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Carbon dioxide capture, transportation and geological storage — Carbon dioxide enhanced oil recovery (CO_2-EOR) — Transitioning from EOR to storage

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National foreword

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Carbon dioxide capture, transportation and geological storage — Carbon dioxide enhanced oil recovery (CO_2-EOR) — Transitioning from EOR to storage

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Foreword

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

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Introduction

Across the globe, interest in and development of projects for the geological storage of captured anthropogenic CO_2 continues to increase. One subset of these projects consists of those that would find some way to increase CO_2 storage through the use of existing hydrocarbon fields and infrastructure. There is a continuum of projects from hydrocarbon fields near the end of their lives that start CO_2 injection before the end of production, thereby accelerating transition to storage and potentially reducing costs, to full-fledged carbon dioxide enhanced oil recovery (CO_2-EOR) projects that can be optimized to maximize CO_2 storage while still producing oil. Alternatively, operators of a producing field can decide to begin storage operations in that field before ceasing production. Such operations would instead be designed to achieve storage simultaneously with production.

Due to the availability of existing infrastructure for CO_2 transport, handling, injection and storage, modifying CO_2-EOR projects nearing maturity to increase CO_2 storage can be a particularly cost-effective way to reduce atmospheric emissions of CO_2. Some such modified projects can also defer project decommissioning, again helping to expand commercial carbon capture and sequestration (CCS) as an emissions-reduction option. CO_2 transport and injection infrastructure, as well as the generally well-characterized geologic formations where CO_2-EOR operation are already undertaken or where operations at CO_2-bearing geological formations occur, can be modified too for CO_2 storage.

Similarly, for producing oil and gas fields, starting CO_2 injection before cessation of production (i.e. having overlapping storage and production licenses) can have significant economic benefits. The CCS project can have certainty in timing and can potentially avoid having to compensate the hydrocarbon operator for “lost production”. There is also no gap between production and storage leading to no challenging questions over who pays for mothballed infrastructure.

There is considerable overlap in technology and infrastructure between standard CO_2-EOR, other hydrocarbon recovery processes and dedicated geological storage of CO_2. Each of the processes – and many of the operational variations discussed in this document – can present different advantages or disadvantages. For example, a number of the operational techniques for maximizing CO_2 storage would tend to increase reservoir pressures affecting the containment risk assessment, CO_2 movement through the storage complex or certain subsurface-engineered facilities. The technical and operational portion of this document examines these issues.

Similarly, the legal, regulatory and even consensus standards framework developed for typical CO_2-EOR operations can no longer be applicable to a modified operation. A given framework can be appropriate for some operational changes, but not for others. Clause 10 provides an overview of these issues.

This document does not address the quantification of greenhouse gases (GHGs) other than CO_2 for carbon dioxide storage projects. CCS projects can address quantifying, monitoring, reporting, and validating or verifying other GHG emissions reductions or removals through the application of ISO 14064-2 or other documents in the ISO 14064 series.

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Carbon dioxide capture, transportation and geological storage — Carbon dioxide enhanced oil recovery (CO_2-EOR) — Transitioning from EOR to storage

1 Scope

This document examines various CO_2 injection operations that involve modifications to CO_2-EOR or other complementary hydrocarbon recovery operations that can be conducted in conjunction with CO_2 storage. The document also examines potential policy, regulatory or standards development issues that can arise in evaluating such operational changes.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

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

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

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

3.1
anthropogenic CO_2
anthropogenic carbon dioxide
carbon dioxide that is initially produced as a by-product of a combustion, chemical or separation process (including separation of hydrocarbon-bearing fluids or gases) where it would otherwise be emitted to the atmosphere (excluding the recycling of non-anthropogenic CO_2)

[SOURCE: ISO 27916:2019, 3.1, modified — Notes 1 and 2 to entry have been deleted.]

3.2
area of review
AOR
geographical area(s) of a carbon capture and sequestration (CCS) project, or part of it, designated for the assessment of the extent to which a CCS project, or part of it, can affect life and human health, the environment, competitive development of other resources, or infrastructure

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

[SOURCE: ISO 27917:2017, 3.3.10, modified — "may be required by regulatory authorities" has been deleted from Note 1 to entry.]

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3.3
enhanced oil recovery complex
EOR complex
project reservoir, trap and such additional surrounding volume in the subsurface as defined by the operator within which injected CO_2 will remain in safe, long-term containment

[SOURCE: ISO 27916:2019, 3.10]

3.4
injection/withdrawal ratio
IWR
relationship, during a defined period, of the volume of all fluids and gases injected into the project reservoir to the volume of all fluids and gases produced from the project reservoir as determined using consistent temperature and pressure conditions

[SOURCE: ISO 27916:2019, 3.11]

3.5
natural-sourced CO_2
gaseous accumulations of CO_2 found in geological settings, such as sedimentary basins, intra-plate volcanic regions, faulted areas or quiescent volcanic structures

3.6
plug and abandon
P&A
permanently close a well or wellbore to prevent inter-formational movement of fluids into strata, into freshwater aquifers, and out of the well

Note 1 to entry: In most cases, a series of cement plugs is set in the wellbore, with an inflow or integrity test made at each stage to confirm hydraulic isolation.

[SOURCE: ISO 27916:2019, 3.17]

3.7
produced water
naturally occurring water in the reservoir that is extracted as part of oil and gas production operations

3.8
produced water cut
ratio of water to total fluids that are produced at the well during oil and gas production operations

3.9
purchased CO_2
CO_2 injected in a formation that is not attributable to recycling of CO_2 previously injected at that site, regardless of whether the supply is acquired through a purchase and sale transaction

Note 1 to entry: Other terms include “incremental”, “new”, “off-site” and “acquired” CO_2. Accounting protocols to preclude double-counting of CO_2 storage are presented in ISO 27916:2019, 8.2, 8.7 and Clause A.14 b).

