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MiReCOL: developing corrective measures for CO_2 storage

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Abstract

CO_2 capture, transport and storage (CCS) has the potential to significantly reduce the carbon emission that follows from the use of fossil fuels in power production and industry. Integrated demo-scale projects are currently being developed to demonstrate the feasibility of CCS and the first such projects are expected to start operating in Europe under the Storage Directive in the period 2015 – 2020. As part of the license application, these projects must develop a corrective measures plan, which describes the measures that can be taken when the CO_2 in the subsurface behaves in an unexpected way. The MiReCOL project supports the development of corrective measures plans and helps building confidence in the safety of deep subsurface CO_2 storage by providing a toolbox of techniques to mitigate and/or remediate undesired migration of CO_2. MiReCOL aims to support the dialogue between CCS project operators and regulators by providing a clear description of the scope and feasibility of corrective measures.

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Keywords: CO_2 storage; corrective measures; mitigation, remediation.

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1. Introduction

CO_2 capture, transport and storage (CCS) has the potential to significantly reduce the carbon emission that follows from the use of fossil fuels in power production and industry. Integrated demo-scale projects are currently being developed to demonstrate the feasibility of CCS and the first such projects are expected to start operating in Europe under the Storage Directive in the period 2015 – 2020. As part of the license application, these projects must develop a corrective measures plan, which describes the measures that can be taken when the CO_2 in the subsurface behaves in an unexpected way.

Funded by the EU Seventh Framework Program, the MiReCOL project supports the development of corrective measures plans and helps building confidence in the safety of deep subsurface CO_2 storage by providing a toolbox of techniques to mitigate and/or remediate undesired migration of CO_2.

This paper gives an overview of currently available corrective measures for undesired CO2 migration outside the reservoir within the storage complex (related to the reservoir, faults and wells) and describes the most relevant migration scenarios, that will be used in the MiReCOL project to describe existing corrective measures and propose new measures. These corrective measures include the following:

- Migration of CO_2 within the reservoir: flow diversion, pressure management;
- Fault related migration: managing fault properties, flow diversion, sealants, hydraulic and gas barriers;
- Well related migration: reactive suspensions, gels, smart cement, resins.

At the end of the project, results will be made available in the form of a Best Practice Manual for corrective measures.

2. Setup of project

The starting point of the MiReCOL project is a storage site in the operational or post-operational phase, i.e., a storage site in which injection of CO_2 is ongoing or has been completed. This implies that all risk mitigation measures have been taken and that a suitable and effective monitoring system is in place. The results from the MiReCOL project become relevant if, at some point during a CCS project, a ‘significant irregularity’ occurs. The scope of MiReCOL therefore includes those corrective measures that can be applied after a significant irregularity is detected. Fig. 1 illustrates this in a bow-tie representation of feature-event-processes (FEP) combination.

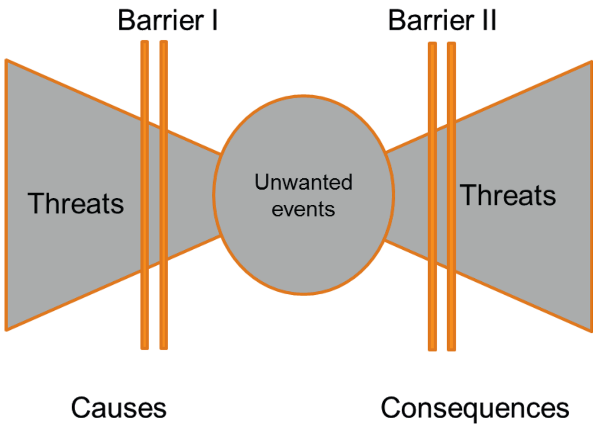

Fig. 1. *Bow-tie representation of threats (left side), events (centre) and consequences or calamities (right-hand side). Barrier II, on the right hand side, represents mitigation and remediation measures, the subject of MiReCOL.*

While a ‘significant irregularity’ may signal a threat to the safety and security of storage, the decision to take action should depend on both the unmitigated risk and the mitigated risk. The former represents the risk associated with the undesired behaviour of CO_2 that is detected in the subsurface, before any corrective actions are taken. The latter is the risk associated with the storage complex after applying the corrective or mitigation measure. A corrective or mitigation measure could completely remediate migrated CO_2, but its effect on the safety and security of storage could be such that the total risk after remediation would be higher than before. As an example, a pressure relief well affects the integrity of the cap rock, which may represent a higher risk than an undesired migration of the plume of free CO_2 in the reservoir. This risk based approach is central to the MiReCOL project.

