
**Carbon dioxide capture,
transportation and geological
storage — Injection operations,
infrastructure and monitoring**

*Captage, transport et stockage géologique du dioxyde de carbone —
Opérations d'injection, infrastructure et surveillance*



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CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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 of 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 www.iso.org/iso/foreword.html.

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

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Carbon capture and storage (CCS) is a key technology to reduce CO₂ emissions to the atmosphere and contribute to the abatement of global warming. To have a significant impact it needs to be deployed globally. ISO 27914 on geological storage of carbon dioxide presents the elements necessary to define performance expectations for onshore and offshore geological storage of carbon dioxide with an aim to establish investor and other stakeholder confidence, regulatory support, and public credibility to encourage deployment of CCS around the globe. ISO 27916 on CO₂-EOR presents the elements for confirming and quantifying associated storage of CO₂ during the production of hydrocarbons, to encourage increased use of anthropogenic CO₂.

The application of these International Standards by project developers for planning, design, and operation will be assisted by information based on existing operational practices and infrastructural requirements for both onshore and offshore geological storage projects. This document supports the implementation of ISO 27914 and ISO 27916 by providing information from selected existing CCS projects that are operated under a variety of geological settings.

Carbon dioxide capture, transportation and geological storage — Injection operations, infrastructure and monitoring

1 Scope

This document covers:

- A description of the existing legal frameworks and associated laws and directives covering current and planned projects.
- Specific information about CO₂ injection facilities based on existing and planned projects that include storage of CO₂ in both saline aquifers and CO₂-EOR as relevant. This information includes aspects of materials used, surface infrastructure, well design considerations, concepts around well placement strategies, considerations for downhole monitoring tool deployment, well completions, and well and infrastructure maintenance and remediation practices.
- Descriptions of current practices regarding operating projects including monitoring, safety, and reporting activities associated with both surface and downhole components of the projects.
- Discussion on operational aspects of storing CO₂ in hydrocarbon reservoirs including depleting gas fields and reusing facilities.
- A description of monitoring requirements and methods including measurements to establish baselines.
- A description of existing and emerging tools, accuracy, and expectations for quantification.
- A description of regulatory requirements for operating and decommissioning CO₂-EOR with associated storage and CCS projects around the world.
- A description of decommissioning activities and timelines associated with end-of-project.

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 terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

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.

[SOURCE: ISO 27914:2017, 3.1]

3.2

acceptable risk

risk borne by the project operator and others having regard to legal obligations and management policies

Note 1 to entry: A tolerable risk is a risk of significant level considered as temporarily or conditionally acceptable. It is tolerated in order to facilitate a gradual response (e.g. monitoring of risk treatment) until the risk has been reduced.

[SOURCE: ISO 27917:2017, 3.4.7]

3.3

anthropogenic carbon dioxide

anthropogenic CO₂

carbon dioxide that is initially produced as a by-product of a combustion, chemical, or separation process (including separation of hydrocarbon-bearing fluids or gases) where it would otherwise be emitted to the atmosphere (excluding the recycling of non-anthropogenic CO₂)

Note 1 to entry: The chemical symbol "CO₂" is synonymous with "carbon dioxide". Accordingly, the two ways of writing out "carbon dioxide" and "CO₂" are used interchangeably in this document.

[SOURCE: ISO 27916:2019, 3.1]

3.4

area of review

geographical area(s) of a *storage project* (3.76), 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.

[SOURCE: ISO 27917:2017, 3.3.10]

3.5

associated storage

CO₂ stored in association with CO₂-EOR that occurs as an inherent result of a dedicated hydrocarbon production operation

Note 1 to entry: The requirements of ISO 27916 are intended to ensure that CO₂ stored in association with a CO₂-EOR operation is stored as effectively as CO₂ stored in a geologic storage operation that complies with ISO 27914.

[SOURCE: ISO 27916:2019, 3.2]

3.6

authority

governmental entity or entities with legal power to regulate or permit CO₂-EOR, to regulate storage of CO₂ in a CCS project or in association with a CO₂-EOR operation, or to regulate quantification of the storage of CO₂ in a CCS project or in association with a CO₂-EOR operation

[SOURCE: ISO 27916:2019, 3.3, modified to add "a CCS project or in" and delete "competent"]

3.7

baseline

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

[SOURCE: ISO 27917:2017, 3.3.2]

3.8**carbon dioxide capture and storage****CCS**

process consisting of the separation of CO₂ from industrial and energy-related sources (or capture directly from the atmosphere), transportation and injection into a geological formation, resulting in long-term isolation from the atmosphere

Note 1 to entry: CCS is often referred to as Carbon Capture and Storage. This terminology is not encouraged because it is inaccurate: the objective is the capture of carbon dioxide and not the capture of carbon. Tree plantation is another form of carbon capture that does not describe precisely the physical process of removing CO₂ from industrial emission sources.

Note 2 to entry: The term "sequestration" is also used alternatively to "storage". The term "storage" is preferred since "sequestration" is more generic and can also refer to biological processes (absorption of carbon by living organisms).

Note 3 to entry: Long-term means the minimum period necessary for geological storage of CO₂ to be considered an effective and environmentally safe climate change mitigation option.

Note 4 to entry: CCS should also ensure long-term isolation of CO₂ from oceans, lakes, potable water supplies and other natural resources.

[SOURCE: ISO 27917:2017, 3.1.1, modified to add " (or capture directly from the atmosphere)"]

3.9**carbon dioxide capture and storage project****CCS project**

consists of one or more connected CO₂ capture systems, transportation systems, and geological storage systems

Note 1 to entry: Each system (capture, transportation, or storage) might be operated by independent operators.

[SOURCE: ISO 27914:2017, 3.56]

3.10**carbon dioxide enhanced oil recovery****CO₂-EOR**

process designed to produce hydrocarbons CO₂ from a reservoir using the injection of CO₂

Note 1 to entry: The process of CO₂ enhanced oil recovery is explained in detail in ISO 27916:2019.

[SOURCE: ISO 27916:2019, 3.4]

3.11**carbon dioxide enhanced oil recovery project****CO₂-EOR project**

EOR complex, underground equipment, wells, surface or above seabed equipment, activities and rights necessary to an enhanced oil recovery operation, including any necessary or required surface or subsurface rights regulated by the authority

[SOURCE: ISO 27916:2019, 3.5]

3.12**carbon dioxide injection well****CO₂ injection well**

well used to inject CO₂ into a project reservoir

[SOURCE: ISO 27916:2019, 3.6]

3.13

carbon dioxide plume

CO₂ plume

region within geologic strata where injected CO₂ is present in free phase

[SOURCE: ISO 27914:2017, 3.6, modified to add “injected”]

3.14

carbon dioxide stream

CO₂ stream

stream consisting overwhelmingly of carbon dioxide

Note 1 to entry: The CO₂ stream typically includes impurities and may include substances added to the stream to improve the injection process or performance of hydrocarbon recovery operation and/or to facilitate CO₂ detection.

[SOURCE: ISO 27916:2019, 3.7, modified to add “the injection process or”]

3.15

carbon dioxide stream composition

CO₂ stream composition

comprehensive description of the CO₂ stream contents that lists the fraction of each component

Note 1 to entry: The CO₂ stream composition is usually subject to regulatory discretion and approval. It is commonly documented on a volumetric basis but may also be documented as a mass fraction.

3.16

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* ([3.58](#));
- 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 the bottom of the well.

[SOURCE: ISO 27914:2017, 3.8, modified to delete “to or through protected groundwater”]

3.17

closure period

period between the cessation of CO₂ injection and the demonstration of compliance with the criteria for site closure

[SOURCE: ISO 27917:2017, 3.1.7]

3.18

communication plan

document describing when, what and how to communicate with project stakeholders

Note 1 to entry: A communication plan may provide information relating to issues such as monitoring and verification, environmental impacts, risk treatment.

[SOURCE: ISO 27917:2017, 3.5.4]

3.19**containment**

status of CO₂ being confined within the *storage complex* (3.74) or *EOR complex* (3.30) by an effective trap or combination of traps

[SOURCE: ISO 27916:2019, 3.8, modified to add "storage complex or"]

3.20**containment assurance**

demonstrating that the features and geologic structure of the CO₂ storage project or CO₂-EOR project are adequate to provide safe, long-term containment of CO₂, and that the CO₂ flood is operated in a way to assure containment of the CO₂ in the EOR complex

[SOURCE: ISO 27916:2019, 3.9, modified to add "the CO₂ storage project or"]

3.21**corrective action**

action taken to correct material irregularities or to contain breaches in order to prevent or minimize damage to, or release of CO₂ from, a *storage complex* (3.74) or *EOR complex* (3.30)

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

[SOURCE: ISO 27914:2017, 3.12, modified to add "or EOR complex"]

3.22**decommission**

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

[SOURCE: ISO 27914:2017, 3.13]

3.23**demulsifiers or emulsion breakers**

specialty chemicals used to break emulsions (that is, to separate the two phases), for example, water in oil

Note 1 to entry: They are commonly used in the processing of crude oil, which is typically produced along with significant quantities of saline water.

Note 2 to entry: The type of demulsifier selected depends on the type of emulsion, either oil-in-water or water-in-oil.

Note 3 to entry: Demulsifiers are used in the chemical analysis of oil and synthetic muds and to treat produced hydrocarbons.

3.24**dense phase CO₂**

CO₂ in its liquid or supercritical phases

Note 1 to entry: Compression and transport of dense phase CO₂ are commonly achieved using compressors and pumps.

Note 2 to entry: Because liquid CO₂ is also considered dense phase, not all dense phase CO₂ is supercritical.

[SOURCE: ISO 27917:2017, 3.2.2, modified Note 1 to entry to add "compressors and" and delete "Compression and transport at lower densities are commonly achieved with turbo-compressors." Note 2 to entry - "Not all supercritical CO₂ is in a dense phase and" has been modified to "Because liquid CO₂ is also considered dense phase" - Note 3 to entry has been deleted.]

3.25

detection threshold

smallest value of a property of a substance that can be reliably detected by a specified method of measurement in a specified context

[SOURCE: ISO 27917:2017, 3.3.3, modified to change “limit” to “threshold”]

3.26

element of concern

valued element or objective for which *risk* (3.60) is evaluated and managed

[SOURCE: ISO 27914:2017, 3.14]

3.27

emergency response plan

systematic procedures that clearly detail what is to be done, how, when, and by whom before, during and after the time an emergency occurs

Note 1 to entry: In some jurisdictions, it can be called “emergency and remedial response plan”, “contingency plan”, etc.

