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Well abandonment and integrity evaluation for CO_2 storage



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About

This document provides guidelines and considerations for well plugging and abandonment (P&A) approaches of both project and legacy wells within a carbon dioxide (CO_2) geologic storage site. This includes well integrity evaluation methods, barrier philosophy, and plugging materials such as cement or alternatives. This document is intended for wells personnel and industry stakeholders who are involved in a CCS project, specifically in the evaluation, planning, and execution phases.

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Introduction

Carbon Capture and Storage (CCS) is a demonstrated technology that is essential for the energy transition.

One of the challenges in CCS projects is to ensure that the carbon dioxide (CO_2) remains in the intended storage reservoir. There are numerous potential leak paths in a storage reservoir. The leak paths could be either natural (pre-existing faults, fractures, insufficient caprock integrity), or man-made (induced seismicity and artificial penetrations such as underground mines and wellbores).

CO_2 storage can be achieved with negligible impact on the environment when potential issues with leak paths, such as wellbores are sufficiently identified and managed. Wells are designed and constructed with barriers to prevent fluid migration throughout the expected lifecycle, including decommissioning. However, there is a need for guidance to address the well integrity evaluation for both project and legacy wells as well as future abandonment of existing CCS project wells.

The purpose of this document is to:

- provide guidelines of well barrier philosophy and material consideration for plug and abandonment (P&A) of wells in the project area
- ecommend well integrity evaluation approaches for wells
- demonstrate uncertainty management and risk assessment methods for legacy wells in storage projects

This document is intended for wells personnel and industry stakeholders who are involved in a CCS project, specifically in the evaluation, planning, and execution phases.

This document does not cover:

- regulatory requirements
- prescriptive requirements for P&A
- definition of acceptable leakage risk
- injection or monitoring well design
- prescriptive requirements for measurement, monitoring and verification (MMV)
- enhanced oil recovery wells

1. Principles of well plugging and abandonment for CO_2 storage projects

The goal of CCS is permanent storage of CO_2 in the intended geologic formations. Project wells and legacy wells may represent potential leak paths that challenge this goal. The objective of P&A in CCS wells is to create an envelope of leak tight barrier elements against any wellbore related fluid movement out of the storage complex.

Abandonment of wells pertinent to CO_2 storage projects will typically be subject to prevailing oil and gas regulations and policies. Planning engineers should be aware that the pressure and temperature regime for wells subjected to abandonment will not follow the usual assumptions for abandoning conventional oil and gas wells following depletion to a lower pressure. For wells in a CO_2 storage project, it should be expected that the storage reservoir pressure will increase to a defined maximum pressure to be determined by the strength of the sealing unit (formation/caprock) and the well abandonment plug(s). All well barriers should be designed to withstand the expected pressures and fluids from below for long term isolation.

Injection of CO_2 will also cause the lateral migration of subsurface fluid, inclusive of existing or remaining hydrocarbons in depleted storage reservoirs. Hence, for every storage reservoir, the evolution of the CO_2 plume and connected volumes of formation fluids needs to be considered to determine which wells will be exposed to new conditions (fluid, pressure) resulting from CO_2 injection.

1.1 Well types relevant to CCS

A typical CO_2 storage project has various types of wells and their integrity is part of the success of the project. Some of these wells have an active role, including CO_2 injector wells, monitoring wells, and pressure management wells. In addition, the field development of a CO_2 storage complex may require dedicated appraisal wells, particularly in the case of saline aquifer storage where there may be a lack of well related formation evaluation history. Many storage complexes will also host legacy wells from historical exploration, oil and gas production, or other legacy operations. While these legacy wells serve no function for the project, they may pose a potential leakage challenge. The number of legacy wells in a storage complex can vary substantially depending on the setting.

See Appendix A for an overview of well types and conditions.

1.2 Barrier philosophy

A well barrier comprises one or more well barrier elements. The general abandonment philosophy (established in modern industry) requires the fluids within the reservoir to be isolated against migration into the overburden or to the surface, usually with two well barriers: a primary and secondary. The secondary well barrier is designed to meet the same conditions as the primary well barrier and is placed to provide redundancy in the event of any leakage past the primary well barrier. See Figure 1.

The purpose of permanent abandonment barriers is to restore the sealing unit (caprock/ confining zone) where it is penetrated by the well and to isolate zones with flow potential from the surface and from one another. In some jurisdictions, isolation at the source (across the perforation or open hole interval) may be accepted.

The specific requirements for the length of abandonment plugs or annular cement included as barrier elements in an abandoned well will vary from one jurisdiction to another. Often, an environmental or 'surface' plug is placed in addition to primary and secondary well barriers to prevent any residual fluid in the well from contaminating the environment.

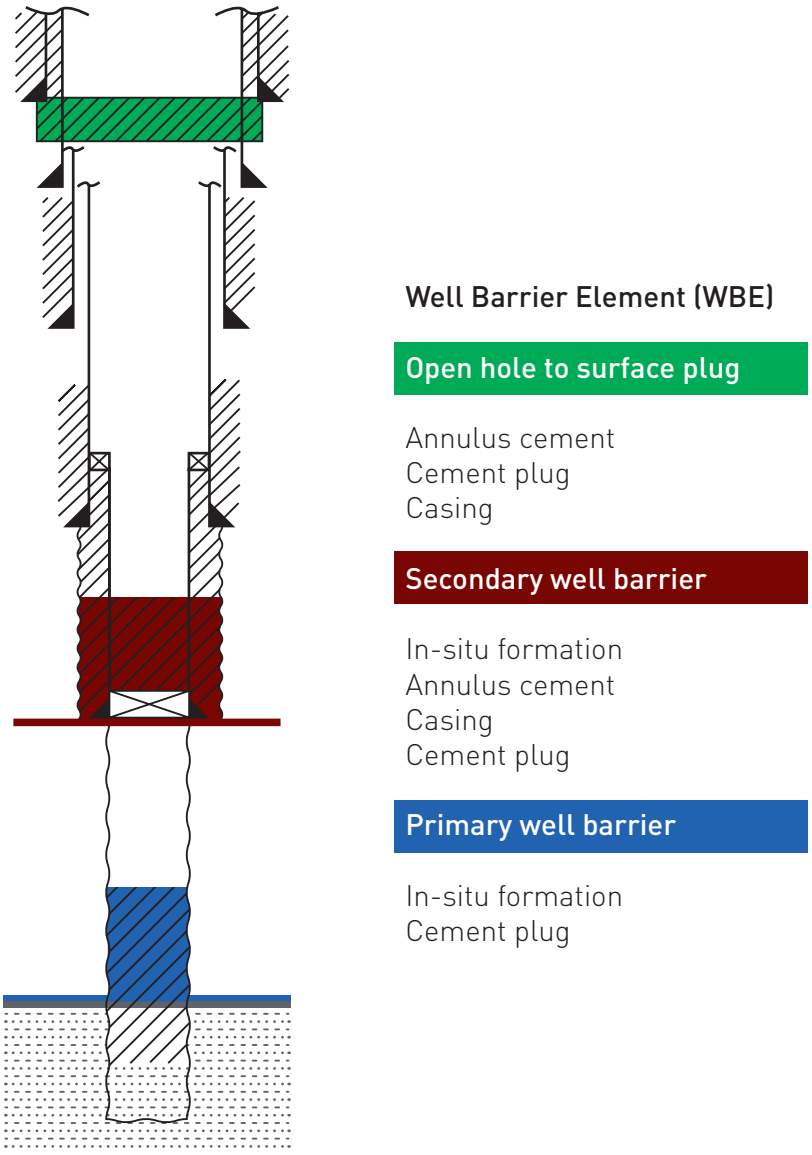


Figure 1 - An example well barrier schematic for P&A wells

Figure 2 illustrates possible leak paths where the fluids could migrate past the intended well barrier. Therefore, it is imperative to evaluate any CCS project and legacy well abandonment barrier philosophy and integrity. Project wells design and construction should incorporate an abandonment strategy, in which the future abandonment of the well is accounted for. Well integrity evaluation is discussed in Sections 2.3 and 3.2.

Permanent barrier construction recommended practices include the following aspects:

- design can be qualified, and placement and seal effectiveness can be verified
- constructed with impermeable or near impermeable materials when set
- installed as close as possible to the potential source of inflow to the well
- extends across the entire cross section of the well, providing a seal at the interface of the barrier and formation and between each barrier element within the overall barrier
- placed within an impermeable, near impermeable, or naturally sealing formation with sufficient formation strength (minimum horizontal stress or fracture pressure)
- capable of withstanding the maximum expected loads without cracking or debonding
- capable of withstanding the environment it will be exposed to without degrading or corroding

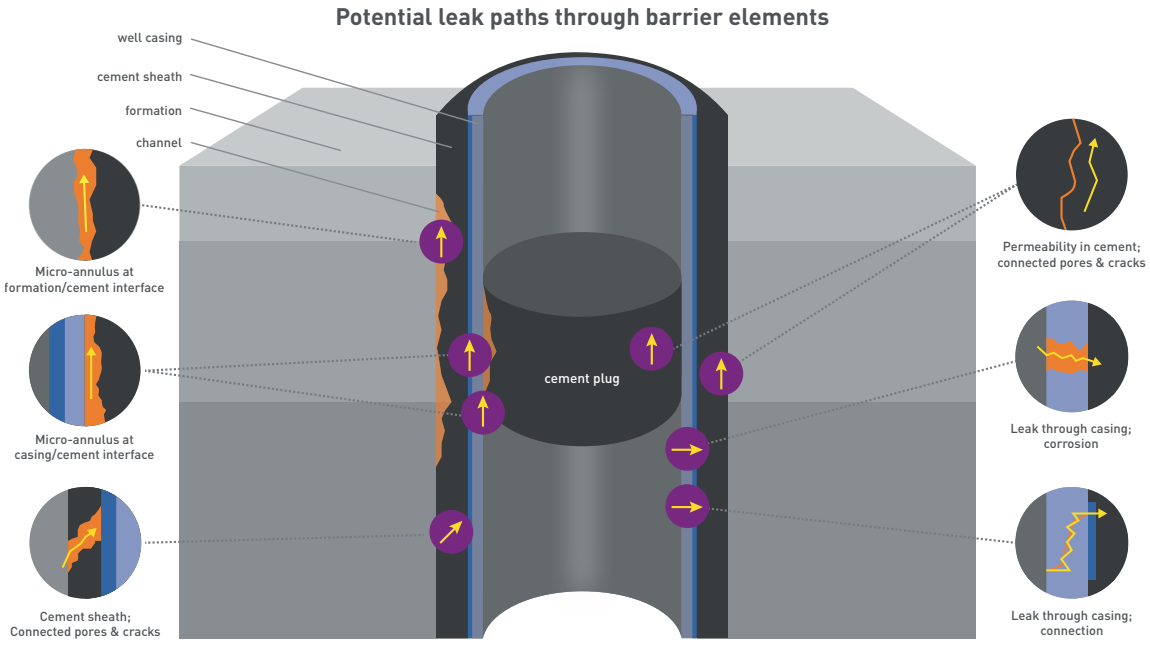


Figure 2 - Schematic cross-section of an abandonment barrier in a well and potential leak paths through or around well barrier elements

In the context of a CO_2 storage project, it can be useful to distinguish the path of travel out of the intended store. Based on the naming conventions set out by the International Energy Agency (IEA 2008[1]), this Report will use the following definitions:

- **Migration**: movement of CO_2 through geologic strata and along the wellbores within a storage unit and/or complex. Typically, there will be multiple potential migration paths.
- **Seepage**: the CO_2 moving out of the storage unit.
- **Leakage**: this is CO_2 reaching the surface and/or unauthorized zone(s).

1.3 Barrier considerations

1.3.1 Cement

Portland cement is the default plugging material in the oil and gas industry and is inexpensive, well known and approved by regulators worldwide for permanent abandonment. Cement is placed in the annulus between casing and formation during well construction and is placed to form a long plug inside the casing or open hole during abandonment. The formulation of cement used for well construction and abandonment should consider the downhole conditions, including pressure, temperature, and formation fluid chemistry.

Cement alteration reactions due to exposure to a mixture of CO_2 and water can be inhibited by reducing the matrix permeability and by mixing non-Portland components (fine-grained silica, typically in ratios of 25% to 35% of the total volume of the cement slurry, fly ash, pozzolans, latex, resins, microfine cements) to reduce the reactive phases of the annular cement or plug once set. The reduced permeability impedes CO_2 penetration into the cement to further react with undegraded cement.

Additives may be included in the cement slurry which reacts on exposure to CO_2, water or mixtures of the two, such as carbonic acid, and swells to close the mechanical fault, micro-annulus, or opening through which CO_2 and water has been able to pass into the plug or annulus cement. Such additives may also be designed to chemically bind or sequester CO_2 upon contact.

In addition to exposure to CO_2, the annular cement and plugs placed in a project well will be exposed to any contaminants present in the captured CO_2 and mixtures with formation fluids including water. The cement slurry should be formulated taking the detrimental effects of expected contaminants into account on a project specific basis.

The cement used for the annular cement of casing and liners of CO_2 injection wells will be subject to cyclic thermal loads during the injection life of the well. The loads arising from cooling during the injection of CO_2 at ambient surface temperature cycle with periods of re-warming toward the undisturbed geothermal temperature of the surrounding formations whenever the well is shut in for maintenance, intervention, or while awaiting additional volumes of captured CO_2. If annular cement placed during well construction is to be relied on as a barrier element of the abandoned well, the cement should have sufficiently elastic mechanical properties to withstand these cyclic thermal loads during the injection life of the well and retain sufficient integrity to qualify as a permanent abandonment barrier element. The suitability of the cement to withstanding such loads should be simulated and tested before well construction to optimize the cement slurry employed to deliver the requisite mechanical properties.

[1] International Energy Agency (IEA), October 2008.

Several modified-Portland and reduced-Portland cement slurries have been developed and promoted as CO_2 resistant cement. These slurries are designed to be less reactive to CO_2 exposure by the replacement of a large fraction of the Portland cement in the slurry with supplementary cementitious materials. These slurries demonstrate a reduced reactivity when exposed to CO_2 based on laboratory experiments of up to six months duration but are not necessarily representative of behaviour in the field where the volume/surface area ratio is many orders of magnitude greater than that of a cement sample in a lab experiment. Higher concentrations of CO_2 gas or dissolved liquid can have an impact on the cement. Furthermore, their long-term mechanical performance is less well-known than Portland cement[2], as is their propensity to close narrow flow paths when exposed to CO_2 migrating through mechanical defects or fractures in the cement, which is discussed further in section 1.4.3.

