Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 37 (2013) 4731 – 4740

Energy Procedia

GHGT-11

Key site abandonment steps in CO_2 storage

Kühn, M.[1,*], Wipki, M.[1], Durucan, S.[2], Korre, A.[2], Deflandre, J.-P.[3], Boulharts H.[3], Lüth, S.[1], Frykman, P.[4], Wollenweber, J.[5], Kronimus, A.[5], Chadwick, A.[6], Böhm, G.[7] and CO_2CARE Group

[1]*GFZ German Research Centre for Geosciences, Potsdam, Germany*
[2]*Imperial College London, Great Britain*
[3]*IFP Energies nouvelles, France*
[4]*GEUS - Geological Survey of Denmark and Greenland, Copenhagen, Denmark*
[5]*TNO - Nederlandse Organisatie voor, Toegepast Natuurwetenschappelijk Onderzoek*
[6]*British Geological Survey, Great Britain*
[7]*Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Italy*

Abstract

The European Commission published a set of Guidance Documents to assist countries and stakeholders to implement the EU Directive 2009/31/EC on geological storage of CO_2. The main objectives of the CO_2CARE project are closely linked to the three high-level requirements of the Directive with regard to post-closure transfer of liability of a storage site to the relevant competent authority: (i) absence of any detectable leakage, (ii) conformity of actual behaviour of the injected CO_2 with the modelled behaviour, and (iii) the storage site is evolving towards a situation of long-term stability. Guidelines for regulatory compliance and "Best Practice" for site abandonment are being established by distillation and integration of all research findings into site closure and abandonment protocols. The work is based on 9 key injection sites in Europe and worldwide.

Keywords: CO_2 storage, containment, safety, risk management, abandonment, guidelines, liability transfer, best practice, dry-runs

1. Introduction

To assist countries and stakeholders to implement the EU Directive 2009/31/EC on the geological storage of CO_2 a set of Guidance Documents are published by the European Commission (EC). Therein the lifecycle of a storage project is subdivided into the 6 phases: (1) assessment, (2) characterisation, (3)

* Corresponding author. Tel.: +49 331 288 1594; fax: +49 331 288 1502.
E-mail address: mkuehn@gfz-potsdam.de.

doi:10.1016/j.egypro.2013.06.382

development, (4) operation, (5) post closure and (6) post transfer, separated by project or regulatory milestones. Focus of the CO_2CARE project, presented here, is on phase 5 in particular, site closure and preparation for transfer of liability.

CO_2CARE is an EU and industry funded project within the FP7-research programme, which started in January 2011 to run for a period of three years (www.co2care.org). It consists of an international consortium of 23 partners from Europe, USA, Canada, Japan and Australia, belonging to universities, research institutes and energy companies. In order to incorporate up-to-date results and monitoring data through the industrial partners of the project and CSLF collaborators, 9 key injection sites in Europe and worldwide are an integral part of the project: (1) Ketzin, Germany; (2) Sleipner, Norway; (3) K12-B, The Netherlands; (4) Rousse, France; (5) Montmiral, France; (6) Frio, USA; (7) Wallula, USA; (8) Nagaoka, Japan and (9) Otway, Australia (Fig. 1).

