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# D8.3

# Assessment of Oil & Gas Remediation Technologies for $CO_2$ Wells

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**Public abstract**


This report is part of the research project MiReCOL (Mitigation and Remediation of $CO_2$ Leakage) funded by the EU FP7 programme. The research activities aim at developing a handbook of corrective measures that can be considered in the event of undesired migration of $CO_2$ in subsurface reservoirs both through geology formations and along wells. Work package 8 (WP8) addresses the O&G industry best practices for remediation of well leakages and consists of three tasks: 1) Task 8.1 Description of leakage scenarios 2) Task 8.2 Overview of available technologies and methods 3) Task 8.3 Assessment of remediation technologies and gaps.

Task 8.3 focusses on assessment of remediation technologies. The technologies and methods described in Task 8.2 and well leakages scenarios defined in Task 8.1 will be assessed in this report. This task will also provide inputs to SP5 containing models and guidelines.

A generic and systematic approach has been used for a discussion of the most critical well barrier elements (WBEs). A large portion of the referred findings and discussions is based on personal field experiences by the authors and well integrity studies for the O&G industry and authorities. Different leakage scenarios for an operating $CO_2$ well with 14 WBEs have been mapped and discussed together with preventive actions based on field experience. Technology gaps for mitigation and remediation operations for leaking wells are given.

The following topics are addressed:

- Key well barrier elements and monitoring methods connected to technology solutions
- Summary of well leakage scenarios as described in a previous report (Task 8.1) to address remediation methods
- Common O&G remediation actions
- Common O&G preventive measures to reduce risk of well barrier failures
- Technology gaps

# TABLE OF CONTENTS

Page

## Abbreviations

| | |
|---|---|
| C | Cost impact for risk assessment |
| CBL | Cement bond log |
| Cr | Chromium |
| CT | Coiled tubing |
| FIT | Formation integrity test |
| HSE | Health, safety and environment |
| LOT | Leak-off test |
| MTTF | Mean time to failure |
| NCS | Norwegian continental shelf |
| O&G | Oil and Gas |
| P&A | Plug and abandonment |
| PBR | Polished-bore receptacle |
| PIT | Pressure integrity test |
| PWC | Perforation, washing, and cementing |
| T | Time and schedule impact for risk assessment |
| V0 | Special grade V0 gas test |
| WBE | Well barrier element |
| WH | Wellhead |
| WIMS | Well integrity management system |
| XLOT | Extended leak- off test |
| XT | X-mas tree |

# 1 INTRODUCTION

This report is part of the research project MiReCOL (Mitigation and Remediation of $CO_2$ Leakage) funded by the EU FP7 programme. The research activities aim at developing a handbook of corrective measures that can be considered in the event of undesired migration of $CO_2$ in subsurface reservoirs both through geology formations and along wells. Work package 8 (WP8) addresses the O&G industry best practices for remediation of well leakages and consists of three tasks: Task 8.1 Description of leakage scenarios, Task 8.2 Overview of available technologies and methods, and Task 8.3 Assessment of remediation technologies and gaps. This report addresses Task 8.3 and provides main inputs to SP5 containing models and guidelines.

For this study, a generic and systematic approach has been used for a discussion of the most critical well barrier elements (WBEs). A large portion of the referred findings and discussion is based on personal field experience and well integrity studies for the O&G industry and authorities. Different leakage scenarios for an operating $CO_2$ well with 14 WBEs have been mapped and discussed together with preventive measures based on field experience. Technology gaps for mitigation and remediation operations for leaking wells are given.

 

# 2 WELL BARRIER ELEMENTS

The NORSOK standard D-010 (Rev.4, June 2013), the Norwegian Standard for well integrity in drilling and well operations, has been used as a useful reference for this study.

Different types of $CO_2$ wells can be referred to such as; producer, injector, monitoring, temporary and permanently plugged and abandoned wells (P&A). The well barrier envelopes and barrier elements can be different for each of the well applications. However, for simplicity only one type of well has been chosen and a typical $CO_2$ well injector is being used for this report to demonstrate the well integrity envelope with different WBEs and leakage scenarios. The schematics of such a well are illustrated in *Figure 1* and used as a reference case.

