)

3.46
risk management plan
scheme specifying the approach, management components, and resources to be applied to the management of *risk scenarios* (3.48)

3.47
risk owner
person or entity with the accountability and authority to manage *risk* (3.39)

3.48
risk scenario
combination or a chain of circumstances through which a *threat* (3.60) can cause an *event* (3.16) to occur and through which the consequences of an event can have a negative impact on *elements of concern* (3.14)

3.49
risk treatment
process to reduce a specified *risk* (3.39) through implementation of *risk controls* (3.42)

3.50
secondary seal
geological unit that effectively restricts migration of fluids in the sedimentary succession between the *primary seal(s)* (3.32) and *protected groundwater* (3.37), protected resources, or the seabed

3.51
site characterization
detailed evaluation of one or more candidate sites for CO_2 storage identified in the screening and selection stage of a CO_2 *storage project* (3.56) to confirm and refine *storage complex* (3.54) integrity, storage capacity, and *injectivity* (3.19) estimates and provide basic data for initial predictive modelling of fluid flow, geochemical reactions, geomechanical effects, *risk assessment* (3.41), and *monitoring* (3.27) and *validation* (3.65) program design

3.52
site closure
end of the *closure period* (3.10), which occurs when the *project operator* (3.33) has demonstrated compliance with criteria for site closure

3.53
site screening and selection
initial evaluation of the suitability of geologically storing CO_2 at the regional or sub-regional scale by identifying, assessing, and possibly comparing candidate storage formations or sites

3.54
storage complex
subsurface geological system extending vertically to comprise *storage unit(s)* (3.59) and identified seal(s), and extending laterally to the defined limits of the CO_2 *storage project* (3.56)

Note 1 to entry: Limits can be defined by natural geologic boundaries, regulation, or legal rights.

3.55
storage facility
area on the ground surface or, in offshore cases, in the sea or on the sea bed, defined by the operator and/or regulatory agency, where CO_2 injection facilities are developed and operational activities [including *monitoring* (3.27)] take place

Note 1 to entry: In many instances, the storage facility and the *area of review* (3.3) may be coextensive. Because the areas have different derivations — the area of review being based on potential impacts and the storage facility being based on operational activities — there is a potential for the areas to be different for a specific project. Therefore, each term is used in this document to reflect its specific derivation and application.

3.56
storage project
physical and temporal extent of activities associated with a project for the *geological storage* (3.17) of CO_2 that includes site selection and characterization, *baseline* (3.4) data collection, permitting, design and construction of site facilities (site pipelines, compressors, etc.), well drilling, receipt of CO_2 at the *storage site* (3.58) and CO_2 injection during the active injection phase, and *site closure* (3.52) (including well and facilities abandonment)

Note 1 to entry: It also includes testing and *monitoring* (3.27) during all project phases.

3.57
storage project life cycle
stages of a *storage project* (3.56), beginning with those necessary to initiate the project (including site screening, assessment, engineering, and permitting) and leading up to the start of injection, followed by operations until the cessation of injection, and culminating in the *closure period* (3.10)

Note 1 to entry: This document does not include a *post-closure period* (3.31) in the storage project life cycle.

3.58
storage site
site that comprises the *storage facility* (3.55), *storage project* (3.56) wells, and the *storage complex* (3.54)

3.59
storage unit
geological stratum (or strata) into which CO_2 is injected for the purpose of storage

3.60
threat
element that alone or in combination with other elements has the potential to cause damage or produce a negative impact

3.61
tolerable risk
risk (3.39) considered as temporarily or conditionally acceptable

Note 1 to entry: It is tolerated in order to facilitate a gradual response [i.e. *monitoring* (3.27) and *risk treatment* (3.49)] until the risk has been reduced.

3.62
tubing
tubular string normally run inside the injection or production *casing* (3.8) that acts as the primary conduit for fluids

3.63
transfer of responsibility
transfer of all rights, responsibilities, and liabilities associated with a *storage site* (3.58) to a post-closure steward

3.64
unacceptable risk
risk (3.39) of a nature and level that is regarded as unacceptable by the *project operator* (3.33) or by an authority whose approval is required for the project to proceed

3.65
validation
confirmation that the system under consideration meets, in all respects, the specification of that system

3.66
verification
confirmation by examination and provision of objective evidence that specified criteria are met

Note 1 to entry: In the context of the Clean Development Mechanism (CDM), verification is the independent review by a designated operational entity of monitored reductions in anthropogenic emissions.

4 Management systems

4.1 Scope of activities

4.1.1 General

Management systems are essential for the implementation and public credibility of geological storage processes. Successful management systems are flexible so that operators can make changes during the project and are robust enough to ensure that they meet site-specific project and regulatory needs. Management systems for a storage project interconnect through all project activities and phases and provide an auditable trail of the decision-making processes.

The intent of management systems is to ensure that existing recommended practices are followed, and to allow and promote improvement in the management of the CO_2 storage site in accordance with 4.3. Management systems also help to ensure that quality assurance and quality control, regulatory compliance, process improvements, and efficiency improvements are integrated into regular management processes and decision-making, as well as ensuring project transparency so that project stakeholders, regulatory authorities, and the public develop confidence in the management and implementation of storage projects. Another important function of management systems is embedding a risk management process into the culture and practices of a storage project to help ensure that the events that can affect project objectives are identified and managed.

4.1.2 Storage project operator's roles and responsibilities

The project operator shall design and develop the injection operations of the CO_2 storage site (see 7.3 and 8.2) and be responsible for operations that fall within the project boundaries as defined within 4.2. In particular, the project operator shall be responsible for

a) all activities related to the storage project and for the coordination and integration of those activities, especially activities that involve the handling and fate of CO_2,

b) formulating a statement of the storage project's principles, values, and quantitative project objectives with reference to the storage permit, and communicating this statement throughout the project organization, to project stakeholders, and to regulatory authorities,

c) coordinating, integrating, and communicating the activities and responsibilities of the project organization to project stakeholders and regulatory authorities,

d) coordinating the activities of the members of the project organization,

e) monitoring compliance with this document by the project organization,

f) defining clear boundaries with the capture and transport operators and establishing the activities and responsibilities necessary to properly address interfaces among these systems,

g) project risk management during the life cycle of the storage project, and

h) determining and ensuring the availability and effectiveness of the energy, physical, financial, and human resources required to meet the objectives and principles (see 4.3) of the storage project.

The project operator can change over the project life cycle prior to site closure. In such cases, the former project operator shall be responsible for ensuring that all necessary documentation, materials, and processes are transferred to the subsequent project operator. The subsequent project operator shall be responsible for the effective transition of management systems and processes. Transferred records shall be retained by the subsequent project operator, and copies of the transferred records should be retained by the former project operators until the end of the closure period.

4.1.3 Stakeholder identification and engagement

The project operator shall identify project stakeholders early in the storage project life cycle and engage them during all phases of the project.

NOTE Examples of project stakeholders are included in the definitions.

4.1.4 Storage project delineation

The project operator shall describe the scope of the key project stages. This can be in accordance with Figure 1. The description of scope should maintain and communicate the clear alignment of project activities with the storage project's objectives and principles (see 4.3).

The project operator should organize, allocate human resources, and direct the activities of a storage project in accordance with the storage project periods specified in this subclause. A project operator may employ project stages different from that specified in this subclause, but should describe and document support for the alternative periods with reference to those specified in this subclause.

As detailed in the other clauses in this document, particular responsibilities apply to the project operator during specific project periods, including:

a) site screening and selection period: identifying and eliminating prospective sites that are unsuitable for storage in a manner consistent with 5.2;

b) site characterization period:

    1) completing a geological and hydrogeological characterization of the storage unit in accordance with 5.4.2 to provide a reasonable estimate of capacity and injectivity and to assess risk;

    2) evaluating and qualifying the sealing capacity of the primary seal in accordance with 5.4.3.1;

    3) characterizing the chemical composition of the CO_2 stream in accordance with 5.4.4 and conducting a geomechanical characterization of the storage unit and seal in accordance with 5.4.5;

c) design, development, and operation period:

    1) developing and implementing a risk management process in accordance with Clause 6;

    2) developing and disseminating protocols that promote the effective integrated functioning of the project organization;

    3) selecting appropriate materials and methods for site development in accordance with Clause 7;

    4) applying industry recommended practices for site design, development, and operations, including design of wellsites, operational procedures for drilling, facility construction,

monitoring hardware installation, and site-security and emergency procedures in accordance with Clauses 7 and 8;

5) developing operations and maintenance procedures for monitoring and improving the performance of the complete integrated storage project over the project life cycle in accordance with 7.6, 8.3 and 9.4;

6) establishing a provisional site closure plan as described in 10.3 and developing the quantitative key performance indicators expected to be used to demonstrate compliance with the criteria for site closure described in 10.2;

d) closure period:

1) finalizing the criteria for site closure as established in 10.2 and closure plan described in 10.3;

2) continuing to implement the risk management plan and risk treatment plans as described in 6.6 and 6.8;

3) plugging and abandoning injection, observation and monitoring wells as specified in the closure plan, and consistent with the requirements of 7.8;

4) implementing the monitoring program for the closure period described in 9.2.4; executing the site-closure qualification process as described in 10.4; and archiving of reports, results, and other data that form the basis for the site-closure qualification process.

NOTE Post-closure period: this document does not cover the post-closure period. See Figure 1.

4.2 Project boundaries

4.2.1 Responsibility

The project operator bears responsibilities attached to multiple overlapping work areas in which project boundaries may be defined in terms of legal descriptions (surveys), contracts, permit conditions, surface, seabed, and/or subsurface operational activities, and the physical effects (current or anticipated) of the project.

4.2.2 Organizational boundaries

The project operator for the storage project shall be identified and specific responsibilities and reporting relationships shall be delineated between the project operator and other members of the project organization. If control of the storage project is shared among organizations, the project's internal boundaries among organizations and areas of responsibility shall be delineated.

4.2.3 Operational boundaries

The operational boundary of a storage project encompasses the storage facility and the storage complex. The project operator shall plan for potential impacts on storage project operational activities from activities associated with the area of review or with other CCS components outside the operational boundaries, such as CO_2 capture, processing, and transportation, including planned and potential variations in these components.

4.3 Management commitment to principles

4.3.1 General

Persons or groups of people who are responsible for a storage project at the highest level shall demonstrate their commitment to industry recommended practices for the long-term safe geological storage of CO_2 by incorporating the principles specified in 4.3.2 to 4.3.4 into their actions and decisions.

4.3.2 Internal principles

The project operator shall:

a) operate on the basis of sound, state-of-the-art science and engineering;

b) seek cost-effective means, but allow a prudent margin for safety and environmental protection;

c) ensure safe CO_2 stream handling;

d) implement an appropriate risk management system;

e) establish systems that ensure the site is monitored throughout the project life cycle so that unplanned occurrences can be addressed promptly (see 9.4.3).

4.3.3 External principles

The project operator shall:

a) operate in an open and transparent fashion with project stakeholders and regulatory authorities to build public understanding, trust, and credibility;

b) establish a local stakeholder interaction strategy and regularly (before start-up of each project phase and then at least yearly or when significant changes occur) engage with and seek input from local stakeholders;

c) provide reports to the public when major milestones are reached or significant unplanned events occur;

d) seek independent assessments of significant project activities to ensure compliance with applicable standards and industry recommended practices.

4.3.4 Health, safety, and environmental principles

The project operator shall:

a) establish health, safety, and environmental protection for project personnel and local communities including ecosystems as the project's highest priorities;

b) develop and put in place an emergency response plan and required equipment or identify providers of equipment and services. Response plans should be coordinated with local emergency services and responsible regulatory authorities;

c) ensure that environmental and human health impacts of the storage project are minimized to an acceptable risk throughout the project life cycle;

d) provide the appropriate resources for continuous improvement of health, safety, and environmental protection;

e) on the basis of the project risk profile, document potential environmental impacts and present them to the project's stakeholders.

4.4 Planning and decision-making

4.4.1 General

The achievement of consistent results by the organization can be reached by the implementation of a management system.

NOTE Examples of management systems standards are ISO 9001 (Quality management systems) and ISO 14001 (Environmental management systems). ISO 31000 provides principles and generic guidelines on risk management.

4.4.2 Intellectual property

The project operator should negotiate and establish early in the storage project life cycle inter-organizational agreements that address the ownership of existing and potential intellectual property.

4.5 Resources

4.5.1 General

The project operator shall evaluate and document at regular intervals the available resource requirements under its responsibility.

4.5.2 Competence of personnel

The project operator shall determine the necessary competence of project personnel who could affect the principles, values and objectives of the project especially in the aspects of health, safety, and the environment, and ensure that these project personnel are competent on the basis of appropriate education, training, skills, or experience. The project operator shall provide training or take other actions necessary to achieve and maintain the appropriate project personnel competence levels.

The project operator shall retain suitable documented information as evidence of competence.

All project personnel shall be trained on safe operating procedures for the duration of the project relating to their job responsibilities and empowered with stop-work-authority related to safety issues.

4.5.3 Equipment management

The project operator shall retain, manage, and direct sufficient equipment and infrastructure to facilitate all project stages. The project operator should document infrastructure and equipment allocations for the storage project. The project operator should establish emergency response and remediation provisions for responding to loss of equipment or infrastructure failure to a point that adversely affects site development, operations, or closure activities.

4.6 Communications

4.6.1 General

The project operator shall develop a stakeholder engagement plan early in the project life cycle. The stakeholder engagement plan should identify a designated media liaison and may include additional liaisons external to the project, e.g. a research body, natural resource agency, or university.

The project operator shall ensure that communication processes are clearly defined in plain language and that they are effective in advancing the storage project’s objectives.

