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RECOGNIZING AND DESCRIBING PROCESSES IN PRODUCING AND ABANDONED OIL- AND GAS RESERVOIRS THAT MAY CAUSE ENVIRONMENT FOOTPRINTS AND IDENTIFYING TECHNOLOGIES TO IMPAIR THESE**

1. HYDROCARBON RESERVOIR BEHAVIOUR DURING THE PROCESS OF ABANDONMENT AND THEREAFTER[1]

This report gives a comprehensive description of CO_2 reservoir injection for EOR and sequestration purposes in depleted oil and gas reservoirs, under various in-situ conditions and with the intention of identifying effects that can cause environmental footprints as part of the process. The report also suggest means for detecting such footprints and possibly remedy them.

Typically, reservoir pressure monitoring is used for examining storage process when CO_2 is injected into the subsurface. The pressure signal may be used to evaluate the pressure impact on both local and regional scale. This is important, since a high injection pressure and large-scale pressure increase can reduce the injectable amount of CO_2 in the long term. Rock and fluid properties as well as reservoir boundary conditions affect the height of the pressure increase within the reservoir and the final CO_2 distribution [1].

Marston [2] presented a pressure profile for an actual operating EOR field from the data reported to a state oil and gas regulator as shown in Figure 1. Prior to the start of oil production, the original formation pressure was about 4850 psig, which is considerably below the formation fracture pressure of about 7800 psig. In an EOR formation, the original reservoir pressure is always below the fracture pressure because if otherwise, the oil would not have accumulated nor trapped [2].

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** A bilateral AGH–UoS research project: Multifield CO_2 Storage for Environment and Energy (MUSE) Work Package 2 progress report.

[1] From report by Victor Chukwudi Anokwuru.

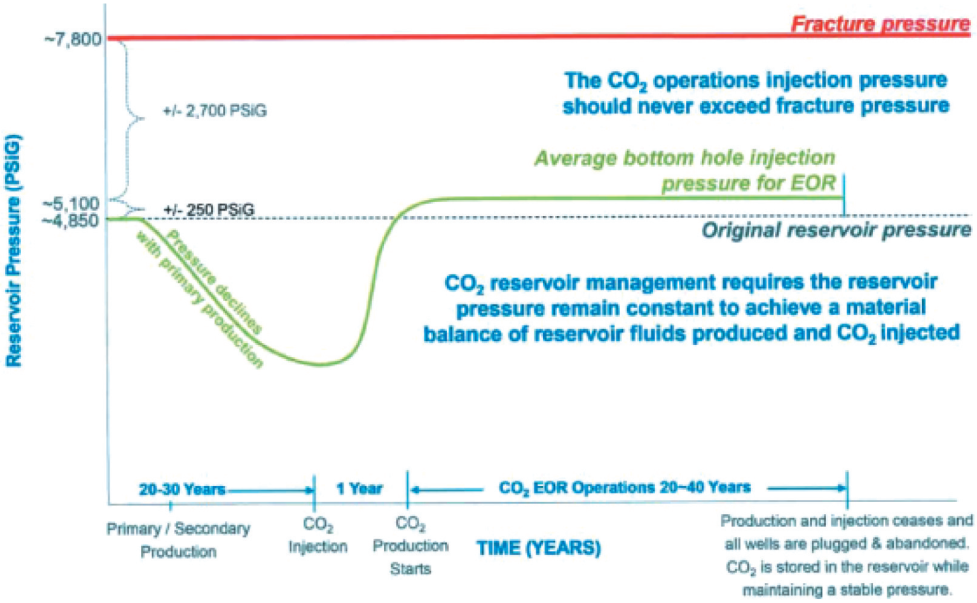

Fig. 1. Illustrative pressure profile of a CO_2 – EOR operation [2]

Flow behavior of the injected CO_2 and causal factors are investigated followed by the trapping mechanisms. Several factors such as buoyancy and viscous forces, number of fluid phases, presence of intra-formational seals, faults and fractures, permeability anisotropy are found to affect the migration of the injected CO_2. The various trapping mechanisms and factors affecting them are presented.

Intra-formational seals strongly affects the shape of the CO_2 plume that rises through the rock matrix [3, 4]. Intra-formational seals are common in reservoir structures. They are advantageous for CO_2 sequestration purposes. Figure 2 shows flow results from the numerical simulation of CO_2 injection at Sleipner Vest Field, in the North Sea, containing intra-reservoir shale units (intra-formational seals).

