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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[1]. Research activities aim at developing a handbook of corrective measures that can be considered in the event of undesired migration of CO_2 in the deep subsurface reservoirs. MiReCOL results support CO_2 storage project operators in assessing the value of specific corrective measures if the CO_2 in the storage reservoir does not behave as expected. MiReCOL focuses on corrective measures that can be taken while the CO_2 is in the deep subsurface. The general scenarios considered in MiReCOL are 1) loss of conformance in the reservoir (undesired migration of CO_2 within the reservoir), 2) natural barrier breach (CO_2 migration through faults or fractures), and 3) well barrier breach (CO_2 migration along the well bore).

Wells are generally considered to be the most likely path for leakage in a CO_2 storage project. Such leakages are caused by failure of one or more well barrier elements (WBE); otherwise the well integrity would be intact. Generally, WBEs that are exposed to CO_2 are most prone to leakage.

This first deliverable on the subject of well leakage remediation best practice describes the well barriers of active and abandoned wells and causes and consequences of leakage through the well barrier elements (WBE). Aging issues with cement degradation, casing corrosion and wear, and thermal loads imposed on the well infrastructure are examples of the most likely causes for well leakages. The tubing is the WBE that is by far the most likely to fail; probably due to corrosion

[1] More information on the MiReCOL project can be found at www.mirecol-co2.eu.

and/or connection failures. Also, the casing and the cement have a considerable record of failure.

A wide range of technologies and methods from the oil & gas industry are available that can also be used for the remediation and mitigation of leakage from CO_2 wells. In the following deliverables, available remediation technologies from the O&G industry and previous EU projects will be reviewed and evaluated towards their application to CO_2 wells.

Public introduction (*)
This report is part of the research project MiReCOL (Mitigation and Remediation of CO_2 leakage) funded by the EU FP7 programme[2]. Research activities aim at developing a handbook of corrective measures that can be considered in the event of undesired migration of CO_2 in the deep subsurface reservoirs. MiReCOL results support CO_2 storage project operators in assessing the value of specific corrective measures if the CO_2 in the storage reservoir does not behave as expected. MiReCOL focuses on corrective measures that can be taken while the CO_2 is in the deep subsurface. The general scenarios considered in MiReCOL are 1) loss of conformance in the reservoir (undesired migration of CO_2 within the reservoir), 2) natural barrier breach (CO_2 migration through faults or fractures), and 3) well barrier breach (CO_2 migration along the well bore). In a CO_2 storage project, well integrity failure is generally considered to represent one of the highest risks of leakage. Generally, WBEs that are exposed to CO_2 are most prone to leakage. Aging issues with cement degradation, casing corrosion and wear, and thermal loads imposed on the well infrastructure are examples of causes of well leakages. Such well integrity failure has the potential to lead to catastrophic CO_2 leakage with large safety and environmental consequences. As the technology for drilling and completion of wells for CO_2 storage is largely the same as is used by the oil and gas (O&G) industry, much of that experience of causes of leakage and remediation methods can be directly transferred. Other aspects that are more relevant to CO_2 wells, such as chemistry and time effects, require some additional consideration. The objective of this first deliverable of related to well leakage remediation best practice is to describe the most relevant scenarios for leakage of CO_2 from storage reservoirs from active and abandoned wells; and to evaluate the consequences of the leak in each scenario. This report presents an introduction to well barriers and well barrier elements (WBE), followed by a description of WBE failure modes and consequences of leakage through those failed WBEs. Next, the report describes the dramatic case of a blow-out during drilling operations in 1968 at the Bečej natural CO_2 field, which was followed by uncontrolled migration of gas from the reservoir into the overburden, that lasted until 2007 when remediation actions were successfully applied. Further, an overview of the work related to well integrity and well leakage scenarios in the EC projects CO_2CARE, SiteChar and ULTimateCO_2 is given. Finally, the report closes with some concluding remarks.

[2] More information on the MiReCOL project can be found at www.mirecol-co2.eu.

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1 INTRODUCTION

This report is part of the research project MiReCOL (Mitigation and Remediation of CO_2 leakage) funded by the EU FP7 programme[3]. Research activities aim at developing a handbook of corrective measures that can be considered in the event of undesired migration of CO_2 in the deep subsurface reservoirs. MiReCOL results support CO_2 storage project operators in assessing the value of specific corrective measures if the CO_2 in the storage reservoir does not behave as expected. MiReCOL focuses on corrective measures that can be taken while the CO_2 is in the deep subsurface. The general scenarios considered in MiReCOL are 1) loss of conformance in the reservoir (undesired migration of CO_2 within the reservoir), 2) natural barrier breach (CO_2 migration through faults or fractures), and 3) well barrier breach (CO_2 migration along the well bore).

In a CO_2 storage project, well integrity failure is generally considered to represent one of the highest risks of leakage. Generally, WBEs that are exposed to CO_2 are most prone to leakage. Ageing issues with cement degradation, casing corrosion and wear, and thermal loads imposed on the well infrastructure are examples of causes of well leakages. Such well integrity failure has the potential to lead to catastrophic CO_2 leakages with large safety and environmental consequences.

As the technology for drilling and completion of wells for CO_2 storage is largely the same as is used by the oil and gas (O&G) industry, much of that experience of causes of leakage and remediation methods can be directly transferred. Other aspects that are more relevant to CO_2 wells, such as chemistry and time effects, require some additional consideration.

The objective of this first deliverable related to well leakage remediation best practice is to describe the most relevant scenarios for leakage of CO_2 from storage reservoirs from active and abandoned wells, and to evaluate the consequences of the leak in each scenario. The partners agreed to approach this task in terms of well barrier element failure, conceptually following the NORSOK D-010 standard from the O&G industry, instead of a qualitative Features-Events-Processes (FEP) approach. If needed for the assessment of large scale processes, such as reservoir pressure and regional stress changes, a FEP analysis will be applied.

This report presents a brief introduction to well barriers and well barrier elements (WBE), followed by a description of WBE failure modes and consequences of leakage through those failed WBEs.

Next, the report describes the dramatic case of a blow-out during drilling operations in 1968 at the Bečej natural CO_2 field, which was followed by uncontrolled migration of gas from the reservoir into the overburden that lasted until 2007 when remediation

[3] More information on the MiReCOL project can be found at www.mirecol-co2.eu.

actions were successfully applied. Although this blowout occurred while drilling into a natural CO_2 field and is therefore not directly relevant for active and abandoned CO_2 injection wells, the description of the remedial actions taken afterwards provide valuable input for the work to be done in SP3. Our project partner NIS is the operator of the Bečej natural CO_2 field and thus brings first-hand experience with CO_2 well leakage and remediation to the Consortium.

As a knowledge base and to avoid duplication of work, an overview of the work related to well integrity and well leakage scenarios in the EC projects CO_2CARE, SiteChar and ULTimateCO_2 is given in the following chapter.

Finally, the report closes with some concluding remarks.

1.1 Objective of this report

This report is the first deliverable within the sub-project "Leakage along wells" of the MiReCOL project. The aim of this subproject is to review and assess the efficiency of measures for mitigation and remediation of CO_2 leakages from wells. Both best practices and current remediation technologies from the oil and gas industry as well as new developments and emerging technologies will be included in the analysis. Future work will focus on the review and assessment of O&G mitigation and remediation measures, the experimental assessment of various novel materials and the review of the new developments in well leakage remediation techniques.

This deliverable aims at describing the most relevant scenarios for leakage of CO_2 from storage reservoirs via different types of wells. Following reports will review measures in the O&G best practice portfolio and assess the efficiency of these as measures for mitigation of CO_2 leakage for the most relevant leakage scenarios. This work will contribute to the integration of the findings from all subprojects, in particular to the discussion of possible new risks associated with the use of wells in the mitigation and remediation measures that are discussed in other subprojects. Furthermore, current knowledge gaps will be highlighted and recommendations for improvements will be provided.

