Deliverable D2.1

Current state-of-the-art assessments and technical approach for assessment of well re-use potential and CO_2/brine leakage risk

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Executive summary

Re-use of existing wells for large-scale CO_2 storage could be beneficial with regard to both economical and safety considerations. The economic aspect comes from the cost of drilling new wells, especially offshore. The safety aspect comes from the objective of having as few as possible wells penetrating a caprock. A CO_2 storage well needs to maintain the well integrity to ensure that CO_2 is permanently contained in the storage reservoir. Although the technical know-how is there, no dedicated tool is available to perform a systematic assessment of the re-use of existing wells.

The goal of the REX-CO_2 project is to develop procedures and a publicly available screening tool for the assessment of re-using existing wells for storage of CO_2. This report, "D2.1 Current state-of-the-art assessments and technical approach for assessment of well re-use potential and CO_2/brine leakage risk" gives an overview of the relevant risk assessment approaches, standards and guidelines currently used for managing well integrity in the petroleum sector. The report also reviews some of the previous cases of assessments made on re-use of existing wells for large scale CO_2 storage, with a focus on identifying the work flow and lessons learned.

Even though none of the existing standards explicitly mention gas storage wells or CO_2 storage wells for the purpose of CCS, they are still relevant because they address wellbore integrity irrespective of the type of fluid that needs to be contained in subsurface reservoirs. The standards have also been successfully used by the petroleum industry on CO_2-EOR projects. The existing procedures take into consideration critically important aspects, including expected temperatures and pressures, reservoir characteristics, well design and so on. The standards can be potentially updated in the future to include considerations relevant to CCS. For example, accounting for parameters such as expected injection volumes, pressure ranges, temperature ranges, the chemical composition and properties of the injected fluids.

Our review of the previous assessments of re-use of wells for commercial scale CO_2 storage operations showed that it is important to *have a standardized workflow*. Many older and exploration wells will have large degrees of uncertainty due to little or insufficient relevant data. The *scarcity of data* could make predictions of the well state difficult and inaccurate, and thus unnecessary costly and unsafe.

Other issues that were considered included whether the original well design would be amenable for reworking to convert the well as a CO_2 storage well, whether the condition of the well barrier elements after years of petroleum extraction may be significantly deteriorated, and whether there might be uncertainties on the state or accessibility of the side-tracks in the well. A re-use procedure including systematic mapping, with a dedicated a tool, of all parameters affecting well integrity would aid the engineering work and give more accurate estimations on field viability and cost.

Another important finding from the review of large-scale assessments of re-use was on how the various groups assessed the suitability of Portland Cement in a CO_2 storage well environment. The review of the Kingsnorth CCS project highlighted the need for a CO_2-resistant cement, and in particular the development and testing of non-Portland cement systems. In contrast, the review of the Peterhead CCS project concluded that the Portland cement systems used were suitable for the use as CO_2 injector wells.

The contrast in the conclusions highlight the need for more systematic research at relevant conditions on the actual suitability of Portland Cement systems in such environments. Such work on cement is already planned in the REX-CO_2 project.

Contents

List of Tables

List of Figures

1. Introduction

The re-use of existing oil and gas wells for storage of CO_2 requires a detailed assessment of the history and current state of the well. Lack of satisfactory initial well integrity can make the well unusable or require extensive workovers which can be costly. As shown in surveys published on the subject, many older wells are prone to leakage (Watson and Bachu, 2009). The leakage rates of hydrocarbons (primarily gases) from these older wells are typically low due to the depleted state of the petroleum reservoirs and the leakage risks have been managed either through monitoring or periodic venting (Watson and Bachu, 2009). However, the expected requirements for accepted levels of leakage for a well to be re-used for CO_2 storage are significantly stringent (Duguid et al., 2018). The general public, the regulatory entities and the stakeholders will have a very little to no tolerance for leakage resulting in higher cost of operation or threat of shutdown. The United States Environmental Protection Agency (US-EPA) Class-VI well regulation requires CO_2 storage well construction and operation done in a manner to ensure no endangerment of drinking water due to fluid migration from storage reservoir (Environmental Protection Agency, 2018) which in effect suggests zero acceptable leakage rate of CO_2 and in-situ fluids from storage reservoir to groundwater aquifer.

1.1. Objective and scope

The objective of this deliverable is to provide an overview of the state-of-the-art quantification of well re-use and leakage risks. The report mainly focusses on current standards, guidelines and previously performed well re-use field assessments Together with the deliverable "D2.2: Summary report of well assessment tool framework" (Pawar et al., 2020), the report will give input to the development of the tool, which can be used to perform more systematic assessments of the re-use of wells. The contents of this deliverable have been divided into different sections. Section 1 provides an introduction to well integrity concepts and approaches for leakage risk assessment relevant for the re-use of wells. The second section provides the review of standards and guidelines, the most relevant being the ISO standard 16530, the NORSOK D-010 standard and Oil and Gas UK Well integrity guidelines. The third section reviews the relevant large-scale engineering assessment of re-use of wells for CO_2 storage that have previously been performed. These include the Kingsnorth CCS project, the Peterhead Goldeneye project and finally the PORTHOS project in the Netherlands aiming at CO_2 storage in the TAQA operated P18 field. The fourth section briefly describes the issues related data availability and quality. Depending on the history of the well and regulatory requirements for management of historic data of a specific well, the future users of the assessment tool might not have access to data needed to do a detailed assessment. It is the goal of the project to develop a flexible tool where the user can perform different levels of assessment based on the quantity and quality of available data.

The report could have included a section on the review laboratory tests. There are many relevant publications on laboratory studies of well barrier elements behavior under CO_2 storage conditions (e.g. see Carroll et al, 2016). However, the scope of this document has been limited to review risk assessment approaches, standards, guidelines and larger field studies relevant for re-using wells for CO_2 storage.

1.2. Well integrity of CO_2 storage wells

A well to be used for Carbon Capture and Storage (CCS) will be assessed on many parameters, though it is likely that the following three will be of primary concern:

- The lifetime of the operation
- The chemical conditions with injection of large quantities of CO_2

- The fact that wells will have been designed for production, and therefore depleted reservoir pressures as opposed to over-pressured conditions

The lifetime issue for a CCS well comes from the fact that any stated demand, whether it be regulatory or other, will expect the well to provide sufficient well integrity over a long time. The Environmental Protection Agency (EPA) of the United States mention that the timescale for the operation of CO_2 storage is in the order of thousands of years (Environmental Protection Agency, 2007). An operational well (either for petroleum extraction or CO_2 injection) will have the infrastructure necessary to mitigate any detected loss of well integrity while the field is in operation. On the other hand, it may be relatively harder to mitigate loss of integrity of a well that is abandoned after the injection is stopped and field is abandoned, especially, for a CO_2 storage field.

CO_2 in the form of carbonic acid can chemically react with many commonly-used wellbore materials such as casing or cement (Yan et al., 2012; Ernens et al., 2018). Composition of Portland cement, for instance, can change when calcium hydroxide reacts with CO_2 to form calcium carbonate, a process known as carbonation. This step might not be detrimental, since the cement becomes less porous and permeable. The reactivity of this system could also be mitigated by injecting dry CO_2. The second step however, where calcium carbonate dissolves into a CO_2-rich brine (i.e. low pH water) may be detrimental to the cement. This step can lead to increasing porosity and permeability of the cement (Carroll et al., 2016; Kutchko et al., 2007; Zhang and Bachu, 2011). The observations above have been primarily based on laboratory experiments. On the other hand, Carey et al. (2007) have shown that Portland cement from an old well in the SACROC CO_2-EOR field maintained its integrity in-spite of evidence of reaction with CO_2. These contradictory points highlight the importance for more controlled tests at relevant and systematic conditions. Many of the laboratory experiments might be designed and performed at conditions that don’t reflect in-situ conditions and could indicate overly severe consequences. Depending on the original design and the choices of materials, many older wells might require significant workovers in order to ensure integrity as CO_2 storage wells. The industry has also developed CO_2-resistant cement compositions that can withstand CO_2-rich conditions.

Another important point is the large amount of masses involved in both petroleum extraction from a reservoir and CO_2 injection into a reservoir (Rentsch and Mes, 1988). For instance, the abandonment of a petroleum well accessing a depleted reservoir will require ensuring integrity of wellbore materials at depleted reservoir conditions. The performance specifications for wells (and well materials) in the field where large quantities of CO_2 is injected resulting into increased pressures will be significantly higher. This will be especially important during the operational phases during and immediately after the injection is stopped, before the CO_2 plume has migrated away from the wellbore (Ivandic et al., 2015; VoTranh et al., 2018). During these time periods the pressure will be higher in the near-wellbore region, potentially exerting more strain on the wellbore materials.

In the petroleum industry, the term "well" is divided into several subcategories such as exploration, storage, production, injection, suspended or temporarily abandoned and plugged & abandoned (P&A) wells. Thus, depending on the intended usage of the well, the requirements of different wells might not be comparable. For instance, the requirements for a P&A well in the NORSOK standard state that it should withstand flow for eternity. However, this requirement might not be necessary for a temporarily abandoned well where operations and infrastructure will be in place within months. This distinction is important to consider for each well to be re-used for the *permanent* storage of CO_2 underground. Is it intended to be:

- an injection well?
- a monitoring well?
- a water production well?

