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SECURE – Subsurface Evaluation of Carbon capture
and storage and Unconventional risks

REPORT ON REMEDIATION STRATEGIES FOR TUBINGS AND CEMENT SHEATHS

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Public introduction

Subsurface Evaluation of CCS and Unconventional Risks (SECURE) is gathering unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to underpin subsurface geoenergy development. The main outputs of SECURE comprise recommendations for best practice for unconventional hydrocarbon production and geological CO₂ storage. The project is funded from June 2018–May 2021.

The project is developing monitoring and mitigation strategies for the full geoenergy project lifecycle; by assessing plausible hazards and monitoring associated environmental risks. This is achieved through a program of experimental research and advanced technology development that includes demonstration at commercial and research facilities to formulate best practice. We will meet stakeholder needs; from the design of monitoring and mitigation strategies relevant to operators and regulators, to developing communication strategies to provide a greater level of understanding of the potential impacts.

The SECURE partnership comprises major research and commercial organisations from countries that host shale gas and CCS industries at different stages of operation (from permitted to closed). We are forming a durable international partnership with non-European groups; providing international access to study sites, creating links between projects and increasing our collective capability through exchange of scientific staff.

Executive report summary

Well integrity has become a special focus in the O&G industry, as well as in research communities, in the recent years, especially after the catastrophic Macondo blowout in 2010. Maintaining well integrity throughout the life cycle of a well is equally important for O&G production and CO₂ storage. Statistics on different incidents of well integrity issues point out that the most vulnerable well components are tubing, casing and cement sheath.

The aim of Work Package 5 (WP5) in the SECURE project is to establish best practices for remedial and mitigation technologies and strategies which would reduce risk for shale gas and CO₂ storage operations. Several potential remediation technologies will be identified and their suitability and effectiveness for risks associated with geoenergy operations will be assessed.

The original aim of this deliverable was to address remediation strategies for tubing and cement sheath only, with the focus on the cement/casing bond failure. Another deliverable (D5.3 Report on remediation strategies for tubing and casings) was planned to address remediation of leakage through tubing and casing mainly caused by corrosion and wear. However, loss of integrity or leakage cannot be meaningfully addressed by looking at different leakage pathways independently of the well barrier envelopes. Moreover, different causes of leakage and failure of different well components often result in application of similar remediation strategies and use of the same technologies that are common practice in the O&G industry. This report will therefore also include a review on the remediation strategies for casings.

The aims of this report are to:

- (1) Describe well barrier approach to well integrity using the NORSOK D-010 standard, review possible leakage scenarios for CO₂ wells and use the same approach to address possible leakage scenarios from shale gas wells.*
- (2) Review remediation strategies and technologies that can be applied to failure of tubing, casing and cement sheath. The following remediation strategies and technologies are reviewed in this report: squeeze cementing; alternative sealing materials; and casing and tubing repair.*
- (3) Describe what is novel in the activities in the SECURE project compared to the work done in the previous related EU projects especially related to leakage remediation and alternative*



sealing materials. Describe the experimental plan for the combined tasks in WP2 on risk assessment strategies and WP5 related to leakage remediation and testing of alternative sealants.



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Figure 2 Schematic illustration of well barriers for a typical active shale gas well with a horizontal interval within the reservoir. Primary well barrier is highlighted in blue, and secondary in red. Different WBEs are numbered as follows: (1, 7) in-situ formation; (2, 8) liner cement; (3, 9) liner; (4) production packer; (5) production tubing; (6) DHSV; (10) liner packer; (11) production casing; (12) casing hanger; (13) tubing hanger; (14) wellhead. Some possible leakage pathways are shown by blue, red and black arrows which indicate failure of one WBE within the primary well barrier, one WBE within the secondary barrier and multiple WBEs, respectively. Adapted after (NORSOK D-010, 2013; Vrålstad et al., 2015; Gawel et al., 2015). 12

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1 Introduction

Well integrity has become a special focus in the oil and gas (O&G) industry, as well as in research communities in recent years, especially after the catastrophic Macondo blowout in 2010. Maintaining well integrity throughout the life cycle of a well is equally important for O&G production and CO₂ storage. Statistics of gas wells from the outer continental shelf area of the Gulf of Mexico showed that out of about 15,500 producing, shut-in and temporarily abandoned wells, 43 % had Sustained Casing Pressure (SCP) (Brufatto et al., 2003) which indicates presence of gas migration through at least one annulus. The majority of the SCP incidents (about 47 %) occurred in the annulus of the production casing (Brufatto et al., 2003), but there was also a significant number of SCP incidents on the surface casing, intermediate casings and the conductor pipe. Sustained casing pressure or development of annular pressure at the surface is an indication of a breach in zonal isolation (i.e. failure of at least one well barrier) which is typically challenging to locate. In another study, statistics on different incidents with well integrity issues offshore Norway pointed out that the most vulnerable well components are tubing, annulus safety valves, casing and cement, but also failure of packers and wellhead infrastructure was not negligible (Vignes & Aadnøy, 2008). Further on, a comparison of statistics of well failures in the Gulf of Mexico, North Sea UK and North Sea Norway (King & King, 2013), revealed that the major causes of well integrity issues were leakage through tubing and cement. Leakage through connections was identified as the most probable cause of tubing and casing failure (Schwind et al. 2001; Vignes & Aadnøy, 2008; King & King, 2013). Casing deformation due to horizontal shear, axial buckling or hydraulic fracturing-induced fault slip, can be another cause of casing failure, especially in the wells drilled into highly pressurized reservoirs (e.g. unconventional resources) (de Pater & Baisch, 2011; Green et al., 2012; Li et al., 2019). Other common causes of tubing and casing leaks are corrosion, thermal-stress cracking and mechanical rupture (Brufatto et al., 2003). Cement failure can be caused by many different issues such as poor mud displacement prior to cementing, development of channels during hardening, shrinkage of cement, high cement permeability, stress cracking and development of microannuli at the interface with formation or casing (Dusseault et al, 2000; Brufatto et al., 2003; Celia et al., 2005; Zhang & Bachu, 2011).

Best practice for remediation of leakage through different well components has been developed by the O&G industry throughout the decades of O&G exploitation, and to a large extent the existing technologies can be applied to CO₂ leakage (Nelson & Guillot, 2006; Manceau et al., 2014; Abdollahi et al., 2016a). There are, however, still many technology gaps and room for improvement for the existing technologies (Abdollahi et al., 2016b).

1.1 REFLECTION ON PREVIOUS EUROPEAN UNION PROJECTS

Two large European Union projects are especially relevant for the topic of this report – MiReCOL (2014-2017) and M4ShaleGas (2015-2017). The MiReCOL project, funded by European Union's FP-7 programme, covered the mitigation and remediation of CO₂ leakage from three different perspectives: (1) undesired CO₂ migration within the reservoir; (2) CO₂ migration through faults and fractures; and (3) CO₂ migration along the wellbore. The general objective of the MiReCOL project was to develop an interactive web-based tool for selection of a mitigation or remediation measure appropriate for particular cases of CO₂ leakage defined by a user. The first part in the well leakage subproject was review of causes and consequences of well leakage, and description of leakage scenarios for active and abandoned CO₂ wells. The best practice for remediation of O&G wells was reviewed, and an assessment of these remediation methods and technologies for application in CO₂ wells was done. The second part consisted of laboratory testing of different sealant materials that could be used for remediation of CO₂ leakage through wells, and field demonstrations at the Ketzin pilot CO₂ storage site (Germany) and the natural CO₂ field in Bečej (Serbia). Some of the sealant materials that were tested in the MiReCOL project were: CO₂-reactive suspensions, polymer-based gels, cements with a latex-based component and a thermally-setting sealant (Neele et al., 2017).