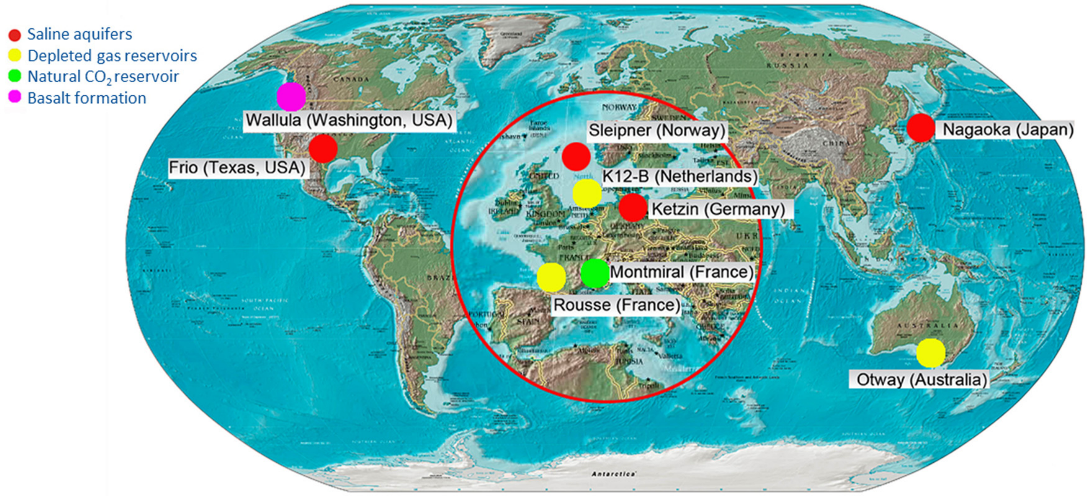


Fig. 1. Field site portfolio consists of 9 European and overseas locations of CO_2 reservoirs.

The main objectives of the project are closely linked to the three high-level requirements of the EU Directive, Article 18 for CO_2 storage site transfer of responsibility which are: (i) absence of any detectable leakage, (ii) conformity of actual behaviour of the injected CO_2 with the modelled behaviour, and (iii) the storage site is evolving towards a situation of long-term stability. These criteria have to be fulfilled prior to subsequent transfer of responsibility to the competent authorities, typically 20 or 30 years after site closure. CO_2CARE formulates robust procedures for site abandonment which will meet the regulatory requirements and ensure long-term integrity of the storage complex.

Results of the first 18 months of the CO_2CARE project are presented here, and focus on:

- current practices and regulatory framework,
- full scale well modelling and numerical results per site,
- relevant trapping mechanisms based on site portfolio and
- risk assessment criteria for decision making in site abandonment.

Overall guidelines for regulatory compliance and “Best Practice” for site abandonment will be established by the project through distillation and integration of all research findings into site closure and abandonment protocols compliant with the EU storage regulations, within the second half of the project based on the results presented here.

2. Current practice and regulatory framework

The basis for future guidelines and "Best Practice" and the ability to identify gaps requires a good understanding of the existing expertise and guidelines. Therefore, the first step was to review and asses international regulatory requirements on CO_2 geological storage and to compare potential site abandonment methodologies with current practice in related and relevant fields.

2.1. International regulatory requirements on CO_2 geological storage and site abandonment

The European and international regulations covering carbon dioxide storage and especially the site abandonment period starting after the end of CO_2 injection were reviewed [1] and are discussed here. According to these regulations, the liability for the storage site can be transferred to the licensing authority/government once the safety and conformity of monitoring with model predictions has been demonstrated. In the EU, the CO_2 storage Directive 2009/31/EC set out the regulatory regime and guidance for permitting CO_2 storage and, while a few EU countries have already transposed this directive to national law, most are still tasked with formulating their own national regulations. Around the world, relevant bills and regulations have also been introduced in recent years.

To demonstrate the safety of the injected CO_2 all regulations require a combination of monitoring, modelling and risk assessment tasks. Although there is large variation in the specifics it is standard to require approval for these tasks as part of a plan submitted to the authority in charge. To demonstrate the safety of the injected CO_2, the results of monitoring, modelling and risk assessment, regulations require meeting the high-level criteria. Some regulations contain additional obligations including demonstrating no environmental impacts, that the plume will not encounter any leakage pathways and the well integrity has been proved. There is a variation in the time period over which safety must be shown in different regulations, and an optimum time period is considered flexible.

Particularly in relation to well abandonment, it is recognised that there are different methods, materials and tests that could be used and most CO_2 storage regulations do not specify techniques to be followed or standards to be met. Specific details on plugging are provided by regulations on the abandonment of hydrocarbon wells and sometimes other injection wells, and these provide the best available guidance for CO_2 storage well abandonment, although they may require updating to deal with CO_2 injection specific issues.

Regulations typically contain a provision for transfer of liability once safety (CO_2 containment and well plugging) has been demonstrated. The EU Directive 2009/31/EC requires further monitoring after transfer of liability as a backup measure, while other regulations (e.g. EPA UIC) do not. The IEA model regulatory framework contains a clause that the operator should also provide suggestions for the monitoring to be conducted after transfer of liability.

The full results, including a breakdown across the various regulations of countries and Europe are given in a public report from the CO_2CARE project [1].