The different roles and associated requirements can lead to contradictory choices of design and selection of materials. The optimal material selected to withstand the conditions during the injection phase might be less optimal for the conditions during the (longer) storage phase. Similarly, the overall engineering work for a CO_2 storage well should be clear. It might consist of the following two phases:

- Injection
- Post-closure

The post-closure phase can include a potentially longer (i.e. many years) intermediate storage phase. During this phase, effects of the CO_2 on the reservoir and the near wellbore region could be carefully mapped before the well is chosen for permanent abandonment with lower levels of monitoring on the well integrity.

The US-EPA has adopted a specific class for permitting CO_2 storage into deep saline formations. Injection wells can be divided into six different classes depending on the fluids to be injected. The "simplest" case in this definition is Class I, valid for waste injection wells. Class II is valid for wells to be used for injecting CO_2 related to oil and gas production. Classes III to V are not valid for CO_2 storage wells. Class V is valid for non-hazardous fluids injection, geothermal power production and aquifer storage and production. The newest subgroup is Class VI, which was adopted for permitting CO_2 storage in deep saline formations.

Class VI are required to have a surface casing extending from surface to the bottom of the bottom-most drinking water aquifer and a long string casing extending from surface to the bottom of target injection zone. Both, casings are required to be cemented to the surface. Also, these wells require more detailed logging, modelling and planning compared to the other well classes. This includes detailed open hole and radial cement integrity logs, detailed reservoir modelling to establish the area of review, and multiple plans for operation and post injection. Class VI wells also require monitoring to ensure that the stored CO_2 behaves according to expectations. The regulation specifically states the objective of protecting underground drinking water from unintended fluid migration, however, it does not explicitly mention leakage to the surface (Duguid et al., 2018).

1.3. Description of Well Barrier Elements (WBE)

The different standards and guidelines share similar notations and schematics for showing the well architecture. For instance, the well barriers are divided into primary and secondary well barrier envelopes (WBE). The definition of a *primary well barrier* is the "*first set of well barrier elements that prevent flow from a source of inflow*" and is normally shown in blue colours in the well barrier schematics. A *secondary barrier* is defined as the "*second set of well barrier elements that prevent flow from a source of inflow*" and is normally shown in red in the well barrier schematics (ISO, 2017). The barriers should be explicitly explained. Figure 1 shows two sets of well schematics from the ISO 16530-10 standard: one is an example of a well during the operational phase and the other from the abandoned phase. Furthermore, a well barrier consists of several well barrier elements, such as cement plug, casing cement, a formation, the fluid column, downhole safety valves, casing/tubing and so on.

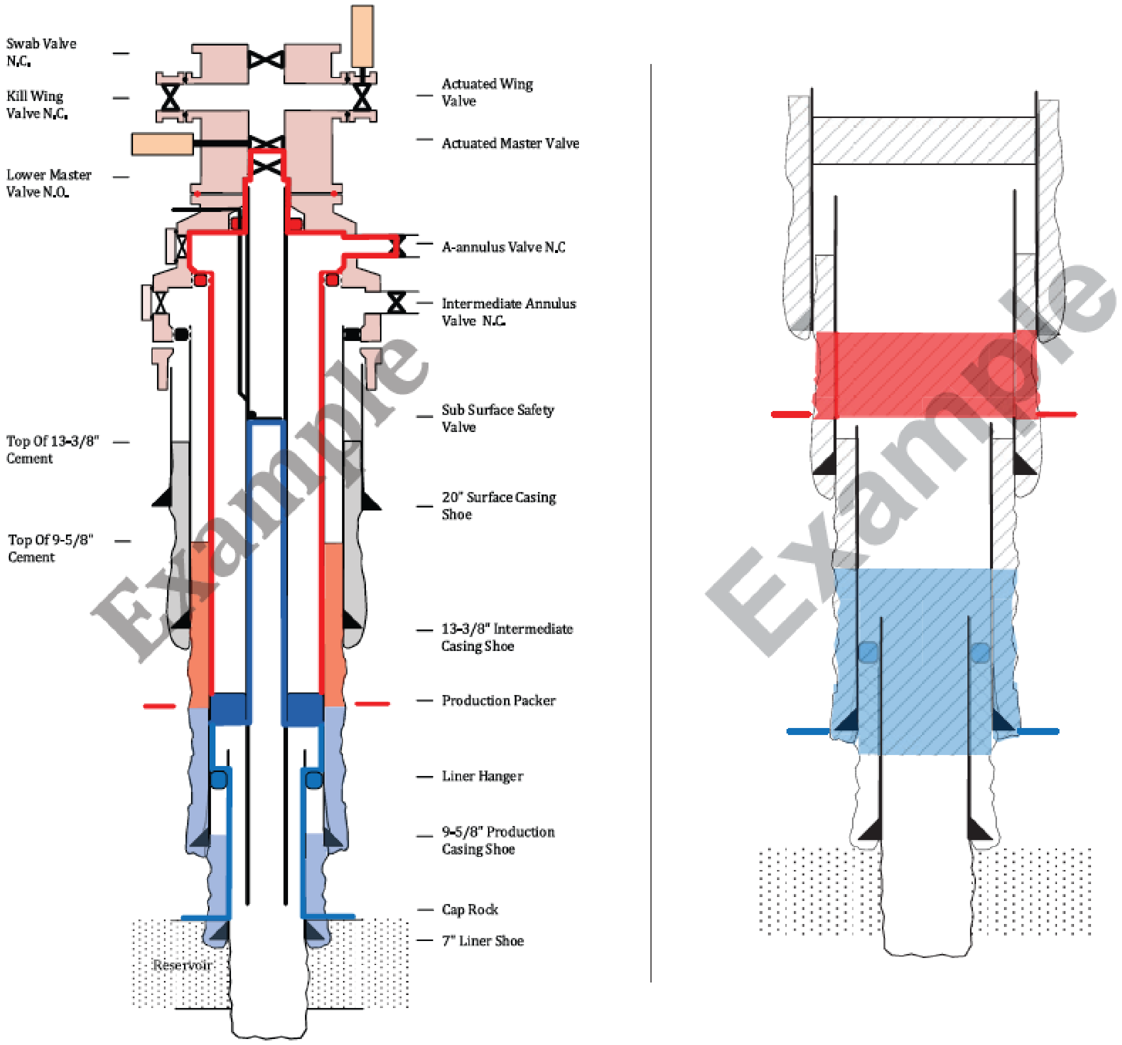

Figure 1. Example of well barrier schematics from the ISO 16530-1 standard (ISO, 2017). Left: a schematic of a wellbore during the operational phase. Right: a schematic of a wellbore after the abandonment phase.

1.4. Leakage risks

When or if a leakage occurs in a well, it is important to identify which well barrier elements have failed. Figure 2 shows an illustration of possible leak pathways in a well. The various well barrier elements can, under certain conditions, be prone to degradation. Steel for instance can *corrode* under certain conditions, and if a corroded steel casing is not attended, the ability of the casing to provide well integrity will diminish and the leakage risk will increase. The same mechanism and consequence apply for downhole safety valves and wellhead/X-mas tree. Cement and steel can also crack or burst if they are strained outside the intended operational boundaries. *Temperature and pressure cycling* could lead to fatigue in the materials and increase leakage risk for these materials. Another potential source of leakage risk is whether the well was drilled and completed properly. *Channels of drilling fluid or gas can be formed in the cement* during construction, and these could act as leak pathways during operation. The same applies to region in the wellbore with extensive washout, as it can be difficult to achieve a successful fluid displacement during the primary cementing operation. This could lead to risk of leakage along *microannuli* between the cement and the formation (Vrålstad et al, 2015).

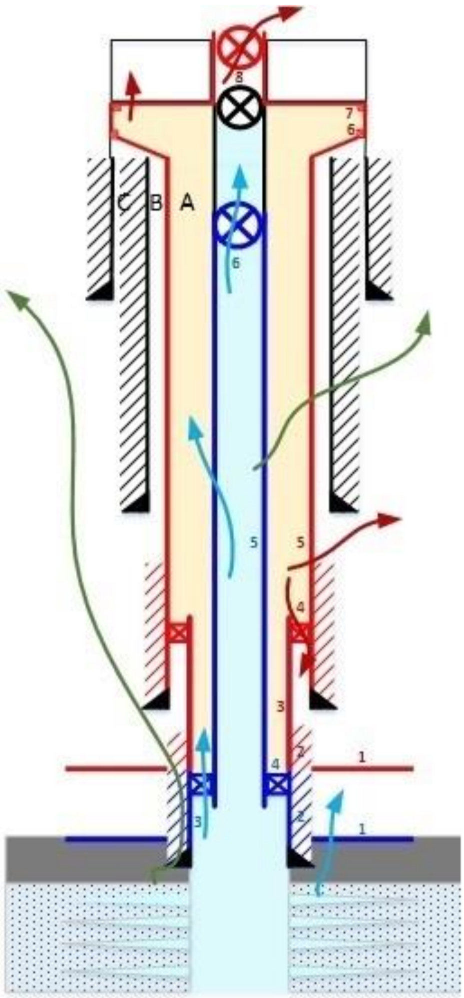

Figure 2. Illustration of possible leakage paths in a well (Vrålstad et al, 2015). The blue arrows indicate failure in the primary WBE, the red arrows indicate failure in the secondary WBE. The green arrow indicate failure of multiple WBEs.