2 WELL INTEGRITY AND WELL BARRIERS

Requirements and guidelines for well integrity can be found in the NORSOK D-010 standard, which describes well integrity for all well operations in Norway. Norwegian regulations are considered as some of the most stringent in the world, and the NORSOK D-010 standard is generally deemed to be a good example for obtaining and managing well integrity; including the two-barrier philosophy.

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). The "technical" aspect of well integrity refers to the installation and use of well barriers to prevent leakages from the well.

2.1 Two-barrier principle

The central aspect of the NORSOK D-010 standard is the "two-barrier principle", which implies that two independent well barriers shall be present at all times, where "Well barrier" and "Well barrier element" are defined as:

Well barrier: Envelope of one or several well barrier elements preventing fluids from flowing unintentionally from the formation into the wellbore, into another formation or to the external environment.

Well barrier element (WBE): A physical element which in itself does not prevent flow but in combination with other WBE's forms a well barrier.

In other words, each well barrier can be seen as a chain of connecting well barrier elements (i.e. well components such as tubing, cement, etc.) that constitute a well barrier envelope, as illustrated in Figure 2.1 below. There shall be at least two such independent well barrier envelopes in the well, the primary and secondary envelope, respectively, and these should not have common well barrier elements.

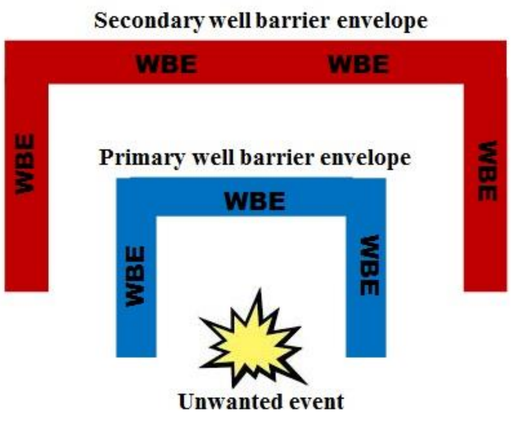


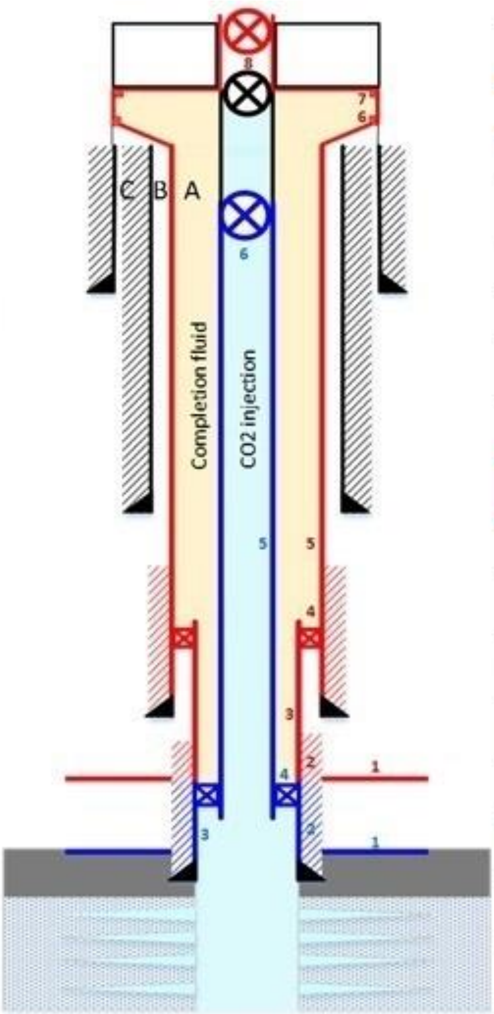
Figure 2.1 Illustration of the two-barrier principle: Two well barrier envelopes that consist of different well barrier elements (WBEs) that contains the leakage (unwanted event).

3 DESCRIPTION OF WELL BARRIER ELEMENTS (WBE)

Well leakages are caused by failure of one or more well barrier elements; otherwise the well integrity would be intact. Below is a description of the most common WBEs found in CO_2 wells, categorized for active wells (i.e. injection/production/monitoring wells) and abandoned wells, respectively.

3.1 Active wells

An example of a well barrier schematic for an active CO_2 well (i.e. injection/ production/monitoring) is shown in Figure 3.1 below, where both primary and secondary well barrier envelopes consisting of different WBEs are shown. Note that this example is for a platform well; the well barrier schematics for a subsea well can be slightly different.



No.	Well barrier element
PRIMARY WELL BARRIER ENVELOPE	
1	In-situ formation
2	Liner cement (below production packer)
3	Liner (below production packer)
4	Production packer
5	Completion string (Production tubing)
6	Downhole safety valve (DHSV)
SECONDARY WELL BARRIER ENVELOPE	
1	In-situ formation
2	Casing cement (above production packer)
3	Liner (above production packer)
4	Liner packer
5	Production casing
6	Casing hanger
7	Tubing hanger (neck seal)
8	Wellhead / X-mas tree with valves

Figure 3.1 Example of a well barrier schematic with WBEs for a CO_2 injection well. Primary and secondary well barrier envelopes in blue and red colors, respectively.

Descriptions of all the WBEs found in Figure 3.1 with possible preventative measures are given below in alphabetical order:

Casing cement: Cement in annulus between casing and formation. The cement is placed as a slurry in the annulus during well construction, and hardens in-situ to support the casing and provide zonal isolation in the annulus.
Possible preventive measures: Ensure good mud removal during cement placement to avoid mud channels in cement and microannuli. Rotate casing during cementing and use sufficient number of centralizers. Material selection: use expandable cement to avoid shrinkage and formation of microannuli, and use flexible cement systems that can withstand the tensile stresses and loads the cement will be exposed to during the well lifetime. Consider using CO_2-resistant cement if directly exposed to CO_2.

Casing hanger: A hanger element made of steel that supports the weight of the casing and provides a seal between the casing, wellhead and Christmas tree.
Possible preventive measures: Material selection; use high-quality corrosion resistant steel that avoids corrosion and that withstands the expected loads and pressures during well lifetime.

Completion string (i.e. production tubing): Steel tubular that is the conduit for injection fluids into the well or production fluids from the well, depending on well type.
Possible preventive measures: Avoid casing wear during well construction. Material selection: use high-quality corrosion resistant steel that avoids corrosion and withstands the expected loads and pressures during the well lifetime. Use premium connections that are gas-tight and that can withstand the expected loads and pressures.

Dowhole safety valve (DHSV): Valve inside tubing with a close/open mechanism that seals off the tubing bore. The valve is controlled by hydraulic pressure through a control line, and is operated in a fail-safe mode.
Possible preventive measures: Use qualified DHSV designs and materials, and avoid corrosion/leak in hydraulic control line, regular maintenance. For production wells avoid potential scale formation.

In-situ formation: The formation that has been drilled through and is located adjacent to the annulus cement. The formation strength must exceed the maximum wellbore pressures expected during the well lifetime in order to be qualified as a WBE.
Possible preventive measures: Good knowledge of the subsurface/formation properties, by logging and by performing XLOT tests.

Liner: Steel tubular, with similar function as casing, that does not extend all the way to surface.
Possible preventive measures: Avoid casing wear during well construction. Material selection; use high-quality corrosion resistant steel that avoids corrosion and that withstands the expected loads and pressures during the well lifetime. Use premium connections that are gas-tight and that can withstand the expected loads and pressures.