Cap-rock systems are also presented in the report. The general belief that sequestration of CO_2 in depleted oil and gas reservoirs is safe as long as the CO_2 injection pressure does not exceed the initial reservoir pressure or rock fracture pressure is herein discussed. Analysis have shown this to be largely untrue especially since the IFT of CO_2 – brine systems in direct contact with the cap-rock after upward migration is less than the hydrocarbon (CH_4) – brine system originally in contact with it.

Structural – stratigraphic trapping is the confinement of mobile (Supercritical, liquid, or gas) CO_2 under low-permeability layers, faults or anticlinal structures [19], as seen in Figure 3. Due to buoyant forces, the injected CO_2 tends to rise upwards until it is trapped by an almost impermeable cap rock. A cap rock seal acts as a trap for CO_2 accumulation over a period of time. If the cap rock is connected to a permeable layer and contains faults and/or fractures, it is not suitable as a sealing barrier. Besides, in order to keep the CO_2 in the supercritical state, the cap rock should be located at a depth above 800 meters [7].

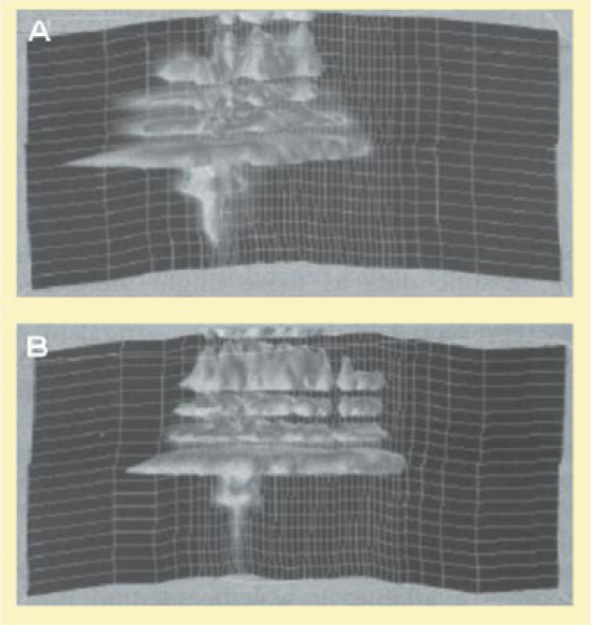

Fig. 2. Numerical flow simulation of CO_2 injection at Sleipner Vest Field, which has been history matched with time lapse 3D seismic reflection data. Two perpendicular cross-sections of a simulation result are shown (A & B). Intra-reservoir shale units (intraformational seals) act as barriers to vertical CO_2 migration [5, 6]

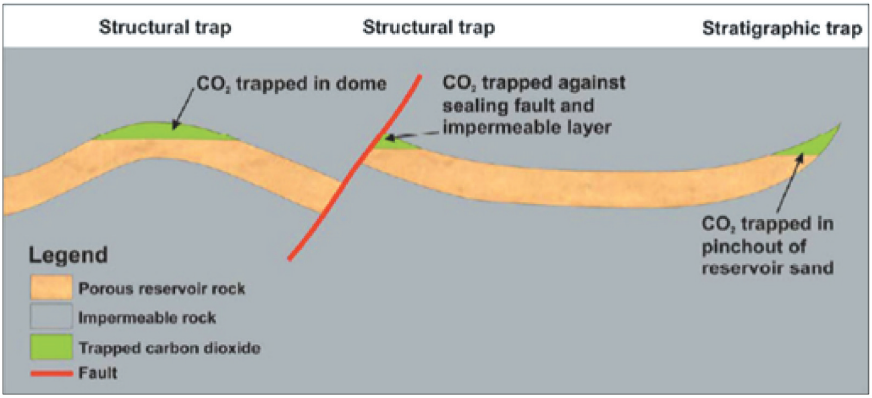

Fig. 3. Diagram showing some typical structural and stratigraphic traps in which CO_2 could be stored [11]

Assessment of the cap-rock potential to ensure containment and qualitative assessment methods are also presented. Pressure development during injection and sequestration is also discussed. Important factors that affect pressure propagation such as compressibility and reservoir heterogeneities are outlined.

2. MONITORING TECHNIQUES APPLIED TO CCS-EOR[2]

This report gives a quite detailed account of well – and reservoir monitoring techniques. The basic idea of monitoring Carbon dioxide Capture and Storage (CCS) projects is not just to monitor storage of CO_2, but to ensure that the gas stay in the deep geological underground, rather than being released to the atmosphere.