3.10
spill point
structurally lowest part of a reservoir that can contain buoyant fluids within the trap

3.11
thief zone
geological formation to which fluids used or produced during CO_2 enhanced oil recovery drilling or production operations are lost

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3.12
water-alternating gas
WAG
enhanced oil recovery production technique in which injections of water are alternated with injections of CO_2 (as opposed to continuous injections of CO_2)

3.13
water out
point in time beyond which the proportion of water in a production stream is so great that recovery of the remaining hydrocarbons in the stream is no longer economically justified

4 Abbreviated terms and symbols

4.1 Abbreviated terms

AOR	area of review
API	American Petroleum Institute
BIO LLC	Brilliant Idea Oil LLC
CCI	continuous CO_2 injection (i.e. not alternating with water injections)
CCS	carbon capture and sequestration
CCUS	carbon capture utilization and storage
CO_2-EOR	carbon dioxide enhanced oil and gas recovery
FPSO	floating production storage and offloading vessel
GOR	gas/oil ratio
HC	hydrocarbon
HCPV	hydrocarbon pore volume
IPL	injection profile logging
IWR	injection/withdrawal ratio
LACT	lease automatic custody transfer
LNG	liquid natural gas
M	one thousand
MDF	mature and depleted field
MIT	mechanical integrity testing
MM	one million
MMRb	one million reservoir barrels
OOIP	original oil in place
PDO	plan for development and operation
P&A	plug and abandon

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psi	pounds per square inch
Rm^3	reservoir cubic meter (i.e. cubic meter at reservoir temperature and pressure)
ROZ	residual oil zone
STB	standard barrel (i.e. barrel of liquid at standard temperature and pressure)
Tcf	trillion cubic feet
USDW	underground source of drinking water
WAG	water alternating gas

4.2 Symbols

T_i	initial temperature
B_{OI}	oil formation volume factor at initial reservoir pressure
P_{BP}	bubble point pressure
P_i	initial reservoir pressure
R_s	solution gas/oil ratio
R_b	reservoir barrel

5 Overview

During CO_2-based enhanced oil or gas recovery operations (CO_2-EOR), CO_2 is injected into a hydrocarbon-bearing geological formation to restore reservoir pressure and to mobilize oil that is trapped in the pore spaces of the rock. As explained in ISO 27916:2019, Clause A.3:

> "Once injected, the CO_2 contacts and swells the oil in the reservoir. At certain pressure and temperature conditions, the CO_2 becomes miscible (mixing in all phases) with the oil, creating a more mobile oil that is more easily displaced through the reservoir. Oil, CO_2, and brine are then produced to the surface at production wells. This mixture of produced fluids is delivered to a separation plant in which pressure is dropped, and oil, water, and CO_2 and other gases are separated from one another. [...] Oil is sent to market and brine is reinjected for flooding as part of the operation or injected in permitted disposal wells."

ISO 27916:2019, Clause A.4 states that, as a natural part of CO_2-EOR operations, CO_2 is “effectively stored in the subsurface and securely isolated from the atmosphere, underground sources of drinking water, and other subsurface resources.” Furthermore, ISO 27916:2019, Clause A.4 explains that:

> "a significant fraction of injected CO_2 becomes trapped in place and is physically unrecoverable. Modelling and core plug studies illuminate the trapping that occurs; it includes CO_2 trapped by capillary processes and in dead end pores, dissolved in immobile oil, dissolved in brine, or moved into 'attic' areas and outside of the active flow paths. Some discussions of CO_2-EOR operations characterize only this non-recyclable CO_2 as 'stored' (e.g. Whittaker and Perkins, 2013).[1] However, others follow the same approach as is used in accounting for saline formation storage projects, where all forms of effective trapping in the reservoir are counted as stored (including CO_2 trapped as a mobile phase beneath the confining system)."

Adsorption counts as another trapping mechanism. A dense layer of CO_2 forms at the solid surface increasing the storage capacity of a reservoir on one hand and reducing the possibility of CO_2 leakage through overpressure on the other. However, residual water or oil films adhering to the surface can prevent the formation of closed adsorption layers.

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The first commercial CO_2-EOR projects began over 50 years ago. The vast majority of the 140 or more projects worldwide are still operational today. Until recently, there has generally been no economic value to be derived from the associated storage of CO_2 that occurs in a CO_2-EOR operation. As a result, in seeking to maximize the ultimate recovery of the hydrocarbon mineral resource (as typically required by the applicable law, permit or commercial agreement), operators have generally sought to economically optimize (i.e. minimize) the quantity of CO_2 injected and stored during the operation. The economic incentives change; however, when a legal or regulatory framework or a commercial agreement creates an economic value for the long-term secure containment of the stored CO_2, in effect, creating a dual revenue stream for a project: revenue from hydrocarbon sales plus revenue from CO_2 emission reduction or avoidance incentives.

In these circumstances, the operator can explore various operational changes to maximize the total economic recovery of the project. While some operational changes can alter spatial distribution and spread of the injected CO_2, others cannot. Increasing the amount of CO_2 that is stored can also affect operating pressures, particularly in the subsurface. These, and related changes, can affect the area of review (AOR) for assessing potential leakage pathways and other aspects of the containment assurance. In addition, legal, regulatory, contractual or mineral property leases or permits can need revising as well. Clauses 6, 7 and 8 examine various potential operational modifications that can be pursued to achieve higher levels of CO_2 storage while Clause 10 addresses related legal, regulatory and property management issues.

6 CO_2 operational scenarios addressed

Operations and facility prerequisites for each field operation, whether oil and gas recovery or CO_2 storage are site specific, depending upon the circumstances for that project. Operations are designed, conducted and modified in accordance with multiple factors, including, for example, geology, infrastructure availability, input costs and availability, projected market prices and costs over time, potential changes in government regulation and public perceptions, and a host of other factors. Accordingly, the operational scenarios discussed in this document are intended to illustrate the range of scenarios that can be considered by different operators; they are not real-world projects.

Transitioning from hydrocarbon recovery to storage can necessitate additional or upgraded infrastructure, depending upon the nature of the project and the regulatory regime in which the project resides.