4.6.2 Public communications

The project operator shall develop an open public engagement strategy to build public understanding, trust, and credibility. The engagement strategy should include publicly communicating clear and accurate information on project plans and activities, including regulatory matters, standards performance, and safety and environmental issues (see 6.10 and 4.3.4) throughout the project life cycle. The project operator should obtain input from the public on the effectiveness of the engagement process and should have a designated individual having published contact information to respond to community questions.

4.6.3 Internal communications

Project personnel shall be fully informed of the nature and circumstances of the storage project, its goals and targets, and its progress in achieving those goals. All internal communications shall be clear, direct, and accurate.

Project personnel shall be briefed on the regulatory expectations and requirements of government agencies and any guidance or operating procedures referenced by government regulations.

Project personnel should be informed of all stakeholder groups and their project concerns to lessen any public opposition and address public concerns.

Internal communications should be conveyed to project contractors and consultants where appropriate.

4.7 Documentation

4.7.1 General

Documentation systems shall be designed to meet the needs of the project operator and the regulatory authorities, from both an internal and external data-collection and reporting perspective. Institutional knowledge should be recorded to allow for the transfer of pertinent project information to a subsequent project operator to meet regulatory reporting requirements, as needed.

4.7.2 Information management

The storage project documentation shall include:

a) statements of objectives and principles;

b) plans, procedures, and records required by this document, including the risk management plan, the monitoring plan, the stakeholder engagement plan and closure plan;

c) storage project information, including documents, records, and other data determined by the project operator to be necessary for the effective planning, operation, and control of its processes.

5 Site screening, selection, and characterization

5.1 General

The purpose of site screening and selection is to identify prospective CO_2 storage sites, gather necessary information on the prospective sites, and use this information to select the candidate sites for further characterization. The purpose of subsequent characterization and assessment of a site is to reduce uncertainty caused by geological heterogeneity and limited data availability. This characterization should demonstrate that the candidate site is capable of accepting the CO_2 stream at the projected injection rates (see 8.2.4.3) and has the appropriate storage-complex characteristics that will ensure effective containment of the injected CO_2 over the time scales required by the regulatory authorities in the applicable jurisdiction.

In addition, based on sound scientific approaches, best practice methodologies, and available data, the characterization and assessment process shall demonstrate that storage of the CO_2 stream at the candidate site(s) does not pose unacceptable risks to:

— other resources;

— the environment;

— existing infrastructure;

— human health;

— project developers, owners, and personnel.

Thus, while this document presents the screening, selection, and characterization process in a linear fashion, users of this document should anticipate applying its guidance iteratively.

Collaboration and coordination are expected between site screening, selection, and characterization and upstream activities, such as capture, which informs about CO_2 stream flow rate, composition, and transportation.

5.2 Site screening

During the site screening process, the following criteria should be accounted for and used to identify and eliminate sites unsuitable for storage. Potential storage sites should be screened and ranked according to the key technical [5.2 a)] and legal and regulatory [5.2 b)] criteria listed below. Site screening should also consider the legal and regulatory requirements and restrictions for storing CO_2 at a particular site and assess the risks of failure to comply. Regulations or policies may determine that failure to satisfy particular criteria makes a site unsuitable for CO_2 storage.

a) Technical:

   1) for a specific project, lacking the necessary capacity and adequate injection rate through one or more wells to match the rate of the CO_2 stream and the volume(s) to be stored;

   2) lacking, based on existing information, containment for the required period of time as required by the responsible agencies;

   3) located in a hydrodynamic system where the initial pore pressure (whether natural or as a consequence of prior injection) is relatively close to the fault or fracture-reactivation pressure, or the rock fracturing pressure, whichever is the appropriate case, and no risk treatment is contemplated or possible to maintain pressure safely below this limit;

   4) located in areas of inter-formational transmissive faults and fractures that can impact the performance of the confining system;

   5) located in areas where current seismicity and tectonic activity will likely have adverse impacts, although the presence of seismicity *per se* should not preclude a site from being suitable for CO_2 storage if the facilities design and planned operations meet earthquake-resistance standards;

   6) located in formations with local-scale (short) hydrodynamic systems, i.e. systems with relatively short travel distances from recharge to discharge areas in outcrop;

   7) lacking adequate monitoring potential in regard to the evolution, fate, and effects of the injected CO_2 stream;

8) where the mechanical integrity of legacy wells penetrating the storage complex in an area expected to be within the CO_2 plume extent or an elevated pressure zone cannot be confirmed or, if known, cannot be adequately remediated.

b) Legal and regulatory:

1) located within the horizons of protected groundwater as defined in the respective jurisdiction;

2) located at depths and locations where hydraulic communication with protected groundwater can be demonstrated and negative impacts on protected groundwater can be expected;

3) located at depths and locations where other natural resources are exploited or are to be preserved and where hydraulic communication with these resources can be demonstrated and negative impacts on these resources can be expected;

4) located at depths and locations used for natural gas storage or for waste disposal, or where hydraulic communication with these activities can be demonstrated and negative impacts on these activities can be expected;

5) located in protected areas, e.g. national parks, and in environmentally sensitive areas as defined by regulatory authorities, that are likely to be negatively affected by operations;

6) located in areas where surface and/or pore space rights or operating permits cannot be obtained, e.g. military bases and aboriginal reservations, unless approved by the proper authorities;

7) located in areas where access to the site (pipelines and/or roads) or for monitoring cannot be secured.

During the site screening process, in cases where no alternate options are available, sites that possess one or more of the above characteristics may still be suitable for CO_2 storage if during the ensuing characterization, assessment and design process, it can be demonstrated that the risk posed by these specific characteristics can be reduced to acceptable levels by reducing geological uncertainty and by including appropriate risk treatment in site design, engineering and operation.

NOTE Evaluation for site screening involves a certain level of site characterization, but this characterization could be based on readily available data and preliminary modelling, and might not require acquisition of new data and a significant evaluation effort. In some cases, sites deemed unsuitable on the basis of these criteria could be found suitable if additional data and information become available through characterization, or alternative field development injection schemes are applied (e.g. horizontal wells or production of aquifer water), or legal and regulatory changes allow development.

5.3 Site selection

Site selection should build on activities performed during the initial site-screening process of 5.2 including geological evaluation and land-use considerations. Data, information, and knowledge acquired during the screening process should be incorporated into the site selection process. In areas where sufficient data (direct and/or analogue) are available, geological and fluid-flow models may be applied or developed. These models can be useful for identifying data gaps and for quantifying uncertainty with respect to initial estimates of CO_2 storage capacity and injectivity. During the selection, the following should be assessed for sites that passed the screening stage:

a) subsurface criteria:

1) capacity — further refinement of site storage capacity as more information is gathered and the injection potential is better understood;

2) injectivity — influences the number of wells, well design (horizontal versus vertical), and injection pressure;

3) storage safety and security (containment of CO_2 plume and displaced fluids), including the potential for leakage through

   i) inadequate seals, including faults and fractures, and

   ii) legacy wells;

4) pore space ownership rights where applicable (identifying pore space owners in the area of review), drilling concessions and exploration permits;

5) proximity to and potential effects on other subsurface activities, e.g. other CCS projects, disposal operations, oil and gas production operations, mining, natural gas storage, and fracturing in or near primary or secondary seals (e.g. for shale oil or gas extractions);

6) proximity to and potential effects on valuable natural, energy, and mineral resources, potable groundwater, geothermal energy, shale oil or gas, dissolved minerals, and sedimentary-basin minerals;

7) handling and disposal of any formation fluids produced;

b) surface criteria:

1) existence of and proximity to rights-of-way between (potential) CO_2 source(s) and the storage site;

2) existence or possibility to establish rights-of-way and build necessary infrastructure such as pipelines, access roads, and power lines;

3) population distribution and density in the area overlying the storage site and along the projected path of the CO_2 plume;

4) land ownership in the area of review;

5) proximity to other industrial facilities and agricultural or forestry activities;

6) proximity and exposure to vehicular traffic, roads, railways, aircraft, or shipping traffic;

7) proximity to protected wildlife habitats (including endangered species) and environmentally sensitive areas (wildlife management areas, community watersheds, conservancy areas, ecological reserves, and protected areas);

8) proximity to rivers and other bodies of fresh water;

9) proximity to national parks and other reserved areas (e.g. military bases, aboriginal reservations, and tribal and territorial lands);

10) proximity to existing offshore projects (e.g. wind and fish farming, sand and gravel extraction);

11) present and predicted development of adjacent properties;

12) site topography and variability in weather and oceanic conditions;

13) cultural and historical resources;

14) socio-economic conditions.

Some surface site-selection criteria are not necessarily related to storage capacity, injection rate, and security, but, nevertheless, should be considered because they can affect site selection. Proximity for economic reasons does not form part of the considerations specified in this subclause.

By evaluating available surface- and subsurface-related information, site selection should result in a list of selected potential sites for further characterization.

5.4 Site characterization and assessment

5.4.1 General

Site characterization shall provide the data needed for modelling and risk assessment. The operator should design a plan for characterization to collect the needed data for modelling and risk assessment. The additional data collected by monitoring during the operational phase of the project should be evaluated and applied for improved characterization.

5.4.2 Geological and hydrogeological characterization of the storage unit

A geological and hydrogeological characterization of the storage unit to provide a reasonable estimate of capacity and injectivity and to manage risk shall be completed before injection for storage of any CO_2 stream. The characterization should include:

a) determination of the extent of the storage unit and establishment of its boundaries, including identification and characterization of fault zones and structural features that could affect containment;

b) mapping of the geometry of the storage unit and evaluation of its distance to subcrop or outcrop;

c) identification of the presence and size of known local traps in the storage unit and evaluation of large-scale vertical and horizontal stratigraphic heterogeneity of the storage unit;

d) evaluation of the spatial distribution of porosity and permeability in the storage unit;

e) development of three-dimensional geological models of the storage complex;

f) estimation of wettability, relative permeability, and capillary pressure for CO_2 and the fluids present in the storage unit;

g) evaluation of the temperature distribution in the storage unit prior to injection of the CO_2 stream;

h) evaluation of the initial pressure distribution in the storage unit (prior to human activities, if any) and of the current pressure distribution if the initial pressure is affected by production or injection of fluids (e.g. oil, gas, or water).

5.4.3 Characterization of confining strata

5.4.3.1 Primary seal

The sealing capacity of the primary seal shall be evaluated and qualified prior to injection of the CO_2 stream to provide adequate confidence in containment of the stored CO_2 stream. A detailed characterization of the primary seal shall be performed and should include:

a) determination of the stratigraphy, lithology, thickness, and lateral continuity of the primary seal based on available data;

b) evaluation of primary seal integrity, including porosity and permeability, and testing where possible (see 5.4.5), and assessment of seal mineralogy to determine the suitability for containment of the CO_2 stream (see 5.4.4);

c) identification of potential leakage pathways, such as fractures, faults and wells, and their potential to transmit fluids, which can require risk management and further monitoring during the operational stages of the project;

d) estimation of the capillary entry (displacement) pressure for CO_2;

e) evaluation of the pressure distribution in the porous and permeable unit immediately overlying the primary seal above the storage unit and below the secondary seal.

5.4.3.2 Secondary barriers to CO_2 leakage

The presence of secondary barriers to CO_2 leakage shall be evaluated and their characterization can include:

a) identification of overlying permeable strata and secondary seals that are present between the storage complex and other subsurface resources, as well as the protected groundwater in on-shore cases or the sea bottom in offshore cases;

b) characterization of the permeable strata, where present, within the storage complex and in the overlying sedimentary succession in terms of the flow and composition of formation fluids, and geomechanical properties;

c) characterization of the secondary seals, mainly in terms of their geometry and lithology.

5.4.3.3 Sedimentary succession from the base of shallow aquifers to the surface

Characterization of shallow aquifers used for water resources, of the vadose zone and soil, and of the surface is critical in risk management and development of a monitoring plan and shall be performed.

5.4.4 Baseline geochemical characterization

The chemical composition of the CO_2 stream proposed for injection and of the fluids in the storage unit shall be characterized. In addition, the mineralogy of the rocks in the storage unit, in the primary seal and in the most proximate permeable units immediately overlying the storage unit and primary seal shall be characterized. The characterization should include:

a) CO_2 stream composition and its variability;

b) the major, minor and trace mineralogical components of the rocks in the storage unit and the primary seal;

c) the composition of and variability in the composition of formation fluids, including dissolved gases, in the storage unit;

d) additional baseline sampling of the geosphere and biosphere based on risk assessment, as the operator decides.

5.4.5 Baseline geomechanical characterization

Site-specific geomechanical characterization of the storage unit, the primary seal, and of the overburden shall be conducted depending on the level of risk as determined by the project operator. Geomechanical characterization should include:

a) evaluation of the natural seismicity and tectonic activity of the region where the prospective storage unit is to be located. Accordingly, the available information related to seismicity and tectonic activities should be collected and analysed;

b) characterization of the *in situ* stress regime (magnitude and orientation of principal stresses). Knowledge of the *in situ* stress regime in combination with the geomechanical modelling procedures described in 5.5.5 should be used to assess the maximum CO_2 injection pressure limits;

c) determination of rock mechanical properties of both storage unit and overlying seal, which includes:

    1) strength and deformation properties according to the observed material behaviour of the concerned rock (e.g. Poisson's ratio and Young's modulus);

    2) thermal properties (e.g. thermal expansion coefficient, specific heat capacity, and thermal conductivity);

3) the attributes (e.g. orientation, spacing, roughness, aperture, infilling, and mineralization) of weak planes and discontinuities (e.g. bedding and natural fractures and faults);

4) estimation of the fracture extension (propagation) pressure (FEP);

d) development of a mechanical earth model (geological model populated with geomechanical properties) that includes an adequately detailed representation of the storage unit, primary seal and storage complex, and a simplified representation of the overlying sedimentary strata. The geometry of the mechanical earth model should be based on the spatial distribution of strata, fractures and faults as represented in the project's geological model. Its constituents should be populated with the mechanical properties and *in situ* stresses obtained as explained within this subclause.