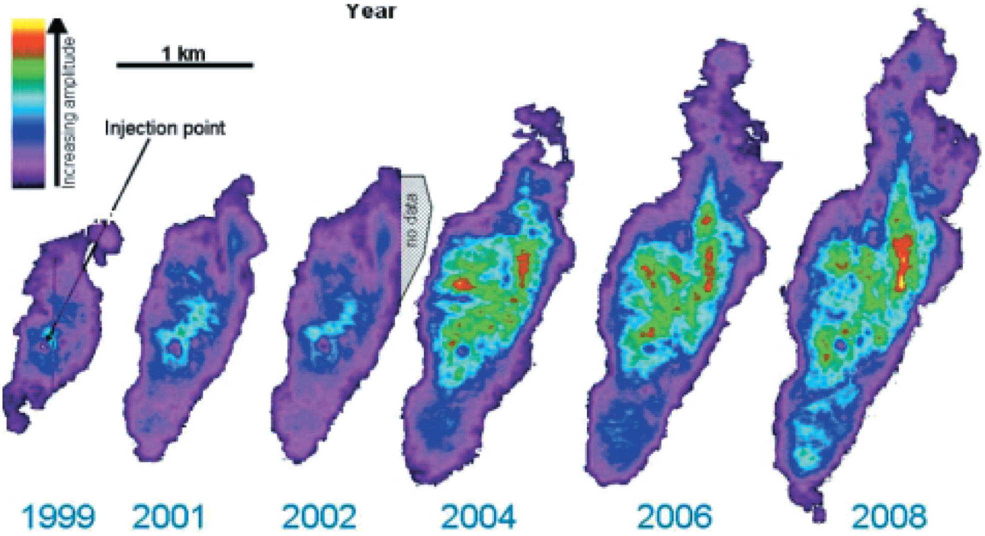

Fig. 4. The time-lapse seismic difference amplitude maps at Sleipner is used to define the lateral extent of the CO_2 plume and to detect potential release into overlying units [8]

Seismic monitoring of CO_2 in the subsurface was first demonstrated as a viable method at the Sleipner CO_2 injection site in the central North Sea [8]. Carbon dioxide injection began at Sleipner in 1996, and a time-lapse seismic program was initiated there in 1999. Six repeat 3-D seismic surveys were acquired from 1999 to 2008, to image the distribution and movement of the CO_2 plume in the Utsira formation, following successive injection stages.

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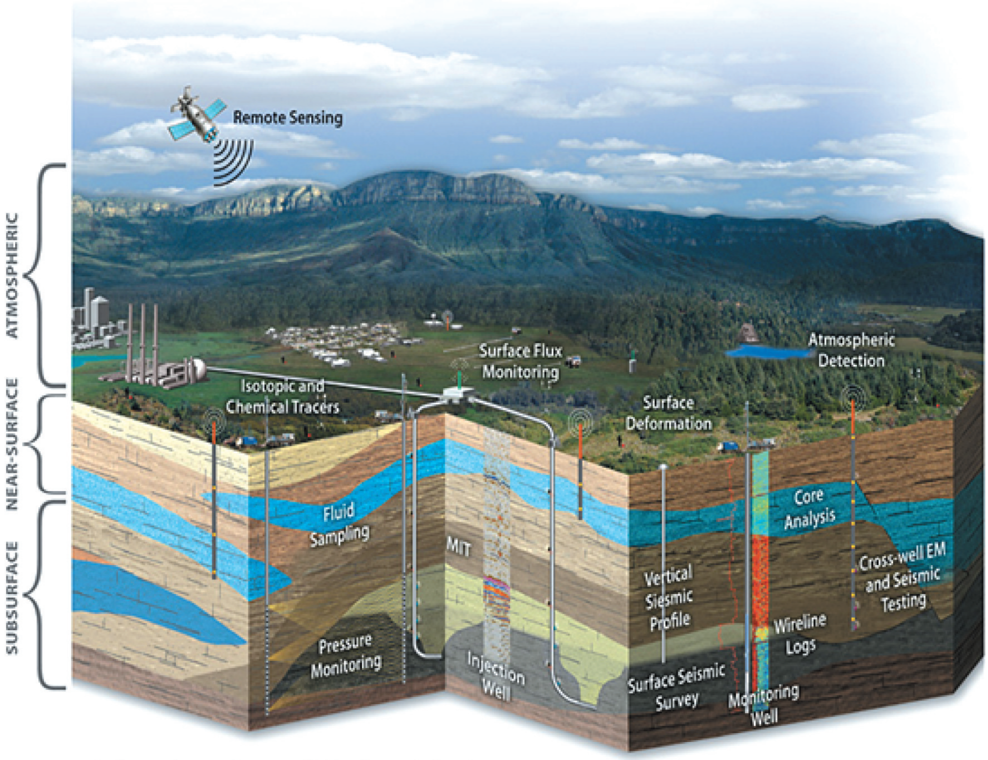
[2] From report by Integrity Obara.