This concept of mitigated risk, or, put differently, the change in the risk 'state' of the storage complex as a result of applying the remediation measure plus that of the mitigated consequences of the threat, is applied throughout this project. All remediation and mitigation measures considered in this project will be studied from all angles, to investigate their impact on all levels of risk. This will:

- provide the information that will allow operators to assess the absolute and relative values of mitigation measures; it even enables them to do so numerically [9];
- help competent authorities understand the options open to CCS storage operators;
- inform the local authorities about available options to mitigate or remediate in case of leakage to the (near-) surface or atmosphere.

When a threat to safe and secure storage or an unwanted migration of CO_2 in the storage complex, or a leakage out of the storage complex (collectively referred to as 'event') is detected, the storage operator is to assess whether corrective measures can be applied. This assessment should include not only the efficacy of a particular measure on the event, but also its impact on the storage complex as a whole. It is the aim of each storage project to minimise the risk to safe and secure storage and to minimise the impact of the project activities on the environment. An event may increase these risks and impact, but the deployment of corrective measures should be assessed from the viewpoint of the aforementioned minimisations.

Therefore, corrective measures will be scored using a series of key performance indicators (KPIs), which together can be used by storage operators and competent authorities to decide:

- whether a corrective measure is relevant for a specific threat or leakage, in a specific storage site (the event) and
- whether deploying the measure leads to an overall reduction in risk to safe and secure storage and
- whether the impact of the measure on the environment is justified by the results.

The list of KPIs includes such aspects as response time, longevity of result, affected volume, technical and operational maturity and (indicative) cost, as well as where in a storage complex the technology can be deployed. These KPIs are related to the assessment under the first bullet in the above list. An essential set of KPIs measures the impact of a technique on the overall risk level of the storage site: the impact of a technique on the safety and security of storage. This set of KPIs, used to assess aspects under the second bullet, constitutes an important part of the progress beyond the state-of-the-art resulting from this project, as they are the result of considering the impact of corrective measures on all possible aspects of the storage system. Finally, KPIs related to impact on the surface environment (third bullet) will be investigated, as such impact may negate a measure's benefits in terms of mitigating or remediating a threat or leakage event.

The complete assessment of corrective measures will be performed on a range of specific storage complexes, to estimate the effects, to discover the limitations, and to define key controlling storage site properties. These results will be used to formulate guidelines for operators to assess the applicability of each technique to their specific storage complex. It is to be emphasized once more that this strategy notably extends beyond a relatively simple assessment of the expected performance of a measure against a threat or leakage: this includes a complete assessment of the impact of a technique on the entire storage complex. These guidelines will be illustrated with the site-specific results, to support the more general conclusions drawn about each technique.

For operators, the handbook that will contain these results and guidelines, will be useful in setting up a corrective measures plan, pursuant to the Storage Directive, as well as in formulating a plan of action in the case of a real threat or leakage event.

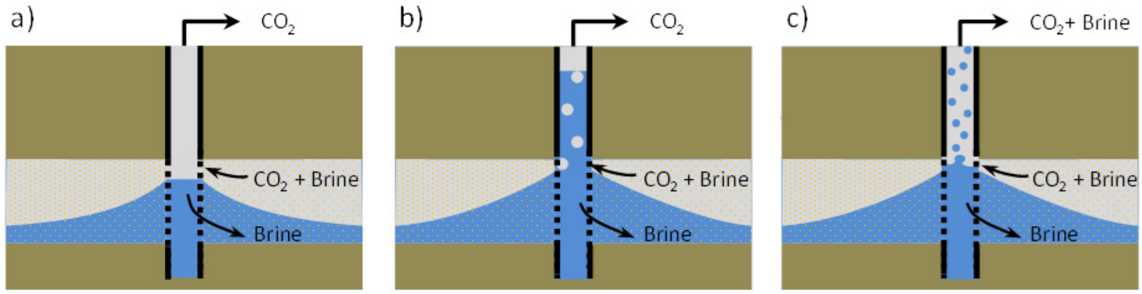

Fig. 2. Schematic of three operational modes during a CO_2 back production test: (a) small production rates produce pure CO_2 at wellhead elevation; (b) increasing production rates evoke a rising water column with CO_2 bubbles inside; (c) production rates beyond a specific level cause dispersed brine entrained by CO_2 at wellhead elevation.