There are three broad categories of operational changes discussed, together with potential variations. The categories define the facility considerations and operational considerations for the project. The three broad categories (see Figure 1) are:

— Scenario category 1: Maximizing or optimizing CO_2 storage quantities in an actively producing CO_2-EOR project. This set of operational changes consists of actions aimed at increasing the amount of CO_2 injected and stored in CO_2-EOR operation either by increasing the amount of pore space in a defined containment that is filled with CO_2 or by extending the previously defined containment either laterally or vertically. These project variations will generally have existing facilities that can be sufficient for the immediate needs of CO_2 storage, but over time can necessitate upgrades for injection system operating pressures, recycle rates and field distribution and gathering. These projects can be termed "CO_2 maximization/optimization" projects.

— Scenario category 2: Projects that do not envision continued hydrocarbon recovery, meaning that no additional production facilities be required. However, if additional saline water production is necessary to provide accommodating pore space for CO_2 storage, some production facilities can be necessary. In addition, the prerequisites for CO_2 injection can necessitate additional injection pressure capability and possibly rate capacity as well. These variations are sometimes referred to as "top off the tank" operations where CO_2 injections continue after hydrocarbon production is terminated.

— Scenario category 3: Projects that are hydrocarbon-recovery related projects that have not previously undergone CO_2 flooding. These projects have hydrocarbon production related facilities, but no existing CO_2 injection capability at all. Such projects need CO_2 injection and compression facilities. In addition, the continued production capability can need adapting to capture CO_2 extracted from the hydrocarbon production stream as well as the capability for handling increased CO_2 concentrations. Field injection infrastructure are needed and upgrades to gathering infrastructure is likely to be necessary.

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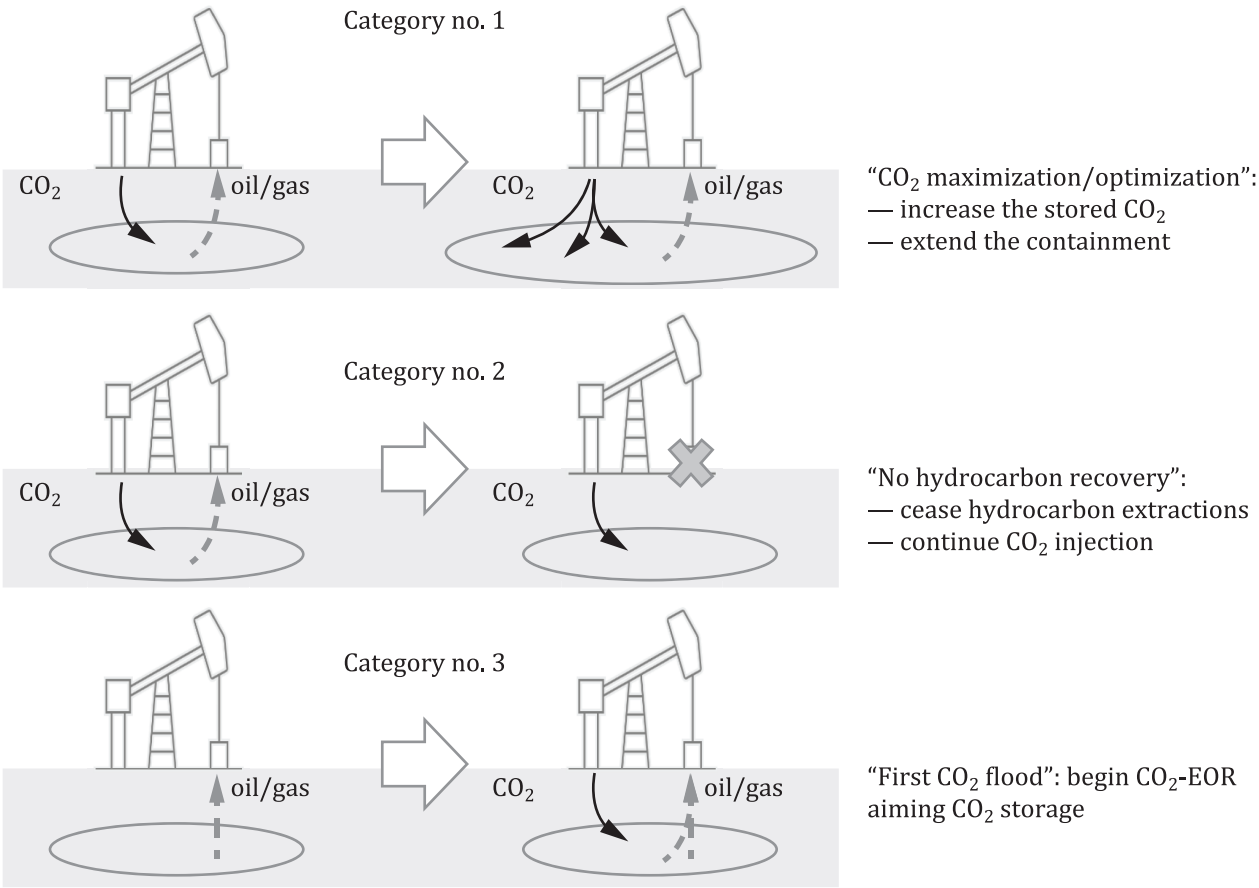

Figure 1 — Operational scenario categories

Although an operator can pursue these operational strategies at any stage, the most likely cases for their implementation are projects in the mature stage of hydrocarbon operations when operators will be looking to either abandon their operations or extend the economic life of the asset. The economic life can be extended through continued or new enhanced recovery processes or in combination with storage incentives, if applicable. However, extending operations in this manner can present questions as to the use of the original equipment. Wellbores and surface facilities that are no longer new can be reviewed vis-à-vis their remaining operating life. Certain equipment will have been maintained but other equipment can be nearing the end of its useful life. Operators will forecast end-of-life relative to expenditure outlays many years in advance and plan and conduct maintenance operations accordingly. Maintenance can well be reduced, allowing the mechanical integrity of wellbores and surface facilities to decline from optimum manufacturer-specified rates or pressures. Replacements or remediation costs most likely will need to be figured for the go-forward storage option.

