CO_2 SITE CLOSURE ASSESSMENT RESEARCH

CO_2CARE

The EU project CO_2CARE...

CO_2CARE has supported the large-scale implementation of CO_2 Capture and Storage (CCS) technology by addressing the research requirements of a specific part of the chain: **CO_2 storage site abandonment**.

To guarantee the safe and long-term storage of CO_2, three main requirements or 'high-level' criteria, must be demonstrated*:

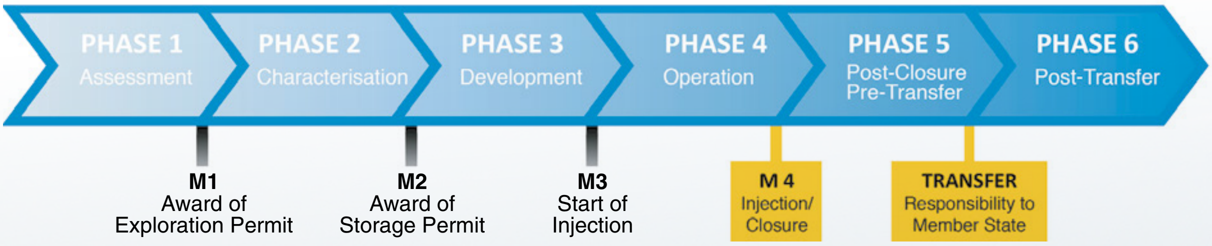
High level criteria

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

CO_2CARE has identified and delivered technologies and procedures to guarantee that these criteria can be met, thus ensuring the post-closure safety and long-term stability of storage sites.

CO_2CARE within a bigger picture . . .

CO_2 Storage Life Cycle can be broken down into phases and milestones*



CO_2CARE's scope covers phases 5 and 6 after the end of CO_2 injection. Ultimately, CO_2CARE has formulated robust procedures for site abandonment that will ensure long-term integrity of the storage complex.

CO_2CARE research has drawn from experiences at real European CO_2 storage sites, focussing particularly on the industrial-scale injection operation at Sleipner in the North Sea and the pilot-scale sites K12-B, offshore of the Netherlands, and Ketzin in Germany. In addition we are including best practice experience from the Rousse full-chain injection project in France, the long-standing research injection projects at Nagaoka in Japan, Otway in Australia and the new Wallula project in the United States. Thus we gain insights into storage issues from an unrivalled range of storage site geology and geographical setting, and from sites in the planning, operational and post-closure phases.

This brochure is laid out as two parallel themes. The main 'white' column summarises findings on the three high-level site abandonment criteria (No Leakage, Predicted and Observed Performance and Long-term Stability) together with Risk Management. The secondary 'blue' column summarises our main sites and provides some samples of results from our research into well abandonment and reservoir management issues.

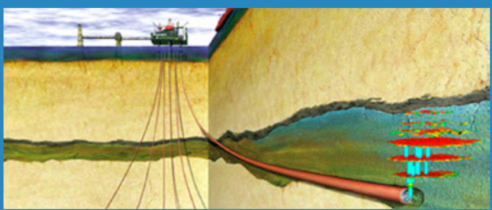
(*) *Source: EC Guidance Document 3 'Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide'*

CO_2CARE is grateful for the funding from the European Commission under the FP7 and from its industrial partners RWE, Statoil, Shell, Total, Vattenfall, and Veolia Environment.

Sleipner

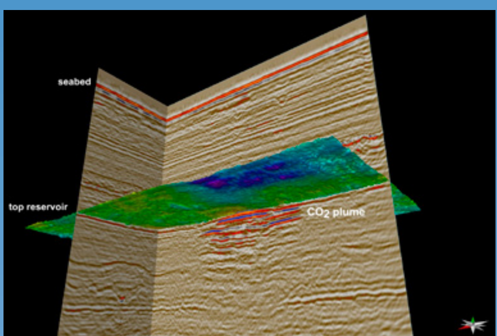
The Sleipner project, operated by Statoil and partners in the Norwegian North Sea, is the world's longest running CO_2 injection operation, and has now stored more than 14 million tonnes of CO_2 in a saline aquifer some 800 m beneath the seabed.