Note 2 to entry: Emergency response plans often also cite preparations to be completed before an emergency occurs.

[SOURCE: ISO 27917:2017, 3.4.12]

3.28

emissions

CO₂ stream releases to the atmosphere over a specified period of time

3.29

environmental impact

change, which may be adverse or beneficial, to the environment, wholly or partially resulting from CCS project activities

[SOURCE: ISO 27917:2017, 3.4.13]

3.30

EOR complex

project reservoir (3.57) *trap* (3.84), and such additional surrounding volume in the subsurface as defined by the operator within which injected CO₂ will remain contained long-term

[SOURCE: ISO 27916:2019, 3.10, modified from “in safe, long-term containment” to “contained long-term”]

3.31

event

material occurrence or change in a particular set of circumstances

[SOURCE: ISO 27914:2017, 3.16]

3.32

geological storage

long-term *containment* (3.19) of CO₂ streams in subsurface geological formations

Note 1 to entry: Long-term means the minimum period necessary for CO₂ 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.

[SOURCE: ISO 27914:2017, 3.17, modified to delete Note 3 to entry]

3.33**greenhouse gas****GHG**

gaseous constituent of the atmosphere, natural or anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds

Note 1 to entry: The most common greenhouse gases are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), nitrogen trifluoride (NF₃) perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). Emissions from these gases are reported under the UNFCCC and aggregated into carbon dioxide equivalents (CO₂-e) using factors called global warming potentials (GWPs).

[SOURCE: ISO 14064-2:2019, 3.1.1]

3.34**impurities**

non- CO₂ substances that are part of the CO₂ stream that may be derived from the source materials or the capture process, or added as a result of commingling for transportation, or released or formed as a result of sub-surface storage and/or leakage of CO₂

Note 1 to entry: As a subset of impurities, contaminants are non- CO₂ substances whose presence in the CO₂ stream is generally unwanted.

Note 2 to entry: As a subset of impurities, additives are substances added to the stream for the purposes of managing its physical or chemical behaviour (e.g. hydrate and corrosion inhibitors), for or from interaction with equipment (e.g. lubricants), and to track its distribution in the subsurface after injection (geochemical tracers).

[SOURCE: ISO 27917:2017, 3.2.12]

3.35**injectivity**

rate and pressure at which fluids can be pumped into the storage unit without fracturing the storage unit

[SOURCE: ISO 27914:2017, 3.19]

3.36**Joule-Thomson effect**

thermodynamic process that occurs when a fluid expands from high pressure to low pressure at constant enthalpy such as across a valve

Note 1 to entry: Under the right conditions, this can cause cooling of the fluid.

3.37**leak****leakage**

unintended release of CO₂ out of a pre-defined containment

Note 1 to entry: Containments can include both surface containers (e.g. compressors, pipelines, trucks, ships, trains) and subsurface containments (e.g. storage complex).

[SOURCE: ISO 27917:2017, 3.2.14]

3.38**leakage pathway**

geological or artificial conduit for leakage of CO₂ out of the storage complex or EOR complex

[SOURCE: ISO 27916:2019, 3.13, modified to add "storage complex or"]

3.39

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

[SOURCE: ISO 27914:2017, 3.22]

3.40

liner

casing ([3.16](#)) string that does not extend to the surface

[SOURCE: ISO 27916:2019, 3.23]

3.41

loss

emissions, leakage, intended releases, and transfers of the CO₂ stream to outside of the CCS project defined boundary

Note 1 to entry: The terms “emissions”, “leakage” and “losses” are all used in this document to refer to CO₂ that would be deducted from quantities captured, transported or stored, but the terms have distinct meanings. The term “emissions” refers to CO₂ entering the atmosphere. The term “leakage” refers to CO₂ emitted but also includes CO₂ that escapes containment without entering the atmosphere, such as CO₂ that escapes a geological storage complex without moving into the atmosphere. The term “loss” is even broader and would include, in addition to emissions and leakage, CO₂ that is transferred out of a CCS project for some other use, which might or might not result in emission to the atmosphere.

Note 2 to entry: The term “loss” as used in this document is to be distinguished from the term “loss” as sometimes used in conjunction with CO₂-EOR operations to mean injected CO₂ that is not returned to the surface for recycling, i.e. is “lost” to the geological formation, necessitating purchase of more CO₂ for injection.

[SOURCE: ISO 27916:2019, 3.14]

3.42

make-up

purchased CO₂

CO₂ newly received from offsite

3.43

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

[SOURCE: ISO 27914:2017, 3.24]

3.44

measurement

determination of quantities using physical devices

Note 1 to entry: Examples of measurements are temperature, flow, concentrations, length, distance, etc. Measurement may be direct (e.g. length with a meter) or indirect. Indirect measurements may require two steps, firstly sampling and then analysis. Indirect measures may also use a model to convert the measurement of a given quantity into the measurement of another one, e.g. from velocity to flow rate, taking into account the pipe and fluid characteristics.

3.45

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 CO₂ are prevented from uncontrolled flow into, out of, along, or across the wellbore, cement sheath, annulus, *casing* ([3.16](#)), *tubing* ([3.86](#)), and/or *packers* ([3.52](#))

[SOURCE: ISO 27914:2017, 3.25]

3.46**mechanical integrity test****MIT**

test performed on a well to confirm that it maintains internal or external *mechanical integrity* (3.45)

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.

[SOURCE: ISO 27914:2017, 3.26]

3.47**mitigation**

limitation or reduction of actual or potential undesirable effects of a particular event or process

[SOURCE: ISO 27917:2017, 3.4.10]

3.48**monitoring**

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

Note 1 to entry: In case of geological storage, 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.

[SOURCE: ISO 27917:2017, 3.3.1]

3.49**nomination process**

pipeline transportation process whereby a shipper enters a “nomination” to put a specified quantity of gas into the pipeline at an entry point, and the same nomination states where and by whom the gas will be removed from the pipeline at the delivery point

3.50**operator**

person or entity that is legally responsible for the CCS project or the CO₂-EOR project

[SOURCE: ISO 27917:2017, 3.5.2, modified to add “person or” and “or the CO₂-EOR project”]

3.51**overburden**

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

[SOURCE: ISO 27914:2017, 3.29]

3.52**packer**

mechanical device that seals the outside of *tubing* (3.86) to the inside of *casing* (3.16) or the outside of casing to the drilled geological formation, isolating an annular space

[SOURCE: ISO 27914:2017, 3.30, modified to add “or the outside of casing to the drilled geological formation”]

3.53**post-closure period**

period that begins after the demonstration of compliance with the criteria for site closure

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

[SOURCE: ISO 27917:2017, 3.1.8]

3.54

pressure limit

pre-defined extrema of pressure for safe and effective operation of components of a CCS project

[SOURCE: ISO 27917:2017, 3.2.13]

3.55

primacy

primary enforcement responsibility

authority for a US state to implement the UIC Program

Note 1 to entry: To receive primacy, a US state, territory or tribe must demonstrate that its Class VI UIC Program is at least as stringent as the federal standards; the state, territory or tribal UIC requirements may be more stringent than the federal requirements. (For Class II UIC Program primacy, states must demonstrate that their programs are effective in preventing pollution of USDWs.) A state may obtain primacy for all or part of the UIC Program, e.g. for specific classes of injection wells.

3.56

primary seal

continuous geological unit (known in reservoir engineering as caprock and in hydrogeology as aquitard or aquiclude) above a *storage unit* ([3.78](#)) that is part of a *storage complex* ([3.74](#)) and effectively restricts migration of fluids out of the storage unit and *leakage* ([3.37](#)) out of the storage complex

[SOURCE: ISO 27914:2017, 3.32]

3.57

project reservoir

geologic reservoir into which CO₂ is injected for production of hydrocarbons in paying or commercial quantities

[SOURCE: ISO 27916:2019, 3.19]

3.58

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

[SOURCE: ISO 27914:2017, 3.37]

3.59

remediation

process of correcting a failure or impacts on affected elements of concern

[SOURCE: ISO 27917:2017, 3.4.11]

3.60

risk

effect of uncertainty on project objectives [e.g. on performance metrics for an *element of concern* ([3.26](#)), expressed in terms of the severity of consequences (negative impacts) of an *event* ([3.31](#)) and the associated *likelihood* ([3.39](#)) 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).

[SOURCE: ISO 27917:2017, 3.4.1]

3.61**risk analysis**

process for understanding the nature and level of *risk* (3.60)

[SOURCE: ISO 27914:2017, 3.40]

3.62**risk assessment**

overall process of *risk identification* (3.66), *risk analysis* (3.61), and *risk evaluation* (3.64)

[SOURCE: ISO 27914:2017, 3.41]

3.63**risk control**

measure whose purpose is to reduce a specific *risk* (3.60) or avoid escalation of risk

[SOURCE: ISO 27914:2017, 3.42]

3.64**risk evaluation**

process of comparing the results of a *risk analysis* (3.61) with *risk evaluation criteria* (3.65) to determine whether the *risk* (3.60), its magnitude, or both are acceptable or treatment is required to reduce the risk

[SOURCE: ISO 27914: 2017, 3.43]

3.65**risk evaluation criteria**

terms of reference against which the significance of *risk* (3.60) is evaluated

[SOURCE: ISO 27914:2017, 3.44]

3.66**risk identification**

process of finding, recognizing, and describing *risk* (3.60)

[SOURCE: ISO 27914:2017, 3.45]

3.67**risk management plan**

scheme specifying the approach, management components, and resources to be applied to the management of *risk scenarios* (3.68)

[SOURCE: ISO 27914: 2017, 3.46]

3.68**risk scenario**

combination or a chain of circumstances through which a *threat* (3.81) can cause an *event* (3.31) to occur and through which the consequences of an event can have a negative impact on *elements of concern* (3.26)

[SOURCE: ISO 27914:2017, 3.48]

3.69**risk treatment**

process to reduce a specified *risk* (3.60) through implementation of *risk controls* (3.63)

Note 1 to entry: Risk treatments could reduce the likelihood or impact severity of a risk.

[SOURCE: ISO 27917:2017, 3.4.4, modified to add Note 1 to entry]

3.70

safe, long-term

period necessary for storage to be considered environmentally safe by the scheme under which the quantification is being implemented

Note 1 to entry: Long-term means the minimum period necessary for CO₂ geological storage to be considered an effective and environmentally-safe, climate change mitigation option.