The general objective of the M4ShaleGas project was to develop science-based best practice recommendations that would minimize the environmental footprint of shale gas exploration and exploitation in Europe. One subproject was dedicated to the environmental impact of subsurface activities: (1) the subsurface impact of hydraulic fracturing and risks of leakage into shallow aquifers; (2) risks of reactivating natural faults and inducing damaging seismicity; (3) seismic monitoring of hydraulic fracturing and gas production; (4) risks of leakage along wellbores; and (5) drilling hazards and well integrity. The well integrity related work packages were focused on shale gas well drilling, completion, production, abandonment and monitoring of well leakage (ter Heege, 2016), which is a highly relevant background for the SECURE project. However, remediation



strategies for different causes of leakage from or within a shale gas well were not addressed in the M4ShaleGas project as a main topic, although this formed a minor side discussion in some of the project reports.

Other European Union projects that are relevant in the context of this report are:

- (1) From the perspective of CO₂ storage – CO₂CARE, SiteChar and ULTimateCO₂.
- (2) From the perspective of exploration and exploitation of shale gas/ unconventional – FracRisk, SHEER and ShaleXenvironment.

Activities related to well integrity in the CO₂CARE project focused on CO₂ well abandonment, well monitoring, well leakage scenarios for pilot storage sites (Ketzin, Sleipner, K12-B), modelling flow along the wellbore and laboratory experiments with CO₂ exposure (for example batch and flow experiments with samples composed of steel casing, cement and sandstone), among other topics (Kühn et al., 2013; Holloway et al., 2013). In the SiteChar project, the most relevant work related to well integrity was: (1) risk assessment of leakage through an onshore well in Denmark penetrating a potential CO₂ storage formation, and options for mitigation and abandonment; and (2) a qualitative risk assessment of CO₂ storage at a depleted hydrocarbon field in Poland (SiteChar, 2012, 2013). In the ULTimateCO₂ project, one work package was dedicated to well integrity, specifically to field (Mont-Terri Underground Rock Laboratory) and laboratory experiments on the sealing ability of wellbore materials and degradation processes upon reaction with CO₂ and brine. However, neither of these projects has addressed directly remediation strategies for different well leakage scenarios.

The main objective of the FracRisk project was assessment of the environmental footprint of shale gas exploitation in terms of seismic activity and undesired release of different contaminants into the environment. One work package was dedicated to mitigation and monitoring strategies associated with leakage events that could arise from shale gas production and waste water injection, which was based on the risk assessment framework developed in another work package. An especially relevant experimental activity was development of a sealing material for leakage mitigation in the well and through the fractures in the shale.¹ However, these results are not publicly available.²

The main objective of the SHEER project was to develop best practices for assessing and mitigating the environmental footprint of shale gas exploration and exploitation. The research was mostly focused on different monitoring methods and risk assessment of shale gas operations. The ShaleXenvironment project had a similar primary objective to FracRisk and SHEER, that is assessment of the environmental footprint of shale gas exploitation in Europe in terms of water usage and contamination, induced seismicity, and fugitive emissions. However, no specific activity was found to be focused on well integrity or remediation of leakage through wells in either SHEER or ShaleXenvironment.

Moreover, a best practice document is being developed that will integrate the research and findings and in the shale gas projects mentioned above (M4ShaleGas, FracRisk, SHEER, ShaleXenvironment). Well integrity from the perspective of shale gas operations will be addressed in this document. However, this is not yet available in the public domain.

1.2 THE AIM OF THIS REPORT

The original aim of this deliverable was to address remediation strategies for tubing and cement sheath only, with the focus on the cement/casing bond failure. Another deliverable (D5.3 Report on remediation strategies for tubing and casings) was planned to address remediation of leakage through tubing and casing mainly caused by corrosion and wear. However, as it is clear from the well barrier approach to well integrity (Vrålstad et al., 2015; NORSOK D-010, 2013), neither loss of integrity nor leakage can be meaningfully addressed by looking at different leakage pathways independently of the well barrier envelopes. Moreover, different causes of leakage and failure of different WBEs often result in application of similar remediation strategies and use of the same technologies that are common practice in the O&G industry (Todorovic et al., 2016a). This report will therefore also include a review on the remediation strategies for casings.

¹ Presentation of the FracRisk project available on the SHEER project website,

<http://www.sheerproject.eu/images/SAM/Day%202/15%20FracRisk%20Blackpool%202017.pdf>.

² Deliverable 6.4 "Report on impact of self healing fluids on migration", data currently confidential, <https://www.fracrisk.eu/communication/project-deliverables>.



The aims of this report are, therefore, to:

- (1) Describe well barrier approach to well integrity based on the NORSOK D-010 standard, review possible leakage scenarios for CO₂ wells (as previously developed in the MiReCOL project) and use of the same approach to address possible leakage scenarios from shale gas wells (supported by the work done in the M4ShaleGas project).
- (2) Review remediation methods and technologies that can be applied to failure of tubing, casing and cement sheath (also largely based on the work done in the MiReCOL project). The following remediation strategies and technologies are reviewed in this report: squeeze cementing; alternative sealing materials; and casing and tubing repair.
- (3) Describe what is novel in the activities in the SECURE project compared to the work done in the previous related EU projects especially related to leakage remediation and alternative sealing materials. Describe the experimental plan for the combined tasks in WP2 on risk assessment strategies and WP5 related to leakage remediation and testing of alternative sealants.

This overview will establish a background for future work in the SECURE project and enable us to choose relevant directions to focus on in the experimental work related to leakage and remediation (WP2 and WP5).



2 Well integrity

In this section leakage scenarios will be briefly described for active and abandoned CO₂ and shale gas wells. The topic of leakage from a CO₂ injection well was covered in detail in the MiReCOL project (Vrålstad et al., 2015). A well barrier failure approach was used in that report, and the same approach will be applied here.

According to the NORSOK D-010 standard, well integrity is defined as "the application of technical, operational, and organizational solutions to reduce risk of uncontrolled release of formation fluids and well fluids throughout the life cycle of the well" (NORSOK D-010, 2013). The well integrity is described by using a concept of well barrier element (WBE) and well barrier. Well barrier element is a physical element which in itself does not prevent flow but in combination with other WBEs forms a well barrier. Well barrier is an envelope of one or several WBEs, and as a whole prevents unintentional flow of fluids from the formation into the wellbore, another formation or to the external environment. The "Two-barrier principle" from the NORSOK D-010 standard implies that two independent well barriers shall be present at all times (i.e. there is no failure) to maintain the well integrity. Failure of one or several WBE(s) in one well barrier means that the entire barrier has failed.

A similar approach to well integrity was used by King & King, and subsequently by Davies et al., but in both cases well barrier was defined as what we here describe as WBE (King & King, 2013; Davies et al., 2014). Multiple barriers in that approach to some degree correspond to well barrier envelope from the NORSOK approach. Distinction was, however, made between well barrier failure and well integrity failure (King & King, 2013), which is an important remark here as well. Well integrity failure occurs when both well barriers (as defined here) fail in such a way that a leakage pathway develops, and there is a source of fluid and a driving force for fluid flow into the surrounding environment (Watson & Bachu, 2009; King & King, 2013; Davies et al., 2014). Degradation or failure of one well barrier increases the risk for well integrity failure, as described by the well categorization approach in the recommended guidelines for well integrity (Borehole Sites and Operations Regulations, 1995; Offshore Installations and Wells Regulations, 1996; Norwegian Oil and Gas Association, 2017). But in such a case, well integrity is not necessarily lost if there is another well barrier(s) that is protecting against the leak into the environment (e.g. surface, seabed or to other permeable zones or aquifers).