5.4.6 Well characterization

Unacceptable performance of various well components poses a high risk to CO_2 storage. Characterization of wells is a principal tool in identifying, remediating, and managing well leakage risk. Therefore, a characterization of the legacy wells that could affect the storage project within the area of review shall be performed (see 7.6.2).

5.5 Modelling

5.5.1 General

Numerical modelling based on *in situ* geological, hydrodynamic, geochemical, geothermal, and geomechanical conditions shall be applied to understand, predict, and communicate the fate and potential impacts of the injected CO_2 stream and corresponding pressure increase. The modelling objectives shall be documented, with a focus on modelling outcomes and performance goals.

NOTE Oil and gas industry modelling software packages can be considered as they have extensive reservoir and uncertainty characterization capabilities and numerical equations of state (EOS) to be able to model multiphase flow of CO_2 and other fluids.

5.5.2 Geostatic model

5.5.2.1 General

Geological models shall be created as a prerequisite for flow, geochemical, and geomechanical modelling, and shall depict the storage complex and all other relevant units in the sedimentary succession, and their flow, mineralogical, chemical, and mechanical characteristics (see 5.4). Models of the CO_2 storage complex shall be built to provide a framework that will be used to evaluate the potential behaviour of the storage complex. The model shall contain sufficient detail to enable prediction and description of the performance of the system over time (see 8.2.3). The up-scaling methodology used in developing the geological model should be specified. The model shall be refined as new data are acquired during site characterization (see 5.4.1).

5.5.2.2 Key modelling parameters

The geological static model shall describe the key geological, hydrogeological, geothermal, and geomechanical features of the storage unit and primary seal, and should describe the same for other geological units as appropriate. This should include, depending on the data requirements of the model being used:

a) areal extent;

b) stratigraphy, lithology, and facies distribution;

c) structure tops and isopachs;

d) geological features (including, for example, faults and fractures, subcrops, karst, large sedimentary features such as channels, and dip angle and direction);

e) the porosity distribution;

f) the permeability distribution;

g) the composition of contained fluids;

h) the initial pressure distribution;

i) the initial temperature distribution;

j) the initial stress distribution;

k) rock mechanical properties;

l) assumptions made and uncertainty or confidence level in various data and parameters, and results.

5.5.3 Flow modelling

5.5.3.1 General

Modelling of the flow of CO_2 and other fluids present in the storage complex shall be performed prior to commencement of injection of the CO_2 stream for the purpose of storage to predict the subsurface movement of the stored CO_2 and assess the storage capacity, injectivity, and risk arising from CO_2 injection activities (see 8.2.3). This modelling should:

a) evaluate the potential total volume effectively available for CO_2 storage using realistic injection scenarios;

b) predict quantitatively the spatial distribution and trapping mechanisms of CO_2 within the storage complex at any stage during the project life cycle;

c) evaluate the pressure buildup and its areal extent as a result of the storage project;

d) evaluate the upward movement and lateral spread (areal extent) of CO_2 (essential for designing effective monitoring programs) and of any constituents of interest (e.g. H_2S, SO_x, NO_x, etc.);

e) evaluate the fate of the displaced formation fluid;

f) evaluate scenarios for the number and placement of injection wells to achieve the needed rate of injection, ensure efficient use of the pore space and minimize pressure interference between injection wells;

g) evaluate whether preferential placement of pressure-relief wells is beneficial and effective in controlling pressure buildup and spread of the CO_2 plume, and how to manage the produced formation fluids;

h) examine potential migration scenarios within and leakage out of the storage complex involving CO_2, other constituents of interest, and/or displaced formation fluid along fractures, faults, and/or wells (for risk assessment);

i) evaluate the effect of temperature on the integrity of the CO_2 injection well.

5.5.3.2 Key modelling parameters

Key flow modelling parameters should include:

a) within the storage unit:

   1) pressure, temperature and fluid saturations;

2) salinity and chemical composition of formation fluids;

3) equations of state and other fluid properties for the fluids;

4) porosity distribution;

5) permeability distribution;

6) formation geometry (e.g. thickness and dip);

7) relative permeability curves;

8) capillary pressure curves;

9) fluid and rock compressibilities;

10) the thermal properties of fluids and rocks (in the case of non-isothermal flow modelling);

b) primary seal: permeability, capillary entry pressure, and other properties [e.g. as specified in a)], depending on the level of modelling for the primary seal;

c) fluids: CO_2 stream injection rate, composition and concentrations, physical properties, and phase behaviour.

5.5.3.3 Modelling outcomes

The results of modelling should provide information needed for risk assessment (see Clause 6), operations design (see 8.2.3), and monitoring (see Clause 9), and should be related to:

a) trapping mechanisms and their contribution over time to CO_2 trapping and total storage capacity estimate;

b) injection rate(s) and injection scenarios;

c) evolution in time of the injected CO_2, including dissolution and mineral precipitation;

d) pressure buildup;

e) movement of displaced fluids;

f) dynamic storage capacity, i.e. the amount of CO_2 that can be stored under given scenarios of injection, regulatory constraints, and the number and type of wells (vertical and horizontal). The site-specific storage efficiency factor is an outcome of flow modelling;

g) sensitivity analysis (indicating which parameters have the greatest influence on uncertainty);

h) assumptions made and uncertainty or confidence level in various results;

i) potential leakage pathways and, where possible, fluxes of leaking fluids;

j) well design and injection operation requirements such as maximum bottom hole injection pressure, wellhead injection pressure, placement and height of perforated interval, tubing size, etc.

5.5.4 Geochemical modelling

5.5.4.1 General

An evaluation of possible geochemical reactions among the injected CO_2 stream, the construction materials of the well, and the rocks and fluids of the storage unit and primary seal shall be performed. Available models and/or analyses can be used to predict changes in baseline geochemical conditions and to predict the potential effect of these changes on injectivity, storage capacity, and storage integrity (security), and to inform risk assessment and the monitoring plan. This modelling should:

a) evaluate the response of the storage unit to geochemical reactions regarding trapping of CO_2 and porosity and permeability alteration;

b) evaluate the response of the primary seal to geochemical reactions, including permeability alterations, which may lead to potential flow of fluids through the primary seal;

c) evaluate the response of the well(s) to geochemical reactions, including cement and/or casing degradation, which may lead to potential flow of CO_2 or CO_2-saturated formation fluid;

d) evaluate the predicted pH and chemical composition of the fluids in contact with the cement sheath in order to select suitable cements and tubular metallurgy for new wells to resist chemical degradation. The same assessment is needed to select remedial materials for legacy wells should the need be demonstrated [see 7.6.2 g)];

e) evaluate chemical reactions, including heavy metal mobilization, in the storage unit, overburden, shallow aquifers and soil for risk management conducted in accordance with 6.8.

The operator should evaluate the need for additional geochemical modelling of geochemical changes, including the potential mobilization of environmentally significant metals, in the geosphere and/or biosphere (e.g. in shallow aquifers) based on the risk assessment conducted in accordance with 6.7. These determinations can also have implications for rock alterations that might affect the geomechanical stability of the reservoir, seal, and wells.

5.5.4.2 Key modelling parameters

Key geochemical modelling parameters should include the following:

a) geostatic model;

b) solids:

   1) mineralogy and relative amounts of each lithological unit;

   2) grain size and composition (mineralogy);

   3) thermodynamic database;

   4) reaction rates and specific surface area;

   5) experimental data;

c) fluids:

   1) relative amounts of water, gas, and oil present;

   2) water composition;

   3) gas composition;

   4) oil composition;

   5) pressures;

   6) temperatures;

   7) thermodynamic database;

   8) pH.

5.5.4.3 Modelling outcomes

5.5.4.3.1 Chemical reactivity of the storage unit

The results of the modelling should provide information related to:

a) dehydration, dissolution, and precipitation reactions and fluid migration through rocks;

b) the effect of long-term geochemical interactions with the CO_2 stream (preferably derived from 2-D and 3-D reactive-transport models);

c) changes in formation fluid composition and behaviour (e.g. interaction with dissolved and residual hydrocarbon species and release of toxic organics and heavy metals);

d) predictions on porosity and permeability changes caused by geochemical reaction;

e) assumptions made and uncertainty or confidence level in various results.

5.5.4.3.2 Chemical reactivity of the primary seal

Diffusion and flow are assumed to be the dominant transport processes in the primary seal, where diffusion dominates in the matrix and flow dominates along discontinuities (fractures) in the primary seal (either pre-existing or created by geomechanical failure during the injection of CO_2 stream). The results of the modelling should demonstrate the presence or absence of changes to original mineralogy of the primary seal and fluid and flow properties (i.e. porosity and permeability alteration as it affects the rock matrix and fractures/faults) over short- and long-term timeframes through exposure to the free CO_2 stream (e.g. clay dehydration reactions) and formation fluids containing dissolved components from the CO_2 stream (e.g. mineral dissolution/precipitation) under diffusive and advective flow regimes. Assumptions made and uncertainty or confidence levels should be provided.

5.5.4.3.3 Chemical reactivity of materials in wells

CO_2-saturated formation fluid or water-saturated CO_2 will likely react with well materials, particularly if mechanical compromise allows fluids to migrate along the wellbore. For wells with mechanical defects, a life-cycle monitoring and remediation plan shall be developed that should include:

a) prediction of the performance of well cement, casing, bridges and plugs;

b) verification of the model predictions with laboratory tests of material resistance;

c) prioritization of the needs for monitoring and remediation of wells found to be prone to defects;

d) assumptions made and uncertainty or confidence levels.

5.5.5 Geomechanical modelling

5.5.5.1 General

Geomechanical modelling shall be performed in a risk management context to predict the potential for and effects of stress changes, deformations and induced seismicity resulting from the planned CO_2 injection. This modelling should:

a) evaluate the integrity of the primary seal based on historical and projected future stress changes;

b) evaluate, if possible, the potential for fault and/or fracture generation or reactivation;

c) evaluate the potential for induced seismicity;

d) evaluate ground surface deformation (e.g. heave) as a result of injection;

e) evaluate mechanical aspects of well integrity;

f) evaluate stress and strain changes and coupled changes of fluid pressure in the area of review to provide reference data for the design of site-specific monitoring plans.

The geomechanical modelling approach should be designed to develop an understanding of the evolution of stress and deformation within the model.

5.5.5.2 Key modelling parameters

Many parameters required for geomechanical modelling are obtained in the development of the mechanical earth model (see 5.4.5) and the flow model (see 5.5.3). The key geomechanical modelling parameters should include:

a) the geological model, which serves as the basis for establishing the mechanical stratigraphic units within the geomechanical model and establishes the presence and orientation of existing faults and/or fractures;

b) initial *in situ* stress regimes (directions and magnitudes) within the storage unit, primary seal, and overlying sedimentary succession;

c) initial fluid pressure regime and distribution, which establish the initial effective stress distribution required for geomechanical modelling;

d) geomechanical properties of the geological units in the model, which include rock strength and deformation properties;

e) thermal properties of the units in the storage complex, such as heat conductivity, heat capacity and thermal expansion coefficients, for the case of induced thermal stresses as a result of the differences between the temperature of the injected CO_2 stream and *in situ* temperatures;

f) additional key geomechanical modelling parameters that control how the strength and pore structure of the storage unit are changed geochemically, depending on the outcome of the modelling specified in 5.5.4.3.1 that models the chemical reactivity of the storage unit with the injected CO_2 stream.

5.5.5.3 Modelling outcomes

The results of modelling should provide information related to:

a) the maximum CO_2 injection pressure that will ensure no loss of integrity of the primary seal (e.g. CO_2 injection will not induce new tensile or shear fractures or reopen or reactivate existing discontinuities such as faults);

b) the effect of geomechanical processes on injectivity;

c) wellbore stability during drilling, which can affect well integrity and the near-well permeability of the primary seal;

d) deformation of the storage unit, primary seal, and overlying sedimentary succession, including any effects deformations can have on surface facilities or the feasibility of pressure buildup monitoring based on ground deformation;

e) potential well integrity issues arising from geomechanical processes during injection and operation;

f) sensitivity analysis (indicating which geomechanical parameters have the greatest influence on uncertainty);

g) assumptions made and uncertainty or confidence level in various results.

6 Risk management

6.1 General

A structured and systematic process for risk management shall be implemented for each storage project, throughout all stages of the project life cycle. The process for risk management should be an integral part of project management, embedded in the culture and practices of and incorporated into the business processes of the project operator.

The responsibility for risk management shall reside with the project operator, but defined tasks may be delegated to and managed by other entities.

6.2 Objectives

The purpose of risk management is to ensure that the opportunities and risk scenarios involved in an activity are effectively managed and documented in a comprehensive, accurate, balanced, transparent, and traceable way. Effective risk management shall be employed throughout the project life cycle. Effective risk management to ensure that the risk is reduced to and maintained at an acceptable level should:

a) help demonstrate achievement of objectives and improve performance relative to elements of concern;

b) support strategic planning and development of robust project management systems;

c) help decision makers make informed choices, prioritize actions, and distinguish among alternative courses of action;

d) account for uncertainty, the nature of that uncertainty, and how it can be addressed;

e) recognize the capability, perceptions, and intentions of external and internal stakeholders that can hinder or support achievement of objectives.