1.4.1. Risk assessment approaches

The re-use of oil and gas facilities is increasingly addressed in the CCUS literature, often dealing with the suitability of depleted reservoirs and site selection for CO_2 injection. The most recent study on re-use of existing infrastructure for CCS is an IEAGHG technical report (IEAGHG, 2018), which summarizes a detailed investigation of five offshore fields on the UK Continental Shelf for their re-use potential. The sites were evaluated by considering aspects including the storage reservoir, existing infrastructure, commercial arrangements, development planning issues, and a site-suitability assessment. This assessment utilized site-specific data on the storage reservoir, pipelines, subsea assets, platform, and wells, and resulted in an infrastructure re-usability index for each case.

The IEAGHG work is interrelated with the ongoing Acorn project, funded through the ERA-ACT Program, which has developed a screening methodology for potential CO_2 injection sites comprised of an initial basis of design, site proximity to transportation pipelines, site screening criteria, ranking criteria and sensitivity analysis. A detailed assessment of well integrity or re-use potential was not an integral part of the analysis, but wells were evaluated based on availability of well data and a higher-level analysis of well data (ACT Acorn, 2018a). Initial screening was followed by a further detailed site selection process to adopt two potential site options for further study (ACT Acorn, 2018b).

Literature on assessment of re-use of wells is extremely limited, though some workflows and approaches for such assessments have been developed. The Acorn project reported qualitative assessment of well re-use by accounting for several key factors including, potential opportunity, general, commercial, technical and regulatory considerations, but limited to the UK (ACT Acorn, 2018c). Another study was performed for fields in Malaysia while focusing on well selection methodology, including screening wells based on their integrity, geological conditions and presence of nearby fractures (Raza et al., 2017). Finally, Nygaard (2010) developed a workflow for assessing work-over needs for improving well integrity at potential CO_2 storage sites and demonstrated it through application to the Wabamun field in Canada.

Despite the above-mentioned studies, a working tool that can be used to assess integrity and re-use potential of oil and gas fields with operational wells is currently lacking. Tools are available for evaluating monitoring and remediation strategies of CO_2 storage sites including existing wells, such as IEAGHG's Monitoring Selection Tool (Beck and Aiken, 2009) and the mitigation and remediation web tool developed by the MiReCOL project (Brunner and Neele, 2017). Tools such as the UK's CO_2 Stored database (Bentham et al., 2014) and US Department of Energy CCS Database (MIT, 2016) are also available for identifying potential storage sites. Additionally, the United States Department of Energy's National Risk Assessment Partnership (NRAP) project has developed tools to assess integrity and leakage risks associated with wells at CO_2 storage sites (Pawar et al., 2016). Finally, TNO has developed the Bayes-I Tool for assessing well integrity (Brunner et al., 2018), which can serve as a foundation for the well re-use screening-tool developed in REX-CO_2.

2. Review of current standards and guidelines

This section compares the standards and guidelines relevant for the re-use of wells for large scale injection and storage of CO_2. The standards and guidelines are assessed with regard to the relevant requirements for CCS and what each document is specified for. Furthermore, the objective is to discuss the difference between a well utilized for CCS and a well utilized for petroleum extraction and if the relevant standards should be potentially updated to make them applicable to a CCS well. Prior to a detailed description the difference between a standard and a guideline should be noted. A standard is an agreement reached between various parties on the acceptable level of quality, something that should be followed. A guideline, however, is less strict and binding, which means that one should intend to achieve the stated level of quality.

The existing standard and guidelines relevant for this work are the following:

- ISO 16530
- Oil & Gas UK Well Integrity guidelines
- Oil & Gas UK Guidelines on qualification of materials for the abandonment of wells
- NORSOK D-010
- API/TR 10TR1 Cement sheath evaluation
- API RP 65-2 Isolating Potential Flow Zones During Well Construction
- API RP 90 Annular Casing Pressure Management for Offshore Wells
- NOGEPA Standard 45 Well decommissioning
- NOGEPA Standard 51 Operational barriers for well integrity
- Norwegian Oil and Gas Recommended guidelines for well integrity

For the scope of this specific deliverable, only the ISO and NORSOK standards and the guidelines from Oil & Gas UK (OGUK) have been reviewed and discussed.

2.1. International Standard Organization

The International Standard Organization (ISO) petroleum standard is developed by the oil and gas producing companies and its intended use is worldwide. The defined scope is written as follows:

"This document is applicable to ***all wells*** that are operated by the ***petroleum and natural gas industry***. " (ISO, 2017)

One can infer from the text that CCS wells could be covered by this standard, if operated by a petroleum company. There is nothing in the standard limiting the scope to hydrocarbons, petroleum or other related fluids. Instead, the neutral word "fluid" is used throughout the document.

This standard divides the different phases of well integrity management into the following:

- Basis of design phase
- Design phase
- Construction phase
- Operational phase
- Intervention phase
- Abandonment phase

The terms "*CCS*" or " *CO_2 storage"* are not explicitly mentioned in the text however CO_2 is mentioned as a potential source of enhanced corrosion on the well barrier elements. Even without explicitly referring to CCS or CO_2 storage, the standard covers the most important points for the purpose of CO_2 storage.

The *well barrier* philosophy is to maintain control of fluids. It is the role of the well operator to ensure that the well barrier can withstand the anticipated loads and function according to the original plan and expected conditions in the wellbore. The barriers should also prevent uncontrolled flow of fluids, either to the (sub)surface or within the wellbore. As mentioned previously, the requirement is to have at least two independent well barriers. It is possible however, to have only a single well barrier, as long as a proper risk assessment is performed on the containment ability of the single well barrier. The performance of the well barriers should also be verified through appropriate functional testing. All materials should be qualified to demonstrate they will retain the integrity at the relevant conditions.

The operator should establish the operating limits of the well by acquiring relevant information such as:

- All relevant wellbore pressure(s): annulus, pore, reservoir, etc.
- Expected or known flow rates
- Chemical composition of fluids, especially for corrosive agents such as H_2S and CO_2
- Water cuts
- Operating temperature
- Wellhead movement from subsidence or thermal expansion
- Cyclic loads from injection
- Thickness of casing wall
- Cement bond log

With regard to leakage risk, monitoring of the well barrier elements and application of any changes to the well are to be documented. The well operator together with the regulator should define the acceptable leakage rates and set the monitoring and testing frequency. Any changes to the well integrity requirement should be dealt with through a Management of Change (MoC) process, which goes through the following process:

- Identify requirement changes
- Identify the impact of the change
- Perform risk assessment
- Submit, communicate record and implement MoC

2.2. Oil and Gas UK

These guidelines are made by Oil & Gas UK which is an organization representing the UK offshore Oil and Gas industry (Oil & Gas UK, 2015a. Oil & Gas UK, 2015b). The guidelines were also reviewed by and agreed upon with the UK onshore Operators Group, which is a body representing the onshore activity in the UK. The guidelines are stated to be relevant:

" …to all wells and well operations in ***Great Britain*** for the extraction of naturally occurring ***hydrocarbons***." (Oil & Gas UK, 2012)

Thus, CCS wells are not explicitly included in this definition. Also, unlike the ISO standard, the term "hydrocarbons" is used instead of the neutral term "fluid". CO_2 is only mentioned in the guidelines in the context of a reservoir characteristic and a potential for enhanced corrosion to well barrier materials. The guidelines state that it is the responsibility of the well operator to ensure that there is no unplanned escape of fluids, and to minimize the risk to health and safety.

The similar neutral language is used on the choice selection of well materials. For instance, no materials are mandatory nor excluded as long as it is possible to ensure that the well is constructed with materials suitable for achieving the purpose of sufficient well integrity and acceptable leak rates.

It is the duty of the operator to identify suitable well barriers throughout the life cycle of the well. The choice of materials and their selection, installation, verification, testing and maintenance should also be documented, and the well barriers should be tested and documented. The well integrity risk assessment should include

- Maximum differential pressure across barriers throughout the life cycle
- Potential fluid chemistry
- Criteria for success (of a pressure test)
- Criteria for failure (of a pressure test)
- Contingency plans if the barrier could not be tested

An important note on the well design and planning of operations is the assessment of subsurface conditions. An assessment for the well integrity should include:

- The intended purpose of the well such as production, exploration, or injection
- A geological prognosis
- Depths and formation type
- Types of hydrocarbons expected
- Potential for hazardous fluids such as H_2S and CO_2
- Potential for hazardous formations such as salt or reactive clays
- Potential for overpressure
- Temperature gradient of the well
- Estimate of fracture gradient and potential lost circulation zones

On the fourth point (*types of hydrocarbons expected*) extra details include relevant factors for CO_2 storage, such as quality of injected fluids and total volume. On process of the well design, the following types of wells are stated:

- Exploration
- Appraisal
- Development which, for instance, includes production, injection, cuttings re-injection
- Combination wells which, for instance, include water injection with cuttings injection

Again, there is no mention of CO_2 storage wells, but such wells could be assessed within the third point (development wells). The important notes on the well design phase is the estimated max pressure, casing depth and sizes and the casing types. On the choice of well materials, they should be chosen based on the known conditions in the well, both temperature/pressure and the chemical conditions. It is also mentioned that the well operator should have in-place processes for long-term planning of the well. On the material durability for P&A wells, the eternal perspective is stated, however, for practical purposes, one million days has been arbitrarily defined.