Due to limited $CO_2$ well integrity data, experience and best practice from the oil and gas industry have been used. It can be noted that the best analogue O&G well for $CO_2$ applications is an operating gas well with high $CO_2$ content and high gas oil ratio (GOR). The fundamental well design for O&G and $CO_2$ are almost identical except for material selection which are more critical for $CO_2$ wells. According to the Oil & Gas UK guidelines, the high concentration of $CO_2$ can have negative impact on WBEs. Typical effects are:

- Potential faster degrading of cement in the presence of water
- Accelerating the corrosion rate of steel
- Dehydration and fracturing of shales leading to leakage through cement-rock interfaces and cap rock

In this report the overall well integrity of $CO_2$ well is discussed and mapped based on the individual WBEs. A WBE is defined as a physical element to prevent flow and will in combination with other WBEs form a well barrier. The key WBEs are numbered and labelled as shown in *Figure 1*and listed in *Table 1*. The different WBEs are grouped as “primary” and “secondary” well barriers. A primary well barrier is the first well barrier that prevents flow from a potential source of inflow while a secondary well barrier acts as a back-up. The primary well barrier envelope is drawn as a blue line while red is used for the secondary well barrier envelope. The WBEs are mainly consisting of; subsurface formation (rock), metal (e.g. casing), cement, and elastomer (e.g. packer and seals).

In total 14 WBEs have been listed for a typical operating $CO_2$ well; 6 primary and 8 secondary WBEs.

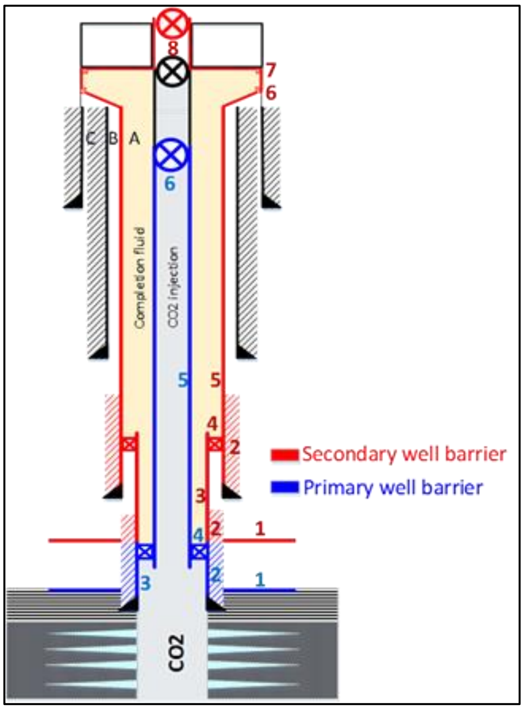


*Figure 1 Well barrier schematics with WBE numbering for a typical operating $CO_2$ well.*

*Table 1 Key well barrier components.*

| No. | Well barrier component |
|---|---|
| PRIMARY WELL BARRIER | |
| 1 | In-situ formation (impermeable and moveable) |
| 2 | Liner cement (below production packer) |
| 3 | Liner tubular (below production packer) |
| 4 | Production packer |
| 5 | Completion string (tubing, components) |
| 6 | Downhole safety valve (including control line) |
| SECONDARY WELL BARRIER | |
| 1 | In-situ formation (impermeable and moveable) |
| 2 | Casing cement (above production packer) |
| 3 | Production liner (above production packer) |
| 4 | Production liner packer |
| 5 | Production casing |
| 6 | Casing hanger seal |
| 7 | Tubing hanger seal (neck seal) |
| 8 | Wellhead / surface tree |

# 3 WELL BARRIER TESTING AND MONITORING

Key WBEs for the primary and secondary well barrier envelopes are listed in Table 2 together with initial testing and verification methods during installation and monitoring methods during well operations.