NOTE These objectives are consistent with the objectives described in ISO 31000.

6.3 Process

This document provides guidance on the steps of the generic process for risk management shown in Figure 2. This process is consistent with the process for risk management described in ISO 31000. The process for risk management should be implemented during the initial site screening, selection, and characterization periods, and be iteratively repeated in a consistent, transparent, and traceable manner throughout the project life cycle. Each iteration of the process for risk management should take into account changes in the context for risk management (see 6.4).

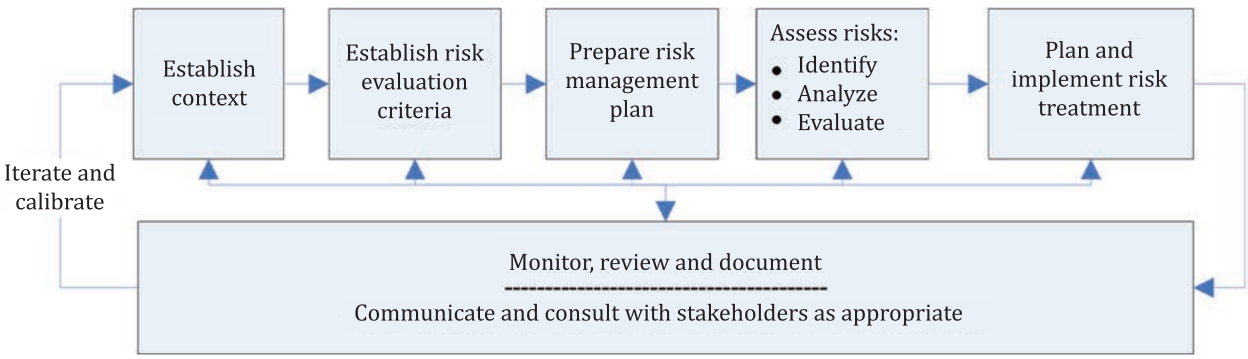

Figure 2 — Schematic of process for risk management for CO_2 geological storage projects

6.4 Context

6.4.1 General

The context for project risk management should be established prior to the creation of a project-specific risk management plan. The context for project risk management should consist of all elements that may influence assessments or perceptions of risk. The context should be updated when elements of the context or evolving knowledge and understanding of site-specific circumstances have changed in a way that can alter assessments or perceptions of risk.

In order to establish the context for project risk management within a CO_2 geological storage project, the project operator shall articulate the objectives of the project and define the scope, conditions, and criteria for the process for risk management.

6.4.2 Context elements

The context elements should be identified in a structured manner based on adequate characterization and understanding of the storage project. The following elements should be evaluated when establishing the context for risk management:

a) natural environment and hazards;

b) regional natural resources and activities;

c) infrastructure and facilities;

d) social, political, and economic context;

e) policy, legal and regulatory environment;

f) industry recommended practices pertaining to effective risk management;

g) project operator and subcontractors, their respective functions, responsibilities and accountabilities, and the relationships between their respective systems for risk management;

h) the state of knowledge of and uncertainty about each aspect of the project (including storage system components, storage plans, socio-political environment, etc.);

i) project scale and duration, project phases, decision points and respective time-scales.

6.5 Risk evaluation criteria

Appropriate elements of concern for the project shall be identified by the project operator. The elements of concern shall include human health and safety, the environment, and system performance (e.g. injectivity, capacity, containment, and service reliability). The elements of concern can also include cost, infrastructure, schedule, and the reputation of project operator.

The project operator shall establish risk evaluation criteria for each element of concern tailored to the scope and objectives of the storage project. This may entail the use of qualitative or quantitative likelihood and consequence classes.

Regulatory authorities shall be consulted when establishing risk evaluation criteria for any elements of concern relevant for regulatory approvals. Relevant stakeholders should be consulted when establishing risk evaluation criteria for any elements of concern for which project activities can have an impact that affects the stakeholders in a material way.

Risk evaluation criteria shall serve to distinguish between acceptable, tolerable and unacceptable risk (see 3.2, 3.61, and 3.64, respectively). These distinctions can be based on a combination of social and political concerns and economic considerations of adding additional risk controls to further reduce risk. Social and political concerns could include internal or external requirements or expectations, explicit policy statements, and regulatory requirements. Economic considerations include cost-effectiveness and practicality in terms of time, effort, likelihood of success, and secondary risk scenarios potentially entailed by risk treatment. A risk evaluated as unacceptable shall be reduced by implementation of risk controls and evaluated as acceptable (including risks found to be tolerable) before the storage project proceeds to a stage where the risk scenario can occur.

6.6 Risk management plan

Project operators shall develop and implement a risk management plan suited to their operation. The individual(s) responsible for the CO_2 storage project within the project organization shall review and approve the initial risk management plan and any substantive changes to this plan. The risk management plan shall be discussed with the regulator and should be discussed with relevant stakeholders. The risk management plan should include a description of the following:

a) organizational procedures and practices to be applied to risk management, including selection and availability of resources and assignment of responsibilities;

b) a schedule for performing iterative risk assessments and activities supporting the risk assessments;

c) principles and guidelines that will be applied to enhance the thoroughness, accuracy, transparency, and traceability of risk assessments;

d) how the site-specific monitoring plan is designed to support iterative risk management activities (see Clause 9);

e) how the site-specific modelling and simulation program incorporates new monitoring results and is designed to evaluate the effects of uncertainties and support the iterative risk analysis;

f) how the risk assessment methodology accounts for uncertainty that can influence the performance of the storage project;

g) an emergency response plan;

h) a plan for iterative review and update of the project risk register (see 6.9.2.3);

i) a schedule and process for the following:

    1) monitoring and review of the overall program for risk management to detect changes in the context for project risk management, for tracking the effectiveness of implemented risk treatment, and for incorporating lessons learned to seek continuous improvement consistent with 4.3 (see 6.9.1);

    2) mapping and recording the process for risk management (see 6.9.2);

    3) external communication and consultation with regard to risk management (see 6.10).

6.7 Risk assessment

6.7.1 General

Risk assessments shall include a comprehensive process for risk identification, technically defensible risk analysis, and a transparent, traceable, and consistent process for risk evaluation that aims to avoid bias. The results of the risk assessments shall set performance requirements for risk treatment and be used to inform the design of the program for monitoring and verification (see Clause 9).

The level of rigour applied to risk assessment shall depend on the available information and the degree of knowledge about risk scenarios required to enable decisions for the relevant stage of the project. In general, the detail in the risk assessment should be gradually enhanced by each pass of the process for risk management in Figure 2 until the identified risk scenarios are thoroughly assessed.

6.7.2 Risk identification

6.7.2.1 Principles

The project operator shall perform a comprehensive process for risk identification. The process for risk identification and the results shall be documented in a traceable and consistent manner. The documentation shall describe the measures taken to provide confidence that the process for risk identification has been adequately comprehensive.

6.7.2.2 Process

The process for risk identification shall include the following activities:

a) identification of threats to meet the performance criteria listed in Table 1;

Table 1 — Criteria description for the identification of threats

No.	Criteria description
1	The site has sufficient capacity to accept required CO_2 injection volumes.
2	The site has sufficient injectivity to allow CO_2 injection at required rates.
3	The site will provide long-term containment, i.e. prevention of leakage at rates or in a total mass sufficient to cause an adverse impact or greater than limits set by local regulations or licence terms.
4	The CO_2 injection operations will not lead to seismicity or earth deformation sufficient to cause an adverse impact.
5	Modelling and cost-effective monitoring are feasible and a) allow timely implementation of appropriate risk treatment, b) provide confidence that the storage site is suitable for continued CO_2 injection operations, and c) ensure that related criteria for site closure will be met [see 10.2 a) to e)].
6	The project operational procedures ensure operational safety and environmental protection, i.e. avoidance of impacts to health, safety and the environment stemming from construction and operation of wells and the project surface infrastructure, and from project interactions with non-project human activities local to the project site and surrounding area.

b) identification and description of risk scenarios for each threat;

c) assessment and description of the biosphere and economic resources in the geosphere that could be affected by CO_2 injection operations. This should include assessment and description of the baseline so that changes attributable to the CO_2 injection operation can be differentiated from changes attributable to pre-injection background variation or to natural or other anthropogenic sources;

d) identification of interdependencies among different risk scenarios, including the potential for cascading effects that could increase the likelihood or severity of consequences;

e) tailored threat identification for novel elements of the project, i.e. elements that are unique to the site under consideration or have not been encountered in previous operations by the project operator.

6.7.3 Risk analysis

6.7.3.1 Principles

The risk analysis shall provide the technical basis for risk evaluation. The risk analysis shall be based on best available knowledge and scientific reasoning, and aim to determine the likelihood and severity of potential consequences for each risk scenario.

If the level of uncertainty for a risk scenario affects the risk evaluation or the selection of risk treatment, then the impact of the uncertainty on the assessed level of risk should be analysed and documented.

6.7.3.2 Process

The project operator shall document in a transparent, traceable, and consistent manner how each of the following elements has been determined in the process for risk analysis:

a) the risk scenarios;

b) the likelihood of each risk scenario;

c) the severity of potential consequences relative to the elements of concern for each risk scenario;

d) sources of uncertainty in the likelihood and severity of potential consequences for each risk scenario;

e) measures to reduce or manage uncertainties that affect the risk evaluation and/or selection of risk treatment;

f) risk controls to prevent or mitigate identified risk scenarios;

g) monitoring locations, parameters, and detection thresholds required for timely implementation of appropriate risk treatment;

h) data requirements and modelling studies to support the risk analysis (including data requirements and modelling studies to predict the effectiveness of risk treatment as well as the uncertainty associated with the effectiveness of risk controls);

i) the aggregate likelihood that a significant impact on each element of concern could follow from a combination of the identified risk scenarios.

6.7.4 Risk evaluation

6.7.4.1 Principles

Risk evaluation is the process of evaluating the level of risk and the tolerability and acceptability of risk. For each risk, the result of the risk evaluation before mitigation sets the performance requirements for the corresponding strategy for risk treatment.

The project operator shall identify and minimize sources of bias in the risk evaluation. When sufficient relevant data can be obtained, quantification of likelihood and consequences shall be based on scientific reasoning or auditable statistics and/or calculations. Otherwise, quantification shall be based on the documented judgement of experts who are qualified in terms of applicable professional expertise and project knowledge.

6.7.4.2 Process

The project operator shall document in a transparent, traceable, and consistent manner how each of the following elements has been evaluated in the process for risk evaluation:

a) level of risk before any risk treatment. If cost-effectiveness or impracticality of risk treatment is used as a basis for determining risk tolerability, project operators should identify and document the rationale applied to support the use of this basis;

b) effect of risk treatment. This shall include evaluating whether the risk treatment options for tolerable risk are reasonably practicable, i.e. justifiable with reference to the principle that the risk should not outweigh the potential benefits of the activity;

c) predicted level of risk after risk treatment, i.e. contingent upon implementation of risk treatment;

d) degree of uncertainty attached to the level of risk, both before and after mitigation;

e) rationale to support elimination of identified risk scenarios from further evaluation on the basis of very low likelihood and/or immaterial significance of potential impacts.

6.8 Risk treatment plan

The project operator shall develop a risk treatment plan for each identified risk scenario that has not been eliminated from further evaluation in accordance with 6.7.4.2 e). The risk treatment plan shall be designed to ensure that risk is reduced to and maintained at an acceptable level. The plan should describe the following:

a) the target level of risk to be achieved through implementation of risk treatment;

b) preferred options for risk treatment and the process for their implementation, including, if relevant, the priority order in which individual risk controls should be implemented. The project operator should explain how uncertainty is taken into account and defend why the selected strategy is robust with respect to the performance requirements for the risk treatment;

c) a contingency risk treatment plan that should guide, and be guided by, the program for contingency monitoring (see 9.4.3), as well as site-specific modelling aiming to support the risk analysis in accordance with 6.7.3;

d) specific individuals responsible for implementation of risk controls in the risk treatment plan, and the relation between their organization and the organization of the respective risk owners for the associated risk scenarios in the risk register (see 6.9.2.3).

6.9 Review and documentation

6.9.1 Review

The risk management plan, the results of risk assessments, and the corresponding risk treatment plans shall be reviewed and modified by the project operator as necessary to ensure that risk is properly managed throughout the project life cycle. Significant revisions to the risk management plan should be discussed with the regulator and relevant stakeholders.

To ensure that a risk management plan is implemented and adjusted as needed, the follow-up and review of the process for risk management should meet the following criteria:

a) responsibilities for follow-up and review within the project organization are clearly defined;

b) the review of the process for risk management ensures that

   1) the elements of concern are appropriate,

   2) risk controls are effective, efficient, and implemented as needed in a timely manner,

   3) data and information are gathered and relevant analysis is performed as needed to achieve continuous risk reduction and improve risk assessment and management,

   4) lessons learned are documented and analysed,

   5) changes in the context are detected, including changes to risk evaluation criteria and the risk itself (which can require revision of risk treatments and priorities), and

   6) emerging risk scenarios are identified in a timely manner;

c) progress in implementing risk treatment plans is measured against the respective risk reduction targets [see 6.8 a)]. This should be done by following a cyclical process of assessing

   1) the effect of the implemented risk treatment, and

2) whether the residual level of risk is acceptable and, if it is not, generating or applying a new risk treatment and assessing its effectiveness;

d) the results of the review of the process for risk management are recorded and externally and internally reported as appropriate, and are used as an input to the review of the risk management plan.

6.9.2 Documentation

6.9.2.1 Principles

The documentation of the process for risk management shall be transparent and traceable.

6.9.2.2 Transparency

The risk evaluation criteria for each element of concern shall be documented. The documentation shall specify the criteria by which risk is deemed acceptable for each element of concern.