Three general scenarios are considered in the MiReCOL project, all related to processes in the (deep) subsurface:

- Lack of conformance in the reservoir due to reservoir compartmentalisation / discontinuity (leading to unexpected increase of injection well pressure), spread of the CO_2 plume beyond the desired region (e.g. spread beyond the spill point, or migration into or through the caprock),
- Natural barrier breach referring to undesired migration of CO_2 or displaced brine through breached seals via faults and fractures (e.g. partial or full seal penetration, migration along faults, induced fracturing of the seal, geochemical alteration leading to or accelerating migration rates)
- Well barrier loss through accessible, plugged and abandoned wells, migration along the wellbore, migration of the CO_2 to an unintended storage complex formation (thief zone) through the wellbore and unknown wells.

Corrective measures that can be deployed to remediate these scenarios and that are studied in MiReCOL are discussed in some detail in the sections below.

3. Reservoir

One of the areas in a storage complex where corrective measures can be applied is the storage reservoir, in cases when unexpected fluid flow represents a threat to safe and secure storage. An example would be a case in which the CO_2 plume is migrating towards a spill point or a fault zone.

Measures to achieve flow diversion that will be studied in the MiReCOL project include:

- localized reduction in permeability by e.g. the injection of gels or foams or by immobilizing the CO_2 in solid reaction products;
- change of injection strategy;
- localized injection of brine creating a competitive fluid movement.

The effectiveness of these measures is elaborated in model studies.

Fluid movement in a reservoir is driven not only by reservoir properties like structural dip or spatial heterogeneity in permeability and/or porosity, but also by pressure gradients. Therefore, migration management in the reservoir can also be achieved by managing the reservoir pressure distribution. A targeted pressure management can be achieved by either brine withdrawal (preferably outside the actual CO_2 plume) or CO_2 back-production from inside the CO_2 plume (Fig. 2). Both measures will create pressure gradients towards the withdrawal point and enforce a specific flow direction.

The feasibility and efficacy of CO_2 back production will be studied in field campaigns that are planned in two CO_2 storage sites that are operated by partners in the MiReCOL consortium. The Ketzin site (Germany) is currently in the abandonment phase and back production of the CO_2 injected over the past years is part of the abandonment procedure. Planned for September 2014, data that are recorded during the back production will be used to draw conclusions regarding back production as a potential mitigation option. The pressure development over time in the reservoir and the rate of CO_2 produced from the reservoir will be relevant data. At the K12-B offshore gas field (in the Dutch sector of the North Sea), preparations are ongoing (Summer 2014) to back-produce the CO_2 that has been injected in one of the compartments of the field. Data and experience from the Bečej field (Serbia), that produced a significant outflow from a natural CO_2 field, will be used to complement the Ketzin and K12-B data.

These field campaigns will be accompanied by extensive numerical modelling work to analyse the results of the tests and to study potential hysteresis effects of brine / CO_2 relative permeability. The aim of this work is to produce generally applicable rules for the feasibility and effects of back production as a mitigation measure.

Brine withdrawal will be studied by numerical simulations. A novel approach, which will also be studied by numerical modelling, is pressure reduction by actively accelerated brine- CO_2 mixing and dissolution.

4. Faults, cap rock

Reduction or interruption of undesired migration through faults and fracture networks will be studied from several viewpoints: (i) a self-healing approach in which the effect of the modification of the stress field after back production may result in a lower leakage rate; (ii) an approach in which one tries to stop or decrease locally the gas flow through fractures by using sealants (gels, foams); and (iii) at larger scales create hydraulic or gas barriers to prevent gas migration through the cap rock.