Liner cement: Cement in annulus between liner and formation. The cement is placed as a slurry in the annulus during well construction, and hardens in-situ to support the liner and provide zonal isolation in the annulus.
Possible preventive measures: Ensure good mud removal during cement placement to avoid mud channels in cement and microannuli. Rotate liner during cementing and use sufficient number of centralizers. Material selection; use expandable cement to avoid shrinkage and formation of microannuli, and use flexible cement systems that can withstand the tensile stresses and loads the cement will be exposed to during well lifetime. Consider using CO_2-resistant cement if directly exposed to CO_2.

Liner packer: Sealing device made of steel and/or elastomer that seals the annulus between the liner and production casing.
Possible preventive measures: Material selection: ensure that the sealing elements in packer withstand the chemical and physical environment throughout the well lifetime. Avoid casing wear at the packer setting depth to ensure good seal around the packer.

Production casing: Steel tubular that extends all the way to surface.
Possible preventive measures: Avoid casing wear during well construction. Material selection: use high-quality corrosion resistant steel that avoids corrosion and that withstands the expected loads and pressures during well lifetime. Use premium connections that are gas-tight and that can withstand the expected loads and pressures.

Production packer: Sealing device made of steel and/or elastomer that seals the annulus between the production tubing and production casing/liner.
Possible preventive measures: Material selection: ensure that the sealing elements in packer withstand the chemical and physical environment throughout the well lifetime. Avoid casing wear at packer setting depth to ensure good seal around the packer.

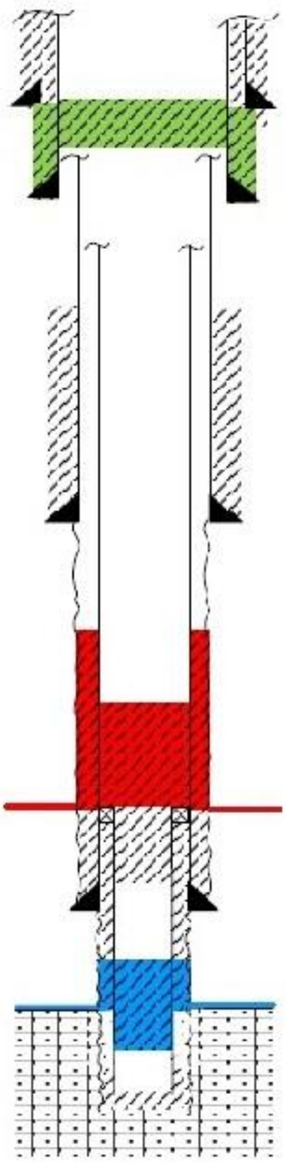
Tubing hanger: A hanger element made of steel that supports the weight of the tubing and provides a seal between the tubing, wellhead and X-mas tree.
Possible preventive measures: Material selection: use high-quality corrosion resistant steel that avoids corrosion and withstands the expected loads and pressures during the well lifetime.

Wellhead/X-mas tree: The wellhead provides mechanical support for casing and tubing strings, and prevents flow from the bore and all annuli to the environment. The X-mas tree, which is supported by the wellhead, consists of a housing with several different valves that controls the flow of injection/production fluids, as well as annuli monitoring.
Possible preventive measures: Material selection: use high-quality corrosion resistant steel that avoids corrosion and withstands the expected loads and pressures during the well lifetime, regular maintenance.

3.2 Abandoned wells

An example of a well barrier schematic for an abandoned CO_2 well is shown in Figure 3.2 below, where both primary and secondary well barrier envelopes consisting of different WBEs are shown.

Descriptions of all the WBEs found in Figure 3.2 with possible preventive measures are given below in alphabetical order:



Well barrier element
PRIMARY WELL BARRIER ENVELOPE
In-situ formation
Casing cement
Casing
Cement plug
SECONDARY WELL BARRIER ENVELOPE
In-situ formation
Casing cement
Casing
Cement plug
OPENHOLE TO SURFACE WELL BARRIER
Casing cement
Casing
Cement plug

Figure 3.2 Example of a well barrier schematic with WBEs for an abandoned CO_2 well. Primary and secondary well barrier envelopes in blue and red colors, respectively, with the "openhole to surface" barrier in green (based on NORSOK D-010).

Casing: Steel tubular that extends all the way to surface.
Possible preventive measures: Material selection: use high-quality corrosion resistant steel that avoids corrosion. Consider removing the casing by milling prior to abandonment.

Casing cement: Cement in annulus between casing and formation. The cement is placed as a slurry in the annulus during well construction, and hardens in-situ to support the casing and provide zonal isolation in the annulus.
Possible preventive measures: Ensure good mud removal during cement placement to avoid mud channels in cement and microannuli. Rotate casing during cementing and use sufficient number of centralizers. Material selection: use expandable cement to avoid shrinkage and formation of microannuli, and use flexible cement systems that can withstand the tensile stresses and loads the cement will be exposed to during the well lifetime. Consider using CO_2-resistant cement if directly exposed to CO_2.

Cement plug: Solid plug of cement in the wellbore that prevents flow of formation fluids.
Possible preventive measures: Ensure good mud removal during cement placement to avoid mud channels in cement and microannuli. Material selection; use expandable cement to avoid shrinkage and formation of microannuli, and consider use of flexible cement systems that can withstand the movements/loads the cement will be exposed to after well abandonment. Consider using CO_2-resistant cement if directly exposed to CO_2. Use of a mechanical bridge plug as a foundation to ensure good plug placement.

In-situ formation: The formation that has been drilled through and is located adjacent to the annulus cement or cement plugs placed in the wellbore. The formation strength must exceed the maximum wellbore pressure expected during the life of the well in order to be qualified as a WBE.
Possible preventive measures: Good knowledge of subsurface/formation properties, by logging and by performing XLOT tests.

4 CAUSES AND CONSEQUENCES OF WELL LEAKAGES

If a leak occurs, the first cause of action will be to determine the cause of the leak; i.e. which of the well barrier element(s) has failed. When the cause of the leak has been determined, remedial actions can proceed.

4.1 WBE failures in active wells

Figure 4.1 shows an illustration of some possible leak pathways due to WBE failures in an active CO_2 well.

An overview of causes and consequences of different WBE failures in active CO_2 wells is listed below in alphabetical order:

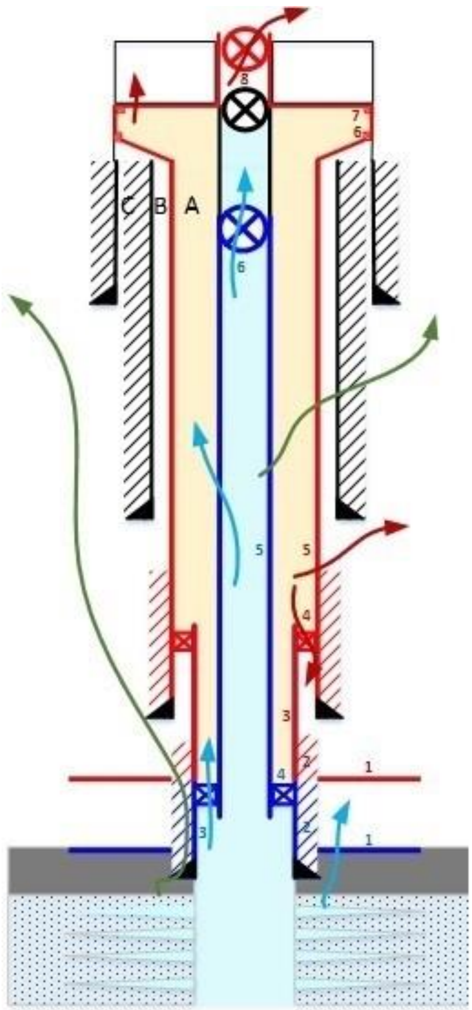


Figure 4.1 Schematic illustration of some possible leak pathways due to WBE failures in an active CO_2 well. Blue arrows show failure of primary well barrier envelope, red arrows show failure of secondary well barrier envelope, and green arrows show failure of multiple WBEs.