7 Technical and operational aspects of transition

7.1 General considerations

7.1.1 Storage volume assessment and estimation of pore volume

One of the key parameters for determining the maximum amount of CO_2 that can be stored in a defined formation is the pore volume available for CO_2 storage within that interval. That pore volume is a function of area, thickness and porosity of the formation. Hence, to calculate the pore volume (V_{pi}) within the CO_2-EOR's producing intervals (i) of the petroleum reservoir, some form of the following volumetric formula is needed:

$$V = A \times h \times \varphi$$

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where

V is the pore volume;

A is the area;

h is the thickness;

φ is the average porosity of the producing intervals.

The inputs for these estimates will come from well and petrophysical data. The locations of the production and injection wells can be used to define the A_i. The thickness from which fluid flows into or out from wells can be calculated by identifying original depth of oil-water contact, as defined by well log measurements, minus the depth to the top of the reservoir. These thickness values calculated for all of the production and injection wells within the CO_2 project area can then be used to estimate the h_i. Porosity values derived from well log estimates or physical measurements can be used to estimate the average φ_i across the h_i of each well.

To estimate the pore volume of an entire geological trap that contains the producing intervals, the volumetric formula can be used with different input values. The area and the thickness of the trap can be defined by locating the spill point of the reservoir, which is defined as the structurally lowest part of a reservoir that can contain buoyant fluids within the trap. As CO_2 is generally less dense than other in situ formation fluids (except CH_4 or light hydrocarbons), it is buoyant relative to those fluids and therefore tends to move upwards in the subsurface. Once the cumulative CO_2 injected "fills" the trap, any additional CO_2 injected into the trap can then "spill" outside of the trap and buoyantly move upwards into the adjacent strata. The spill point can be identified using seismic data if available, or cross-sections based on well log interpretations, or structural maps of the reservoir. The trap as defined by the spill point gives a maximum CO_2 column thickness, and a maximum area of the trap. The bulk volume ($A_i \times h_i$) can be estimated from the spill point, typically using stratigraphic software. If the spill points are not known, the area defined by the location of active and previously active production wells can serve as a proxy for A_i, but the potential CO_2 column thickness will need to be estimated. The well logs, core and well-based measurements used in the volumetric formula, can also be used to calculate the φ_i and the maximum CO_2 column thickness for the h_i within the defined area of the trap.

Due to the density difference between CO_2 and other in situ fluids, the CO_2 column thickness used in the volumetric method is subject to limitations. If CO_2 immediately underlies the seal to the trap, the pressure of the CO_2 can be excessive, depending on the thickness of the vertically continuous CO_2 column. As the CO_2 column thickness increases, there is a corresponding increase in the pressure at the top of the column and hence the vertically continuous CO_2 column must be compared to the thickness of the trap. The maximum CO_2 column thickness is determined by using the minimum of the seal's fracture pressure and capillary entrance pressure and the average CO_2 density in the column. If the calculated maximum CO_2 column is greater than the thickness of the trap, the entire trap can be used to store CO_2. If the calculated maximum CO_2 column is lesser than the thickness of the trap, the entire trap cannot be used to store CO_2, and the thickness used in the volumetric formula equals the maximum CO_2 column thickness.

7.1.2 Current fluid saturations, including CO_2, in the reservoir/storage zone at the time of transition

To facilitate the transition from CO_2-EOR to CO_2 storage, the distribution of fluids within the pore volume of the intervals defined by the CO_2-EOR well patterns at the time the transition begins is important in determining the predominant storage mechanisms and thereby quantify CO_2 storage for each mechanism. The challenge is to determine which of the remaining fluids will be displaced from the CO_2-EOR patterns to accommodate storage of the injected CO_2, and hence identify the storage mechanisms.

The possible fluids present are hydrocarbon gas, non-hydrocarbon gases such as nitrogen or H_2S, hydrocarbon liquid (oil), formation fluid or injected water (brine), and CO_2. If the CO_2-EOR project was a miscible flood, it is less likely that hydrocarbon gas is present. Furthermore, due to the vaporization/condensation process of CO_2-EOR, the oil will be enriched with CO_2, and the CO_2 will be enriched with hydrocarbons; therefore, there can be minimal native oil or pure CO_2 in the subsurface. The distribution of the fluids at the end of CO_2-EOR operations can be assumed using material balance calculations, which

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provides average estimates for the system and numerical flow modelling methods, which can provide more granular insight into the fluid distribution.

7.2 Mechanisms for additional storage

When evaluating the storage available within the volume of the intervals defined by the CO_2-EOR well patterns, using the operating practices at the time of the transition to storage, additional storage can be available via:

— an increase in CO_2 saturation within the CO_2-EOR patterns;

— an increase in storage pressure above CO_2-EOR operating pressure;

— an expansion of the storage area beyond the volume defined by the CO_2-EOR patterns or in different geological formations; or

— a change in operating practices to improve CO_2 sweep efficiency (e.g. change in pattern shape or size) or to optimize CO_2 storage (e.g. horizontal to vertical flooding).

To increase CO_2 saturation, hydrocarbon gas, hydrocarbon oil or water must be displaced or produced. The removal of water used during a water-alternating- gas (WAG) CO_2-EOR project, for example, can create significant additional CO_2 storage volume. Furthermore, displacement of hydrocarbons can be difficult to achieve, because a primary reason to transition from a CO_2-EOR to storage is that the CO_2-EOR project is producing high volumes of CO_2 relative to oil, which would be a consequence of high CO_2 saturation.

Depending on the operating pressure of the CO_2-EOR project, it is possible to increase storage pressure. However, if the CO_2 was injected near the regulated injection pressure, which is common with CO_2-EOR projects, then it is not possible to increase reservoir pressure. Nevertheless, the additional pressure within the same pore space would increase the density of CO_2 and therefore increase CO_2 storage.