1.3.2 Cement alternative materials

Alternative materials to Portland cement that are inert or unreactive to CO_2 or products of its reaction such as carbonic acid, are available for CCS project wells, including resins and geopolymers.

Calcium Aluminate Phosphate cement is an alternative to Portland cement comprising hydraulic calcium aluminates produced from limestone and low-silica bauxite. Compared to Portland cement, Calcium Aluminate Phosphate cement develops strength rapidly, maintains strength at high temperatures, and demonstrates high resistance to CO_2 and acidification (reduced carbonation reactions) and resistance to sulphide corrosion. When tested, Calcium Aluminate Phosphate cement retains higher compressive strength and lowered porosity after exposure to CO_2 than Portland cement. There are limited suitable additives to control the water loss from the aqueous slurry. Contamination with Portland cement causes the Calcium Aluminate Phosphate slurries to set very rapidly. This material is not commonly available at present.

Resins are epoxy, phenolic, or furan thermosetting polymers which have pumpability and strength properties similar to cement but contain no Portland cement and are inert or unreactive to CO_2. Resins can be tuned with respect to density, viscosity, curing time and to suit the temperature of the depth and formation to be plugged. Resin plugging material can be free flowing when pumped or squeezed into fractures and other leak paths. Some resins may also be suitable for resin-cement composites.

Geopolymers are ceramic materials derived from alumino-silicates or fly ash, alkali silicate reagents. They may contain slag for increased mechanical strength. By virtue of the total replacement of Portland cement, these alternative plugging materials do not undergo carbonation reactions. At the time of writing, geopolymer use in wells is immature and subject to limitations with respect to temperature and available additives.

Biomineralizing plugging materials are pumped into a wellbore as low viscosity liquids containing soil bacteria, which then crystalize the liquid solution as gas tight minerals such as calcium carbonate. These are intended primarily to plug fractures, micro-annuli, or other leak paths in the well bore wall, annular cement, or cement plugs in response to observed leakage. The use of biomineralizing plugging materials should be subject to compatibility testing compared to relevant fluids present within the project, for example formation water.

[2] Carey, J.W., 2013

Non-cement plugging materials may be sensitive to contamination with conventional Portland cement residues in bulk storage, mixing, or pumping equipment on a rig. Care should be taken during planning to keep these materials separate. The use of alternative materials should only be considered if such technologies are qualified and acceptable to the regulator in the relevant jurisdiction.

1.3.3 Swelling formation as an annular barrier

Formation movement over time within the casing annulus has been proven to create effective barriers to flow.[3] Formations that are of favourable characteristics and prone to swelling or creeping could be qualified for use as an annular barrier on a field in lieu of, or to complement, annular cement. To be suitable for use as an annular barrier, a formation should be:

- of suitable mineralogy, with plastic properties, commonly shale or potentially salt
- of sufficient strength to withstand the maximum expected pressure that could be applied to it
- able to seal over the full annular circumference of the casing and extend over a suitable interval along the well
- subject to a displacement mechanism suitable for closing the annulus and thereby preserving the well barrier properties

In a CCS context, formation strength should be capable of withstanding the fluids and pressure it may be exposed to; at least equivalent to the maximum expected storage pressure extrapolated up to the base of the barrier formation via the worst case annular gas gradient.

Typical displacement mechanisms include:

- compaction failure and/or consolidation
- liquefaction
- thermal expansion
- chemical effects
- creep

Qualification of the formation as a barrier element will require certain features be verified by testing. Possible qualification methods may include:

- electric logs or cuttings description logs to identify a suitable formation over a sufficient interval
- formation integrity test or extended leak off test (LOT) at the base of the barrier formation to demonstrate sufficient formation strength
- observations in wells, on electric logs, or in test jigs to identify the main displacement method occurring in the formation
- 360° circumferential cement bond log to identify that the casing is fully mechanically bonded by the formation around its full circumference and over a sufficient interval
- annular pressure test to demonstrate the absence of pressure communication behind the casing

[3] Williams S et al., 2009

Pressure testing the annulus should demonstrate the barrier formation can withstand a differential pressure in the annulus between the base of the barrier formation and at surface represent the potential pressure escalation due to planned CO_2 injection.

Once a barrier formation has been qualified as a barrier on the field, it could be verified for use on subsequent wells on the field by cement bond log without requiring pressure testing.

A formation qualified for use as a barrier in one field may be considered qualified as an annular barrier in an adjacent field if it can be demonstrated that the formation properties are consistent, bond log responses are the same, and the formation is continuous across both fields.

1.3.4 Open hole collapse

For the case of legacy wells in some jurisdictions, in the absence of a qualified barrier, the collapse or closure of the open hole section of a well bore may provide zonal isolation and be demonstrated by testing, to provide a margin of confidence that no migration of fluids will occur from the injection zone.[4]

1.3.5 Casing and tubulars

Oilfield casing and tubing can often form part of the barrier envelope of a well in operation but do not, on their own, form permanent barriers in abandoned wells. The tubulars will often serve as one element in a barrier system – for example, casing strings remaining in-situ between annular cement and an abandonment cement plug.

The products of corrosion of steel casings will, under ambient conditions, occupy a larger volume than the uncorroded steel. Provided the products of corrosion remain confined by the cement plug and annular cement or creeping shale, the resulting material will be impermeable. This should restrict the penetration of corrosive fluids further up the barrier and thus mitigate against further corrosion of suitable mineralogy, commonly shale.

Material selection in CO_2 injector wells is dependent upon the specification of CO_2 acceptable for injection. In particular for captured post combustion CO_2, the presence of impurities such as NOx and SOx can create aggressive acids in the wells.

To maximize the design injection life of a CO_2 injector well, corrosion resistant alloys may be used in some parts of the well construction to minimize corrosion rates during the injection life of the well. The choice of the alloy employed should be determined by corrosion testing against fluid samples and environmental conditions representative of those existing in the storage unit. It should not be assumed that such corrosion resistant alloys will resist corrosion indefinitely, particularly if the fluids in the storage unit are mobile. In addition to corrosion resistant alloys, tubulars with increased wall thickness compared to standard may be employed in the well construction to maximize the well's design life.

Composite or coated casing materials may be considered for use in CO_2 injectors as an alternative to steel or steel alloy casings.

[4] Clark J E et al., et al, 2005

1.4 Challenges

1.4.1 Formation pressure within the CO_2 storage unit

A fundamental difference between well abandonment in an oil or gas field and a CO_2 storage project is the evolution of pressure over time. An operating or decommissioned oil or gas field experiences a reduction in formation pressure relative to its undisturbed state. A well abandoned in an active CO_2 storage project may be subject to an increase of formation pressure relative to the initial conditions at the time CO_2 injection begins. This consideration also applies to exploration and production wells that are drilled and abandoned in prospects or field developments that are considered for future CO_2 storage projects and should be examined when planning well abandonment.

Once injection has ceased, pressure will begin to decrease due to factors including pressure redistribution. Over geological time, the elevated formation pressure in the storage will decline as stored CO_2 is dissolved into formation water and eventually a portion is precipitated as carbonate minerals within the pore spaces of the storage unit. However, pressure within the storage unit may remain above hydrostatic pressure, depending on local conditions.

1.4.2 Thermal loads

Permanently abandoned wells within a CO_2 storage unit may be subject to temperature reduction compared to the undisturbed geothermal gradient as a result of CO_2 being injected. In addition to cooling relative to undisturbed temperature, injection wells in operation and legacy wells near active CO_2 injection wells will be subject to temperature fluctuations when injection begins (cooling toward the inlet temperature of the injected CO_2) or is shut in (warming toward the undisturbed geothermal gradient). This phenomenon is similar to that observed in water injection wells. Some depleted fields may have very low temperatures inside the well due to Joule-Thomson (J-T) cooling when injecting.

It is unlikely that injection wells will be placed directly adjacent to legacy wells, and it is good practice to maintain an adequate stand-off, determined for the specific field conditions, to minimize the impact of cooling. Lifecycle analysis or laboratory testing of representative cement samples at expected temperatures could be instructive to planning. At the depth of the abandonment plug(s), however, the temperature decrease will be very limited since the CO_2 can only approach the plug through the elongated structure of the well. Given the very limited rates, this will result in a heat exchange that brings the temperature of the CO_2 close to that of its surroundings. Consideration should also be given to the impact cooling will have on the caprock strength or the potential for fault reactivation when planning the CCS field development.

In the event of a CO_2 leakage or loss of well control, conditions may exist in which liquid CO_2 can flash to gas and expand after passing through a restriction to flow. In such cases, Joule-Thomson (J-T) cooling may occur, leading to localized low and possibly sub-zero temperatures.

In well planning, abandonment should be considered. For CCS injector wells, in particular, the annular cement placed during well construction should allow for thermal loads, and not be damaged to the extent that repair would be required for abandonment purposes.

Simulating cement failure due to thermal loads is highly dependent on knowledge of the mechanical properties of the rock, cement, and the rate and magnitude of thermal loading. It is also highly dependent upon the assumptions made by the model such as the initial state of stress of the cement. Results may vary significantly depending upon the model used.

1.4.3 Cement alteration

The most common plugging material in the oil and gas industry is Portland cement and modified Portland cements whose chemical and mechanical properties are well-understood. When exposed to CO_2 and water, the hydrated phases of set cement undergo a carbonation reaction; being chemically altered to form calcium carbonate. The reaction of cement, producing calcium carbonate, acts to buffer pH which inhibits further reaction. However, if sufficient acid replenishment occurs at the reaction front, the further reaction of calcium carbonate to bicarbonate increases permeability. The reaction can continue further, producing water soluble calcium bicarbonate ($Ca(HCO_3)_2$) which may diffuse out of the cement, increasing porosity and allowing the continuation of the reactions further into the cement. See Figure 3.[5]

However, these reactions occur slowly. Consequently, degradation of the cement in the vertical direction is limited to a few meters at most, even for geological time scales and thus the cement barrier should remain acceptable.[6] In the radial direction, only a few centimetres of cement is available and therefore cement may not be considered as a durable barrier in that direction.

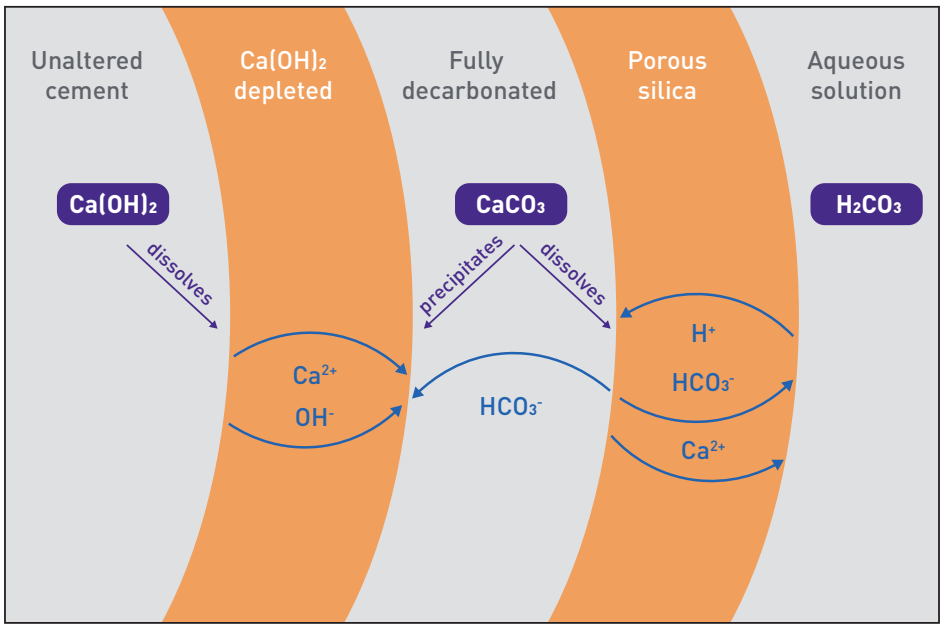


Figure 3 - Stages of cement reaction due to exposure to CO_2 and formation water

[5] Kutchko Barbara G et al. et al., 2007

[6] Wolterbeek T K, Snippe J R, and Hangx S JT, 2024

If cement has a micro-annulus or micro-cracks, and is exposed to CO_2, self-healing of the micro-channel may occur due to precipitation of calcium carbonate, the effectiveness

depending on the width of the micro-channel, the length of the cement-plug, and the prevailing pressure conditions.[7]

1.4.4 Corrosion of tubulars

Once injected, CO_2 and any associated contaminants mixtures with formation water, carbonic acid, and other strong acids can be formed which forms a corrosive environment in the storage unit. The corrosion risk to tubulars is increased if the in-situ formation fluid is saline or contains other oxidizing impurities such as H_2S. The corrosion risk can also be increased or if the formation fluid is mobile, for example migrating due to depletion in existing oil or gas fields.

While casing or liner does not on its own form part of the permanent abandonment barrier of a well, corroded tubulars may limit options when planning the abandonment of project wells or re-abandonment of legacy wells.

1.5 Verification of barriers for permanent abandonment

Barrier verification is a set of analyses performed to ensure the barrier elements will function as per the intended objectives. Barrier position and integrity should be confirmed.

A combination of analysis could include the following for each Well Barrier Element (WBE):

- for an internal cement: physical verification results (tagging, pressure testing) with details from weight and pressure applied, test duration, and leak paths tested. Test pressure should cover the max anticipated load case.
- for annular cement: physical pressure data such as sustained casing pressure presence or absence
- for annular cement: indirect measurements (e.g., logging tools such as CBL/VDL, impedance, and flexural maps, passive acoustic, etc.), and its interpreted reports
- general: data recorded during well construction and P&A operations (design and surface indicators). Advanced cement slurry modelling may be used to verify position.
- general: quality data available for in-situ stresses around the well, for the correct pressure rating of the plug

Specific requirements for depths and length of barriers and verification methods from local authorities may exist, and they should be followed.

[7] IEAGHG, 2023.

2. Plugging and abandonment for project wells in CO_2 storage projects

Following the operating life of a CO_2 storage project, all wells constructed during the development of the storage complex will require permanent abandonment. This section provides guidance for the abandonment of CO_2 storage project wells and the well integrity evaluation.