Annulus cement (for casing and liner):
Causes of failure: Presence of mud channels, gas channels or microannuli formed during well construction that act as leak pathways. Formation of radial cracks and microannuli (i.e. de-bonding) due to temperature and pressure cycles during injection/production. Possibly CO_2 degradation.
Consequences: Loss of zonal isolation and pressure build-up in annulus. Possible upwards migration of formation fluids along the outside of the well, if formation strength is too low, i.e. failure of a second WBE and potential leak to the environment.

Casing hanger / Tubing hanger:
Causes of failure: Material degradation due to corrosion and/or fatigue. Poor initial design with respect to material selection and/or expected loads and pressures. Exposure to annulus pressures and loads outside design envelope; for example due to wellhead growth.
Consequences: Leakage into the environment (if the primary WB fails as well).

Completion string (i.e. production tubing):
Causes of failure: Material degradation due to fatigue, corrosion and/or erosion. Failure of tubing connections. Poor initial design with respect to material selection and/or expected loads and pressures.
Consequences: Pressure communication through tubing, resulting in pressure build-up in annulus A.

Downhole safety valve (DHSV):
Causes of failure: Material degradation due to corrosion of flapper valves and/or control line. Scale build-up preventing proper valve closure, overpressure.
Consequences: Loss of sealing ability for flapper valve failure or loss of functionality for control line failure (hydraulic failure).

In-situ formation:
Causes of failure: Drilling-induced damage to formation. Reduced formation strength due to presence of microcracks and fracures. Poor bonding to cement.
Consequences: Fracture propagation and growth upwards through formation or along wellbore. May create leak to surface.

Production casing / liner:
Causes of failure: Material degradation due to corrosion or casing wear. Burst or collapse of casing if internal or external annulus pressures exceed casing strength. Failures of casing connections. Poor initial design with respect to material selection and/or expected loads and pressures.
Consequences: Pressure communication between adjacent annuli through casing, thereby possibly causing pressure build-up in several annuli.

Production packer / liner packer:
Causes of failure: Chemical or thermal degradation of sealing material in packer. Poor sealing towards oval casing damaged by casing wear.

Consequences: Loss of sealing ability. Pressure build-up in annulus above packer, or downwards fluid migration from annulus into surrounding (weak) formation, which may lead to further fracture propagation.

Wellhead / X-mas tree:
Causes of failure: Material degradation due to corrosion and/or fatigue. Poor initial design with respect to material selection and/or expected loads and pressures. Exposure to annulus pressures and loads outside design envelope; for example due to wellhead growth.
Consequences: Leakage into the environment and to the surface, if the primary barrier fails as well.

4.2 WBE failures in abandoned wells

An overview of causes and consequences of different WBE failures in abandoned CO_2 wells is listed below in alphabetical order:

Casing:
Causes of failure: Material degradation due to corrosion. For legacy wells, possible degradation due to vertical stress changes (reservoir de-compaction).
Consequences: Formation of leak paths along/through casing if degraded. Fluid migration upwards through the barrier.

Casing cement:
Causes of failure: Presence of mud channels, gas channels or microannuli formed during well construction that act as leak pathways. Formation of radial cracks and microannuli (i.e. de-bonding) due to previous temperature and pressure cycles during injection/production phase. Possibly CO_2 degradation. For legacy wells, possible cracking and de-bonding due to vertical stress changes (reservoir de-compaction).

Consequences: Loss of zonal isolation, fluid migration upwards through barrier and pressure build-up in well above cement. Possible upwards migration of formation fluids along the outside of the well, if formation strength is too low. For surface barrier: Leakage into the environment.

Cement plug:
Causes of failure: Presence of mud channels or microannuli formed during plug placement that act as leak pathways. Shrinkage of cement during setting can create considerable microannuli/gaps around plug. Possibly CO_2 degradation. For legacy wells, possible cracking and de-bonding due to vertical stress changes (reservoir de-compaction).
Consequences: Fluid migration upwards through cement plug and pressure build-up in well above cement. For surface barrier: Leakage into the environment.

4.3 Most likely WBE failures

Relatively few studies have been published that provide reliable statistical information on the failures of different well barrier elements, but one such study has been published by Vignes and Aadnøy (2008).

In this study, a total of 406 wells from 7 different operators where mapped by the Norwegian Petroleum Safety Authorities (PSA). It was found that 75 of these wells had well integrity issues; i.e. 18 % of all the wells had experienced problems. An overview of which WBEs that failed in these 75 wells was also given in the study. Table 4.1 lists the failure percentages of the WBEs most relevant for CO_2 wells. As this study surveyed only wells in operation, it is only relevant for active CO_2 wells, not abandoned wells.

From these results it is seen that the tubing is the WBE that is by far the most likely to fail; probably due to corrosion and/or connection failures. The casing and the cement also have considerable failure percentages.

Table 4.1: Overview of WBE failures for wells in operation (Vignes and Aadnøy, 2008)

Casing	**Cement**	**DHSV**	**Packer**	**Tubing**	**Wellhead**
11 % of failures	11 % of failures	3 % of failures	5 % of failures	39 % of failures	5 % of failures

Furthermore, the study also revealed a difference between production and injection wells. Of the 406 wells included in the study, 323 were production wells and 83 were injection wells, as listed in Table 4.2 below. 48 production well failures were reported (i.e. 15 % of all production wells), whereas 27 injection well failures were reported (i.e. 33 % of all injection wells).

Table 4.2: Well integrity failures of production and injection wells (Vignes and Aadnøy, 2008)

	Total number wells	**Wells with WI failure**
Production wells	323	48
Injection wells	83	27
TOTAL	406	75

Injection wells are therefore significantly more likely to fail than production wells, and this finding is very relevant for CO_2 storage since most CO_2 wells are injection wells. The reason for this difference is, however, unknown.

5 BLOW-OUT AT BEČEJ NATURAL CO_2 FIELD IN 1968/69

In the following, the dramatic case of blow-out during drilling operations at the Bečej natural CO_2 field is described. Although this blowout occurred while drilling into a natural CO_2 field and is therefore not directly relevant for active and abandoned CO_2 injection wells, the description of the remedial actions taken afterwards provide relevant input for the work to be done in SP3.

The natural CO_2 gas field Bečej was discovered in 1951 by the borehole Bč-2. It is situated between Bačko Petrovo Selo and Bečej, and extended partially beneath the city Bečej, in northern part of Republic Serbia – Vojvodina Province, at the bank of Tisa River (Figure 5.1).

Figure 5.1: Location of Becej (A) in Serbia (courtesy of Google Maps)

During drilling of well Bč-5 by the end of 1968, an uncontrolled and spontaneous gas eruption happened when the bit entered the Miocene layer at the depth of 1,092.50 – 1,093.35 m (Figure 5.2). The blowout could not be controlled and lasted for eight months (until mid 1969 - 209 days) when the lower section of the open borehole collapsed. After that, the blowout continued for another 57 days. During this second period of the blowout, the free gas jet created a crater at the surface around the borehole and discharged high amounts of clay and sand containing slurry (www.youtube.com/watch?v=-riYk2J0B0c 0:46-1:44). Unfortunately, the eruption claimed several human lives and caused serious damages in surface facilities.

After this second period of blowout, the surface eruption ceased, however, gas continued to migrate from the geological reservoir. Regular periodic measurements and monitoring of the reservoir pressure after 1975 showed an intensive leakage/migration of CO_2 into the upper/shallower horizons through the collapsed borehole, i.e. an underground gas migration. This was also supported by chemical analysis of gas stored in those layers. From 1968 to 2001, the reservoir pressure dropped from 150 bar to 117 bar, which cannot solely be accounted to CO_2 production.