Photograph of the Sleipner platform in the North Sea.



Cartoon of the Sleipner CO_2 storage operation, showing the deviated injection wellbore and the CO_2 plume accumulating in the storage reservoir.

Sleipner is being intensively monitored with a number of geophysical tools including 3D time-lapse seismic which has provided dramatic images of the progressive development of the CO_2 plume in the storage aquifer. Interpretation and analysis of the time-lapse datasets give detailed insights into flow processes in the reservoir as the plume grows and also show no evidence of CO_2 leakage from the reservoir.

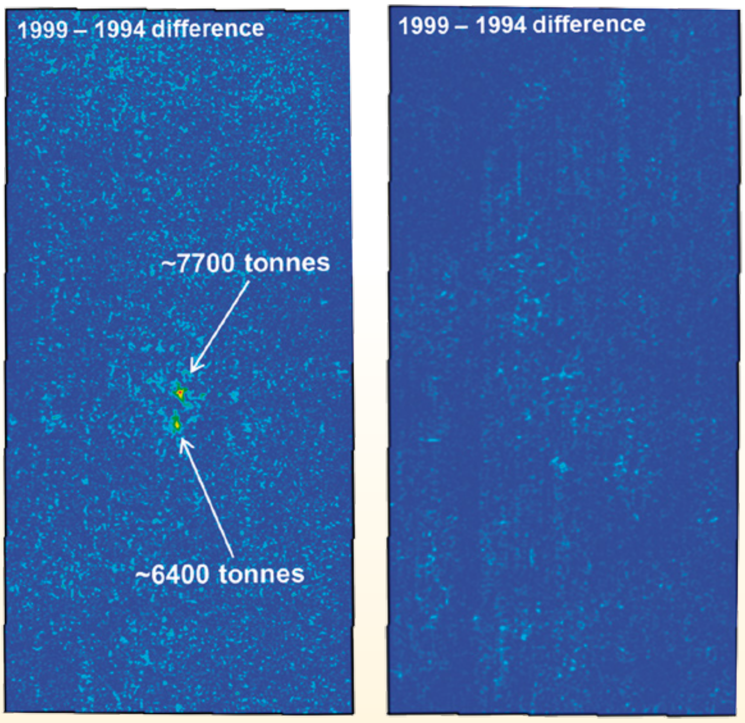


3D time-lapse seismic image at Sleipner from 2006, after 10 years of injection. Image shows two intersecting vertical seismic sections, the mapped top reservoir surface viewed from below and very bright reflections corresponding to the CO_2 trapped within the reservoir.

No detectable leakage

A key part of the regulations for site transfer is for the site Operator to demonstrate an absence of detectable leakage. During site characterization (Phase 2 of a storage project), the reservoir caprock will be shown to have satisfactory sealing qualities with no permeable faults or other structures. For this purpose baseline geophysical surveys are acquired to establish pre-injection images of the geological overburden, and laboratory tests on the mechanical and hydraulic properties of reservoir and overburden rocks are performed.