Project wells are those wellbores used to develop and operate a CO_2 storage project, which includes:

- CO_2 injector wellbores; either new wells, planned sidetrack wellbores, or wells re-purposed through workover
- exploration, appraisal, confirmation, or verification wells drilled to confirm the stratigraphy of a storage complex and suitability of a saline aquifer or depleted field for CO_2 injection, to de-risk the geological properties of the storage complex, and to estimate the committable storage capacity of the storage complex
- observation wells drilled or re-purposed from other project wells for monitoring purposes in the storage complex
- pressure management wells drilled to remove formation water displaced by injected CO_2 to mitigate pressure increases which may risk caprock integrity or fault reactivation
- injection or disposal wells for produced water from pressure management wells
- intercept wells for abandonment or remedial re-abandonment of inaccessible legacy wells that cross the storage complex
- other project wells which may be re-purposed for monitoring once their injection objectives are achieved, leading to a longer total well life than originally planned

To meet the requirement for safe permanent storage of injected CO_2, injection wells should be plugged and abandoned upon cessation of injection. Operators may be required by regulators to continue monitoring the storage project after wells are permanently abandoned upon closure of the site. The operator may consider the possibility of abandoning the reservoir section of selected wells while maintaining access to the overburden sections of the well during the monitoring period. Post-closure monitoring may include monitoring the abandoned wells at the surface or seabed for evidence of leakage.

2.1 Well plugging and abandonment guidelines

2.1.1 Prioritization

Project well abandonment planning includes prioritization, a higher prioritization being accorded to abandoning wells taking account of the risk and consequences for factors including:

- if the well remains within a CO_2 plume after injection has ceased
- if the well will be in the CO_2 plume after injection has ceased, due to plume migration
- communication with zones of flow potential in the overburden or beyond the defined storage complex
- impact potable water aquifers in the event of leakage
- in-situ barriers or barrier elements that do not meet regulatory requirements for either caprock restoration or isolation, such as insufficient length of annular cement, poor bond log results, lack of testing
- non-corrosion resistant casings as barrier elements in the well while in operation across the storage unit and potentially into the sealing unit
- if it has known well integrity issues or concerns (e.g., casing pressure anomaly, casing damage, etc.)

2.2 Timing and approach

The timing of abandonment of CCS project wells will depend on the conditions existing in the storage unit, the plan for the well after the injection objective is achieved, compliance with regulatory requirements including those applicable to post-closure monitoring, and any well specific concerns regarding the well integrity.

Thorough record keeping from the planning, drilling, completion, well intervention, workover and MMV phases of project well construction and intervention will expedite and improve P&A planning.

While local regulations may encourage the immediate abandonment of a CCS project well, this may not be achievable for a number of reasons, and the abandonment may be deferred. In the case of a planned campaign abandonment of several CCS project wells, priority may be lower for a given well if the CO_2 plume or elevated pressure zone is not in contact with the well, such as in the case of an appraisal, monitoring, or water production well.

When planning to abandon an injection well, in some jurisdictions, the operator may be required to flush the well with fresh water or some other buffer fluid to displace injected CO_2 away from the well and determine the downhole pressure and mechanical integrity of the well to start planning abandonment activities.

Pressure testing of the well may be required to prove the integrity of the well before abandonment and to direct remedial activities where required to prevent future leakage from the storage complex via a leaking well.

The abandonment planning approach may depend on a number of considerations for each well to be abandoned:

- Regulatory requirements for timing and the number of plugs in particular circumstances such as where potable aquifers are present.
- In the case of an active storage complex, continued injection of CO_2 may expose any abandoned well to degradation and corrosion of the barrier elements.
- An active CO_2 storage project may exploit additional potential CO_2 storage units in the overburden for future development and therefore abandonments should consider this potential.
- Live project wells may be partially abandoned to provide zonal isolation between separate geological units within a storage complex as each is exploited to its maximum committable storage potential over the life of the well, with a complete well abandonment at the end of the well life.

An operator may use or develop a well integrity evaluation matrix to generate a "traffic light" showing the state of the well integrity. The matrix could then be used to prioritize the abandonment activity by focusing on the highest risk wells. Any wells with more "red" flags will be prioritized accordingly to ensure the integrity of the CO_2 storage reservoir.

2.2.1 Re-purposing project wells

Once appraisal or injection objectives for CCS project wells have been fulfilled, the wells may be re-purposed as monitoring wells, in which case a partial abandonment and re-completion in accordance with the new objectives of the well may be considered. Any re-completion should be planned as soon as possible after the cessation of injection to maintain continuous pressure monitoring with minimum interruption. The opposite conversion, from monitoring to injection well, could also be a possibility but this should be carefully engineered as design principles might differ.

Cement and tubular wall thickness evaluation should be performed before a well is temporarily abandoned or repurposed to address risk from corrosion and degradation from exposure to CO_2. This evaluation should include review of the casing and tubing string load cases based on the current condition of the well.

2.3 Well integrity evaluation

Well barrier elements in abandoned CCS project wells will require verification. At present, CCS project wells are commonly subject to the same regulatory requirements as oil and gas well abandonment.

The Minimum Setting Depth (MSD) of abandonment plugs should be determined and documented. This should be based on the formation strength integrity (fracture gradient or minimum horizontal strength) being sufficient to withstand the pressure accumulated in the storage unit without fracture or other mechanical failure. The operator should make allowance for the increase in pressure within the storage unit due to the injection of CO_2 and displacement of in-situ formation fluids when planning well abandonment and determining the minimum safe plugging depth of the wells to be abandoned. Abandonment

planning should account for the maximum expected pressure increase in the storage complex over the expected life of the storage project, not just the expected life of the well. Consideration should also be given to the integrity and leak potential of future storage units penetrated by the well to be abandoned. Planning for cement jobs should demonstrably follow prevailing recommended practices. Depleted hydrocarbon field-based CCS projects may, as a worst-case, consider a gas column gradient above the storage reservoir recharge pressure when evaluating well integrity. The Minimum Setting Depth (MSD) for legacy wells is discussed in section 3.2.2.1.

The most basic demonstration that the cement plug has been successfully placed is that the cement slurry has been pumped and displaced without fluid loss or gain and that the pressure observed while pumping and displacing should be a close match to the pressure simulated as part of the cement job planning. The application used should address all possible leak paths, including shrinkage, corrosion, and long-term mechanical properties.

The techniques used for verifying barrier elements in CCS project wells are the standard tools and services available for oil and gas wells. These include primarily cement bond logging of annular cement and swelling shales/creeping formations which have been qualified as a barrier for the location, tagging of cement plugs, and inflow testing of completed barriers where possible.

When pressure testing cement plugs and annular cement, the applied load on cement could lead to irreversible damage to the cement if fully set up which could result in micro-annuli or cracking of the cement. The applied load during a pressure test may be the most severe load expected for the cement plug or annular cement and operators may consider alternative verification methods to minimize the risk of irreversible damage to the cement. Alternative verification methods are outlined in section 1.5.

To consider the casing annular cement as a permanent abandonment barrier element, an operator will need to demonstrate its ability to maintain zonal isolation, for example by verification of the cement bond by logging in preparation for abandonment. Such verification may be required even if the annular cement was verified by the cement bond log during well construction, as directed by ISO 27914.[8]

The interpretation of a cement bond log may be challenging for some types of unconventional cement or alternative materials, and protracted setting times may be required before a satisfactory cement bond interpretation can be made.

In addition to cement bond logging, regulators may also require periodic testing of other aspects of the integrity of the well construction, including calliper logging or evaluating fluid flow behind casing, which may be achieved with temperature or noise logging for project wells.

Control lines, while not a new or unique consideration to permanently abandoning a CO_2 project well, may be prolific owing to the monitoring obligations that operators of CO_2 project wells may be subject to in some jurisdictions. In addition to electric lines to downhole gauges, fibre optic lines installed for Distributed Acoustic Sensing (DAS) may be present in the annulus of a project well ready for abandonment. Control lines left in-situ represent a penetration through any abandonment barrier elements placed which may compromise the resulting barrier over the long term.

[8] ISO 27914, 2017

3. Plugging and abandonment for legacy wells in CO_2 storage projects

Legacy wells, as reflected in a representative plumbing diagram shown in Figure 4, are a common challenge in many CO_2 projects as they may represent potential leakage paths for the injected CO_2, or formation fluids. These wells can be prevalent in potential sites and their integrity should be evaluated to ensure the safe and effective storage of CO_2 and to minimize the environmental and economic risks associated with potential leakage.

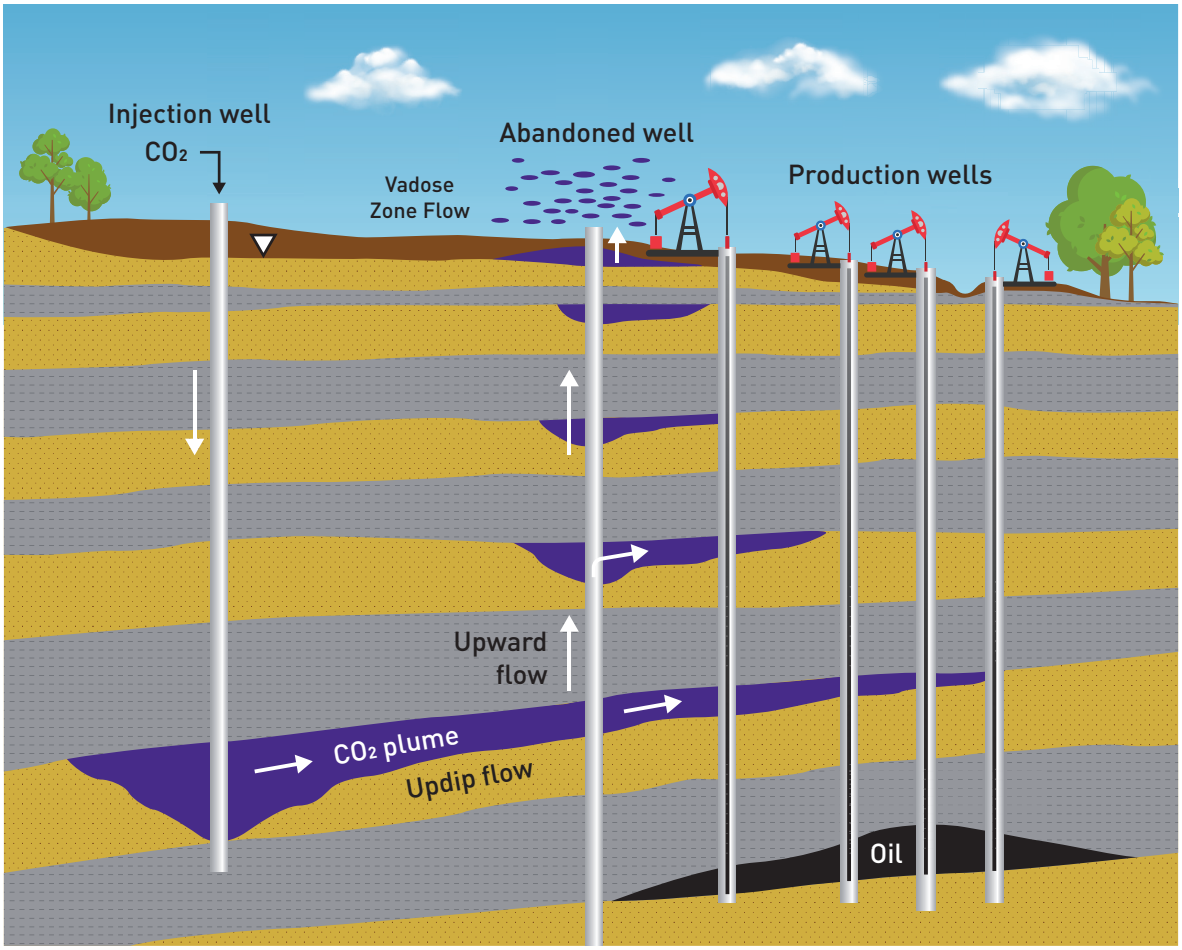


Figure 4 - Illustrative plumbing diagram of a CO_2 injection plume and potential leak pathways along existing wells

For the purposes of this report, legacy wells are defined as any pre-existing well that is expected to be impacted by the CO_2 plume or pressurization front and will not be used to develop and operate a CO_2 storage project. This includes both documented (actively owned or orphaned) and undocumented wells. Due diligence should be performed to identify all existing wells penetrating the CO_2 store. Legacy wells can be categorized as described in Table 1.

Table 1 - Legacy well categorization

Category	Descriptor
1	Active wells (producer, injector, and water)
2	Inactive wells needing to be permanently plugged and abandoned; wellhead is intact
3	Inactive wells that have been temporarily plugged and abandoned; wellhead is intact
4	Decommissioned wellbores – permanently plugged and abandoned; wellheads may have been removed, and casing may have been cut below the surface

This section describes the guidelines and considerations specific to legacy wells present in CO_2 storage projects that are expected to be in contact with the CO_2 plume or pressurization front. These guidelines provide a framework to evaluate the integrity of legacy wells and to inform risk-based decisions.

When applying these guidelines to legacy wells that are in categories 1 or 2 above, the most likely scenario will be similar to abandoning CO_2 project wells, while also ensuring that the hydrocarbon zone and defined drinking water zones are also secured following standard oil and gas P&A practices. The guidelines should also be considered by operators who are decommissioning oil and gas wells in areas that could be future sites for CO_2 storage projects. This practice would significantly reduce the potential need for more complex re-entry and remediation of category 3 or 4 wells in the future when a CO_2 project is established.

The more challenging scenarios of legacy wells described in categories 3 and 4 will benefit the most from the application of these guidelines, enabling the performance of a detailed evaluation and integrity assessment to inform the potential risk of the legacy well within the CO_2 project and subsequently guiding a risk-based and pragmatic approach to next steps.

Given the heterogeneity of well types and P&A strategies, a risk-based approach is recommended to evaluate the suitability of legacy wells for CO_2 storage. These guidelines provide an approach to assess the integrity of each well and to make informed decisions relating to the acceptability of potential risks or the need for remediation actions. By identifying higher risk wells, appropriate mitigation measures can be implemented to minimize the risk of CO_2 leakage. Operators and regulators should align on an appropriate fit-for-risk approach to legacy wells and CO_2 projects, similar to the strategy taken in developing conventional oil and gas projects.

3.1 Barrier philosophy

The barrier philosophy for legacy wells is principally the same as described in section 1.2 with the primary objective being to block or close leak paths that could allow fluid (CO_2, brine, residual hydrocarbon) to migrate from the defined storage unit and ultimately the storage complex. Typically, in modern industry's recommended practices, this is achieved with two barriers, a primary and secondary barrier, to isolate fluids at the source and restore the rock-to-rock barrier in the caprock.