Within the CO_2-EOR patterns, storage can be increased by increasing CO_2 sweep efficiency. This can be achieved by changing the injection well locations by increasing or decreasing the pattern size and thereby changing CO_2 flow paths from those developed from the previous injectors (during CO_2-EOR) to those during storage.

7.3 Assessing containment assurance in modified operations

The operator of a hydrocarbon recovery operation can use one or more operational changes to increase the quantity of CO_2 safely contained long-term in the EOR complex. Many of these changes can utilize elements of the existing physical infrastructure, the geological and geophysical data acquired from the prior operations, and general practical operational experience. Regardless of whether the particular action is viewed as coming within the scope of ISO 27916 or ISO 27914, the key operational concern will be on continuing to evaluate the containment assurance and, in particular, the impact that pressure changes can have on existing engineered systems and the EOR complex itself. As such operations are intensely site and project specific, the various scenarios discussed in this subclause are given for illustrative purposes only. Actual projects can resemble one or more of the scenarios discussed in this subclause or can follow different approaches or combinations of approaches over time or can apply different techniques for different sectors of an overall operation.

In each case, however, the containment assurance can be impacted by the proposed operational modification. In many instances, the key parameter will be potential changes in operational pressures, whether on the engineered systems (including surface facilities, wells and well components), the subsurface movement of the injected CO_2, or the geological formations themselves. Hence, the review and revision of the operational containment assurance and the EOR operations management plan as required by ISO 27916:2019, 6.1.3 would play an integral role in reviewing whether the proposed changes “have the potential to adversely affect containment”, considering the factors enumerated in ISO 27916:2019, 6.1.3 a) through g), i.e.: "a) unexpected changes in project performance that have potential to influence associated storage of CO_2; b) addition or abandonment of injection zones; c) change to the areal extent of the project reservoir; d) addition or abandonment of wells; e) anomalous change of injection-withdrawal ratio (IWR);

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f) development of reservoirs which are located above or below the project reservoir; or g) discovery of CO_2 beyond the boundary of the CO_2-EOR complex."

Within the context of this review of containment assurance, 7.4 to 7.7 explore a number of operational modifications that can be undertaken.

7.4 Reservoir management

7.4.1 General

A critical component of any successful and secure CO_2-EOR project is a reservoir management plan that coordinates the injection for CO_2 and production of fluids (water, oil and gas, including CO_2) to maintain reservoir pressure and balance, and to progress the flood front. In a transition from EOR to increasing CO_2 storage, the reservoir management strategy would transition on a continuum towards increased storage effectiveness and generally decreased fluid production.

7.4.2 New CO_2 volumes — Increase of supply

In a typical EOR operation, the CO_2 purchase volumes decrease over time as quantities of CO_2 recycled from the production stream increase. Eventually, the need for incremental CO_2 decreases to a minimal volume that allows for pressure maintenance or even to zero if water chase is used. To transition a field to an operation that increases CO_2 storage, the CO_2 purchase volumes likely will be increased and managed throughout the reservoir to replace remaining free water.

7.4.3 Management of displaced water

Although displacing and producing oil allows for some associated storage in an EOR project, most opportunities for increasing CO_2 storage space are through displacement of water in the formation. In a typical reservoir management plan, the patterns or areas of the flood are managed by allocating CO_2 injection to the most efficient patterns that produce the most oil. As patterns become less efficient and oil production declines, the injectors in those patterns generally spend more time on water injection and less on CO_2. The patterns maintain pressure and continue producing, but eventually water out.

In a transition scenario, the oil production efficiency of a pattern would not play nearly as large of a role on CO_2 injection distribution as in a typical EOR project. Additional purchase CO_2 would be distributed to all patterns, effectively drying them up and filling some portion of the space from which the water is produced or displaced. This would allow the final state of the project to include mainly CO_2 in the pore space.

To dry up the system, an additional zone must be located, if disposal wells do not already exist, to inject the produced water to make room for the CO_2. This need for disposal capacity would be the highest initially as the wells are dewatering and would decrease with time as the CO_2 gets closer to production wells and decreases their produced water cut.

The reservoir management strategy for a transition project likely will include the reduction of recycled CO_2 where possible. This would include shutting in higher gas/oil ratio (GOR) wells while still balancing the overall injection/withdrawal ratio. Effectively this would mean tapering down the flood as the CO_2 gets to and dominates the production wells until eventually the project ceases and the CO_2 is safely and securely stored within the EOR complex.

7.4.4 Redesign of patterns

Pattern development for an EOR operation is designed to maximize the value of the flood given defined operating and capital costs as well as oil price. This optimization will generally lead to patterns that minimize capital spending while accelerating oil response as quickly as possible to offset large initial capital costs. This pattern development would not be the same optimization in a transition to storage where additional revenue streams other than oil sales are available.

As with the base design in any EOR flood, pattern redevelopment would involve updates to reservoir characterization including geological and simulation modelling. An updated history match of the flood

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performance would be critical to understanding where the current CO_2 is stored and predict what opportunities there are to increase the storage efficiency of the project. All these mechanisms would be modelled together and then, alternate pattern designs can be investigated and economics can be calculated to drive to the ultimate pattern reconfiguration. At a high level, the pattern reconfiguration is likely to involve an increase in well spacing that allows for a greater retention time of CO_2 injection between the injection well and the producers.

A critical component of any reservoir management plan, whether in EOR or through the transition, is to maintain reservoir pressure at the target levels. Elevating the pressure would cause a decrease in injectivity, distribution of gas beyond the pattern boundaries and decreased storage efficiency, all of which run counter to maximizing the efficiency of the project. In most cases, reservoir pressure balance is monitored and maintained through balancing the IWR at a pattern, area and full field level.

7.5 Well operations

7.5.1 General

As the presence of existing wellbores, transitioning existing hydrocarbon fields, particularly CO_2-EOR fields, provides an opportunity to access a high-quality reservoir for use as CO_2 storage. However, the existing wellbores can also be a risk for containment assurance due to the potentially large number of well penetrations and vintage completions of those wellbores. Clause 7 will explore the issues involved to allow the successful transition from CO_2-EOR to storage.