2.2. Current site abandonment methodologies in relevant industries

Site abandonment in the oil and gas industry is defined as actions taken by the operator to close down a previously operated field. It can generally be divided into two main activities, i) the abandonment of the wellbores drilled during operation and ii) the removal of surface installations. Site abandonment typically includes the plugging of wells; removal of well equipment, production tanks and associated installations; and surface remediation.

Among these processes, well abandonment is considered as the most important. Proper well abandonment for isolation of subsurface reservoirs should: (i) prevent all physical hazard potentially induced by the well; (ii) prevent any migration of contaminants between various formations and (iii) prevent the possibility of hydrologic communication between originally separated aquifer systems.

Regulatory guidelines, as well as industry best practices, specify the requirements for proper abandonment with respect to long-term safety of the sites. Proper abandonment should also regard the reason for abandonment of a site/well and the condition and construction details of the wellbore. Several industry practices were considered mainly from Europe, e.g. the Norwegian NORSOK D-10 guideline [2] and the Guidelines for the Suspension or Abandonment of Wells from UK Oil and Gas Association (UKOOA) [3]. These sources provide a general overview of the current state-of-the-art of abandonment methodologies in the oil and gas industry. Requirements to ensure safe CO_2 containment for hundreds of years differentiate from the methodologies of regular oil and gas site abandonment mainly due to the repressurisation of the reservoir, the corrosive nature of the stored CO_2 and the long time frame involved.

For well integrity in CO_2 environments, mechanical processes appear to be more significant than chemical degradation of wellbore cement, since chemical degradation is considered to be based on diffusion and is too slow to be an issue. Fractures or other pathways through the cement present high-permeable pathways for the CO_2. The behaviour at interfaces in the wellbores remains an issue, particularly if chemical, mechanical and physical processes interact. Potential leakage pathways could arise along these interfaces as a result of processes such as debonding. However, recent research has shown that even degraded cement maintains its mechanical strength and low permeability. Calcite healing of induced fractures or micro-annuli is also considered likely. However, this could be governed by local chemical equilibria dictated by the formation water composition and mineralogy.

It is recommended that guidelines on practices related to CO_2 geological storage should provide more specific guidance in terms of:

- How to abandon a CO_2 storage well properly, including the reinstatement of seal/caprock integrity and removal of the tubing.
- The materials which are recommended for use in injection, production, monitoring and abandonment of wells. New, CO_2-resistant materials, such as sealing gels or CO_2-resistant cements should be tested extensively in CO_2 environments before considering their application in CO_2 storage activities.
- How to properly assess the actual state of previously abandoned wells penetrating the storage complex. Often old, inaccessible wells do not match safety standards for CO_2 storage. If (adequate) regulations were not in place at the time of abandonment, a proper evaluation of the actual state of the well barrier materials is challenging. Consequently, the integrity of old wells, particularly if critical data is missing, is difficult to predict.

Considering that particular attention has to be paid to both cement sheath placement (after drilling) and cement plug placement at abandonment, it is recommended that more detailed procedures describing cement (sheath) evaluation and integrity test activities should be provided:

- Pancake plugging of the wellbores is thought to provide a promising solution to plug the wellbore adequately, but it is not a standard procedure. In case the operation fails, the placement has to be repeated (if possible) and/or even higher leakage risks could be generated. In such cases, the remediation operations will be technically challenging and expensive.
- Particularly the highly deviated wells may pose integrity problems due to improper cement placements and should be carefully evaluated by state of the art monitoring tools (e.g. ultrasonic or calliper tools), if considered as injectors. Especially in highly deviated wells placing an effective pancake cement plug will be impossible.

Finally, it is advised that guidelines regarding the implementation of appropriate monitoring schemes, particularly during the period between site closure and the transfer of responsibilities from the operator to the authorities/site owner, have to be defined depending on site-specific criteria [4].