Documentation should include outputs from monitoring and modelling that form a basis for the risk assessments and describe the implications of monitoring detection thresholds and sensitivities for the results of risk assessments.

6.9.2.3 Traceability

6.9.2.3.1 Risk register

The results of risk assessments shall be recorded in a project risk register in a consistent manner so that risk assessments are comparable over time. For each recorded risk scenario, the risk register shall include the following information:

a) description of the risk scenario;

b) the designated risk owner;

c) a description of the risk treatment planned or implemented to mitigate the risk scenario;

d) a description of the assessed effectiveness of each risk control in the risk treatment;

e) the persons responsible for execution of the risk controls in the risk treatment;

f) a schedule for the timely execution of the risk treatment;

g) the estimated residual risk for each relevant element of concern following implementation of risk treatment and a description of the basis or rationale for the risk evaluation.

6.9.2.3.2 Documentation

The operator should document in a consistent manner the following information:

a) changes in the assumptions and design of programs for modelling and monitoring, and the corresponding rationale to justify these changes;

b) physical or digital locations of existing database(s) with monitoring data, reports with results from risk assessments, modelling and monitoring;

c) names of experts involved in expert elicitation based processes for risk assessment.

If different methodologies for risk assessment have been applied, the results of updated assessments shall be compared to the most recent assessment. If the results of an updated risk assessment deviate significantly from the prior assessment, the reasons for the differences shall be documented.

6.10 Risk communication and consultation

6.10.1 General

Communication and consultation regarding project opportunities and risk shall take place with both internal and external stakeholders.

6.10.2 Objectives

Risk communication and consultation should be tailored to the knowledge level of CO_2 geological storage of those involved and should aim to accomplish the following objectives:

a) to facilitate understanding of the nature of risk associated with CO_2 storage, the possible causes of risk, the potential consequences, and the measures being taken to manage risk;

b) to provide to interested parties accurate and objective information about CO_2 storage in general and about the project in particular, including a balanced picture of opportunities and risk;

c) to identify and record stakeholders' perceptions of risk and their values, needs, assumptions, concepts, and concerns that could affect decisions based on risk considerations;

d) to provide internal and external stakeholders with a common understanding of the basis on which decisions about risk tolerability and acceptability are made, and the reasons why particular actions are required to adequately manage opportunities and risk;

e) to address the thoroughness, accuracy, transparency, traceability, and consistency of the risk assessments, and the nature and degree of understanding of known or perceived risk scenarios.

6.10.3 Scope of risk communication and consultation activities

The scope of risk communication and consultation activities varies depending on the recipients and the underlying objectives. A program for communication and consultation shall be developed to support the following three objectives:

a) to facilitate open and effective dialogue with regulatory authorities during permit application and review regarding:

    1) the process and rationale for site selection and characterization;

    2) the base of knowledge and understanding to support site and concept selection;

    3) the iterative process for risk management;

    4) the program for monitoring and verification;

    5) the site and risk management performance;

    6) the plan for site closure;

    7) coordination of roles for risk communication and consultation among operator and regulatory authorities;

b) to facilitate open and effective communication and consultation with stakeholders and the public regarding:

    1) the rationale for site selection (location of the storage site);

    2) plans for proactive and environmentally responsible risk management;

    3) concerns and questions raised by stakeholders directly affected by the project;

4) procedures for recording and responding to concerns from stakeholders and the public in a transparent and constructive manner;

c) to facilitate open and effective communication of responses regarding site performance that represents a deviation from expected or predicted site behaviour. This should include:

1) plans to notify the authorities, stakeholders, and the public;

2) plans to assess the scale and origin of the deviation;

3) plans to identify and implement appropriate risk treatment;

4) lessons learned and, if relevant, how the deviation could have been predicted and possibly avoided;

5) the deviation's impact on the environment and/or economic resources, if any;

6) modifications to site-specific risk management plans, if required.

6.10.4 Performance goals

The program for communication and consultation should aim to achieve the following performance goals:

a) the context for risk management is established;

b) the interests of stakeholders are understood and their needs met to the extent practicable within the scope and resources of the project (see 4.3.3);

c) risk scenarios and risk perceptions are thoroughly identified and analysed;

d) stakeholder views are considered when defining the elements of concern, the risk evaluation criteria, and in evaluating risk;

e) regulatory authorities and relevant internal stakeholders agree that the risk management plan, including procedures for management of change, is robust.

7 Well infrastructure

7.1 General

7.1.1 Scope

The materials, design and construction of wells related to geological storage of CO_2 are based on principles and methods developed by the oil and gas industry. Processes and procedures associated with well infrastructure, including material requirements, design, and construction, are thoroughly described within existing industry standards and in industry recommended practice documents (see References [16], [17] and [18]). This clause addresses aspects of well infrastructure specific to the geological storage of CO_2 without associated hydrocarbon production. The scope of well infrastructure addressed by this clause includes components from the point of delivery of CO_2 to the storage facility through to the wellhead(s) and well(s). Other above ground or surface facilities such as compressors and storage tanks are not considered by this clause. Detailed design of the wells should be in accord with the specific requirements of injection operations of each CO_2 storage project (see 8.2).

7.1.2 Documentation

Accurate records shall be kept of all well-related activities, such as design, drilling, testing, workovers, remediation and abandonment, and retained throughout the life of the storage project.

7.2 Materials

7.2.1 Conditions for use

Materials and equipment that are selected, constructed, and used as part of well infrastructure in accordance with this clause shall be suitable for the conditions to which they will be subjected including, where anticipated, exposure to CO_2.

7.2.2 Materials selection

The selection of materials for surface infrastructure and wells, such as pipe, tubing, casing, pumps, cement, electrical and safety equipment, instrumentation, elastomers, and all other components, shall include evaluation of the influences of the following elements:

a) state and composition of the CO_2 stream to be processed, transported, and stored;

b) range of operating pressures;

c) range of operating temperatures;

d) planned operating life of the component or project;

e) site-specific environmental conditions;

f) galvanic corrosion between dissimilar metals;

g) possible exposure to CO_2 stream.

Oil and gas industry recommended practices shall be used to evaluate corrosion allowances and pressure and temperature ratings. Particular care should be taken with design temperatures where blowdown or large pressure drops may cause cooling by Joule-Thomson effects due to expansion of CO_2.

7.2.3 Material requirements

In general, CO_2 is not corrosive to carbon steel, but the presence of free water in the CO_2 stream can create carbonic acid that is corrosive to carbon steel, and other constituents can make a CO_2 stream corrosive. Potentially corrosive constituents of CO_2 streams, such as free water, O_2 and H_2S, shall be identified to establish material requirements. Carbon steel may be used in process piping and equipment, surface pipelines, and wellbore tubulars that handle CO_2 streams not containing free water or other components of concern at corrosive concentrations.

For infrastructure exposed to CO_2 streams that contain components of concern at concentrations sufficient to make the CO_2 stream corrosive, materials shall be corrosion-resistant and may require chemical treatment to maintain mechanical integrity (see Reference [18]). Performance of chemical inhibition programs shall be monitored by industry recommended practice to confirm their effectiveness.

NOTE 1 For further information, see References [19], [20], [21], [22], [23] and [24].

Elastomers required shall be chemically and mechanically stable in the presence of CO_2, and their selection criteria should be based on operating pressure and temperature conditions, constituents of the CO_2 stream, and evaluation of the diffusive characteristics of CO_2.

NOTE 2 Not all elastomers sealing elements are rated for CO_2 service. For further information, see References [25], [26] and [27].

Well cement should be non-shrinking during setting and sufficiently ductile to sustain deformation due to change of pressure and temperature over the expected operating conditions of the well. Cement composition should offer additional chemical resistance to CO_2 degradation. Cement should achieve hydraulic isolation across the primary seal of the storage reservoir.

NOTE 3 For more information on materials, see References [28], [29], [30], [31], [32] and [33].

NOTE 4 For additional information on drill stem design and operational limits, see Reference [34].

7.3 Design

7.3.1 General

The infrastructure design shall facilitate safe and effective CO_2 storage.

7.3.2 Safety

Applicable regulations shall be followed for entering CO_2 wellhead enclosures, fire prevention, placement of indication signs including name of the well or storage facility, name of the project operator, contact information for emergency purposes, and other warning signs. Windsocks should be visible to indicate wind direction (i.e. for assistance in emergency situations).

All site activities shall be performed in a manner that minimizes environmental impact and avoids endangering protected groundwater. Safety preparedness (response plans) shall be in place to mitigate spills caused by unexpected circumstances, e.g. drilling into high-pressure formations, which can cause kicks and the release of formation fluids to weak zones or to the surface.

NOTE For further information, see References [35] and [36].

7.3.3 Wells

7.3.3.1 Wellsite

The selection of wellsite(s) and the siting of (a) well(s) and infrastructure shall:

a) provide adequate access to wellsites, wells, and wellheads by rigs and service vehicles for drilling, inspection, maintenance, repair, renovation, treatment, and testing;

b) avoid topographically low areas where the density difference between CO_2 and air can cause CO_2 accumulation;

c) avoid near-surface, underground facilities such as mines.

The design of CO_2 injection and monitoring wells, including whether they are to be vertical, horizontal, or deviated, should evaluate wellsite requirements for CO_2 handling, including spatial access, or other limitations. A thorough evaluation of all surface and subsurface activities and their potential impact on the integrity of the storage complex shall be conducted. Appropriate permits shall be obtained prior to building the wellsite for drilling.

7.3.3.2 Well design

Wells designed for use in CO_2 storage projects can include injection wells to deliver CO_2 to the storage unit, monitoring wells to measure and record necessary information, and pressure relief (formation fluid extraction) wells for pressure management of storage unit. In some storage units, the volumes of CO_2 required for injection operations can be more efficiently delivered by horizontal and deviated wells than by vertical wells. The design, planning and drilling of wells shall adhere to stated project objectives and minimize impact on any protected groundwater zones or other identified resources. Drilling plans should document the potential for fluid invasion and formation damage when drilling through target storage unit(s).

The drilling and cementing plan should be based on standard engineering considerations similar to those used in oil and gas wells, and for CO_2 storage project-specific factors including:

a) longevity of, and abandonment requirements for, the well;

b) intermediate and long-string casing requirements and the need for corrosions-resistant alloy;

c) cement formulation and placement;

d) location and orientation of potential migratory paths from the storage unit to nearby geological formations.

The design of all wells shall evaluate location, storage complex characteristics, and material requirements specific to their function at the storage site, as per the following:

— Design of injection wells to deliver CO_2 to the storage unit shall evaluate injectivity, permeability, and porosity of storage unit to avoid excessive subsurface pressure interference and to ensure acceptance of anticipated volume of CO_2 (see 5.5.3).

— Design of pressure relief wells that can be used for pressure management within the storage unit should evaluate well spacing, connectivity within storage unit, and surface facility requirements for treatment or re-injection of produced formation fluids.

— Design of monitoring wells shall support the specified monitoring purpose and measurement objectives, including longevity and access for remediation or modification.

7.3.4 Tubulars

7.3.4.1 General

Tubulars such as well casing, production tubing, and liners are components of wells that are essential for long-term well integrity and for the injection and production of fluids. They provide barriers that ensure protection of groundwater resources and the safe operation of CO_2 injection or fluid production at the geologic pressures and temperatures encountered within storage complexes.

7.3.4.2 Conductor casing

The conductor pipe or casing prevents caving and washout (loss of material from the borehole wall) at the rig base and encases the cement for the surface casing at ground level. Once in place, the conductor casing should be secured and may be cemented to maintain integrity around the casing and to prevent washouts. The well shall be drilled out through the conductor casing to below protected groundwater and the surface casing(s) shall be run and cemented back to the surface through the use of single or multiple strings of casing and cement if it is necessary to protect any groundwater encountered.

7.3.4.3 Surface casing

Well surface casing shall be set and cemented at sufficient depths to ensure

a) isolation of protected groundwater sources, and

b) control of the well under maximum formation pressures and operating pressures prior to the next casing interval.

NOTE For further information, see References [37] and [38].

7.3.4.4 Intermediate and long-string casing design

Onshore and offshore wells in a CO_2 storage project shall be cased with the recommended grade, weight, and size of casing to achieve the stated objective(s) of the well for safe injection, production or monitoring. The casing program shall be designed to ensure safe operation for the planned life of the well under the expected physical and chemical environment.

NOTE For further information, see References [39] and [40].

7.3.4.5 Tubing string design

The design of the tubing string shall apply the same material and environmental requirements as applied to casing design, including whether corrosion-resistant alloy (see 7.3.3.2) is required and in what location(s) of the tubing string.

The expected maximum injection rate of the CO_2 stream required by the well to meet project objectives should be used to determine the minimum diameter of tubing required. The maximum injection pressure should be used to determine the weight and grade of tubulars for the well. Packers of adequate internal diameter should be used where subsequent wireline work might be desired during the life of the injection well.

7.3.4.6 Liners

Liners can be used for remedial purposes or installed during initial construction and shall meet the same design requirements as for casing strings and tubing (see 7.3.4.4 and 7.3.4.5).

7.4 Construction and completions

7.4.1 General

All wells involved in CO_2 storage projects shall be constructed and completed in a manner that meets project goals while maintaining wellbore integrity. A detailed completion plan shall be developed and subjected to stakeholder review to address project goals. All materials used shall meet the requirements as outlined in 7.2.

NOTE For information regarding well integrity in drilling and well operations, see Reference [37].