As described by Vrålstad et al. and in the Norwegian standard for well integrity (Vrålstad et al., 2015; NORSOK D-010, 2013), a typical active CO₂ well has two well barrier envelopes. A schematic illustration of well barriers for a typical active CO₂ well is shown in Figure 1. Note that all illustrations of wells in this section are simplified so that the main well components are included, with special focus on WBEs that are relevant for this discussion. This example is valid for injection, production or monitoring wells. The primary well barrier envelope consists of the following WBEs (numbered as in Figure 1):

1. In-situ formation
2. Liner cement (below production packer)
3. Liner (below production packer)
4. Production packer
5. Production tubing with components (i.e. completion string)
6. Downhole safety valve (DHSV)

The secondary well barrier envelope consists of the following WBEs (numbered as Figure 1):

7. In-situ formation
8. Liner cement (above production packer)
9. Liner (above production packer)
10. Liner packer
11. Production casing
12. Casing hanger
13. Tubing hanger (neck seal)
14. Wellhead/ X-mas tree with valves

Some possible leakage pathways for an active CO₂ well are also illustrated in Figure 1. Blue and red arrows indicate failure of one WBE within the primary and secondary well barrier respectively, whereas black arrows indicate failure of multiple WBEs. Leakage pathways indicated by the black arrows in Figure 1 can be classified as well integrity failure, according to the definitions given above.



Based on well barrier schematics for a typical gas well capable of flowing and shut-in (section 8.8.1 in NORSOK D-010), well barrier schematics for a typical CO₂ well, and well construction of shale gas wells as described in a M4ShaleGas report (NORSOK D-010, 2013; Vrålstad et al., 2015; Gawel et al., 2015), a schematic illustration of well barriers was developed for a typical active shale gas well, as shown in Figure 2. This is a simplified illustration where only main well components are included, and there may be variations in the well construction for specific cases, but this does not affect discussion about the well barrier. Well construction of a vertical gas well was modified to include a horizontal interval in the production zone, which is a typical case for a shale gas well. Hydraulic fracturing is performed within a selected interval of the production casing which is perforated, but this interval is not included in the primary well barrier. A fresh water aquifer was included at a shallower depth to indicate additional environmental receptors in the shallow subsurface relevant to shale gas wells. Two well barriers are defined, as in the case of a CO₂ well. The primary well barrier envelope consists of the following WBEs (numbered as in Figure 2):

1. In-situ formation
2. Liner cement (below production packer)
3. Liner (below production packer)
4. Production packer
5. Production tubing with components (i.e. completion string)
6. Downhole safety valve (DHSV)

The secondary well barrier envelope consists of the following WBEs (numbered as Figure 2):

7. In-situ formation
8. Liner cement (above production packer)
9. Liner (above production packer)
10. Liner packer
11. Production casing
12. Casing hanger
13. Tubing hanger (neck seal)
14. Wellhead/ X-mas tree with valves

Although the final part of the wellbore (i.e. within the reservoir) in a shale gas well may be horizontal, there is no essential difference compared to a CO₂ well from the perspective of well barriers and WBEs. Some possible leakage pathways for an active shale gas well are also illustrated in Figure 2. Blue and red arrows indicate failure of one WBE within the primary and secondary well barrier respectively, whereas black arrows indicate failure of multiple WBEs. Leakage pathways indicated by the black arrows in Figure 2 can be classified as well integrity failure. As it can be seen from Figure 1 and Figure 2, possible leakage scenarios are essentially the same for the CO₂ and shale gas wells from the well barrier failure approach.

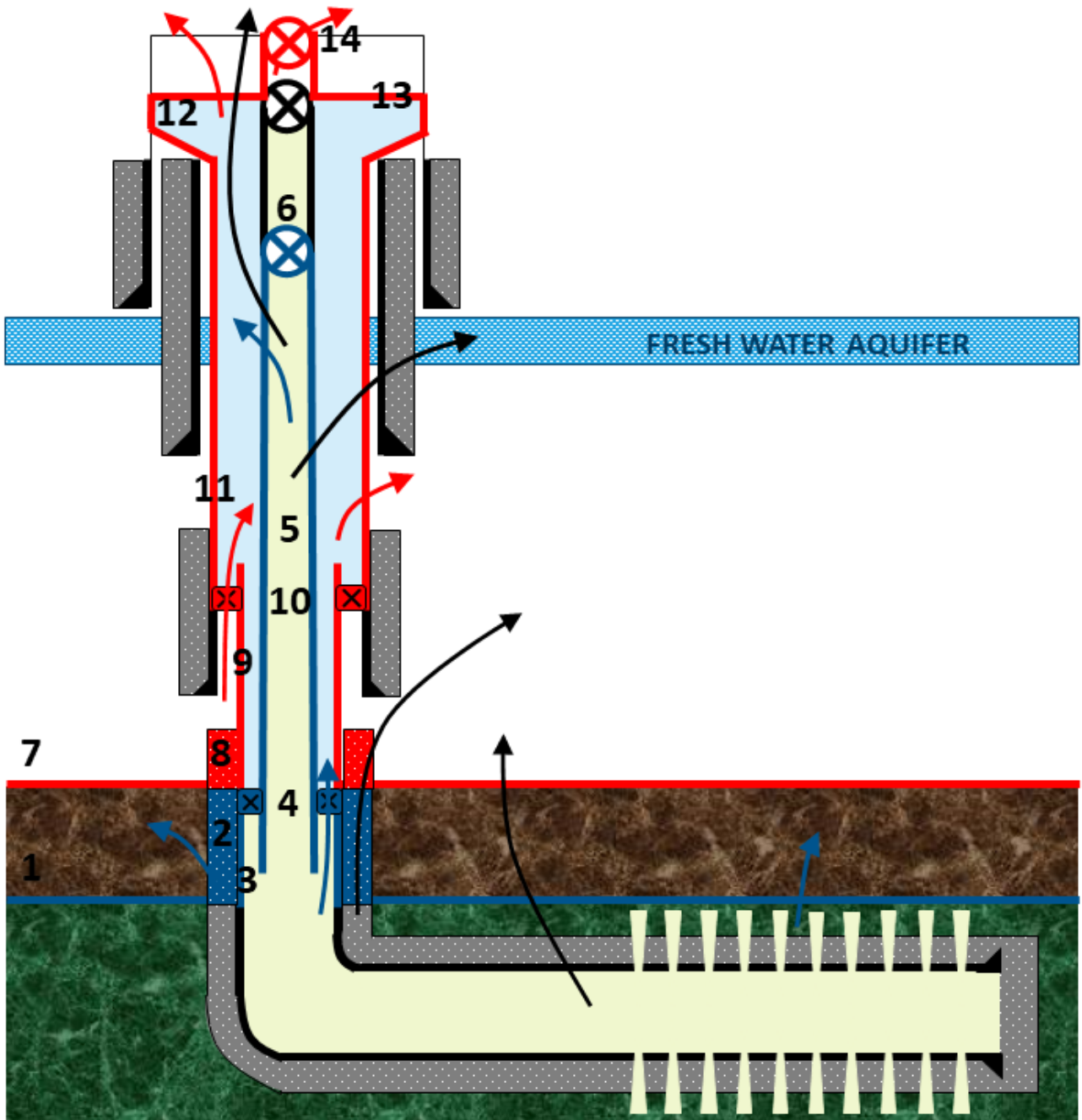


Figure 2 Schematic illustration of well barriers for a typical active shale gas well with a horizontal interval within the reservoir. Primary well barrier is highlighted in blue, and secondary in red. Different WBEs are numbered as follows: (1, 7) in-situ formation; (2, 8) liner cement; (3, 9) liner; (4) production packer; (5) production tubing; (6) DHSV; (10) liner packer; (11) production casing; (12) casing hanger; (13) tubing hanger; (14) wellhead. Some possible leakage pathways are shown by blue, red and black arrows which indicate failure of one WBE within the primary well barrier, one WBE within the secondary barrier and multiple WBEs, respectively. Adapted after (NORSOK D-010, 2013; Vrålstad et al., 2015; Gawel et al., 2015).