3. Full scale well mechanical modelling methodology for well abandonment scenarios

Wellbores have been recognised as one of the main potential leakage pathways in geological storage of CO_2. Important lessons regarding wellbore cement seal integrity can be learned from the oil industry, which has been conducting oil and gas production for many years including EOR (enhanced oil recovery) techniques. However, while the oil industry is primarily concerned with the cement sheath integrity over the lifetime of a well (decades of production and abandonment after depletion), geological storage of CO_2 requires the consideration of a much longer time frame (hundreds to thousands of years). The primary concerns are that the standard Portland cements used to seal wellbore react with CO_2, and the geomechanical/geochemical response of the wellbore to injection, abandonment and post-abandonment processes may compromise the integrity of the wellbore at both short and long term. Studies have shown that changes in downhole conditions can cause mechanical damage to the cemented annulus that may lead to a loss of zonal isolation. It is therefore important to have a clear understanding of the long-term behaviour of the complete mechanical system formed by the steel casing, the cement sheath and the formation rocks. The integrity of the casing-cement and cement-rock interfaces are the most important issues in the performance of wellbore systems in a CO_2 storage reservoir.

Within the project a specific portfolio of wells is included to cover a broad range of typical wells to be encountered in future projects. These wells represent complementary scenarios with different conditions of pressure, temperature and in-situ stress:

- Sleipner: Off-shore, abandoned appraisal well within the migration path of the stored CO_2.
- Ketzin: On-shore, observation well which is going to be closed soon.
- Montmiral: On-shore, natural CO_2 accumulation with CO_2 producer well, in process of closure.
- Rousse analogue: On-shore, deep old gas producer converted to CO_2 storage injection well.

These applications correspond to very different pressure evolution, in situ stresses and temperature conditions. They also represent a panel considering the in situ fluid properties, the completion time and initial utilisation. To study the mechanical history of these wells, it is necessary to consider the way they have been completed, considering the cement and steel used but also the surrounding formation properties in term of rock facies and fluids. This requires elaborating a methodology that will allow evaluating the mechanical state while making some acceptable assumptions and simplifications and identifying potential zones of risk to be considered prior to abandonment.

The full-scale model of the near-wellbore must integrate the different elements: casing, cement sheath and rock formation. Those elements occur with different ratios according to width and length which could lead to numerical difficulties in the finite element modelling. A mesh discretisation has to be adopted in the vertical direction coherently with the layering of the geological formation. In the radial direction fine meshes are used near the wellbore where the rock/cement and casing/cement contact interfaces have to be taken into account for more than 1,000 m length/depth. The whole loading history should be introduced in the model during the following consecutive operations: drilling, completion, injection/production phase and finally abandoned phase. From case to case it seems important to know the stress evolutions at wellbore consecutive to drilling and completion phases.

So far, results indicate that the stress and strain evolution in the various elements of the well needs to be considered with regard to the drilling and completion process. However, the initial stress state must be taken into account as well. In the future, a better understanding about the various contact interactions will help to simulate the well integrity. Further, the historical mechanical loading path of the well during its lifetime will be considered since thermal and mechanical stresses change in time.

4. Relevant trapping mechanisms based on site portfolio

The mechanisms for long-term stabilisation and immobilisation of CO_2 are: (i) structural and stratigraphic trapping, (ii) residual trapping, (iii) dissolution in the brine (+dissolution enhancement by induced convection) and (iv) mineral trapping by geochemical fluid/mineral reactions and precipitation of minerals. The quantitative contribution of each of these trapping mechanisms will be site-dependent, as the combination of the injection strategy, geological architecture and the migration pattern at later stages of stabilisation will determine their efficiency in immobilising parts of the CO_2 plume. The ultimate goal is to be able to supply input data for a site-specific "Trapping-Safety-Time" plot for the risk assessment.

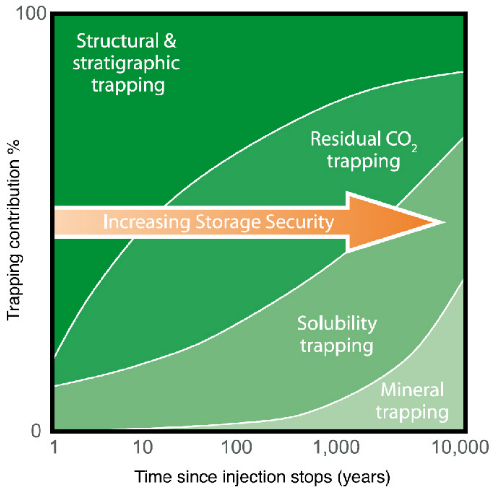
The very common illustration of the trapping mechanisms and the storage safety development over long time perspectives is the trapping mechanism/safety plot as published in the Chapter 5 of the IPCC report (Fig. 2 and [5]). This generic diagram has for some time been used to promote the concept about diminishing fraction of free CO_2 in "gas" phase, which is considered the most risky part and thereby increasing safety over time. The exact amount of CO_2 residing in the different categories of storage mechanisms obviously must be site-specific. The quantification of this over long time spans heavily depends on the ability to simulate the different processes and their interaction for the specific site. The simultaneous simulation of all the processes in question is a demanding task and has only been carried out for very few storage sites. For the purpose of generating a site specific plot, the published data from a study of a generic case [6] are used in order to illustrate the principles behind the generation of the trapping-mechanism diagram (Fig. 2 and [7]).