[SOURCE: ISO 27916:2019, 3.21]

3.71

site characterization

detailed evaluation of one or more candidate sites for CO₂ storage identified in the screening and selection stage of a CO₂ *storage project* (3.76) to confirm and refine *storage complex* (3.74) integrity, storage capacity, and *injectivity* (3.35) estimates and provide basic data for initial predictive modelling of fluid flow, geochemical reactions, geomechanical effects, *risk assessment* (3.62), and *monitoring* (3.48) and *validation* (3.89) program design

[SOURCE: ISO 27914:2017, 3.51]

3.72

site closure

end of the *closure period* (3.17), which occurs when the project *operator* (3.50) has demonstrated compliance with criteria for site closure

[SOURCE: ISO 27914:2017, 3.52]

3.73

stakeholder(s)

individual, group of individuals, or organization whose interests are or could be affected by a *storage project* (3.76)

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.

[SOURCE: ISO 27914:2017, 3.36, modified]

3.74

storage complex

subsurface geological system extending vertically to comprise storage units, and identified seals, and extending laterally to the defined limits of the CO₂ storage project

Note 1 to entry: Limits are defined by natural geological boundaries, regulation or legal rights.

Note 2 to entry: Some jurisdictions could allow boundaries to be redefined if CO₂ moves outside the original boundary yet still achieves safe, long-term containment.

[SOURCE: ISO 27914:2017, 3.54, modified to add Note 2 to entry]

3.75

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 CO₂ injection facilities are developed and operational activities [including *monitoring* (3.48)] take place

Note 1 to entry: In many instances, the storage facility and the *area of review* (3.4) 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.

[SOURCE: ISO 27914:2017, 3.55]

3.76**storage project**

physical and temporal extent of activities associated with a project for the *geological storage* (3.32) of CO₂ that includes site selection and characterization, *baseline* (3.7) data collection, permitting, design and construction of site facilities (site pipelines, compressors, etc.), well drilling, receipt of CO₂ at the *storage site* (3.77) and CO₂ injection during the active injection phase, and *site closure* (3.72) (including well and facilities abandonment)

Note 1 to entry: It also includes testing and *monitoring* (3.48) during all project phases.

[SOURCE: ISO 27914:2017, 3.56]

3.77**storage site**

site that comprises the *storage facility* (3.75), *storage project* (3.76) wells, and the *storage complex* (3.74)

[SOURCE: ISO 27914:2017, 3.58]

3.78**storage unit**

geological stratum (or strata) into which CO₂ is injected for the purpose of storage

[SOURCE: ISO 27914:2017, 3.59]

3.79**supercritical CO₂**

CO₂ at pressures and temperatures above both the critical pressure and critical temperature

[SOURCE: ISO 27917:2017, 3.2.1]

3.80**termination**

process beginning with the cessation of quantification of associated storage, and ending with both the termination of hydrocarbon production from the project reservoir, and the plugging and abandonment of wells unless otherwise required by the authority

[SOURCE: ISO 27916:2019, 3.22]

3.81**threat**

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

[SOURCE: ISO 27914:2017, 3.60]

3.82**threshold**

limit value, which can be a function of time, space or other variables, beyond which an action or frame of reference is triggered

[SOURCE: ISO 27917:2017, 3.3.4]

3.83**transfer of responsibility**

transfer of all rights, responsibilities, and liabilities associated with a *storage site* (3.77) to a post-closure steward

[SOURCE: ISO 27914:2017, 3.63]

3.84

trap

any feature or mechanism that alone or in combination provides safe, long-term containment below a low-permeability confining geologic layer (cap rock or seal), including in the pore spaces of the EOR complex (physical, stratigraphic, or structural trapping); by capillary pressure from the water in the pore spaces between the rock (residual trapping); by dissolution in the in situ formation fluids (solubility); by hydrodynamic trapping; by adsorption onto organic matter; or by reacting in geologic formations to produce minerals (geochemical trapping)

[SOURCE: ISO 27916:2019, 3.23]

3.85

treater

vessel used to treat oil-water emulsions, so the oil can be accepted by the pipeline or transport

Note 1 to entry: Treaters use heat, gravity segregation, chemical additives, or electric current to break emulsions and are sometimes called heater treaters or emulsion treaters.

Note 2 to entry: Residence time in treaters varies, with residence generally shorter in vertical treaters than in horizontal ones.

3.86

tubing

tubular string normally run inside the injection or production *casing* ([3.16](#)) that acts as the primary conduit for fluids

[SOURCE: ISO 27914:2017, 3.62]

3.87

unacceptable risk

risk of a nature and level that is regarded as unacceptable by the project operator and others or by an authority whose approval is required for the project to proceed

[SOURCE: ISO 27917:2017, 3.4.8]

3.88

uncertainty (of measurement)

parameter associated with the result of a measurement that characterizes the dispersion of values that could reasonably be attributed to the measurement property

[SOURCE: ISO 27917:2017, 3.3.7]

3.89

validation

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

[SOURCE: ISO 27917:2017, 3.3.6]

3.90

venting

intended release of a gas into the atmosphere from pre-defined containment

3.91

verification

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

Note 1 to entry: Verification examines what has happened in the past. The objective of verification is to express a conclusion designed to enhance the degree of confidence in the declared outcomes of the CCS project quantification as evaluated against agreed criteria.

[SOURCE: ISO 27917:2017, 3.3.5]

3.92 well wellbore

holes created into the ground in which are emplaced combinations of tubing, casing and cement to be used for conveying fluids

Note 1 to entry: In this document “well” is used to refer generally to the entire well (including wellhead, valves, etc.) whereas “wellbore” refers to the downhole portion of the well.

4 Symbols and abbreviated terms

3D	Three dimensional
ADM	Archer Daniels Midland Company
AEP	American Electric Power
AOR	Area of review
API	American Petroleum Institute
BPM	Best practice manual
BSEM	Borehole to surface electromagnetic
BTC	Buttress thread casing
CBL	Cement-bond log
CCI	Continuous CO ₂ injection
CCS	Carbon dioxide capture and storage
CCS Directive	Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide
CFR	US Code of Federal Regulations
CO ₂	Carbon dioxide
CO ₂ -EOR	CO ₂ -Enhanced oil recovery
CSA	CSA Group (formerly Canadian Standards Association)
CSEM	Controlled source electromagnetic
DAS	Distributed acoustic sensing
DOE or USDOE	US Department of Energy
DTS	Distributed temperature sensing
EEA	European Economic Area
ELD	Environmental Liability Directive
EOS	Equations of state
EPA or USEPA	US Environmental Protection Agency

ETS Directive	Directive 2003/87/EC
FRP	Fiber reinforced plastic
FWKO	Free water knockout
GPS	Global positioning system
H ₂ S	Hydrogen sulfide
HCl	Hydrochloric acid
IEAGHG	International Energy Association Greenhouse Gas Programme
InSAR	Interferometric synthetic aperture radar
KCl	Potassium chloride
KSpG	Carbon dioxide storage law
LACT	Lease automatic custody transfer
LNG	Liquefied natural gas
MD	Measured depth. The length of the wellbore
MMscf	Million standard cubic feet
MMV	Monitoring, measurement and verification
N ₂	Nitrogen
NACE	National Association of Corrosion Engineers
NETL	US DOE National Energy Technology Laboratory
NO _x	Nitrogen oxide(s)
O ₂	Oxygen
PISC	Post injection site care
ppg	Pounds per gallon
PVT	Relation between pressure, specific volume, temperature
RA	Risk assessment
ROV	Remotely operated vehicle
SCADA	Supervisory control and data acquisition
SDWA	Safe Drinking Water Act
SECARB	Southeast Regional Carbon Sequestration Partnership
SWP	Southwest Partnership on Carbon Sequestration
TD	Total depth
UIC	Underground injection control

USDW	Underground source of drinking water
Vshale	The volume of shale in a given volume of rock
VSP	Vertical seismic profiles
WAG	Water alternating gas

5 Legal framework

5.1 General

In this clause, some general introduction and observations on regulatory frameworks relevant to CO₂ storage operations and the case studies selected for this document are highlighted.

For most jurisdictions, CO₂-EOR operations are subject to the regulatory framework for petroleum operations whereas other types of geological storage are regulated separately under dedicated CCS frameworks. For some jurisdictions, such as the United States, this distinction has consequences for the activities required by the operator and the legal liability to which the operator is subject. In other jurisdictions, as in many countries in the European Union, the distinction is not of the same significance. The EU regulatory framework contains identical requirements for storage of CO₂, regardless of the primary intended purpose of the CO₂ injection (i.e. CO₂-EOR or CCS).

[Subclauses 5.2](#) to [5.9](#) present the regulatory frameworks for the US, Germany, France, Norway, Canada, Japan, and Australia. These jurisdictions are chosen as case studies and presented in this document as they have different legal traditions and maturity level regarding CO₂ injection and storage.

The United States has a well-developed regulatory framework for CO₂ storage onshore, both associated storage during CO₂-EOR and non-associated geological storage. However, there is currently no regulatory framework to regulate such activities offshore in federal waters. In state waters, the same regulations that govern onshore operations are generally applicable. Further, the distinction between Class II and Class VI permits for storage associated with CO₂-EOR and geological storage, respectively, results in some differences regarding post-injection responsibilities and liability for the operator. Some of these issues are subject to federal regulation and others are subject to state requirements and permitting. Regulatory frameworks in other countries with a federal governmental structure (for example Canada and Australia) also distinguish between federal and state/province regulation and the content and maturity of the federal and state/province regulations vary. For the European Union and the UK, the framework for CO₂ storage is applicable for 31 countries and covers both onshore and offshore operations for CCS and CO₂-EOR. Despite some distinct differences among the member states' frameworks, the default responsibilities and liabilities for the operators storing CO₂ are the same. Meanwhile, the regulatory framework for CO₂ storage in Japan is still developing.

5.2 United States

5.2.1 General

Onshore underground injection projects in the US are regulated through the Underground Injection Control (UIC) program adopted by the US Environmental Protection Agency (EPA) in the 1980s under the federal Safe Drinking Water Act (SDWA). The UIC program is directed at protecting underground sources of drinking water (USDWs) from underground injection activities that would endanger human health through contamination. At present, very few wells are injecting CO₂ solely for the purpose of geological storage as compared with a much larger number of wells injecting CO₂ for the purpose of EOR. The permitting, operation, and closing of oil and gas related injection wells is governed by a vast body of contracts, industry practice, mineral property ownership and leasing, judicial decisions, as well as statutory law and regulation, in addition to the provisions of the UIC Program. Wells used exclusively for the storage of CO₂ are not subject to the pre-existing framework for CO₂ injection wells, which

presupposes linkage of the activity to the extraction of a valuable economic commodity, resulting in the UIC Program being the predominant framework for the injection of CO₂ solely for storage purposes.