The industry practice for verification of the WBEs during the well construction phase is by *pressure testing* using drilling fluid (mud). The testing period for an oil and gas well is rather short and typically 10 to 15 minutes. The mud often contains solid particles and also has high viscosity. For gas and $CO_2$ wells, mud may not be a good test fluid. It has been experienced that in some cases, despite a positive pressure test, the well started to leak once put on operation. For example, this was seen from well integrity data which was collected through a Sintef task force studies for Norsk Hydro in 2005 – 2007. Gas will leak more easily through seals and tubing connections than mud so it cannot be considered as an ideal testing fluid for gas / $CO_2$ wells.

The integrity test requirements described in governing guidelines and standards do not distinguish between oil and gas wells. However, it may be beneficial to develop a new and more representative testing criteria's for $CO_2$ wells. For instance, one should use low or no solid mud for pressure testing during the installation phase if practically feasible and the testing period should be increased. The lack of a fit for purpose integrity testing of $CO_2$ wells is considered as a technology gap.

In the operation phase the two main well integrity testing and monitoring methods are:

1. Period leak testing of the downhole safety valves, wellhead and X-mas tree valves
2. Continuous pressure monitoring through annuli valves (e.g. production packer, tubing and casing leaks)

For WBEs "*in-situ formation*" and "*casing / liner cement*" it may not be possible to implement direct and continuous monitoring solutions after the well has been put into operation. In some cases the leaks occur through a fracture or fault and the released fluid enter to another permeable formation located at a shallower depth. These kind of leaks are referred to as underground leaks or cross flow. The leakage through or along casing / liner cement can be observed as a pressure build-up at the wellhead if a leakage path is present. This is referred to as sustained casing pressure. Even if there is no observed sustained casing pressure at the surface, the well may still have an integrity problem deep down. For instance, a poor liner cement may not be detected if located below good casing cement (WBE number 2 in *Table 2*).

It will be beneficial to develop new monitoring methods and verification technologies for "*in-situ formation"* and *"casing / liner cement"* (WBE 1 & 2). One may use reservoir pressure data in offset monitoring wells to investigate leakages through in-situ formations. For casing / liner cement, one may run advanced logging and imaging tools but this will have impact on the operational costs. In the presence of a production tubing there is no commercial available tools to log through multiple tubulars.

*Table 2 Well barrier component and verification and monitoring methods.*

| No. | Well barrier component | Initial test and verification | Monitoring during operation |
|---|---|---|---|
| PRIMARY WELL BARRIER | | | |
| 1 | In-situ formation (impermeable and moveable) | FIT, LOT, XLOT, field model | n/a after initial verification |
| 2 | Liner  cement (below production packer) | CBL, PIT, volumetric calculation | n/a after initial verification |
| 3 | Liner tubular (below production packer) | Leak test (differential pressure) | n/a after initial verification |
| 4 | Production packer | Differential pressure in direction of flow | Pressure monitoring annulus A |
| 5 | Completion string (tubing, components) | Pressure testing | Periodic leak testing |
| 6 | Downhole safety valve (including control line) | Differential pressure in direction of flow | Periodic leak testing |
| SECONDARY WELL BARRIER | | | |
| 1 | In-situ formation (impermeable and moveable) | FIT, LOT, XLOT, field model | n/a after initial verification |
| 2 | Casing cement (above production packer) | CBL, PIT, volumetric calculation | Pressure monitoring annulus A |
| 3 | Production liner (above production packer) | Leak test (differential pressure) | Pressure monitoring annulus A |
| 4 | Production liner packer | Differential pressure in direction of flow | Pressure monitoring annulus A |
| 5 | Production casing | Leak test (differential pressure) | Pressure monitoring annulus B |
| 6 | Casing hanger seal | Leak test | Periodic leak testing |
| 7 | Tubing hanger seal (neck seal) | Leak test | Periodic leak testing |
| 8 | Wellhead / surface tree | Leak test | Periodic leak testing |

# 4 CLASSIFICATION OF WELL LEAKAGES

Well leakage scenarios were discussed in Task 8.1 (Todorovic et al., 2014). Based upon this, we use a "*well leakage classification*" based on; type of WBEs, time, and location of leaks. Well leaks can occur through a single or multiple WBEs. The classification system referred to in this report is based on experience from a task force study on the Norwegian Continental Shelf (NCS) including eight fields and several hundred wells (Abdollahi et al., 2007).