Most legacy wells were drilled for exploration and production of hydrocarbon reservoirs and have a unique construction which depends on multiple factors, such as the intended purpose of the well, geology, reservoir characteristics, geographic location, and time of construction.

Previously decommissioned legacy wells were plugged and abandoned to the standards and practices relevant at the time and location to isolate these hydrocarbon zones. As a result, many of these wells may not meet the barrier requirements of today's regulations and standards in terms of barrier placement, length, or material to isolate the CO_2 storage zone. Additionally, saline aquifers typically would not have been isolated during decommissioning. This is of particular significance where brine displaced from the storage zone can pressurise the wider regional aquifer.

It is also recognized that re-entering to remediate a well can introduce complexity, giving rise to its own set of operational, safety, and environmental risks, especially when the well has been previously decommissioned and may no longer be readily accessible. There is also a risk that the remediation may not be successful and could introduce additional leak paths and essentially increase the risk of a leak.

The diversity in well architecture and P&A plans precludes a single approach for assessing and remediating legacy wells and it is essential to individually evaluate and plan for each legacy well. A risk screening and detailed evaluation should be completed for each legacy well to assess the potential leak risk and inform a risk-based and pragmatic approach to managing legacy wells to ensure the success of CO_2 storage projects. While a two-barrier philosophy is recommended, fewer may be accepted based on the risk evaluation. This may include cement alternative materials or flow mitigators, such as collapsed open hole described in Section 1.3.4.

3.2 Legacy well integrity evaluation process

In terms of when to perform legacy well assessments, operators should comply with regional specific regulations. However, accelerating the legacy well assessment can be beneficial in the early project phases to gain a better understanding of the overall risk picture and to define early de-risking actions before making firm commitments (e.g., exploration/appraisal work scope). The following sections provide guidance on the legacy well integrity evaluation process. Here, recommended geological background information and details on how a legacy well assessment can be conducted are described before presenting the output that should be generated.

3.2.1 Geological background and context

Any legacy well evaluation should be a holistic process involving the subsurface teams, as the sealing formations, overburden, under-burden, and faulting regime all play an integral part in the overall risk assessment.

Specific regulatory requirements may exist across various jurisdictions. ISO 27914[9] and IOGP Report 670 - *Risk and uncertainty assessments for geologic storage of CO_2* provide useful guidance for the overall process. Before embarking on a specific evaluation of the integrity of any legacy wells either inside or outside lease/license boundary, the geological environment needs to be considered, covering:

- definition of the storage unit or injection zone – usually the porous rock in which CO_2 will be stored
- definition of the storage complex – depending on the regulatory regime, this determines the envelope of the sealing or confining structures both over and under the reservoir, of which the cap-rock forms part
- any overlying or underlying potable aquifers
- other flow zones, observation, or producing/unabandoned wells
- geological artifacts (faults, subsidence, and compaction, etc.)
- naturally sealing or creeping formations such as salts and shales that may enhance the seal
- potential for natural or induced seismicity
- initial in-situ pressure at the start of injection, previous reservoir pressure (e.g., the field was originally at a higher pressure), and final reservoir pressure
- pressure changes are likely to impact fracture gradient over time and subsidence/compaction phenomena
- initial in-situ temperature profile across all formations
- buffer zones (isolation or separation) between horizons
- lateral distribution of formation and communication between wells in the storage site

3.2.2 CO_2 plume migration and pressurization

The areal extent and timescale of the CO_2 plume migration and pressurization front defines the Area of Review (AoR) and determines the number of wells and the type of legacy well integrity analysis. This concept is shown in Figure 5 and also shows the full extent of the reservoir model, identified as the Area of Interest (AoI) that extends beyond the AoR that defines the estimated extent of pressure and CO_2 plumes. Noting the following points:

- The CO_2 plume should be modelled across a range of reservoir outcomes to determine which wells may be affected and when – timing may be important because it can help determine when any legacy well remediations may need to be carried out (if not required at the start of injection), e.g., legacy wells closest to injectors will see higher concentrations of CO_2 than those on the periphery. CO_2 plume migration for geological risk and events of uncertainty should also be evaluated, and model uncertainty/accuracy should also be considered. Monitoring plume migration can

[9] ISO 27914, 2017

help calibrate models and lead to a better determination of when a legacy well needs to be abandoned, re-abandoned, or remediated. Uncertainty should be included in the modelling of the CO_2 plume and can also include consideration of plume movement dynamics due to potential out of zone migration.

- The subsurface parameters, coupled with injection parameters (rate, pressure), will control the dimensions of the extent of the plume. In some cases, the CO_2 plume may dominate in areal extent, in others, the pressure wave, or some mix in between (as shown in Figure 5).
- The impact of CO_2 plume migration displacing fluids out of the lease/license boundary and giving rise to a pressure wave should be evaluated. Legacy wells impacted by the pressure front will also require integrity and risk assessments, even though they will not be contacted by CO_2. Different regulatory regimes will have differing requirements in this area.

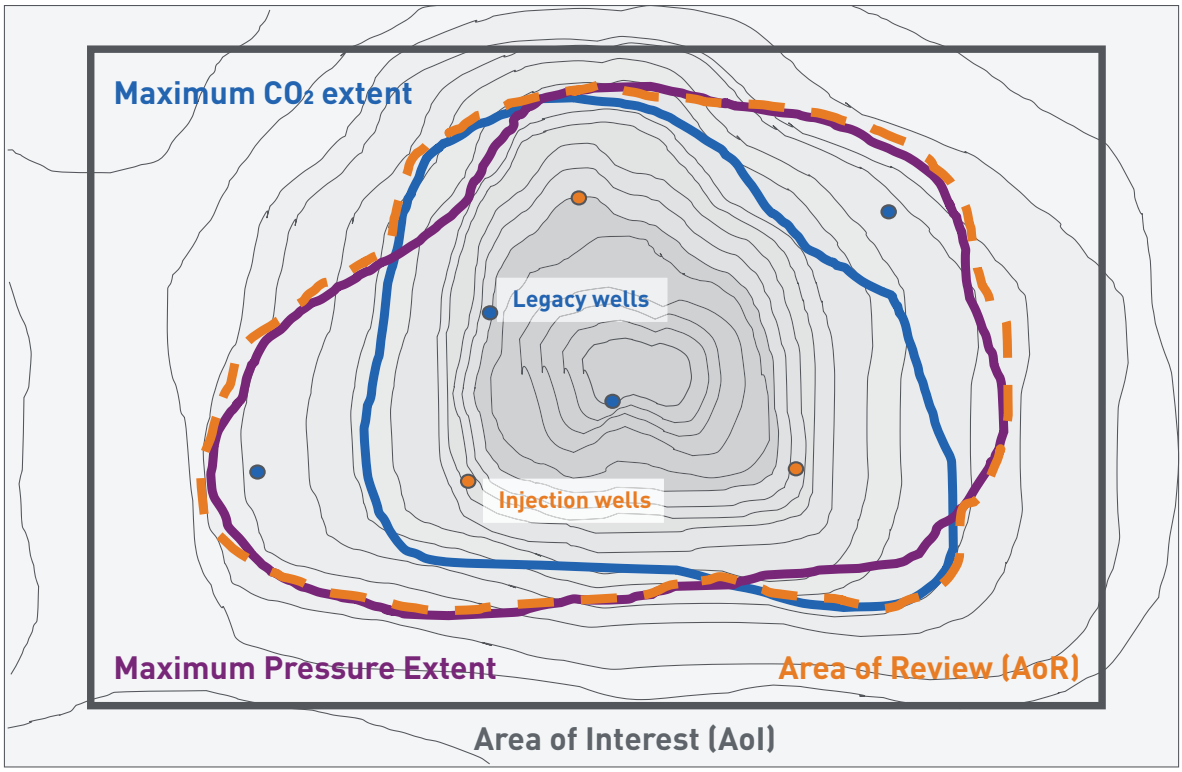


Figure 5 - Example – Area of Review

3.2.2.1 Minimum setting depth

The Minimum Setting Depth (MSD) of an abandonment plug or barrier is the shallowest depth at which the formation can withstand the maximum anticipated wellbore pressure without being fractured. This calculation can be used to assess the location of existing plugs in legacy wells and determine the location of future plugs. To calculate the MSD for a particular reservoir, it is necessary to know the reservoir pressure, in-situ stresses (fracture gradient, minimum horizontal stress), the profile of the well, and expected wellbore fluid density (which may exhibit gradient change if multi-phase). See Figure 6.

For a CO_2 storage project, this calculation takes on additional importance because in the case of a saline aquifer, the final storage pressure (or maximum anticipated pressure) may be higher than the present or original reservoir pressure (unless pressure management is applied). For depleted field storage, the in-situ stresses may have changed due to depletion and will potentially be subject to hysteresis as the pressure raises again. There is also the time element to consider – pressure may take many years to stabilize. In addition, there may be regulatory requirements to address in the evaluation.

Cement plugs are generally stronger than the rock they are set in, but nevertheless, it is still instructive to model the cement plug integrity to verify the seal.

The wellbore pressure curve is calculated by subtracting the internal wellbore fluid's (e.g., gas, CO_2, or formation water) hydrostatic pressure from the reservoir pressure. The MSD is the point at which this wellbore pressure curve intersects and begins to exceed the in-situ stress. The MSD can also be calculated mathematically as follows:[10]

$$P_{FP} - G_{WF} \times (H - h_{msd}) \leq 0.052 \times G_{In} - Situ \times h_{msd}$$

$$h_{msd} \geq \frac{P_{FP} - G_{WF} \times H}{(0.052 \times G_{In-Situ}) - G_{WF}}$$

Where P_{FP}= Final (or maximum anticipated) Reservoir Pressure; G_{WF} = Well bore fluid pressure gradient (psi/ft); H = TVD of the reservoir (ft); h_{msd} = minimum setting depth (ft); $G_{In\text{-}Situ}$ = In-Situ stress gradient (ppg).

Note that a CH_4 column gradient above the final reservoir pressure may be the worst-case for depleted hydrocarbon-based CCS projects.

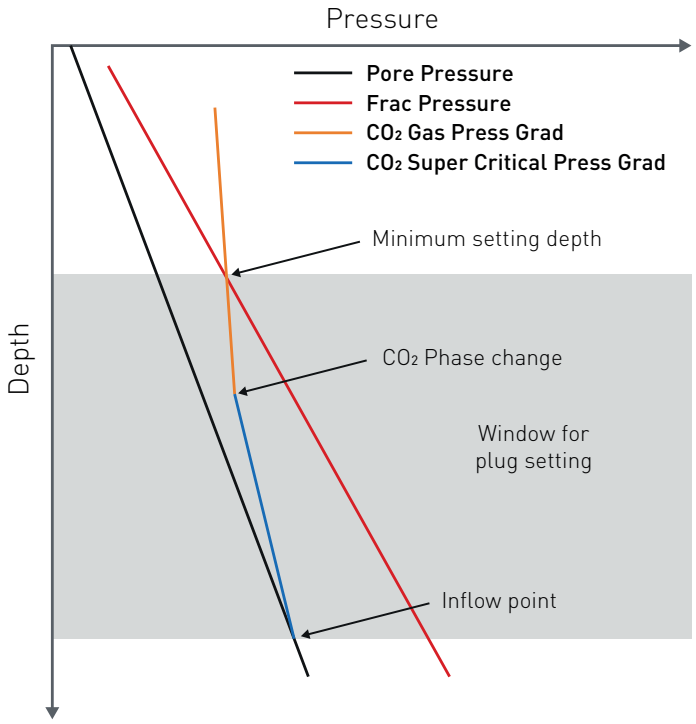


Figure 6 - Example Minimum Setting Depth (MSD) visualization

3.2.3 Legacy well information analysis

The integrity status of legacy wells directly impacts the safety and effectiveness of CO_2 containment. In this context, a comprehensive well information analysis is essential.

An information assessment comprises:

- identifying and validating the location of the legacy wells within the Area of Review (AoR)
- performing and documenting an evaluation of a set of historical documents that identify and locate all wells and reflect their current condition

It typically covers the following main areas:

- Wellhead placement identification: evaluation from database records, geophysical survey, satellite survey analysis, and aeromagnetic surveys allow for identification of the wellheads and wells within the area.
- Drilling, casing running, cementing, and completions operations: design and execution data from the well trajectory including sidetracks, casing shoe depths, casing centralization, and running events, cementing events (volumes pumped, pressures, and losses), completion operations (perforation details and depths, packer information and depth, packer fluid) allow for the understanding of well configuration and identification of practices applied.
- Well materials (casing, tubing, and cement): data gathered from casing sizes, thickness, and metallurgy, drilling fluids, spacers, and cement slurries' properties and composition may show significant performance differences, depending on the well conditions encountered in the past and in the future CCS.
- Well integrity data and history from the operational phase, including interventions: all logs (casing wear, cement evaluation) and other barrier verification analysis run during well construction, workovers, and abandonment comprise relevant information for the assessment of barrier integrity. In addition, the events that occurred in the well lifecycle (sustained casing pressure, tubing leaks, casing/tubing collapse, remedial cementing, reperforations) should be registered to help identify existing leak paths.
- Well abandonment: the abandonment configuration and barrier placement information, if performed, should be part of the evaluation documentation. In addition, any further information relevant in the last interventions (wellhead removal, equipment/ tools/ fish inside the well, collapsed or leaking casing/tubing) should be known, as they influence future access. Subsurface lithology: the formations penetrated by the well should be confirmed, which may require adjustment and interpretation especially when different operators have been involved over the well's lifecycle.

Possible data sources may be found in the operator, service company, and regulator records and databases, both in a physical and digital format. While analysis should not be limited to the well information provided in Table 2 below, examples of data to be looked at are shown.

It should be noted that, depending on the geographical location, operator, and age of the wells, there are likely to be data gaps or incompleteness in the information mentioned below. The impact of each data absence or incompleteness can vary on a well-to-well and/ or field-to-field basis.

It is recommended to indicate information which is present for the legacy well and information that is missing. In the case of missing information, general practices of the region and time can be leveraged, and additional engineering analysis may be needed to mitigate uncertainty. When conducting a subsequent risk analysis, uncertainty in the available data can be supplemented through statistical analysis, modelling, or probabilistic sampling techniques.