Under the SDWA, responsibility for regulating well permitting, operation, and closure is divided between the state and federal governments. The federal UIC program establishes minimum standards or requirements for regulation of certain types of injection wells, while allowing states to assume primary authority (called “primacy”) for implementation and enforcement of the program, while EPA retains oversight to ensure compliance with the minimum standards.

5.2.2 UIC Class II and Class VI

The UIC program originally divided fluid injection wells into five different classes, depending on the activity and the nature of the injectate. Class II wells are used to inject fluids associated with production of oil or natural gas. Thus, Class II wells include principally (a) disposal wells for injecting produced water and oilfield wastes; (b) wells used to inject brine, freshwater, steam, polymers, or carbon dioxide to enhance oil recovery; or (c) wells used for underground storage of liquid hydrocarbons.

In 2010, EPA added a Class VI program for wells used for injection of CO₂ for the purpose of geological storage. The Class VI rules provide well design and permitting requirements for the injection of CO₂ for storage in saline formations. Adapting the existing UIC regulatory framework to address the unique buoyant and corrosive nature of CO₂ injectate, the Class VI rule sets minimum technical criteria for permitting, geologic site characterization, delineating an area of review (AOR), corrective action on existing wellbores, financial assurance, well construction, operation, mechanical integrity testing, monitoring, well plugging, post-injection site care (PISC), and site closure. Following issuance of the Class VI rule in 2010, the EPA issued multiple non-binding guidance documents providing additional information to assist those operating under the rule (<https://www.epa.gov/uic/final-class-vi-guidance-documents>).

At the time of publication, the regulatory bodies of essentially all of the oil and gas producing states have obtained primacy for administration of Class II injection wells. Initially, EPA directly administered the Class VI well program in every state, and has issued permits for six Class VI wells since 2010 including provisions governing post-injection site care and closure (see 11.5.4), although only two of these wells have ever been operated. More recently, individual states are requesting and obtaining primacy for the UIC Class VI well program.

5.3 The European Union

5.3.1 General

The European Union (EU) consists of 27 member states, and three other European Economic Area (EEA) states (Iceland, Liechtenstein and Norway) that collaborate with the EU. The UK also adopted the EU approach before leaving the Union.

The member states of the EU and to a large extent the EEA states are obliged to implement all legally binding directives and regulations and adopt all measures of national law necessary to do so. For both regulations and directives, the EU can pass legislation that sets minimum standards, which do not preclude member states from setting more stringent standards and enables member states to maintain more stringent regulatory provisions than those prescribed, if these are otherwise compatible with EU law.

Below, the two most relevant EU legal instruments for CCS and CO₂-EOR, which are relevant for 31 countries, are summarized.

5.3.2 The EU CCS Directive

The EU CCS Directive (EU Directive 2009/31/EC) was adopted in 2009 to provide for environmentally safe deployment of CCS. Specifically, it aims to ensure that there is no significant risk of leakage of CO₂ or damage to public health or the environment, and to prevent any adverse effects on the security of the CO₂ transport network or storage sites. As per the CCS Directive’s definition, enhanced hydrocarbon

recovery (EHR) – including CO₂-EOR - is not in itself included in the scope of this directive. However, where combined with geological storage of CO₂, the provisions apply accordingly.

Pursuant to the CCS Directive, CCS activities are subject to permit requirements which include having separate exploration and storage permits issued pursuant to the ETS Directive. The CCS Directive harmonizes administrative procedures for the whole cycle of carbon capture, transport and storage across member states, however leaving each member state with the freedom to decide how site operators are to prove their ability to safely operate and monitor a storage site up to the point of closure and later transfer of responsibility to the competent authority.

The storage permit contains information about the operator, location and delimitation of the storage site and administrative information about the permit itself. As well, the permit requires a large amount of technical data comprising characterization of the storage site, identification of CO₂ stream composition, an approved monitoring plan, a plan for corrective measures to prevent significant irregularities, a proposed plan for corrective measures in case of leakage and significant irregularities, reporting criteria, criteria for closure, and an approved provisional post-closure plan. Prior to granting the permit, the application with supporting material, as well as information of the designated authorities planned decision relating to the permit, are sent to the European Commission for review. State regulators are obligated to ensure that the operator is “financially sound and technically competent to operate and control the site”.

The CCS Directive contains a number of detailed requirements to be implemented for the operational phase, leaving room for member states to decide on the details and to take into consideration the commercial and operational specifications. As an example, the CCS Directive requires monitoring of the injection facilities, the storage complex and the surrounding environment based on what is set out in the operator’s monitoring plan. The purpose is to detect significant irregularities, migration and leakage of CO₂ and significant adverse effects on the surrounding environment. In case of leakage or significant irregularities, the operator is obligated to immediately notify the designated authorities and to take necessary corrective measures. In case the operator fails to take the appropriate measures, the designated authorities need to initiate such measures themselves, recovering the costs from the operator. Consequently, the CCS Directive requires the operator to establish and maintain a mechanism for financial security prior to start of injection and throughout the operational phase. The CCS Directive does not provide the details on how this financial security should be documented. It is up to the Member States to decide what type of instrument is desired.

5.3.3 The Environmental Liability Directive

EU’s Environmental Liability Directive (ELD) establishes the framework for environmental liability, based on the polluter pays principle, to prevent and remedy environmental damage. Where CCS operations result in damage to the local environment, the CCS Directive relies upon the ELD for allocation of liability. This framework thus applies in parallel with the requirements to monitor, report, prevent and implement corrective measures pursuant to the CCS Directive and ensures that damage to the environment beyond the storage site is not neglected.

Under the ELD, liability for both preventive and remedial action is assigned to the operator, who is in control of the activity which causes or threatens to cause the environmental damage. That responsibility remains even after active storage operations have ceased, throughout the post-closure period until responsibility is transferred to the Competent authority. More details regarding closure, post-closure and transfer of liability are provided in [Clause 11](#).

5.4 Germany

In 2012, Germany passed a law entitled the ‘Demonstration and application of technologies for the separation, transport and permanent storage of carbon dioxide’ (or ‘KSpG’). The KSpG represents an almost direct implementation of the EU CCS Directive containing the prerequisites for examining the subsurface for its suitability for CO₂ storage and for the planning approval of a CO₂ storage facility. The planning approval is subject to strict environmental requirements and is only adopted if these are met. The operator needs to demonstrate that the CO₂ storage does not adversely affect the general interest,

its long-term safety is guaranteed, that no danger to humans and/or the environment will be caused and that the necessary precautions will be taken.

The KSpG limits the annual storage quantity of CO₂ both with regard to each CO₂ storage facility as well as the total amount in Germany. Not more than 1,3 Mt of CO₂ is stored per storage facility, nor more than 4 Mt nationwide. The KSpG further requires that requests for permits for investigation, construction and operation of a CO₂ storage facility must be submitted by 31 December 2016. No applications came in prior to the deadline.

5.5 France

France started the transposition of EU CCS Directive in 2010 and Decree 2011-1411 completed the transposition into French national law. Whereas the scope of the CCS Directive excludes R&D pilots with a storage capacity below 100 kt, French law regulates these operations. Pursuant to the French Environmental Code, the quantity of CO₂ injected for testing purposes should not exceed the quantity strictly required for the characterization of the formation and cannot exceed 100 kt. Pursuant to the decree 2012-384, geological storage of CO₂ facilities must comply with specific regulations regarding the protection of the environment.

5.6 Norway

5.6.1 General

The current Norwegian regulatory regime for CO₂ storage is based on implementation of the EU CCS Directive and the EU ETS Directive. CCS activities in Norway (Sleipner project) preceded Norway's implementation of the CCS Directive by almost 20 years.

The competent authorities have implemented the CCS Directive through three regulations. The Storage Regulations were adopted under the Continental Shelf Act ("CSA"). Amendments were also made to the original Petroleum Act and Regulations and Pollution Regulations. Petroleum related CO₂ storage activities, including CO₂-EOR, are regulated pursuant to the petroleum framework, whereas non-petroleum related CO₂ storage activities are regulated pursuant to the new Storage Regulations. The operator also needs a permit pursuant to the Greenhouse Gas Trading Act.

5.6.2 The permitting regime for CCS activities

During the lifetime of a project, there are several required permits and operator obligations for either petroleum related or industrial CO₂ storage in compliance with the CCS Directive. Also, in order to develop a storage site, the Plan for Development and Operation stands out as being of special importance, containing considerations relating to for example economic, commercial, resource management, technical, safety and environmental aspects, as well as preliminary plans for decommissioning. The plan is not a permit per se, however it is subject to the approval of the Ministry of Petroleum and Energy. The Pollution Control Act and the subordinate Regulation are applicable for any injection of CO₂. Further, the operator needs a "permit for injection and storage" from the Norwegian Environment Agency. The permit is mainly aimed at ensuring the environmental aspects of CCS projects are secured, i.e. monitoring, reporting and corrective measures.

5.6.3 Financial security

Norway has implemented its own regulations for financial security in which the Competent authority is provided with flexibility and discretion based on a case-by-case basis assessment regarding how the operator is able to fulfil this requirement. The use of parent company guarantees has a long tradition in the Norwegian petroleum industry. In both the Sleipner and Snøhvit CCS projects, a parent company guarantee was provided by the operator and approved by the Ministry of Petroleum and Energy.

5.6.4 Monitoring

The operator issues a plan for monitoring and this plan is to be updated every five years. The Storage Regulations specify the kind of monitoring required during operations and after closure. The monitoring objectives fall into three main categories:

- Conformance monitoring: ensuring that the behaviour of CO₂ in the reservoir is understood.
- Containment monitoring: ensuring that CO₂ stays within the storage unit.
- Contingency monitoring: assessing effect of contingency measures in the case of leakage.

5.7 Canada

In Canada, governing authority is divided between the federal government and the ten provinces, each having primary authority within defined limits and with some areas of dual authority (Krupa, 2018). Jurisdiction over the environment is shared. CO₂-extraction activities such as EOR fall under provincial authority because the provinces have primary authority over local works, property rights, groundwater protection and nonrenewable resources. The authority of the federal government with respect to CCS stems from its responsibility for matters of national concern as well as international cooperation and agreements (e.g. international agreements on GHG emissions). The federal and provincial governments have worked together and in cooperation with other nations and international organizations to foster the development of specific CCS projects and activities related to CCS operations, such as Saskatchewan's Boundary Dam project and monitoring activities at Weyburn-Midale. All Canadian jurisdictions have environmental, safety and resource conservation regulations that could apply to the component systems of CCS projects (capture, transport, and storage) through the issuance of licenses or permits as appropriate. Most aspects of CCS projects, including storage related issues, are covered by the existing provincial regulations for oil and gas production and mining. Component systems also require a federal or provincial environmental assessment to evaluate potential impacts and the need for mitigation.