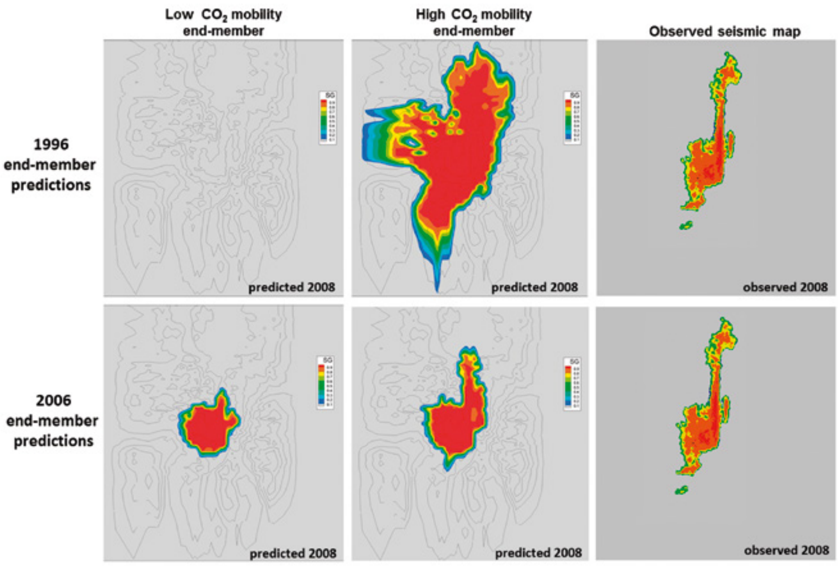
Repeated acquisition of the geophysical data during site operation and after closure (Phases 4 and 5) allows detection of CO_2 leakages by analysing differences between the baseline and repeat surveys. Leakage detection by time-lapse 3D seismics is particularly sensitive offshore. CO_2CARE work at Sleipner shows that accumulations of CO_2 at the top of the reservoir with masses of around 7000 tonnes can easily be imaged, with a 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.



Repeated seismic surveys at Sleipner show that the CO_2 accumulates at several levels within the Utsira Sand. Maps of seismic changes between the baseline survey in 1994 and the first repeat survey in 1999 show two small accumulations of CO_2 at the top of the reservoir (left) but no systematic changes in the overburden (right).

Predicted and observed performance

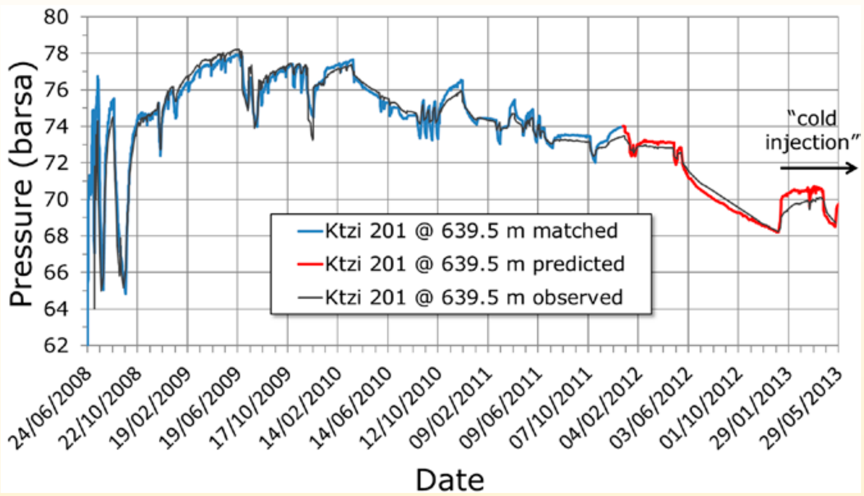
It is important for the Operator to demonstrate that they understand storage processes at the site, and that predictions for future behaviour will be reliable. One way to do this is to show agreement or 'conformance' between predictive reservoir models and monitoring observations. CO_2CARE carried out a very detailed study of predictive modelling and time-lapse seismic observations at Sleipner to assess modelling accuracy and how this improved with time as more monitoring information became available. It is clear that at the start of injection in 1996 a very wide range of predictive outcomes was possible, but by 2006 uncertainty had reduced dramatically.



Maps of the topmost CO_2 layer in the Sleipner plume, showing alternative distributions of CO_2 predicted for 2008 and the corresponding 2008 seismic observation.

It is also clear that even by 2006, perfect conformance is very difficult to achieve, due to necessary simplifications and uncertainties in the reservoir models and imperfect resolution of the monitoring data. Nevertheless, the major reduction in uncertainty as more monitoring data has been acquired indicates that storage processes at Sleipner are well understood.