If one of the primary WBEs leak, the secondary WBEs may control the leak and this is referred to as an "*internal leaks*". However, if the leak penetrates through both primary and secondary WBEs, the leak is referred to as an "*external leaks*" and is more critical as the released fluid may harm both people and the environment.

*Figure 2* illustrates the different well leakage scenarios. Leaks that penetrate through primary WBEs are shown in blue arrows while leaks through secondary WBEs are shown in red and leaks through both primary and secondary WBEs are shown in purple.

The Norwegian regulations describe a two independent well barrier philosophy (NORSOK, 2013). Normal well operations are generally stopped and operators have to implement measures to repair any failed WBEs. In some cases, the operator may apply for dispensation if only one barrier fails but a careful monitoring program will be needed with a plan for repair.

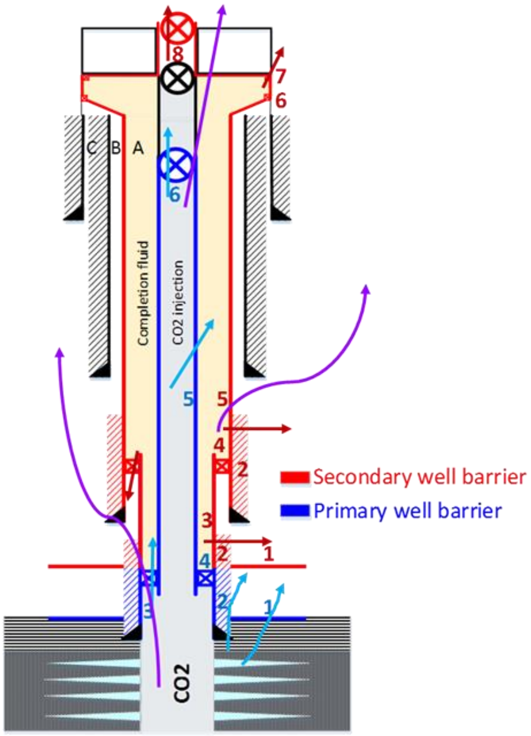


*Figure 2 Well leakage scenarios; leak crosses primary (blue) secondary (red) and both primary & secondary (purple), from PRORES.*

The time factor of the leaks is important for investigation of the root causes of the failures. In this report the terminology "*early leaks*" and "*late leaks*" are introduced. Early leaks are referred to those leaks that occur after a short period of time after the installation and testing of the WBEs. A typical early leak as reported in well integrity studies on the NCS (e.g. Norsk Hydro task force study) is described as a leak occurring after approximately one month after the well has been put on operation. A late leak are referred to leaks that occur later than this period.

The reasons behind early leaks are often related to:

- Improper well design
- Wrong material selection
- Improper installation of WBEs
- Operational envelope outside the well design envelope
- Insufficient / non effective testing methodology

The reasons behind late leaks are often related to:

- Corrosion and erosion
- Fatigue and degradation of materials
- Loads on WBEs outside initial design due to change of well applications (e.g. converting producer to injector)

Typical conditions leading to leaks are thermal and mechanical loads due to well interventions and stimulations.

# 5 MITIGATION AND REMEDIATION OF WELL LEAKAGES

The report D8.2 has highlighted on some technologies for remediating of leaking wells (Vrålstad et al., 2014). In this chapter we give some operational practices for mitigation and remediation actions based on individual WBE failures as listed in the previous chapter. Actions are referred to as common practices and technologies implemented in the O&G industry. In addition some new ideas are given, based on personal experiences from the authors. The root causes for the well barrier failures are also given. Probabilities for leakages and level of the complexity for remediation have been considered as well. *Table 3* summarizes the findings for the primary well barrier and include well components, cause of failures, remediation practices, probability of failures and consequences. The colour codes are used to define high levels of risk with probability and consequences:

- Green: low
- Yellow: medium
- Red: high

The consequence of failures need to be assessed on a case based study from the individual operator and should be based on: cost impact (C), time and schedule impact (T) and health safety and environment (HSE). The risk evaluation required is qualitative and is based on a detailed description of uncertainty and development of causes and impacts. This has to a large extend to rely on the individual operators experience.