Alberta has built the regulation of CCS into its framework for exploitation of fossil fuels, under which it has historically regulated EOR and acid-gas injection. The province amended its Mines and Minerals Act (hydrocarbons being considered a mineral in legislation) and Energy Resource Conservation Act in 2010 with the Carbon Capture and Storage Statutes Amendment Act to address long-term CO₂ storage liability, underground property rights (land tenure and pore space), and financial responsibility for post-closure monitoring, maintenance, and remediation. The concept of pore space was not previously identified in legislation. However, the legislation further clarifies that no expropriation of title occurred as a result of the legislation; rather the legislation provides clarity that the Crown (or freehold owner of mines and minerals) has and will continue to have title of the pore space as well as the minerals and water contained in the pore space. The legislation also clarified the right to explore and develop those lands for the purpose of CO₂ sequestration (storage). In addition to the existing oil and gas regulations which cover many aspects of CO₂ storage projects, the Carbon Capture and Storage Funding Act, Carbon Capture and Storage Funding Regulation, Carbon Capture and Storage Amendment Act, and Carbon Sequestration Tenure Regulation are also in place.

In British Columbia, amendments to the Petroleum and Natural Gas Act and the Oil and Gas Activities Act were passed with the purpose of enabling CCS under existing regulations for natural gas storage and acid gas disposal (Krupa, 2018). The legislation authorizes storage and disposal of CO₂ as a "prescribed substance" in naturally occurring underground reservoirs and also addresses capture, transport, storage, ownership and liability issues relating to CCS.

In Saskatchewan, many aspects of CCS projects also fall under the oil and gas and mining regulations of the established Oil and Gas Conservation Act, which regulates the storage of other substances in addition to oil and gas storage. Some of the main pieces of legislation governing the CCS related activities in Saskatchewan include The Crown Minerals Act, The Oil and Gas Conservation Act and its regulations, The Management and Reduction of Greenhouse Gases Act and its regulations, as well as amendments to these regulations.

5.8 Japan

The foundation for the Japanese regulatory framework for CO₂ storage operations offshore is the London Protocol and especially its CO₂ Waste Assessment Guidelines. These guidelines form the backbone of Act on Prevention of Marine Pollution and Maritime Disaster (2007 amendments) that were implemented to support the deployment of CO₂ storage demonstration projects in Japan. The amendments were followed up by a guideline “For Safe Operation of a CCS Demonstration Project” in 2009.

The current Japanese framework for CO₂ storage requires an operator to obtain a permit prior to operations. The permit is granted by the Japanese Ministry of Environment and needs to be renewed every five years. Such permits are limited in time and contain strict criteria to monitor and report to the Japanese Ministry of Environment. Several documents are required to apply for a permit including a project plan, a monitoring plan, a site selection report, an environmental impact assessment report and documents to demonstrate financial and technical capabilities. The Ministry will evaluate this documentation to decide whether the CO₂ to be stored meets official requirements, and that the operator’s pre-assessment demonstrates that only minor influence and changes to the surrounding sea area results in the case of potential leakage, and that the monitoring plan adequately takes into account leakage detection and a recovery plan to minimize the influence on the marine environment. The CO₂ injectate must be captured by a method using chemical reaction between amines and CO₂, with a CO₂ concentration of 99 % or more (98 % or more if captured for hydrogen production for oil refining) and have no waste or other matter added.

The guideline “For Safe Operation of a CCS Demonstration Project” focuses on site characterization to define pre-operational baseline conditions, detailed modelling of the storage system including the reservoir, simulations to predict the behaviour of the CO₂ plume, and water injection tests. During operation, monitoring of both the storage site and the overlying sea area is required including injection volume, temperature and pressure, CO₂ location and extent, changes in geological properties, seawater chemistry and marine organisms.

5.9 Australia

Australia has comprehensive legal and regulatory regimes for storage of CO₂ offshore under the Australian Federal and Victorian jurisdictions and onshore frameworks in Queensland, South Australia, and Victoria (Gibbs, 2018). Western Australia lacks a generic framework but has specific legislation for the Gorgon LNG Project’s storage of CO₂ under Barrow Island. Regulation of CCS in Federal offshore waters, Victorian offshore waters and onshore in South Australia has been accomplished through modifications to the regulations for oil and gas exploration and production, whereas Queensland and Victoria have developed separate regulatory frameworks for the onshore geological storage of CO₂. The frameworks commonly require obtaining a GHG tenure first to undertake exploration for acceptable geological storage reservoirs (including injection testing) and second to inject CO₂ for storage in the covered reservoirs. Detailed risk management plans are required to be submitted in the form of work plans. For example, the Victorian onshore regulations require a demonstration that even the testing during exploration will not present an unacceptable risk to public health or the environment or a significant risk of contaminating or sterilizing other resources in the area permitted for exploration. Similar demonstrations are required to support approvals for storage injection operations. After storage injection operations cease, project operators apply to surrender their tenures by making risk-based demonstrations that they have complied with all legal requirements, that the wells have been plugged or secured, that the stored CO₂ is conforming to predicted behaviour, that risks have been reduced to as low as reasonably practical, and that stored CO₂ will not present a risk to human health or the environment. After closure, the relevant State or Federal government assumes responsibility for monitoring and verification of the stored CO₂ at the project operator’s cost. Regulators have considerable discretion to impose more requirements backed by their authority to suspend or cancel storage operations and to withhold closure approval, subject to normal administrative requirements of reasonableness and procedures for review (Gibbs, 2018). The regulations impose detailed monitoring, verification, and reporting requirements beginning with establishing baselines and continuing through the life of the project, including after injection ceases. A variety of enforcement tools are available for regulators to ensure appropriate risk-based compliance. Regulators have authority to intervene and require actions to avoid, remedy, or mitigate a “serious situation,” including ceasing injection (Gibbs,

2018). In addition, regulators require “removal of property, plugging or closing wells, conservation and protection of natural resources, and making good any damage to the seabed or subsoil” (Gibbs, 2018).

6 Well design

6.1 General

Wells play a key role in CCS projects. They act as conduits for injection and house technology for monitoring purposes. In the simplest terms, wells are a nested series of casing (pipe) and cement installed in a hole in the earth. Perforations are shot through the casing and cement into the injection zone to allow the well to access the injection formation. [Figure 1](#) presents a general well schematic to present the basic components of a well. Since wells represent a possible leakage pathway for CO₂ out of the storage unit, because they penetrate the confining system to reach the storage formation, care must be taken in their design and construction.

The design, construction and completion of wells is dictated by their purpose, age, depth, rate of injection and regulatory regime. Further, the drilling program is designed to achieve the safe drilling to the targeted formation while also facilitating the acquisition of key geologic and reservoir data and end use of the well. For example, an additional casing string is required if abnormally pressured (either much higher or lower) horizons are penetrated prior to reaching the final total depth of the well. Drilling practices also play a role. For example, lower weight on bit, and its resulting longer drilling time, yields a straighter hole with drill bit selection perhaps improving those slower drilling times. Higher mud circulation rates and pressures improve drilling rates but result in more washout and poorer quality cementing. Regulatory requirements, such as groundwater protection, require deeper surface casing setting depths than would otherwise be required for blowout prevention or lost circulation control.

The well completion is the final installation of piping (tubing string) and associated equipment such as packer assemblies that will convey the injection of the CO₂ stream from surface to the storage zone. The completion tubulars will isolate the injection stream from the casing strings, thereby protecting the integrity of the casing from the surface to the injection zone. Once again, the design of the completion string will be fit-for-purpose for the specific well’s objective. For example, a commercial injection well has a simple tubing assembly and injection packer set above the storage zone while a monitoring well completion includes an array of instrumentation like fibre-optic cables.

As CO₂ storage is a relatively new technology and additional study has been conducted to assess the ability and security of the CO₂ injected and stored, wells are drilled for research purposes in advance of commercial projects. Research wells have a variety of objectives and are designed to test different aspects of geology, seal characterization, regional hydrology and injection zone quality and characterization. As a result, the design of the drilling program and well construction attributes for research wells are not necessarily considered as a best practice for commercial wells.

6.2 Components

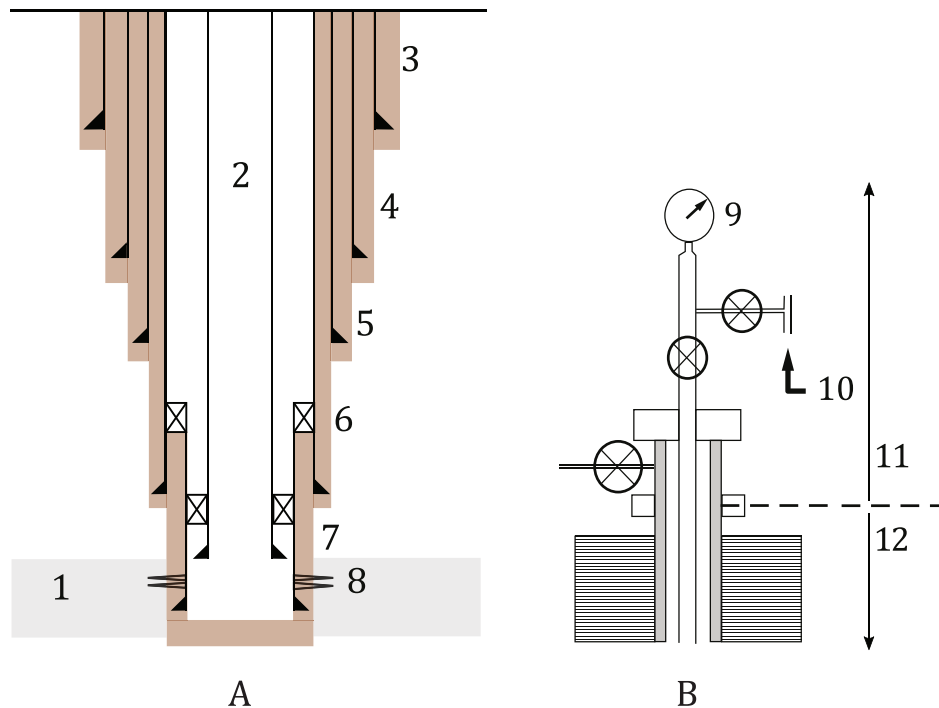
6.2.1 Conductor casing

Conductor casing (see [Figure 1](#)) is a short section of casing pipe that is used to initiate the drilling of the well. Often it will comprise a single joint of casing placed at surface to facilitate the return of drilling mud during drilling of the surface hole. In some cases, it is set prior to the drilling rig arriving on the drilling location.