7.4.2 Cementing

Completion of wells for CO_2 storage projects shall be designed to place a well-bonded cement sheath between the casing and wall-rock from the casing shoe to planned top of cement. The cementing design should:

a) structurally support the casing;

b) resist all expected well and formation loads;

c) completely seal the annulus to isolate pore pressures in covered zones or to isolate different reservoir intervals;

d) protect the casing from corrosive fluids in relevant zones.

NOTE For further information on cementing and completion of wells, see References [41] to [55].

7.4.3 Groundwater protection

The cement and casings installed in a well designed for a CO_2 storage project shall maintain hydraulic isolation across all strata above the storage unit, and in particular, across all protected groundwater source zones above the storage unit.

7.4.4 Post-cementing evaluation and remediation

After cement has been placed in the annulus, the cement sheath should be evaluated to determine that no leaks are detectable. Pressure testing of the casing should only be performed after significant cement slurry gel strength has developed. The evaluation should confirm that the top of cement is in accordance with the design depth.

NOTE 1 Other methods to determine that the cemented annulus's seal is suitable and has no leaks or defects can be performed, e.g. wireline logs that detect flow behind the casing by measuring temperature, noise, and the flow of oxygen-activated water and CO_2 molecules.

Defective cement sheaths shall be repaired using selected remedial methods and materials that meet the structural support and sealing requirements of the primary cementing design.

NOTE 2 For further information, see References [55], [56] and [57].

7.4.5 Completion and stimulation

Access through the casing shall be provided by perforation or other means to establish sufficient communication for injection of the CO_2 stream into the storage unit. If stimulation or injection enhancement treatments are necessary, the treatment shall be performed in a manner that ensures the integrity of the wellbore and primary seal.

7.4.6 Wellbore monitoring requirements

Wells should be designed to facilitate the use of continuous or periodic monitoring equipment including logging and pressure testing in accordance with 8.5.2 and 8.5.3. An injection well shall have a metering device associated with it to monitor the mass of the fluid stream injected. An injection temperature gauge is useful for determining the density of the injected fluids to allow estimation of bottom-hole injection pressures (see 8.5.3.3).

Well monitoring equipment shall be designed based on the specific conditions expected in the well, such that the monitoring equipment provides meaningful data on the condition of the well. Monitoring equipment can include wellhead pressure and temperature gauges, annulus pressure and temperature gauges (see 8.5.3.1), downhole pressure and temperature gauges (see 8.5.3.3), and other equipment as required to be run in the hole with tubing.

7.5 Corrosion control

7.5.1 General

The CO_2 stream can contain corrosive constituents in addition to CO_2 such as NO_x, SO_x, H_2S, H_2O, and O_2 that can cause corrosion to steel components, and the general mechanical integrity of the wells should be routinely evaluated.

7.5.2 Well maintenance

The CO_2 stream shall be monitored to determine the presence of corrosive constituents to assist with maintaining well and component integrity. Ongoing maintenance should include external coatings and periodic visual inspection of the interior portion of all vessels for corrosion and chemical programs designed to prevent internal and external corrosion of steel components. External corrosion can be influenced by the weather, ability of pipe to maintain external coatings, and whether the steel is exposed to the air (e.g. buried pipe versus pipe in a pipe rack). Offshore piping and structural steel shall be evaluated and specifications adopted as necessary to accommodate salt laden air.

A monitoring program should be used to determine the effectiveness of the corrosion mitigation efforts. The program can include, but is not limited to, the following:

a) chemical analysis of injected fluids for indications of trace metals;

b) corrosion coupons placed in the injection stream;

c) ultrasonic or other non-destructive testing of vessels and pipe for wall thickness (metal) loss.

7.5.3 Cathodic protection systems

Piping and vessels should be adequately protected against galvanic corrosion by using cathodic protection in accordance with industry recommended practices or applicable regulations.

7.5.4 Environmental compatibility

The components of the injection stream (i.e. the CO_2 and minor constituents) shall be determined to be compatible with the existing storage unit environment to ensure that the formation near the wellbore and the well components are not damaged by injectate-storage unit interactions. Compatibility may be checked by laboratory modelling or geochemical simulation.

7.6 Evaluation of wells

7.6.1 General

During the life of the CO_2 storage project, well workovers and recompletions are likely to be required to maintain or repair well components, or to obtain information concerning wellbore integrity (see 7.4.5 and 7.4.6). A detailed workover plan shall be established, taking into account CO_2 in the reservoir prior to starting any workover operation. Necessary permits and approvals from all regulatory authorities involved shall be obtained prior to starting workover operations.

Wells that have both known significant mechanical defects (e.g. cement cracks and fractures, cement debonding, surface casing vent flow, sustained casing pressure, gas migration, casing failure, etc.) and are likely to be contacted by the injected CO_2 or elevated pressure zone in the near-mid-operational term shall be remediated. Remediation in other wells may be deferred until conditions warrant.

7.6.2 Legacy wells

All legacy wells identified in the area of review shall be evaluated using all available records to determine their history including how the wells were plugged and whether the method of plugging met the objectives of 7.8.1. Legacy wells within the area of review shall be evaluated as potential leakage pathways (see 5.4.6). The evaluation should comprise:

a) identification of the wells that penetrate the storage unit within the area of review;

b) a determination of the status (exploration, producing, injecting, suspended, or abandoned) and ownership of the wells within the area of review;

c) characterization of the population of legacy wells by vintage, construction type, and type and extent of mechanical defects and identification of problematic wells, if any;

d) an evaluation of the potential of the wells to leak and an identification of the wells that need observation and/or remediation;

e) identification of wells within the area of review that penetrate shallower horizons than the storage unit or adjacent structures (including use of surveys to locate old, unrecorded wellbores) and their status and characteristics;

f) identification of wells that have inadequate or no available plugging records to assess the integrity of the plugs to seal during CO_2 storage;

g) determination of the chemical composition of well materials that will come in contact with a CO_2-charged fluid.

7.6.3 Inspection and testing

Prior to conversion for CO_2 storage, the long-string casing shall be inspected and tested for integrity over its full length by:

a) obtaining and evaluating cement integrity logs;

b) running and evaluating a casing inspection log for casing corrosion or damage;

c) pressure testing the casing in accordance with field pressure testing techniques without damaging the cement or cement-casing bond.

In addition, a baseline saturation log should be obtained to establish gas saturations near the wellbore.

7.7 Recompletion and workover of wells

7.7.1 General

Recompletion designs for converting existing wells shall ensure that the requirements of their function and this document are met. Converting legacy wells for use in storage projects should only be undertaken after careful evaluation. All recompletion work shall ensure well control and wellbore security.

7.7.2 Conditions for recompletion and workover of wells

A well should be recompleted or subject to a workover in the following situations:

a) hydraulic isolation is not indicated across the storage complex;

b) remedial cementing is needed to adhere to 7.4.2;

c) loss of mechanical integrity has occurred that may be indicated by:

   1) a failed pressure test;

   2) communication occurs between the tubing and the casing annulus, indicating a leak in tubing or packer.

7.7.3 Wellbore integrity

7.7.3.1 General

During or immediately following recompletion and workover activities, wellbore integrity should be tested and evaluated in accordance with industry recommended practices.

7.7.3.2 Casing integrity

Recompletion of existing wells shall be dependent on the construction details of the original well. Wells to be converted shall use casing that meets the requirements of 7.3.4. Allowance should be made for the age and condition of the casing so that no recompletion is performed in wells that cannot meet the requirements of 7.3.4.

Casing leaks shall be repaired. In the instance that flow is detected along the casing, cement integrity shall be re-established. In the instance that fluid movement is detected outside the casing, cement integrity shall be established prior to the installation of a liner or casing patch. In these cases, the available options can be limited to those that involve repairing the casing without pipe replacement, e.g. installing expandable liners and cement or chemical sealant squeezes.

Casing should be pressure-tested after casing repair. The packer and tubing should then be re-run into the well and mechanical integrity should be re-established by pressure testing the tubing casing annulus.

7.7.3.3 Tubing and packer integrity

A leaking tubing or packer shall be repaired through development and implementation of a workover plan that shall, where required, be reviewed and approved by the proper regulatory authority. If the well cannot be repaired, it should be plugged and abandoned in accordance with 7.8.

7.8 Abandonment of wells

7.8.1 General

Well abandonment design shall ensure the protection and isolation of potential CO_2 storage units, prevent leakage, and ensure that the surface is returned to near-original condition. This activity shall be guided by the regulatory authority issuing the well permit, as well as the requirements outlined in 10.4.

For further information, see Reference [58].

7.8.2 Evaluation of existing abandoned wells

All abandoned wells, including legacy wells, identified in the area of review shall be evaluated using all available records to determine its history including how the well was plugged and whether the method of plugging met the objectives of 7.8.1. If the well cannot be identified and no records on how the well was plugged can be found, or the well was plugged in a manner that did not meet the objectives of 7.8.1, the well shall be reviewed where possible, assessed for leak risk, and qualified for the intended function for the storage project. Where such assessment is not possible, the potential impacts of such wells should be considered through risk assessment methods.

7.8.3 Abandonment

Well abandonment during construction or at the end of the life of a well associated with the project shall be conducted in a manner that meets the objectives of 7.8.1. During plugging, care shall be taken to maintain well control at all times so that no injected fluids are released into the wellbore or the atmosphere. All CO_2 shall be flushed from the wellbore and the wellbore should be filled with a fluid of a density that will maintain well control. Casing and cement integrity logs should be re-run and compared to the original baseline logs to confirm cement and wellbore integrity. If either the cement or the casing is found to be deficient, repairs shall be made if required to maintain a seal so that the wells can be successfully plugged to meet the objectives of 7.8.1. All open perforations should be sealed and then plugged or isolated according to appropriate regulations.

8 CO_2 storage site injection operations

8.1 General

8.1.1 Objectives

The primary objective of CO_2 storage site injection operations is to inject a CO_2 stream into the storage unit at the required rate over the planned duration of the storage project to store the project's target mass of CO_2 in a safe and efficient manner. Operations associated with the subsurface injection of fluids are based on principles and methods developed by the oil and gas industry that are described within existing industry standards and in industry recommended practice documents. The intent of this clause is to address operational activities specific to the injection of a stream of CO_2 for the sole purpose of geological storage of CO_2.

Results from site selection and characterization modelling (see 5.5) are essential to the design and development of CO_2 injection operations. These models should be used, and enhanced as required, to assist in calibration of performance modelling of active injection to enable forecasting of CO_2 operations.

8.1.2 Scope of operations

CO_2 injection operations for geological storage take place within the storage site. This can include the location where custody of the CO_2 stream is transferred to the storage project operator. CO_2 stream injection activities occur during the operation period (see Figure 1) beginning at the time the CO_2 stream first enters a wellhead(s) at the storage site until cessation of CO_2 injection. Initial planning and design of the injection operations occur during the design and development period [see Figure 1 and 4.1.4 c)].

NOTE Transfer of custody can be identified differently for individual projects such as at the location of the last flow or mass meter in the major CO_2 pipeline prior to entering the storage site, or the legal boundary of the land encompassing the storage project, or from other delivery methods.

Operational activities not related to CO_2 stream injection that may occur outside the operation period, such as abandonment of an injection well during the closure period (see Figure 1), are not considered by this clause. CO_2 injection testing for the purpose of site characterization prior to the operation period also is not considered by this clause. Non-injection wells, such as monitoring wells, are not considered by this clause; however, many of the operational and maintenance principles described in this clause are applicable to other well types.

8.2 Design of CO_2 injection operations

8.2.1 General

Injection operations should be designed to achieve project objectives. The plans and designs should be prepared and documented for all CO_2 storage sites during the design and development period prior to the commencement of injection [see 4.1.4 c)].

8.2.2 Components of operations design

Components of the storage site's operations design should include the following:

a) storage complex parameters;

b) storage facility's operational design parameters [e.g. plant, gathering line(s), and well(s)];

c) operational protocols and maintenance schedules;

d) communication procedures;

e) safety procedures;

f) site security.

8.2.3 Injection design parameters

8.2.3.1 General

The elements and parameters of the storage complex and storage facility required for designing the operations and maintenance plan for CO_2 stream injection should be identified, collected and documented during site characterization and assessment (see 5.4).

8.2.3.2 Storage complex design parameters

The hydraulic, geochemical, and geomechanical characteristics of the storage unit(s) and primary seal(s) shall be evaluated to establish constraints and limitations specific to CO_2 injection operations (see 5.4). Geostatic models (see 5.5.2) shall be constructed to enable geochemical modelling (see 5.5.4), geomechanical modelling (see 5.5.5), and to provide a framework for designing the components of the storage facility through flow modelling (see 5.5.3). Final specifications of the components of the storage facility (e.g. compressor outlet pressure and temperature) should bound the modelled scenarios.

In addition to the information delineated within 5.4, the design of the injection operation shall evaluate:

a) available pressure and production history data, drilling and completion data, and test information from legacy wells located in the proposed storage complex and in surrounding formations that might be in communication with the storage unit;

b) all available well histories to assess well design and well performance as related to operations;

c) acceptable and safe operating conditions by conducting tests necessary to establish maximum operating pressure and temperature of the storage project [e.g. step rate tests to determine fracture pressure of storage unit(s) or seal(s)];

d) the expected range of operating pressures and temperatures during the operating life of the wells including start-up and shutdown criteria for injection;

e) the behaviour of the phase envelope of the CO_2 stream associated with expected changes in storage unit pressure resulting from the injection.

8.2.3.3 Pre-injection flow modelling

Flow modelling of the injection of a CO_2 stream into the storage complex shall be performed prior to commencement of injection to assist in site facility design and developing the operations and maintenance plan. The flow modelling shall describe the predicted behaviour of CO_2 in the subsurface and assess storage capacity, injectivity, and risk arising from CO_2 injection activities (see 5.5.3.2 and 5.5.3.3). The flow modelling should evaluate scenarios for the number and placement of injection wells required to achieve the needed rate of injection, and evaluate whether preferential placement of any pressure relief wells would be beneficial and effective in controlling pressure buildup and spread of the CO_2 plume (see 5.5.3.1).