Table 2 - Example dataset for a legacy well analysis

General data	• Wellhead or well location (with coordinate and datum) • Lifecycle interventions dates (drilling, completions, workover, and abandonment and operational time) and scope of interventions • Operator handovers throughout the well lifecycle • Type of well (production, injector, monitoring) • Accessibility status • Daily drilling reports
Subsurface data	• Potential flow zone's location, length, and properties (permeability, in-situ fluids, etc.) • Flow potential estimations • Potential cap rocks, including respective properties such as in-situ stresses, lithology, position along the well, etc. • Interpreted seismic (faults, etc.) or interpreted logs • Geological information (from logs, cuttings analysis, core, etc.) • Observed leakages in Area of Interest (AoI)
Drilling	• Well trajectory (surveys), including possible sidetracks • Drilling issues events (stuck pipe, washouts) • Drill bit/hole opener sizes and caliper logs • Lost Bottom Hole Assembly (BHA), junk, and radioactive sources • Inflow (kick) and loss circulation events • Formation Integrity test (FIT)/Leak Off Test (LOT)/Extended Leak-Off Test (XLOT) data results (FIT/LOT) • Drilling induced damage
Casing and wellhead	• Setting depths • Casing sizes and thickness • Grade/corrosion performance • Connection type and performance data (gas tight, metal seal, etc.) • Centralization • Casing wear logs or analysis (baseline logs or logs ran during lifecycle) • Issues while running casing/liner

Annular cement and fluids	• Cement slurry characteristics (type of cement, slurry density, rheology, laboratory results, additives used) • Spacers and flushes characteristics (type, additives, rheology) • Pumping sequence (spacers, flushes, and cement slurry volumes and pump rates) • Displacement fluid type, properties (density, rheology), displacement pump rates, mud removal modelling design output • Casing hardware used and functions (centralizer type and placement, wiper darts/plugs, flowback from float equipment) • Fluid conditioning before cementing • Relevant events (presence of losses, inflow, final circulation pressures, bumping of plugs, etc.) • Post cementing events (ballooning, shoe track drill out) • Cement verification (bond logs, pressure tests, weight tests, design, lift pressure, volumetric and surface indicators, etc.) • Remedial cementing operations (if performed) • Annular fluids pumped ahead of cement (type, barite sagging potential)
Completions	• Completion type (open hole, cased hole) • Perforation details (depth, shots per foot, phasing) • Packer information (type, depth, setting mechanism) • Isolation and safety valves • Operational reports
Operational phase, including interventions	• Production/injection fluids history • Integrity issues (casing/tubing leaks, sustained casing pressure) • Workovers and other important events in interventions (plugs, reperforation, remedial cementing, re-completion equipment, sidetracks, etc.) • Caliper, casing/tubing wear, and cement evaluation logs • Pressure/temperature sensors • Well barrier schematics • Barrier performance/verification/monitoring

Plug and abandonment (if performed)	• Steel removed from well (tubing/casing cut and removed, milled sections of casing/tubing), if any • Mechanical plugs installed in casing or tubing (depth, type) • Cement plugs depth (top and bottom) and placement method (balanced plug, bullhead, Perforate-Wash-Cement (PWC), pump-and-pull) • Cement slurry characteristics (type of cement, volume, slurry density, rheology, additives used) • Spacers and flushes characteristics (type, additives, rheology) • Pumping sequence for plugs (spacers, flushes, and cement slurry volumes and pump rates) • Displacement fluid type, properties (density, rheology), and displacement pump rates • Operational reports for plug placement (use of cement foundation, viscous fluids) • Plug verification (tag, pressure tests) • New casing cement evaluation logs or casing wear logs run (if performed) • Remedial annular cementing operations reports and verification (if performed) • Creeping formation evaluation • Completion fluid type and properties
Post-P&A relevant information	• Wellhead removal • Leak reports (if any) • Monitoring reports (if any) • Current location accessibility difficulties (onshore/offshore)

3.2.4 Minimum documentation recommendations

The minimum documentation for a legacy well integrity assessment is described below and will be essential input to risk screenings and risk assessments, as discussed in section 3.3.

3.2.4.1 Regulations and standards

It is recommended that the internal and external regulations or standards used as the basis for the legacy well assessment are clearly stated. It might be necessary to use a combination of well integrity guidelines and CCS specific regulations.

3.2.4.2 Available information

The available information, as highlighted in section 3.2.3, should be clearly stated in combination with the other output recommendations.

3.2.4.3 Minimum setting depth

A depth versus pressure chart illustrating the Minimum Setting Depth (MSD). An illustration of this kind can provide an easily understandable view of acceptable pressure elevations for future CO_2 injection.

3.2.4.4 Well barrier schematic and summary

A well schematic, including an assessment summary. Here, the barrier information and the integrity status should be stated clearly by using, for example, a matrix table or a traffic light approach. Figure 7 illustrates a one-page legacy well summary for an example well.

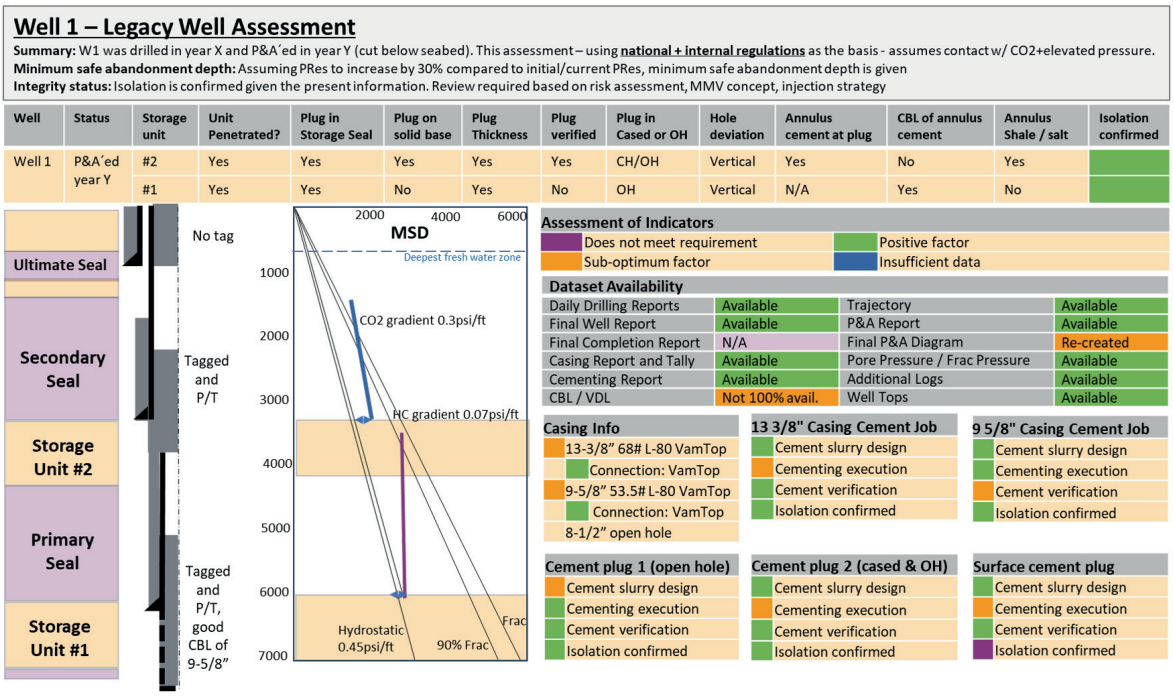


Figure 7 - Example legacy well assessment output

A plumbing diagram, as set out in Figure 8, is recommended if several legacy wells and/or multiple storage units are present in the storage complex. In this way, more complex inter-zonal leak paths via wells can be visualized effectively. A plumbing diagram can support the process of evaluating which storage units are the safest for CO_2 injection or to evaluate how far remediation options need to be implemented in some storage units.

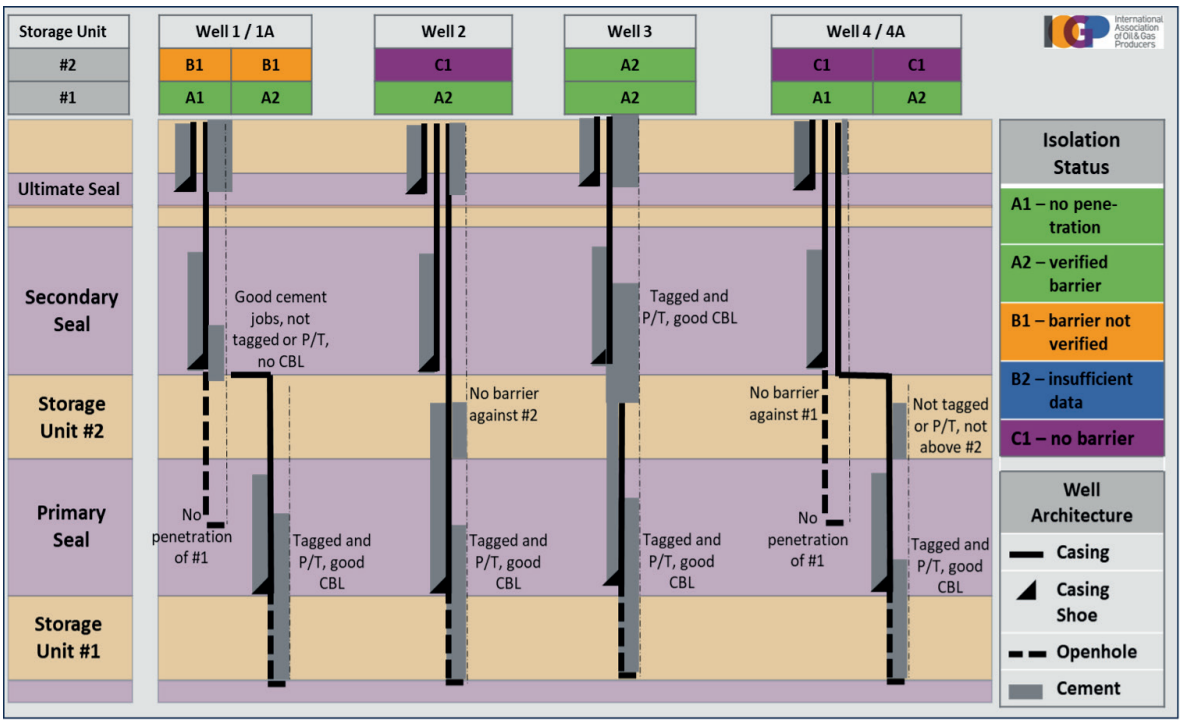
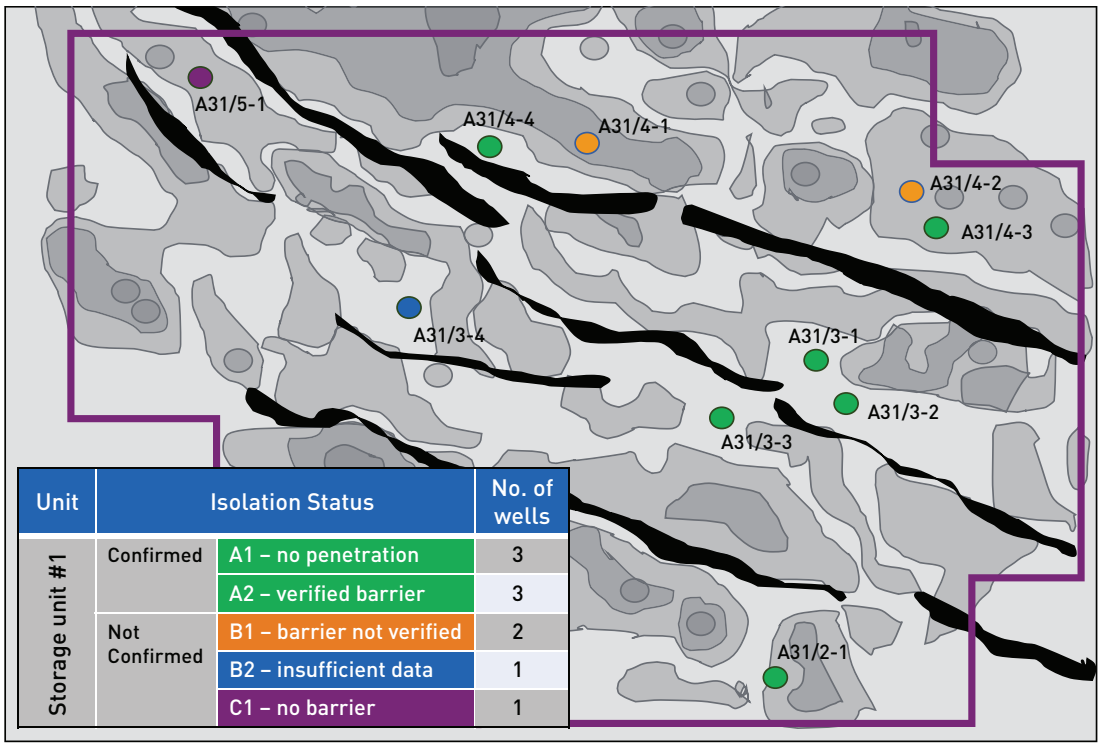


Figure 8 - Example of a plumbing diagram

A top-view, as illustrated in Figure 9, is a recommended output as part of the legacy well assessment. An illustration stating the well tops while clearly indicating the integrity status towards a storage unit provides a good visualization for understanding the risk picture for CO_2 injection.



Unit	Isolation Status		No. of wells
Storage unit #1	Confirmed	A1 – no penetration	3
		A2 – verified barrier	3
	Not Confirmed	B1 – barrier not verified	2
		B2 – insufficient data	1
		C1 – no barrier	1

Figure 9 - Example of a top-view map

3.3 Uncertainty management and risk assessment

The legacy well integrity evaluation process will be largely qualitative depending on the age, quality, and completeness of records and documentation. Documentation available for older wells is unlikely to provide definitive evidence that barriers remain effective; however, it is likely that barrier elements that served during original construction of the well retain that capability. Barrier quality assessment is part of the overall risk evaluation.