6.2.2 Surface casing

Surface casing (see [Figure 1](#)) is the first primary string of pipe cemented into the drill hole to provide integrity to the wellbore. In the early oil and gas industry, surface casing was primarily used to mount blowout preventors and provide pressure containment while drilling of the main hole. This meant that the setting depth of the surface casing was dependent upon the anticipated pressures that would be encountered while drilling the main hole and the ability to contain those pressures based upon

the parting pressure at the surface casing shoe setting depth. The casing pipe itself needed to have sufficient collapse or internal yield burst strength to contain the anticipated pressures. Over time, surface casing became the means of protecting potable water zones and, as a result, surface casing depths are now set deeper than previous practices to protect those potable water zones. Surface casing strings are cemented to surface.



Key

- A casing plan
- B wellhead & Christmas tree
- 1 storage unit
- 2 tubing
- 3 conductor casing
- 4 surface casing
- 5 1st casing
- 6 2nd casing
- 7 liner
- 8 perforation
- 9 pressure gauge
- 10 CO₂ stream
- 11 Christmas tree
- 12 wellhead

Figure 1 — General well schematic showing the basic components of a well

6.2.3 Main section casing

Drilling of the main section of hole is protected by at least one string of casing often referred to as the long string or production casing. If additional strings of casings are required it is referred to as the intermediate casing or first, second, etc., casing string. To facilitate drilling the well, intermediate casing strings are used where pressures above or below the intermediate setting depth possibly create unsafe drilling conditions and/or mud weights which are either too great (resulting in fracturing of the

formation, or differential sticking) or too low (resulting in formation fluid influx and possibility of a blowout).

In the past, main hole casing strings were cemented to ensure isolation of porous formations and therefore may not have been cemented to surface. Modern day drilling practices for CO₂ storage are to cement the main string to surface to provide coverage over all formations penetrated. In cases where the hydrostatic head of the cement column exceed the formation fracture pressure, stage tools are used to cement the upper portion of the main hole.

The casing pipe itself must be of sufficient strength (internal yield pressure, tensile strength and collapse pressure) to facilitate placement of the pipe, drilling of the remainder of the well (if necessary) and containing the formations pressures expected. In the case of CO₂ storage, the casing strength must be suitable for the anticipated maximum storage pressure. The metallurgy of the casing may also be modified for those portions of the well that are exposed to CO₂, for example some operators place Nickel-based alloy or 13Cr-L80 pipe over the storage zone.

6.2.4 Liner

Liners (see [Figure 1](#)) are sections of casing that are set inside the last casing string, but sometimes do extend back to surface. The strings are landed in the last casing string with hanger and packer assemblies and may or may not be cemented in place. Liners are typically used where the cost of extending the pipe to surface would be cost prohibitive or where cementing of the pipe is not required. Liners are not typically used in CO₂ storage applications.

6.2.5 Tubing and completion assemblies

Once the well has been drilled and cased, the wellbore is secure and will contain the formation pressures and fluids. To facilitate injection of CO₂, a tubing (see [Figure 1](#)) and completion assembly is installed. The casing at the injection zone may be perforated with wireline conveyed perforating guns before the completion string is installed or with tubing conveyed perforating guns as part of the completion string. The completion string isolates the casing from the injected CO₂ and provides a secure conduit for the transport of the CO₂ to the injection zone. As a result, the metallurgy of the tubing material and completion assemblies are typically more corrosion resistant or corrosion resistant coatings are applied to protect the tubing and completion equipment. Tubing connections in CO₂ injection applications will often have seals, either Teflon or other CO₂ resistant material, to prevent CO₂ from leaking through mechanical thread connections.

6.2.6 Wellhead and Christmas tree

The wellhead and Christmas tree assembly (see [Figure 1](#)) are the surface equipment installed on the well to connect the well to surface pipelines and for hanging the tubing string inside the well. The Christmas tree is essentially the valves installed on the wellhead to contain the wellbore fluids and pressure and to facilitate running of wireline equipment into the well. The gauges for monitoring surface injection pressures are installed on the Christmas tree and other pressure gauges for monitoring the tubing/casing annulus and casing/surface casing annulus are also installed on the wellhead equipment. The material selection for the wellheads and Christmas tree equipment may be specialty alloys but often are internally coated steel. Valves will also have specialty trim materials (internals) for corrosion protection.

6.3 CO₂ Injection wells

Injection wells for both CCS and CO₂-EOR projects have included wells used for injecting smaller masses of CO₂ for research purposes (kt-scale) and larger masses (Mt-scale) for commercial-projects. The earliest CO₂ injection wells were constructed as part of CO₂-EOR projects, such as SACROC and Seminole floods in the Permian Basin, and Joffre and Weyburn-Midale in the Western Canadian Sedimentary Basin. Many research-scale CCS projects started earlier than commercial-scale projects and have longer history of injection and include, for example, the AEP Mountaineer, Ketzin, Illinois Basin Decatur Project, Lacq, Tomakomai and Nagaoka projects. Commercial-scale projects for CCS include,

for example, Sleipner, Illinois Industrial CCS Project (IL-ICCS), Quest and numerous CO₂-EOR Projects within North America.

6.3.1 Well design and construction

Well construction for CO₂ injection wells is site specific for the geologic conditions and applicable government regulations. Additional consideration may be given to the corrosive nature of CO₂ through the installation of sections of specialty casing (i.e. Nickel-based alloy or 13Cr-L80) over the primary seal and injection zone. This interval would correspond to the injection packer setting depth and perforated interval where the casing would be most exposed to corrosion.

In addition to specialty materials, efforts to mitigate corrosion can also be applied through material selection, chemical additives, and regular monitoring. When corrosion has an impact, replacement of well components may be necessary, which adds expense and down-time to injection projects. Corrosion mitigation impacts well design and operation in the following ways.

- CO₂ resistant cement - selection of a cement which resists chemical, and subsequent mechanical degradation of the cement. Typically, cement is circulated to surface to provide full coverage over the well, with specialty cements placed over and proximal to the injection zone. A baseline cement log run prior to completion will provide a reference to subsequent integrity logging (see [8.5.4.3](#)).
- Coated or lined injection tubulars are typically used in portions of the well that are exposed to water. In the case of injection wells that also inject water, this would constitute the entire string.
- The annular space filled with diesel or corrosion inhibited fresh water provides additional corrosion protection to both casing and injection tubulars.

6.3.2 Well completion

The well completion will provide the conduit for the transport of the CO₂ stream to the injection zone. Depending upon the corrosive nature of the CO₂ stream, specialty tubulars may or may not be needed. Dehydrated CO₂-streams are not necessarily corrosive and therefore the material selection is dependent on-site specific conditions. Other equipment on the completion string, such as packer assemblies and profiles may often be coated or made of specialty alloys. Injection packers, whether permanent or retrievable, typically have packer element materials that are resistant to CO₂ and the swelling effects that may pose issues with seal integrity and tool operability.

Since the injection tubulars and packer assemblies protect the casing strings, the injection packer is placed as close as practical to the injection zone perforations and in intervals with strong casing cement bond.

The decision to install permanent packers, with the appropriate stinger assembly on the tubing string, or retrievable packer assemblies is another site-specific decision. With either approach, should replacement portions of the tubing string need to be replaced, it is important to be able to place a plug in the packer such that the tubing string can be removed from the well without having to pump kill fluids into the injection zone.

Lastly, the design of the tubing string will also be dependent upon the injection rates required for the project. Restrictions in the completion string (i.e. profile nipples or injection stinger ID) will reduce the injection capacity. The well's casing ID will dictate the size of injection tubulars and packer assemblies, therefore flow modelling is required prior to the drilling of the well such that the total system configuration will provide the injection capacity needed.

6.3.3 CO₂-EOR injection well construction

CO₂-EOR wells represent the most mature class of wells used to inject CO₂ as CO₂-EOR has been employed commercially for approximately 50 years. Wells can vary from being converted oil production wells with conventional well construction and materials to fit-for-purpose CO₂ injection wells constructed with special materials and cements. Wells at SACROC and Weyburn oilfields provide some examples of construction practices.

SACROC

The Scurry Area Canyon Reef Operators Committee (SACROC) unit was the first CO₂-EOR project in the US, with injection operations started in 1972. The field has both vertical and horizontal wells. Vertical wells are typically completed at approximately 2 100 m using a 140 mm (5 1/2 inch)¹⁾ or 178 mm (7 inch) long-string casings with 219 mm (8 5/8 inch) and 244 mm (9 5/8 inch) surface casing, respectively. The surface casing is cemented to surface using Class C Portland cement. The long-string casing is generally cemented several thousand feet up from TD, leaving portions of the long-string annulus uncemented within the surface casing. Sometimes, the long-string cement job does not extend into the surface casing, which also leaves a portion of the wellbore uncemented. These production well construction scenarios are common within the field and many of the CO₂ injection wells in the SACROC field are converted production wells.

Weyburn

Similar to SACROC, the well construction design for Weyburn wells has evolved over time. The field was initially developed using vertical wells, cased and perforated over the producing zone. Over time, producing wells were converted to water injection wells for secondary (waterflood) recovery. During the 1990's, to improve sweep efficiency, horizontal wells with open hole completions (uncased over injection zone) were drilled and successfully improved the field's productivity. To facilitate CO₂ flood, dedicated horizontal CO₂ injection wells were drilled, most with dual laterals to target specific reservoir zones. To allow the use of dual laterals, the casing was set above the producing zone. Later the design changed to set the casing in the injection zone itself. Other variations of CO₂ injection wells were used including recompletion of existing vertical water injection wells, but these were prone to well integrity issues and replaced with horizontal injection wells with the casing landed in the injection zone (Majer et al., 2018).

6.3.4 Research injection well construction

Research injection wells represent the first set of injection wells developed specifically to inject CO₂ into saline formations for storage. The construction of these wells is very similar to that used for oil and gas production or CO₂-EOR.

Nagaoka

The Nagaoka project CO₂ injection well was constructed in 2003. It was constructed using mild steel (Grade J-55) casing, with buttress thread and coupling (BTC) casing on the 244 mm (9 5/8 inch) 53,6 kg/m surface string, and 8 round thread (RD-Long) on the 140 mm (5 1/2 inch) 23,1 kg/m long-string casing. Both casing strings were cemented using common oilfield Class A well cement. The injection tubing in the well was a 60 mm (2 3/8 inch) 6,8 kg/m chrome string (13Cr-L80) for improved corrosion resistance.