Carbon capture and storage (CCS) is vital to reduce CO_2 emissions to the atmosphere, potentially caple of providing about 20% of the needed reductions in global emissions. A review of research and demonstration projects are important to increase scientific understanding of CCS processes.

Quantitative verification of long-term storage has been demonstrated. A direct measurement of storage efficiency has been made, confirming that CO_2 storage in depleted gas fields can be safe and effective, and that these structures could store globally significant amounts of CO_2. Cost analysis is made based on reasonable assumptions because, just like in oil and gas exploration, significant investment can be made on a site before discovering that it is not suitable for storage (or production). The cost can vary depending on the type of reservoir, weather it is onshore or offshore, deep or shallow reservoir etc.

Near-surface monitoring objectives are; Soil gas monitoring, Crustal deformation, Leak detection, Vegetative stress monitoring and Vadose zone characterization, as depicted in Figure 5.



Background Image Courtesy of Schlumberger Carbon Services, Inc.

Fig. 5. Monitoring zones and methods. Different monitoring zones showing subsurface, near-surface and atmospheric monitoring using different methods [18]

3. RISK ASSESSMENT[3]

The report starts out with discussing the conceptual definition of risk; risk identification, – analysis and – evaluation, where also levels of risk are discussed. This concept is then applied on different aspects of well-bore problems, mechanical aspects of the well and reservoir fluid rock interaction. Risks related to leakage and geomechanics are also discussed.

The level of detail included in a risk assessment should depend on the level of confidence that is required to support various types of reservoir safety decisions. This can be expected to vary with the level of risk posed by a specific reservoir. A guide for handling risks therefore uses a tiered approach to risk assessment. Table 1 [9] provides a summary of the tiered approach. Tier 1 is the simplest approach, comprising a qualitative assessment of risk; Tier 2 introduces basic quantitative analysis and Tier 3 more detailed quantitative methods.

Table 1

Tiered analysis [9]

Tier	Type of Risk Assessment	Description
1	Qualitative	Ranking of potential failure mode, and order of magnitude likelihood and consequences using a descriptive risk matrix. Optional sensitivity analysis
2	Simplified Quantitative	Threshold analysis using hand calculations i.e. with basic calculator. Optional sensitivity analysis
3	Detailed Quantitative	Range of levels. Include system response curves, with range of initiating events (threats) using computer software for risk calculations.Uncertainty dealt with by formal sensitivity to full uncertainty analysis

Models describing risk offer a great opportunity for managers to understand risks, to engage operational actions to manage the performance of their structures (assessment and mitigation), and to demonstrate the safety of the structure over long time periods.

The methodology work flow gathers different steps to go through for risk quantification and for recommending risk mitigation actions to ensure the well integrity performance, are described in Figure 6. Quantification of mechanisms including uncertainties, ageing processes and their impact on the function of a technical system, allows an accurate assessment of the best strategies to design high performance structures or to manage the performance of existing structures.

The principal geomechanics related risk mechanisms have been reviewed. Equations have been provided that identify the parameters influencing these geomechanics-related risks, and enable first-order estimation of the magnitudes of these risks. A risk-based approach is adopted to predict risks associated with CO_2 leakage along the well-bore from a plugged and abandoned well in contact with a CO_2 plume (Fig. 7).

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[3] From report by Emil Gazizullin.

From this approach, quantitative risks associated with well integrity were assessed and operational recommendations for mitigating non acceptable risks were formulated.

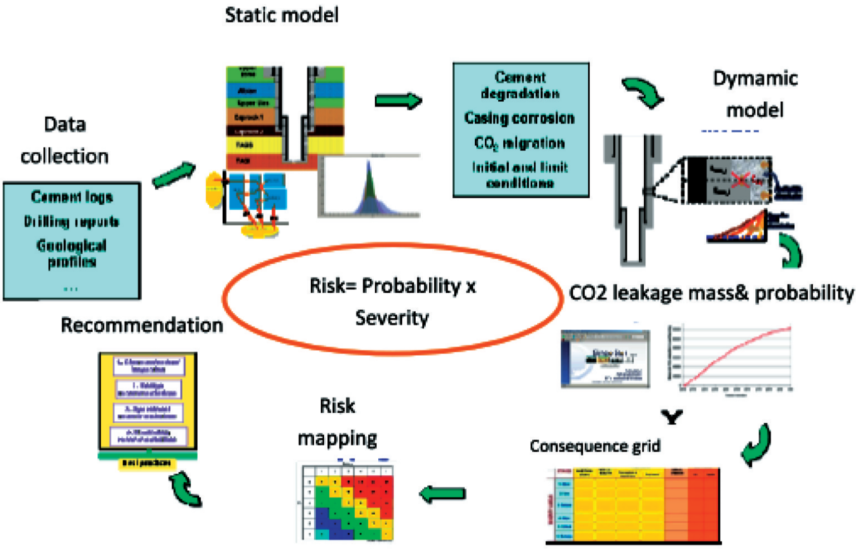

Fig. 6. Methodology workflow [10]

