CO_2CARE

CO_2 Site Closure Assessment Research

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D5.4 Best Practice Guidelines

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List of Acronyms

CA	Competent Authority
The Directive	Directive 2009/31/EC of the European Union, on the geological storage of carbon dioxide
EC	European Commission
GD	EC Guidance Document
D5.4	CO_2CARE report, e.g. Deliverable 5.4

Executive Summary

This report presents a set of pragmatic and workable generic procedures, suggested best practices and other recommendations and observations for the safe and sustainable closure of geological CO_2 storage sites. These have been distilled from the results of the CO_2CARE project and represent the most important messages that will be of benefit to Regulators, storage site Operators and other stakeholders.

Key observations and recommendations are set out below.

Transfer of responsibility for all legal obligations for a storage site from the Operator to the Competent Authority (CA) marks a radical change in the balance of responsibilities between stakeholders in a storage project. The CA is ultimately the representative of the public, and this implies an acceptance by the public of the benefits and associated liabilities.

Acceptance of the Transfer Report and transfer of responsibility for all legal obligations for the site to the CA marks the end of a process that began with site selection and a permit application by the Operator many years previously. It is vital that a relationship based on transparency and openness should have developed between the Operator and Regulator during that period, to build mutual confidence into the regulatory process and, ultimately, the transfer of responsibility. Continuity of knowledge through changes of personnel should also be ensured. This, together with the regular reporting requirements that most jurisdictions require (e.g. those required under the EU Directive) should help to ensure that the transfer of responsibility proceeds smoothly and to the satisfaction of all parties involved.

When CO_2 injection at a storage site has ceased, the storage site is described in the EU CO_2 Storage Directive as being closed and the project life cycle enters the post-closure phase, leading to transfer of responsibility. During the post-closure phase the wells will not necessarily be sealed immediately, the site will continue to be monitored and reservoir management will continue, in accordance with the project risk assessment and management plan, which will have been updated at site closure.

The main purpose of reservoir management in the post-closure phase is to demonstrate that the key regulatory requirements for transfer of storage site liability to the Competent Authority have been met. In the EU CO_2 Storage Directive these are:

- Observed behaviour of the injected CO_2 conforms to the modelled behaviour
- No detectable leakage
- The storage site is evolving towards a situation of long-term stability

Meeting these criteria involves demonstrating understanding of reservoir processes, the ability to make robust predictions of future behaviour and providing assurance against leakage.

Demonstrating conformance between predictive models of reservoir performance and monitoring observations is technically challenging because a unique and perfect match is near-impossible to achieve. CO_2CARE recommends that conformance is based on demonstrating that predictive modelling capability increases systematically with time as monitoring data is progressively acquired. This indicates that storage processes are well understood and the modelling approach is robust.

If predictive modelling is robust, uncertainties will progressively reduce as more monitoring data is acquired through time. Nevertheless it is necessary to maintain a sufficiently wide range of predictive scenarios, such that any reasonable outcome will fall within it.

Measurements that fall outside the predicted range are likely to be embarrassing for the Operator and may trigger remediation requirements if they look likely to result in unexpected outcomes. It is important therefore to focus strongly on the end-members of the predicted range, particularly those that might lead to divergent future outcomes. Regulators should realise that a level of residual uncertainty in the predictive modelling is unavoidable, and is acceptable provided that end-members of the predicted range will not lead to unacceptable outcomes.

At the point of transfer of liability, predictive models calibrated by monitoring data will have a residual uncertainty envelope, but this should be sufficiently small for unexpected or divergent future outcomes to be ruled out.

The definition of no detectable leakage is problematical. All leakage monitoring systems have a finite (and site-specific) CO_2 detection capability. To be fit for purpose, the detection capability of the monitoring system needs to be able to detect a sufficiently small amount or rate of leakage to ensure the necessary health, safety, environmental and greenhouse gas mitigation objectives are met. As far as the emissions mitigation objective is concerned, a number of studies have suggested that leakage rates of around 0.01% per year or less would ensure effective mitigation performance. It is recommended that regulators use the term “no detectable leakage” in the context of whether the leakage monitoring system can show a site is performing effectively in terms of health, safety, environmental and greenhouse gas emissions mitigation.

Emphasis should be on achieving the earliest possible detection of CO_2 migration from the reservoir, to maximise the time available for suitable mitigation actions to be implemented before leakage (migration of CO_2 out of the Storage Complex), actually occurs, and also to provide sufficient time for full remediation prior to any planned transfer date.

Proving that a site is evolving towards long-term stability is challenging because predictive modelling of the longer-term processes is subject to significant uncertainty, and so far we have little field experience of post-injection processes. Full use of additional analogue information is important therefore, to develop a logical case for site stabilization. Use should be made of monitoring data from sites already in the post-injection period (e.g. Nagaoka), experimental data and relevant geological analogues which demonstrate stabilization processes in similar circumstances and the time-scales on which they operate.

Best practice in well abandonment starts with ensuring the integrity of the well by its proper construction and safe operation. New wells in a CO_2 storage site should be constructed according to best practice for long-term integrity in a corrosive CO_2-rich environment. This means selecting appropriate materials and ensuring the long-term geomechanical and geochemical integrity of the wells. However, not all wells in CO_2 storage complexes will have been constructed and operated with CO_2 storage in mind. The risks associated with these older wells, including abandoned wells, should be assessed and, if necessary, remediation plans should be prepared for them.

The main elements of managing the environmental and safety risks of CO_2 storage, namely risk assessment, monitoring and the application, if necessary, of corrective measures, are well embedded in the rules of the EU Storage Directive. CO_2CARE has developed a detailed scheme of milestones and procedures to be followed to ensure the safe and sustainable closure of CO_2 storage sites. It was observed that the EU Storage Directive and its associated Guidance Documents propose minimum periods to fulfil certain key criteria, which are not based on any scientific fundamentals. It is recommended that the EU Directive could be amended such that all decisions as to whether a criterion for the safety of a site has been met should be based on technical criteria only and should not be linked to prescriptive time spans.

The Storage Complex should be defined at all stages of the project life cycle from the Characterisation phase onwards, because it is a fundamental concept in the Storage Directive. The term storage complex means the storage site and surrounding geological domain which can have an effect on overall storage integrity and security, that is, secondary containment formations. Views of other stakeholders involved or potentially involved in this volume and area should be addressed in the transfer report. The limits of the Storage Complex could be redefined at any point in the project.

Possible interactions with the site from future operations (CO_2 storage or other uses), and other legitimate users of the subsurface or marine environment, should be considered in the transfer report, and any potential hazards of this kind should be identified to the CA. Recommendations for risk reduction, risk management and mitigation/remediation options for potential post-transfer interactions with other subsurface operations should also be included in the transfer report. That said, ultimately, only CAs can assess the risks that might arise from operation and closure of multiple assets within a storage formation or region.

The regulators participating in the CO_2CARE project indicated that liabilities for certain risks may remain with the Operator post-transfer. It is recommended that the EC should investigate these views further as they may have implications for the Directive or the way in which it is implemented in practice.

As CO_2 storage is a multi-generational operation, consideration should be given to what tools and data should be transferred to the CA. Models may need to be used post-transfer, if a significant irregularity or leakage was detected.

Finally, communication and engagement with the public is something that should start very early in the CO_2 storage project life cycle – as soon as, or even before, a site is selected. Communication and engagement then should continue throughout the project life cycle, including during closure and up to and beyond the transfer of responsibility for the site to the Competent Authority.

Introduction

CO_2CARE supports the large-scale demonstration of CCS technology by developing and testing procedures and best practices for the safe and sustainable closure of geological CO_2 storage sites. These are intended to provide information to operators, regulators and the wider public about how the regulatory requirements for the closure of CO_2 storage sites and the subsequent transfer of responsibility for the site from the site operator to the State, can be met.

Directive 2009/31/EC of the European Union, on the geological storage of carbon dioxide (henceforth the Directive) sets specific requirements for both the transfer of responsibility of geological CO_2 storage sites after injection has definitely ceased and for the abandonment of the storage site.

Before such a transfer can be approved it is required that:

a) all available evidence indicates that the stored CO_2 will be completely and permanently contained
b) the financial obligations have been fulfilled
c) the site has been sealed and the injection facilities have been removed[1]

In addition, the operator has to demonstrate:

a) the conformity of the actual behaviour of the injected CO_2 with the modelled behaviour
b) the absence of any detectable leakage
c) the storage site is evolving towards a situation of long-term stability

In addition to the Directive, the European Commission has issued four Guidance Documents (henceforth GDs) that provide advice on implementing the Directive, of which GD3: Criteria for the Transfer of Responsibility to the Competent Authority (CA) is the most relevant to the closure of CO_2 storage sites and transfer of responsibility from the operator to the State. However, the suggestions in the GDs have not yet been implemented in the Directive and therefore not binding law.

CO_2CARE uses the three active European CO_2 injection and storage sites: Sleipner (offshore Norway), K-12B (offshore Netherlands) and Ketzin (onshore Germany) as trial sites for the development and application of procedures and best practices. It also draws on experiences at six other CO_2 storage or analogue storage sites worldwide (Nagaoka, Otway, Rousse, Frio, Wallula and Montmiral). This means that the real, practical issues that may be encountered in the future closure and long-term post-closure safety of these sites have been examined. As a result, a set of pragmatic and workable generic procedures and best practices have been developed. These are summarised in the main body of this report.

Following this Introduction the Best Practice Recommendations are arranged as follows:

[1] There could be exceptions to this: in the ‘contract’ between the CA and storage operator, it may be agreed that the CA has the option to takeover not only the responsibility but also the operatorship of either the storage and/or the injection facilities. This may be efficient, if further storage sites could be served from the injection facility and/or the storage has not been filled to its capacity by the first operator.

Section 1: Recommendations for well abandonment

Section 2: Recommendations for post-closure reservoir management

Section 3: Recommendations for risk management

Section 4: Recommendations for transfer of responsibility from the Operator to the State

Section 5: Recommendations related to communication with the public

Section 6: Recommendations for the possible modification of Directive 2009/31/EC of the European Union, on the geological storage of carbon dioxide (henceforth the Directive) and its associated Guidance Documents (henceforth GDs).

Sections 1-5 correspond to the main Work Packages of the CO_2CARE project.

1. Recommendations for post-closure wellbore management

Best practice in well abandonment starts with ensuring the initial integrity of the well by its proper construction and safe operation. New wells in a CO_2 storage site should be constructed according to best practice for long-term integrity in a corrosive CO_2-rich environment. However, not all wells within the Storage Complex will have been constructed and operated with CO_2 storage in mind. The risks associated with older wells, including abandoned wells, should be assessed and, if necessary, appropriate remediation plans should be prepared.

1.1. Well abandonment

1.1.1. Recommendations from a review of current regulatory frameworks and practices

Active (open) wells in a CO_2 storage site

A review of current regulatory frameworks and practices in CO_2 storage site abandonment[2] showed that most CO_2 storage-specific regulations and guidance do not stipulate particular materials, methods or protocols that should be used for plugging CO_2 injection or monitoring wells, or the performance standards that should be achieved. This is probably because CO_2 storage is a relatively new technology – practice is actively evolving – and the techniques employed need to be tailored to the specifics of a given site.

However, national or jurisdictional regulations on the abandonment of hydrocarbon wells and, other types of deep injection wells, commonly specify both the outcomes required and some specific requirements, e.g. the lengths of plugs required in abandoned wells and where they should be placed[3]. Most sets of regulations agree that proper well abandonment for isolation of subsurface reservoirs should:

- Prevent any leakage of fluids up the well to the surface
- Prevent all physical hazards potentially induced by the well
- Prevent any migration of contaminants between formations
- Prevent the possibility of hydrologic communication between originally separated aquifer systems

It is recommended that existing abandonment regulations should be adapted for application to CO_2 storage wells and should:

- Cover any open wells in a CO_2 storage site, i.e. injection wells, monitoring wells and (contingency) wells kept open in case needed during the project
- Not allow well plugging until after:

[2] CO_2CARE D1.1 International regulatory requirements on CO^2 geological storage and site abandonment (http://www.co2care.org).

[3] CO_2CARE D1.2 Report on the current site abandonment methodologies in relevant industries (http://www.co2care.org).

  - The acquisition and analysis of any required monitoring data (e.g. final well logging)
  - The acceptance by the Competent Authority (CA) that the monitoring data is of satisfactory quality and the analysis indicates the well is in a satisfactory condition for abandonment

- Require tubing to be removed
- Specify plugging across the injection zone and the caprock
- Include and regularly update plugging material requirements using knowledge gained from the performance testing of plugging materials in CO_2 environments

Previously abandoned wells in a storage complex

Previously abandoned wells often do not comply with recommended standards for CO_2 storage. If adequate regulations were not in place at the time of abandonment, a proper risk 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.

A risk assessment of legacy wells and the specification of potential preventive measures (if required) should have been part of the characterisation phases of a CO_2 storage project i.e. it should be in place long before the site is closed. However, it is recommended that a general risk assessment procedure that describes how to deal with previous abandoned “old” wells penetrating the storage complex should be developed.

1.1.2. Recommendations from a review of current industry best practices

Experiences from CO_2 storage site demonstration projects and industrial CO_2-EOR applications indicate that CO_2 storage site abandonment can be performed safely, provided that the following have been properly undertaken:

- A full Storage Site and Storage Complex characterisation
- An accurate well integrity assessment
- Operational activities performed according to industry best practices, particularly proper cement placement and well operations
- A comprehensive project risk assessment which has been progressively updated through the entire lifetime of the storage project
- Design of a risk-based monitoring plan
- Design of a risk-based remediation plan
- Definition and, if required, execution of preventative and mitigating measures

It is recommended that national and jurisdictional guidance on practices related to CO_2 geological storage should provide more specific information about:

- How to abandon a CO_2 storage well
- How to demonstrate the caprock integrity in and around a well
- The materials which are recommended for use in the construction and abandonment of CO_2 storage wells:
    - It is recommended that new, CO_2-resistant materials, such as sealing gels or CO_2-resistant cements should be tested thoroughly in CO_2-rich environments before considering their application in CO_2 storage activities. Special attention should be paid to the long term performance of well barrier materials exposed to the corrosive CO_2 environment.

It is recommended that particular care should be paid to both cement sheath placement (during construction) and cement plug placement at abandonment. It is also recommended that more detailed procedures describing cement bond evaluation and integrity testing activities should be provided.

It is recommended that further research should be undertaken into pancake plugging (Randhol et al. 2007). Pancake plugging of wellbores is thought to provide a promising solution for plugging the wellbore effectively e.g. Kuhn et al. 2013, but it is not a standard procedure. Should the operation fail, the placement has to be repeated (if possible) or even higher leakage risks could be generated. In such cases, the remediation operations will be technically challenging and expensive. Highly deviated wells in particular may be prone to 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). It may be difficult or even impossible to place an effective pancake plug in highly deviated wells.

1.1.3. Summary of experience with abandoned CO_2 wells

Globally, there is little experience with purpose-designed CO_2 storage wells at present – only a few such CO_2 storage projects have been completed and there has been little published feedback about the details of well abandonment methods and performance of the materials used. However, after about 30 years of experience with CO_2-floods, the CO_2-EOR industry has a proven track record of safely injecting and storing residual CO_2 in geological formations, and successfully plugging and abandoning CO_2 injection wells (NETL, 2010).

Hovorka and Tinker (2010) summarise the achievements of 38 years of CO_2-EOR and refer to the relevance and importance of experiences on CO_2-EOR for safe geological storage of CO_2. The authors assess implications for reservoir management, monitoring and risk assessment in CO_2 sequestration, and address well integrity issues and abandonment in generic terms.

A recent review paper (Syed and Cutler 2010) summarises the improvements in wellbore materials used in the CO_2-EOR industry.

The CO_2-EOR industry has also improved the design and operating methodologies for CO_2 injection wells, particularly in the following fields (Parker *et al.*, 2009):

- Selective use of corrosion-resistant materials and alloys for surface piping, metal component trim and speciality coating applications
- Use of CO_2-resistant elastomers, teflon, and nylon for packer elements and seals

- Use of novel tubular coatings or liners using plastic, epoxy resin or fibre glass/resin materials

- Use of speciality cements and additives

- Use of automatic controls and real time monitoring systems.

A recent review (IEA-GHG 2010) provides a comprehensive overview of materials that should be used in CO_2 injection and storage and the API lists materials used in modern CO_2-EOR operations (Table 1).