Ketzin

The Ketzin project CO₂ injection well was constructed and completed in 2007 with injection commencing in 2008. It was constructed using a 632 mm (24 7/8 inch) 186,8 kg/m St 37 steel stand pipe (welded), a 473 mm (18 5/8 inch) 130 kg/m X56 steel conductor string, a 340 mm (13 3/8 inch) 81,1 kg/m K-55 surface casing, a 244 mm (9 5/8 inch) 54 kg/m K-55 steel intermediate string (all three strings with BTC connection), and a 140 mm (5 1/2 inch) 30 kg/m 13Cr80 production string. All casings reached from the top of the well down to their respective depths, and the longest was the 140 mm (5 1/2 inch) production string ending at 755 m. The cement selected in all casing cementations was standard class-G cement with fresh water and no additives, with the exception of the plug cementation of the 140 mm (5 1/2 inch) casing for which a specially designed CO₂-resistant class-G salt cement was used (Prevedel et al., 2009).

Mountaineer Project

1) 1 inch = 25,4 mm

The American Electric Power (AEP)-1 CO₂ injection well was drilled as a stratigraphic test well in 2002 and 2003. It was later completed as an injector in 2009. AEP-1 was constructed with a 508 mm (20 inch) 140 kg/m H-40 steel surface casing set at 79 m, a 244 mm (9 5/8 inch) 60 kg/m L-80 steel intermediate casing set at 1 191 m, a 178 mm (7 inch) 34 kg/m P-110 steel intermediate casing set at 1 918 m, and a 114 mm (4 1/2 inch) 17,3 kg/m N-80 long-string casing set at 2 803 m. The well was plugged back to 2 608 m. The surface casing had a BTC thread, the 244 mm (9 5/8 inch) intermediate casing had an 8 rd short-thread connection (STC) connection, the 178 mm (7 inch) intermediate casing used an 8 rd long-thread connection (LTC) connection, and the long-string casing also employed an 8 rd LTC connection. The surface casing was cemented from its setting depth to surface with Class A cement. The 244 mm (9 5/8 inch) intermediate casing was cemented with a 50/50 pozzolan mix lead slurry and a Class A tail slurry. The 178 mm (7 inch) intermediate casing was cemented from with cement consisting of a 65/35 pozzolan mix lead slurry and a Class A tail slurry. The long-string was cemented in two stages, with the stage collar positioned at 1 657 m. The first stage was a C-poz cement slurry. The second stage consisted of a 65/35 poz mix lead slurry and a Class A tail slurry. Cement bond logs revealed poor cement quality, with zones of missing cement and a micro-annulus attributed to a high-pressure acid job, and gas intrusion across the long-string casing (described in Duguid et al., 2018).

Tomakomai

In the Tomakomai Project, two CO₂ injection wells were constructed in 2014 and completed in 2015. They were drilled from an onshore site targeting the Takinoue Formation and the Moebetsu Formation offshore reservoirs, respectively. They were constructed using an 800 mm conductor casing set at 10 m, a 508 mm (20 inch) surface casing, 340 mm (13 3/8 inch) intermediate casing, a 244 mm (9 5/8 inch) production casing and 178 mm (7 inch) liner. The surface and intermediate casing strings were steel. The production casing was CO₂ corrosion resistance steel (TN110CR13S) with a TSH-W563/TSH-Blue threads. The intermediate and production casings were cemented with CO₂ resistant cement.

The injection well for the Takinoue Formation had a maximum inclination of 72° with a measured depth of 5 800 m, vertical depth of 2 753 m and horizontal reach of 4 346 m. The injection interval of the well for the Takinoue Formation was completed with slotted liners achieving a length of 1 134 m.

The injection well for the Moebetsu Formation was an extended reach drilling (ERD) well with a maximum inclination of 83°. It had a measured depth of 3 650 m, vertical depth of 1 188 m and horizontal reach of 3 025 m. The injection interval of the injection well for the Moebetsu Formation was 1 194 m in length and completed by perforated liners covered by sand control screens. The perforated liners and sand control screens help minimize sand flow back into the well.

6.3.5 Commercial-scale injection

Commercial-scale CO₂ injection wells for storage are still uncommon. There are two permitted injection wells in the United States that are part of the Decatur, Illinois projects at ADM's facility, three injection wells at the Shell Quest project in central Alberta, Canada, one at the Aquistore (Boundary Dam) project in Estevan, Saskatchewan, Canada, and one each at Sleipner and Snovit in the Norwegian North Sea. These wells represent the beginning of commercial CCS and their design and construction may provide insight to future projects.

Illinois Basin Decatur Project (IBDP)

CCS#1 well planning began in 2008. The injection well was initially permitted as a Class I nonhazardous injection well because U.S. EPA Class VI CO₂ injection well regulations had not been finalized. However, the well was constructed to the draft Class VI standards. After the final UIC Class VI regulation was adopted, the permit was converted to Class VI status. The well was constructed with a 508 mm (20 inch) surface casing set at a depth of 110 m. A 445 mm (17 1/2 inch) open hole was drilled to 1 391 m where circulation was completely lost. Traditional lost circulation methods failed to regain circulation. Five cement plugs were placed, and circulation was reestablished; the intermediate hole was drilled to 1 627 m where a 340 mm (13 3/8 inch) casing was set. The casing was cemented to surface in two stages. After the intermediate casing was set, a 311 mm (12 1/4 inch) hole was drilled to TD (2 204 m). After reaching TD the well was logged and tested extensively.

A 244 mm (9 5/8 inch) long-string casing was set and cemented to surface in one stage. The casing had 244 mm (9 5/8 inch) 70 kg/m 13Cr-L80 from TD up to 1 608 m, where 244 mm (9 5/8 inch) 60 kg/m N-80 was used to the surface. The long string was cemented using a 1 898 kg/m³ (15,84 ppg) CO₂ resistant cement from TD back to around 1 500 m. A 1 498 kg/m³ (12,5 ppg) pozzolan cement was placed from 1 500 m to the surface. Cement simulators were employed during the design phase to set centralizer placement and model mud removal. Following completion, the well was logged using an ultrasonic radial cement evaluation tool and a cement bond logging tool, which showed good integrity despite the presence of a micro-annulus (Duguid, 2018).

Shell Quest Project

Three injection wells have been drilled and placed on CO₂ injection. The basic well design includes a conductor pipe set at 20 m, the 406 mm surface hole section was cased with 340 mm, 107 kg/m, L-80 IRP LTC R3 seamless and set at approximately 445 m and cemented to surface with Class G cement. The intermediate holes section was drilled with a 311,1 mm bit and the intermediate casing string consisting of 245 mm, 60 kg/m L-80 IRP LTC R3 seamless was cemented to surface (using a stage tool set at approximately 835 m with Class G cement. The main hole was drilled with a 216 mm bit and cased with 178 mm, 39 kg/m, L-80 LTC R3 seamless (surface to above the injection zone) and 178 mm, 34 kg/m, 25Cr-125 seamless set over the injection zone to TD, all cemented to surface with Class G cement.

Aquistore (Boundary Dam) Project

The Aquistore CO₂ storage project drilled and completed one injection well and an observation well in 2012, bottoming at depths of 3 324 m and 3 400 m, respectively. The injection well (PTRC INJ 5-6-2-8 W2M) was constructed with a 508 mm conductor to 36 m depth, pressure cemented to surface. The surface casing extended to 620 m, with 340 mm outer diameter L-80 casing, 107 kg/m, BTC joint type, cemented with a lightweight cement blend plus 2 % calcium chloride. The production casing extended to 3 324 m, with 194 mm OD, 50 kg/m, L-80 casing except over the interval of 2 150m to 3 200m, where 58 kg/m Q-125 was used. Joint types varied from top to bottom to accommodate the varying casing hardware installed in the well. A stage tool was set at 2 143 m and the well was cemented using an expanding cement followed by a CO₂ resistant cement placed from TD to 2 825 m depth. Above the stage tool to surface a lightweight lead cement blend was followed by Class G cement with good returns to surface reported.

6.4 Monitoring well construction

6.4.1 General

Monitoring wells borrow heavily from conventional wells and CO₂ injection wells in terms of construction. Monitoring wells are often drilled and cemented using the same technologies, and the specific monitoring objectives will guide construction design and materials. Differences between CO₂ injection and monitoring wells are largely the technology that is employed including pressure and temperature sensors, fibre-optic lines, sampling lines, electrodes, and other equipment.

6.4.2 Perforated monitoring well

The Illinois Basin Decatur Project had one fluid sampling well that penetrated the storage reservoir, which also allowed sample collection from zones overlying the reservoir. The well, VW#1, was constructed in a similar manner to the project's injection well (CCS#1). VW#1 was constructed using 340 mm (13 3/8 inch) surface casing, 244 mm (9 5/8 inch) intermediate casing, and a 140 mm (5 1/2 inch) long-string casing. Like CCS#1 construction, loss of circulation occurred in the Potsosi Formation, which was sealed with two plugs when encountered. The 311 mm (12 1/4 inch) intermediate hole was drilled to 1 623 m. the 244 mm (9 5/8 inch) intermediate casing was run to 1 623 m and cemented to surface in two stages. A 216 mm (8 1/2 inch) open hole was then drilled to a TD of 2 216m. After logging, the 140 mm (5 1/2 inch) casing was run into the well. The casing string consisted of 140 mm (5 1/2 inch) 25 kg/m 13Cr-L80 casing from TD to 1 541 m and 140 mm (5 1/2 inch) 25 kg/m N-80 casing from 1 541 m to surface.

The cement slurry design was adapted from CCS#1 and eliminated the hollow microspheres and added an expansion agent. A computer simulation of the drilled hole trajectory was used to guide centralizer placement. The displacing fluid was changed from fresh water to an 1 054 kg/m³ (8,8 ppg) NaCl brine. The well was cemented in a single stage with 4,8 m³ mud flush, 65/35 cement-pozzolan lead mixed at 1 498 kg/m³ (12,5 ppg) and of CO₂ resistant cement mixed at 1 895 kg/m³ (15,82 ppg). Cased hole logging results showed almost total cement coverage across all the open hole section and no micro-annulus present.

Completion of VW#1 included installation of a multilevel monitoring and sampling system that continuously monitored pressure and temperature in and above the storage reservoir. The stainless-steel completion system obtained data at 11 different depths in the well; each sampling zone was isolated from other sampling ports by redundant packers. Fluid samples were additionally collected from each port at determined time intervals for geochemical analyses. This system was used for about seven years and was replaced by a new system that samples from three discrete intervals, two in the storage reservoir and one above.