2.3. NORSOK

The NORSOK D-010 standard is developed by the Norwegian petroleum industry and is administered and published by Standards Norway. The standard is based on the ISO standard and adds provisions where it would be necessary for the needs of the Norwegian petroleum industry. The defined scope in the standard is as follows:

"This NORSOK standard focus on well integrity by defining the minimum functional and performance oriented requirements and guidelines for well design, planning and execution ***of well operations in Norway***." (Standards Norway, 2004)

Thus, this specific standard is not limited to petroleum wells, but could also include CO_2 storage wells. Neither is there an explicit specification between onshore/offshore, but this could be due to the lack of onshore activity for the Norwegian petroleum industry. The standard contains details on the description of well barriers, their design, schematics, acceptance criteria, verification procedures, etc.. The standard has categorized the well barrier requirements into several operations.

The general philosophy for permanently abandoned wells are:

- The explicit acceptable leakage rates (across the wellbore element) is zero, unless specified otherwise.
- A permanently plugged well should be abandoned with an eternal perspective.
- The last open hole section should have a permanent well barrier installed, and the complete borehole shall be isolated.

The well barrier element shall cover the full cross section of the well and seal both horizontally and vertically. This means that if the casing has not been cut and pulled, the quality of the annular cement should be verified. The *eternal* perspective of this operation also ~~put~~ places practical constraints on the properties of the well barrier elements. For instance, any potential element should be impermeable, non-shrinking, have long term integrity (at the relevant conditions), be ductile and bond properly to steel.

On "Suspension, plugging and abandonment design" the following points are included:

- The depth and size of the permeable formations with flow potential should be known.
- The elements should also withstand the pressure difference across the well barrier as long as the barrier will be in use.
- The well configuration should be available/known (this includes depths and specification of permeable formations, casing strings, cement behind casing status, sidetracks, etc.
- Stratigraphic sequence, and information about their current and future production potential, of each wellbore should be gathered.
- Logs, data and information from the primary cementing operation(s)
- The estimated formation fracture gradient
- Various details on the well condition such as scale build-up, casing wear, collapsed casing and similar.

2.4. Summary

Of the relevant standards and guidelines reviewed, none explicitly mention gas storage wells or CO_2 storage wells for the purpose of CCS. However, due to the neutral language of the various documents, this does not imply that the standards and guidelines are not relevant or would have to be revised for the use on wells to be used for CO_2 storage. The existing language makes adaptation of the standards and guidelines to other applications relatively easy. For instance, with no requirements on any specific materials, utilization of *new* materials could be implemented provided that it has the appropriate properties. As seen in literature, there are several materials that can be suitable for operations in P&A. Materials such as Portland G is already commonly used, but Blast Furnace Slag, bentonite, thermosetting polymers, unconsolidated sands, geopolymers and Thermite have also been used (Vrålstad et al., 2019). The requirement to maintain isolation of hydrocarbon-bearing intervals following well abandonment will apply even if a well is converted to a CO_2 storage well. Because of this, the reviewed standards and guidelines remain relevant, regardless of whether a well is permanently abandoned or re-used for CCS.

The existing procedures contain important aspects, such as including relevant parameters on ranges of expected temperatures, pressures, reservoir characteristics and, material selection and so on. Also, the overall management procedures contain sufficient attention to detail on documentation of any design philosophy, changes in design, and workover operations.

A guideline made specifically for the use of existing wells for CO_2 storage is the CO2WELLS guidelines (Det Norske Veritas, 2011). The guidelines use a risk assessment process to identify, analyse and evaluate the risks of existing wells and an assessment of the qualification needed to have sufficient integrity risk.

One aspect that should be considered in the future is impact of CO_2 injection parameters on well design. This could include parameters such as planned or expected injection mass/volume, pressure ranges, temperature ranges, the chemical composition and properties of the injected fluids. An explicit mentioning of the reservoir capacity and expected CO_2 plume migration in the reservoir might be valuable inputs for defining the maximum injection rate to ensure safe well operation. Another difference between the commercial-scale permanent CO_2 storage and hydrocarbon extraction is the requirement of long-term monitoring. Dry hydrocarbon exploration wells and wells in depleted hydrocarbon reservoirs may not require sophisticated long-term monitoring. But re-pressurized reservoirs due to CO_2 storage operation, however, would need monitoring to ensure that injected CO_2 remains in the reservoir. Table 1 provides a brief comparison of the differences between the reviewed two standards and the guidelines. It should be noted that even though the Oil & Gas UK and NORSOK documents state their formal political limitations, they are used informally by operators outside the United Kingdom and Norway.

Table 1. Comparison between the ISO and NORSOK standard and the OGUK guidelines

	ISO	**Oil & Gas UK**	**NORSOK**
Specified for type of well	Wells operated by the petroleum and natural gas industry	To all wells and well operations for the extraction of naturally occurring hydrocarbons	Defined for well operations
Stated regional limitations	Worldwide	United Kingdom	Norway
CCS or CO_2 storage explicitly mentioned	no	No	no

3. Review of previous assessments for large scale gas storage and well integrity

This chapter will review and compare some of the published plans for large-scale CO_2 storage and assessment of the well integrity. The following case studies have been identified (IEAGHG, 2018):

- Camelot outside Norfolk, UK
- Atlantic & Cromarty Outside Aberdeen, UK
- Hamilton offshore Liverpool, UK
- Goldeneye offshore Aberdeen/Peterhead, UK
- Beatrice offshore north Scotland, UK
- Kingsnorth CCS project outside Thames estuary, UK
- PORTHOS P18 project outside The Hague, the Netherlands

These cases have been previously selected for re-use assessment based on their reservoir characteristics, existing infrastructure and maturity of the field. For the scope of this deliverable, the Peterhead, Kingsnorth and PORTHOS P18 CCS projects have been described in depth. Figure 3 shows the location of the three cases to be reviewed. The TAQA operated P18 field is situated right outside The Hague in the Netherlands. The Kingsnorth and Peterhead CCS projects were designed in response to successive UK Government CCS commercialisation programmes.

Figure 3. Map showing the locations of the various relevant large-scale projects for re-use of wells for CO_2 storage. The orange circle shows the P18 field. The red circles show the Kingsnorth power station and the Hewett field. The blue circles show the Peterhead power station and Goldeneye field. Original map downloaded from Openstreetmap.org.

Due to the lack of governmental funding neither project was commissioned, however numerous technical reports were published following the Front-End Engineering and Design phases. The Kingsnorth power station is located in Kent in South East England, where CO_2 was planned to be captured for storage in the offshore Hewett gas field, which is located offshore Norfolk. The Peterhead Power station is located in Aberdeenshire in Scotland, from where captured CO_2 was intended to be stored in the Goldeneye gas condensate field offshore in the Moray Firth.

3.1. Kingsnorth CCS, UK

Due to stricter regulations on pollution/efficiency a project was initiated to upgrade the Kingsnorth power plant located in the south east England. The initial project included a plan to sequester CO_2 from the coal-fired power plant and store the CO_2 offshore in the depleted sandstone gas reservoir of the Hewett field (Tilling and Manning, 1989). The project did not receive sufficient funding, and the plant finally closed in July 2015. However, the plans for the (re-)use of wells for storage are available and will be reviewed in this section (E.ON, 2011).

Both the production and exploration/appraisal wells were included in the assessment. A total of 28 production wells and 5 exploration/appraisal wells were identified and considered as relevant for the entire field re-development. The available data on the exploration wells was limited and the report was completed with the assumption that they were fully abandoned according to best practices.

The use of the Hewett field for CO_2 storage was considered to have favourable aspects, such as no recorded fracturing or acidizing of the reservoir itself. Also, the 28 production wells were all accessible with the possibility of converting them to CO_2 injectors. However, there was no access to the 5 exploration/appraisal wells, which penetrate the caprock and may provide potential migration/leak paths, contributing to the overall uncertainty.

The conclusion from the review and assessment was that the existing wells were not suitable for re-use for CO_2 injection and storage. The reasoning was the high level of uncertainty around the well and the condition of the well barrier elements. Scarcity of data would make predictions and assessment difficult and/or inaccurate. The infrastructure on the field was also considered to be old. Potential integrity issues arose because the wells were not originally designed for CO_2 storage operations. A primary objective for the redevelopment of the Hewett field was to limit the number of wells penetrating the caprock, so drilling new wells specifically for the injection would counteract this point and also be costly. The migration/leak paths along wells identified that could potentially compromise CO_2 storage were the following:

- Corrosion
- Degradation of cement
- Cracks in the cement
- Micro-annuli and channels in cement

The review mentioned that the wells needed to be abandoned using CO_2-resistant cement, and the need for non-Portland cement systems was explicitly mentioned. Three wells with recorded partial abandonment and sidetracking also contributed towards the uncertainty. The condition of these old legs was not clear, and this gave further uncertainties about the well integrity. Re-entry into these three old legs was considered to be difficult or impossible. Figure 4 shows the schematics for this specific well, with the details of the original A6 well and the side-track A14. There was a potential leak path between the liner and the cemented annulus, which could be accessed and a proper workover by milling could have been performed, but such an operation would have been costly. In the other wells the casing was not cemented all the way to the surface which would have made it easier to pull casing for annulus access. It was also expected that there was mixing of bentonite with the cement, making the cement more susceptible to acid corrosion.