Table 1: **Materials recommended by API for CO_2 injection well design and construction (mostly WAG services; modified after Meyer, 2007).**

Component	Materials
Christmas Tree (Trim)	316 SS, Electroless Nickel plate, Monel
Valve Packing and Seals	Teflon, Nylon
Wellhead (Trim)	316 SS, Electroless Nickel plate, Monel
Tubing	Glass Reinforced Epoxy (GRE) - lined carbon steel, Internally plastic coated carbon steel, Corrosion resistant alloy (CRA)
Tubing Joint Seals	Seal ring (GRE), Coated threads and collars (IPC)
ON/OFF Tool, Profile Nipple	Nickel plated wetted parts, 316 SS
Packers	Internally coated hardened rubber etc. Nickel plated wetted parts; corrosion resistant alloys particularly in old wells to improve sealing to worn casings
Cements and cement additives	API cements and/or acid resistant cements

Additional information on new procedures and materials such as novel cement and sealing agents is provided in CO_2CARE deliverable D1.2[4].

1.1.4. Summary of the track record of abandoned hydrocarbon wells

Generic studies of well leakage in hydrocarbon provinces with large numbers of abandoned oil and gas wells have been published. These provide an overview of well leakage rates in the oil and gas industry. Table 2 summarises the results from a number of studies reporting well leakage in North America. Marlow (1989) showed that 6% of the 6953 gas storage wells surveyed in the USA had leaked. The three main recorded causes of leakage were:

- Microchanneling in cement

- Poor cement job

- Failed wellhead seals

[4] CO_2CARE deliverable D1.2: Report on current site abandonment methodologies in the oil and gas and other relevant industries.

Table 2. Occurrence of leakage as reported by authors in six sample studies of well leakage. Source: Loizzo et al. (2011)

Large Sample Studies	(Marlow 1989) survey	6.1% of approx. 7,000 UGS wells in the USA Leakage rate: 61% of wells leak <35 t/y; 90% of wells <200 t/y
	(Bourgoyne et al. 1999)	11.6% of approx. 30,000 wells in the Gulf of Mexico leak through casing strings
	(Watson and Bachu 2009)	9.8% of approx. 20,000 wells in the Test Area in Alberta 6.3% of wells leak gas through the soil (gas migration) → almost 1:1 ratio to casing leaks
Smaller Samples, Anecdotal Studies	(Watters and Sabins 1980)	15% of 250 casing strings
	(Xu and Wojtanowicz 2001)	85% of 26 wells in the Gulf of Mexico
	(Chilingar and Endres 2005)	75% of 50 wells in Santa Fe Springs, California, oilfield

Analysis of leakage data collected by the Energy Resources Conservation Board (ERCB) in Alberta (Bachu and Watson, 2006), from approximately 316,000 oil, gas and injection wells, has identified the critical parameters which are believed to have the greatest impact on well leakage in that region as:

- *Wellbore deviation:* the occurrence of leakage was found to be significantly higher for deviated wells
- *Well Type:* cased and abandoned wells were found to be subject to a greater likelihood of leakage than uncased drilled and abandoned wells. This difference may be a consequence of different regulation requirements for the different well types
- *Abandonment Method:* abandonment by bridge plugs capped with cement was found to lead to larger failure rates than other abandonment methods, such as placing cement plugs across completed intervals using a balanced plug method, or setting a cement retainer and squeezing cement through perforations
- *Oil price and regulatory changes:* A significant positive correlation was found between leakage occurrence and oil price
- *Cement job:* The most important indicator for leakage was determined to be low cement top. The majority of casing failures were attributed to regions of poor and no cement in the annulus above the top of the injection/ production interval.

Although over 11,000 CO_2-EOR wells have been permitted in more than 40 years of CO_2 flooding in Texas, a study by CO_2CARE of the regulatory records at the State Agency in charge of regulating the oil and gas industry (Railroad Commission of Texas) yielded no reported CO_2 leakage events. However, there is evidence from the literature that well leakage does occur in the Texas region (Paine et al., 1999) and the possible reason for the absence of reported failures in CO_2 wells may be that operators invest heavily in well preparation as part of CO_2-flood development and leakage remediation. In addition, operators have financial incentives to maintain reliable operational control of the wells. Therefore preventive maintenance and effective monitoring are implemented.

The greatest problem identified over decades of CO_2-EOR operation has been old or historic wells which are not plugged or are plugged incorrectly. It is believed that many non-technical parameters, such as regulatory background in the region, level of enforcement, and certain economic and social events, have a critical impact on well failure and leakage risk in these wells. Experience from the CO_2-EOR wells in Texas suggests that in order to minimise the risk of well failure and potential well leakage, it is essential that mechanical integrity testing is a requirement for every fluid injection and gas storage well:

1. Before the injection operations starts

2. At least once every 5 years, or more often if required by the permit

3. After any workover disturbing the seal between the tubing, packer, and casing or after any repair work performed on the casing

4. When a request is made to suspend or re-activate the injection or disposal permit.

Generically, it is clear that a significant proportion of well abandonment problems result from the poor application of drilling and completion protocols or the fact that wells are suspended for a long time without being properly abandoned (often because of costs). There is evidence that this is a situation that arises more from poor application of the regulations than through imperfect understanding of wellbore technical issues.

In younger hydrocarbon provinces, detailed information is available on the completion and abandonment of each individual hydrocarbon well. Information is also available from many natural gas storage and geothermal operations

1.2. Wellbore integrity

A wellbore should ideally be mechanically and chemically stable from its initial construction onwards. This is extremely difficult to achieve because wellbores are constructed of layers of materials of different composition (steel, cement, etc.) and different properties (some expand or contract more than others during temperature changes, some deform in a brittle manner under stress and some in a ductile manner). Therefore inevitable variations in temperature and stress on a typical set of well construction materials during the project life-cycle mean that the bonds between the different layers of materials that provide well integrity might be compromised. Moreover, the strength and integrity of wellbore materials and surrounding strata may also be affected by reactions with formation brine acidified by dissolved CO_2.

There is potential for these effects, acting either individually or in combination, to create or enhance a leakage pathway for fluids. Consequently the wellbore's likely stress path and the requirements for its mechanical and chemical stability over the full CO_2 storage project life cycle need to be assessed during the site characterisation phase. This assessment should allow appropriate materials to be selected for new wells, and any potential remediation measures for existing wells to be planned. It is recommended that at least one further assessment of the stress history and long term geomechanical / geochemical stability of any open wellbore should be undertaken - prior to its abandonment.

1.2.1. Recommended workflow for geomechanical wellbore stability assessment

It is recommended that the evaluation of geomechanical wellbore stability should include:

(a) Examination of drilling and completion reports for existing wells to identify any non-conformance or specific issues that occurred and identify any possible zones of weakness along the wellbore

(b) Modelling the stress-state of the well over time

(c) Plotting the predicted stress-state of the wellbore at various times in the project life cycle in a mechanical stress representation such as Mohr-Coulomb or Drucker-Pragger, the choice of representation depending on materials. This will determine whether stress variations applied to the wellbore completion over time result in stresses reaching the damage envelope (the stress region in which adverse effects on the wellbore integrity may occur).

We have used this approach (Figure 1), to model wellbore geomechanical history at full scale on a portfolio of wells that have relevance to CO_2 storage: the Ketzin CO_2 injection well, an old oil and gas appraisal well near the Sleipner CO_2 storage site, the Montmiral CO_2 producer well and a Rousse-analogue case for a strongly depleted gas producer well re-used for CO_2 injection.

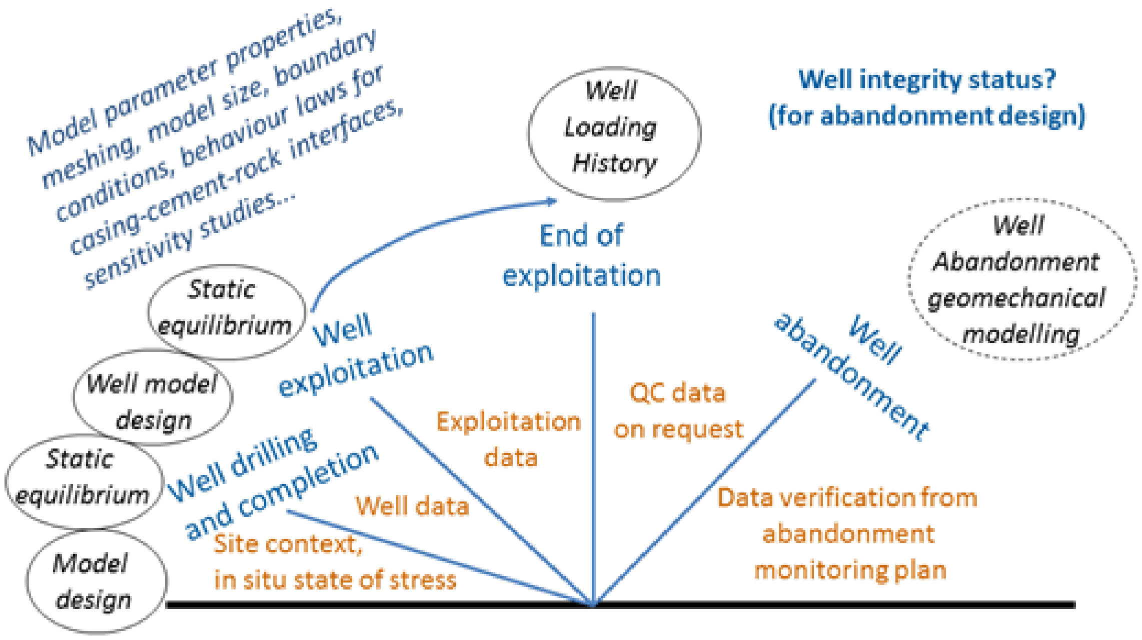

Figure 1. Graphical display of well mechanical history modelling workflow (prior to abandonment).

Our investigations showed that in order to carry out such an analysis, it is of prime importance to understand:

1. The mechanical properties of the formations drilled and the timing and effects of any potential CO_2/water/rock reactions on these

2. The initial state of stress of the formations drilled, and the timing of any likely changes in effective stress around the wellbore

3. The mechanical properties of the well construction materials and the timing and effects of any potential CO_2/water/materials reactions on these

4. The wellbore production history - the early, as well as the later, steps in the life of a well have to be modelled to confirm that wellbore mechanical history will not result in the wellbore materials entering their damage envelope over time.

For new wells, it is recommended that the initial *in situ* state of stress in the rocks to be penetrated by the well should be evaluated prior to drilling, ideally during the site characterisation phase, and this evaluation should be updated after each relevant step in the well construction and operation. An estimate of *in situ* stresses can be made using local information on principal stresses if no direct measurements are available.

The main challenge for geomechanical modelling of wells is the lack of data necessary to characterise likely wellbore materials behaviour, particularly with respect to what might happen at materials interfaces and the likely development of leakage pathways as a result of both thermo-mechanical and corrosion issues. It is necessary to know the mechanical properties and behaviour laws of the materials under a range of pressure and temperature conditions, in the presence of the fluids they may contact. It is likely to be easier to obtain the necessary physical properties data for steel and cement than for rocks. We suggest that rock cores might be systematically collected for these purposes during drilling operations and down-hole cement samples collected to better understand its initial *in situ* properties. This would help provide the best available material properties for the analysis.

In order to maintain geomechanical stability during the operational phase of the project, it is recommended that a warning is activated each time the modelled stresses approach a failure criterion during operation of a well, generating an expert analysis. Should this indicate any need, an early remediation action or specific monitoring action should be deployed to minimise present and future risks

It is recommended that an update of the initial well mechanical behaviour modelling, towards the end of the operation phase, should be used to inform the well plugging and abandonment programme during the post-closure, pre-transfer stage.

After abandonment, the correct implementation of the state-of-the-art and local regulations for well abandonment should be verified.

1.2.2. Geochemical and geomechanical interactions

There is significant evidence that CO_2 dissolved in brine will react with commonly used borehole cements and steels to some extent. The key issue is whether this will cause significant degradation in the isolating properties of the engineered seals over relevant performance timescales. There is a lack of observational data on this; laboratory experiments typically last months to a very few years, and recovered samples of borehole cements that have been exposed to high concentrations of dissolved CO_2 down-hole have only been exposed for a few decades at most (Carey et al. 2007). Though predictive modelling may give a useful indication of long-term behaviour, it is important that future research provides constraints on these calculations – if only through the observation of similar naturally-occurring systems (e.g. natural analogues).

Interaction of CO_2 with cement via diffusive transport will cause a series of reaction fronts that progressively degrade cement minerals such as portlandite and calcium silicate hydrate (CSH) phases, and replace them with carbonate minerals and other phases such as silica. Initially new porosity can be created due to dissolution, but this tends to seal with subsequent precipitation (Rochelle & Milodowski 2013). Importantly, the carbonated cement retains significant mechanical stability. Very slow rates of carbonation may also produce a denser, lower permeability carbonated zone that is not seen in laboratory experiments. Indeed, for very low flow conditions, some naturally-carbonated, natural CSH minerals appear to have been carbonated to a depth of only about 1 cm even after 10,000 years reaction - under near-surface conditions (Rochelle & Milodowski 2013). Whilst limited carbonation may not be a major issue in terms of short-term sealing longevity, continued flow of CO_2-rich water past cement may cause the dissolution / leaching of secondary carbonate phases in the carbonated cement, so flow pathways may increase in size over extended time periods. That said, if the host rock contains a significant amount of carbonate minerals, migrating CO_2-rich water may already be saturated with respect to these, and leaching of the carbonated cement will be minimised. Knowledge of host rock mineralogy and fluid chemistry is therefore important in terms of assessing potential overall cement performance.

Within a borehole setting, there will be interfaces between cement and wall-rock, and also cement and borehole steel. Any imperfections along these will provide potential flow pathways ***if*** there is a driver for fluid flow. Indeed studies of borehole cement from a 30 year old well show evidence for CO_2 migration over several metres along these interfaces (Carey et al. 2007).

Wellbores in CO_2 storage reservoirs are often subjected to fluctuating pressure and temperature conditions, with potential damage to the well infrastructure, so it is critical that interfaces are initially well sealed (there is a good 'cement job'). It is also important that the well is not exposed to extremes of temperature and/or pressure during its operational phase, as these may cause stresses to develop and, for example, for the steel well liner to 'pull away' from the cement, producing a microannulus along which CO_2-rich fluids could flow. The increase in acidity from alkaline cement pore-waters to acidic CO_2-rich waters will also increase rates of corrosion of borehole steel. Removal of (a section of) the steel liner prior to final plugging of the well may help alleviate some issues by reducing the number of interfaces and potentially reactive materials.

During the operational lifetime of a well, periodic logging can provide some indication of the state of cement seals, and also allow for remedial action to be taken. However, once sealed and abandoned it will be very difficult to monitor for, or remediate, leaks at depth. It is important therefore to understand even slow geochemical processes affecting well stability, or design the borehole seals to cope well with a certain amount of carbonation (e.g. swelling slightly during carbonation to create a better seal over time).

Experiments on wellbore materials

In CO_2CARE, a range of experiments carried out with various configurations of wellbore materials over a wide range of time-scales have provided additional information on wellbore geochemical and geomechanical stability[5].

Batch and flow experiments with samples that modelled steel casing cemented into a sandstone geological formation indicated that plugging of the porosity in the sandstone with minerals released from the cement helps prevent further cement degradation (Asahara et al. 2013). This further contributes to securing the integrity of non-CO_2-resistant wells.

[5] CO2CARe deliverables D2.1: "Report on laboratory wellbore experiments and near-wellbore numerical modelling" and D2.2: "Report on the analysis of chemical changes in wellbore materials with reference to Sleipner".

Experiments to assess the effects of CO_2 plus impurities on caprock and well materials

A series of batch experiments using caprock, borehole cement and steel from Sleipner, and synthetic formation waters were conducted to assess the effect of low levels of SO_2, NO_2, or H_2S impurities (individually, not in combination). The experimental conditions were representative of actual *in-situ* conditions within the caprock (30°C, 8 MPa [80 bar]).

Caprock

In general, the CO_2-pressurised experiments appear to have attained approximate steady-state concentrations for most dissolved species after about 2 months. The main solid phase reaction observed upon addition of CO_2 was carbonate mineral dissolution. The addition of the impurities caused some increased reaction in comparison with previous experiments (Rochelle 2006) using only pure CO_2 and N_2 as a control.