Cranfield

Two monitoring wells, CFU31F-2 and CFU31F-3, were constructed on the periphery of the Cranfield oilfield near Natchez, Mississippi in 2008 to access the D and E sands of the Tuscaloosa formation. These wells are down dip from injection well CFU31F-1 and are arranged in a line with CFU31F-2 being approximately 61 m away from CFU31F-1 and CFU31F-3 being approximately 90 m away from CFU31F-1.

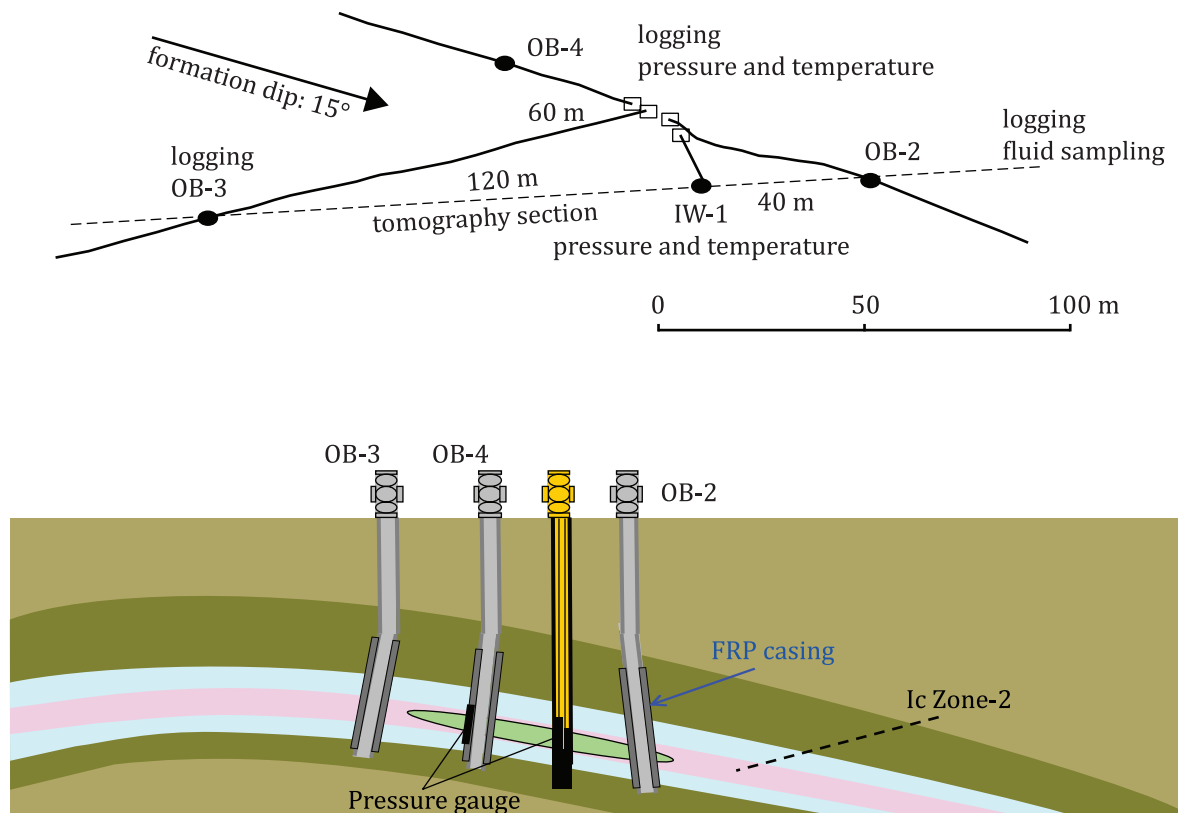
Each monitoring well was constructed with multiple monitoring technologies attached to the long-string casing. The specific construction details of each well are provided in (Duguid et al., 2016). The surface and intermediate strings of each well were of conventional design. The long-string section of each well was made up of N-80 grade steel casing and Bluebox-2500 fiberglass casing. The steel casing section had temperature and pressure sensors mounted on the outside, the fiberglass section held electrical resistivity tomography electrodes in, above, and below the storage reservoir. Fiberoptic systems were mounted to the outside of the casing and extended from the reservoir to the surface on both wells.

These wells were logged after construction in 2009 using cement bond logging tools and ultrasonic imaging tools. After the project was completed the wells were re-logged using similar tools and a sidewall coring tool was employed to collect samples of the casing and cement (Duguid et al., 2016). The time-lapse study revealed all cores had at least some carbonization and indicated that the CO₂ was moving along the control lines behind the casing.

6.4.3 Induction logging monitoring well (Plastic casing: Nagaoka, Cranfield)

The Nagaoka project installed three monitoring wells named OBS-2, OBS-3 and OBS-4 designed to allow induction resistivity logging for monitoring purposes. The location of these monitoring wells is shown in [Figure 2](#). The injection well is denoted as IW-1 and three observation wells are shown as OBS-2 to OBS-4. The fiber reinforced plastic (FRP) casing portion was set through the target reservoir in all three monitoring wells of which two wells, OBS-2 (952,2 m to 1 210,5 m, Total FRP length 258,3 m) and OBS-3 (1 044,2 to 1 142,0 m, Total FRP length 97,8 m) were extensively utilized for logging. Cement evaluation logging using ultrasonic and cement bond logging tools was carried out in both wells, indicating that the cement bond is good across the FRP interval.

Permanent pressure gauges were also placed in IW-1 and OBS-4.



Key

well location



ground surface



top of Zone-2

Figure 2 — Nagaoka well locations

Ketzin

The three wells drilled at the Ketzin project in 2007 were equipped in the storage reservoir with coated casing segments within the 140 mm (5 1/2 inch) production casing string to allow the application of permanent downhole electrodes. The coated casing segments were positioned as follows in

1. Ktzi 201 (injection well) from 595 m to 735 m depth,
2. Ktzi 200 (monitoring well) from 595 m to 735 m depth, and
3. Ktzi 202 (monitoring well) from 590 m to 730 m depth.

The stainless-steel casing was internally coated by an epoxy resin layer and externally by a two-layer coating made of an epoxy resin matrix and a Ryton (polyphenylene) membrane. This electrically insulated region of the borehole completion allowed electrical resistivity tomography in the near-wellbore area, as well as in-hole measurements as a kind of permanent CO₂ saturation log.

6.5 Discussion

All wells described were successful for their specific application. As the application changed from CO₂-EOR to commercial storage, well designs changed, including both the casing and cement. Some of the CO₂ wells discussed in [Clause 6](#) had been the subject of significant well integrity studies. These studies looked at the well materials and construction execution to identify possible well integrity issues and mitigations.

Changes to casing design consisted of the selection of more corrosion resistant materials and proprietary threads to address leakage of CO₂ from the casing. The change from mild steel to 13Cr-L80 steel provides additional protection from corrosion. However, 13Cr-L80 requires special handling during installation and adds significant cost to the well. One way to reduce this cost is to employ 13Cr-L80 casing across the storage zone and caprock with mild steel continuing to the surface as was done at the Illinois Basin Decatur Project wells.

Cementing programs were also changed in response to exposure to wet CO₂ and carbonic acid. In conventional cements, the calcium hydroxide and calcium silicate are susceptible to carbonation. In cements with high amounts of calcium hydroxide, like conventional well cements, can be severely altered by CO₂ interactions. The AEP1 well used a C-poz slurry which is a mixture of reactive pozzolans (siliceous material) and Portland cement. The addition of the pozzolans changes the hydration chemistry of the cement; it reduces or eliminates the calcium hydroxide phase. This provides a level of CO₂-resistance because calcium hydroxide is most susceptible to carbonation. CCS#1 and VW#1 employed a highly engineered proprietary slurry that controlled both the hydration chemistry to eliminate calcium hydroxide and the matrix permeability to slow fluid transport reducing the availability of fresh carbonic acid if the cement comes in contact with any.

Several of the wells detailed in [Clause 6](#) had been the subject of well integrity studies as part of the project or as parts of related projects. Many of the wells detailed in [Clause 6](#) were logged using conventional cement bond logging tools and radial mapping tools. The use of two tools provides multiple metrics to assess the integrity of the cement job. In the case of the Nagaoka monitoring wells the variable density measurement provided some assurance of competent cement in the FRP section where the ultrasonic image could not provide information.

AEP1, CCS#1, VW#1, and the Cranfield wells provide information that provide valuable insight into well construction. The cementing issues identified during the AEP#1 and CCS#1 show that more than just CO₂ compatibility is important. The inflation of the external casing packer and the hydration properties of the cement may have combined to affect the cement job after successful returns to surface. This was possibly further exacerbated by high pressures applied to the well after cementing. The cement slurry for CCS#1 was affected by the mixing equipment before it was even pumped down the well. The smooth 13Cr-L80 casing and the temperature difference between the bottom hole static temperature and cementing circulating temperature may have contributed to the development of a micro-annulus. The construction of VW#1 built on the lessons learned from the construction of CCS#1 and did not exhibit a micro-annulus in the log results.

Monitoring wells have deployed many different technologies depending on the needs of the project. These include temperature gauges, pressure gauges, fibreoptic lines, sampling lines, sampling ports, and electrical resistivity hardware. Many of these technologies are on the outside of the casing and can present leakage pathways if not properly installed and cemented.

The Cranfield wells provide examples of construction and monitoring choices that affected the integrity of the wells. The control lines were visible in all of the image logs that were run. The analyses of the cement sections with the sidewall cores showed carbonation at every zone collected. The sidewall core that cut through the control line and sampling port exhibited severe carbonation. It is likely that CO₂ was able to move up the sampling line and the other control lines. In addition, the fiberglass section was severely affected by the downhole conditions in the storage zone. It is important to point out that the objectives of the wells were met and that the monitoring was successful. Furthermore, the monitoring wells did not allow any detectable amounts of CO₂ to leave the reservoir. However, the Cranfield project was relatively short compared to a commercial-scale project and similarly complicated wells on a long-term project may have affected the project negatively. The complicated external geometry of the control and sampling lines affected the placement of the cement. The overall lesson is that complicated geometry and material choices need to be reviewed and simplified to the extent possible.

Each of the well integrity analyses point to places for learning that can be applied to future projects. In general, each of the problems identified could be summed up to problems with design, execution, and operations. The overall lesson is that careful detailed design and planning need to be followed by thorough execution and operation.