7.5.2 Creating a well inventory

Regardless of the age of the existing hydrocarbon field there can be wells that are no longer active and have been previously plugged and abandoned or are penetrations to deeper producing horizons. Creating a thorough well inventory is the first step to containment assurance and is one that has likely been done in preparation for CO_2-EOR. Depending upon the storage approach and the wellbores required, it can be necessary to deactivate or secure many wells. Other wellbores can be useful for their location, but their condition can be unknown. With a complete well inventory, a systematic review of the wellbores in comparison to the future needs, can be conducted. Potential future use of wells for injection, monitoring or production can be identified for further evaluation and integrity testing based on the known condition. Screening of wellbores for casing size, landing depth and known integrity issues can provide planners the ability to design the injection scheme and conduct additional reservoir performance modelling. Other factors such as surface casing setting depth and top of cement can provide insight to other storage considerations such as groundwater protection.

7.5.3 Repurposing wellbores for storage injection

Existing CO_2 injection wellbores can provide continued use as injectors for CO_2 storage. Operators and regulatory authorities can require additional assurance of integrity prior to commencement of conversion from injection for CO_2-EOR to CO_2 storage operations. While the type of well permitting required, if applicable, will vary by jurisdiction, the basic engineering and well construction issues involved are likely to be similar regardless of how a particular well permitting regime addresses them.

For example, in the United States, CO_2 injection wells used in EOR operations are permitted as Class II injection wells, while CO_2 injection wells for storage are normally permitted as Class VI wells [although continued permitting under Class II is possible where there is no increased risk to underground sources of drinking water (USDWs)]. Both well permitting processes serve to protect the USDWs and to ensure that there are no conduits for CO_2 to adversely impact usable drinking water.

When transitioning an EOR field to a non-EOR, dedicated CO_2 storage operation, several technical considerations will be reviewed to determine whether the wells can qualify for conversion to Class VI injectors. These considerations will be site-specific and weighed under the prevailing rules for the jurisdiction, as appropriate, including for example:

— Is the AOR sufficient for the updated development and reservoir management plan?

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— Does changing the source of CO_2 from natural to anthropogenic impact the well permit or operations?

— Does the well construction provide sufficient protection to the USDW considering proposed changes to the reservoir management plan?

— Will there be adjustments to the operational monitoring plan to ensure containment?

— Is there a post-injection monitoring plan in place?

— How do the changes to the reservoir management plan impact field abandonment plans?

7.6 Application of operational modifications — Illustrative analysis

7.6.1 Containment assurance assessment in base case — Typical EOR

ISO 27916:2019, 3.9 defines the term "containment assurance" as a demonstration that the features and geological structure of a CO_2-EOR project are adequate to provide safe, long-term containment of injected CO_2 and that the CO_2 flood is operated in a way to assure containment of the CO_2 in the EOR complex. ISO 27916:2019, 6.1.3 specifies that the containment assurance and the EOR operation management plan "shall be revised as necessary if changes occur that have the potential to adversely affect containment." ISO 27916:2019, 6.1.3 a) through g) provides a non-exclusive enumeration of some of the changes that can lead to such revisions. Hence, containment assurance is an active process applied by the operator to create a project that provides safe, long-term containment of the injected CO_2.

During typical EOR, the CO_2 plume is managed by fluid injection and fluid withdrawal by wells that are systematically arranged in patterns to achieve control. (See ISO 27916:2019, Clauses A.3 and A.13). The control of injected fluids is motivated by hydrocarbon production. The main factor that limits the production rate is the need to maintain pressure that creates miscibility with CO_2 in the hydrocarbon phase while avoiding viscous fingering or channelling of the CO_2 in direct paths from injection to production wells. This can be complicated by reservoir heterogeneity where preferential flow paths can be established via high permeability streaks within the formation.

To maintain the pressure sufficient to maintain miscibility, while maximizing the extraction of hydrocarbon, the operator will "balance" the flood project by assuring the sum of all injection (I) equates to the sum of all withdrawals (W) at reservoir conditions. This leads to an IWR of 1, which is to say a balanced system. The result of maintaining a balance between injections and withdrawal (i.e. where IWR = 1) is that both the magnitude and the area of elevated pressure reaches a quasi-equilibrium, and the project impact is aerially limited. This means that the appropriate AOR closely overlies the project area.

The impact of the pattern of injection and withdrawal wells is that hydrocarbons and CO_2 are drawn to production wells. Although cases of CO_2 by-passing the nearest production well are known, the pressure sink provided by production is reasonably effective at controlling the CO_2 migration. In a risk management context, the effect of the pattern flood is therefore to limit the area of the CO_2 flood. If the injection and withdrawal patterns are well designed and the reservoir properties cooperative, the area occupied by CO_2 is effectively limited to the project area.

In addition, EOR conducted in a hydrocarbon trap also has an important impact on CO_2 migration risk reduction. The lateral migration of CO_2 down-dip from injectors can be calculated from a review of a balance of viscous forces and gravitational forces.[2] Far from the injection well (100 m to 1 000 m), the drop off in viscous forces will cause gravitational forces to dominate and CO_2 downdip migration will reach a geographic limit.

Additional CO_2 and pressure management strategies have been used in EOR operations to manage the pressure distribution and extent and thickness of the CO_2 plumes. In many projects, CO_2 injection is augmented by water injection. This can take the form of alternating water injections with CO_2 gas injections, a technique known as WAG in the same injection wells to reduce preferential flow in high permeability thief zones or dedicated water injection wells that form curtains that limit CO_2 migration, for example into areas of the field that are not in part of the CO_2-EOR project. These strategies add control and reduce risks of unexpected CO_2 migration. Other combinations of strategies to optimize the CO_2-oil contact are available, including for example strategic perforations or additives to control relative permeability with additives of CO_2.