Several other issues, especially unfavorable reservoir geological parameters led to the conclusion that the gas migration problem could not be solved by conventional and routine well treatment or work-over techniques such as cementing. In order to control and stop the CO_2 migration (Medic et al. 2008, Lakatos et al. 2009), NIS engaged in 2007 in a series of activities, which are described below.

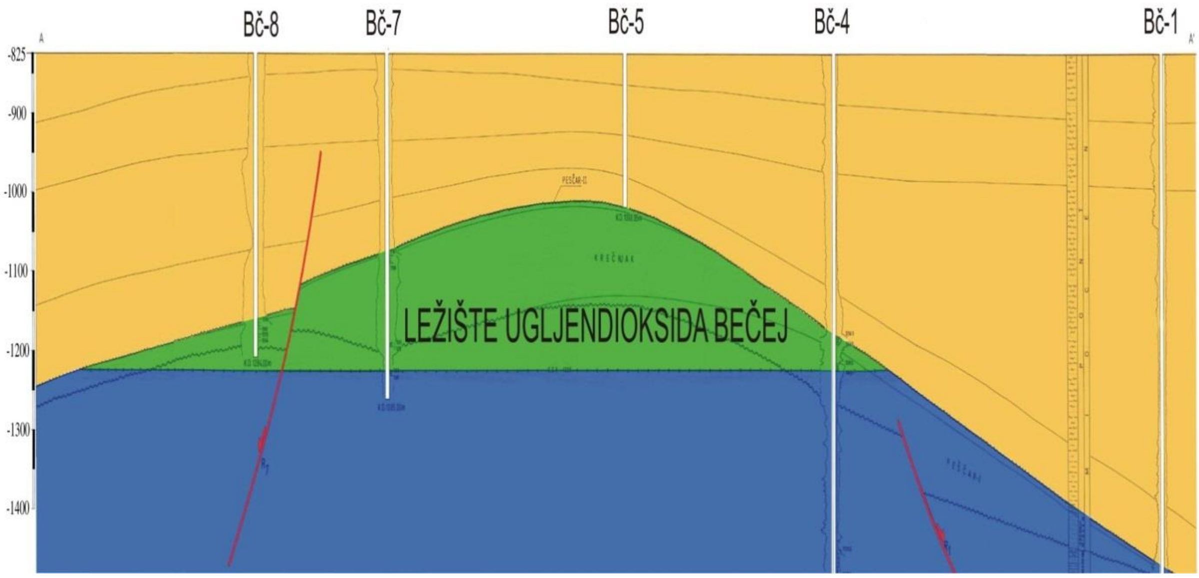


Figure 5.2 Geologic profile of Bečej field at the location of Bč-5 well.

5.1 Summary of Bč-5 drilling operation and blow-out/eruption

The exploration well Bč-5 was spudded on 30th October 1968. All drilling operations stopped after 12 days on 10th November 1968 due to the blow-out, at total depth of 1092.50 – 1093.25 m in the Miocene sandstone formations. The well Bč-5 was drilled with bentonite mud with sodium hydroxide additive, and occasionally weighted by barite.

During the drilling operation, at a depth of 361m there was gas influx into the mud that reduced the mud density from 1.28 g/cm^3 to 1.17 g/cm^3. On this occasion, the mud was pulsating and spilled out for 2-3 minutes over the flowline. By the end of the third shift the mud was weighted to 1.20 g/cm^3. In the interval of 400-480 m the well continued to pulsate occasionally and mud was increasingly weighted first to 1.24 g/cm^3, and then because of continuing pulsation to 1.28 g/cm^3. Drilling operation was continued during 6th November with this mud weight.

Due to the risk of possible mud loss on 7th November the mud density was reduced to 1.25 g/cm^3 and later to 1.24 g/cm^3. At a depth of 628.30 m, during circulation/washing prior to coring operation (core no. 2), a slight increase of gas concentration in the mud was noticed. During 8th, 9th and 10th November, the mud density ranged from 1.26 to 1.30 g/cm^3 while the viscosity ranged between 38 and 40 sec.

Drilling operations were taking place normally, without major delays or problems, until 10th November at 01:45 h. During drilling at depth 1092.50 – 1093.25 m, the whole assembly of drilling tools suddenly dropped 0.75 m and the tools were pulled up for circulation/washing. During circulation, it was noticed that mud spilled out on the wellhead, over flow line and mud pits. The BOP was activated immediately but was not successfully closed completely. The blowout became more intensive and after 5 minutes the ejected mud column was as high as the drilling rig. After approximately 15 minutes, the well started to blow out only gas; methane for about 30 minutes, and then “pure” CO_2. The blowout could not be stopped after that.

Possible reasons for the blow-out of well Bč-5 are:

- Unfavorable geological (reservoir) parameters, such as very complex geological conditions, tectonic stress, existence of networks of faults and fractures, several superimposed shallower sandy layers/horizons – secondary CO_2 accumulations/ reservoirs/pools, over-pressurized major Bečej CO_2 pool etc.
- Despite the fact that Bč-5 was the fifth well, it can be said that there was not enough data, and that the quality of the data did not give the possibility of creating more accurate/reliable geological model which implies different well construction, mud design etc.
- The technological standard of the time was much lower than today

Figure 5.3 shows the prognosticated vs the actual well Bč-5.

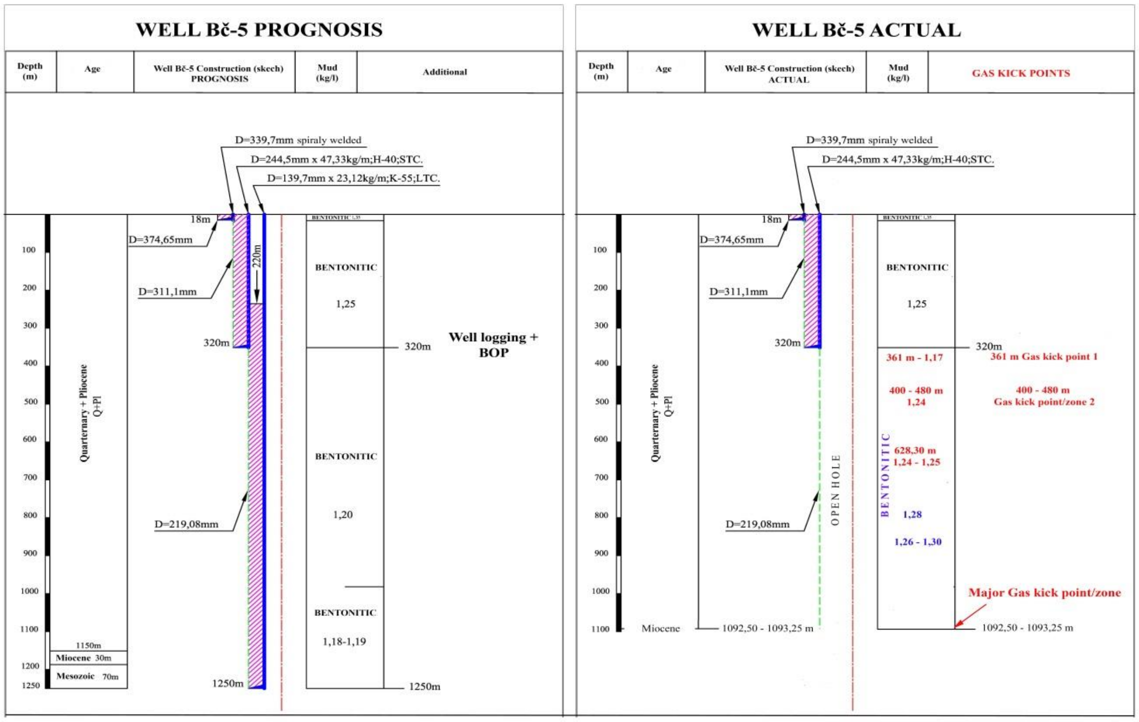


Figure 5.3 Schematic of prognosticated (left) and actual (right) well Bč-5.