For an abandoned well, two well barrier envelopes are necessary to ensure long term integrity (NORSOK D-010, 2013; Vrålstad et al., 2015; Vrålstad et al., 2019). However, if there are other potential flow zones at shallower depths, additional barriers may be necessary for permanent abandonment (i.e. decommissioning). This is a general description that can be applied to abandoned O&G, CO₂ and shale gas wells for the purpose of this analysis. P&A operations have been thoroughly described in a review article by Vrålstad et al. (Vrålstad et al., 2019). A schematic illustration of well barriers for a typical abandoned well with perforated reservoir and without tubing is shown in Figure 3 (developed after section 9.8.4 in NORSOK D-010). For a shale gas well, permanent abandonment scheme for slotted liners in multiple reservoirs (section 9.8.6 in NORSOK D-010) may be a more suitable description since it includes a horizontal section in the reservoir and another potential reservoir at a shallower depth that can represent a fresh water aquifer. However, in this schematic, the active WBEs are the same, and only additional well barriers are present. Further details about abandonment of shale gas wells are provided in the M4ShaleGas report by Gawel et al. (Gawel et al., 2015).

The valves and wellhead/ X-mas tree are removed in the plug and abandonment (P&A) operations, whereas tubing and casings can be left in place or removed if necessary (NORSOK D-010, 2013). In the illustration, the tubing is removed whereas the casings are left in place, which is typically done when both cement and casing are verified as intact WBEs. This means that cement/casing bonding is of good quality, and there is no leak behind or through the casing. The primary well barrier envelope consists of the following WBEs (numbered as in Figure 3):

1. In-situ formation
2. Casing cement
3. Casing
4. Cement plug

The secondary well barrier envelope consists of the following WBEs (numbered as in Figure 3):

5. In-situ formation
6. Casing cement
7. Casing
8. Cement plug

An additional barrier, that is not classified as a well barrier envelope (NORSOK D-010, 2013; Vrålstad et al., 2019), is called openhole-to-surface or environmental barrier and it consists of (numbered as in Figure 3):

9. Casing cement
10. Casing
11. Cement plug (i.e. openhole-to-surface plug)

Some possible leakage pathways for an abandoned well are also illustrated in Figure 3. Blue, red and green arrows indicate failure of one WBE within the primary well barrier, secondary well barrier and openhole-to-surface barrier respectively, whereas black arrows indicate failure of multiple WBEs. Leakage pathways indicated by the black arrows in Figure 3 can be classified as well integrity failure.

Possible causes of failure of different WBEs (tubing, casing, cement, etc.) in O&G wells were covered in numerous previous publications, as for example (Brufatto et al., 2003; Vignes & Aadnøy, 2008; King & King, 2013; Davies et al. 2014). As for active and abandoned CO₂ wells, possible preventive measures and causes and consequences of failure for each WBE have been discussed by Vrålstad et al. in the MiReCOL report D8.1 (Vrålstad et al., 2015). This discussion was further developed in the MiReCOL report D8.3 where barrier verification, monitoring, preventive measures, leakage mitigation and remediation technologies were the main topics (Abdollahi et al., 2016a). Causes of failure of different WBEs in shale gas wells during drilling, completion and production operations were reviewed in the M4ShaleGas report D5.5 (Gawel et al., 2017). However, causes of failure and leakage will not be discussed here as the main topic of this report is review of the remediation strategies. Further information is given in the MiReCOL reports on description of leakage scenarios in CO₂ wells (Vrålstad et al., 2015) and assessment of O&G remediation technologies for CO₂ wells (Abdollahi et al., 2016a), and the M4ShaleGas reports on shale gas well drilling, completion and production (Gawel et al., 2015; Gawel et al., 2017).

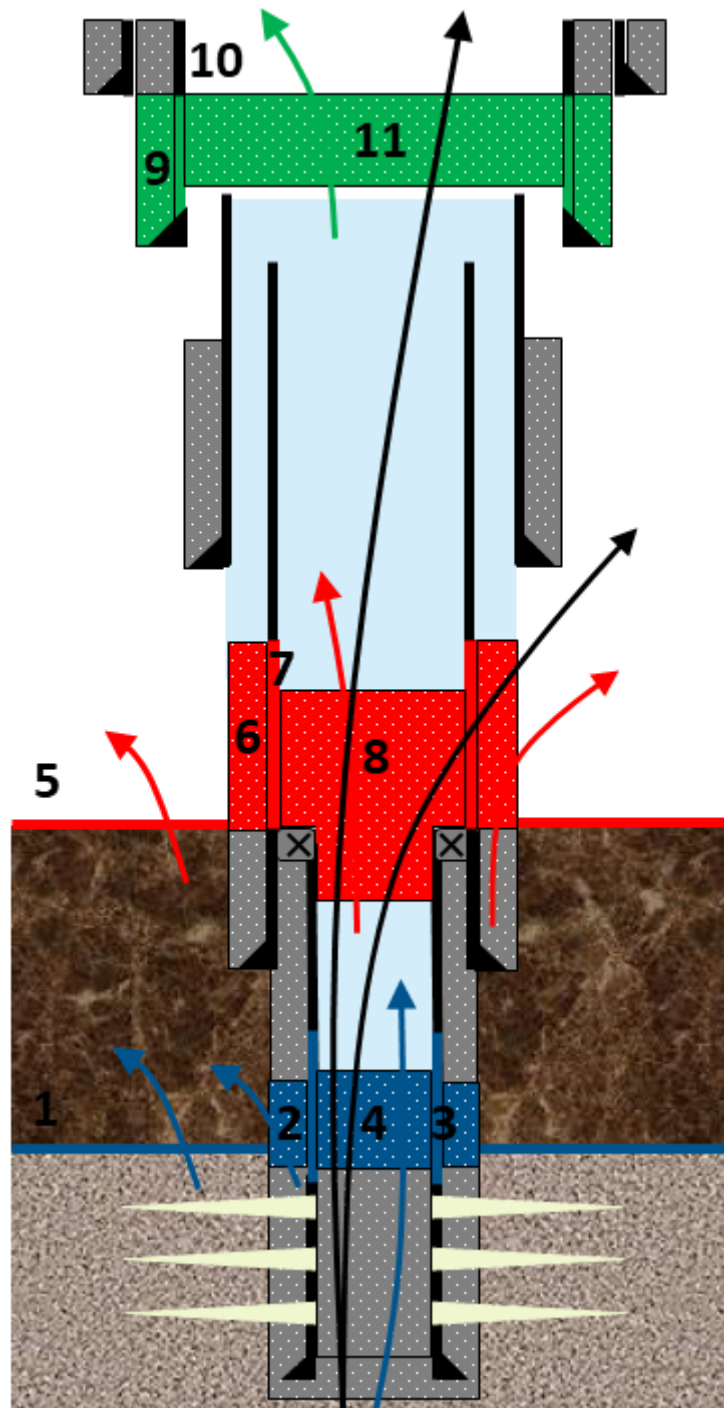


Figure 3 Schematic illustration of well barriers for a typical abandoned well with perforated reservoir and tubing removed. Primary well barrier is highlighted in blue, secondary in red, and openhole-to-surface barrier in green. Different WBEs are numbered as follows: (1, 5) in-situ formation; (2, 6, 9) casing cement; (3, 7, 10) casing; (4, 8, 11) cement plug. Some possible leakage pathways are shown by blue, red, green and black arrows which indicate failure of one WBE within the primary well barrier, one WBE within the secondary barrier, one WBE within openhole-to-surface barrier and multiple WBEs, respectively. Adapted after (Celia et al., 2005; NORSOK D-010, 2013; Vrålstad et al., 2015; Vrålstad et al., 2019).