Borehole cement

Borehole cement experiments involved small pucks of cement were run for two months. The presence of CO_2 initiated significant carbonation reactions on and within the cement samples. Although there was extensive reaction of the cement pucks the reaction did not result in their wholesale disintegration. The presence of the impurities, other than the formation of gypsum when sulphur was present, did not significantly affect the nature of the reactions.

Steel borehole liner

The steel casing used was 13% chrome steel, which has been used in the casing joints in the Sleipner platform wells. The exposed parts of the injection well itself are made of 25% chrome steel. The most noticeable effect of dissolved CO_2 was to initiate significant dissolution of the steel. The addition of the impurities caused some increased reaction in comparison with previous experiments (Rochelle 2006) using only pure CO_2 and N_2.

In general for all the materials studied here, the addition of impurities to CO_2 did cause some enhanced reaction but it is the presence of CO_2 (with and without impurities) that has the most impact on the reactions of the caprock and the borehole infrastructure.

Very long term experiments with pure CO_2

A 7-year experimental study completed in CO_2CARE was undertaken to identify the long-term (on a laboratory scale) geochemical impact of CO_2 on minerals within the caprock at the Sleipner CO_2 storage site. Batch experiments run for 7 years utilised caprock core material from Sleipner, with synthetic formation waters based upon measured compositions of nearby samples, and experimental conditions representative of the *in-situ* conditions within the caprock (30°C, 8 MPa [80 bar]). The experiments were pressurised with either N_2 or CO_2, the former providing a 'non-reacting' control with which to compare the more reactive CO_2 experiments.

Fluid analytical data for the N_2-pressurised experiments showed little or no reaction, indicating that the synthetic Utsira pore-water used in the experiments was a reasonable approximation for the actual *in-situ* pore-water composition. Reactions in experiments involving high-pressure CO_2 were dominated by carbonate mineral dissolution. No significant changes in fluid chemistry were found compared to shorter-term experiments, which suggests that CO_2 driven water-rock reactions were essentially complete early on in the experiments. There is some limited evidence that aluminosilicate minerals may have reacted slowly over time. In terms of the overall impact of storing CO_2 at Sleipner; other than some dissolution of carbonate phases, data from these experiments show no indication of major or deleterious reaction processes occurring.

Experiments to assess the impact of pressure-temperature conditions on leakage potential at the wellbore casing-cement interface

Long-term experiments in CO_2CARE, simulating the sealing characteristics of well casing-cement interface and the microannulus, for a range of depth, temperature and pressure conditions representative of CO_2 geological storage sites have suggested that risks posed by leakage of CO_2 from well casing and cement interface for shallow reservoir conditions (800-1,000m deep) are minimum as continuous flow (leakage) of CO_2 would eventually seal the microannulus. On the other hand, potential leakages from wells in deeper fields (~3,000m deep), operating at higher temperatures and pressures, need to be assessed very carefully and a contingency plan for remediating such leakages has to be put in place as the same self-sealing behaviour was not observed for these conditions (Figure 2).

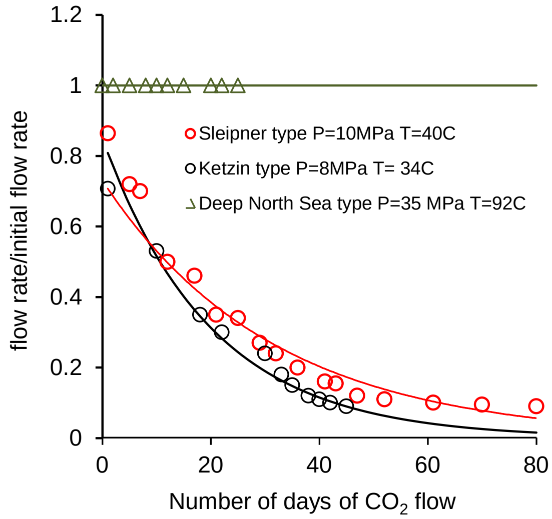

Figure 2. Variation of permeability with time during flow of CO_2 through microannulus

1.3. Novel well-abandonment methodologies

A novel abandonment technique exploiting the ductile behaviour of rock salt was studied within CO_2CARE (Deliverable D2.4). In areas where rock salt forms the sealing layer above potential CO_2 storage reservoirs, its ductile behaviour under high P/T-conditions can be used to generate an impermeable, durable wellbore plug closing potential pathways in the wellbores (Orlic *et al.*, 2008). In order to utilise this for permanent plugging of wellbores, a section of casing should be milled out at the rock salt formation depth, so that the salt can creep into the inner wellbore. The main benefit of this method would be to actually reinstate the cap-rock, with no corrodible engineering materials or material interfaces or annuli that could leak at the sealing level.

The study showed an increase in the creep strain rate with depth due to increasing temperature and differential stresses. The creep strain rate decreases exponentially with decreasing wellbore radius. The shortest borehole closure time for a milled out open hole section of a 7 5/8” casing at a depth of 3.5 km is about 500 days. Backfilling of the wellbore with crushed salt and reducing the fluid pressure in the wellbore will speed up the process of wellbore closure.

It is recommended that the model results should be verified in a field trial in order to evaluate the applicability of this novel method.

1.4. Well integrity logging

1.4.1. Integrity logging in the Nagaoka CO_2 storage project

The Nagaoka CO_2 Storage Project is an onshore pilot test conducted in the Minami-Nagaoka oil and gas field. 10 400 tonnes of CO_2 were injected into a saline aquifer at a depth of 1,100 m from July 2003 to January 2005 (Xue et al. 2006). There are four wells, one for injection and three for observation. In the latter, various technologies for monitoring the injected and stored CO_2 have been successfully employed and post-injection monitoring is still ongoing on an annual basis.

Well integrity examination has been conducted in the observation well closest to (40 m) the injection well. At reservoir depth, fiberglass-reinforced plastic (FRP) was installed to conduct induction logging. In the 40 mm annulus between the casing and the formation, Class-A cement was poured to bond the FRP. According to logging data, the well has been exposed to injected CO_2 since February 2004, around the 240th day after the start of the injection.

Two types of tools were used to verify well integrity: cement bond logging (CBL) and ultrasonic logging (Nakajima et al. 2013). CBL is a proven technology, used to investigate both casing-cement bond (using the CBL signal amplitude) and cement-formation bond (using the Variable Density Log (VDL) wavetrain display), but its data represent the radially averaged status of cement bonding and do not identify the exact location of any poor bonding. Ultrasonic logging is capable of measuring the internal radius of the casing, the thickness of casing and the status of the well and cement indirectly. The tool provides data coverage over 360 degrees and, generally speaking, has higher resolution than the CBL, but is not proven to the same extent. The tools have their own advantages and disadvantages and both of them have been tested at Nagaoka.

The two kinds of loggings have been conducted four times each, including one in the pre-injection period. The recent CBL and ultrasonic log were conducted in 2010 and 2011, respectively. Results from the CBL indicated that the casing and formation were well cemented before the CO_2 injection, and the cementation remains sound despite being exposed to CO_2 for more than eight years. Analysis from the ultrasonic logging shows that there has been no severe damage or deformation in the FRP casing at the reservoir depth, no significant change in casing thickness, and no significant change in the properties of the cement behind the FRP casing at the reservoir depth. In addition, it is noteworthy that two large earthquakes occurred closed to the site during and after the CO_2 injection period but the well loggings show no clear difference between the results before and after the earthquakes.

The 10,000-tonne storage test in Nagaoka provides us with time-lapse data dedicated to investigating the integrity of a well exposed to CO_2 for eight years. Data acquired with two kinds of loggings show no clear evidence of CO_2 leakage or wellbore degradation.

Consequently, well logging with multiple tools (for example the combination of CBL and ultrasonic logging) is recommended for verifying well integrity.

2. Recommendations for post-closure reservoir management

2.1. Conformance

One of the three key regulatory requirements for transfer of responsibility for the storage site is to demonstrate conformity between predictive models of reservoir performance and monitoring observations. Robust conformance shows that the Operator understands how the site is performing and increases the likelihood of longer-term (post-transfer) predictions being reliable.

The types, and quality, of monitoring data acquired will depend on the characteristics of the site. For example, seismic monitoring data is less likely to be acquired, or at least is likely to have a more restricted application, in a deep depleted gas field beneath a thick salt caprock such as K12-B than in a shallow aquifer storage site such as Sleipner. Experience from storage sites to date suggests critical performance measures could include *inter alia*:

- Reservoir pressure and, where applicable, pressure footprint
- Vertical and horizontal extents of the CO_2 plume
- Surface displacements

Demonstrating conformance is technically challenging because a perfect match between observed and modelled behaviour, that is also demonstrably unique, is likely to be impossible to achieve. The aim of CO_2CARE research therefore has focussed on three related elements:

- To show that predictive modelling capability increases systematically with time as monitoring data is progressively acquired. This indicates that storage processes are well understood.
- To show that as more monitoring data is acquired through time, uncertainties progressively reduce, but focus must still be maintained on the less likely ‘end-member’ model scenarios to avoid the possibility of unexpected or divergent future outcomes.
- To show that, at site abandonment, predictive models calibrated by monitoring data can reduce the uncertainty envelope sufficiently for unexpected or divergent future outcomes to be ruled out.

The conformance modelling and monitoring studies carried out at Sleipner and Ketzin have focussed on plume extents and reservoir pressure evolution respectively[6]. The results from this type of conformance assessment would be used to provide model- monitoring offset (MMO) data to input to the risk management activities such as the traffic light system (Section 3.1.2).

2.1.1. CO_2 plume evolution at Sleipner

In the case of the commercial-scale Sleipner project, multiple 2D (axisymmetric) and 3D reservoir simulations were compared to results of 3D time-lapse seismics. Research focussed on predicting and measuring the progressive development of the CO_2 plume. Conformance testing was based on a number of performance criteria:

[6] CO2CARE deliverable D3.3: “Processing and modelling using measurements and geophysical forward (history matched) modelling”.

- Plume footprint area
- Maximum lateral migration distance of CO_2 from the injection point
- Area of CO_2 accumulation trapped at top reservoir
- Volume of CO_2 accumulation trapped at top reservoir
- Area of all CO_2 layers summed
- Spreading co-efficient (storage efficiency)[7]

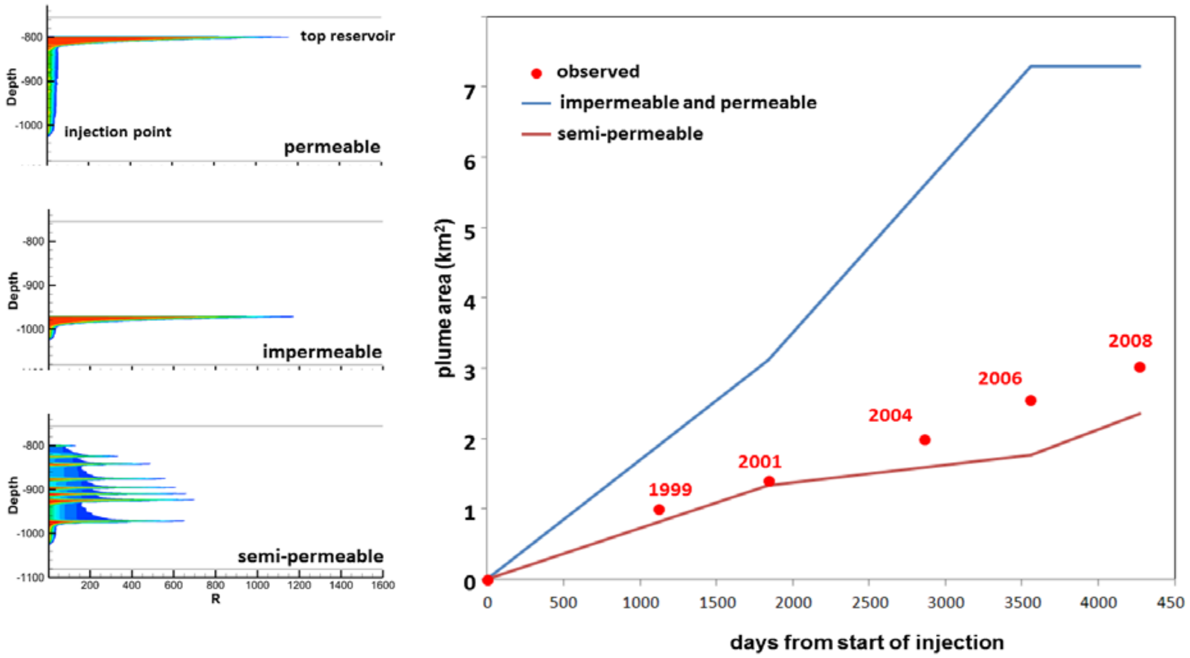

Figure 3. Predictions (axisymmetric model) based on baseline information showing single layer and multi-layer plumes (left) and predicted / observed ranges for one of the performance measures (plume footprint area)

Initial predictions in 1996, using only baseline observations, with no plume monitoring data, had a high degree of uncertainty (Figure 3) arising mostly from uncertainty in how the CO_2 would be trapped within the reservoir. Possibilities ranged from a single layer at the reservoir top or several layers at different levels within the reservoir. As a consequence, performance measures, such as plume area footprint, had high range of possibilities.

Monitoring data, comprising a suite of repeat 3D seismic surveys (Figure 4), was able to confirm that CO_2 was trapped at multiple levels within the reservoir, and provide additional constraints such as arrival time of the CO_2 at the reservoir top, estimation of CO_2 flux into the topmost layer and individual layer extents. Improved reservoir temperature data also became available as the injection progressed.

[7] The spreading co-efficient is the plume footprint area divided by the total (summed) area of all the layers in the plume and gives a measure of the efficiency of lateral spread of the plume. Thus, a single layer plume would have an SC of 1.0, whereas multiple layered plumes would have an SC <1.

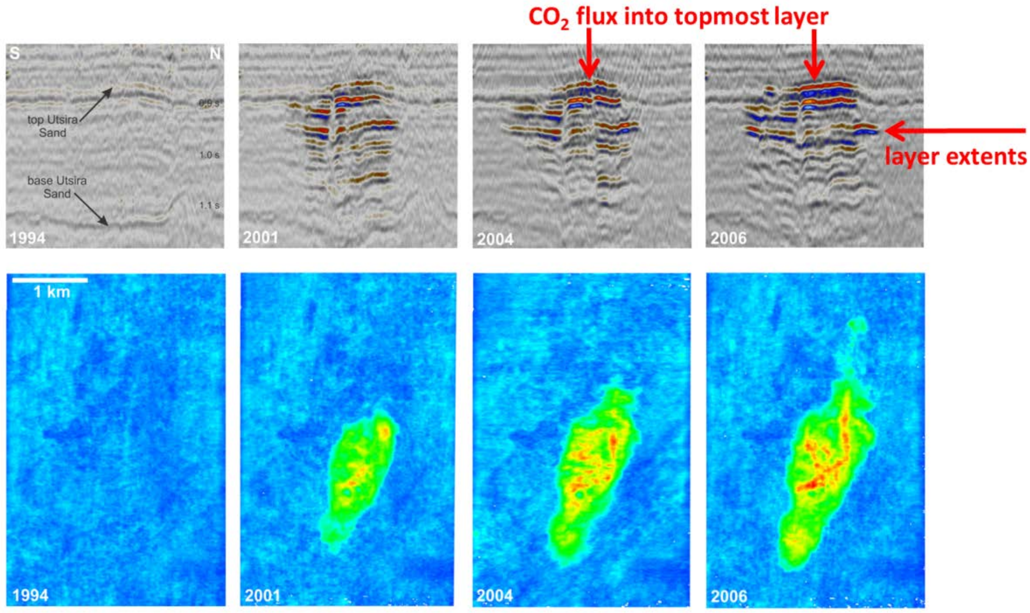

Figure 4. A subset of the time-lapse seismics showing progressive development of multi-layer plume (top) and of the plume spatial footprint (bottom)

Subsequent predictions (2001, 2006) included only multi-layer plumes (Figure 5), so end-member possibilities were much closure together.