*Table 3 List of causes of WBEs failures and proposed mitigation and remediation actions for individual primary well barrier.*

| No. | Well barrier component | Cause of barrier failure / defect | Mitigation and remediation practice | Probability | Consequences (C, T , HSE) |
|---|---|---|---|---|---|
| PRIMARY WELL BARRIER | | | | | |
| 1 | In-situ formation (impermeable and moveable) | Fractures, faults, permeable cap rock (geology uncertainty), CO2 may cause hydrate and fracturing of shale | • Pump sealing materials (if leakage point is close to the well and possible to access reservoir through well)<br>• Drill relief well, if no access through well | | |
| 2 | Liner cement (below production packer) | Poor cement bonding, micro channelling, improper displacement, casing movements, improper cement composition | • Section milling – rock to rock<br>• Squeeze cement, one-trip P&A<br>• Perforating Washing and Cementing (PWC)<br>• CannSeal (cure micro channel) | | |
| 3 | Liner tubular (below production packer) | Casing wear, casing corrosion & erosion, connection leak, deformation due to formation stress | • Straddle packer<br>• MetalSkin,<br>• Liner milling and run new liner<br>• Squeeze cementation | | |
| 4 | Production packer | Casing wear (non-circular), packer components, casing movements, fatigue | • Run tie-back<br>• Use sealing material on top of packer (CannSeal) | | |
| 5 | Completion string (tubing, components) | Tubing corrosion and erosion, fatigue, connection leak, leakage through completion components, | • Pull old completion and run new completion<br>• Sealing and coating material | | |
| 6 | Downhole safety valve (including control line) | Not functioning properly, scale, corrosion, material degradation | • Remove malfunctioning DHSV and install new DHSV<br>• Run new completion string | | |

According to experience and supporting documents, the production packer including polished-bore receptacle (PBR) together with the completion tubing with downhole equipment and valves have a higher probability for leakages. Production packers are being exposed to high well loads and stresses due to thermal and pressure changes during the well life cycle. Ballooning and piston effects due to pressure changes also generate stresses and loads. In many cases the elastomer material of the packers may not tolerate or even be designed for such higher level of stress.

*Table 4* summarizes the findings for the secondary well barrier.

*Table 4 List of causes of WBEs failures and proposed mitigation and remediation actions for individual secondary well barrier.*

| No. | Well barrier component | Cause of failure | Common mitigation remediation practice | Probability | Consequences (C,T, HSE) |
|---|---|---|---|---|---|
| SECONDARY WELL BARRIER | | | | | |
| 1 | In-situ formation (impermeable and moveable) | Fractures, faults, permeable cap rock (geology uncertainty), CO2 may cause hydrate and fracturing of shale | • Pump sealing materials (if leakage point is close well and possible to access reservoir through well)<br>• Drill relief well, if no access through well | | |
| 2 | Casing cement (above production packer) | Poor cement bonding, micro channelling, improper displacement, casing movements, improper composition | • Section milling – rock to rock<br>• Squeeze cement, one-trip P&A<br>• Perforating Washing and Cementing (PWC)<br>• CannSeal (cure micro channel) | | |
| 3 | Production liner (above production packer) | Casing wear, casing corrosion & erosion, connection leak, | • Straddle packer<br>• MetalSkin,<br>• Liner milling and run new liner<br>• Squeeze cementation | | |
| 4 | Production liner packer | Casing wear (non-circular), packer components, casing movements, fatigue | • Run tie-back<br>• Use sealing material on top of packer (CannSeal) | | |
| 5 | Production casing | Casing wear, casing corrosion & erosion, connection leak, | • Straddle packer<br>• MetalSkin,<br>• Liner milling and run new liner<br>• Squeeze cementation | | |
| 6 | Casing hanger seal | Wrong material, casing and wellhead movements, design envelope outside operating envelope | • Pull casing and run new liner / casing<br>• Use sealing material on top of packer (CannSeal) | | |
| 7 | Tubing hanger seal (neck seal) | Wrong material, tubing movements due to hot / cool fluid production / injection, high axial load due to ballooning, design envelope outside operating envelope | • Pull completion tubing and run new completion<br>• Use sealing material on top of packer (CannSeal) | | |
| 8 | Wellhead / surface tree | Design capabilities exceeded in operation, poor cleanliness, erosion, corrosion, improper sealing element, sand production, vibration, | • Chemical sealant<br>• Workover of XT / WH<br>• Replace valves | | |