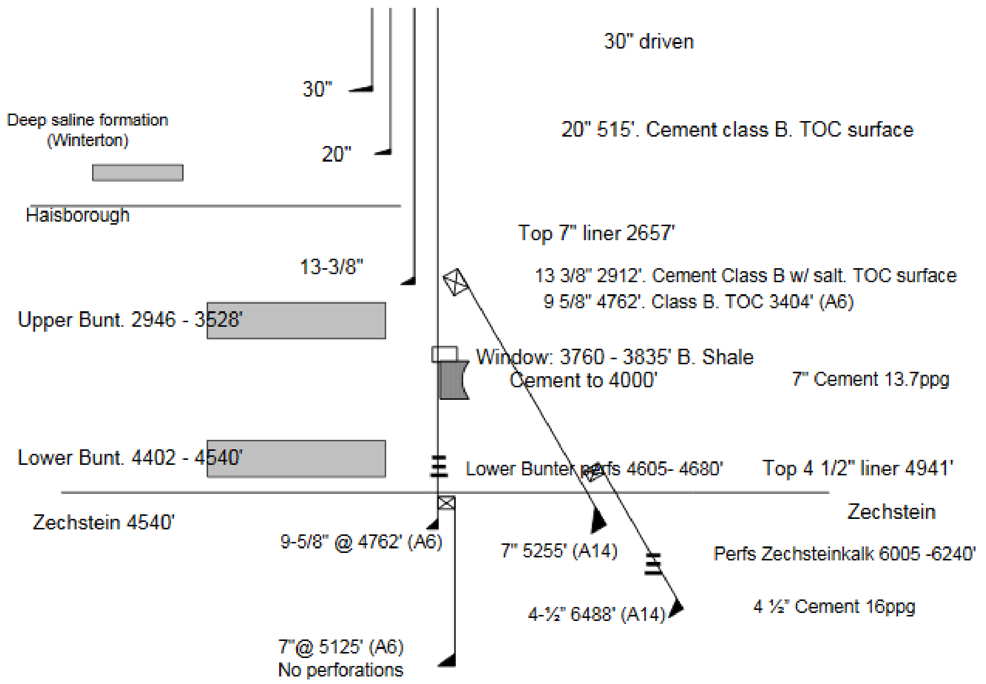

Figure 4. Wellbore schematic from Well 52/05-A14 including original well schematic to A6

3.2. Peterhead, UK

The Peterhead CCS Project objective was to capture approximately 1 million tonnes CO_2 per year from the gas-fired power station at Peterhead, Aberdeenshire, over 15 years. CO_2 would be captured, compressed and conditioned for transport at the power station. The CO_2 stream would then be transported offshore to the Goldeneye Field storage site via the existing Goldeneye pipeline, tied in sub-sea to a new offshore pipeline from the power station (Shell, 2016). Existing hydrocarbon infrastructure would require some modification to inject dense-phase CO_2 into the reservoir. The storage site, facilities and pipeline had previously been studied in substantial detail for the Longannet CCS project (Scottish Power CCS Consortium, 2011). The transport and storage components of the Peterhead CCS Project built on this appraisal to assess the engineering, commercial and regulatory requirements for progressing a CCS demonstration project through to construction.

Goldeneye is a depleted gas condensate field with an estimated CO_2 storage capacity of a least 24 Mt (Shell, 2016). The main reservoir is the Captain Sandstone, located at a depth of approximately 2,500 meters below mudline (seabed), which is sealed by mudstones of the Rodby and Carrick formations. The structure has an extent of approximately 7 km by 4.5 km. Four exploration and appraisal wells and five production (development) wells have been drilled on the structure. An active aquifer supports the Goldeneye Field, with water breakthrough observed in all of the wells during the production phase (Shell, 2014a). The field was operated by Shell and production ran from 2004 to 2011.

Following the cancellation of the proposed Peterhead CCS project, a proposal for decommissioning of the Goldeneye Field infrastructure was submitted to BEIS in October 2018 and issued for public consultation in November 2018. Subsequently, the decommissioning programme was separated into two parts. The proposal for decommissioning of the Goldeneye topsides, jacket, wells and subsea infrastructure (up to but excluding the main pipeline tie-in flanges) was approved in November 2019. A second proposal for decommissioning of the Goldeneye pipelines, which have both been identified as having potential for re-use, will be submitted when the UK has finalised its policy on the re-use of oil and gas infrastructure for CCUS.

The assessment included all wells in proximity to the Goldeneye field for a review on the ability to ensure well integrity during and after injection of CO_2. The original design parameters of all wells and the quality of the abandonment plugs set in wells were included in the assessment. The study was divided into two parts, where in the first part a selected area was chosen and the existing 13 Exploration & Appraisal (E&A) in this area was assessed. The second part of the study assessed the five proposed injection wells.

The five gas production wells are jack-up drilled wells, gravel packed, with the casing strings cemented in place. They were suspended with deep-set downhole plugs. The wells are all similar in terms of construction elements and have no severe doglegs, although the packer is set at different formations within the wells. None of the production wells, or the abandoned exploration and appraisal wells, are considered to have any major integrity issues (Shell, 2014c). The Peterhead CCS project planned to use three of the Goldeneye production well for CO_2 injection, and one for monitoring (Shell, 2015). The fifth production well was planned to be abandoned.

The assessment of the abandoned E&A wells found that eight of these wells had no contact with the reservoir and are located outside the predicted maximum area to which CO_2 could migrate. One of the wells had no reservoir contact but was close to the maximum projected CO_2 migration distance. The assessment on the state of the barriers was good, and the risk of leakage was considered very low. Two E&A wells were in contact with the reservoir but had good primary seal to the reservoir.

Two E&A wells were considered to have a *credible, but low risk* of leakage to the surface. Both wells were in contact with the reservoir, but a closer study indicated that the CO_2 would take over 20 years to migrate, and thus the monitoring program would detect this leakage and remediation work could be undertaken. An example of the workflow for the assessment of the wells is shown in Figure 5.

The condition and quality of the conductor and casings were analysed reviewed with a focus firstly on casing size placement and loads. The second focus was on the suitability of the materials in an CO_2 environment. The summary of the casing review was that the original design and choice of materials was sufficient for re-use. The cement quality, including the *cement placement* and the *cement properties* was also reviewed. The Portland cement used in the wells was concluded to be suitable for a CO_2 injection environment.

The project planned to run CBL during the workover operations to better assess the current integrity of the cement. The existing lower completion was found to be suitable for CO_2 service following an analysis of the materials (13Cr steel), corrosion, screen performance, and plugging of the screens and formation (Shell, 2015).

The existing upper completions and christmas tree were deemed not suitable for CO_2 service, so needed to be modified. After consideration of various completion designs, a single tapered completion was selected as the simplest and most robust option (Shell, 2014b). The proposed changes to the wells to make them fit for CO_2 injection included (Shell, 2014c):

- All completion equipment to have 13Cr or S13Cr metallurgy
- Christmas tree and tubing hanger to be replaced with extremely low temperature compatible equipment (API 6A, temperature class ‘K’), rated to -60°C
- New Subsurface Safety Valve (SSSV) to be developed (and set at a depth of approximately 760 metres) to ensure well integrity at low temperatures
- 7” tubing above the SSSV to be replaced by 4.5” tubing made of S13Cr, to provide back pressure in the well
- New packer to be set deeper in the well, within the primary seal
- Perforated pup joint in the tubing below the production packer to be removed

- “A” annulus fluid to be changed from inhibited seawater to base oil
- Elastomers to be replaced with suitable material to mitigate against explosive decompression
- Polished Bore Receptacle (PBR) to be replaced.