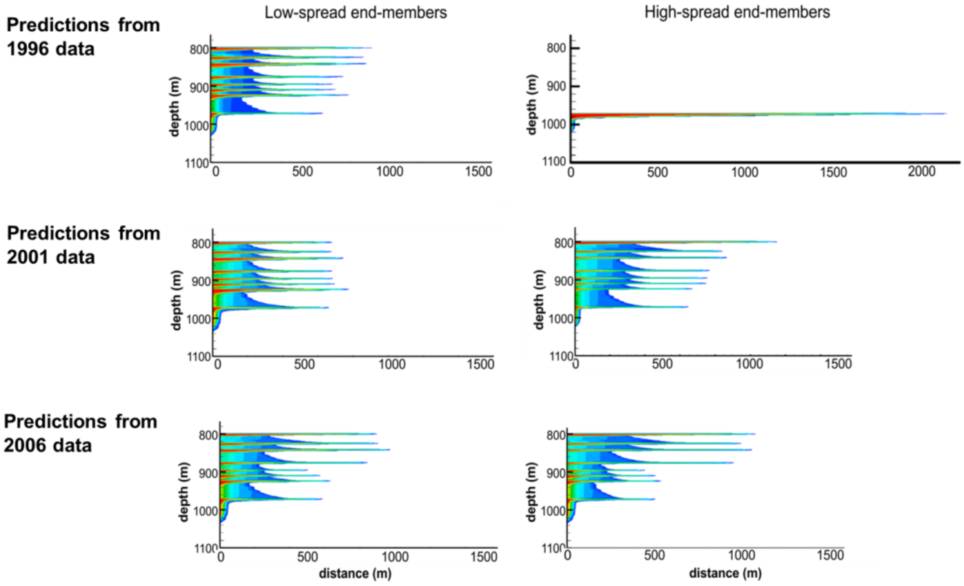

Figure 5. Plume predictions (axisymmetric model) showing end-members based on 1996, 2001 and 2006 datasets

As a result, predicted ranges for the performance measures are much reduced (Figure 6) and the likelihood of the end-members leading to unexpected or divergent future outcomes is much reduced.

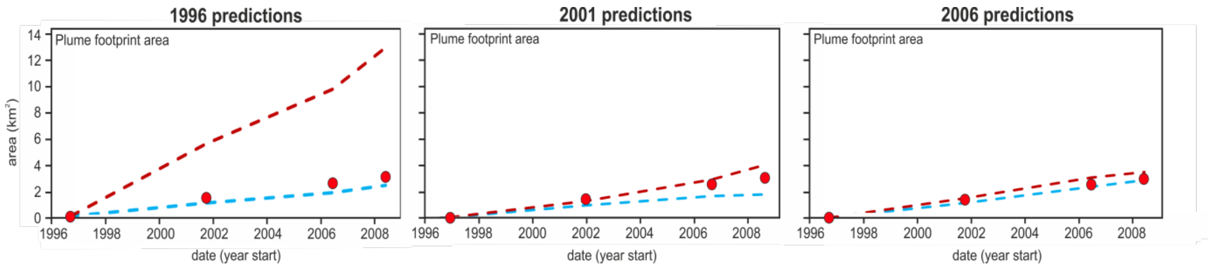

Figure 6. Predictions (axisymmetric model) of one of the performance measures (plume footprint area) showing progressive decrease in uncertainty through time

A key performance measure that cannot be accurately assessed by the axisymmetric modelling is the lateral migration of the topmost layer of the plume, directly beneath the topseal (whose topography is known from the baseline data). Initial 3D models based on 1996 data had a very wide spread, but uncertainty reduced markedly as the time-lapse datasets became available (Figure 7).

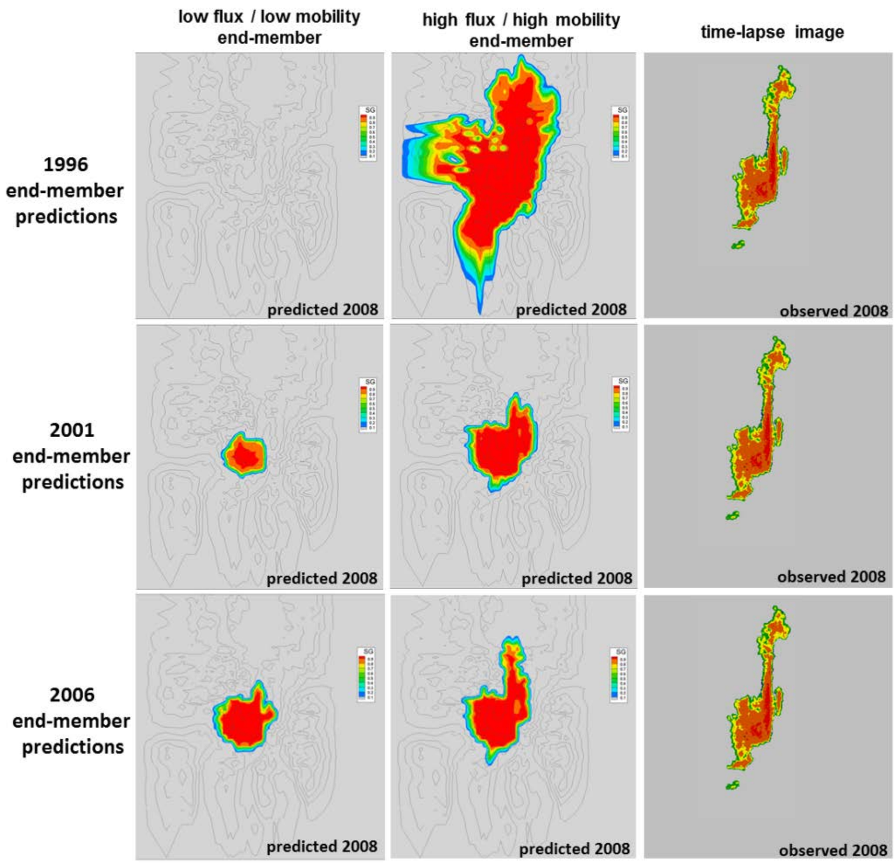

Figure 7. Predicted development of the topmost layer of CO_2 in the plume by 2008 (3D model) showing progressive decrease in uncertainty through time

It is clear however that even by 2006, a perfect prediction of the 2008 plume was not easily obtainable. This is due to continued (though much reduced) geological uncertainty and also to likely limitations in the predictive model itself. Nevertheless, it is also clear that the basic process of layer development (buoyancy-driven migration by fill-spill beneath the topseal topography) is well understood. As more monitoring data is acquired uncertainty will reduce still further and the likelihood of unexpected divergent future outcomes is very small. Thus, as more seismic data became available, predictive models could be matched more accurately to the observations and became more reliable predictors of future performance.

2.1.2. Reservoir pressure evolution at Ketzin

Monitoring wells, equipped with pressure and temperature sensors, provide direct observations concerning the propagation and the physical state of the CO_2 plume. These direct monitoring installations complement the more indirect geophysical observations from the Earth surface (such as 3D seismics). For the Ketzin pilot site, pressure data from the injection and monitoring wells, arrival times of the CO_2 plume at the monitoring wells, and the lateral and vertical extension of the CO_2 plume in the reservoir were monitored, simulated, and compared as a performance measure.

Matching the recorded pressure data at the injection well and CO_2 arrival times at both observation wells of the Ketzin pilot site required the introduction of distinct near-well and far-field permeability tensors. Taking this into account, simulation results using different simulation software tools showed a good to excellent agreement of simulated and observed pressures, with a maximum pressure mismatch of about 1 bar (Figure 8).

Regarding the arrival times, the model reacted very sensitively to geological features which can change greatly locally when different mesh resolutions are applied. Thus, a matching of the arrival time - trying to predict an event at a single point, is associated with large uncertainty regarding the underlying geological model. Our recommendation is that this type of observation should not be used as a key measure of prediction performance.

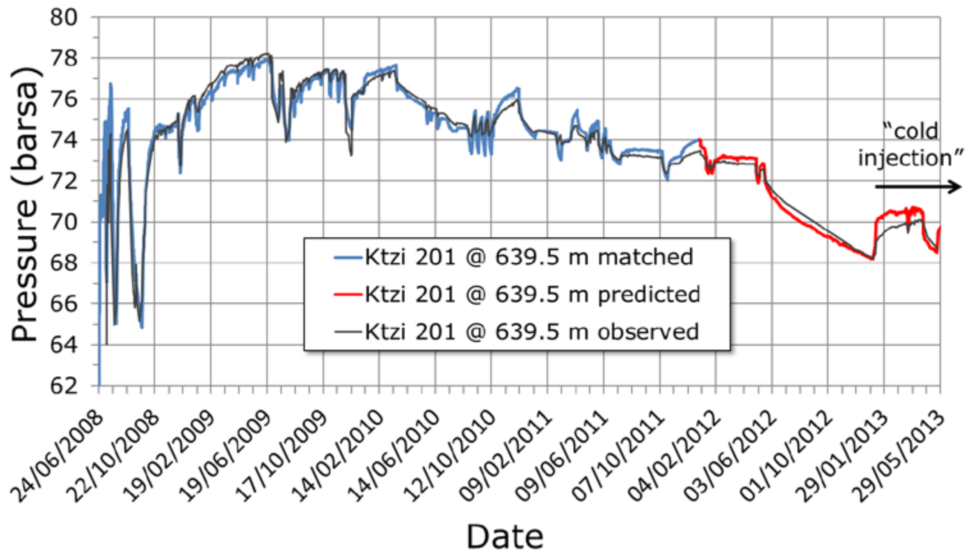

Figure 8. History-matching of modelled and observed reservoir pressures at Ketzin, showing accuracy of post-2011 prediction.

Comparisons of horizontal and vertical CO_2 plume distribution between simulations and monitoring data (commonly repeat 3D seismic surveys) must take into account detectability and resolution issues for the time-lapse monitoring surveys. This may be done by seismic modelling incorporating realistic signal-noise ratios and involving different saturation scenarios and considering homogeneous as well as patchy CO_2 distribution. If the CO_2 is accumulated in thin layers only, these may remain undetected by surface geophysical measurements. Also, in CO_2-saturated rock mass, units with low saturation (below 20% CO_2 saturation) may be hard to detect, as demonstrated in simulation studies performed for the Ketzin pilot site.

2.1.3. Conclusions on conformance

3D time-lapse seismics and down-hole pressure measurements are proven technologies and have been the key monitoring tools for reservoir management at the CO_2CARE sites. It is likely that this will be the case for storage sites elsewhere, albeit with varying site-specific requirements. It is also worth stressing that the roughly two yearly repeat survey frequency at Sleipner mostly reflects the requirements for monitoring the deeper gas field. A dedicated monitoring programme for the CO_2 storage site would very likely involve a much lower time-lapse repeat frequency. Other tools are likely to be of complementary value in certain situations; down-hole logging and fluid sampling to characterise longer-term stabilization processes for example.

From the examples shown above, it is clear that as more monitoring data becomes available during the course of a project, and the initial model is adapted to produce a better match with it, conformance improves dramatically. Nevertheless perfect matching is likely to be impossible due to the various limitations of model resolution, model parameters, observational limitations and other residual uncertainties. It is important for regulators to accept this and realise that at a certain, less than perfect, level of conformance (which will be very site-specific) it can still be clear that the key storage processes are robustly understood.

Quality of future performance prediction also improves progressively as more monitoring data becomes available, resulting in a progressive reduction in uncertainty. However, a key aspect is to maintain a sufficiently wide range of predictive scenarios, such that any reasonable outcome will fall within it. Measurements that fall outside the predicted range are likely to be embarrassing for the Operator and may trigger remediation requirements if they look likely to result in unexpected outcomes. It is important therefore to focus strongly on the end-members of the predicted range, particularly those that might lead to divergent future outcomes. It is important for regulators to realise that a level of residual uncertainty in the predictive modelling is unavoidable and acceptable, provided that the end-members of the predicted range will not lead to unacceptable outcomes.

A possible example of this is the predicted future plume at Ketzin (see below). Although the exact spatial disposition of the plume in future is uncertain, all of the predicted range lies within a stable outcome – the plume will migrate into a closed trapping structure.

2.2. Demonstrating 'No detectable leakage'

Leakage is defined in the EU Directive as the migration of CO_2 outside of the Storage Complex. Note that leakage is not synonymous with surface emission of CO_2, but leakage detection might, in certain circumstances, give early warning of future emissions. Leakage measurement in might provide an upper bound on a future or concurrent surface emission. Migration out of the Storage Complex might be either upwards, laterally or even downwards - the latter perhaps in dissolved form. In CO_2CARE we have focussed on assessing techniques for detecting the upward (buoyant) migration of CO_2 through the overburden where detection requires some form of robust spatial coverage of potentially large geographical areas. Any form of point-wise or profile based detection tool has deficiencies in this respect due to spatial sampling issues (Figure 9).

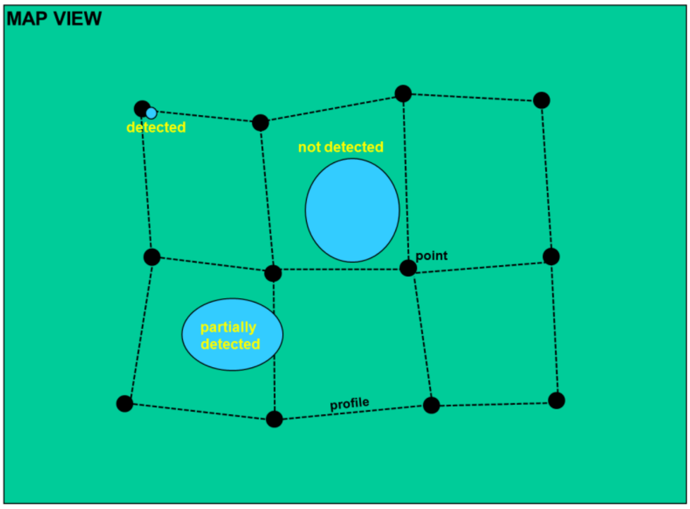

Figure 9. Point sampling or profile-based detection techniques are potentially very sensitive if carried out in the vicinity of the leak, but are susceptible to missing or only partially detecting leaks which fall between the sampling points or profiles.

One approach is by pressure detection in a suitably permeable monitoring horizon closely above the Storage Complex. Issues associated with this have been explored at other storage sites (e.g. Meckel et al. 2008, Taoa et al. 2013).

In CO_2CARE we have focussed on the leakage detection ability of 3D time-lapse seismics[8]. The technique can provide robust and uniform spatial subsurface coverage of the overburden above the storage reservoir particularly in offshore situations. This is applicable to all storage reservoir types, be they aquifers or depleted hydrocarbon fields. Accumulations of CO_2 in the overburden, either as sub-horizontal layers or sub-vertical 'chimneys', will lead to changes in reflectivity and time-shifts. These are extremely sensitive to even small amounts of CO_2.

A key factor in the ability of time-lapse data to detect small time-dependent changes is the degree to which successive datasets can be accurately repeated. Perfect repeatability would produce a noise-free difference dataset capable of detecting very small time-lapse changes. In practice, repeatability is far from perfect - difference datasets suffer from a variable amount of repeatability error or noise which acts to obscure real changes in signal. Repeatability noise has essentially three causes:

- changes in ambient noise on repeat surveys which lead to an overprint of essentially random repeatability noise
- changes in acquisition parameters (e.g. source/receiver characteristics, recording geometry) which give imperfect repeat imaging of the subsurface and lead to repeatability noise which adumbrates the geological reflectivity
- In onshore datasets, changes in elastic properties of the near-surface low-velocity layer due to varying humidity and necessitating updated static corrections for repeated time-lapse surveys

Detection threshold therefore depends on repeatability noise (Figure 10) and is therefore highly site and position dependent (varying with depth and depending on seismic quality, repeatability, geology and CO_2 properties). It is also a statistical measure varying with both the thickness and area of a CO_2 accumulation, and trade-offs therein. CO_2CARE work at

[8] CO_2CARE deliverable D3.5: "Report on monitoring techniques for site abandonment based on site portfolio".

Sleipner shows that accumulations of CO_2 at the top of the reservoir with masses of around 7000 tonnes can easily be imaged, with a statistically-determined detection threshold of around 2100 tonnes. In the overburden detection thresholds are likely to be even lower, perhaps as small as a few hundred tonnes in favourable circumstances at certain depths.