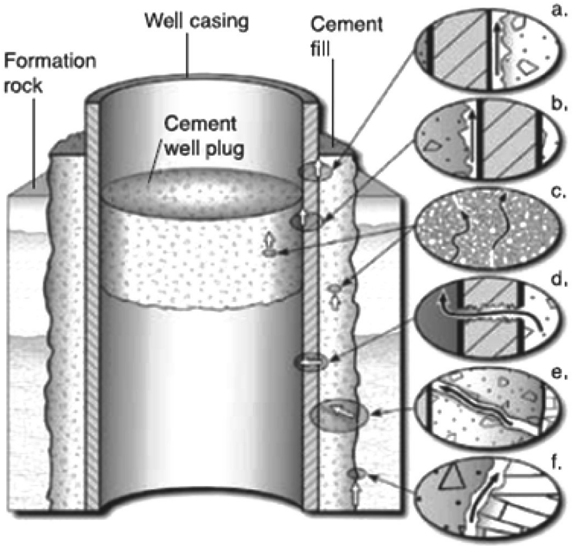

Fig. 7. Possible leakage pathways in an abandoned well: (a) and (b) between casing and cement wall and plug, respectively; (c) through cement plugs; (d) through casing; (e) through cement wall; and (f) between the cement wall and rock [11]

A tiered (complexity) approach has been offered, ranging from qualitative through to quantitative methods of risks assessments. Statistical studies show that leakage risk can be controlled. Both prevention and mitigation measures should be developed and deployed on CO_2-injection wells. Because most well-bore leaks will be of low severity, mitigation can be a very effective risk-management strategy. Leaks can be monitored to predict their evolution and to plan effective intervention without costly shutdowns.

4. ENVIRONMENTAL CONSIDERATIONS OF CO_2 PROJECTS[4]

In this work, a general survey of possible environmental concerns of CCS and CO_2 injection for EOR projects are presented. Various environmental concerns and in some cases propose mitigation techniques already practiced are also reported. Proper understanding of the environmental threats of CCS could inform decision-making and form a foundation for designing sustainable solutions.

CO_2 capture can be applied to fossil fuel power plants, industrial processes and in the fuel production and transformation sectors [12]. Capture technologies are based on those that have been applied in the chemical and refining industries for decades. Three main technology options currently exist for CO_2 capture: post-combustion, pre-combustion and oxyfueling. CO_2 capture requires energy, reduces overall energy efficiency and adds cost. The capture phase represents the largest cost as it requires capture-specific equipment and entails additional energy consumption. Approximately 60–80% of the cost of CCS is attributed to capture, 10–20% to transport and 10–20% to storage (IEF, 2012). Achieving reductions in CO_2 capture costs and their associated risks is critical for sustainable and large scale deployment of CCS.

Carbon capture and storage (CCS) is among the most promising Green House Gas (GHG) reduction technologies (Fig. 8). Its development and deployment offer part of the solution that can contribute, along with energy efficiency and renewable energy, to delivering a sustainable energy future. However, as all kind of technology or even human intervention in nature, CCS processes may involve undesirable effects on the environment.

The environmental impact of carbon capture and storage (CCS) is a critical issue in determining whether this technology should be part of the suite of options used to combat increasing greenhouse gas emissions, both nationally and internationally. As the purpose of CCS technology is to reduce the negative impact of anthropogenic greenhouse gas emissions on the environment, the environmental benefits of CCS need to outweigh the potential environmental risk.

The greatest environmental risk associated with CCS relates to the long-term storage of the captured CO_2. Leakage of CO_2, gradual or in a catastrophic leakage could

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[4] From report by Oduro Takyiwa Susanna and Yen Adams Sokama-Neuyam.

negate the initial environmental benefits of capturing and storing emitted CO_2. On the other hand, CCS has the long-term potential to make a substantial positive impact on the amount of CO_2 emitted into the atmosphere by the stationary energy sector.