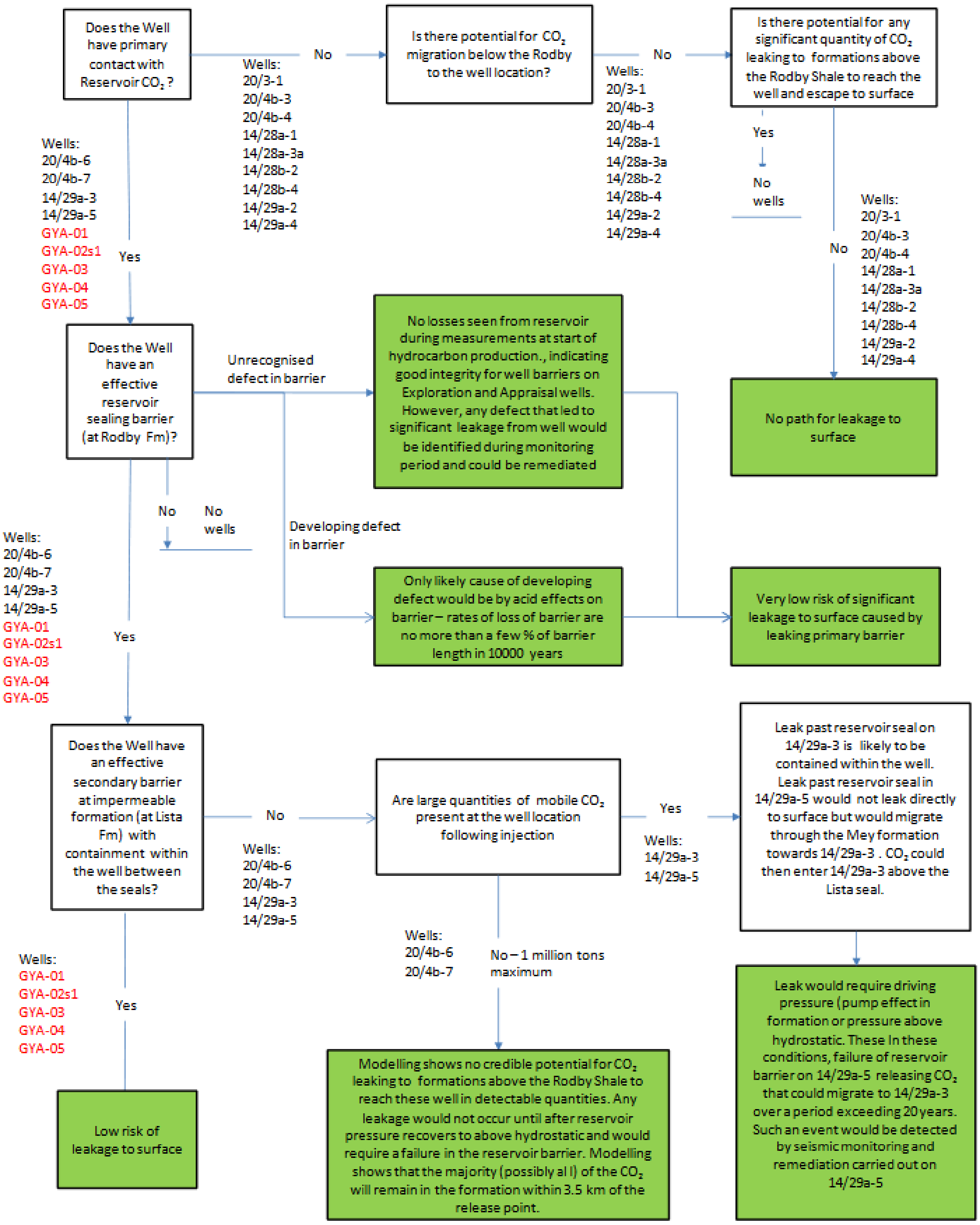

Figure 5. Assessment flowchart illustrating the potential leak scenarios and risk of leak for each well at the Peterhead/Goldeneye CCS project (Shell, 2014c).

3.3. PORTHOS P18, NL

In 2011, TNO conducted an independent storage assessment for offshore CCS application close to Rotterdam. The study focused on storage options that could be used for CCS in the relative short term at that time (Figure 6). A total of six clusters have been analysed. The report suggests that in the short term, the TAQA operated P18 cluster, just offshore of Rotterdam, would be the best option (Neele et al., 2011). At the time it was expected that first injection could take place in 2015, and the total storage capacity would be 42.4 Mt CO_2 with an injection rate of about 2.4 Mt CO_2 per year. The investment costs were estimated at 65 M€ for the workover of six wells and the platform, excluding the pipeline and onshore installations. Operational costs were estimated at 3.2 M€/year.

Field name	P18-2	P18-4	P18-6	K12-B	Q01 + Q01 oil fields	Q08-A	P06-AB	P06-MP	P15-9	P15-11	P15-13
Type	gasfields			gasfield	saline formation associated with hydrocarbon production	gasfield	gasfields		gasfields		
Availability	2018	2014	2011	post 2015	2012	2008	2015	2015	2014	2014	2007
Capacity (Mt)	33	8	1.4	25	110	10	22.6	7.2	12	17	8.6
Start injection	2019	2015	2015	>2016	>2016	2015	2017	2017	2015	2015	2015
Injection rate (Mt/yr)	>1,1	>1,1	0,2 for 5 yrs	3.1 Mt/yr	high	0.9	1,6 - 2,2	1 for 5 yrs	1,4 for 5 yrs	1,4 for 5 yrs	0,73 for 5 yrs
Containment	good (claystone)			good (claystone)	to be checked	good (claystone)	average		good (claystone)		
CAPEX (M€), OPEX (M€), storage cost UTC (€/tCO2), injection period	CAPEX: 65 OPEX: 32 UTC: 2.8 Period: 10 years			CAPEX: 26 OPEX: 90 UTC: 4.6 Duration: 8 years	new injection well and platform; wells to be abandoned	CAPEX: 20 OPEX: 18 UTC: 3.8 Duration: 10 years	CAPEX: 48 OPEX: 280 UTC: 14,3 Duration: 24 years	CAPEX: 16 OPEX: 42 UTC: 8,1 Duration: 10 years	CAPEX: 29 OPEX: 74 UTC: 6,0 Duration: 12 years	CAPEX: 29 OPEX: 46 UTC: 5,6 Duration: 19 years	CAPEX: 27 OPEX: 55 UTC: 9,5 Duration: 10 years
Risks	workover diverted well			well bores: risk factor; injection from ship to be tested	Integrity of many abandoned wells	obtaining (transport) permits is difficult	sealing quality five abandoned wells questionable, heavily fractured reservoir, possibly uneven CO2 distribution		suspended exploration well (Phase 1)	none identified (Phase 1)	none identified (Phase 1)
Other / notes	Best short term storage option. Costs are in combination with other P18 fields				option for the medium term (post 2020)	Good candidate CO2 storage	development with P06-MP and P06-D. Complex infrastructure	OPEX shared with P06-MB	Close to P18 cluster		

Figure 6. Assessment of potential CO_2 storage fields offshore Rotterdam. Green: no hurdles identified; yellow: less favourable or not assessed; red: possible (from Neele et al., 2011)

As part of the CATO program in the Netherlands, a more detailed assessment on the wells of P18-2 was conducted in 2010. The seven relevant wells were identified, and the available data was collected and assessed as shown in Table 2 (Akemu et al., 2011).

For the assessment, a definition of the well barriers was prepared for a generic P18 well. The assessed elements were:

1. The primary cement across the caprock,
2. The production line,
3. The production casing,
4. The wellhead,
5. The production tubing (incl. jewellery, e.g. SC-SSSV),
6. Primary cement around the production casing,
7. The production liner hanger and
8. The production packer.

Based on the available data, the seven wells were assessed for these barrier elements. The assessment concludes that the feasibility of CCS is primarily determined by the accessibility and suitability of the wells. One of the wells in the P18 reservoir (P18-2) has been suspended with cement plugs; it was concluded that the well has to be revisited for abandonment to ensure zonal isolation.

Table 2. Data availability for qualitative well integrity assessment (from Akemu et al., 2011).

Wells/boreholes	P18-2A1	P18-2A3z	P18-2A5 (S1)	P18-2A6z	P18-6A7	P18-4A2	P18-2
Well status	Producing	Producing	Producing	Producing	Producing	Producing	Abandoned
Spud date	11-1993	14-5-1993	18-11-1993	17-11-1996	7-2003	4-6-1991	11-3-1989
Abandonment date							28-5-1989
Final Well Report	N/A	x	x	x	N/A	x	x
Well/completion diagrams	x	x	x	x	x	x	x
Casing and cementing reports		x		x		x	x
Drilling reports	x	x	x	x		x	x
Well tests	N/A	x	x	x			N/A
Cementing and corrosion logs (mentioned in EOWR)	CBL (7" L)	CBL-VDL (5" L)	USIT-CBL (5"L), CBL-CET (7"L)[1]	USIT-CBL (7" L)[2]	N/A	N/A	CBL (7", 9 5/8")
Openhole logs over reservoir section only	x		x	x	x	x	x
Stratigraphy along the well	x	x	x	x	N/A	x	x
Annulus pressure reports	N/A	N/A	N/A	N/A	N/A	N/A	
Production data	Dec 1993 - March 2010	Dec 1993 - March 2010	Dec 1993 - March 2010	June 1997 - April 2003	Dec 1993 - March 2010	Dec 1993 - March 2010	

The main worry for the other wells is the questionable cement quality at the caprock, based on CBL data, which would require further analysis. This poses a long-term integrity risk but could already impact the operational phase. One of the wells has been sidetracked and would require additional work to make it suitable. Some of the additional checks and remediations that have been proposed are to confirm the packer load envelopes and material (elastomers, metals, pack-offs) compatibility to chemical and mechanical loads. In general, it was concluded that the wells can be accessed and therefore can be remediated to be re-used as CCS wells.

The assessment did not look at abandonment in detail. It is suggested to keep some of the wells for monitoring purposes. Actual abandonment is dependent on common practice and standards and regulations, which were not available at the time. TNO has been involved in these assessments and will make use of that experience for creating the assessment framework that will be developed in this project.

The planning for 2020 of the PORTHOS project is to focus on three aspects to be able to make a final investment decision in 2021. It is expected that the system will be operating by the end of 2023. Royal HaskoningDHV will prepare the M.E.R. (environmental impact report) and the permit applications, and it is expected that this will generate some new and more detailed information and assessments publicly, including a technical elaboration on the transport and storage facilities.