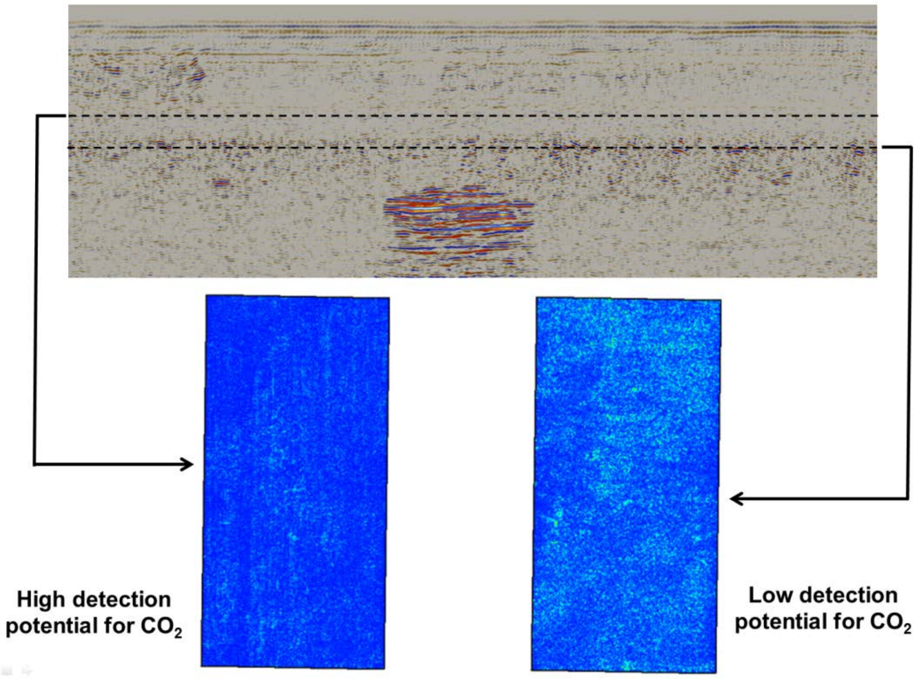

Figure 10. Seismic line through the Sleipner CO_2 plume and overburden (top) with horizontal time-slice maps showing time-lapse changes in the overburden (bottom). Random signal across the time-slice is due to repeatability noise, levels of which limit the detectability of real changes due to CO_2.

The question then arises as to the significance of the term 'no detectable leakage' in the context of finite detection capability. We can relate detection capability to the leakage limit required to fulfil a storage site's emissions mitigation objective. Hepple and Benson (2003) have suggested that an average annual leakage rate of 0.01% per year for storage sites would enable us to stabilise atmospheric CO_2 concentrations below 550 ppm and other studies have cited similar figures.

Let us take a hypothetical case injecting 5 Mt of CO_2 per year into the Utsira Sand for 20 years, giving a total injected amount of 100 Mt. If such a site were to leak 0.01% of injected CO_2 per year from the start of injection, then, at site closure, around 100 kt would have leaked out. Such an amount should be readily detectable and the 'no detected leakage' criterion would be failed. Looked at another way, a leaked amount of only 1000 tonnes (compatible with leakage detection thresholds in the Sleipner overburden), would correspond to an annual leakage rate of only 0.0001%. This is two orders of magnitude below the effective mitigation criterion and so, 'no detected leakage' in such a situation would provide robust confirmation that the site was meeting its emissions mitigation objectives.

It is recommended therefore that regulators use the term 'no detectable leakage' in the context of whether a site is performing effectively in terms of emissions mitigation. In practice it is likely that a regulator will also require that detectability limits are sufficient to ensure that necessary health and safety objectives are met.

2.3. Demonstrating long-term stabilization

The long-term security of storage sites over time-spans of 1,000-10,000 years has been the focus of various types of modelling studies involving predictions and extrapolations. It is generally accepted that four CO_2 trapping processes (buoyancy trapping, capillary trapping, dissolution and mineralisation), operating on progressively longer time-scales, are key to the process of site stabilization. One of the very first published illustrations of this was a fully conceptual diagram of time evolution of trapping proportions by these mechanisms (Fig. 111), included in the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC 2005).

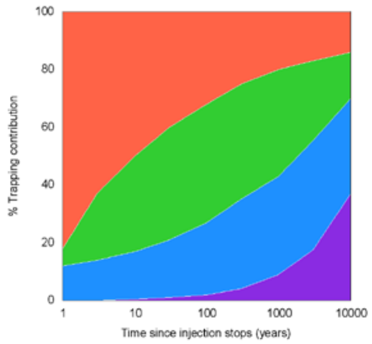

Figure 11. Re-coloured version of the conceptual diagram from IPCC 2005). The concept is that the safety of the site is linked to the significant reduction in the mobile phase for CO_2 (red), whereas the proportion trapped in residual phase by capillary forces (green), the dissolved CO_2 in the water (blue), and the precipitation of minerals incorporating the CO_2 (purple) steadily increases over time.

A CO_2CARE meta-study of published results from simulations of long-term trapping in a variety of potential storage sites[9] shows that there might be significant deviations from the conceptual description. The only consistent agreement seems to be the very limited amount of mineral trapping on the thousand year timescale.

Despite the uneven background data for the meta-study, and sometimes the lack of information about input for the simulations, it seems clear that the trapping diagram must be highly site-specific. The distribution of trapping between the different mechanisms depends on reservoir architecture, depth, brine salinity, and injection strategy. This diversity among different injection sites is exemplified with a few examples (Fig. 12).

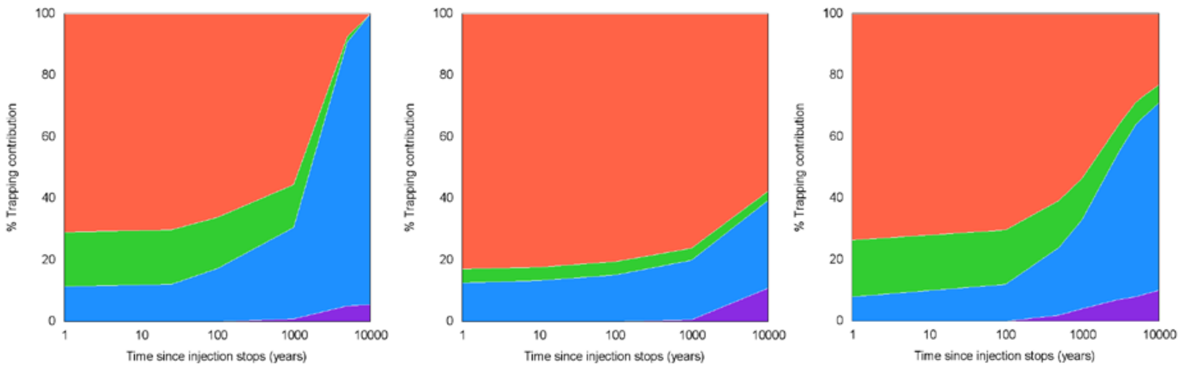

Figure 12. Trapping diagrams (colours as above) constructed from results in Audigane (2007). Zhang (2009) and Ranganathan (2011).

It is clear that fully coupled modelling of all the trapping processes is computationally very demanding, and that the suggested upscaling strategy for the geochemical modelling must be developed further to allow assessment of this trapping contribution. A recommended addition to these studies is to engage also in sensitivity studies and mapping of the uncertainty in the trapping estimates, since we have learned that some of the input

[9] CO_2CARE Deliverable D3.1: “Review of relevant trapping mechanisms based on site portfolio”.

parameters can have significant effect on the results that are commonly based on long-term extrapolations.

Uncertainty can be addressed by multiple model realisations and statistical analysis. A long-term predictive modelling exercise was carried out for the Ketzin site to assess CO_2 plume behaviour during the post-closure period, especially in the far-field region where the uncertainty in the reservoir heterogeneity is high. The study used the most recent and history-matched static model developed for the Ketzin site. In order to model these uncertainties, 25 stochastic realisations of fluvial channel distributions, that represent some of the possible far-field heterogeneities, were created and implemented in the flow simulations. Further details of the methodology proposed and recommendations made are presented in Section 3.2.

Because predictive modelling of long-term processes is subject to significant uncertainty, it is likely to be necessary to provide additional knowledge support for the stabilization process. This can include observed monitoring data from storage sites already in the post-injection phase such as Nagaoka (Sato et al. 2011), experimental data, or geological analogues which demonstrate stabilization processes and time-scales.

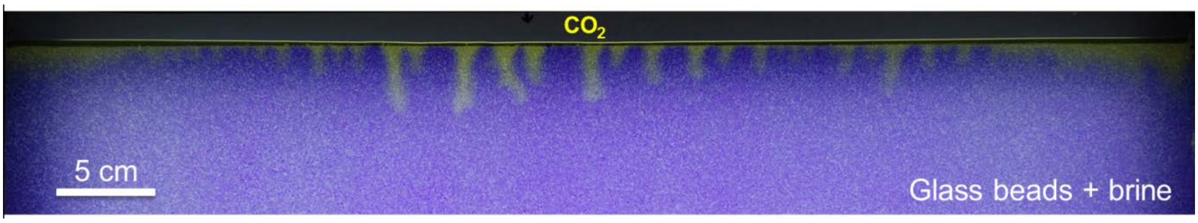

Figure 13. Photograph of the upper part of a laboratory Hele-Shaw cell, containing a water-filled porous medium, showing dissolution of CO_2 and sinking plumes (yellow) of CO_2 saturated water (after 90 minutes).

As an illustration, in order to assess the possible efficacy of dissolution as a trapping process, CO2CARE has run a series of experiments to observe the onset of convection (density-driven sinking) as CO_2 dissolves in reservoir brine[10] (Fig. 13).

For these very long-term processes, there is a need to collate and integrate knowledge from very disparate sources and approaches, and there is a strong argument for setting up a worldwide learning platform on this topic.

[10] CO_2CARE deliverable D3.4: “Assessment of long-term integrity and site stabilisation by coupled THMC modelling”.

3. Recommendations for risk management

The main elements of managing the environmental and safety risks of CO_2 storage are well embedded in the rules of the Storage Directive, which are risk assessment, monitoring and corrective measures. The detailed requirements for risk assessment are laid down in Annex I of the Directive and the requirements for monitoring are described in Annex II of the Directive. The need for a corrective measure plan is described in Article 16 of the Directive. More technical details of CO_2 storage risk management are provided in the Guidance Documents accompanying the Storage Directive. The present chapter directs particular attention to risk management activities for the closure and transfer of responsibility of a CO_2 storage site.

3.1. Risk management plan

The risk management plan developed in the CO_2CARE project is designed to meet the requirements of the Directive for site closure and transfer of responsibility for the site to the CA. However, risk management activities, i.e. the cycle of risk assessment, monitoring and risk reducing measures, should be continuously revolving during all phases of the CO_2 storage lifetime and is thus not exclusive to the closure milestone and the post-closure phases of a CO_2 storage project. In fact, risk management in terms of assessment and planning actually starts in the site qualification phase. An application for a storage permit should already address the major items required for site closure and post-closure, albeit in a provisional way. These include the risk management plan, post-closure plan, transfer requirements, and abandonment plan.

Just as the early phases of the storage project life cycle deal with the *planning* of the closure and post-closure activities, the latest stages focus on updating the plans and *implementing* them. The risk management plan for the site closure and post-closure phases assumes that a complete risk assessment and a set of plans, with optional updates made during the operational phase, are available once a project moves into the final stages of the operational phase.

Risk Management in the context of closing and abandoning a CO_2 storage site encompasses all the measures required to demonstrate the site's long-term safety. The latter represents a pre-condition for transfer of the responsibility for the abandoned site from the operator to the CA.

Monitoring is an essential element in risk management, not only during the operational phase of a CO_2 storage project but also in the post-operational phase. Appropriate site-specific monitoring measures need to be set up very early in the project life cycle, during the licensing procedure for a CO_2 storage site, which marks the starting-point for demonstrating how the requirements for the transfer of responsibility can be met.

3.1.1. Timeline and milestones

The timeline considered by the risk management plan developed during the CO_2CARE project encompasses the final part of the injection period within the operational phase as well as the post-closure/pre-transfer and post-transfer phases of a storage project. Figure 17 illustrates the timeline of the project phases covered by the CO_2CARE risk management plan, i.e. the final stages of the operational phase, the post-closure/pre-transfer and the post-transfer phase (Phases 4-6 of EC GD3). It also shows a proposed breakdown of the operation phase and post closure/pre-transfer phase into 3 sub-phases, based on the terms used in the Directive, namely:

- final operational sub-phase (Part of Phase 4, including site closure)

- post-closure sub-phase (first phase of Phase 5)

  pre-transfer sub-phase (second phase of Phase 5, including transfer of the site)

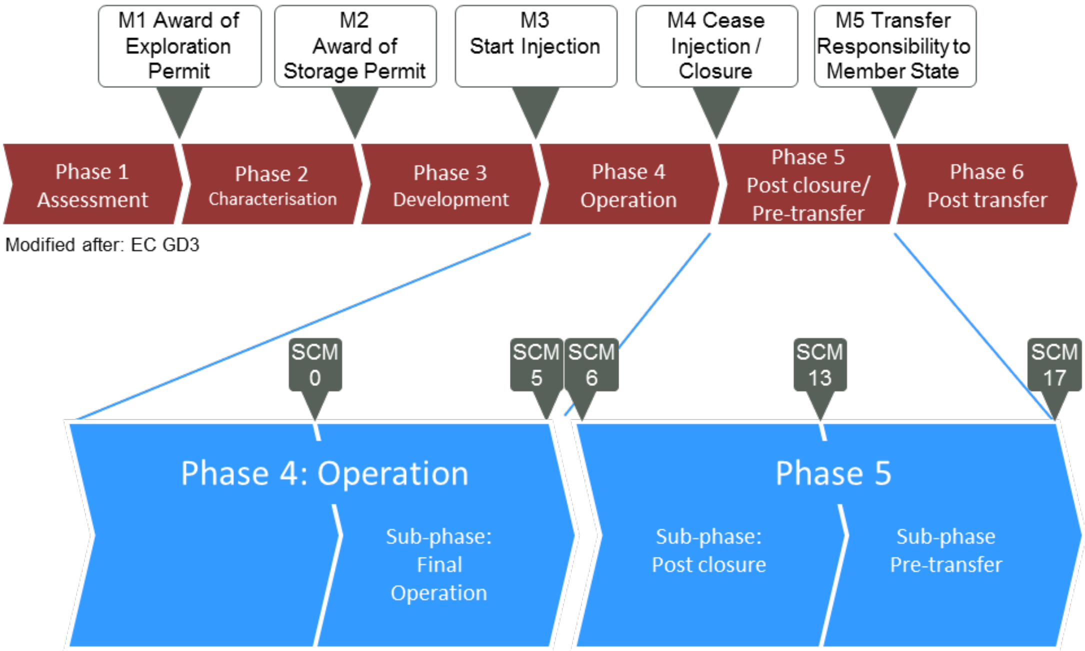

Figure 14. Timeline for CO_2 storage site closure risk management modified after EC Guidance Document 3. M=milestone defined in DIRECTIVE 2009/31/EC, SCM= New defined Site-Closure Milestones for risk management of CO_2 storage site closure

In order to provide a well-structured procedure for risk management within these project phases and sub-phases, 17 Site-Closure Milestones (SCM) have been introduced that we recommend should be implemented during the relevant project phases The milestones are closely linked to the requirements of the Directive and describe key actions or key moments in time during site closure and transfer.

The SCMs are ordered on a chronological basis allowing the operator and the CA to monitor the progress of the preparations for transfer. The requirements of Article 18 of the Directive have been integrated into the proposed set of milestones, thus ensuring that all conditions for transfer of responsibility are fulfilled when the set of milestones is passed.

The correspondence between SCMs and timeline is summarised in Table 2. It is important that the milestones should be passed in the order given in Table 2. For instance, the final evaluation of the absence of leakage must be undertaken after accordance of modelling and monitoring data have been demonstrated, i.e. the behaviour of the storage complex is shown to be understood by the operator.