8.2.4 Storage facility design plan

8.2.4.1 General

A storage facility design plan shall specify the location and number of CO_2 injection wells required to achieve the target rate and mass of CO_2 injection (see 7.3.3.2). The plan shall also specify gathering lines and surface facility requirements that can be newly developed or modified from existing facilities. The design plan should include injection and monitoring infrastructure [see 4.1.4 c), 7.3, and 7.4].

8.2.4.2 CO_2 receiving facility and CO_2 composition

The CO_2 stream composition and the expected ranges of pressure, temperature and flow rate at the CO_2 receiving facility such as the storage site custody meter shall be determined (see 5.4.4).

8.2.4.3 CO_2 injection requirements and schedule

The target CO_2 stream injection rate of individual wells should be determined from the target rate for the site and the maximum injection rate of individual wells. The duration of injection or life of the storage site, and the injection rate for each well, should be within the estimated capacity of each storage unit identified as suitable for storage.

An injection rate schedule should be forecast for each injection well based on storage complex design parameters and pre-injection modelling results. If multiple wells are involved, the injection rate schedule should provide for redistribution of the delivered CO_2 stream to other injection wells, or for venting or flaring so that injection pressure thresholds are not exceeded.

8.3 Operations and maintenance plan

8.3.1 General

An operations and maintenance plan shall be developed based on the design of the storage site to achieve project objectives using safe and efficient processes. The operations and maintenance plan may be documented in an ensemble of maintenance, operational and planning documents. The operations and maintenance plan shall be in accordance with all applicable regulatory permits and industry recommended practices. The project operator and project personnel supervisors shall have knowledge of permit requirements pertaining directly to the injection of a CO_2 stream.

The project operator shall establish a policy for use of the operations and maintenance plan, and this policy should be clearly communicated to all project personnel.

The operations and maintenance plan should define required competencies for project personnel.

The operations and maintenance plan shall be periodically reviewed and updated whenever changes to operational process or equipment usage occur (see 8.3.3).

8.3.2 Operational protocols and maintenance schedules

The operations and maintenance plan shall define a planned schedule for the inspection, maintenance, and replacement of onshore and offshore facility equipment following industry recommended practices to ensure safe and efficient site operations. The operations and maintenance plan shall have protocols in place that ensure maintenance issues are promptly addressed by qualified personnel.

8.3.3 Recording management of change

Records of routine and preventive maintenance at the storage facility should be maintained by the project operator. These records should include decisional changes in operations. Deviation from a permit, original design, or routine operations shall be recorded. The operations and maintenance plan should be updated to reflect these changes. A management of change database (see 3.24) should be established and maintained.

8.3.4 Communication plan

The storage project operator shall have a communication plan for contacting and being contacted by the transportation project operator, capture project operator, and any other operators of components of the project. The storage project operator shall have a plan for communicating with relevant regulatory agencies and stakeholders. The communication procedures shall be available to the control centre personnel.

8.3.5 Safety plan

A storage site safety plan shall be developed as a component of the operations and maintenance plan and implemented to integrate with routine operations, maintenance procedures, and emergency responses (see 7.3.2 and 8.4.3.2) for dealing with CO_2. A comprehensive safety plan should include the following:

a) an emergency response procedure;

b) an emergency response team;

c) a site-specific health and safety procedure;

d) requirements for safety training.

The safety plan should ensure that safe operating procedures are developed, and that all project personnel are properly trained to work with CO_2 and follow these operating procedures.

The safety plan should include authorization and defined procedures for any employee to communicate safety concerns to management and to stop injection if necessary to prevent injury, equipment damage, or damage to the environment.

8.3.6 Security plan

A security plan shall be a component of the operations and maintenance plan to restrict unauthorized access to the storage facility including wells, monitoring equipment, and associated operational infrastructure.

8.4 Injection operations

8.4.1 General

The purpose of CO_2 injection operations is to inject a stream of CO_2 into the storage complex at the scheduled rate over the planned duration of the storage project to store the project's target mass of CO_2 in a safe manner.

8.4.2 Injection

8.4.2.1 General

Monitoring of the key operational parameters defined in the operations and maintenance plan shall be performed by the operations control personnel.

Detailed flow diagrams of all site facilities should be accessible to project personnel together with operational set points (e.g. maximum injection flowline pressure) and preventive maintenance schedules.

8.4.2.2 Initial (start-up)

The procedures for the commencement of CO_2 stream injection (start-up) shall be defined in the operations and maintenance plan to include specific instructions regarding the operation of relevant well and facility components.

The project operator shall ensure that start-up (i.e. the CO_2 stream enters the injection flowline and wellhead) is communicated in advance to the pipeline project operator, CO_2 capture facility operator, and all project personnel.

The site supervisor, control room supervisor, and field supervisor shall know the type and composition of fluid in the injection flowlines and well prior to commencing CO_2 injection.

8.4.2.3 Continuous operational protocols

The design of the CO_2 stream injection system shall provide the injection protocol and operational guidelines that stipulate limits to injection rate, annulus pressure, and injection pressure. These parameters should be recorded by an automated data recording system and monitored automatically and continuously to ensure they remain within operational limits.

Automated shutdown systems should be tested according to the operation and maintenance plan. Any conditions prior to shutdown should be summarized and reviewed.

8.4.3 Shutdown

8.4.3.1 General

Shutdown in this document describes a period in which CO_2 stream injection is discontinued temporarily for planned, unplanned or emergency reasons.

8.4.3.2 Scheduled, unscheduled and emergency shutdowns

Scheduled shutdowns are initiated by project personnel and can take place for testing, routine maintenance, or because of expected interruptions in CO_2 stream supply, and the purpose of the scheduled shutdown should be clearly stated in the operations and maintenance plan (see 8.3) and recorded in the management of change database.

Unscheduled shutdowns are not initiated by project personnel and can occur due to equipment failure, automated fail-safe shutdowns, or unexpected interruptions in CO_2 stream supply.

Emergency shutdowns are initiated by project personnel based on observations or communications internal or external to the site or system.

Shutdown procedures specific to planned shutdowns shall be defined in the operations and maintenance plan.

The near-term and long-term operational impacts of an unscheduled or emergency shutdown should be reviewed. The review should evaluate whether changes are required to operational threshold limits or operational protocols. Operational changes should be made as appropriate and recorded by management of change procedures (see 8.3.3).

NOTE 1 Notification of shutdowns of any nature may need to be given to the regulating authority and subject to permit conditions.

NOTE 2 The use of isolating valves, pressure relief valves, and downhole shut-in devices to prevent uncontrolled release of CO_2 from the wellhead, flowlines, or other infrastructure is based on the design and location of the storage facility.

8.4.3.3 Start-up following shutdowns

A start-up procedure shall be defined in the operations and maintenance plan to follow a scheduled shutdown. The start-up procedure should be reviewed and updated as needed.

The cause of unscheduled shutdown shall be determined before initiating the injection start-up procedure. All safety issues associated with the shutdown and ensuing start-up shall be discussed with the project personnel. Use of an incremental start-up rate should be evaluated in the instance of a preceding unscheduled shutdown.

Communication to the pipeline operator, compression operator, capture facility operator, and all site employees shall be made immediately in advance of all start-ups following planned shutdowns.

8.5 Data acquisition, monitoring and testing

8.5.1 General

The operations and maintenance plan and monitoring plan shall identify the pressure, temperature and injection fluid data to be acquired during operations to assess injection system performance and ensure safe and effective injection operations. These operational data should also provide input to fluid flow models for predictive and performance verification purposes.

8.5.2 Surface equipment and injection line data

8.5.2.1 CO_2 receipt monitoring

The CO_2 stream delivered to the site shall be continuously metered and periodically sampled at the custody transfer or receipt point to the storage facility for safety, regulatory, and accounting purposes.

Metering should include:

a) calibration of meters at regularly scheduled intervals (at least once per year) following manufacturers and industry recommended practices;

b) recording of calibration measurements for accounting audit purposes;

c) determination of the composition of the CO_2 stream at regularly scheduled intervals (at least once per year) to estimate the mass of CO_2 injected;

d) measurement of pressure and temperature of the CO_2 stream to account for density variations in CO_2 to ensure accurate metering and functionality of the meter;

e) recording the quantity of CO_2 stream injected for accounting, engineering, and regulatory purposes.

8.5.2.2 Injection flowline metering

Metering at individual CO_2 injection flowlines and/or wellheads should include the specifications listed in 8.5.2.1.

In the cases of multiple injection wells downstream from a custody transfer meter, individual meters should be installed on each well. A comparison of the sum of mass flow rate readings from all wellhead meters with the mass flow rate reading from the custody transfer meter should be performed.

NOTE Any deviations in stream composition from the design criteria may require changes in process or equipment; these changes are documented through the management of change process.

8.5.3 Wellbore monitoring

8.5.3.1 Annulus pressure and temperature

The annulus between the CO_2 injection tubing and the casing shall be monitored at the wellhead for pressure and temperature to provide data to support assessment of casing, injection tubing, and packer integrity (see 7.4.1).

The wellhead annulus pressure shall not exceed the wellbore design pressure rating or regulated maximum pressure. The wellhead annulus temperature shall not exceed the wellbore design temperature rating or regulated maximum or minimum temperatures.

The wellbore should be examined periodically to ensure the injection fluid is not entering the annulus and annulus fluid is not entering the tubing or geologic formations penetrated by the well (see 8.5.4.4.2).

8.5.3.2 Surface injection tubing pressure and temperature

Surface injection tubing pressure and temperature shall be monitored and recorded continuously at the wellhead to ensure these parameters remain within the operating design specifications. These data can be used to estimate the density and mass of the injected fluids.

8.5.3.3 Downhole injection pressure and temperature

The use of permanent or temporary downhole gauges or sensors for direct measurement of downhole pressure and temperature should be evaluated for ensuring pressures and temperatures are within operating limits. If a downhole gauge is used, it should be placed as close to the active storage unit as possible.

In cases where downhole pressure gauges are not installed or are not functioning properly, data acquired directly from the injection wellhead should be used to estimate the bottom-hole injection pressures.

8.5.4 Well testing

8.5.4.1 General

Well testing should be designed to determine whether the injection well(s) is in a suitable condition for safe and continued injection of a CO_2 stream and to ensure regulatory compliance. A well control procedure shall be documented for each specific test. A safety meeting shall be conducted immediately preceding all tests.

8.5.4.2 Cased hole logging

The integrity of the injection tubing and wellbore shall be confirmed to ensure safe and efficient CO_2 stream injection operations. The operations and maintenance plan shall include wellbore inspection procedures that describe the techniques and frequency of inspection.

The operations and maintenance plan shall include procedures for addressing results of logging tests that can include mitigation of identified defects, or identify subsequent tests to verify changes to the wellbore components that may adversely affect CO_2 stream injection operations.

Wireline logs should be used and should be capable of measuring:

a) inside surface of the injection tubing;

b) inside surface of the casing;

c) cement integrity, including bond to pipe and formation;

d) CO_2 (saturation) within the geologic formations penetrated by the well;

e) fluid movement (formation fluid and CO_2) within the geologic formations penetrated by the well.

Interpretation of logging results should be designed to address:

— changes in fluid saturation in the storage unit below the primary seal and above the primary seal;

— changes to the injection tubing thickness;

— changes to the casing thickness;

— changes to the cement.

NOTE While standalone interpretation of well logs is standard practice, the most useful interpretation of logging results could be comparisons of logs run at different times. During the first several years of operations, the frequency of the well log tests can be required more often than in subsequent years.

8.5.4.3 Pressure transient testing

The annual average pressure of the storage unit shall be determined. A pressure transient test should be used to estimate annual average pressure. A comparison shall be made between the annual measured value to the projected pressure of the storage unit. This data comparison should be evaluated with respect to the primary seal integrity, surface compression and pipeline delivery pressure at the surface.

Alternatively, a shut-in period may be used in lieu of a pressure transient test, provided the operator can show adequate shut-in period to reach near static conditions.

8.5.4.4 Wellbore integrity testing and monitoring

8.5.4.4.1 Casing-tubing annulus, cement, surface casing

The project operator shall maintain wellbore integrity and abide by all regulations regarding wellbore integrity.

Mechanical integrity testing (MIT) should be conducted to guard against movement of wellbore fluids (annular or injected) into geologic formations other than the storage unit via the tubing-casing annulus or outside of the casing (i.e. behind pipe).

The operations and maintenance plan should indicate how project personnel routinely collect and analyse data regarding the mechanical integrity of wells.

8.5.4.4.2 Injection profile logs

Injection profile logging (IPL) should be used to determine where fluid is exiting the wellbore, identify fluid movement when the well is shut-in (not injecting), and estimate the total volume of CO_2 injected into the storage unit.

IPL should be completed at a frequency adequate to record changes in the vertical distribution of injected CO_2.

8.5.5 Corrosion mitigation

The operations and maintenance plan should include a procedure to monitor the effectiveness of the corrosion mitigation efforts of the wellbore, wellhead, surface pipe and facilities (see 7.5.2, 7.5.3, and 7.6.3).

8.6 Well intervention (workovers)

Well interventions (workovers) are performed for maintenance and performance reasons. Examples of these include stimulating injection rate, reducing injection pressure, cleaning the inside walls of the injection tubing, removing fill from the bottom of the wellbore that may block or cover perforations, and repairing leaks (see 7.7). Any changes in the well configuration shall be recorded in accordance with management of change procedures (see 8.3.3).