For summary, the mitigation and remediation practices for primary and secondary well barrier leakages are listed below:

- Squeezing different sealing materials (cement, polymer, etc.) in different methodologies (PWC, bullheading, squeeze, etc.)
- Drill relief well, if no access to the leaking well
- Section milling of damaged tubulars
- Cover and isolate the leakage point(s) by use of extra a short tubular (e.g. liner) and straddle packer
- Pull whole leaking completion string and run new completion string
- Pull and remove leaking completion components and install new components

# 6 PREVENTIVE ACTIONS

The experience from the O&G industry on leaking wells has shown that mitigation and remediation actions can be complex and costly. On this background, a chapter on preventive actions are also included as a guide for the construction of more robust $CO_2$ wells.

*Table 5* and *Table 6* list potential preventive actions to reduce the risk of WBE failures. These actions should be implemented in the planning and installation phases.

*Table 5 Proposed preventive actions in the planning phase for primary WBEs.*

| No. | Well barrier component | Leakage preventive measures |
|---|---|---|
| Primary well barrier | | |
| 1 | In-situ formation (impermeable and moveable) | • Provide high quality seismic to improve reservoir imaging and cap-rock sealing.<br>• Provide logs, core, FIT from cap-rock.<br>• Use of abandoned depleted gas fields for CO2 injection (proven cap-rock sealing). |
| 2 | Liner cement (below production packer) | • Centralize and rotate liner while cementing to achieve good cement bonding.<br>• Run cement long to verify cement bonding and top of cement.<br>• New cement material and cement compositions to prevent micro channel, resistance against corrosive environment, tolerate against temperature and pressure changes during well life cycle. |
| 3 | Liner tubular (below production packer) | • Select fit-for-purpose liner with high connection performance (high Cr percentage, coated pipe).<br>• Minimize casing wear during well construction.<br>• Choose deeper depth for production packer as possible to cover liner. |
| 4 | Production packer | • Use high standard sealing element such as V0 elastomer seal, V0 metal-to-metal seal<br>• Optimize packer setting depth (avoid depths with high casing non-circular). |
| 5 | Completion string (tubing, components) | • Use high quality tubing, high Cr percentage, coated pipe, metal-to-metal seal connection<br>• Evaluate revolutionary solution such as joint-less pipe (e.g. CT). |
| 6 | Downhole safety valve (including control line) | • Deploy high reliable and robust down hole safety valve (e.g. Exprosoft database). |