The risk evaluation should:

- identify the barriers, barrier elements, and flow mitigators and their respective placement (tops and bottoms) in each legacy well
- assess the likelihood of leakage past any existing well barrier elements
- consider the expected effect on overburden layers, including permeable layers that might act as a dissipation or thief zone
- consider the location of the CO_2 store; proximity to any populated areas, onshore or offshore (the latter typically having less utility of shallower water zones)
- evaluate the consequences of any leakage that may occur, including the likely final location of leaked fluids
- estimate the possible magnitude of leakage in a range of barrier failure scenarios

Any identified legacy well of compromised or uncertain integrity could be considered for re-entry and remediation. If wells of this nature are identified during a screening process, the candidate storage complex may be redefined, deemed unsuitable for further development, or monitoring, measurement, and verification plans developed to continue with the original plan. A further option may be to exploit the storage complex but cease further injection of CO_2 once the injected CO_2 plume or the pressure front reaches a point where modelling suggests it will continue to migrate towards and impact the compromised legacy well post-injection.

In the early scoping phase of a project, a risk screening is commonly performed to categorize the legacy wells qualitatively. Screening methodologies can be based on criteria such as a well's potential leakage risk and the complexity of required remedial action. This can provide a ranking of legacy wells into categories and provide early identification of wells with greater potential risk or higher uncertainty. Output can often be in the form of numerical (1,2,3,4) or colour coded (green, yellow, orange, red) categorizations. As the project matures, a more comprehensive and thorough risk assessment of identified high-risk legacy wells should be completed. The result of the risk assessment should be documented as part of the field development planning package and is often part of the permitting process. It can also be used to guide the selection of relevant monitoring techniques or technologies to be included in the project Monitoring Measurement and Verification (MMV) plan.

3.3.1 Methods

The operator may approach risk assessment in a number of ways. Risk assessment is intended to identify risks to CO_2 storage and the existing or planned mitigations to those risks. Having identified risks and existing mitigations, a project may then seek to determine whether additional mitigations could be considered and whether the risk reduction benefit is sufficient to warrant implementation.

3.3.1.1 Bowtie analysis

A common method of conducting and documenting a leakage risk assessment is bowtie analysis. This method results in a qualitative assessment of the risk relating to a hazard. In a bowtie analysis, a multi-disciplinary team (e.g., Subsurface and Wells) will identify a 'top event', which is a single, undesirable event which can be identified as the point where control over the potentially damaging properties of the energy source of interest is lost. The team will then identify the sequence of threats, or causes, leading to the top event occurring and the resulting consequences. See Figure 10. IOGP Report 652 - *Recommended practices for measurement, monitoring, and verification plans associated with geologic storage of carbon dioxide* and IOGP Report 657 - *Seabed and overburden integrity monitoring for offshore CO_2 storage* provide more details on the bowtie risk assessment framework.

When assessing legacy well risk, the hazard may be defined as the stored CO_2 and the top event as its leakage from the storage complex. The threats will be the initiating steps of a leak path. Threats may include:

- uncemented annuli
- cement barriers of inadequate length and/or quality
- casing annular cement which was subject to losses when being originally pumped
- casing annular cement which was interpreted as having channels or micro-annuli

The consequences will describe the Health, Safety, or Environmental (HSE) outcome once the CO_2 has further migrated after it has leaked from the storage complex.

Consequences of CO_2 and formation fluids may include but are not limited to:

- impact to communities or environment
- contaminating drinking water aquifers
- contaminating oil and gas reservoirs
- cross-flow to other permeable formations above the caprock due to increased fluid pressure in the storage unit (cross-flow within the storage complex may impact storage utilization, but would not be an HSE risk)

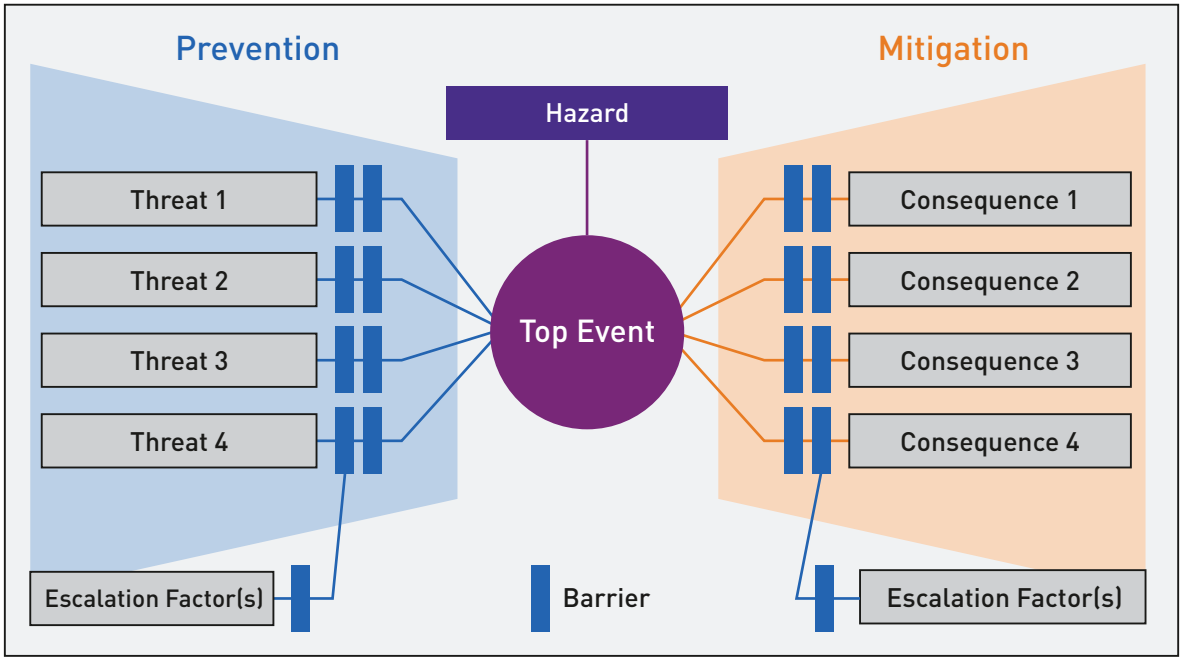


Figure 10 - Example of a bowtie diagram

For each branch of a bowtie, the risk assessment team will identify barriers or safeguards, between the initial threat, the top event, and the consequence. These identified safeguards, are not limited to the primary and secondary well barriers of the abandoned wellbore but may include:

- formation collapse and formation creep in the annulus
- screen plugging in any completion left in-situ
- barite settling in the wellbore above cement plugs

The risk assessment team will consider, qualitatively, the effectiveness of each of the identified safeguards as effective, partially effective, or ineffective. The identified safeguards may in turn also be subject to escalation factors, these being mechanisms or events which undermine or enhance the effectiveness of a preventive or mitigation barrier. Relevant examples of escalation factors may be:

- CO_2 migration through existing internal or external cement
- effects of future pressurization of storage units
- future depletion of other permeable formations
- early warning signs enabled by active monitoring

Once the effectiveness of a safeguard is assessed, the uncertainty attached to it is also qualitatively evaluated as reasonably certain, partially certain, or uncertain. This is highly relevant for older legacy wells where poor, incomplete, or missing records are likely.

A bowtie analysis provides an intuitive and structured review of the hazards, threats, consequences, and any preventive or mitigating controls in place to manage the risk. The bowtie can also be used to identify how control of the hazard may be improved and what additional controls could be established to better mitigate the threat or consequence. An example could be focused monitoring of the injected CO_2 plume.

3.3.1.2 Risk matrix

Another common method for conducting and documenting a leakage risk assessment of a storage complex hosting legacy wells is a risk matrix (see Figure 11). The two axes of the matrix are probability and consequence categories. A matrix analysis results in a qualitative assessment of a risk relative to other risks. In a matrix analysis, a multi-disciplinary risk assessment team will identify a 'scenario' and assign estimates of the probability that the scenario occurs and the level of consequence if it occurs. Similar to the bowtie approach, the risk matrix approach also incorporates identification of additional mitigators and preventative actions that could lower the assessed risk of the evaluated scenarios.

Figure 11 provides an example matrix from which multiple matrices can be developed for the expected risks, e.g., environmental, personal safety, public impact, economic. Industry studies and applications are emerging that provide examples of defining probabilities, consequences, and acceptable leak risks.[11] The risk matrix approach can be an efficient method to sort for the highest risks.

The bow-tie analysis and the risk matrix do not exclude each other and are complementary approaches for risk assessments.

Consequences		Negligible Impact	Minor Impact	Major Impact	Severe Impact
Probability	Frequently				
	Occassionally				
	Unlikely				
	Rarely				

Risk Rating			
Low	Moderate	High	Very High

Figure 11 - Example of a risk matrix

3.3.1.3 Assessing additional risk reduction measures

As Low as Reasonably Practicable (ALARP), describes risk reduction or mitigation work being progressed to a point where the time, cost, and difficulty in further reducing the risk becomes highly disproportionate to the additional risk reduction achieved. In some jurisdictions, CO_2 storage projects are regulated by the expectation that there will be no significant risk of leakage that potentially leads to harm to the environment or human health.

[11] Open Government License, 2023.
Torsæter M et al.et al., 2024.
California Air Resources Board, 2018

Having identified existing or planned risk reduction measures, a CCS project may identify additional measures that can effectively improve the existing or planned controls. The recommendations may include:

- targeted environmental monitoring of high-risk legacy wells
- limiting the migration of the injected CO_2 plume toward high-risk legacy wells
- re-entering a high-risk legacy well to remediate or replace abandonment barriers
- MMV with plume monitoring

3.3.2 Semi-quantitative leak evaluation

A key input into a project risk assessment is an evaluation of leak potential that can be based on empirical data and/or analytical models. A detailed empirical study performed for the UK Continental Shelf provides such leakage estimates.[12]

Leakage assessment models make numerical assumptions about the resistance to migration of brine and CO_2 generally based on 'flow through porous media' and via different mechanisms (displacement, buoyancy, diffusion, capillary).

Models feature the field reservoir simulation coupled with well penetrations. Inputs and assumptions may include the following:

- difference in pressure between the storage formation and the destination (receptor)
- resistance of the flow path depending on the tortuosity of the pathways around or through the cement and formations
- estimates of cement quality and resistance which may be based on records of placement operations or of integrity tests, bond logs, or other evaluation logs and field offsets
- transient behaviour that captures storage reservoir pressure and fluid type at the well penetration and the rate of migration along the tortuous path
- incorporation of rate of casing corrosion and cement alteration

A simplified approach to estimating the leakage rates of wellbore fluids is to apply a modified version of Darcy's equation to estimate the flow based on the barrier's permeability, pressure differential, and fluid characteristics.[13] Since it is difficult to measure the properties of the legacy well barriers (plugs and annulus cement) accurately, a probabilistic approach can be implemented, making this evaluation semi-quantitative.

This involves a statistical distribution of the key parameters (cement permeability, crack aperture, crack width, and micro-annulus gap) and using Monte Carlo simulations through a range of potential leak scenarios to estimate potential leakage rates and their respective probabilities. Users should leverage probabilistic models with an awareness of their limitations and to pair them with other decision-making tools and expert insights.

Results can be sensitive to assumptions about the geologic formations. Shallower permeable formations adjacent to the flow path may serve as the destination for the migrating brine and CO_2. If the shallower formation is deeper than the caprock or another sealing formation, it may serve as additional long-term containment volume.

[12] Open Government License, 2023.
[13] Moeinikia F., et al., 2018

Due to the scale of models and the need for many Monte Carlo simulation iterations, sampling, and simplifying assumptions are necessary. Simplifications may include:

- grouping wells into 'types' rather than considering each one individually
- using reduced-order representations of sophisticated component models
- reducing the number and complexity of geologic zones
- ignoring dynamic flow behaviour

The output from the coupled model may include the following:

- storage reservoir – pressure at the top of the formation, CO_2 saturation, and areal extent of the pressure and CO_2 plumes
- fluid movement pathway – probable pathway(s) and fluid type(s)
- destination (receptor) – areal extent of fluid movement

Despite the possible limits regarding the validity of the individual models, the overall likelihood of a leak is still well-represented.

A more robust assessment can be done using a Computational Fluid Dynamics (CFD) simulation in combination with other modelling software, such as Finite Element Analysis (FEA). The solution selected will be defined based on the risks present in the storage site and risk tolerance. To represent the complex physics of leak modelling more fully, an ideal model would include not only flow considerations but also mechanical and chemical interactions between cement and CO_2 along with appropriate experimental and field data for calibration. This comprehensive and integrated modelling approach is not currently available.

It is important to account for CO_2 phase transition into models. Pure CO_2 reaches the supercritical state at around 1,070 psi (73.8 bar) and 87.8°F (31°C). However, due to the contaminants that are common in the injected CO_2 stream, the conditions in which the supercritical state will be reached may vary considerably. It is critical, therefore, to perform a proper Pressure Volume Temperature (PVT) simulation and calculate the CO_2 pressure gradient for the plug minimum setting depth definition, as shown in Figure 6.

3.3.3 Remediation options for legacy wells

Whenever evaluating remediation options for legacy wells, the complexity of remediation activities typically requires a tailored intervention design, contingencies, and barrier verification. The considerations should include:

- Well location and environment (onshore, offshore shallow-water, offshore deepwater). For example, site surveys could also be required to identify undocumented wells, confirm the wells location, and shallow hazards.
- Probable and possible sources of inflow along the well. The analysis should identify risks to personnel and environmental safety to determine the resources required for the intervention. For example, when missing or failed barriers need to be constructed or replaced, the intervention should consider the possible well control scenarios.
- Well configuration and materials uncertainties (see section 3.2.3). The analysis should identify the confirmed and possible limitations of adopting certain P&A scopes.

- Well accessibility issues such as a removed wellhead, damaged wellhead/casing system, cut casing, corroded casing, tubing/casing buckling, or collapse.
- The risks to the well entry activity and subsequent barrier restoration operations taking into consideration the placement and verification of the abandonment plug relative to the well architecture. For instance, it may be more challenging to access the open hole interval to place an abandonment plug. Likewise, it would be difficult to intersect a legacy well where there is no existing casing string.

The main methods are described below.

Method 1: Rigless intervention

The simplest approach for remediation considers direct intervention in wells to install new barriers inside the casing or tubing using rigless intervention. Several options (e.g., wireline, slickline, coiled tubing, cementing) are available to achieve the objectives of the abandonment.

Diagnostics options include wireline logging (for cement evaluation, casing integrity, directional data, fluid sampling and data, etc.), pressure verification of barriers, cross-well seismic data, etc. The verification of barriers through these options should be considered on a case-by-case basis, as they may be inadequate or insufficient depending on the well architecture, the logging technology applied, and other conditions.

For barrier placement, cement plugging options through the tubing or casing with coiled tubing considers easily accessible intervals and the application of proper plugging techniques to ensure long term zonal isolation.