Table 3. Site-closure milestone chart leading to the transfer of responsibility according to Article 18 (EC Storage Directive)

Site-Closure Milestone (SCM)	Description	Sub-Phase	Phase/ Moment
0	Specify models and monitoring selected for conformity check	Final Operation	Operational
1	Check model/monitoring conformity during final operational phase; if necessary update models		
2	Provisional post-closure plan updated		
3	Final (updated) post-closure plan submitted		
4	Final (updated) post-closure plan approved		
5	Site Closure	-	Site Closure
6	Optional update of risk management plan	Post-Closure	Post-Closure/Pre-Transfer
7	Model check-update loop terminates		
8	Models and monitoring data are within acceptable conformance after M7 has been reached without significant adjustment (EC GD3 proposes a minimum period of five years)		
9	Optional final update of risk management plan		
10	Evidence of absence of leakage presented to CA		
11	Effectiveness of storage concept: Evolution to long-term stability demonstrated		
11a	Pressure evolution demonstrated to match model prediction		
11b	Plume movement is demonstrated to be an acceptable match to model predictions (within tolerances)		
11c	Verification of other (optional) parameters/features related to the storage concept		
12	Final wellbore check before abandonment (final well logging)		
13	(Draft) Report for transfer of responsibility submitted	Pre-Transfer	
14	Report approved		
15	Surface facilities removed		
16	Well abandonment accepted		
17	Transfer of responsibility approved and accomplished	-	Site Transfer

3.1.2. Judgment criteria for milestones

As the SCMs are defined at a high level, they have to be complemented with more specific risk management (R-type) and technical (T-type) criteria that can be applied on an operational level to determine whether the site closure milestones have been reached.

The risk management criteria, termed “R-type” criteria (Table 4), have been directly extracted from the risk management plan presented in Table 3.

Some of these R-type criteria refer to input from the verification of modelling by the results of monitoring. Parameters are predicted by modelling and measured by monitoring to verify the conformity of actual and modelled behaviour as stated in the Directive. For risk management-related treatment of such parameters, requiring comparison of modelled and measured data, a traffic light system with an associated workflow has been set up (Fig. 16). This workflow provides an additional set of technical criteria ("T-type" criteria), specifically relating to model-monitoring conformity. The major goal of the traffic light system is to provide a framework for dealing with offsets (differences) between model predictions and monitoring data (MMO, i.e. model monitoring offset).

The three criteria levels, fundamental criteria of the Directive, R-type criteria and T-type criteria, have been connected to each other in order to form a practical generic set of criteria for CO_2 storage site abandonment and the transfer of responsibility to a Competent Authority (CA).

Table 4. List of the criteria derived from Risk Management Plan (R-type criteria)

<table>
<tr><th>R-type criteria</th><th>Description of criteria</th><th>EC requirements and Site Closure Milestones</th><th>Sub-Phase</th></tr>
<tr><td>R1</td><td>Pressure evolution conforms to the reservoir models</td><td rowspan="5">Absence of leakage
(SCM10 & SCM12)</td><td rowspan="11">Post-Closure</td></tr>
<tr><td>R2</td><td>No detectable indication of leakage by monitoring measures</td></tr>
<tr><td>R3</td><td>Evidence for the location of the CO_2-plume within the storage site by periodic seismic surveys or other appropriate measures</td></tr>
<tr><td>R4</td><td>Leakage has not been detected for at least 10 years, this period may include the operational phase</td></tr>
<tr><td>R5</td><td>Well integrity is checked directly before abandonment according to best practices</td></tr>
<tr><td>R6</td><td>Model recalibration iteration loop ends and model recalibration not required any more</td><td rowspan="2">Conformity of Monitoring data and model predictions (SCM7 & SCM8)</td></tr>
<tr><td>R7</td><td>Model recalibration iteration loop ended at least five years ago</td></tr>
<tr><td>R8</td><td>Pressure is developing towards an equilibrium pressure and according to models</td><td rowspan="4">Site evolution towards long term stability
(SCM11)</td></tr>
<tr><td>R9</td><td>Plume movement is matching model predictions</td></tr>
<tr><td>R10</td><td>Plume is not moving out of the storage site, confirmed by modelling and monitoring</td></tr>
<tr><td>R11</td><td>Optional verification of other parameters/features related to the storage concept</td></tr>
</table>

In order to assess whether R-type criteria which invoke model-monitoring verification are met, a traffic light system, explained in the next section, has been set up. The traffic light system establishes whether or not the monitoring and modelling data are in compliance and provides a procedure for handling offsets of observed and predicted data. Figure 15 shows the high level criteria of the EC Directive, the associated R-type criteria, and when to deploy the traffic light system. Table 5 indicates which T-type criteria are to be assessed on the basis of this traffic light system. The scheme depicted in Figure 16 has to be applied **independently for any parameter subject to monitoring and modelling** within the scope of a storage project.

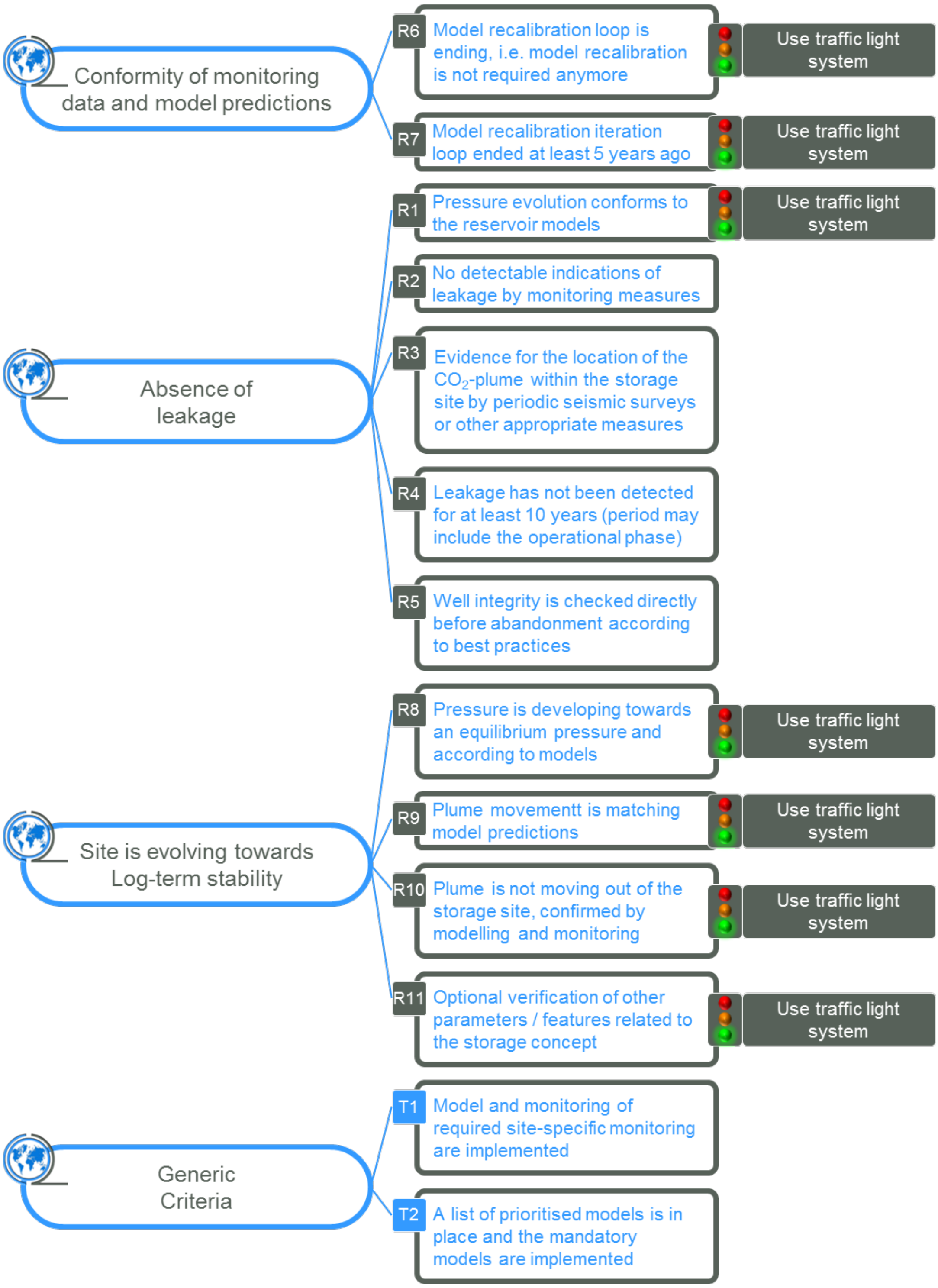

Figure 15. List of criteria for post-operational decision making and responsibility transfer as well as the interconnection between the fundamental, R-type criteria, and the traffic light system

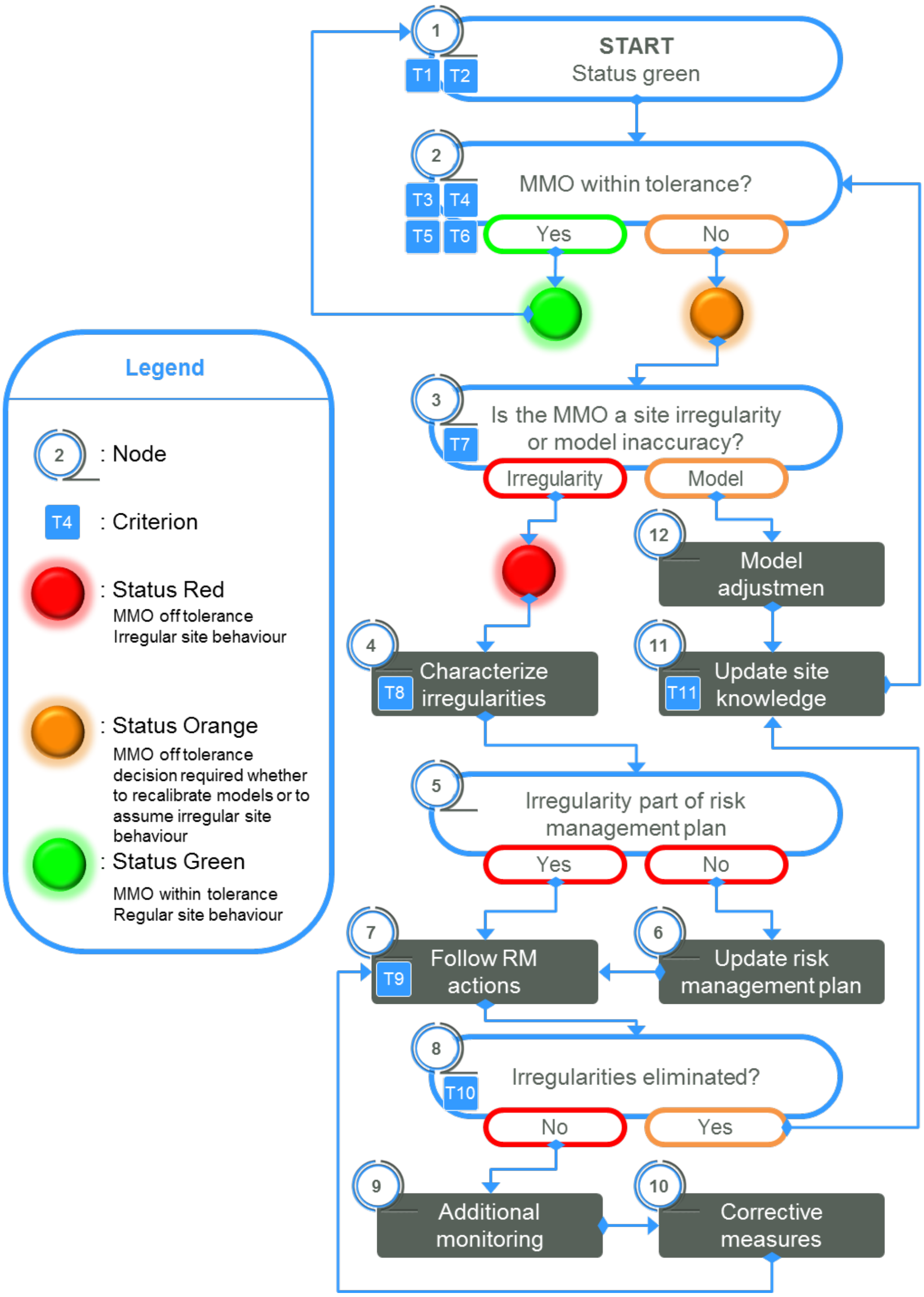

Figure 16. Flow diagram of the traffic light system for risk-related decision making in the post-closure sub-phase and definition of the three risk priorities (status red, orange and green). MMO= model-monitoring offset, RM = risk management

Table 5. List of the criteria derived from the traffic light approach (T-type criteria).

Crit.	Description	General criterion
T1	Models and monitoring of required site-specific monitoring parameters are implemented	yes
T2	A list of prioritised models is in place and the mandatory models are implemented	yes
T3	Duration of the time interval to check for MMO	no
T4	Relative amount of the tolerable MMO	no
T5	Accuracy/precision of monitoring technique	no
T6	Accuracy/precision of models	no
T7	Does a gathered MMO refer to site irregularity or is model recalibration required?	no
T8	In case of site failure: Are the primary and all connected irregularities identified?	no
T9	In case of site failure: are all required RM measures ready to be applied?	no
T10	Are the irregularities eliminated by the RM measures applied?	no
T11	Is there data to improve the site knowledge?	no

The development of the above approach to defining criteria to enable transfer of responsibility for the site to the CA[11] revealed that, although based upon a generic framework, the definition of such criteria is highly site dependent. In particular, the definition of tolerable model-monitoring deviations and accuracies/precisions of models is ambiguous and requires thorough consideration and agreement between the operator of the site and the CA.

Please note that the application of the traffic light system is not limited to the final operational and post-operational phases, but can also be deployed in earlier stages of the storage project whenever a mismatch between modelled and observed site behaviour has occurred.

3.1.3. Minimum periods in the Directive to fulfil criteria for transfer

The Directive and its Guidance Documents (GDs) propose minimum periods to fulfil certain key criteria, which are not based on any scientific fundamentals. It is recommended that the decision as to whether a criterion for the safety of a site has been met should be based on technical criteria only and should not be linked to prescriptive time spans. Instead, a post-operational CO_2 storage site should be sealed as soon as possible after all criteria for the transfer have been fulfilled and the Competent Authority is satisfied that the long-term integrity of the storage site has been sufficiently proven[11].

[11] The definition of criteria for transfer of responsibility and abandonment, and the developed workflow are presented in detail in two separate public CO_2CARE documents available via the CO_2CARE web portal: Report D4.12 “Plan for risk management supporting site abandonment” (CO_2CARE, 2013b) and Report D4.22 “Criteria for decision making in site abandonment” (CO_2CARE, 2013c). The traffic light system and a case example of how to deal with an observed model-monitoring offset (MMO) is presented in detail in the latter document (explaining the nodes used in the system).

3.1.4. Irregularities

The Directive states that if significant irregularities occur during the storage process, corrective measures specified in a risk management plan have to be taken in order to ensure the safety of the site. According to Article 3 (17) of the Directive, a “significant irregularity” is defined as any irregularity (or non-conformance) during the injection, post-injection/pre-closure or post-closure phase, which pose a risk of leakage or implies a risk to the environment or humans.

Hence, irregular site behaviour can be defined as a state or predicted evolution of the site which deviates from the expected behaviour. Parameters or indicators of irregular behaviour (such as pressure or plume extent) need to be identified and one or more threshold values need to be defined for non-conformance. As mentioned above, it is not clearly technically specified *a priori* what constitutes an irregularity (MMO, i.e. “Model Monitoring Offset”) and which deviations of the project plan (e.g. Monitoring-Model-Conformance) or uncertainty ranges (e.g. for models) are acceptable. This connects directly with the high level criterion of conformance of real and predicted behaviour in the Directive but, for site-specific reasons, technical criteria constituting an irregularity can probably only be defined by agreement between the site operator and the CA.

The other two fundamental abandonment criteria (absence of significant risks and site evolution to a stable situation) also rely - at least partly - on monitoring and predictive model data. Thus, MMO is a central issue in decision making. Therefore, a traffic light decision support system (Figure 16) has been set up to enable the operator and CA to determine whether model predictions and monitoring data are in agreement, and any irregularity is being appropriately managed. The workflow has been evaluated thoroughly on the K12-B CO_2 injection site[12] and the practicality of the proposed traffic light workflow can be demonstrated.