*Table 6 Proposed preventive actions in the planning phase for secondary WBEs.*

| No. | Well barrier component | Leakage preventive measures |
|---|---|---|
| Secondary well barrier | | |
| 1 | In-situ formation (impermeable and moveable) | • Provide high quality seismic to improve reservoir imaging and cap-rock sealing.<br>• Provide logs, core, FIT from formations above cap-rock.<br>• Consider overburden formations (permeable/impermeable) with respect of height of casing cement<br>• Use of abandoned depleted gas fields for CO2 injection (proven cap-rock sealing). |
| 2 | Casing cement (above production packer) | • Centralize and rotate liner while cementing to achieve good cement bonding.<br>• Run cement long to verify cement bonding and top of cement.<br>• New cement material and cement compositions to prevent micro channel, resistance against corrosive environment, tolerate against temperature and pressure changes during well life cycle. |
| 3 | Production liner (above production packer) | • Select fit-for-purpose liner with high connection performance (high Cr percentage, coated pipe).<br>• Minimize casing wear during well construction.<br>• Choose deeper depth for production packer as possible. |
| 4 | Production liner packer | • Use high standard sealing element such as V0 elastomer seal, V0 metal-to-metal seal.<br>• Optimize packer setting depth (avoid depths with high casing non-circular). |
| 5 | Production casing | • Select fit-for-purpose casing with high connection performance (metal-to-metal seal, high Cr percentage, coated pipe).<br>• Minimize casing wear during well construction.<br>• Design fit-for-purpose completion fluid (packer fluid), non-corrosive, durable and compatible fluid. |
| 6 | Casing hanger seal | • High standard and fit-for-purpose casing hanger for CO2 injection / production, high capacity load, non-corrosive materials. |
| 7 | Tubing hanger seal (neck seal) | • High standard and fit-for-purpose tubing hanger for CO2 injection / production, high capacity load, non-corrosive materials. |
| 8 | Wellhead / surface tree | • High standard and fit-for-purpose wellhead equipment and X-mas tree, non-corrosive materials. |

# 7 STATISTICS ON LEAKING WELLS

Statistics on leaking wells are important source of information for the improvement of well integrity management. One may investigate robustness and reliability of individual WBEs based on the mean time to failure (MTTF) data. According to the experience of the authors such statistics for $CO_2$ leaking wells are not yet available. However, there are studies and reports for O&G well integrity that are relevant and can be used. Well integrity studies on the Norwegian Continental Shelf (NCS) have given useful information on the nature of leaks and root causes. Abdollahi (2007) mapped leaking wells from three oil fields on the NCS as a part of his PhD thesis. Eight kinds of leakages were mapped and ranked from a severity point of view as shown in *Figure 3*. Together with other sources of information such as production history and well operations, important well integrity trends can be revealed and will enhance future well robustness. It is advised to develop well integrity management software and well components reliability data bases for $CO_2$ wells as been used in the oil and gas industry.

Typical MTTF for an oil production well is experienced to be around seven years (Abdollahi et al., 2007). Injector wells have the tendency to leak earlier due to higher pressure and temperature cycling. For $CO_2$ wells, the MTTF can be expected to be even shorter due to a more corrosive environment. The use of high quality and corrosive resistant materials and improved testing procedures can prolong the well life cycle for $CO_2$ wells.