3 Remediation strategies

3.1 OVERVIEW

This section reviews remediation strategies and technologies that can be applied to leakage caused by failure of different WBEs with the focus on the tubing, casing and cement sheath. The discussion is largely based on the work done in the MiReCOL project (Todorovic et al., 2016a; Abdollahi et al., 2016a). An overview of the application of different remediation strategies with respect to failure of different WBEs within both the primary and secondary barrier is presented in Table 1. The main purpose of this overview is to show that there are limited options for remediation of leakage in the common practice in the O&G industry, and often the same strategies are used to fix different problems. For more information, causes, probability and consequences of failure of different WBEs are covered in two MiReCOL reports (Vrålstad et al., 2015; Abdollahi et al., 2016a).

Table 1 An overview of application of different remediation strategies with respect to failure of different WBEs within both the primary and secondary barrier. Adapted after (Todorovic et al., 2016a; Abdollahi et al., 2016a). Additional information can be found in (Manceau et al., 2014).

WBE failure	Remediation strategy
In-situ formation	<ul style="list-style-type: none"> • Pumping sealing materials (if the leakage point is close to the well and can be accessed through the well) • Drill relief well (if there is no access through the well)
Liner cement (below and above the production packer)	<ul style="list-style-type: none"> • Section milling, rock to rock • Squeeze cementing (different sealing materials can be used) • Perforate, wash and cement (PWC) • P&A
Liner tubular (below and above the production packer) or production casing	<ul style="list-style-type: none"> • Straddle packer • Expandable casing/liner (i.e. casing patch) • Swaging • Squeeze cementing (different sealing materials can be used) • Liner/casing milling and replacement (requires well workover)
Production packer or liner packer	<ul style="list-style-type: none"> • Install tie-back liner • Use a sealing material on top of the packer • Replacement (requires full well workover, i.e. temporary plugging, removal of the X-mas tree and retrieval of the tubing etc.)
Completion string (tubing with other components)	<ul style="list-style-type: none"> • Use sealing and coating materials • Straddle packer • Expandable casing/liner • Swaging • Completion string pulling and replacement (requires well workover)
DHSV	<ul style="list-style-type: none"> • Use a sealing material • Replacement of DHSV • Completion string replacement
Casing hanger or tubing hanger (neck seal)	<ul style="list-style-type: none"> • Casing/completion string pulling and replacement • Use a sealing material on top of the packer
Wellhead/ X-mas tree	<ul style="list-style-type: none"> • Use a sealing material • Replacement of valves • Workover/repair on the site • Replacement (removal of the X-mas tree requires setting a reservoir plug followed by filling the tubing with a kill fluid)



Replacement of a WBE that failed is almost the last resort strategy, if a simpler and less expensive solution cannot be applied to remediate the leakage. WBEs that can be replaced are production liner, production casing, completion string (tubing with components), packers (a complex operation that cannot be performed independently of the connected well components), downhole safety valves, casing and tubing hanger seals, and the wellhead (X-mas tree with BOP). For a well component that cannot be repaired or replaced through the X-mas tree and BOP, a well workover is required, which entails temporary plugging (i.e. setting a reservoir plug and then filling the well with a kill fluid) and removal of the X-mas tree and BOP (Manceau et al., 2014). This is the case for the production liner, production casing, completion string, packers and casing and tubing hanger seals. Replacement of any of these well components is a relatively complex operation, and this will not be discussed in further details here. Squeeze cementing techniques, alternative sealing materials, methods for casing, liner and tubing repair are described in the following sub-sections. Technology gaps and novel technologies for repair of cement, casing and tubing are also briefly discussed within these sub-sections.

3.2 SQUEEZE CEMENTING

Squeeze cementing is a term used for different methods of pumping cement slurry or some other sealing material through perforations in the casing/liner to remediate failure of the cement in the annulus, or to fill holes or fissures in the casing/liner itself. There are other applications of this method such as sealing lost circulation zones and zonal isolation. Squeeze cementing is usually performed during well completion (when the casing is run into the well), but it can be used later on in the lifetime of the well as a remediation method. Squeeze cementing techniques have been thoroughly covered in the following references (Nelson & Guillot, 2006; Manceau et al., 2014; Todorovic et al., 2016a), and therefore only a summary is provided in this report.

Squeeze operations are classified according to the bottomhole treating pressure, which can be below or above the formation fracturing pressure. An appropriate pumping method is selected for a particular application, and different squeeze tools typically assist the squeeze operation.

Low-pressure squeeze is the safest option for remediation operations in the production zone as it operates below the formation fracturing pressure. A small volume of cement slurry (that is squeezed behind the casing) is necessary, because it is not pumped into the formation. For best efficiency, the perforations and defects in the cement need to be cleaned from the mud and solids. There are two commonly used low-pressure techniques:

- Circulating squeeze is a low-pressure technique where cement slurry is circulated between two sets of perforations which are isolated by a packer or cement retainer. Usually large volumes of cement slurry are used in this technique, and excess slurry can be reverse circulated out of the well. Drawbacks are that the slurry may leak behind the packer/retainer and flow into drillpipe, tubing, casing or annulus above the packer/retainer.
- Bradenhead squeeze (named after a legacy manufacturer of casing heads) is a low-pressure technique that is applied when the casing can endure the squeeze pressure. It is commonly used due to good success rates and simplicity of the procedure. An open-end tubing is run down to the bottom of the perforated interval, and a bridge plug may be placed below. After the slurry (or a sealing material) is placed, the tubing is pulled above the top of the slurry, and pressure is applied through the tubing which necessitates casing integrity. After waiting-on-cement time interval, reverse circulation is performed through the tubing to clean up the excess slurry in the wellbore. One potential drawback of this technique is that the casing expands during pressurization and then shrinks back, which can limit the efficiency of filling the voids and micro-annuli in the cement behind the casing.

High-pressure squeeze is applied when there are disconnected channels or small cracks or micro-annuli in the cement, or it is impossible to clean up the wellbore fluids and debris at low pumping pressures. During high-pressure squeeze, fractures are induced in the formation, and therefore large volumes of cement slurry need to be pumped in. Drawbacks of this method are that fractures in the formation cannot be controlled, and it may be difficult to achieve a squeeze pressure that will result in filter cake build-up. High pressure is also used for cementing the casing shoe, block squeeze or cementing liner top. Block squeeze is a high-pressure technique that is used for prevention of leakage below or above a poorly isolated production zone. This operation is performed during well construction, before perforating the production zone.



There are two pumping methods:

- Running squeeze, that is continuous pumping of the sealing material (or cement slurry) until the desired pressure is achieved. The pumping rate and pressure should be low enough to avoid fracturing the formation, and to fill micro-annuli and voids in the cement.
- Hesitation squeeze, that is cyclic pumping of the sealing material (or cement slurry) while monitoring the pressure at the surface. This method is used for remediating different types of wellbore issues. It is more efficient in remediating voids and micro-annuli in the cement than the running squeeze method. However, this method is more complex as it requires careful design of the cement slurry, precise estimation of the hesitation time, pumping rate and slurry volume, correct placement of the squeeze tool and a longer operation time.