It is recommended that threshold values for irregular behaviour and tolerances for deviations should be agreed upon by the Competent Authority (CA) after discussion with the Operator, and it is recognised that these will depend greatly on the characteristics of each individual site. As stated GD3: “*The choice of the percentage (of monitoring-modelling offset) would be determined by the CA and different ranges of tolerances can be specified for each particular measured parameter in order to determine conformity. The CA should specify the applicable percentages for various parameters for each storage site at the time of the storage permit, taking account of site specific characteristics”.*

Predictive models are key tools in the risk assessment and management process. On the other hand it is clear that a model can never replicate monitoring data perfectly or uniquely. It is advisable therefore to maintain a range of predictive modelled scenarios during the lifetime of the project. The modelled range would include the preferred or most likely scenarios, but also scenario end-members in order to track whether unacceptable ‘divergent’ outcomes remain possible. In some circumstances statistical (e.g. Bayesian) tools might be appropriate to help quantify the likelihood of certain scenarios and outcomes occurring (see below).

3.2. Uncertainty analysis for leakage risk assessment

It is recognised that mobile CO_2 phase in the storage reservoir has a tendency to follow the general topography of the reservoir/caprock interface and migrate up dip with time, further beyond the area the plume is located at the time of site closure. This observation has implications for storage risk assessment and site monitoring during CO_2 injection and post closure. For example at Ketzin, above-zone pressure monitoring, which allows the probing for brine leakage of a wider area beyond the current CO_2 plume footprint, has been

[12] CO_2CARE Deliverable D4.22: “Criteria for decision making in site abandonment”.

employed to ensure that CO_2 would be contained by structural trapping as it migrates up an anticline and, according to model predictions, eventually rests against a fault.

To facilitate leakage risk assessment, it is recommended to divide the simulated CO_2 plume footprint broadly into a transient (free CO_2 largely passing through) and a non-transient source regions. A third region – the near wellbore region - may also be defined to evaluate the source for potential leakage through the injection well. The amount of free CO_2 in different regions over time can then be tracked, through reservoir modelling, to evaluate when and for how long the leakage risk might be present in any given region, as well as the size of the source available for leakage. Considering the uncertainty in reservoir heterogeneity and the petrophysical properties used in simulations, especially in the far-field region at the time of site closure, long term assessment of the plume migration should involve the use of multiple realisations of the reservoir model whilst honouring the available 4D seismic data. Represented as the free CO_2 distribution probability maps in time and space, the results of these simulations can then be used for post-closure leakage risk assessment (Figure 17).

For quantitative leakage assessment, potential CO_2 leakage through a leaky patch of the caprock should be simulated for different scenarios regarding the leakage path permeability and detection threshold. The outcome of this step would be the mapping of leakage profiles (magnitude and duration) at different caprock locations within the plume footprint. This knowledge would be significant in informing both the monitoring strategy and appropriate remediation methods for a storage site, during the post-closure period in particular.

The overall risk management for a storage site would combine the properties of leakage pathways (leakage probability, likely rates etc.) for an individual risk component identified (such as natural or induced pathways in the caprock, failed injection well cement or abandoned wells) and assess risk and the associated uncertainty for a storage site in conjunction with the source behaviour.

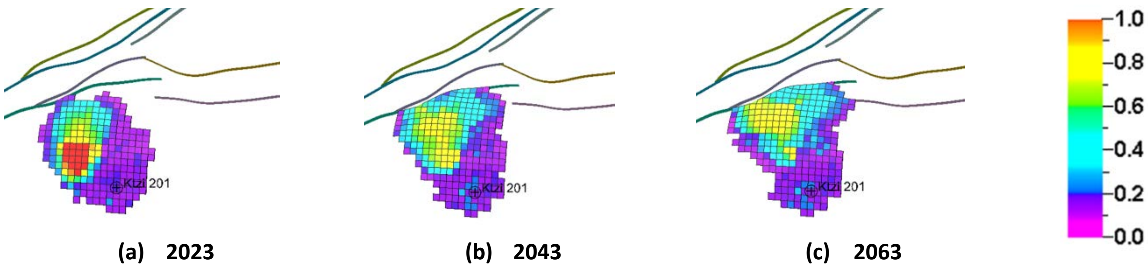

Figure 17. Probability map of the mobile CO_2 distribution at the top layer of the reservoir in years: (a) 2023; (b) 2043; (c) 2063 at Ketzin.

3.3. Monitoring strategies – pre and post transfer

The design of a monitoring strategy fits naturally into the pre- and the post-transfer phases.

3.3.1. Pre-transfer phase

The monitoring strategy in the pre-transfer phase will depend on the geological conditions of the site and will focus on fulfilling the remaining risk management requirements and completing the evidence-base upon which the three transfer criteria depend (no detected leakage, conformance and long-term stabilisation).

The monitoring programme will generally continue the same suite of monitoring surveys as was deployed before closure. However, survey coverage will likely become temporally and spatially sparser, so that time intervals between repeat campaigns will become longer, and repeat surveys might become more focussed with a reduced quantity or spatial coverage of observations, depending on the post-closure risk scenarios. An example of this would be concentrating on detecting possible leakage related to specific identified risk locations rather than necessarily monitoring the whole storage footprint.

3.3.2. Post-transfer phase

At the point of transfer the storage site will have met the rather stringent requirements laid down by the Directive, so post-transfer monitoring is expected to be minimal.

A hypothetical example can be drawn from the Sleipner dry-run, wherein injection was assumed to have ceased in 2006. Thus monitoring during the pre-transfer phase will have verified the following performance details:

1) Plume is migrating, as predicted, into the northern structural closure.

2) Plume is not migrating towards a wellbore

3) No CO_2 is detected in the overburden

4) Intra-reservoir CO_2 layers are developing as predicted

In addition, as pointed out in the Sleipner Dry-run document[13], the three transfer criteria have been satisfactorily addressed so it is proposed that no post-transfer monitoring is required.

For public acceptance purposes however, it is suggested that a further shallow survey be acquired to image and sample any bubble-streams at seabed to confirm nothing unusual is happening.

3.4. Tool for comparison of modelling and monitoring data

One of the requirements of the Directive is that modelling results are verified by comparison with monitoring results. Monitoring data can never constrain a model in full so it is prudent to keep a range of models up and running during the lifetime of the storage site (which is not common practice with reservoir engineers).

At site transfer a final choice of the most appropriate model should be made. To this end a tool was developed which enabled a statistical comparison of monitoring data with a suite of model outcomes and selection of the most appropriate model(s)[14].

3.5. The risk matrix

The CO_2CARE site 'Dry-run' closure documents[13] have included a 'Risk Matrix'. This is a device that assigns non-conformances or other undesirable 'events' that might occur during storage operations to a matrix on the basis of their likelihood and the severity of consequence should they occur.

[13] CO_2CARE Deliverable D5.3: "Final 'Dry-Run' for Site Abandonment and Transfer of Responsibility: Sleipner, K12-B and Ketzin".

[14] More details on this tool are to be found in CO_2CARE deliverables D4.4: "" and D4.5: "".

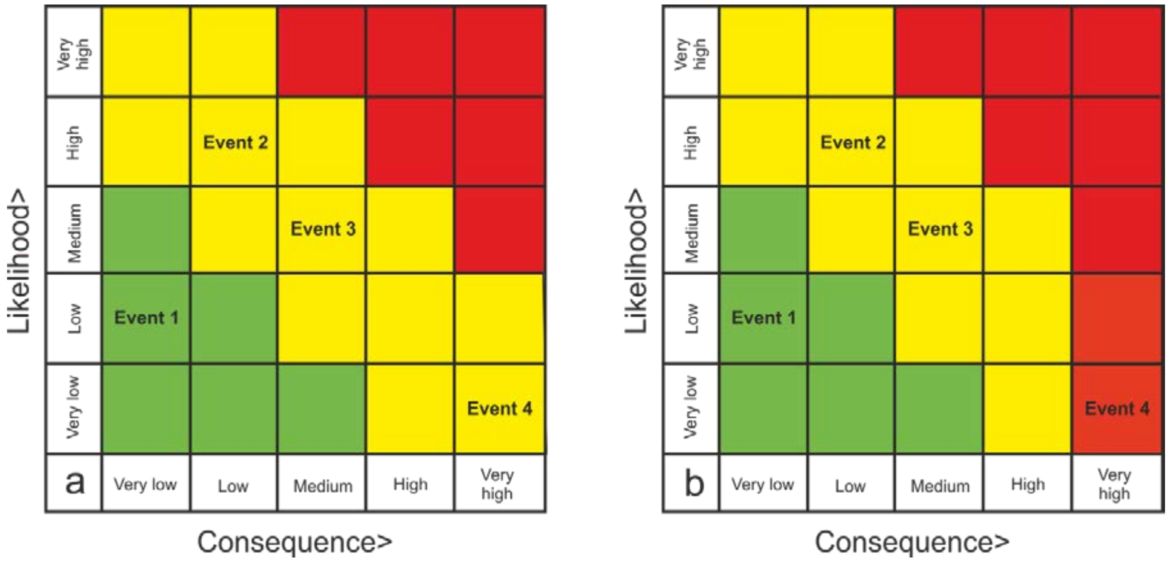

Figure 18. The Risk Matrix for CO_2 storage, a) After DNV (2010) b) Suggested modification herein

Introduced as part of CO2QUALSTORE (DNV 2010) the matrix is essentially a traffic-light system designed to guide an operator in the prevention or treatment of potentially serious events. Thus, for a storage site, the operator and the regulator should carefully assess the likelihood and consequences of identified events and rank the resulting risks according to the traffic light system. This will depend on the type and characteristic of a storage site, so for example consequences of specific events will likely be completely different for onshore and offshore locations. Proposed colour ranking of risks is as follows:

- Green: low-medium risk; no action needed
- Yellow: high risk; countermeasures required
- Red: unacceptable risk; showstopper if no effective countermeasures are available

The risk matrix proposed in CO2QUALSTORE (Fig. 18a) has a symmetrical arrangement of colours, such that, for example, an event of very high consequence but very low likelihood (Event 4 in Fig. 18) would have a yellow traffic light risk ranking. Recent events in the oil exploration industry have shown that very low probability events do, nevertheless, occasionally occur and they can have catastrophic consequences; environmental, financial and/or reputational.

CCS is an immature discipline, currently very much under public scrutiny, and it is essential that high consequence, high profile accidents are avoided completely. We recommend therefore that the risk matrix be modified such that any event with a very high consequence will be allocated the red risk ranking (Fig. 18b). In other words, sites should be designed, operated and monitored in such a manner that very high consequence events are, to all intents and purposes, impossible.

4. Recommendations concerning transfer of responsibility from the Operator to the State

4.1. General observations

Many of the recommendations below arose from the CO2CARE Dry Runs Regulator's Workshop[15]. The CO2CARE participants are grateful to the participating regulators for their valuable contributions, which provide an important perspective on the transfer of responsibility from the Operator to the CA.

- Acceptance of the Transfer Report (and transfer of responsibility for all legal obligations for the site to the CA) marks the end of a process that began with site selection and a permit application by the Operator many years previously. It is vital that a relationship based on transparency and openness should have developed between the Operator and Regulator during that period. Consequently CO2CARE recommends that the CA and Operator should ensure that sufficient face-to-face contact to build mutual confidence, and to ensure continuity of knowledge through changes of personnel, is built into the regulatory process. This, together with the regular reporting requirements that most jurisdictions require (e.g. those required under the EU Directive) should help to ensure that the transfer report should contain no surprises.
- Transfer of responsibility for all legal obligations for the storage site from the Operator to the CA marks a radical change in the balance of responsibilities between stakeholders in a storage project. The CA is ultimately the representative of the public, and this implies an acceptance by the public of the benefits and associated liabilities.
- The Storage Complex should be defined at all stages of the project life cycle from the Characterisation phase onwards, because it is a fundamental concept in the Storage Directive. The term storage complex means the storage site and surrounding geological domain which can have an effect on overall storage integrity and security, that is, secondary containment formations. Views of other stakeholders involved or potentially involved in this volume and area should be addressed in the transfer report. The limits of the Storage Complex could be redefined at any point in the project.
- Possible interactions with the site from future operations (CO_2 storage or other uses), and other legitimate users of the subsurface or marine environment, should be considered in the transfer report, and any potential hazards of this kind should be identified to the CA. Recommendations for risk reduction, risk management and mitigation/remediation options for potential post-transfer interactions with other subsurface operations should also be included in the transfer report. That said, ultimately, only CAs can assess the risks that might arise from operation and closure of multiple assets within a storage formation or region.

4.2. Recommendations for Risk Assessments prior to transfer

- The risk assessment matrix used in the CO_2CARE K12-B and Sleipner risk assessments, which ranks the likelihood and consequence of an event, was found useful by the regulators (but see Section 3.4). It was also mentioned that more information on how the likelihood and consequence of an event were estimated would be useful.
- As part of the risk assessment, technical criteria that signal significant irregularities should be defined for each site. These might be necessary as part of general recommendations for the CA when recommending post-transfer monitoring. Threshold values would be a part of the definitions in some cases[16].

[15] CO_2CARE deliverable D5.2: "Regulators workshop and review".

[16] See also Section 4.1.1 of this report

- Competent Authorities may wish to undertake their own simulations, based on static models developed by the operators, to make an independent evaluation and consider the effectiveness of monitoring. Static geological models and numerical reservoir simulations run on in-house software platforms rather than commercially available platforms such as Petrel and Eclipse may not be acceptable for transfer purposes because the Competent Authority would not be able to run the models.
- The participants in the Dry Runs Regulators Workshop felt that there was a lack of clarity in the use of terms describing the various phases of the CO_2 geological storage project life cycle such as closure, post-closure and post-injection, both within the Directive and between the Directive and its accompanying Guidance Documents. It was agreed that further clarity was needed on the exact order of key stages of the regulatory process during the closure, transfer and post-transfer periods. CO_2CARE therefore developed tools and procedures for a successful closure and transfer of CO_2 storage sites[17].

4.3. Recommendations for Transfer Reports

- The Transfer report has the function of a contract – and it needs to contain key messages for the public. The CA is likely to produce a counterpart document as well.
- From an Operator's perspective, it may be necessary to include a statement in the storage permit along the lines of: "If the storage site performs as predicted, no leakage is detected by the monitoring technologies deployed according to the monitoring plan, the site is evolving towards a state of long term stability, and all the terms and conditions in the storage permit are met, then the Competent Authority will accept transfer of all legal obligations for the storage site from the operator". This would provide comfort to the investors and Operator that the State would accept the site back once the storage operation had been successfully completed.
- As predictions of the future site performance are based purely on forward modelling, a very large number and range of numerical reservoir simulation runs in which model parameters are varied may be necessary to assure the CA of the satisfactory future performance of the site. It will also be necessary to conduct modelling of other aspects of the site performance, e.g. geomechanical and geochemical stability. Predictions based on single lines of evidence are likely to be insufficient.
- A high level of detail on how models were constructed and how they evolved throughout the storage site characterisation, construction and operation should be included. Furthermore, information on how such models take uncertainty into account would likely be necessary in a transfer report.
- In the section on conformance of models and monitoring, at least three reasons for monitoring should be addressed: monitoring to improve knowledge of the site and its performance, early warning of potential departures from modelled performance allowing time to intervene, monitoring of the efficacy of corrective measures, technical and social baseline needs.
- Financial arrangements and a plan for post-transfer monitoring need to be made – it is too easy and not sufficient to say monitoring can stop; it will be needed as part of the CA's duty of care.
- The regulators participating in the CO_2CARE Dry Runs Regulator's Workshop indicated that liabilities for certain risks will remain with the Operator post-transfer. It is recommended that the EC should investigate these views further as they may have implications for the Directive or the way in which it is implemented in practice.

[17] And as a consequence, CO_2CARE has made the recommendations given in Section 4.1.1 and Section 7.

- As CO_2 storage is a multi-generational operation, consideration should be given to what tools and data should be transferred to the CA. Models may need to be used post-transfer, if a significant irregularity or leakage was detected.

5. Recommendations related to communication with the public

Communication and engagement with the public is something that should start very early in the CO_2 storage project life cycle – as soon as, or even before, a site is selected. Communication and engagement then should continue throughout the project life cycle, including beyond the transfer of liability. Examples of successful engagement for pilot-scale research projects are given below.