5.2 Implementation of remediation project

In order to remediate the uncontrolled migration of CO_2 gas from Bč-5, a co-operation with the Institute of Applied Chemistry at the University of Miskolc, Hungary, was established in 1991. A project for remediation and mitigation “Revitalization Project for CO_2 gas migration control in the Bečej-5 Well” was initiated in 1992, but was not realized.

During 2007, a remediation operation to stop the uncontrolled gas migration was performed successfully. This operation was performed in a triangular well layout formed by the damaged well Bč-5 and the two directional wells Bč-x1 (Figure 5.4) and Bč-9 (Figure 5.5). The remediation procedure consisted of injecting various chemical solutions to clog the flow paths, via the directional well Bč-9, with constant monitoring of wells Bč-x1 and Bč-5 as control points. This is described in more detail below.

Well Bč-x1, a deviated well, was drilled 240 m away from Bč-5 targeting the bottom hole of the collapsed wellbore, with the aim of mitigating gas loss and observing the underground flow processes. The well Bč-x1 was completed at a depth of 1150.70 m, but mitigation works were not performed because of self-strangulation of well Bč-5. It is assumed that the bottom of well Bč-x1 is located within a diameter of about 15 m from the nominal borehole Bč-5, as shown in Figure 5.4 below. The deviated, directional well Bč-x1 served as observation well and/or as an alternative remediation well. The Bč-x1 well was reworked and completed in a similar manner as well Bč-9, except that the tubing was equipped for pressure monitoring.

Well Bč-9, another deviated recovery well, was also drilled in the immediate vicinity of the damaged well Bč-5. The well was properly completed with minor issues of kicks and fluid loss. The final depth reached was 15 m above the planned depth of the well, and it approached the nominal shoe of the Bč-5 well to a horizontal distance of 11 m, as shown in Figure 5.5. The last casing, 5", was completely cemented and perforated in the interval of 1131-1133 m.

Remediation operations took place in the period 01.05.-01.07.2007. The operations were performed with the use of a number of new methods and technical procedures that had not been used before by NIS Naftagas. The operation was performed through the well Bč-9 with the permanent monitoring wells Bč-5 and Bč-xl as control points. In accordance with the designed protocols (physical-chemical properties of the fluids, pressure and volume), a total of 1700 m^3 of different chemical solutions (water glass, polymer, activators, cross linking agent and acid) were injected into the bottom region of the damaged well Bč-5, with 150 m^3 of water as a precursor and 200 m^3 of water to finish. Injection capacity was 50 m^3 per day, and the pressure in the injection well head 5 – 35 bar.

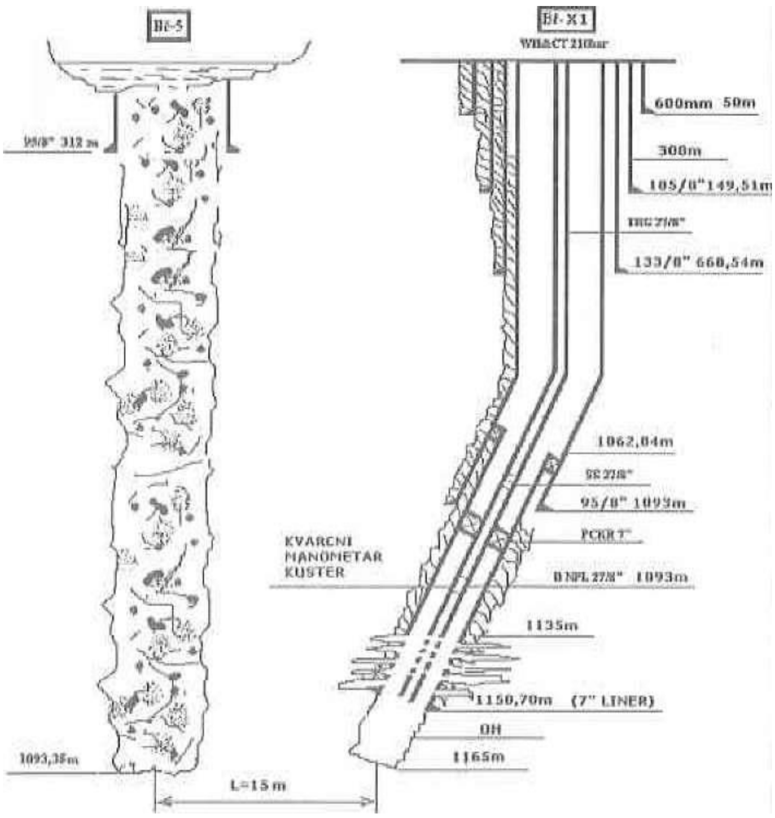


Figure 5.4 Well schematics for wells Bč-x1 and Bč-5.

A field laboratory was established at the site to check the physical-chemical characteristics of the fluids, and also for fluid preparation such as a new type of gel-breaking polymers. The injection was performed using two triplex pumps plunge Union TD 60 on electric drive, which was also a novelty. Early monitoring measurements in the control wells Bč-5 and BC-x1 indicated that a positive result could be expected and that the uncontrolled migration of CO_2 would be significantly reduced or completely stopped.

5.3 Effect of remediation action

During injection of chemicals into well Bč-9, permanent reduction of gas was registered by accumulation of water in well Bč-5, which at the end of the operation practically ceased. Also, at well Bč-x1, a constant moderate growth of pressure at the bottom of the borehole was recorded during the early phase of operations, and by the confluence of fluids through opened intervals in the last week of the operation and after its completion. The level of fluid in the tubing at Bč-x1 in the period 07.01.2007-28.08.2007 increased from 900 m to 400 m, with an increase in pressure at the bottom of the borehole of 20.8 bar. These were the first encouraging signs that the damaged well Bč-5 and well Bč-x1 were filled with chemicals injected through well Bč-9. Therefore, the remediation procedure seems to have been successful.

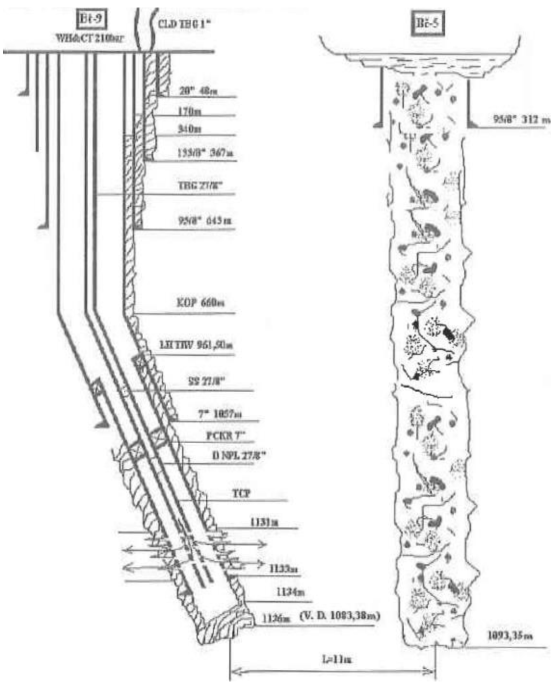


Figure 5.5 Well schematics for wells Bč-9 and Bč-5.