The background data for the site specific analysis are derived from the plot of output from using TOUGHREACT to simulate dissolution and mineral trapping contributions (Fig. 2) [6]. These data are then re-plotted on the logarithmic time-scale for the safety time plot. In the context of safety and immobilisation of CO_2, the residual CO_2 is comparable to the concept of residual oil for a produced oil reservoir. The question to answer is how much CO_2 could possibly not escape if we choose at some time step to create maximum leaking conditions for the storage site. For a crude evaluation of this one can then apply the standard hysteresis calculation given that the imbibition endpoint for residual gas is known.

While this effect is considered formation-specific, it has been demonstrated that residual CO_2 saturations may be as high as 15–25 % for many typical storage formations.

The simulation of the dissolution process is significantly influenced by the gridding scheme, numerical dispersion and the simulator description of the process. The large amount of dissolved CO_2 reflected in the TOUGHREACT simulation could be caused by these effects as it is usual to operate with instantaneous equilibration for downstream schemes. With large grid cells this implementation cause substantial numerical dispersion and over-estimation of the dissolved part.

The quantitative contribution of each of the trapping mechanisms will be site-dependent, as the combination of the injection strategy, geological architecture and the migration pattern at later stages of stabilisation will determine their efficiency in immobilising parts of the CO_2 plume.



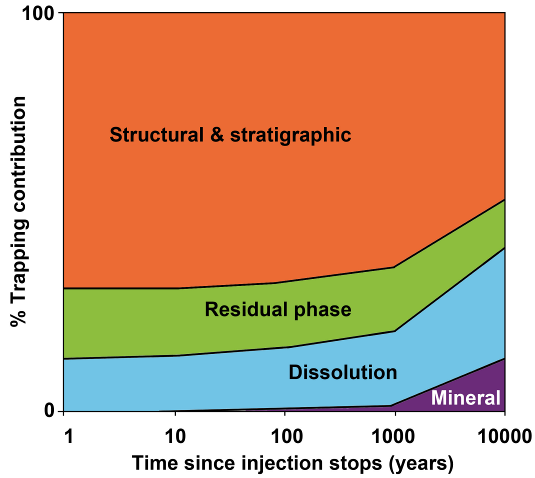


Fig. 2. Left) Diagram showing the concept of increasing amount of immobile CO_2 and thereby increased security of the storage facility with regard to the responsible mechanisms [5];. Right) Trapping-mechanism/time diagram based on data from simulations of the processes of mineral reaction and dissolution [7].

In the frame of the CO_2ReMoVe (at first) and CO_2CARE (later) projects a similar study has been achieved on a 2D cut of the Sleipner reservoir for different geochemical models, using the 3D fluid flow simulator COORESTM coupled with ARXIMTM to consider reactive transport. This limited and preliminary study concludes on the necessity of analysing the impact of parameter uncertainties when evaluating the relative percentages of trapping mechanisms. Results might vary e.g. significantly for chemically models with regard to the reactive surface area [8].

5. Risk management and criteria for decision making in site abandonment

The high level criteria (see above) for decision making in site abandonment are related to demonstrate fulfilment of the site conditions required for a liability transfer from the operator to a competent authority. As those criteria are defined on a high level, they have to be complemented with criteria allowing to be applied on an operational level.