In the case when the slurry is injected bottom-off, a plug needs to be set below the squeeze interval to prevent slurry loss further downhole. In this regard, the most commonly used tools are:

- Retrievable squeeze packer, which can be set above or below the target interval for squeeze operation. The retrievable packer has a valve that allows circulation before the slurry is pumped, prevents flow during squeezing, and allows reverse circulation after squeezing.
- Drillable cement retainer (i.e. bridge plug), which is used to isolate the wellbore below the target interval for the squeeze operation.

Coiled tubing is another tool typically used in squeeze cementing operation. It is guided down the wellbore through the tubing (with a packer) to the target interval. Use of coiled tubing significantly reduces costs and enables accurate placement of small volumes of cement slurry (or a sealing material). Coiled tubing is typically used in the Bradenhead squeeze technique. Another example is use of a coiled tubing in the PWC method which is a fairly recent technology development (Abdollahi et al., 2016b).

Examples of different squeeze cementing techniques and possible applications are listed in Table 2.

Table 2 Examples of squeeze cementing techniques and possible applications, adopted from (Todorovic et al., 2016a).

Squeeze cementing technique	Possible applications
Low- pressure squeeze	Failure of cement or casing/liner in the production zone
Circulating squeeze at low pressure with cement retainer or packer	Cement failure; casing or liner leak
High-pressure squeeze	Cement failure (mud channels, cracks, micro-annuli, repairing casing shoe or cement at the top of the liner)
Block squeeze at high pressure with cement retainer or packer	Zonal isolation of a permeable zone – a preventive measure
Bradenhead squeeze with coiled-tubing and retainer or packer; hesitation pumping	Cement failure; casing or liner leak; cementing casing shoe; loss of circulation during drilling

3.3 ALTERNATIVE SEALING MATERIALS

There are many novel materials and commercially available products that have potential to replace standard wellbore cement for certain applications, such as remediation of leakage caused by failure of the cement in the annulus. Some of the requirements for materials that could replace cement are long-term durability, no shrinkage, negligible permeability (also for gas), non-brittleness, deformability and chemical stability (Abdollahi et al., 2016a). Another application of the alternative sealing and/or reactive materials, which was mentioned in the overview of the remediation strategies (Section 3.1), is remediation of leakage within the reservoir formation itself (see Table 1).

Sealing materials that could be alternatives to cement for a squeeze cementing operation are summarized in Table 3, including their other applications. Other alternative sealing materials that could be used for different well cementing applications, including leakage prevention and cement repair, are listed in Table 4 for a more



complete overview. Some of these sealant materials are well-known in the O&G industry, whereas others have been developed relatively recently and are the focus of current research and development. Experimental work on alternative sealants within the MiReCOL project is especially relevant for the SECURE project. Hence, Table 3 and Table 4 have special focus on the materials investigated in the MiReCOL project.

Table 3 Overview of alternative sealing materials that could be used for squeeze cementing (e.g. remediation of leakage caused by failure of the cement in the annulus).

Sealing material	How it works?	Potential applications
Polymer-based gels	Most polymer-gel systems are based on cross-linking of polymers with a heavy metal ion in a brine or water solution. Polyacrylamide is mainly used by the industry. Chromium III is the most commonly used cross-linker, but boron, aluminium and zirconium could be more environmentally friendly alternatives.	<ul style="list-style-type: none"> • Cement failure and formation failure in near well region (Syed et al., 2014; Mosleh et al., 2016a; Korre et al., 2017) • Injection of polymer-gels is a common practice in the O&G industry for enhanced oil recovery and reservoir treatment.
Thermosetting polymers (resins)	Resins are particle-free fluids that are designed to solidify into an impermeable material at a predefined temperature according to the downhole conditions in question.	<ul style="list-style-type: none"> • Repair of cement failure by squeeze operation (Al-Ansari et al., 2015; Todorovic et al., 2016b) • Repair of casing leaks (Sanabria et al., 2016) • Lost circulation material (Knudsen et al., 2014) • P&A (Beharie et al., 2015; Davis, 2017)
Silicate-based gels	Silicate-based solutions are very reactive and form amorphous silica in the presence of CO ₂ . The complex process of precipitation is described elsewhere (Fleury et al., 2016, 2017; Castaneda-Herrera et al., 2018).	<ul style="list-style-type: none"> • Repair of cement failure by squeeze operation • Formation failure in the near well region (Lakatos et al., 2009, 2012a; Karas et al., 2016; Wiese et al., 2019)

Since remediation of leakage within the reservoir is not the main topic in this report, only a brief overview of possible sealants and reactive materials that were previously studied (experimentally and/or numerically), mostly in the MiReCOL project, is given in the following section. Loss of conformance within the reservoir can be mitigated by CO₂ mobility control and flow diversion. To achieve this, different materials can be injected into the reservoir, for example reactants (e.g. CO₂-reactive solutions; brine with a surfactant which generates foam upon reacting with CO₂) and polymer-based gels (Manceau et al., 2014; Syed et al., 2014; Wessel-Berg et al., 2015; Wasch, 2016; Durucan et al., 2016; Mosleh et al., 2016a; Korre et al., 2017). For natural barrier breach, sealant injection was identified as an acceptable prevention and remediation method, and foams and polymer-gels were also studied in this context in the MiReCOL project (Mosleh et al., 2016b; Pizzocolo et al., 2016; Korre et al., 2017). Use of foams, polymers and inorganic gels is common practice in the O&G industry for mitigating different issues that may arise during production. For example, injection of a cross-linked hydrolysed polymer-gel is typically used in the O&G industry for enhanced oil recovery, to improve conformity of fluid flow in the reservoir and for remediation of leakage in the near-well region.

In the scope of the MiReCOL project different CO₂-reactive suspensions were also studied for the purpose of clogging the reservoir in the near-well region (Fleury et al., 2016, 2017). Two types of solutions were considered, lime solutions and silica-alkaline solutions. The latter were further used in laboratory experiments on sandstone cores to test efficacy of silica precipitation for clogging of porous media (Fleury et al., 2016, 2017). Efficacy of lime-saturated solutions was on the other hand, studied by a geochemical modelling approach from another perspective – to remediate CO₂ leakage above the caprock (Wasch, 2016).



Table 4 Overview of alternative sealing materials that could be used for different well cementing applications.