3.4. United States CO_2-EOR experience

Commercial projects for enhanced recovery by CO_2 injection (CO_2-EOR) has been performed for many years in the United States. For instance, the SACROC unit in Texas initiated in 1972 (Langston et al, 1988). Even though the primary objective for a CO_2-EOR well might not be for the *permanent* storage of CO_2, the technology and requirements to the well barrier elements will be similar to those of permanent CO_2 storage. The numerous CO_2-EOR wells have led to an extensive know-how on dealing with well integrity and managing leakage risks of CO_2. The experience from the activity on the various wells and fields has resulted in development of a clear overview on suitable material for re-using existing wells to CO_2 storage. Many of the re-purposed wells were old, up to 50 years of age. They were affected by corrosion and/or erosion on the liner, production casing and surface casing (Folger & Guillot, 1996). The corrosion of casing can in some cases be quite severe. Exposed to formation fluids and CO_2, older wells with completely corroded lower casing have been reported (Lamb et al, 2016). Many of the wells were also previously used as water injectors with relatively large wash-outs. The washed-out zones could be re-filled with resin coated sands, and by removing the old liner and placing new fibre-coated liners. Pozzolan was also added to the cement to give enhanced CO_2 resistance (Power et al, 1990. Bowser et al, 1989). Table 3 shows a summary of the commonly used materials for the retrofitting of older wells for CO_2-EOR projects in the US.

Outside the experience on suitable material selection for CO_2-EOR wells, the engineering workflow and assessment of the CO_2-EOR wells followed those of a standard petroleum workover based on the requirements from the standards. Thus, the available literature is less relevant for to the development of re-use procedures and the tool.

Table 3. Overview of commonly used materials for CO_2 injection wells in the USA projects (Smith et al, 2011).

Component	**Materials**
Xmas Tree (Trim)	316 SS, Electroless Nickel plate, Monel
Vale Packing and Seal	Teflon, Nylon
Wellhead (Trim)	316 SS, Electroless Nickel plate, Monel
Tubing	Glass Reinforced Epoxy (GRE) – lined carbon steel; internally plastic coated carbon steel, Corrosion Resistant Alloys (CRA)
Tubing Joint Seals	Seal ring (GRE), Coated threads and collars
ON/OFF Tool, Profile Nipple	Nickel plated wetted parts
Packers	Internally coated hardened rubber, etc. Nickel plated wetted parts; corrosion resistant alloys particularly in old wells to improve sealing to worn casings.
Cements and Cement Additives	API cements and/or acid resistant cements

3.5. Summary

The previously performed assessments of re-use of older petroleum wells to CO_2 injection wells follow a similar pattern. The workflow followed the steps as outlined by the standards and guidelines, by including factors such as the original well design, material choices, side-track, reservoir properties and monitoring and logging of the well during the lifetime. There was significant focus on determining integrity of existing well materials under proposed operational envelopes including pressure, temperature and injectant composition.

A natural difference for these cases compared to a "normal" petroleum extraction project was the inclusion of an overview of all wells in proximity of the field, both active and abandoned. This is natural in order to maintain *the integrity of the field*. There was also emphasis on having a clear overview of the expected properties of the CO_2 fluid, and the ranges of loads to the well during the injection.

One noteworthy difference between the cases, however, was in relation to the properties of cement. The Kingsnorth review mentioned that the wells needed to be abandoned using CO_2-resistant cement, and the need for non-Portland cement systems was explicitly mentioned. This differed from the review performed in the Peterhead project. This review did not mention any issues with the properties and state of the Portland cement used in those wells. The difference between these two reviews shows how the long-term performance of cement needs to be further investigated.

4. Implementation of available data

The major objective of the Rex-CO_2 project is to develop a well-screening-tool for the purpose of re-using existing wells for CO_2 storage. A description of the conceptual framework of the workflow that will be used to develop a well reuse assessment tool is provided in the report “D2.2: Summary report of well assessment tool framework” (Pawar et al, 2020). This section will discuss the input that will be available for both the developers of this tool, and the future user of the tool. The level of available data will vary from case to case. It is the intention of project to develop a tool that can be used to perform different levels of assessment based on the quantity and quality of available data. The term "data quality" can be categorized into *data volume* as in (scarce or plenty), and *data accuracy (high or low level of accuracy/uncertainty).*

Some wells, either due to age and/or governing standards, might have little relevant data available for making a proper assessment of well re-use. Whereas other wells will have satisfactory amount of data for making an assessment. The various techniques used for gathering well data over the years has improved, meaning that newer wells will in most cases have more and better data recorded compared to older wells. Another relevant issue are the potential differences in demands from regulators and operators worldwide on data management for wells. Various regulators and operators might have differences in the minimum requirements on data management. And again, these differences might also have changed over time. Examples of such differences could be on the management on what *kind* of data to obtain, *how much* data should be gathered, and also how easily accessible it might be. These potential differences can make an impact on uncertainty on the assessment of a specific well.

As was shown from the case studies, the required data to perform an assessment on the well integrity of a well to be re-used for CO_2 storage should contain:

- An understanding on the formations in contact with the well:
  - For instance, the formation strength, pore pressures, fracture gradients, depth of caprock, size of permeable zones, temperature gradient
- Original well design, characteristics, history of usage and current state of well:
  - Such as, well trajectory, depth, side-tracks, material choices of casing, packer and cement, quality of primary cementing, cement bond logs, documented sustained casing pressure, known previous work overs.
- The intended objective and usage of the well:
  - Whether it should be an Injection or monitor
- Properties of the fluid to be injected:
  - Purity, temperatures and pressures
- Timeline and procedure for fluid injection:
  - Planned or potential intervals of injection parameters such as total volume, pressures, flow rates

5. Conclusions

In order to *reduce the number of wells penetrating the caprock*, the concept of re-use wells for large scale CO_2 storage is beneficial. Re-use *could* a be beneficial from an economical viewpoint, as drilling new wells is expensive. Many wells have been converted to CO_2 injection wells for EOR in the United States, so there is already operational experience available for this operation. However, there is no established workflow or tool for an effective well re-use assessment. Such a systematic workflow could also make it easier to quickly identify promising wells for re-use.

Since it is the petroleum industry that has the experience and infrastructure for performing large scale handling of fluids in the subsurface, it is natural that they will take an important role for storing of CO_2 in the underground. *Even though none of the standards or guidelines currently used by the petroleum industry explicitly mention gas storage wells or CO_2 storage wells for the purpose of CCS*, they are still relevant since they define requirements necessary to ensure well-integrity under different operational conditions. Also, due to the generic language used to define fluids adaptation of the standard to other applications is relatively easy for projects were CO_2 is to be injected and stored permanently.

The existing standards and guidelines highlight the importance of taking into consideration aspects such as the ranges of expected temperatures, pressures, reservoir characteristics, well design, material selection of the well barrier elements, well history, etc. The management procedures also contain sufficient attention to detail on documentation of relevant information.

The summary from the previous large-scale assessments of re-use of existing wells in CO_2-EOR as well as CO_2 storage operations shows the *importance of having a standardized workflow* for assessment. The primary focus of previous assessments was ensuring well integrity under expected operational conditions. The integrity assessments included both mechanical and chemical integrity. The assessments incorporated data from logs (for corrosion) as well as tests (for mechanical integrity). Many fields will have large degrees of uncertainty due to little or insufficient data on some of the wells. This is especially relevant for older fields, and for E&A wells. The *scarcity of data* would make predictions on well integrity difficult and inaccurate. Thus, it is important that the tool should be developed in such a way that it gives the user flexibility. Migration (or leak paths) along wells that could compromise the CO_2 storage could be from:

- Corrosion of casing
- Degradation of cement
- Cracks in the cement
- Micro-annuli and channels in cement

Also, the original well design for a used well might not be acceptable for retrofitting to CO_2 storage, the condition of the well barrier elements after years of petroleum extraction might be deteriorated, or there might be uncertainties on the state or accessibility of the side-tracks in the well. Many wells will require workover to be able to operate with acceptable well integrity. A systematic mapping, with a dedicated tool, of all parameters affecting the well integrity would aid the engineering work and give more accurate estimations on field viability and cost.

Another key finding from the review of previous assessments of re-use was on how various groups will assess the suitability of Portland Cement in a CO_2 storage well environment. For instance, the review of the Kingsnorth CCS project highlighted the need for CO_2-resistant cement, and in particular non-Portland cement systems. In contrast, the review of the Peterhead CCS project concluded that the Portland cement systems used were suitable for the use as CO_2 injector wells. The contrast in the conclusions highlight the need for more systematic research at relevant conditions on the actual suitability of Portland Cement systems in such environments. Such work on cement is already planned in Work Package 3 in the REX-CO_2 project.

6. References

ACT Acorn (2018a). D04 Site Screening Methodology. 10196ACTC-Rep-07-01, January 2018.

ACT Acorn (2018b). D05 Site Selection Report. 10196ACTC-Rep-08-01, January 2018.

ACT Acorn (2018c). D11 Infrastructure Re-use. 10196ACTC-Rep-16-01, May 2018.

Akemu O., Miersemann U., Benedictus T., 2011. CATO-2 Deliverable WP3.4-D22 Well integrity Assessment of the P18 gas field (TAQA).

Beck, B. & Aiken, T. (2009). An introduction to the IEA GHG international research network on monitoring. Energy Procedia, 1, 2383–2387

Bentham, M., Mallows, T., Lowndes, J. & Green, A. (2014). CO_2 STORage Evaluation Database (CO2 Stored): the UK's online storage atlas. Energy Procedia, 63, 5103–5113.

Bowser P.D., Corey J.D., Darr C.D.K., Caro D.A. 1989. Innovative Techniques for converting old waterflood injectors to State-of-the-art CO_2 injectors. Low permeability reservoirs symposium, 6-8 March, Denver, Colorado Society of Petroleum Engineers. SPE-18976-MS

Brunner, L. & Neele, F. (2017). MiReCOL–A handbook and web tool of remediation and corrective actions for CO_2 storage sites. Energy Procedia, 114, 4203–4213.