Within this study a workflow has been developed to facilitate an industrially applicable roadmap for risk management measures in the context of site abandonment, covering the requirements of the CCS-directive and the OSPAR guidelines [9]. A milestone chart with 17 risk criteria have been extracted from the risk management plan for the post-operational phase termed “R-type” criteria [10]. Some criteria therein refer to input from models and monitoring measurements. If a parameter is predicted by modelling and measured by monitoring the second condition of the CCS directive (see above) is of primary application. For risk management related treatment of such parameters, requiring comparison of modelled and measured data, a traffic light system (Fig. 3) with an associated workflow has been set up [11]. This workflow provides an additional set of technical criteria ("T-type" criteria), specifically relating to the CCS directive. The major goal of the traffic light system is to provide a framework for dealing with offsets of model predictions and monitoring data (MMO, i.e. model monitoring offset). The three criteria levels (fundamental criteria of the CCS directive, R-type criteria, T-type criteria) have been connected to each other in order to form a generic set of criteria for CCS site abandonment and the liability transfer to a competent authority.

The definition of T-type criteria is highly site-dependent. Trials to define such criteria for the Sleipner, K12-B and Ketzin-site revealed that particularly the definition of tolerable MMOs and the estimation of model accuracies and precisions are currently difficult and ambiguous.

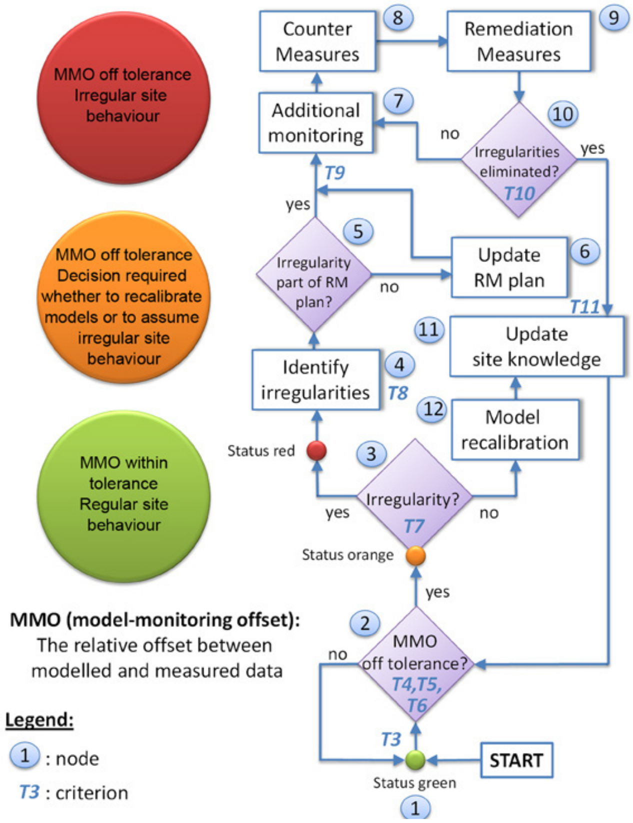


Fig. 3. Flow diagram of the suggested traffic light system for risk-related decision making in the post-operational phase and definition of the three risk priorities (status red, orange and green).

6. Summary and outlook

The CO_2CARE project (CO$_2$ Site Closure Assessment REsearch) focuses on site closure and preparation for transfer of liability with regard to the life cycle of a CO_2 storage project to assist countries and stakeholders to implement the EU Directive 2009/31/EC. CO_2CARE consists of an international consortium of 23 partners from Europe, USA, Canada, Japan and Australia, belonging to universities, research institutes, and energy companies. In order to incorporate up-to-date results and monitoring data 9 key injection sites in Europe and worldwide are an integral part of the project: (1) Ketzin, Germany; (2) Sleipner, Norway; (3) K12-B, The Netherlands; (4) Rousse, France; (5) Montmiral, France; (6) Frio, USA; (7) Wallula, USA; (8) Nagaoka, Japan and (9) Otway, Australia. The main objectives of the project are closely linked to the three high-level requirements of the EU Directive, Article 18 for CO_2 storage site transfer of responsibility.

Major results of the first 18 months of the project include the review and assessment of international regulatory requirements on CO_2 geological storage and site abandonment practices. Herein combinations of monitoring, modelling and risk assessment tasks are defined. There is a variation in the time period over which safety must be demonstrated in different regulations, and an optimum time period is considered flexible. Regulations typically contain a provision for transfer of liability once safety (CO_2 and well plugging) has been demonstrated. The EU Directive requires further monitoring after liability transfer as a back-up measure, while other regulations (e.g. EPA UIC) do not.