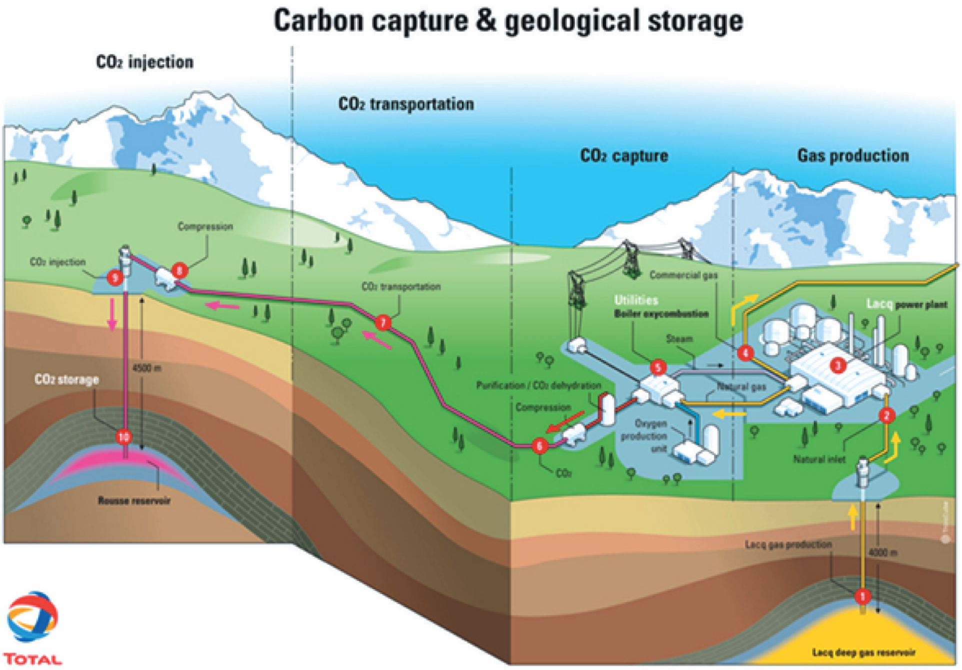

Fig. 8. Carbon capture and storage processes [13]

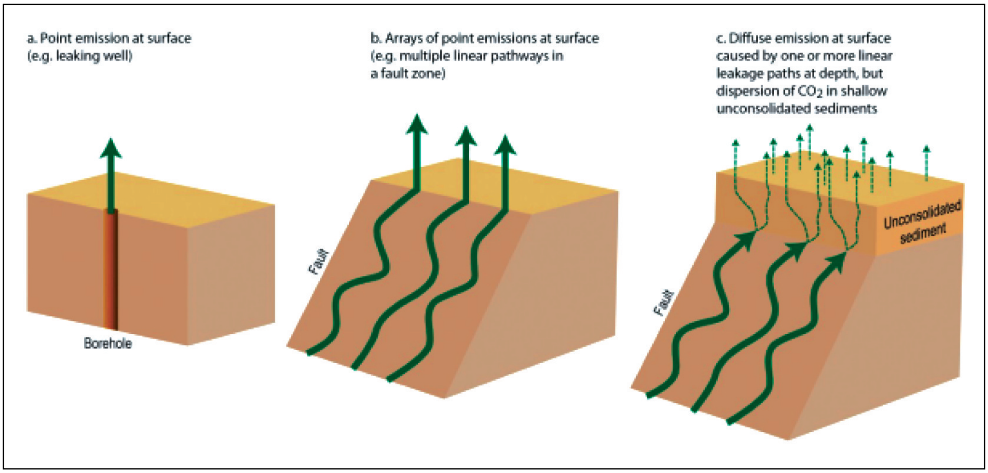

Fig. 9. Schematic illustrations of leakage patterns considered by RISCS [20]

Leakage pathways depend upon the nature of the migration pathways for the CO_2 through the rock, leakage from a storage complex could give rise to different kinds of emission at the earths solid surface. The RISCS project [20] has considered three kinds of main emission pattern.

1. Emissions at single point leaks (a few metres to tens of metres across), most likely due to old improperly sealed wells, although surface expressions of leakage may be considerably wider than the width of a well, owing to dispersion of CO_2 in the shallow subsurface.
2. Emissions at multiple points (each one typically a few metres or tens of metres across) distributed along the intersection between a fault zone and the earths solid surface, such that the leakage points lie within a zone that is much longer than it is wide (perhaps several kilometres to tens of kilometres long and a few metres to tens of metres wide).
3. Diffuse emissions, over a wide area (perhaps up to tens to hundreds of metres across). Figure 9 summarizes the three possible kinds of subsurface leakage of stored CO_2.

The potential risks need to be weighed against the potential benefits, and the possible consequences. Carbon dioxide is part of the atmosphere we breathe and is essential to all life forms and it is odorless and non-toxic. However, as it is denser than air, if it accumulates in low-lying areas in high concentrations, it can prove harmful to humans and animals. Therefore, rigorous risk mitigation strategies should be developed and implemented in order to reduce the risk of CO_2 leakage.