Brunner, L., Koenen, M., Orlic, B. and Wollenweber, J., 2018. A Bayesian Belief Network to Assess Risk of CO2 Leakage Through Wellbores. *14th Greenhouse Gas Control Technologies Conference Melbourne*, 21-26 October 2018 (GHGT-14). Available at SSRN: https://ssrn.com/abstract=3365825.

Carey J.W., Wigand M., Chipera S.J., WoldeGabriel G., Pawar R., Lichtner P.C., Wehner S.C., Raines M.A., Guthrie G.D., 2007. Analysis and performance of oil well cement with 30 years of CO_2 exposure from SACROC unit, West Texas, USA. International Journal of Greenhouse Gas Control 1, 75-85.

Carroll, S., Carey, J.W., Dzombak D, Huerta N.J. Li L., Richard T., Um W., Walsh S.D.C., Zhang L., 2016. Review: role of chemistry, mechanics and transport on well integrity in CO_2 storage environments. International Journal of Greenhouse Gas Control 49, 149-160.

Det Norske Veritas, 2011. CO2WELLS Guideline for the risk management of existing wells at CO2 geological storage sites. DNV report NO.: 2011-0448.

Duguid A., Kirksey J., Riestenberg D., Koperna G., Holley C., Loizzo M., Locke R., 2018. CO_2 well construction: Lessons learmed from United States Detartment of Energy Sponsored projects. 14th International Conference on Greenhouse Gas Control Technologies, GHTH-14. 21st-25th October 2018, Melbourne, Australia.

Environmental Protection Agency, 40 CRR parts 144 and 146: Federal Requirements Under underground injection control (UIC) Program for Carbond Dioxide CO_2 Geologica sequestration (GS) wells:proposed rule , federal registrer , Bol 73 , No 144, 2008, pp 43492-43541

E.ON. February 2011. Kingsnorth Carbon Dioxide Capture and Storage Demonstration Project.

Ernens D., Hariharan H., van Haaften W., Pasaribu H., Jabs M., NcKim R., 2018. Improving Casing integrity with induction brazing of casing connections. SPE Drilling and Completion 33, issue 3. SPE-184703-PA

IEAGHG (2018). Re-Use of Oil & Gas Facilities for CO_2 Transport and Storage. 2018/06, July 2018

ISO, Petroleum and natural gas industries – Well integrity Part 1: Life cycle governance. ISO 16530-1:2017

ISO, Petroleum and natural gas industries – Well integrity Part 2: Well integrity for the operational phase. ISO 16530-2:2013

Folger L.K, Guillot S.N., 1996. A case study of the development of the sundown slaughter unit CO2 flood Hockley County, Texas. Permian Basin oil and gas recovery conference 27-29 March, Midland, Texas. SPE-35189-MS

Ivandic, M., Juhlin, C., Lüth, S., Bergmann, P., Kashubin, A., Sopher, D., Ivanova, A., Baumann, G., Henninges, J. (2015): Geophysical monitoring at the Ketzin pilot site for CO_2 storage: New insights into the plume evolution. International Journal of Greenhouse Gas Control 32 (2015) 90-105. Ivandic, MISO, Petroleum and natural gas industries – Well integrity Part 2: Well integrity for the operational phase.

Kutchko, B.G., Straziar, B.R., Dzombak, D.A., Lowry, G.V., Thaulow, N., 2007. Degradation of well cement by CO_2 under geologic sequestration conditions. Environ. Sci. Technol. 41. 4787-4792.

Lamb J.D., Glazewski K.A., Hamling J.A., Azenkeng A., Watson T.L., 2016. Wellbore corrosion and failure assessment for CO2 EOR and stoarge: Two case studies in the Weyburn field. International Journal of Greenhouse Gas Control. Volume 54, part 2. Pages 479-489.

MIT (2016). Carbon Capture and Sequestration Project Database. Last updated September 30, 2016. Available at https://sequestration.mit.edu/tools/projects/index.html.

Neele F, Hofstee C, Dillen M, Nepveu M. (2011). Independent storage assessment of off shore CO2 storage options for Rotterdam – summary report, TNO report TNO-060-UT-2011-00809, 2011 (http://www.globalccsinsti tute.com/publications/independent-storage-assessment-offshore-co2-storage-options-rotterdam-summary-report).

Nygaard, R. (2010). Well design and well integrity – Wabamun area CO_2 sequestration project (WASP). Energy and Environmental Systems Group report, University of Calgary.

Standards Norway, 2004. NORSOK Standard D-010. Well Integrity in drilling and well operations. Rev 3.

Oil & Gas UK, 2012. Well Integrity guidelines. Issue 1, July 2012

Oil & Gas UK, 2015a. Guidelines for the abandonment of wells, Issue 5, July 2015

Oil & Gas UK, 2015b. Guidelines on qualification of materials for the abandonment of wells, Issue 2, July 2015

Pawar, R.J., Bromhal, G.S., Chu, S., Dilmore, R.M., Oldenburg, C.M., Stauffer, P.H., … & Guthrie, G.D. (2016). The National Risk Assessment Partnership's integrated assessment model for carbon storage: A tool to support decision making amidst uncertainty. International Journal of Greenhouse Gas Control, 52, 175–189.

Pawar, R.J., van der Valk, K., Brunner, L., Cangemi, L., Chen, B., Constanta-Dudu, A., Greenhalgh, E., Harp, D., Opedal, N., Williams, J., 2020. REX-CO2 D 2.2 – Summary report of well assessment tool framework,

Power M.T., Leictht M.I., Barnett K.L., 1990. Converting wells in a mature west Texas field for CO2 injection. SPE Drilling Engineering. Volume 5, issue 4. SPE-20099-PA.

Raza, A., Gholami, R., Rezaee, R., Bing, C.H., Nagarajan, R. & Hamid, M.A. (2017). Well selection in depleted oil and gas fields for a safe CO_2 storage practice: a case study from Malaysia. Petroleum, 3 (1),167–177.

Rentsch H.C. and Mes M.J., 1988. Measurement of Ekofisk Subsidence. Offshore Technology Conference, 2-5 May, Houston, Texas. Offshore Technology Conference. OTC-5619-MS

Scottish Power CCS Consortium. 2011. SP-SP 6.0 – RT015 FEED Close Out Report. UK Carbon Capture and Storage Demonstration Competition. April 2011.

SHELL. 2011. Cement Concept Selection, Doc No. UKCCS - KT – S7.16 –Shell – 007. *UK Carbon Capture and Storage Demonstration Competition. Produced by Shell.*

SHELL. 2014a. Well Functional Specification (WFS) Document. *Peterhead CCS Project Doc No. PCCS-05-PT-ZW-7180-00005, Revision K02, DECC Ref No 11.098.*

Shell, 2014b. Well Completion Concept Select Report. Peterhead CCS Project Doc No. PCCS-05-PT-ZW-7180-00003, Revision K02, DECC Ref No 11.097

Shell, 2014c. Well Integrity Assessment Report. Peterhead CCS Project Doc No. PCCS-05-PT-ZW-7180-00004, Revision K02, DECC Ref 11.113

SHELL. 2015. Well Technical Specification. Peterhead CCS Project Doc No. PCCS-05-PT-ZW-7770-00001 , Revision K03, DECC Ref No 11.099.

SHELL. 2016. FEED Summary Report for Full CCS Chain. *Peterhead CCS Project, K03-11.133.*

SMITH L., Billingham M.A., Lee L-C, Milanovic D., 2011 Establishing and maintaining the integrity of wells used for sequestration of CO2. Energy Procedia. Volume 4, pages 5154-5161.

Tilling G.M. and Manning G.E., 1989. The Rejuvenation of Hewett Field. *Offshore Technology Conference, 1-4 May, Houston, Texas. Offshore Technology Conference*. OTC-6118-MS.

VoTranh H., Sugai Y., Sasaki K., 2018. An Object-base modelling and simulation of CO_2 plume dynamic in saline formation in Nam Vang field, Cuu Long Basin, Vietnam. SPWLA 24th Formation Evaluation Symposium of Japan, 11-12 October, Chiba, Japan. Society of Petrophysicists and Well-Log Analysts.

Vrålstad T., Todorovic J., Wollenweber J., Abollahi J., Karas D., Buddensiek M., 2015. D8.1 Description of leakage scenraios for consideration in the work in SP3. MiReCOL deliverable number D8.1, revision 1

Vrålstad T., Saasen A., Fjær E., Øia T., Ytrehus J.D., Khalifeh M., 2019. Plug & Abandonment of offshore wells: Ensuring long-term well integrity and cost efficiency. Journal of Petroleum Science and Engineering 173, 478-491.

Watson T.L. and Bachu S., 2009. Evaluation of the potential for Gas and CO_2 leakage along wellbores. SPE Drilling and Completion (01), 24 SPE-106817-PA.

Yan W., Deng J., Dong X., Zhang C., Li W., 2012. Experimental Study of 3% Cr Tubing steel in CO_2 and CO_2/H_2S corrosion environment. Oil and Gas Facilities 1 Issue 5. SPE-157302-PA.

Zhang M and Bachu S., 2011. Review of integrity of existing wells in relation to CO_2 geological storage: what do we know? International Journal of Greenhouse Gas Control 5, 826-840.