Sealing material	How it works?	Potential applications
Cement with a latex-based component	A latex-based sealant was used as an additive to Portland G cement, that was mixed into the slurry. The latex-component solidifies and expands in contact with CO ₂ , which is expected to further reduce cement permeability and potentially seal a micro-annulus.	<ul style="list-style-type: none"> • Cement failure, as preventive or remediation measure for CO₂ leakage through the cement sheath (Mosleh et al., 2017)
Geopolymers	Aluminosilicate materials with low calcium content that are activated by alkali activators, which results in solidification into a rock-like material (Davidovits, 2015).	<ul style="list-style-type: none"> • Potential for different well cementing applications including P&A (Khalifeh et al., 2016, 2017, 2018; Salehi et al., 2016)
Blast Furnace Slag (BFS)	BFS consists of lime, silica, alumina, magnesia and iron oxides. It can be used on its own, in certain water-based drilling fluids or as an additive to Portland G cement (Vrålstad et al., 2019).	<ul style="list-style-type: none"> • It has been used in well cementing applications (Saasen et al., 1994). • Mud-to-cement system with BFS (Cowan et al., 1992; Daulton et al., 1995)
Low melting point metal alloys	A low-melting-point metal alloy is dropped behind the casing with sustained annular pressure, and then melted by an electromagnetic induction tool. The melted metal accumulates on the top of the cement or another WBE present at the target location, and it forms an annular seal upon cooling.	<ul style="list-style-type: none"> • Mitigation of sustained casing pressure caused by cement, casing or tubing failure (Carpenter et al., 2004)

For remediation of leakage in the near-well region of the reservoir, the case of remediation of CO₂ leakage from a collapsed well drilled in the natural CO₂ field in Bečej (Serbia) is an excellent example (Vrålstad et al., 2015; Karas et al., 2016). The remediation operation that was conducted in 2007, included injection of different silicate solutions (i.e. pure, with polymers and other chemicals) and cross-linker solution (Lakatos et al., 2009, 2012a; Karas et al., 2016). Another remediation operation was conducted in 2016, in the course of the MiReCOL project, and this was described in a recent publication (Wiese et al., 2019). The laboratory studies on silicate gels, where characterization of different silicate-based solutions (gelation time, viscosity, etc.) and core flooding injection experiments were performed (Fleury et al., 2017), were preparatory work for the field tests in Bečej. However, a formulation that had no requirement for the presence of CO₂ in the reservoir to achieve gelation was especially developed for the field test (Wiese et al., 2019).

Prior to the MiReCOL project, use of nanoparticles in silicate gels was also investigated as a measure for improving the stability and flexibility of silicate gels (Lakatos et al., 2012b). It is worth mentioning that use of nanoparticles is also a novel approach for foams (Yu et al., 2012) and mobility control (DiCarlo et al., 2011).

3.4 CASING, LINER AND TUBING REPAIR

Casing or liner leaks can be repaired by the following methods (Nelson & Guillot, 2006; Manceau et al., 2014; Todorovic et al., 2016a; Abdollahi et al., 2016a):

- (1) Straddle packer is an assembly of two packers (the simplest version), used to selectively inject sealing materials by isolating a short interval where the leak is located, or to shut off a target interval. It has a central opening that allows for flow of fluids between the intervals below and above the packer. Straddle packer can be retrieved, but it can also be applied permanently over the leaky interval. This method can be applied to tubing leaks as well.



- (2) Installation of an expandable casing/liner (i.e. casing patch) over the interval where the leak is located. After placement, the patch is expanded to cover the damaged interval. An expandable casing patch can also completely replace a damaged interval by using tie-back connections. Expandable casing/liners can contain many joints to achieve the necessary length. Upon expansion, the diameter increases and the length decreases, but this has no significant effect on the wall thickness. The expansion process creates hydraulic and gas-tight contacts between the existing casing/liner and the patch. Expandable casing/liner has become a standard technique in the O&G industry within the past 15-20 years. This method can be applied to tubing leaks as well.
- (3) Swaging is a method for restoring the form of a collapsed or deformed casing by using a special tool. The tool forces the casing walls outwards while it is run through the damaged interval. This method can be applied to deformed tubing as well.
- (4) Squeeze cementing can be applied to casing/liner leaks, but this is an expensive and not the most effective method as it can damage the casing even further.
- (5) Casing/liner milling or completion string pulling, and replacement. Casing or tubing replacement is a complex operation that requires well workover (i.e. temporary plugging and removal of the wellhead) which results in costs comparable to a packer replacement operation. A typical case of tubing repair is that leaking joints and possibly other damaged sections are replaced, and then the tubing is run back into the well.

Note that these methods can be applied only on the casings and liners that are directly accessible, that is which belong to the primary and secondary well barriers. Repair of the casings that end at shallower depths (i.e. that are outside the well barrier envelope) would be a much more complex operation, as well as the detection of leakage on the periphery of the well.

Some examples of **technology gaps** for repair of tubing or casing are novel materials for internal tubing/casing patch and platelet technology, which is developed for pipeline leaks but is still in the research & development phase for downhole applications (Abdollahi et al., 2016b). Another possibility for tubing or casing replacement instead of pulling could be a technology for melting the tubular away, which is in the research & development phase (Abdollahi et al., 2016b).

3.5 RELEVANCE FOR THE SECURE PROJECT

Squeeze cementing technique is the most relevant remediation measure where the SECURE project can contribute with research, as several tasks deal with characterization of different sealants. Knowledge and research gaps that can be covered by the SECURE project are much more related to material engineering and efficacy of squeeze operation than the remediation method itself. This is emphasized in this report in description of the common practice for squeeze cementing to repair the cement sheath or damaged casing/liner. Potential for innovation in the SECURE project lays also in developing new experimental setups for the laboratory study of squeeze cementing under relevant conditions (e.g. confining pressure and temperature). These activities are planned within Subtask 5.1 where efficacy of squeeze cementing of different sealants will be tested in a radial geometry (i.e. wellbore model consisting of formation rock and cement sheath). The proposed experimental set-up is shown in Figure 4. The experiments will be run in a shale hollow cylinder plug, in which the borehole will be partially cemented. Practically, this will be achieved by drilling axially halfway through the shale, cementing the borehole and then drilling again axially through the cement and out of the shale on the other end. This setup will allow testing of the developed remediation fluids in demanding stress and pressure conditions, through a tortuous pathway from borehole and out into the fracture.

Stress-induced fractures will be created to ensure field-realistic crack geometry. Fractures in the shale will be created by hydraulically pressurizing the borehole within an interval that will be isolated by two packers. The fracture permeability will be evaluated, before and after remediation fluid placement. Remediation fluid will be pressed into the stress-induced fractures from the borehole, testing difficult placement tortuosity with diversion from axial flow to radial flow into the fracture. Inside the fracture, wall roughness and tortuosity will test the fluid's rheology and its capacity to completely fill the voids. X-ray computed tomography (CT) scanning will be used to visualise placement efficiency in three dimensions and estimate void space in the shale and cement before and after the remediation. CT images prior to remediation squeeze will give a measure of the risk of undesired fracturing, e.g. along the cement sheath and the formation, compromising zonal isolation of the injection well.

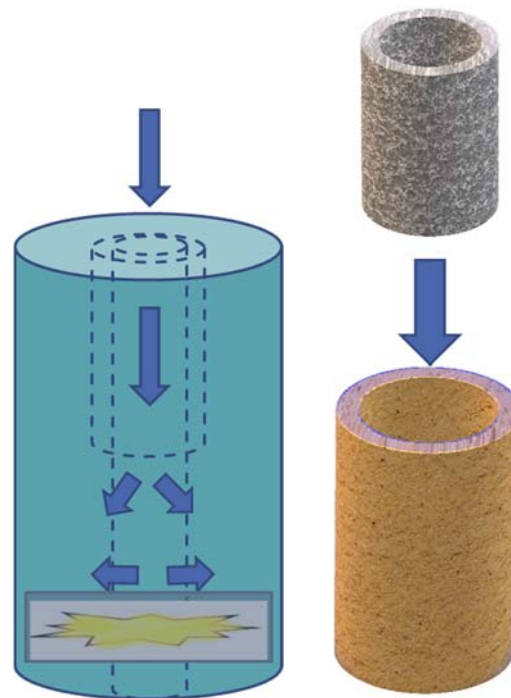


Figure 4 Schematic illustration of planned remediation fluid placement and testing. At left: a shale core with a partially cemented borehole section is fractured by pressurising the borehole. Right: geometry of the assembly showing the cement sheath covering part of the internal surface area of the borehole.