5. HOW TO REDUCE THE LIKELIHOOD OF ENVIRONMENTAL IMPACTS DURING PLUG AND ABANDONMENT[5]

In this report Plug and Abandonment (P&A) is described in great detail. For the most part, Norwegian regulation and practises are being described, but adequate examples of regulation and practises from America (USA) are also included.

As late as in 1934, the first instructions were issued by the Texas Railroad Commission about using cement in P&A operations. Before this time, wells were often plugged by various objects like tree trunks, stones, paper material and similar, as seen in Figure 10. Such objects were not suitable for either stopping hydrocarbons from flowing out from wells, nor to remain stationary when the pressure in the reservoir eventually would increased [14].

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[5] From report by Alexander Steine Johnsen, Preben Emil Haugen and Jann Rune Ursin.

Fig. 10. Wooden tree trunk used as well plug [14]

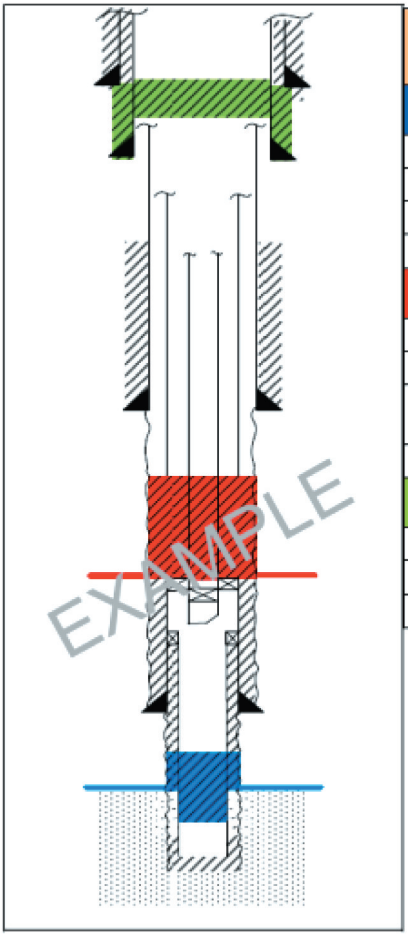
Plug and Abandonment is appearing to be a serious challenge technical as well as economically. This report describes various pats in plug and abandonment, where the following items are explained and described:

- Requirements and regulations.
- Planning of P&A.
- Location and testing of cement plugs.
- How the well barriers are affected by fluids.
- Pressure build-up and aquifer inflow in reservoirs.
- Environmental and remediation.

With respect to P&A, Norwegian requirements and procedures are recorded in Chapter 9 in *NORSOK D-010*. Requirements for barriers in general are described in Chapter 4, in the same publication, while the more quantitative demands and requirements relating to barriers, can be found in Chapter 15 [15].

The facilities regulations are listed as follows:

1. Well barriers shall be designed so that well integrity is ensured and the barrier functions safeguarded for the lifetime of the well.
2. Well barriers shall be designed so that unintentional well influx and outflow to the external environment is prevented, and so they do not obstruct well activities.
3. By temporary abandonment of production for wells without completion string, there shall be at least two qualified and independent barriers.
4. By temporarily and permanently abandonment of a well, barriers shall be designed so that they safeguards well integrity for the maximum time period the well is expected to be abandoned.
5. When plugging of wells, the casings could be cut without damaging the environment. Well barriers shall be designed so that performance can be verified.



Well barrier elements	EAC table	Verification/monitoring
Primary well barrier		
In-situ formation	51	
Liner cement	22	
Casing	2	
Cement plug	24	
Secondary well barrier		
In-situ formation	51	
Casing cement	22	
Casing cement (between casing and tubing)	22	
Cement plug*	24	
Open hole to surface well barrier		
Casing cement	22	
Casing	2	
Cement plug	24	

*Inside tubing.

NOTE Tubing is centralized.

Fig. 11. Well barrier schematic [15]

Well barriers can be divided into *classes* (Fig. 11). Moreover, these classes have different function [15]:

Main well barrier: The first well barrier shall prevent the flow of fluid, oil and gas from a potential source to any surface or formation.

Secondary well barrier: Act as a back-up for the main well barrier. Should halt further flow in the event of failure in the main well barrier.

Cross flow well barrier: Prevent flow between formation where cross flow is not acceptable. Can also function as the main well barrier.

Open hole to surface well barrier: Permanent isolating flow channels from exposed formation to surface after the casing is cut and removed. To prevent harmful fluids from reaching the surface. This well barrier is essentially a environmental barrier.