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Another type of control is production management. Production is an essential part of pressure balancing the system. The ratio of hydrocarbon, CO_2, and water components in the production stream can vary considerably since it is not the composition of the production stream but the overall quantity of production withdrawal that is used to balance the pressure of CO_2 injections. One main limit on the amount of production is CO_2 breakthrough. When a production well produces more CO_2 or water than the operator wants to handle, the operator can choose to stop or reduce production in addition to changing injection strategies.

7.6.2 Assessing containment assurance in modified operations

7.6.2.1 General

If the operator seeks to increase the quantity of CO_2 stored in the reservoir, the operator can choose a different management strategy. It is important to assess if such modifications affect the assurance of secure long-term containment.

7.6.2.2 No change to operations (base case)

In some cases, the operator can continue to inject CO_2, recycle and produce decreasing hydrocarbons without changing the operational strategy. In this case, the risk profile of the project would not change and the same process can be used to ensure containment.

7.6.2.3 Changes in injection strategy

There are a number of changes that can be made to the injection strategy that can impact the project, including:

a) Substituting the CO_2 for water injection in a WAG (case 1A): This likely will cause minimal change in the risk profile but benefits the overall storage efficiency of CO_2. However, after a short time, it will likely result in faster CO_2 cycling and perhaps decreasing CO_2 storage amounts over time as the benefits of WAG injection will be lost. The storage assurance assessment will therefore be similar to the “no change” case.

b) Increasing fluid extraction to offset injection (case 1B): If the CO_2 injection rate is increased such that the overall injection volumes increase, fluid production will need to rise to maintain an IWR of 1. This additional fluid handling will have a cost. In some cases, well locations and completions can be changed to preferentially extract water, which would then be disposed of in a different zone.

7.6.3 Project IWR exceeds 1 (case 2)

7.6.3.1 General

This case arises when more CO_2 is added and is not completely offset by production volumes. Either the magnitude of pressure or the area of elevated pressure will therefore increase, thereby increasing the risk of the project. Issues such as exceeding the regulatory pressure limits, induced seismicity or hydraulically fracturing the reservoir or seal can arise. Wells at the periphery of the project will likely continue longer than wells in central patterns.

7.6.3.2 Project start is strongly pressure depleted (case 2A)

If a reservoir is strongly pressure depleted prior to start of the conversion operations, the “pressure space” available before the maximum safe operating pressure can be large. Hence, injection volumes can be much larger than production volumes as the reservoir system builds pressure. In some cases, production can become negligible as the operator “shuts-in” production wells to build reservoir pressure more quickly and allow for miscible operations. However, such an approach can prompt a desire for re-evaluating any geomechanical risk associated with this depleted to overpressure condition (e.g. on wells, thermal effects or induced seismicity).

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7.6.3.3 Storage assurance assessment of CO_2 migration outside of the previously qualified EOR complex (case 2B)

Once the IWR exceeds 1, the risk of CO_2 migration outside of the CO_2-EOR project increases. The risks associated with this fugitive movement are dependent on the makeup of the neighbouring wellfield. Wells outside of the project can belong to another operator and not be prepared to receive CO_2 service. Thus, the risks for loss of containment due to zonal isolation, including corrosion-induced failures, can increase. Anomalous increases in oil and water production outside of the project can be indicative of a loss of areal integrity.

Movement outside the project also provides CO_2 access to geology that can contain transmissive features. These can be a vertical or horizonal transmissive section of a fault or fracture system that defined the original hydrocarbon-water contact. Additionally, this lateral movement can move CO_2 beyond the structural trap's spill point, resulting in a loss of containment.

7.6.3.4 Risks of pressure increase beyond the original project area (case 2C)

If IWR exceeds 1, the additional injection quantities will result in a pressure increase. This can become a problem if it encounters pathways that allow formation fluid to be lifted into a USDW or to the surface. In this instance, there can be an impact to water quality, which can necessitate remediation. In addition, this elevated pressure can cause unacceptable geomechanical impacts, such as induced seismicity, reactivation of faults or changes in land surface elevation.

7.6.4 Change in storage assurance assessment related to long term stabilization change during transition (case 3)

During EOR, active control of CO_2 is an important aspect of maximizing hydrocarbon recovery. As the reservoir management plan changes, the value lies in assuring storage. In most cases, after EOR conversion, containment assurance is high because there is a proven trap and the solubility of CO_2 into oil increases trapping. However, the long-term containment assurance of storage can be assessed to identify outlying cases, where long term migration of CO_2 cannot be ensured. For example, if the project does not include the crest of the structure or has incomplete coverage of the crests of the structure, understanding the long-term movement of the CO_2 and its ultimate position will become important. In addition, some hydrocarbon fields are dynamically charged, leaking hydrocarbons and possibly increasing the rate of CO_2 leakage as well.

7.7 Wells

7.7.1 Re-use

During the transition process, the existing well field must be evaluated to ensure the wells are suitable for further use. While wellhead equipment and tubing/packers can be changed, if necessary, reconfiguring the wells for more rigorous use can be more challenging.

The first step is to evaluate each well and its completion. The metallurgy employed in the casing strings and the quality, composition and coverage of the cement sheaths are evaluated to ensure:

— a lack of micro-annuli that can encourage fugitive CO_2 movement,

— the coverage of cement meets regulatory guidelines (e.g. some jurisdictions require cementing back to surface) and provides adequate coverage to provide storage complex integrity,

— the installed casing is compatible with the injectant, and

— the installed casing is free of pitting, wall thinning or other defects that can necessitate remediation.

In addition, the well service history can be reviewed as the past history of intervention can be predictive of possible future issues with the well. Also, it can be necessary to run new wireline logs (i.e. casing integrity or cement bond logs) and pressure testing to provide a current snapshot of the well's condition and integrity.

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In most cases, if intervention is necessary to place additional cement to ensure a well is suitable for further use, this can be accomplished through cement squeeze operations. This is a process whereby the casing is perforated, and cement is "squeezed" through the perforations until the desired coverage is obtained. A casing pressure test then follows to ensure integrity has been re-established.