4.1. Self-healing approach

Anomalous migration of CO_2 can typically be detected by seismic methods. However, the flow rates cannot be determined accurately using such methods and one must rely on other methods including reservoir simulations. Since the fault system or the fracture network may not be described with enough accuracy, or its geometry is uncertain, simulation parameters may have to be determined using general knowledge of fault behaviour, in particular as derived from naturally leaking fault systems. Furthermore, pore-pressure changes result in stress and strain changes in the cap rock (reservoir depletion, e.g., generally results in an increase in horizontal stress in the caprock), and those stress/strain changes will affect the permeability of the fractures/faults. This can be simulated by geomechanical modelling in combination with a fracture-flow model.

4.2. Use of sealants for reducing gas flow

The oil and gas industry has long-term experience in reducing the flow rate of a given fluid, or maximizing oil or gas recovery by injecting viscous fluids or other fluids with specific properties (see for example [1]). We intend to select or adapt such techniques for reducing or stopping the migration of CO_2 through faults and fractures. Using polymers, their rheological characteristics when injected into the subsurface reservoir are modified in time either by adding an additive, or just by interaction with the environment such as variation in temperature, pressure or surrounding fluids [2]. The design of an efficient remediation strategy using polymer gel for possible CO_2 leakage would depend on engineering the gelation time of the polymer and cross-linker combination for the targeted subsurface reservoir conditions.

The use of foams is another potential leakage remediation method. A foam is a dispersed system consisting of water and gas bubbles stabilized by surfactants. For CO_2, the mobility reduction factor is usually lower than for nitrogen and the maximum attainable value decreases rapidly with CO_2 density [3-5]. It was inferred from laboratory study, using classical foaming agents, that for dense CO_2 probably only coarse foams-emulsions could be formed. However, more recent results showed that, even with dense CO_2 and using dedicated surfactant formulations, gas mobility reduction factors as high as 25 could be obtained [6]. This indicates the formation of strong foams. The design of a foam remediation process consists of choosing the appropriate surfactants and determining the onset of the foam as a function of gas-water flow rate ratio.

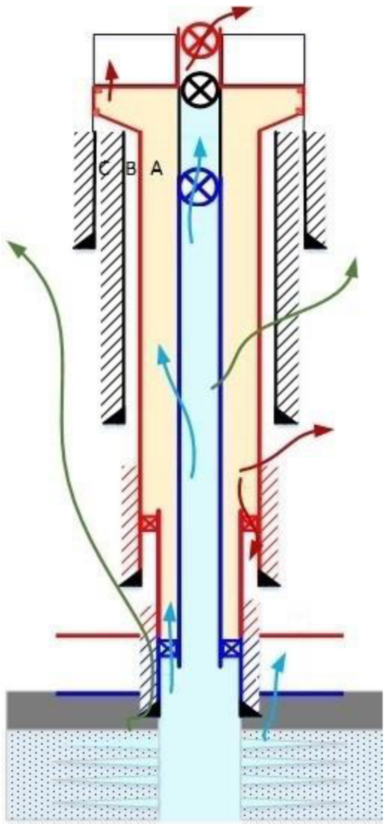

Fig. 3. Schematic illustration of some possible leak pathways due to well barrier element failures in an active CO_2 well.

4.3. Hydraulic and gas barriers

Two methods will be studied. The first one is to inject nitrogen either as a preventative or remediation measure. The principle of nitrogen injection is to increase the interfacial tension between water and gas. Since N_2 is lighter than CO_2, the fluid system effective at the base of the cap rock will be nitrogen-water, and not CO_2-water. Therefore, higher overpressures are allowed, or from a safety perspective, the safety margin is increased.

The second method is to generate a hydraulic barrier. The principle of the hydraulic barrier is to inject water continuously in an aquifer above the cap rock in order to decrease the pressure gradient across the cap rock, or if possible to create an inverse pressure gradient [7]. Such measure will decrease the leakage rate occurring across the cap rock. This remediation technique can be applied at low cost but is only temporary.

5. Wells

Wells are generally considered to represent the highest risk of leakages in a CO_2 storage project. Ageing issues with cement degradation, casing corrosion and wear, and thermal loads imposed on the well infrastructure are well-known examples of causes for well leakages. A wide range of technologies and methods from the oil & gas industry are available that can be used for the remediation and mitigation of leakages from CO_2 wells.