Method 2: Rig intervention

Rig interventions may be applied when the previous approaches are not sufficient to complete a remediation. Typically, these options require more complex/robust rig and well control equipment, and a high-end set of well services to allow the remediation objectives to be completed.

A representative list of applicable techniques includes:

- structural restoration of casing/wellhead and manufacturing of specific well access equipment for P&A
- re-establishing access to intervals to be plugged by cut and pull, casing/tubing expansion, or milling/fishing
- section milling through casing/existing cement to establish access and place new cement plugs
- remedial cementing through casing/tubing such as perforate and squeeze, Perforate-Wash-Cement (PWC) and perforate and circulate

Method 3: Intercept well

An intercept well may be necessary if unable to re-enter the legacy well via methods 1 and 2 described above. Intercept well planning and execution are highly complex operations, and their viability depends on several factors such as well location, well architecture, and formations exposed during drilling and P&A. The intercept well design should consider the feasibility of intercepting and plugging the legacy well. Uncertainty and risk management should be used to assess the best technique for the placement of barriers and their verification. Some of the aspects to be evaluated are:

- nearby wells survey data to avoid unintended interception and communication with other inflow potential zones
- bullheading reservoir and other permeable zones
- necessity and feasibility for placing annulus barriers
- barrier verification options are usually limited from intercept wells
- feasibility of re-entering a well with the required downhole tools via a milled window

3.3.3.1 Materials and technologies to (re-)establish permanent barriers

If there is insufficient evidence of cement plug or annular cement isolation (e.g., sustained casing pressure, or any type of cement bond logging), or evidence suggests insufficient cement quality, remediation of the annulus integrity should be considered. A variety of methods are available and are common industry practice. This could include, but is not limited to, the following:

Cement squeeze

Squeeze cementing is typically a dehydration process necessary to correct a problem in the original annular cement. A cement slurry is prepared and pumped down in the wellbore up to the problem area or squeeze target. The target casing/liner may be perforated and later isolated with a packer or cement retainer, and pressure applied from the surface to force the cement slurry into all voids. The slurry is designed specifically to address the identified issue: small crack or micro-annuli, casing split, large vug, formation rock type, formation fracture, or another kind of cavity. There are several squeeze techniques (cement retainer, packer, hesitation, high-pressure, etc.) used for annular remediation during abandonment operations.

Section milling

Section milling is a method of opening a window in the casing so a rock-to-rock cement plug can be placed. Section milling is a time-consuming and complex operation that may require under-reaming and may generate a lot of swarf (metal shavings), requiring specific milling fluids and surface handling equipment.

Perforate, wash, and cement

Perforate, wash, and cement is the process where casing or liner is perforated across a zone with poor annular cement. The annulus is then jetted through the perforations until returns at the surface are clean, after which cement is squeezed both into the annulus through the perforations and inside the casing or liner being abandoned.

Alternative materials

The techniques mentioned above are widely accepted to restore the cap rock integrity. Portland cements are the most frequently used material to achieve primary isolation in the casing strings and abandonment plugs. An extensive review of Portland cement and alternative barrier materials is covered in sections 1.3.1 and 1.3.2. Looking at CO_2 storage, the industry has started considering non-standard cement slurries or alternative plugging materials, such as:

- Bismuth: this dense alloy is melted downhole and quickly solidifies, creating a solid plug. Due to its low viscosity, it can quickly fill up gaps.
- Thermite: creates a high-temperature reaction downhole, melting the casing, the cement, and the formation, creating a solid plug barrier. It can also be combined with other materials like bismuth.

The materials mentioned above should be considered for remedial abandonment purposes, though a thorough risk assessment and engineering design are required on a case-by-case basis, including their limitations to act as standalone barriers such as creeping behaviour, shrinkage, degradation, etc. Specific approval from the relevant regulatory authorities, further technology development, and qualification of barrier material may be required for the alternative materials to be applied.

3.3.3.2 Considerations for accessing abandoned legacy wells

Deciding to intervene and remediate a legacy well should not only consider abandonment and well integrity specific factors but also whether it is technically feasible to access a well. Well access may prove to be difficult or even impossible.

It is necessary to first determine the well context and gain a further understanding of the complexities associated with each scenario. The following topics should be thoroughly considered:

- amount, quality, and trustworthiness of data available
- whether the well is onshore or offshore
- vertical access and well type (open or cased hole)
- wellhead removal during original abandonment
- the existence of sidetracks to abandon

Available data

The availability of legacy well data, as highlighted in section 3.2.3, is key for evaluating accessibility. Deviations between reported and actual well location and wellhead removal status are common problems for legacy wells. Conducting a site survey to locate these wells and assessing their current conditions is therefore a good practice.

Well location

Offshore legacy wells have a substantially more complex and costly intervention and remediation. Some of these wells can be particularly challenging to locate and reconnect to, especially if the wellhead has been removed, or the location is not properly reported.

Onshore wells are generally only limited if location access is inconvenient or prohibited. No presence of the wellhead is also an additional challenge. This topic is discussed in the sections below. Because of the multitude of likely scenarios which may complicate and even fully prevent locating legacy wells, it may be necessary to conduct other geophysical surveys including the use of magnetometers, sonar, and high resolution seismic.

Re-abandonment of legacy wells that are not easily accessible can lead to a high degree of technical complexity and financial expenditure. The technical and economic risks should be properly evaluated.

Vertical access and well type

One important factor is the ability to have vertical access to the legacy well, i.e., the possibility to mobilize a drilling unit directly above to conduct a normal well re-entry. If this is not possible for any of the reasons mentioned below, an intercept well may be considered, if feasible.

There are a number of factors which may hinder or completely rule out direct vertical re-entry, namely:

- the ability to excavate and expose the top part of the well or remaining casing
- the condition of the top part of the well or its materials being unsuitable for vertical re-entry (e.g., corrosion, material degradation, collapsed top sections, load case restrictions)
- the legacy well location at or in the vicinity of:
  - populated areas
  - sites with existing surface facilities or any other structure preventing access for drilling unit or associated equipment, e.g., roads, buildings, surface water
  - sites with multiple producing or injecting wells
  - areas of special environmental protection
  - zones intended for certain practices, e.g., marine anchorage, agriculture, etc.

In some legacy wells, the storage complex and/or injection target is in the open hole. Remediation options for these wells are limited and well re-drill or wash down to access the desired zone is not a guaranteed success. Additionally, when the targeted zone is below abandonment plugs previously set in the open hole, the risk of departing from the wellbore while milling the plug should be assessed.

Wellhead reconnection

During abandonment of the legacy well, casing is typically cut below surface level, and the wellhead is removed to restore the site to its original state. As wellheads are the interface permitting connection to high-pressure containing envelopes, i.e., casing strings and Blowout Preventers (BOP); it is the first requirement of any well intervention needing pressure integrity to re-instate such an interface.

Should legacy wells be onshore, it is likely a re-heading process would take place, i.e., attaching a new wellhead to the previously abandoned well. This is typically done by performing an excavation around the confirmed well location until the conductor or guide pipe stub is uncovered and cutting and or welding work can be accommodated.

Offshore wells would require a different approach as most of the techniques or technical solutions proposed are less common to the sector. The approach will depend on whether casing strings and wellhead were severed through cutting knives or explosives, as the "end-product" differs greatly. An explosively severed tubular will likely deform and flare out at the severance point and adjacent zones, which could complicate or entirely prevent the reconnection to the well through an overshot, thus requiring other operations to be conducted before successful reconnection is possible, such as further dredging, cutting, etc. Additionally, severely deformed areas of the tubular would not yield the same original physical properties, potentially requiring careful load distribution over the legacy well upon reconnection.

Conducting a detailed structural, conductor, and riser analysis is a good approach to fully understand loads exerted over legacy wells under multiple reconnection scenarios. This would clarify whether reconnection is deemed feasible and under which assumptions, e.g., connection interfaces, equipment to be used, existing conductor conditions and mechanical properties, and operations to be withstood.

If a wellhead is present, inspection by the manufacturer or qualified personnel should take place to determine if the current condition is suitable to be used during a well re-entry operation. Any repair work needed is likely to be substantially less complex and cost restrictive than the equivalent re-heading or offshore well reconnection.

Sidetracks

The existence of sidetracks also introduces additional complexity as it could require multiple activities to regain access to old wellbores which may be partially collapsed, if open hole, or obstructed by whipstock systems, bridge plugs, cement plugs; or even need the retrieval of liner or casing sections. It is possible that access to sidetrack boreholes may not be technically feasible.

Intercept wells

If access to a well or wellbore is deemed not feasible, a contingency solution is drilling an intercept well and conducting operations as required. Here, it is worth mentioning that intercept wells can be drilled from the legacy well itself, e.g., drilling a sidetrack out of the motherbore to intercept an inaccessible leg of the existing wellbore.

For such cases, the implications and technical challenges are similar to those in conventional relief well planning, i.e., adequate directional planning to avoid intercepting potential nearby wells, accurate well ranging, correct well interception, and execution of re-abandonment operations. Developing technologies, such as acoustic ranging, may allow for ranging and interception of an uncased open hole. Verification of newly installed barriers may also pose a particular challenge.

Intercept wells should target intercepting the legacy well at a depth shallower than the sealing formation to establish a sufficient barrier for caprock restoration. Under such a scenario, directional trajectories for intercept wells could be challenging or compromised.

In summary, all legacy wells with a potential need for remediation in a CO_2 storage project should be assessed for re-entry by looking at all the factors described above, to then categorize into three groups, namely:

- accessible
- not easy to access (possible, but technically/economically challenging)
- non-accessible (technically not possible)

3.3.4 Remediation timing and de-risking options

Initial CO_2 plume and pressure simulations in combination with the legacy well analysis, risk assessment, and the feasibility of well re-entry and remediation activities provide a preliminary leakage risk picture for each well and for the complete CO_2 storage complex. This enables the CCS operator to evaluate alternative de-risking and remediation timing options. The following list describes some possible options. The lists are not exhaustive, and evaluation of implementation would require consideration of overall project economics and risk.

Injection strategy and pressure management

The CCS operator might re-evaluate the amount or rate of CO_2 to be injected to limit the maximum pressure at legacy wells or to prevent CO_2 reaching the wells. Additionally, pressure management activities could be considered, such as water production wells to remove water from the store thereby reducing the pressure.

CO_2 injector placement

Another de-risking option is represented by re-evaluating the location or subsurface target formations of CO_2 injection wells via reservoir simulation. By this, it might be that the legacy wells will no longer be in contact with CO_2. In addition, the maximum pressure seen at legacy well locations can be lowered, or its increase can be delayed. Here, the top-view map in combination with CO_2 plume and pressure simulations can be used to improve the injector placement. Figure 12 presents a simplified example of optimized injector well placement with respect to legacy well assessment to avoid wells with insufficient data or no confirmed barrier.

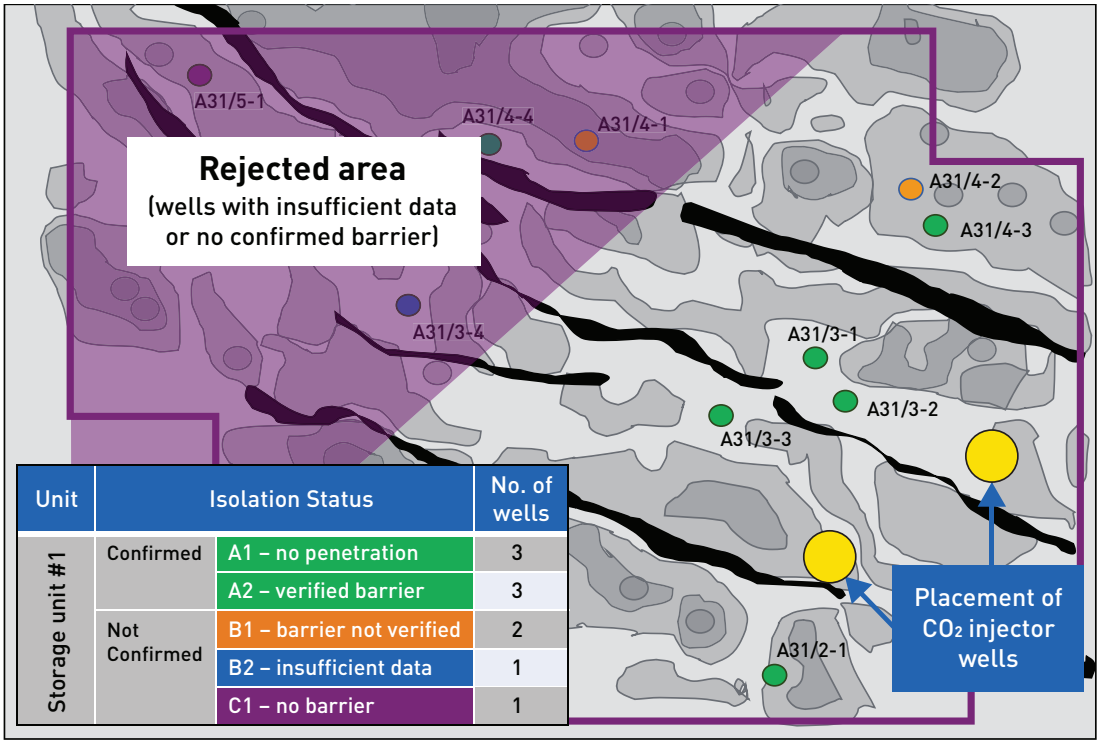


Figure 12 - Example of a CO_2 injector placement

Measurement, Monitoring, and Verification (MMV) program

A tailored MMV programme can serve to further de-risk the likelihood of leakages via legacy wells. Many techniques, such as observation wells and monitoring of the CO_2 plume, might enable the CCS operator to re-evaluate the way forward for present legacy wells. Here, IOGP Report 652 provides guidance and recommended practices for measurement, monitoring, and verification plans for the geological storage of CO_2. MMV plans should be risk-based and project-specific in terms of applied technologies and their frequency to be appropriate for different legacy well scenarios and their leakage risk. MMV plans should also be revised during the project life as data are collected, and the uncertainties are reduced.

Partial P&A and re-P&A

For legacy wells that have not yet been completely plugged and abandoned, part of the de-risking strategy might be to perform only partial P&A. One method would be to establish a deep barrier without losing the accessibility of the well. This allows the installation of monitoring equipment in the partially plugged wellbore to prove the sealing ability of P&A methods. If any problem is detected on the primary barrier, the option is available to restore well integrity and to P&A the well(s) before CO_2 would reach the surface, seabed, or protectable formation above the storage unit. The same principle might be considered for wells where re-P&A and access can be restored.