5.1. Stakeholder Engagement Strategy for Wallula Basalt Pilot

The Pacific Northwest National Laboratory and Boise, Inc. under the Big Sky Regional Carbon Partnership in August 2013 successfully executed a nominal 1000 tonne CO_2 injection into the Columbia River Basalt at a site located near the township of Wallula in Washington State. The success of this pilot project can be traced in large part to effective engagement of a broad spectrum of people and organizations in the region designed to build understanding and acceptance of the project's objectives, conduct, and potential benefits. However, that engagement did not happen by accident. A formal, written public engagement strategy was prepared, reviewed, and approved by the key partners on the project to ensure commitment to execution of the strategy throughout the various phases of the pilot project, which spanned more than four years. Key aspects of the engagement strategy included:

- Developing basic project information materials with key messages about the project, which were revised and augmented as the project progressed, including information for citizens, interest groups, elected officials, and media.
- Identifying people and organizations in the local area that have an interest in the project, and proactively approaching them to explain the purpose, process, and expected outcomes of the demonstration, and to learn about their questions and concerns.
- Working to resolve issues raised by stakeholders, and keeping them informed as the project proceeded to try to address their concerns and help them appreciate the potential contribution of this technology to clean energy and climate change goals.
- Engaging with local universities to host student tours of the field site and research facilities at the national laboratory.
- Coordinating media and open house events at the field site during important phases of the project (i.e. drilling, CO_2 injection) with local stakeholders.
- Identifying and engaging with broader set of stakeholders with a statewide and regional view about the potential of emerging technology to address energy and climate change goals as a foundation for permitting, sharing results, and potential future application of the technologies in areas beyond the immediate Wallula community.

The strategy developed represents an overall vision for stakeholder engagement and ensures that stakeholders are actively engaged and issues addressed successfully as the project transitions from planning, execution, monitoring, and finally closure.

5.2. Community engagement with the Otway CO_2 storage project, Victoria, Australia

Community engagement was made a major priority by the Otway CO_2 storage project operator (CO2CRC) both in the initial stages and throughout the continuing project.

5.2.1. Five critical factors that helped successful community engagement

Ashworth, Rodriguez & Miller (2013) highlight five critical factors that helped in the development of a well structured communications plan and affected the outcome of the community engagement were:

1. Gaining a baseline understanding of perceptions of CCS in the local community
2. Early, proactive engagement
3. Establishing trust
4. Appointment of Community Liaison Officer from the local community
5. Development of protocols for engaging with local landowners

5.3. Experiences in Germany:

The Federal Republic of Germany considers CCS to be a promising key technology to reduce CO_2 emissions into the atmosphere. However, critical public perception, especially of storage, turned out to be a severe hindrance to the development of CCS (TAB 2008). Public interest in and opposition to CO_2 storage projects has been particularly high in the potential target areas. GFZ led the public outreach and acceptance activities associated with the CLEAN (Kühn et al., 2012; Hübner et.al 2013) and Ketzin CO_2 storage projects. While the CLEAN project never entered active injection, the Ketzin pilot site for geological CO_2 storage, which has been operated by GFZ since 2004 near the town Ketzin/Havel in Brandenburg (Germany), has been accompanied by an extensive and successful public outreach program (Schilling et al., 2009; Martens et al.; 2012, 2013).

The following recommendations result from a study by Fischedick et al. (2008), and the analysis of the two public outreach and acceptance activities based on newspaper articles and direct on-site experiences (Kollersberger, pers. communication):

1) Any information campaign should start as early as possible with contact to the local politicians and general public.
2) Initially, any campaign should first focus on the local stakeholders.
3) Communicators should be trained individuals with high societal reputation and sound scientific background.
4) Legal and technical aspects as well as the role of CCS as a climate change mitigation option should be comprehensively addressed.
5) A targeted, group-specific communication strategy should be generated.
6) Transparent information about the research motivation and objectives and factual arguments is necessary to allow the general public to make a decision based on scientific knowledge and transparent discussion of concerns, benefits and knowledge gaps.
7) The contact with the different stakeholders should be maintained throughout the project lifetime.
8) A visitor centre directly at or near the site including guided tours on-site is able to develop trust due to the direct contact with the persons involved in the project (Martens et al. 2012).
9) It is of particular importance to provide a variety of media, information tools and materials, tailored to the respective target groups, and to transfer knowledge to individuals and groups/institutions with very different background knowledge (Kühn et al., 2012, Hübner et al., 2013).

However, conducting effective public outreach does not necessarily guarantee the success of a project or an improved public perception of the project. Acceptance depends on many more factors which can only be influenced by public relations to a limited extent (Hübner et al., 2013). It must also be stressed that the public reaction to a small-scale, short-term research project is likely to be significantly different to its reaction to the development of a permanent industrial-scale storage site.

6. Recommendations for the possible modification of Directive 2009/31/EC of the European Union, on the geological storage of carbon dioxide and its associated Guidance Documents

- The Directive and its Guidance Documents (GDs) propose minimum periods to fulfil certain key criteria. These are not based on any scientific fundamentals. It is recommended that the decision as to whether a criterion for the safety of a site has been met should be based on technical considerations only and should not be linked to a prescriptive time span.
- The significance of the evidence from hydrocarbon exploration and production in meeting the requirements for the transfer of responsibility of CO_2 storage in hydrocarbon reservoirs should be better acknowledged.
- It is advised to include the system of site-closure milestones and related criteria which were developed in CO2CARE, in an updated version of Guidance Document 3.
- It is recommended that a consistent terminology should be used throughout all relevant documents, particularly with respect to phases and sub-phases of the storage lifetime. The terminology should be outlined in a “Definition of Terms” section in each document.
- A generic template for the (preliminary) risk, closure and transfer reports would clarify the requirements for passing these steps during the project lifetime and would allow the operator (and the regulator) to work towards these from the start of the project.
- The regulators participating in the CO2CARE Dry Runs Regulator’s Workshop[18] indicated that liabilities for certain risks will remain with the operators post-transfer. It is recommended that the EC should investigate national and jurisdictional regulators’ views on this further as they may have implications for the Directive or the way in which it is implemented in practice.
- As CO_2 storage is a multi-generational operation, consideration should be given to what tools and data should be transferred to the CA at site transfer. Models used up to the point of transfer may also need to be used post-transfer if a significant irregularity or leakage is detected.
- All leakage monitoring systems have a finite (and site-specific) CO_2 detection capability, so the question arises as to the usefulness of the term ‘absence of any detectable leakage’. Detection capability can be equated to the maximum allowable leakage rate consistent with a storage site meeting its greenhouse gas emissions mitigation objective. A number of studies have suggested that leakage rates around 0.01% per year or less would ensure effective mitigation performance in terms of greenhouses gas reduction (see Section 3.2 above). So for a hypothetical large-scale storage project, injecting around 100 Mt of CO_2, the detection capability of the Sleipner seismics would be some two orders of magnitude below the effective mitigation leakage limit. ‘Absence of any detectable leakage’ in such a situation would therefore provide robust confirmation that the site was meetings its greenhouse gas emissions mitigation objectives. It is recommended therefore that regulators use the term “absence of any detectable leakage” in the context of whether a site is performing effectively in terms of emissions mitigation.

[18] CO_2CARE deliverable D5.2: “Regulators workshop and review”.

References

Asahara, Y., Mito, S., Xue, Z., Yamashita, Y. & Miyashiro, K. 2013, Chemical impacts of CO_2 flooding on well composite samples: Experimental assessment of well integrity for CO_2 sequestration, *Energy Procedia* **37**: 5738-5745.

Ashworth, P. Rodriguez, S. & Miller, A. 2013. Case study of the CO2CRC Otway project. Downloadable from: http://www.csiro.au/Organisation-Structure/Divisions/Earth-Science--Resource-Engineering/Otway-case-study.aspx. Accessed 24/10/2013.

Audigane, P., Gaus, I., Czernichowski-Lauriol, I., Pruess, K., & Xu, T. 2007. Two-dimensional reactive transport modeling of CO2 injection in a saline aquifer at the Sleipner site, North Sea. *American Journal of Science* **307**: 974-1008.

Benson, S.M., & Cook, P.J., 2005. *Underground geological storage of carbon dioxide*. In: Metz, B., et al. (Eds.), Intergovernmental Panel on Climate Change Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press, pp. 195–276 (Chapter 5).

Carey, J. W., Wigand, M., Chipera, S., WoldeGabriel, G., Pawar, R., Lichtner, P., Wehner, S., Raines, M., Guthrie, G. D., Jr., 2007. Analysis and performance of oil well cement with 30 years of CO_2 exposure from the SACROC Unit, West Texas, USA. *International Journal of Greenhouse Gas Control* **1**: 75–85.

CO2CARE 2012: Report on the current site abandonment methodologies in relevant industries. CO2CARE report, Deliverable D1.2. https://www.co2care.org/SciPublicationsData.aspx?IdPublication=30&IdType=327

CO2CARE 2013. CO2CARE Deliverable 5.2: Regulators Workshop and Review.

CO2CARE 2013a: Report on innovative abandonment: geochemical treatments for intentional clogging and salt plugging. CO2CARE report, Deliverable D2.4.

CO2CARE 2013b: Plan for risk management supporting site abandonment. CO_2Care report, Deliverable D4.12.

CO2CARE 2013c: Criteria for decision making in site abandonment. CO_2Care report, Deliverable D4.22

CO2CARE 2013d: Tool for assessing model probabilities by comparing measurement and computations. CO_2Care report, Deliverable D4.4

CO2CARE 2013e: Results from comparison of modelled and measured behaviour at the K12-B site. CO_2Care report, Deliverable D4.4

DNV (2010): CO2QUALSTORE: Guideline for Selection and Qualification of Sites and Projects for Geological Storage of CO_2. DNV Report No. 2009-1425

Fischedick, M., Cremer, C., Esken, A., Gruber, E., Idrissova, F., Kuckshinrichs, W., Linßen, J., Pietzner, K., Radgen, P., Roser, A., Schnepf, N., Schumann, D., Supersberger, N., Zapp, P. (2008): Sozioökonomische Begleitforschung zur gesellschaftlichen Akzeptanz von Carbon Capture and Storage (CCS) auf nationaler und internationaler Ebene. Endbericht, Wuppertal-Institut für Klima, Umwelt, Energie; Forschungszentrum Jülich; Büro für sozialverträgliche Ressourcennutzung Sustainability GmbH -BSR-, Karlsruhe; Fraunhofer-Institut für System- und Innovationsforschung -ISI- Karlsruhe. http://publica.fraunhofer.de/eprints/urn:nbn:de:0011-n-815843.pdf (Abruf am 06. Januar 2014)

Hepple, R. P. & Benson, S. M. 2003. Implications of surface seepage on the effectiveness of geological storage of carbon dioxide as a climate change mitigation option. In: GALE, J. & KAYA, Y. (eds) *Greenhouse Gas Control Technologies*. Volume 1, Elsevier Science Ltd, Oxford, UK, 261–266.

Hovorka, S. and Tinker, S.W. 2010: EOR as sequestration: Geoscience perspective: presented at the Symposium on the Role of Enhanced Oil Recovery in Accelerating the Deployment of Carbon Capture and Storage, Cambridge, MA, July 23, 2010. GCCC Digital Publication Series #10-12.

Hübner, A., Kollersberger, T., Pilz, P. & Tesmer, M., Kühn, M. (2013): Public Outreach in Kühn, M. and Münch, U. (Eds.): CLEAN: CO_2 Large-Scale Enhanced Gas Recovery in the Altmark Natural Gas Field. GEOTECHNOLOGIEN Science Report 2013: 19. Series: Advanced Technology in Earth Sciences. P 199, ISBN 978-3-642-31676-0. Springer Verlag

IEA-GHG 2010: Corrosion and Materials selection in CCS.

IPCC (Intergovernmental Panel on Climate Change), 2005: *Special Report on Carbon Dioxide Capture and Storage*, Metz, B., O. Davidson, L. Meyer and H.C. de Coninck (eds.) Cambridge University Press, Cambridge, United Kingdom, 440 pp.

Kuhn, M., Hübner, A., Kollersberger, T., Pilz, P., Tesmer, M. (2012): Abschlussbericht zum F&E-Verbundvorhaben CLEAN (CO2 Large-Scale Enhanced Gas Recovery in the Altmark Natural Gas Field) „Öffentliche Akzeptanz“ (CO2-Akzeptor), Sonderprogramm GEOTECHNOLOGIEN

Kühn, M., Wipki, M., Durucan, S., Korre, A., Deflandre, J.P., Boulharts, H., Lüth, S., Frykman, P., Wollenweber, J., Kronimus, A., Chadwick, A., Böhm, G., 2013. Key Site Abandonment Steps in CO_2 Storage. *Energy Procedia* **37**: 4731-4740.

Martens, S., Kempka, T., Liebscher A, Lüth, S., Möller, F., Myrttinen, A., Norden, B., Schmidt-Hattenberger, C., Zimmer, M., Kühn, M. (2012): Europe’s longest-operating on-shore CO2 storage site at Ketzin, Germany: a progress report after three years of injection. Environ Earth Sci. doi:10.1007/s12665-012-1672-5

Martens, S., Liebscher, A., Möller, F., Henninges, J., Kempka, T., Lüth, S., Norden, B., Prevedel, B., Szizybalski, A., Zimmer, M., Kühn, M. and the Ketzin Group (2013): CO2 storage at the Ketzin pilot site, Germany: Fourth year of injection, monitoring, modelling and verification. Energy Procedia, Volume 37, Pages 6434-6443, doi:10.1016/j.egypro.2013.06.573.

Meckel, T.A., Hovorka, S.D., Kalyanaraman, N., 2008. Continuous pressure monitoring for large volume CO_2 injections: presented at the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9), Washington, D.C., November 16-20, 2008. GCCC Digital Publication Series #08-03a.

Meyer, J.P. 2007: Summary of Carbon Dioxide Enhanced Oil Recovery (CO2-EOR), Injection Well Technology, API, August 2007.

Nakajima, T., Xue, Z., Watanabe, J., Ito, Y. &Sakashita, S. 2013, Assessment of Well Integrity at Nagaoka CO2 Injection Site Using Ultrasonic Logging and Cement Bond Log Data. *Energy Procedia*, **37**: 5746-5753.

National Energy Technology Laboratory (NETL) 2010: Carbon Dioxide Enhanced Oil Recovery (2010), report: http://www.netl.doe.gov/technologies/oil-gas/publications/EP/small_CO 2_eor_primer.pdf.

NORSOK 2004: Standard D-010 - Well integrity in drilling and well operations, Rev 3. 2004. Oslo: Standards Norway. http://www.standard.no/en/sectors/Petroleum.

Orlic, B. and Benedictus, T. 2008: Some geomechanical aspects of well integrity, 4th Meeting of the IEA-GHG Wellbore Integrity Network, 18–19 March 2008, Paris, France.

Parker, M.E., Meyer, J.P., Meadows S.P. 2009. Carbon dioxide enhanced oil recovery injection operations technologies. *Energy Procedia* **1**: 3141-3148.

Randhol, P., Valencia, K., Taghipour, A., Akervoll, I., Carlsen, I.M., 2007. Ensuring well integrity in connection with CO_2 injection. SINTEF Petroleum Research, Report no. 31.6920.00/02/07, 27 December, 2007.

Ranganathan, P., van Hemert, P., Rudolph, E.S.J., & Zitha, P.Z.J. 2011. Numerical modeling of CO_2 mineralisation during storage in deep saline aquifers. *Energy Procedia*, **4**: 4538-4545.

Rochelle, C.A. and Milodowski, A.E. 2013. Carbonation of borehole seals: comparing evidence from short-term laboratory experiments and long-term natural analogues. *Applied Geochemistry* **30:** 161-177.

Sato, K., Mito, S., Horie, T., Oukuma, H., Saito, H., Watenabe, J. & Yoshimura, T. 2011. Monitoring and simulation studies for assessing macro- and meso-scale migration of CO_2 sequestered in an onshore aquifer: experiences from the Nagaoka pilot site, Japan. *International Journal of Greenhouse Gas Control*, **5**: 125-137.

Syed T. and Cutler T. 2010: Well integrity technical and regulatory considerations for CO_2 injection wells. SPE 125839.

Taoa,Q., Bryant S.L. & Meckel, T. 2013. Leakage fingerprints during storage: modeling above-zone measurements of pressure and temperature. *Energy Procedia* **37**: 4310 – 4316.

Zhang, W., Li, Y., Xu, T., Cheng, H., Zheng, Y. & Xiong, P. 2009. Long-term variations of CO_2 trapped in different mechanisms in deep saline formations: A case study of the Songliao Basin, China. *International Journal of Greenhouse Gas Control* **3**(2): 161-168.

Xue, Z., Tanase, D. & Watanabe, J. 2006, Estimation of CO2 saturation from time-lapse CO_2 well logging in an onshore aquifer, Nagaoka, Japan, *Exploration Geophysics* **37**: 19-29.