Well leakages are caused by failure of one or several well barrier elements (i.e. well components such as tubing, cement, etc.); otherwise the well integrity would be intact. If a leak occurs, the first course of action will be to determine the cause of the leak; i.e. which well barrier element(s) that has failed. When the cause of the leak has been determined, remedial actions can proceed. Fig. 3 shows an illustration of some possible leak pathways due to well barrier element failures in an active CO_2 well.

The MiReCOL project will review the available remediation technologies and evaluate how these can be applied to remediate leakages for a selection of the most likely CO_2 leakage scenarios. A number of laboratory tests are planned to examine the merits of new materials for remediation of well leakages. 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.

6. Near surface

In the event that CO_2 migration leads to leakage to the surface or near surface, then it may contaminate drinking water supplies (potentially mobilizing heavy metals) or enter buildings. A review of techniques used in pollution control and clean-up is being undertaken, to identify techniques for the remediation of the CO_2, and to assess likely costs.

7. Corrective measures toolbox and web-based tool

The (technical) feasibility and effect of corrective measures, as described in the previous sections forms the basis for a more complete definition of the feasibility and impact of remediation technologies for the leakage scenarios considered in this project. This additional layer includes a description of the impact on the overall risk level of a storage project and on the environment, thus taking into account the effect of deep-burial based remediation techniques on the risk for shallow leakage that is of greatest concern for stakeholders.

The combined description of remediation techniques will feed into guidelines, tailored to stakeholder requirements. The guidelines will contain, for each remediation technique considered, an evaluation based on carbon footprint; other environmental impact; timescale to effective cessation of leakage; likelihood of success; economic cost; stakeholder acceptability and location of retention of the CO_2 (i.e. within reservoir, storage complex etc), longevity of remediation. A comparison between different techniques will be enabled through a traffic-light system, enabling an informed choice by CCS project operators. This way, the guidelines can be seen as toolbox of corrective measures available to operators, with the means to compare different techniques.

The guidelines represent the project’s main result. The guidelines will contain all the information needed for site operators to set up a corrective measures plan for their site, and for competent authorities to understand the options open to site operators in case of a significant irregularity in the storage operation. To improve the applicability of the guidelines and help clarify options open to site operators, a web-based tool will be developed that applies the guidelines to specific sites, or to specific threats or events.

8. Conclusion

This paper gives an overview of the MiReCOL project, which focuses on mitigation and remediation measures that can be taken in the event of ‘significant irregularities’ in a CO_2 storage system. The latter term is used in the EU CCS Directive and refers to a (serious) mismatch between expected behaviour of the storage system and the data from the monitoring system. Such a mismatch could indicate that a potential threat to human health or the environment is developing inside the storage complex, due to undesired behaviour of the CO_2. Once the cause of the mismatch is defined and the conclusion has been reached that such a threat is present, the operator of the site may have to deploy corrective measures to remove the threat.

Started in 2014 and continuing until 2017, the project will combine currently available corrective measures with new techniques and study their applicability in the most relevant scenarios of migration of CO_2. The project considers migration scenarios associated with the reservoir itself, the cap rock, faults and wells. Corrective measures applicable to each of these elements of the storage complex will be described in detail, using performance indicators such as area of volume affected, longevity of the result, response time and, perhaps most importantly, impact on the risk level of the storage complex. A key aspect that should be assessed when considering the deployment of corrective measures is whether the effect of the measure itself is to increase the risk of breach of containment to a level that is higher than that of the unmitigated system.

The combined description of remediation techniques will feed into guidelines, tailored to stakeholder requirements. The guidelines will contain, for each remediation technique considered, in addition to the indicators listed above, an evaluation based on carbon footprint, other environmental impact, timescale to effective cessation of leakage, likelihood of success, economic cost, stakeholder acceptability and location of retention of the CO_2 (i.e. within reservoir, storage complex etc.). A comparison between different techniques will be enabled through a traffic-light system, enabling an informed choice by CCS project operators. This way, the guidelines can be seen as toolbox of corrective measures available to operators, with the means to compare different techniques.

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The MiReCOL results will support the dialogue between CCS project operators and regulators by providing a clear description of the scope and feasibility of corrective measures.

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