Timing and approach

The P&A strategy should include a risk assessed approach to the timing of the P&A based on CO_2 plume diffusion in the reservoir while also accounting for inherent uncertainties on the associated model. The timing to plug and abandon a nominated legacy well may be before starting CO_2 injection and should be before the well is impacted by the injected fluid and/or pressure front.

3.4 Legacy wells risk scenario outcomes

Following the conduct of a legacy well analysis and considering all de-risking options, the following scenario outcomes might be possible:

Leave the legacy well as is

Legacy wells with low leakage risk can lead to the decision that no additional P&A activities are required. However, a tailor-made MMV program should support and enable this decision to be revised before and throughout the CO_2 injection phase.

Re-purposing of the legacy well

Intact wells with good well integrity might represent suitable candidates for observation or monitoring purposes. Well integrity screening tools are available which can be used for a preliminary re-purposing assessment.

Abandonment or re-abandonment

Legacy wells with an unacceptable leakage risk having considered de-risking options can trigger the decision to abandon or re-abandon.

Change in injection strategy

Even though the injection volumes and economics might be impacted, a change in injection strategy might still enable the economic development of a CO_2 storage project while mitigating risk to legacy wells.

Threat to the project

Legacy wells with an unacceptable leak risk that cannot be technically or economically remediated can represent a showstopper for the CO_2 storage project. All remediation technologies and de-risking options should be evaluated while following new technological advancements.

Figure 13 illustrates the legacy well evaluation process and the scenario outcomes.

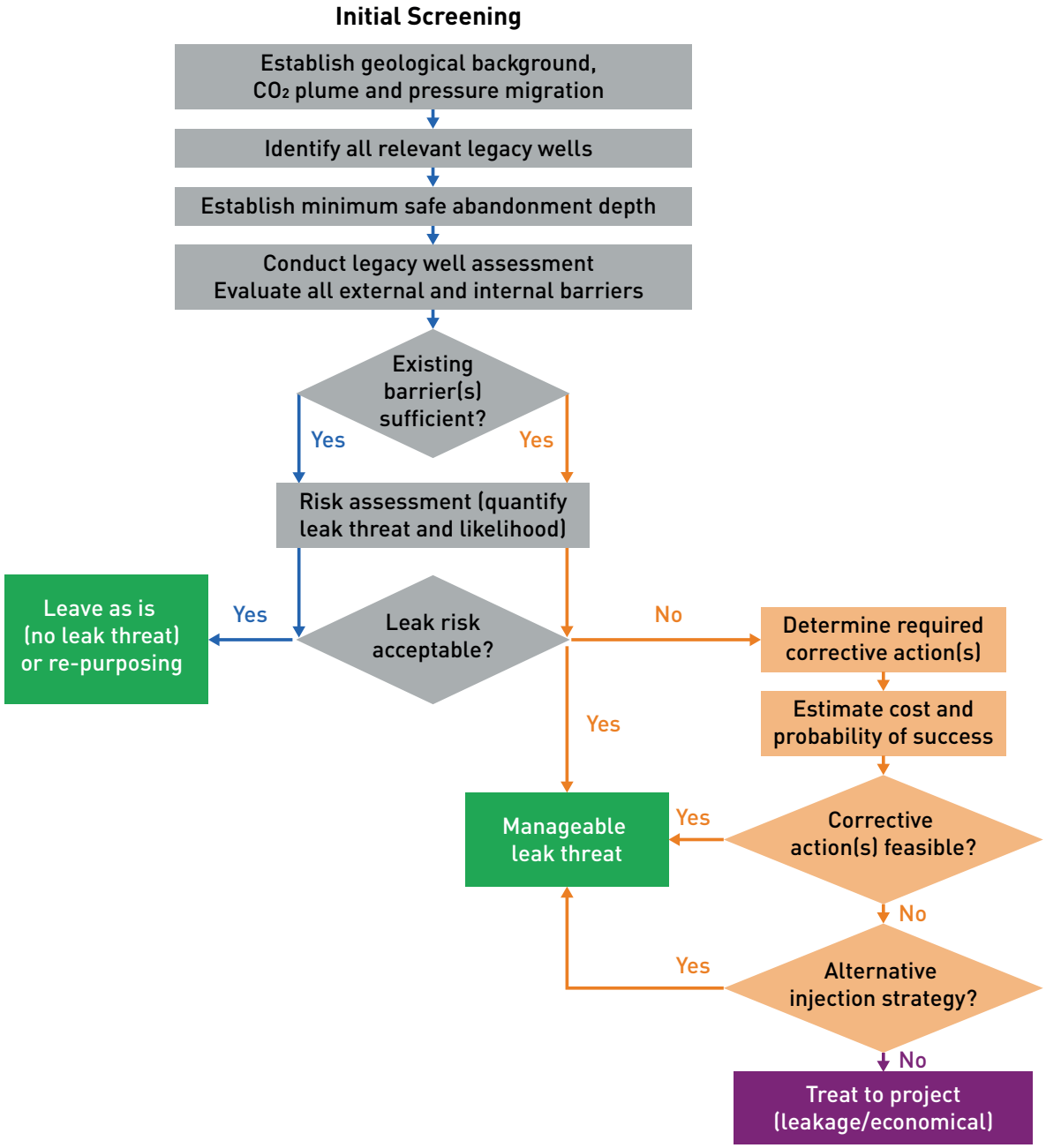


Figure 13 - Example of high-level decision flow chart for legacy well scenario outcome

Considerations relating to the risk scenario outcomes are set out below:

- The outcome may differ, subject to specific regulatory mandates in each country.
- Re-assessment of the legacy well integrity evaluation process should be completed when key parameters change, or when new information has been collected. This would cover changes during injection until site closure (or even post-closure).
- New penetrations (e.g., additional project wells, exploration or appraisal well, producer or observation well) in Area of Review (AoR) should follow this process.
- A decommissioning plan should be prioritized and should incorporate the outcomes above.

4. Conclusion

CCS remains an emerging industry in comparison to oil and gas exploration and production. However, many of the same principles apply in terms of well abandonment and integrity evaluation. The effectiveness of CO_2 storage projects for climate change mitigation relies on safe and secure storage capture in subsurface formations without harming human health and/or the environment. All well penetrations that exist within a CO_2 storage complex can serve as potential pathways for CO_2 injectate or formation fluid movement out of the designated store. For this reason, operators of CCS projects should ensure the integrity of both the CO_2 storage project wells and all legacy wells within CO_2 storage complex by performing a comprehensive evaluation, risk assessment, and mitigative measures as necessary throughout the planning and execution phases.

This report aims to provide CCS operators with guidance and primary considerations for well abandonment and integrity evaluation for CO_2 storage projects. It is not intended to be exhaustive nor supersede any presiding regulatory requirements. Not all CO_2 storage projects are the same as site-specific conditions will vary (e.g., onshore or offshore, depleted reservoir or saline aquifer, injection operation parameters, etc.) and a universal approach may not be appropriate. Therefore, a tailored approach is recommended that is site-specific and risk-based for the given CO_2 storage project conditions, drawing on the guidance in this report. Ultimately, it is the responsibility of the operator to address well abandonment and integrity evaluation of all existing wells within a CO_2 storage complex that is consistent with their own internal requirements and risk tolerance, and which complies with local regulations.

Legacy wells present a significant challenge due to the wide range of conditions and uncertainty. Consequently, diversity exists in the maturity, approaches, and requirements of regulations and supporting technical guidance. It is important for stakeholders to stay abreast of the evolving regulatory landscape and ensure compliance with applicable regulations and standards. Harmonization of regulatory standards and technical guidance, along with sharing recommended practices globally will foster consistency, efficiency, and effectiveness. In the assessment and management of legacy wells, collaboration between operators, government agencies, and project stakeholders will be of the utmost importance.

Appendix A: Well types and conditions

Table 3 – Well types and typical conditions in terms of pressure, temperature, and chemical exposure that can be expected during operation and after abandonment

	Saline Aquifer	Depleted Gas field
Injector well - New	• Substantial temperature fluctuations in the transition between static and injection conditions • Increasing pressure differential from start of injection • Higher pressure than original • Exposure to refreshed CO_2 stream	• Large temperature fluctuations in the transition between static and injection conditions due to JT cooling effects • Pressure in the storage complex is lower than in overburden for the early part of injection • Final pressure, after stopping CO_2 injection may be below hydrostatic • Risk of losses during the construction phase • Effect of different stress regime due to depletion • Exposure to refreshed CO_2 stream
Injector well - Re-purposed (Possibly above produced zone)	• Well has a temperature/pressure history due to its production history • Inherited cement quality/placement • Exposure to refreshed CO_2 stream • Casing and tubing may not be adequate for CO_2 injection	• As above, the well has a temperature/pressure history due to its production history • Inherited cement quality/placement • Exposure to refreshed CO_2 stream • Effect of different stress regime due to depletion • Casing and tubing may not be adequate for CO_2 injection
Monitoring well	• Limited or no temperature fluctuations dependent upon separation from active injectors, gradual decrease as CO_2 plume approaches well • Gradual increase in pressure from the start of CO_2 injection • Exposure to near stagnant CO_2 stream at end of injection life of storage complex and possibly flipping of the fluid column due to density differences	• Limited or no temperature fluctuations dependent upon separation from active injectors, gradual decrease as CO_2 plume approaches well • Gradual increase in pressure from the start of CO_2 injection • Final pressure may be below hydrostatic • Effect of different stress regime due to depletion • Exposure to near stagnant CO_2 stream at end of injection life of storage complex and possibly flipping of the fluid column due to density differences
Infill well	• Possibility of a supercritical CO_2 kick out of the plume • Potentially large temperature differences in the storage rock • Potential interaction between cement and CO_2 during placement	• Potentially combined presence of CO_2, hydrocarbons, brine • Potential combined kick in case of major losses • Potentially large temperature differences in the storage rock • Potential interaction between cement and CO_2 during placement

	Saline Aquifer	Depleted Gas field
Pressure management well	• Limited or no temperature fluctuations, gradual decrease as CO_2 plume approaches well • Potentially high temperatures at surface, depending on the depth of the store • Gradual increase in pressure from the start of CO_2 injection, fully or partially diminished by water production • Exposure to stagnant CO_2 stream at end of injection life of storage complex	• Not an applicable well type for a depleted store
Legacy well (including previously abandoned) in CO_2 plume or in the migration path of the plume	• Very limited temperature fluctuation due to lack of flow • Upward pointing pressure differential when pressure, and later plume, reaches the well • Well has a temperature/pressure history if it has been an active producer/injector • Exposure to CO_2 and brine	• Very limited temperature fluctuation due to lack of flow • Pressure in the storage complex is lower than in overburden for the early part of injection (potential leakage would be in downwards direction at that stage) • Final pressure, after stopping CO_2 injection may or may not be below hydrostatic • Upward pressure may come from displaced methane or from CO_2, depending on the circumstances • Exposure to CO_2, brine, methane, condensate, possibly oil
Legacy well (including previously abandoned) in pressure front but not CO_2 plume	• No temperature fluctuation • Upward water/brine pressure on abandonment plug • Well has a temperature/pressure history if it has been an active producer/injector	• No temperature fluctuation • Pressure in the storage complex is lower than in overburden for the early part of injection. Hence, potential leakage would be in downwards direction at that stage • Final pressure, after stopping CO_2 injection may or may not be higher than hydrostatic • Upward pressure may come from water or methane

Glossary

Term	Definition
Leakage	CO_2 reaching the surface and/or unauthorized zone(s).
Legacy well	Any existing well within the region surrounding the CO_2 storage project that is not associated with the CO_2 storage project including, but not limited to, active, idle, or abandoned oil, gas, or water production or injection wells.
Migration	Movement of CO_2 through geologic strata and along the wellbores within a storage unit and/or complex. Typically, there will be multiple potential migration paths.
Plug and Abandon	During well construction, and completion, production, or injection operations, well integrity is maintained so that fluids are contained within and flow only along specific pathways within the tubulars installed in the well. At the end of active operations, barrier plugs are set to permanently block the flow pathways, separating pressurized zones and/or zones of flow potential from one another and from the surface. Access to the downhole zones through those pathways is thus abandoned
Project well	A well that is associated with a CO_2 storage project which includes CO_2 injection wells and any monitoring or water production wells that may be necessary for the safe operation of the CO_2 storage project. Excludes legacy wells.
Seepage	CO_2 moving out of the storage unit.
Storage complex	The storage unit and surrounding geologic formations that influence overall storage integrity. This typically includes the storage unit and overlying or underlying confining zone(s) or layer(s) based on site specific characterization. However, it is ultimately defined by the applicable regulatory authorities and may vary by region.
Storage unit	The subsurface formation(s) into which CO_2 is intended to be injected for geological sequestration. This is also referred to as the storage or injection zone, interval, or reservoir.
Well barrier element	A physical element (including a fluid column), in combination with other well barrier elements, forms a well barrier envelope to prevent flow.
Well barrier envelope	One or several verified well barrier elements that collectively prevents unintentional flow from a source. Often abbreviated to well barrier, e.g., primary or secondary well barrier.

Abbreviations

AoI	Area of Interest
AoR	Area of Review
ALARP	As Low As Reasonably Practicable
BHA	Bottomhole Assembly
CBL	Cement Bond Log
CCS	Carbon Capture and Storage
CFD	Computational Fluid Dynamic
CO_2	Carbon Dioxide
CRA	Corrosion Resistant Alloy
DAS	Distributed Acoustic Sensing
FEA	Finite Element Analysis
FIT	Formation Integrity Test
J-T	Joule-Thompson
LOT	Leak-Off Test
MMV	Monitoring, Measuring, and Verification
MSD	Minimum Setting Depth
P&A	Plug and Abandonment
PWC	Perforate-Wash-Cement
PVT	Pressure-Volume-Temperature
ROV	Remotely Operated Underwater Vehicle
SCP	Sustained Casing Pressure
USDW	Underground Source of Drinking Water
VDL	Variable Density Log
WBE	Well Barrier Element

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This document provides guidelines and considerations for well plugging and abandonment (P&A) approaches of both project and legacy wells within a carbon dioxide (CO_2) geologic storage site. This includes well integrity evaluation methods, barrier philosophy, and plugging materials such as cement or alternatives. This document is intended for wells personnel and industry stakeholders who are involved in a CCS project, specifically in the evaluation, planning, and execution phases.

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