The report also contain some novel developments related to more time efficient P&A procedural techniques. This new technology will replace today's more conventional plug and abandonment methods and lead to great economical savings in such operations.

A new and more efficient plug method is developed, where the location and setting of the well plug in the annulus of a well, is the main task in P&A. Performing this task properly, and in accordance to requirements and regulations, will reduce probability for future leaks.

The most commonly used method in P&A is the balance approach, even so the twoplug method and dump-bailer methods are also frequently used. A new method for placing cement plugs has emerged, namely the Hydra-Wash, an innovative method form Hydra Wells (Fig. 12).

This method represent an enhancement with respect to the of the quality of the plug set, thus allowing a reduced risk for environmental footprint.

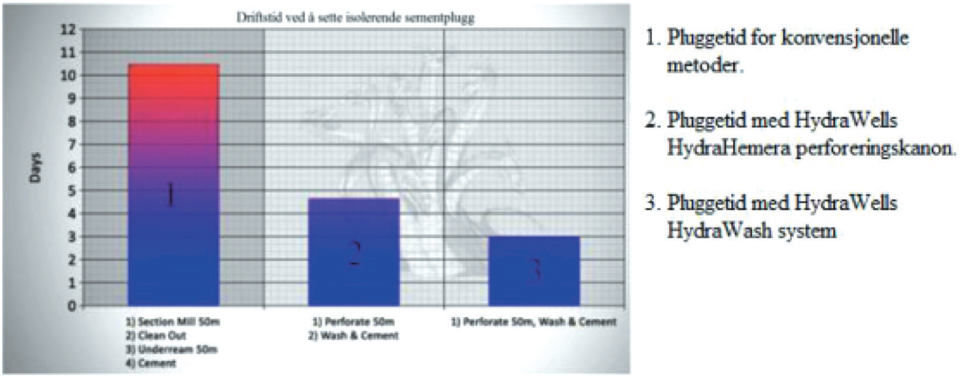


Fig. 12. Comparing time of P&A for different methods [16]

This report address primarily the various considerations related to plug and abandonment operations, but at the same time key points related to how the environment might be affected by improper P&A are also discussed.

Problems with well barriers in temporarily abandoned wells on the Norwegian shelf is a relevant theme. In 2011, Ptil, Sintef andWellBarrier did a study on temporarily abandoned wells (Fig. 13). It was found that there were 193 temporarily abandoned wells on the Norwegian continental shelf, and 38% of these had some failures with one or more well barriers. Some temporary abandoned wells were more than 40 years old, and 8 unnamed operators were given the responsibilities to rectify those wells with integrity problems [17]. During the past, all 8 operating companies have submitted plans for the repair of the wells.

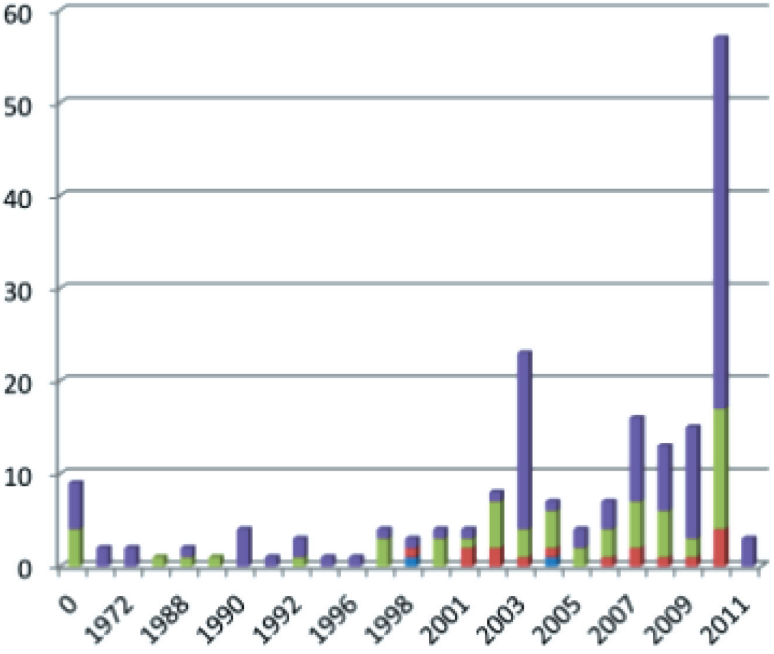


Fig. 13. Investigation conducted by Ptil, Sintef and WellBarrier [17].
The blue column are "healty" wells, the green are wells with only one broken barrier, read indicate a broken barrier that might lead to leackage

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