Application of alternative sealing materials for remediation of leakage is addressed from many different angles in the SECURE project. However, there are some common science questions addressed in previous research especially in the MiReCOL project. For remediation or monitoring of leakage within the reservoir, the following materials will be studied or developed:

- Calcium chloride solution injection to mitigate CO₂ release (Subtask 5.1.1 Geochemical remediation through engineered precipitation);
- Novel chemical solutions that could be injected into fault zones and/or where precipitation is catalysed by exposure to CO₂ (Subtask 5.3.1 Remediation of far-field leakage by subsurface injection);
- Molecular microbial methods for monitoring shale gas leakage (Subtask 4.3.2 Microbial based monitoring sensors).

For remediation of leakage primarily through the cement sheath, the following materials will be studied:

- Silicate gels, foams and other sealants to mitigate CO₂ release (Subtask 5.1.2 Remediation of leakage using silicate gels);
- Bio-clogging to mitigate methane release (Subtask 5.1.1 Geochemical remediation through engineered precipitation).

Polymer gels have been studied in the MiReCOL project, both experimentally and numerically, in the context of CO₂ mobility control and flow diversion, and remediation of leakage in the near-well region and through the cement sheath. Moreover, silicate gels (with polymers) have been applied in the Bečej field for remediation of CO₂ leakage (Lakatos et al., 2009, 2012a; Karas et al., 2016; Wiese et al., 2019). The novelty in the SECURE project regarding silicate or polymer gels would be in the application for sealing leakage through the cement sheath and developing improved and novel formulations.

Microbial methods for remediation and monitoring are a novel approach for mitigation of methane release. In the context of CO₂ storage, biofilms and biomineralization are expected to enhance CO₂ structural trapping by pore clogging and induce mineralization of carbonate minerals (Mitchell et al., 2010; Cunningham et al., 2011), but this was not studied experimentally in the MiReCOL project. Only a review of the state-of-the-art research on micro-organisms and bacteria for mitigating CO₂ leakage by clogging the reservoir pores has been done in MiReCOL – restricted report D9.6, which is referred to on page 530 in the Handbook of corrective measures,



(Neele et al., 2017). In the MiReCOL report D9.6, laboratory scale experiments have been reviewed to assess the effectiveness of biofilms and biomineralization in permeability reduction of a porous medium. One concern with biofilms is potential presence of H₂S-generating sulphate-reducing bacteria which would increase the risk for casing corrosion and leakage through the cement (Manceau et al., 2014; Daly et al., 2016). Therefore, subtasks related to bio-clogging have a potential for innovation within the SECURE project.

As a summary of remediation strategies for cement, casing and tubing, this report is especially relevant for subtask 2.1.3 "Risk framework and barrier performance indicators". This SECURE subtask aims to integrate the outcomes of different SECURE tasks into a risk assessment framework, develop guidelines, and provide inputs for the other work packages in terms of indicators for monitoring and communication of risks. The well barrier approach to well integrity and review of remediation strategies is especially significant for development of bowties for different leakage scenarios through wells - specifically for CO₂ injection well, shale gas well or an abandoned well.



4 Conclusions

In this report, we have reviewed:

- Relevant work from the previous EU projects related to CO₂ storage or unconventional resources;
- Well integrity for CO₂ injection wells, shale gas wells and abandoned wells from the well barrier approach;
- Remediation strategies for different well components with a special focus on the cement sheath, casing and tubing;
- Alternative sealants were reviewed from the perspective of squeeze cementing and leakage from a CO₂ reservoir.

Knowledge of the remediation technologies and their testing in previous projects is very valuable for the ongoing effort in the SECURE project, as it both helps avoiding unnecessary repetition of proved work and points to identified weaknesses and gaps not addressed in the past efforts. The literature also shows that whereas much was done in the MiReCOL project addressing CO₂-related remediation, much remains to be done for shale gas exploitation; perhaps adapting the existing O&G remediation technologies to shale gas can be an effective way forward, highlighting the subsurface similarities between CO₂ storage, O&G exploitation and shale gas exploitation.

The planned work in WP5 in SECURE comprises two levels of laboratory testing: first, elaboration of remediation fluid and bench-top to moderate pressure testing in axial flow conditions will be performed at UNOTT, BGS and GEUS, followed by testing in a higher-pressure environment at SINTEF. These last tests will also involve field-relevant radial flow of the fluids into stress-induced fractures, with concentric well elements and surrounding rock.

The planned experiments are relevant to both WP2 and WP5, in as much as the initial parts of the tests whereby fractures are created to place the remediation fluids will yield valuable information on crack geometry. This will aid in choosing input parameter for well integrity modelling; additional tests prior to remediation will include monitoring of permeability change upon fracturing as well as mechanical property changes of the constituents (rock and cement primarily).

Other tasks in the SECURE project that are related to remediation will benefit from this report and the ongoing experimental work:

- Subtask 2.1.2 Risk Analysis of long term acid gas sequestration operation at Borzęcín (INIG-PIB, UNOTT, TNO);
- Subtask 2.1.3 Risk framework and barrier performance indicators (RISKTEC, TNO, BRGM);
- Task 2.2. Well Integrity (TNO, SINTEF, PGI-NRI);
- Subtask 5.3.2 Natural attenuation in the saturated zone (UNOTT, GEUS);
- Subtask 5.3.3 Mitigating impact of fracking on well integrity (SINTEF, UNOTT).



Glossary

<i>BOP</i>	Blowout preventer.
<i>CCS</i>	Carbon capture and storage.
<i>CO₂CARE</i>	"CO ₂ Site Close Assessment Research", a project that was funded by the European Commission's Seventh Framework Programme in the period of 2011-2013, www.co2care.org .
<i>DHSV</i>	Downhole safety valve.
<i>FracRisk</i>	"Furthering the Knowledge Base for Reducing the Environmental Footprint of Shale Gas Development", a project funded by the European Union's Horizon 2020 Research and Innovation programme in the period of 2015-2018, www.fracrisk.eu .
<i>M4ShaleGas</i>	"Measuring, Monitoring, Mitigating, Managing the Environmental Impact of Shale gas", a project that was funded by the European Union's Horizon 2020 Research and Innovation programme in the period of 2015-2017, www.m4shalegas.eu .
<i>MiReCOL</i>	"Mitigation and remediation of CO ₂ leakage", a project that was funded by the European Commission's Seventh Framework Programme in the period of 2014-2017, www.mirecol-co2.eu .
<i>NORSOK</i>	Norwegian standard.
<i>O&G</i>	Oil and gas.
<i>P&A</i>	Plug and abandonment, a common term for the end of a well's life cycle that typically includes tubing retrieval, casing milling, placing several cement plugs in the wellbore to isolate the reservoir and other potential flow zones, and removal of Wellhead/ X-mas tree.
<i>PWC</i>	Perforate, wash and cement.
<i>SCP</i>	Sustained casing pressure.
<i>ShaleXenvironment</i>	A project funded by the European Union's Horizon 2020 Research and Innovation programme in the period of 2015-2018, shalexenvironment.org .
<i>SheerProject</i>	"Shale gas exploration and exploitation induced risks", a project funded by the European Union's Horizon 2020 Research and Innovation programme in the period of 2015-2018, www.sheerproject.eu .
<i>SiteChar</i>	"Characterisation of European CO ₂ Storage", a project that was funded by the European Commission's FP-7 programme in the period of 2011-2013, www.sitechar-co2.eu .
<i>ULTimateCO₂</i>	"Understanding the long-term fate of geologically stored CO ₂ ", a project that was funded by the European Commission's Seventh Framework Programme in the period of 2011-2015, www.ultimateco2.eu .
<i>WBE</i>	Well Barrier Element.



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