6 OVERVIEW OF RELEVANT EC PROJECTS ON CO_2 WELL LEAKAGES

This section gives an overview of research on well leakage scenarios performed in preceding EC projects. Previous research will be used in MiReCOL as a knowledge base and this summary will help to avoid duplication of work. Certainly not all relevant work performed earlier can be mentioned here. The work presented in this section can be regarded as exemplary for (some) research performed under the EC FP-7 framework.

Research activities in recent EC projects did not particularly focus on WBEs and their failure modes (to our knowledge). Basic research on degradation mechanisms of steel and cement, also on the long term, and fluid flow behavior through and along wellbore interfaces present the main focus of EC research, at least in EC projects the MiReCOL partners participated in. However, this knowledge can also be seen as highly relevant for work in MiReCOL and will be considered in the ongoing and future research in MiReCOL.

The overview focusses on three previous EC research projects:

- CO_2CARE: "CO_2 Site Closure Assessment Research" Grant agreement no: 256625; THEME ENERGY.2010.5.2-3
- SiteChar: "Characterisation of European CO_2 storage" Grant agreement no : 256705; THEME ENERGY.2010.5.2-1
- ULTimateCO_2: "Understanding the long-term fate of geologically stored CO_2" Grant agreement no.: 281196; THEME ENERGY.2011.5.2-1

6.1 CO_2CARE (2011-2013)

The aim of CO_2CARE was to support the large implementation of CCS demonstration projects by investigating the requirements for CO_2 site abandonment and to develop procedures for site closure. The work focused on three key areas:

- Well abandonment and long-term containment
- Reservoir management from closure to long-term
- Risk management methodologies

The technologies and procedures developed were evaluated on the three real CO_2 injection sites at Ketzin, Sleipner and K12-B; and dry-run applications for site abandonment have been performed for hypothetical closure scenarios.

The work included the review of current regulatory frameworks (CO_2CARE D1.1) and industry best practices (CO_2CARE D1.2) with respect to well and site abandonment.

<u>Examples of relevant work performed:</u>

<u>CO_2CARE report D1.3</u> "Database of first abandoned CCS/ CO_2- exposed wells" (CO_2CARE,2012) refers to three CO_2 leakage events in the United States related to wellbores all of which can be used as examples and analogues for leakage events related to CO_2 storage operations.

In 1936, an exploration well at **Chrystal Geyser (Utah, USA)** hit an aquifer with high CO_2 concentrations, which let to regular eruptions and the release of 11.000t of CO_2 per year (Wilson et al., 2007). The well does not have a plug and can therefore act as an analogue for a worst case scenario of a leaking abandoned well. The CO_2 concentration next to the wellbore was found to be lower than environmental and safety thresholds, implicating that the risk for human and nature posed by a leaking abandoned well seems to be low (Wilson et al., 2007). It is recommended to model the impact of CO_2 release scenarios for wells at a potential storage sites before the injection of CO_2 commences to assess the actual risk for humans and environment.

At **Sheep Mountain (Colorado, USA)** a CO_2 blowout occurred in 1982 from a natural CO_2 reservoir, which led to a loss of well control for 17 days. After five attempts, the well was back under control and no subsequent leakage was reported. The remediation method was not further specified. The total amount of leakage was estimated to be 200.000 t of CO_2. Due to lucky circumstances (terrain, weather) nobody was seriously injured. This event can be seen exemplary for the upper limit leakage rates from a single well (Wilson et al., 2007).

An example of how to deal with legacy well has been shown at the **Salt Creek CO_2-EOR operations (Wyoming, USA)**. It is a reasonable example of leakage over a broad area with many old wells and provides recommendations on remediation. In 2004 and 2005, approximately 0.008% of the total amount of CO_2 injected seeped to the surface in a small area which could be attributed to legacy wells and existing migration pathways in the shallow subsurface (natural oil seeps). Some seepage could be eliminated immediately. “Substantial efforts have been undertaken to locate undocumented old wells that may exist throughout the field which include magnetic detection techniques (aerial and surface), radon, methane, and CO_2 detection (spectroscopy) and well file research” (CO_2CARE D1.3). Many wells, producers, injectors or P&A, were re-worked or re-plugged to bring them up to current safety standards, and sometimes new casing strings have been set. According to the operator, well integrity can still be improved by deploying modern completion tools and advanced cementing techniques, such as cement squeeze. If standard countermeasures were not successful, the detailed remediation plan included retrieval well drains for the extraction of leaking CO_2.

<u>In CO_2CARE WP4 “risk management”</u> well leakage scenarios for Sleipner, Ketzin and K12-B have been investigated that were used to establish a dry-run license application for the (hypothetical) closure of the three sites (CO_2CARE D4.6 and D4.8).

Relevant work performed at the **Ketzin** pilot site focused on well integrity monitoring. Besides typical operational parameters, such as BHP and BHT, the extensive monitoring program included

- Permanent ring chamber pressure monitoring in all the wells
- Electromagnetic inspection of the casing thickness
- Reservoir Saturation Tool (RST)
- P-T logging
- Magneto-Inductive-Defect Detection (MID) logging measurements
- Camera inspections
- Monitoring of saturation changes is performed in a time-lapse mode by PNG (Pulsed-Neutron-Gamma)
- a Distributed Temperature Sensonr (DTS) string, installed behind the borehole casing and cemented in place

All methods confirmed that there is no risk for the confinement of the CO_2 and no leakage could be detected. The methods listed above represent state-of-the-art measures for the validation (or failure) of well barriers (in particular behind the casing), also after remedial actions have been performed.

A FEP (Features-Events-Processes) approach has been used to assess risk scenarios for **Sleipner** in CO_2CARE Deliverable D4.8. One of the main risk scenarios is the leakage along wellbores encountered by the CO_2 plume, also associated with earthquakes. Two main risk factors were defined regarding wells (also in combination with natural pathways):

- Corroded annular cement and/or casing of the injector as a result of the dissolution of injected CO_2. Cement plugs would also be affected after abandonment.
- Leakage through an abandoned exploration or appraisal well, if it gets in contact with the CO_2 plume

Further investigation of these scenarios revealed very low likelihood with minor consequences for both. The integrity of the injection well annulus was confirmed e.g. by a leak-off test (below the 13 3/8” casing) and a formation integrity test (FIT) below the 9 5/8” casing. In addition, they used fit-for-purpose well barrier materials, 25% chrome (stainless) duplex casing steel and Class G cement. Additionally, the steel casing joints in the storage formation are made of 13% chrome steel which is much more resistant to corrosion than typical carbon steel casings. Numerical simulations showed that the plume will (probably) not reach legacy wells penetrating the storage complex and it is recommended to have a remediation plan in place for one well close to the plume.

Well leakage scenarios at **K12-B** can be compared to those at Ketzin and Sleipner and are related to geo-chemical and geo-mechanical attack of the cement sheath, casing and cement plugs. But the fact that K12-B is a depleted gas reservoir requires a different approach. In the first place, the risk scenarios of well leakage in K-12B are related to geo-mechanical issues as a result of compaction of the reservoir (from >350 bars to ~40 bars) and strains along the wellbore due to subsidence, in particular de-bonding. This is representative for all depleted hydrocarbon fields as potential candidates for CO_2 storage. A proper investigation includes reservoir-scale geo-mechanical modelling to assess the strains on the wellbore and the actual condition of well barriers. The favorable geological setting of K12-B with its massive overlaying ductile rock salt layers minimizes this leakage option to almost negligible proportions, also proven by the fact that no migration along any wellbore has been detected.

CO_2CARE WP2 was dedicated to well integrity research and many relevant studies have been performed including e.g. modelling flow along the wellbore, lab experiments on potential sealants for well remediation. However, this work package did not consider leakage scenario and risk assessment procedures in detail.