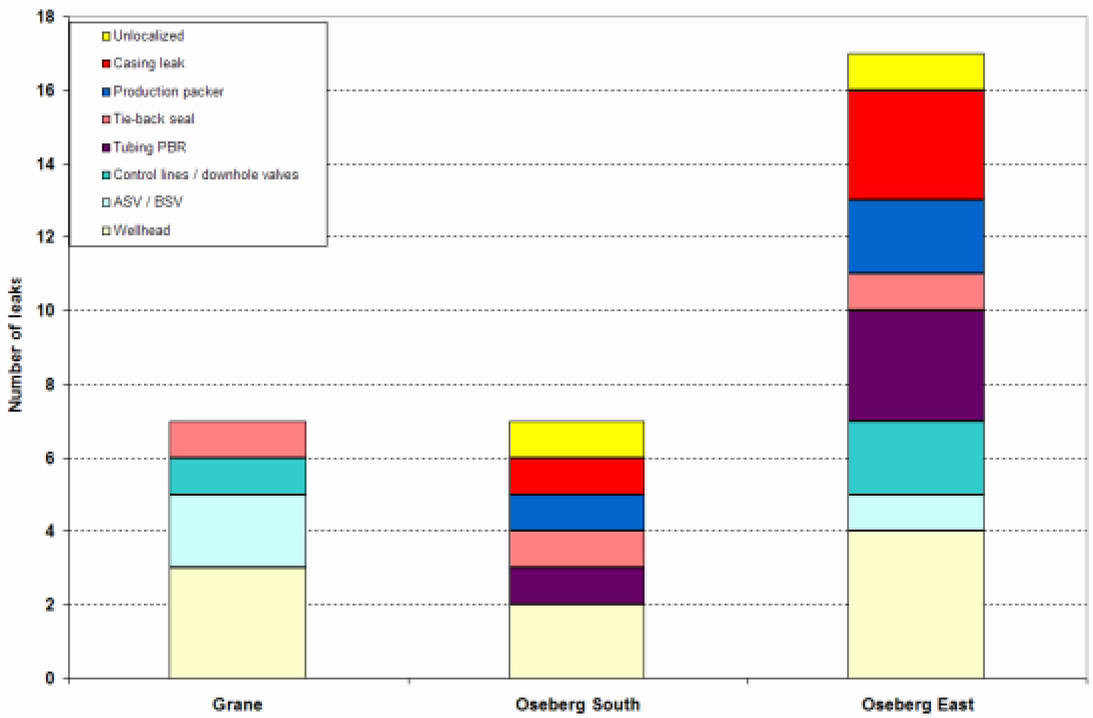


*Figure 3 Example showing well leakage statistics for three fields on Norwegian Continental Shelf (Abdollahi, PhD thesis, 2007).*

# 8 TECHNOLOGY GAPS

This chapter summarizes technology gaps for more robust $CO_2$ well design.

Well integrity testing during the installation phase is critical. The pressure testing procedure should be improved for $CO_2$ wells. Longer test periods and the use of new testing fluid such as Nitrogen for V0 gas-tight rating of downhole completion and components should be considered.

Another important technology gap is related to the re-installing of annular well barriers and verification. Well integrity failure due to poor annulus cement or lack of integrity behind casing string normally requires section milling. This operation is both expensive and associated with several operational risks. For well plugging and abandonment (P&A), the O&G industry is looking for new and cost efficient technologies for annular barrier replacement without section milling and tubular removal. One approach is the use of so called PWC (perforate, wash and cement) technology. Even more challenging is the placement of annular cement barrier behind multiple casing strings. As an example, the service companies HydraWell and Archer are working on new technologies to fill this technology gap. This technology is still in its infancy and needs further development and qualification. One important challenge is the verification and testing of newly installed annular cement barriers. PRORES is currently working on a concept called One-trip P&A which is targeting operational efficiency for annular cement installation and integrity verification.

Technology gaps are also related to logging of the well status including cement bonding behind two or multiple casing strings. For instance, through tubing logging operations without the need to pull the production tubing has great potential for cement bond logging behind the 9-5/8" casing.

Alternative and improved materials to conventional cement is much sought after and is critical for $CO_2$ wells. The sealing requirements are related to many parameters such as; long durability, impermeable, non-shrinking, non-brittle, deformable, gas tight, chemically stable, etc. Recent achievements with use of low viscosity and particle free resin systems have a great potential as for example the ThermaSet material from WellCem.

Efficient and reliable downhole sealing material placement techniques are also crucial to achieve a robust WBE installation. The main challenges of today's practices are related to cement contamination and shrinkage.

Continuous barrier monitoring of in-situ formations and cement behind liner is a great challenge. Some of these issues are covered in other MiReCOL work packages under SP2.

# 9 CONCLUSIONS

Altogether, fourteen key well barrier elements important to the integrity of $CO_2$ wells have been mapped and discussed in this report. Knowledge and experience from the oil and gas industry relevant to $CO_2$ wells have been used to classify well leakage scenarios. Methods and technology for mitigation and remediation of leaking $CO_2$ wells are discussed, including preventive measures.

Important findings on preventive and corrective countermeasures for each WBE are summarized in schematics and tables.

Some of the identified technology gaps are listed below:

- Improved well testing procedures and criteria during the construction and well barrier installation phase to be more suitable for gas / $CO_2$ wells
- Re-installing of annular cement and barrier verification through multiple casing strings
- Through tubing cement bond logging for external casing cement
- Alternative sealing materials to conventional cement with improved long term properties
- Continuous monitoring of well integrity of in-situ formations and liner cement

In addition, well integrity management system for $CO_2$ wells should be implemented as routinely used in conventional oil and gas operations.

# 10 REFERENCES


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