Procedures for safe well abandonment for CO_2 storage sites are elaborated and developed. The primary concern is that the Portland cements used to seal wellbore react with CO_2, and the geomechanical and geochemical response of the wellbore to injection, abandonment and post-abandonment processes may compromise the integrity of the wellbore at both short and long term. Due to the long timeframes in the range of several thousands of years, the behaviour of a system can be demonstrated by using field and laboratory experiments coupled with predictive modelling tools to study potential leakage pathways.

Long-term integrity and stabilisation of abandoned CO_2 storage sites, an associated monitoring program and potential remediation methodologies are highly site-specific. Thus, the approach is to focus on different storage sites representing different (hydro) geological and environmental settings (i.e. on-shore/off-shore, natural gas reservoirs/saline aquifers). The various trapping mechanisms for CO_2, physically captured, capillary bound, dissolved, and precipitated CO_2 in form of specific mineral phases, are stabilised or destabilised by physical and chemical processes. A scheme how to evaluate quantitative contribution from each mechanism to the trapping over time has been developed.

Risk management for the post-operational phases is another essential part of the workflow. A decision support system has been created by means of a number of high-level and low-level criteria, most of which had to be defined in advance. The system provides instructions for the operators on how to act in case of irregularities after site closure.

Guidelines for regulatory compliance and “Best Practice” for site abandonment will be established by distillation and integration of all research findings into site closure and abandonment protocols compliant with the EU storage regulation, within the second half of the project.

Acknowledgements

The results presented here belong to the CO_2CARE project which is funded by the European Commission within the 7th Framework Programme and also co-financed by an industrial consortium consisting of RWE, Shell, Statoil, TOTAL, Vattenfall and Veolia. The financial support of the EC and the industry partners is greatly appreciated.

References

[1] Korre A, D1.1 – Report on the international regulatory requirements on CO_2 geological storage and site abandonment. *CO_2CARE - CO_2 Site Closure Assessment Research, Grant Agreement number: 256625,* 2011; www.co2care.org.

[2] NORSOK Standard D-010 Norway (http://www.npd.no/).

[3] UK Oil and Gas Association (UKOOA) Guidelines for the Suspension and Abandonment of Wells (http://www.ukooaenvironmentallegislation.co.uk).

[4] Wollenweber, J., D1.2 - Report on the current site abandonment methodologies in relevant industries. *CO_2CARE - CO_2 Site Closure Assessment Research, Grant Agreement number: 256625,* 2011; www.co2care.org.

[5] IPCC - Special Report on Carbon Dioxide Capture and Storage, Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2005, 442 pp.

[6] Zhang, W., Li, Y., Xu, T., Cheng, H., Zheng, Y. & Xiong, P. 2009. Long-term variations of CO2 trapped in different mechanisms in deep saline formations: A case study of the Songliao Basin, China International Journal of Greenhouse Gas Control, 2009, Vol. 3(2), pp. 161 – 18.

[7] Frykman, P., Nielsen, C.M., Dalhoff, F., Sørensen, A.T., Klinkby, L. and Nielsen, L.H.: 2010. Geological modelling for site evaluation at the Vedsted structure, NW Denmark. GHGT-10, Proceedings of the 10th International Conference on Greenhouse Gas Control Technologies.

[8] Estublier, A., Fornel, A., Parra. T., Deflandre, J.-P.: 2012. Sensitivity study of the recative transport model for CO_2 injection in to the Utsira saline formation using 3D fluid flow model history matched with 4D seismic, GHGT-11, Proceedings of the 11th International Conference on Greenhouse Gas Control Technologies.

[9] 1992 Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR) (http://www.ospar.org)

[10] Kronimus, A.R., Nepveu, M., Korre, A., D4.11 - Draft and updated plan for risk management supporting site abandonment. *CO_2CARE - CO_2 Site Closure Assessment Research, Grant Agreement number: 256625,* 2011; www.co2care.org.

[11] Kronimus, A., Vandeweijer, V., Arts, R.. D4.21 - Draft and updated criteria for decision making in site abandonment. *CO_2CARE - CO_2 Site Closure Assessment Research, Grant Agreement number: 256625,* 2011; www.co2care.org.