Main findings of CO_2CARE and recommendations, also with respect to ensure well integrity throughout the entire life-cycle (including post-abandonment) are provided in a Best Practice Guideline and a brochure (open-access). The chapter on wellbore safety with special focus on well abandonment management comprises information on:

- Recommendations from a review of current regulatory frameworks and industry best practices
- Summary of experience with abandoned CO_2 wells
- Summary of the track record of abandoned hydrocarbon wells
- Recommended workflow for geo-mechanical wellbore stability assessment
- Geochemical and geo-mechanical interactions
- Novel well-abandonment methodologies
- Well integrity logging

All public CO_2CARE reports can be downloaded at the CO2CARE Website.

6.2 SiteChar (2010-2013)

SiteChar aimed to improve and extend site characterization workflows for CO_2 storage and investigated the feasibility of several potential storage complexes in the EU. Main focus was on the assessment of risks and the design of monitoring plans for different storage types. Comparable with CO_2CARE, dry-run applications were developed for storage licenses at the end of the site characterization phase. Site characterization studies that also focused on well integrity were done on a site in Denmark and on a site in Poland:

Examples of relevant work performed:
In Deliverable D4.5 "Old well state, Danish site", an onshore well in Denmark penetrating a potential storage formation has been investigated with respect to work-over and different options for mitigation and abandonment. The well is not in line with

current requirements, and the abandonment method that was used poses the risk of CO_2 leakage and is being considered as not ready for CO_2 storage. Main issues are the lack of isolation between two permeable formations and the insufficient length and unknown quality of the cement plugs.

Different options are discussed for intervention:

1. Remediation could be postponed until the CO_2 plume has reached the well or a leak has been detected. This option poses high safety risks and will probably not be accepted by the competent authority for a storage license, unless the probability is very low that CO_2 reaches the well gets or experiences elevated pressure during injection.
2. The well could be reactivated to be used for monitoring and possibly as a back-up injector/producer. Given the initial results of simulations and analysis, the operational value of the well appears to be small and the option to turn it into a (stand-by) producer or injector is not attractive. To re-complete it and turn it into a monitoring well is costly, but an interesting option. Before this option becomes a viable alternative, various leakage and monitoring scenarios would have to be considered. Overall, however, the only saving that the existing well can bring with respect to a new one is an existing 13⅜" casing cemented at shallow depths.
3. It could be plugged and abandoned; or an instrumented abandonment could be attempted. Plugging & Abandonment (P&A) presents the simplest solution at minimum risk, however, at the cost of reduced opportunity. Instrumented abandonment increases the residual risk of hydraulic connection. Additionally, this method has not been tested extensively to the knowledge of the authors, so some research & development work is needed before applying instrumented plugs for CO_2 storage site abandonment.

It was recommended that proper plugging and abandonment after well re-entry is the best option at this point. When further details on injection scenarios and operational plans are available, this decision should be reconsidered. This study can be seen as exemplary for dealing with legacy wells in a potential storage area. Each well and its risks have to be investigated separately, options and costs have to be established and a decision on how to proceed has to be made. For many cases, one can expect that properly re-abandoning the old well is the best possible solution.

Report D5.5 "Qualitative assessment of potential risks, Zalecze & Zuchlow site":
To evaluate the risk of the potential Polish storage site, a qualitative risk assessment has been performed using the TNO CASSIF approach (Yavuz et al., 2009) as a first step. The study also included the assessment of well leakage risks. A first generic workshop was followed by another workshop dedicated to well integrity issues. This site can be seen to be representative of a depleted hydrocarbon field in an extensively explored oil & gas area with many abandoned wells. The assessment revealed that the major risk related to wells can be described by two scenarios:

1. Plug failure in older, abandoned wells that do not fulfil CO_2 storage requirements, which could lead to CO_2 migration to a shallow saline aquifer or to potable groundwater resources and soil.
2. Cement sheath failure for all, also recent wells, however with very limited consequences.

It was recommended to monitor annular pressures of old wells. Also soil, adjacent aquifer and groundwater should be monitored chemically for all wells. Remediation plans would have to be in place for working over the leaking wells in case significant leakage is detected; and plans to adapt the injection strategy accordingly would have to be developed and evaluated before injection starts. An appropriate risk assessment should be performed before injection is started, including accurate evaluation of existing and additional wells logs. Typically for this kind of assessment, the lack of information and uncertain condition of well barriers are the major issues to be addressed in every well integrity evaluation of this type.

Main results of SITECHAR, including relevant well integrity research, has been summarised in dry-run storage permit applications for the different European sites. Key messages concerning wellbore integrity drawn from SITECHAR are:

- It can be confirmed that existing or old wells represent the highest risk for all SITECHAR storage sites
- Well integrity evaluation is time consuming depending on the number of wells included in the assessment and turns out most often as insufficient as a result of missing data. As a consequence worst-case scenario (modelling) is required.
- Lack of data is of major concern for a proper well integrity evaluation, particularly for depleted hydrocarbon fields with many of wells
- Downhole monitoring might be necessary to ensure the absence of leakage if old (abandoned) wells are not remediated beforehand. Both operations are very cost-intensive and can be technically challenging.

The FEP method provides a vital tool to assess and evaluate risks related to well integrity

6.3 ULTimateCO_2 (2011-2015)

This project aimed at increasing the knowledge of the long-term fate of geologically stored CO_2 and at developing tools for predicting long-term storage site performance. The work focusses on the understanding of chemical and physical processes and their impact on:

- Trapping mechanisms in the reservoir
- Fluid-rock interactions and effects on mechanical integrity of the caprock system

- Leakage due to mechanical & chemical damage in the well vicinity

Since the work on well integrity focusses on the well material testing and investigation of the actual degradation processes, leakage scenario definition plays a minor role. However, the field test at Mont Terri will provide valuable insights on well material behavior, multiphase flow along a wellbore and the evolution of well material failures, which can be relevant for this subproject in MiReCOL. Leakage pathway evaluation is currently performed at small scale (e.g. in the annulus) in Task 5.3 and will be extrapolated to large scale. Both can be of high importance for future work in MiReCOL. Related ULTimateCO_2 deliverables on experimental and numerical studies on transport properties and well leakage pathway investigations are due next year. Since several institutes participate in both projects, a regular knowledge exchange takes place with focus on deliverables within “Long-term process study – near-well sealing integrity” work package.

Main outcomes of future ULTimateCO_2 deliverables will be monitored and regarded in related work in MiReCol.

7 CONCLUSION

Wells are generally considered to represent the highest risk of leakage in a CO_2 storage project. Such leakages are caused by failure of one or more well barrier elements; otherwise the well integrity would be intact.

The well barriers of active and abandoned wells have been described and causes and consequences of leakage through those well barrier elements (WBE) have been presented. Ageing issues with cement degradation, casing corrosion and wear, and thermal loads imposed on the well infrastructure are examples of the most likely causes of well leakages. The tubing is the WBE that is by far the most likely to fail, probably due to corrosion and/or connection failures. Also the casing and the cement have a significant chance of failure.

A wide range of technologies and methods from the oil & gas industry are available that can also be used for the remediation and mitigation of leakages from CO_2 wells. In the next deliverables available remediation technologies from the O&G industry and previous EU projects will be reviewed and evaluated towards their application to CO_2 wells. The remedial actions taken after the blow-out and following migration of CO_2 at the Bečej natural gas field will provide valuable input for this review.

As future work a number of laboratory tests are planned to examine the merits of new materials for remediation of well leakage. These materials include CO_2-reactive suspensions, polymer-based gels, smart cements with a latex-based component and a polymer resin for squeezing. If possible, the efficiency of a CO_2-reactive suspension will be investigated in a field test at the Serbian Bečej natural CO_2 field.

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