9 Monitoring and verification

9.1 Purpose

The primary purposes of monitoring and verification (M&V) are (1) to assist in managing health, safety, and environmental risks, and (2) to assess storage performance. M&V activities shall be an integral part of risk management, enabling an assessment of the storage project performance and providing confidence that CO_2 emission reductions are effective. It is important to acknowledge that site-specific geology and project-specific conditions need to be understood within a risk assessment framework to customize M&V to be most effective.

Monitoring refers to all measurement and surveillance activities necessary to ensure safe storage including activities to:

a) assess integrity of the storage complex, wells, and specific geological features;

b) detect loss of containment and assess potential impacts of leakage;

c) determine movement and fate of injected CO_2, pressure fields, and formation fluid displacement;

d) assess performance and effectiveness of risk control measures (e.g. mitigation, remediation).

Accounting refers to the determination of emissions reduction by a storage project and forms the basis for allocating storage credits. M&V supports accounting by providing the necessary data, but procedures related to accounting are not addressed in this document. For additional information, see ISO/TR 27915.

9.2 M&V program periods

9.2.1 General

The project M&V plan shall be flexible and adapt to changes in storage or injection conditions, be tailored to the specific requirements of the different periods of the storage project and of the geological features, and be adaptive to relevant scientific understanding and available technology. M&V activities should not increase unacceptable project risks (e.g. contamination or leakage to units not intended for storage). The M&V plan shall cover activities throughout the duration of the project. The project operator should plan and implement activities in stages that correspond to distinct periods in the project life cycle, i.e. pre-injection period, injection period, and closure period. Each of these periods has different M&V requirements that relate to periods in the project life cycle (see Figure 1) and, as such, can require adaptation throughout the life of the project. The post-closure period is not covered by this document.

9.2.2 Pre-injection period monitoring

During the pre-injection period (which occurs before sustained injection starts and corresponds to the site screening and selection, site characterization, design and development periods in Figure 1), project vulnerabilities shall be identified, parameters to monitor shall be specified, solutions to mitigate recognized vulnerabilities shall be proposed, and monitoring tasks shall be defined. An M&V plan shall be developed, and site-specific field data shall be acquired to establish pre-injection conditions to support future performance assessment of the storage project.

9.2.3 Injection period monitoring

During the injection period (which corresponds to the operation period in Figure 1 and can also include pilot injection tests), M&V activities shall provide sufficient information to manage safe injection operation and leakage risk, assess integrity of the storage complex, and calibrate predicted storage and injection performance. Monitoring practices shall be evaluated and adapted during the course of injection to ensure that monitoring activities continue to be appropriate and effective.

9.2.4 Closure period monitoring

During the closure period, M&V activities shall:

a) provide sufficient information to manage leakage risk;

b) demonstrate understanding of reservoir processes, robustness of predictive modelling approaches and consistency between monitoring observations and predictive models based on comparison with key performance indicators;

c) continue monitoring for leakage as appropriate to verify integrity of the storage complex.

In particular, M&V activities shall be designed and executed to support demonstration of the site closure acceptance criteria listed in 10.2.

9.3 M&V program objectives

Project operators shall develop and implement an M&V plan suited to their storage project that should be defined according to the storage project stages specified in 9.2. The M&V plan shall be designed to serve the following objectives for the project through to site closure:

a) to protect health, safety, and the environment by providing sufficient evidence to verify leakage of CO_2 or formation fluid beyond the storage complex has not occurred;

b) to support risk management (see 6.6) including assessing the effectiveness of corrective measures;

c) to provide adequate information for

1) decision support within the project among the project operators and principal project partners and for communication with regulatory authorities (e.g. see 4.3), and

2) communication with other stakeholders external to the project, including the local community or local landowners as appropriate (see 4.6.2);

d) to determine the frequency and duration of monitoring activities;

e) to identify the subsurface distribution of the CO_2 plume, to enable calibration and verification of dynamic models, and to support demonstration that site closure acceptance criteria are attained;

f) to continuously improve the M&V program and maintain data comparability consistent with 4.3 by adapting it to changing project circumstances, advances in industry recommended practices, and advances in technology, where appropriate;

g) to provide necessary data for quantification calculations for injected and stored CO_2 (and to detect, locate, attribute and quantify leakage, if it happens to occur) in accordance with requirements identified for accounting purposes (see 8.5.2.1);

h) to support management of CO_2 stream injection operations in a safe and environmentally responsible manner that complies with applicable laws and regulations by gathering information that demonstrates that storage site operations are within the performance limits accepted by the project operator and the regulatory authorities;

i) to support maintenance or improvement of storage project efficiency, safety, and economic performance (see 8.4.2.3).

9.4 M&V plan design

9.4.1 M&V program procedures and practices

The M&V plan shall:

a) describe the explicit purpose and performance metrics for monitoring activities;

b) define the procedures for the monitoring activities and the processes to be implemented for evaluating monitoring performance against the original purpose and pre-defined operational metrics;

c) describe the alignment of the M&V plan with the risk management policy established by the project operator in conformance with existing laws and regulations, and specify accountabilities and responsibilities for monitoring activities that support the risk management plan (see 6.6);

d) be subject to external inspection and review, and where applicable, be subject to approval by regulatory authorities;

e) contain communication of M&V requirements to internal and external stakeholders as appropriate;

f) describe operational procedures to provide an assurance that monitoring activities are carried out in a diligent and timely manner.

9.4.2 M&V plan specifications

The M&V plan shall be developed specifically for the planned CO_2 stream injection operation and designed to achieve the objectives stated in 9.3. The M&V plan shall be based on the expected subsurface distribution of CO_2, expected distribution of pressure in and adjacent to the storage complex throughout the project, and elements of concern (see 6.5) identified in the risk management plan.

The M&V plan should evaluate and, as applicable to site-specific conditions, describe the:

a) risk assessment for the site;

b) monitoring locations, parameters, and detection thresholds relevant to:

   1) address elements of concern from the project risk evaluation;

   2) identify when there is a need for modifications to the numerical prediction models or monitoring protocols;

   3) manage CO_2 stream injection operations, including the composition of the injectate, the injection rate, injection volumes, and reservoir pressures;

   4) verify that criteria for site closure are attained (see Clause 10);

c) design of the monitoring plan for the atmosphere, near surface, and subsurface, specifying the assumptions and expected conditions for which the monitoring plan is designed;

d) parameter changes that the program is designed to observe, as well as the frequency, spatial resolution, and duration of monitoring activities for each monitoring parameter and location for each monitoring period;

e) performance measures (i.e. criteria for evaluating the success of the monitoring program) to be met by the monitoring program;

f) method(s) used to assess movement of the CO_2 plume;

g) process and frequency for reviewing and updating the M&V plan;

h) schedule and reporting procedures to document compliance with M&V requirements in applicable regulations or as imposed by or agreed with regulatory authorities;

i) response plan to observations that are outside the anticipated ranges;

j) remediation strategy including, if necessary, reassessment of risk scenarios, monitoring programs, and operations, based on the information gathered through response plan investigations.

NOTE Examples of specific monitoring needs for a project can include data collected to assess the following:

— project well integrity (see 8.5.3);

— legacy well integrity;

— integrity of the confining zone;

— pressure within the storage complex;

— spatial distribution of the elevated pressure zone;

— pressure changes in the deepest permeable formation above the primary seal to the storage unit(s), and where applicable, permeable formations below the storage unit;

— displacement of formation water in the storage reservoir or adjacent strata;

— induced seismicity or microseismic activity;

— deformation (uplift, subsidence) of the earth surface in the area of review;

— characteristics and variability of atmospheric, near-surface, and subsurface conditions;

— geochemical changes in the reservoir during CO_2 injection.

9.4.3 M&V program contingency monitoring

The M&V plan should describe how the project plans to respond to observations that indicate conditions other than normal expected system performance of the storage system and monitoring systems.

The M&V plan should describe operational changes most likely to be required, based on the occurrence of specific conditions other than normal operational parameters, and the appropriate risk-based preparations to make those changes.

10 Site closure

10.1 General

The purpose of this clause is to identify criteria for site closure that, if met, provide a high degree of confidence that injected CO_2 will be retained within the storage complex and that risk associated with the project are *de minimis*, and to outline the requirements of a process that will allow the project operator to demonstrate compliance with these criteria. At the end of the closure period, the storage facility should be suitable for other uses and no need for future interventions should be anticipated.

10.2 Criteria for site closure

This subclause sets forth generic criteria for site closure that shall be met by the project operator during the closure period. These criteria shall be elaborated in such a way (e.g. through establishment of quantitative performance indicators) that compliance with these criteria can be demonstrated as part of the closure qualification process (see 10.4.1). The criteria for site closure shall be as follows.

a) The project operator shall demonstrate that the site meets established project objectives, including those relating to the absence of detectable leakage and impacts to human health, the environment, and economic resources.

b) The total CO_2 storage complex shall be understood sufficiently to assess its future evolution with a high degree of confidence. Particular attention should be given to the following aspects of the storage complex:

   1) observed CO_2 plume dispersion and migration and implications for the future, long-term distribution of CO_2 in the storage complex;

   2) historical reservoir pressure evolution and the predicted future evolution of the reservoir pressure;

   3) displacement of and compositional changes in formation fluid during the operational period and implications for future fluid movement.

c) The likelihood of future leakage of injected CO_2 and potential negative impacts on human health, the environment, or economic resources shall be demonstrated to conform to acceptance criteria established for the project [see 6.8 a)].

d) All wells shall be plugged and abandoned following the requirements of 7.8 unless otherwise directed by the regulatory authority.

e) Surface facilities and equipment associated with the storage project should be removed. Surface facilities integral to other operations or intended for different uses may be left in place.

10.3 Closure plan

The project operator shall develop a closure plan for the storage project that specifies key performance indicators for site closure and documents the closure qualification process. This plan shall be developed prior to the commencement of injection, shall be reviewed regularly and updated as appropriate during the project life cycle, and shall be finalized prior to the project entering the closure period. The plan:

a) shall specify quantitative key performance indicators used to measure compliance with the criteria for site closure (see 10.2), which should include:

   1) operational requirements, as updated throughout the life of the storage project;

   2) any site-specific requirements for site closure specified by the regulatory authority;

   3) generic procedural requirements for site closure, as stipulated in applicable regulations;

b) shall specify the provisional closure qualification process and timing;

c) should specify plans for ongoing site monitoring consistent with 9.2.4 and 10.2 b) that, in particular:

   1) identifies appropriate monitoring technologies;

   2) presents a schedule of planned monitoring activities;

d) should specify provisional plans for corrective actions, which should include plans to address any migration of fluids (CO_2 or formation fluids) out of the storage complex via wells;

e) should specify plans for collecting, reviewing, assessing, and structuring the information necessary for obtaining regulatory approvals for decommissioning of storage site infrastructure;

f) shall specify provisional plans for decommissioning of storage site infrastructure, including plans for plugging and abandonment of wells (see 7.8) and decommissioning of surface facilities associated with CO_2 stream injection and monitoring operations;

g) should specify means of notifying future landowners and (if applicable) resource owners of the stored CO_2 and remaining subsurface infrastructure.

10.4 Closure qualification process

10.4.1 Process

During the closure qualification process, the operator shall finalize the closure plan (see 10.3) and carry out activities in the plan. The closure qualification process should be structured and transparent, should take input from project stakeholders into account, and should demonstrate that risk and uncertainty have been gradually reduced and managed throughout the project life cycle. The closure qualification process should include:

a) a dialogue between the project operator and regulatory authority expressing the intent to cease injection, initiate execution of the closure plan, and establish agreement on the interpretation of any regulatory requirements for site closure specified in the closure plan [see 10.3 a) 2)];

b) revisions (as necessary) to finalize the closure plan, which details the process by which compliance with the criteria for site closure will be demonstrated and necessary approvals requested from the relevant regulatory authorities;

c) compilation of reports, results, and other data that will form the basis for the assessment of compliance with criteria for site closure and trends in risk and uncertainty [see 10.4.1 f)], including:

   1) operational logs that document the history of the storage project;

   2) monitoring logs that document and map the history of monitoring and verification activities;

3) an updated project risk database showing how individual risk scenarios that have been analysed and managed have evolved throughout the life of the project, including a description of the reasons for upgrading or downgrading risk during the life of the project;

4) a description of how key uncertainties have been analysed and managed throughout the life of the project;

5) compilation of results and conclusions drawn from monitoring, modelling, and risk assessments to support a demonstration of compliance with the criteria for site closure;

6) a description of historical storage performance relative to iterative predictions from modelling and simulations;

d) updating of storage performance predictions and identification of residual health, safety, and environmental risk, including risk to future containment stemming from well abandonment and site decommissioning;

e) verification of storage performance predictions and environmental impacts;

f) demonstration of compliance with the criteria for site closure and risk reduction targets [see 6.8 a)] for risk scenarios relevant to site closure.

10.4.2 Documentation

Reports, results, and other data that form the basis for the site closure qualification process, including that recommended in 10.4.1 c), should be archived following site closure.

10.4.3 Related activities

Other clauses in this document create requirements for the project operator during the closure period. The following activities should be included as part of the closure period:

a) risk management (see Clause 6):

1) implementation of the risk management plan (see 6.6);

2) implement and review risk treatment plans (see 6.8);

b) well infrastructure (see Clause 7):

1) operation and maintenance of monitoring wells (see 7.6, and 8.5.4.4);

2) the eventual abandonment and closure of injection, observation and monitoring wells (see 7.8);

c) monitoring and verification (see Clause 9):

1) implementation of monitoring program for the closure period (see 9.2.4).

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