In some cases, existing wells are not suitable for operational use (e.g. injection or production). If completion is appropriate within the jurisdiction, these wells can be converted to deep monitoring wells for pressure, fluid sampling or time-lapse logging.

7.7.2 Abandonment

If the well is in such a state that it is no longer useful to the project due to integrity concerns, the well is plugged and abandoned commensurate with the field development plan. This process can include the following steps:

— removal of all non-permanent tubulars and downhole equipment,

— squeeze cementing the perforations,

— placing cement across the perforations and over the confining unit,

— cement plugs at key positions throughout the wellbore, including above the primary confining unit, at casing shoe locations, above any notable hydrocarbon producing zones (if applicable), just below any underground sources of drinking water, and at surface,

— cutting off the casing and welding a plate cap with the well details inscribed.

This process is designed to meet or exceed the minimum requirements of the regulatory authority and can require advanced approval of field abandonment executions by the jurisdiction.

7.8 Facility operations

7.8.1 Design assessment

Facilities designs for CO_2 storage projects are approached in the same manner as any oil and gas production project, with a needs assessment based upon the reservoir and production (injection) circumstances. Facility design will be dependent upon operating pressures, fluid compositions, rate projections and fluid dynamics. Therefore, a project assessment is necessary to identify the gaps between the existing facility components and design to those needed for the storage project. This gap assessment also needs to consider the remaining lifespan of the existing facilities within the context of an extended storage project to identify those modifications that would reasonably be expected in the future.

7.8.2 Facility integrity testing

The existing infrastructure for the current project can be assessed to identify whether it meets the requisites for the CO_2 storage project. Based upon the design assessment for the project, the existing infrastructure can be complementary and useful, need upgrades or need to be replaced entirely. Inspection of original design and as-built documents (design basis memoranda, process flow diagrams, regulatory applications, etc.), if available, will be a useful first step as not only will the capacities and design considerations be stated but will inform potential design change or upgrades as well.

A second step can include a review of recent inspection documents like pipeline smart pig log data and interpretations, corrosion tests, and vessel internal inspections. These inspections can be done at periodic facility turnarounds where vessels are depressured, drained and internally inspected to identify corrosion or defects in internal coatings.

Lastly, if there are areas of specific interest or concern, further inspections can be designed and carried out to assess the viability of the infrastructure for ongoing storage operations. Conducting these inspections prior to finalization of design basis documents would allow any necessary upgrades or replacements to be

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included in the cost estimate for the storage project instead of revising documents and cost estimates during the construction phase.

7.8.3 Measurement

For existing oil and gas production projects, lease custody transfer metering is the most rigorously maintained and calibrated method as it is the basis on which the operator is compensated for sales (i.e. oil and gas sales) or expensed for supply (i.e. CO_2 purchases). Field measurement at a well level is more often done for regulatory and reservoir management purposes and can be less frequently maintained. In the situation where CO_2 storage becomes a part of the project, additional scrutiny will be necessary for the recycle stream volume and mass estimates and compositions. In CO_2 storage projects, the compositional data becomes important for both reservoir management and storage quantification purposes, making meter calibration and accuracy particularly important. This can necessitate upgraded field measurement facilities on both the injection and production streams. At a field level, if a second CO_2 source is delivered to the project, then additional lease custody transfer meters will be necessary.

The ultimate goals for measurement is financial (CO_2 supply, oil and gas sales, water disposal), regulatory (quantification of storage, facility permits and well reporting) and reservoir management. Each of those goals will prompt their own individual and overlapping design and operational requisites.

7.8.4 Projects that are not currently CO_2-EOR projects

Oil and gas fields with no prior CO_2 will need new CO_2 injection facilities. This will primarily be those fields that have previously produced oil or gas but where no hydrocarbons are expected to be produced (unless as part of a dewatering scheme necessary for pore space voidage) or where ongoing hydrocarbon production continues concurrently with CO_2 storage injection (see case study no. 3).

For those fields where water removal is requisite, the facility infrastructure can make use of hydrocarbon production pipelines and facilities, although upgrades will be necessary for corrosion control when CO_2 breakthrough occurs. It can be reasonably assumed that if water production is conducted during CO_2 injection operations, CO_2 breakthrough will occur. The operator can simply mitigate breakthrough and the impact on facilities by shutting in those wells when CO_2 breakthrough occurs.

Methane and other components dissolved in produced water can also necessitate management. If the project is a gas field, the existing inlet separation will likely be for higher operating pressures and liquids handling capacity, which can become the concern. On the injection side, the CO_2 injection infrastructure will need to be installed, much in the same manner as for a new CO_2-EOR system, except for CO_2 recycle compression. If CO_2 breakthrough is expected as part of the reservoir management plan, then some small CO_2 compression will be necessary to conserve and re-inject the produced CO_2.

For those fields where future production is not necessary for reservoir management and therefore no production capability is necessary, minimal additional infrastructure will be needed; only those injection distribution pipelines, injection well metering satellites/manifolds and injection well flowlines will be needed.

7.8.5 Recycle compression capacity

For storage projects that would be extensions of existing CO_2-EOR projects one of the significant benefits is the pre-existence of recycle compression. If the current CO_2-EOR utilizes a WAG recovery approach, the existing infrastructure will be undersized if the WAG cycles become drier (less water injected and more CO_2 per cycle) or if the recovery process changes to continuous CO_2 injection. Additional trains of CO_2 compression can be installed, but a site and design reassessment will be necessary to ensure the necessary plant site footprint can accommodate the additional equipment. Furthermore, if electrically driven, electrical power supply through wired connections and substations will be needed as compression power demand will be significant. If powered by natural gas, then alternatively an adequate fuel supply will be needed for the increased compression demand.

Furthermore, inlet separation and cooling facilities are also associated with additional recycle compression. WAG operations use larger free water knockout vessels for inlet separation and often have lower pressure ratings. If the CO_2 storage approach is targeting increased CO_2 pore saturation in the reservoir, then over time, the produced fluid stream will consist less of water and more of CO_2. The pressure of the inlet stream to

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