At Ketzin, a key determinant of storage performance is reservoir pressure and a comprehensive programme of down-hole pressure monitoring has been carried out.



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

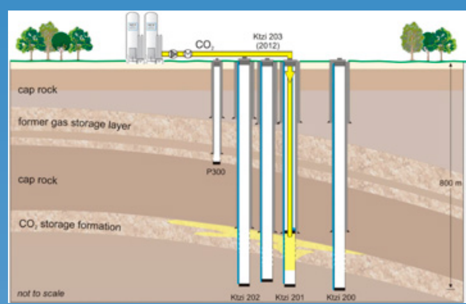
Modelled pressures were history-matched to observed readings from the start of injection in 2008 to about the end of 2011. Satisfactory conformance was obtained with good matching of both pressure increases following injection start-ups and pressure declines following injection cessations. The preferred reservoir model was then run forward in time to predict pressure evolution through to mid-2013. Comparison with measured results shows a good fit and emphasizes the predictive reliability of the current reservoir model.

Ketzin

The Ketzin pilot site is located near Berlin in Germany. Until 2000, seasonal underground storage of natural gas took place at this location close to the town of Ketzin/Havel. The knowledge gained during this storage operation was the basis for the development of the pilot site for research into geological CO_2 storage. From 2004, the GFZ German Research Centre for Geosciences, together with German and international partners, has been developing the pilot site. The infrastructure at Ketzin consists of five wells (one combined injector/observer, four pure monitoring wells), an injection facility, a variety of monitoring technologies permanently installed or frequently applied in field campaigns, and a visitor centre for knowledge dissemination activities.

View of the Ketzin pilot injection site, showing the injection well.

Injection took place from June 2008 to August 2013 using sandstone layers of the Triassic Stuttgart Formation at 630 m – 650 m depth as the storage reservoir. In total 67271 tons of CO_2 have been injected safely and reliably.



Simplified sketch of the Ketzin anticline including the wells.

Time-lapse seismics have been acquired and also permanently deployed tools such as electrodes for resistivity tomography, pressure sensors, fibre optic cables for temperature and pressure monitoring, and a down-hole seismic receiver array have been installed. No CO_2 migration out of the storage formation has been observed by the intensive monitoring programme. The CO_2 injection has now been completed, but post-injection activities are planned, with further monitoring, field campaigns, step-wise well abandonment and final site closure in 2017.

K12-B

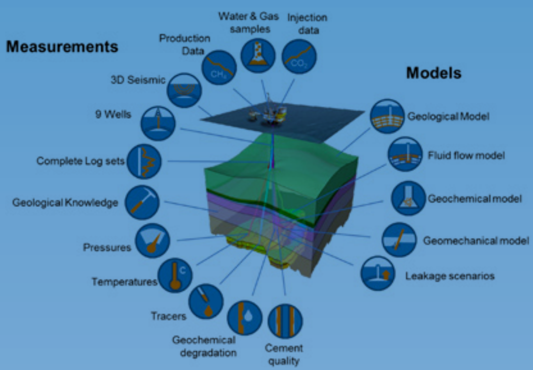
The K12-B site, operated by GDF SUEZ E&P Nederland B.V., is a producing gas field at 87% recovery (01/07/2013) and 52 bar reservoir pressure in the main compartment where CO_2 is currently being re-injected. The field is located in the Dutch sector of the North Sea, located about 150 km north-west of Amsterdam. The top of the reservoir lies at ~3800m depth below sea bottom and is overlain by some 500 m of sealing Zechstein salt layers, which make it a potentially optimal CO_2 storage candidate.

The K12-B platform in the Dutch North Sea.

The storage operation is performed under the gas production licence. CO_2 comprises 13% of the produced gas and since 2004 has been re-injected into the reservoir, where it had been contained effectively for millions of years before production started in 1985.

K12-B serves as a pilot site to investigate the behaviour of injected CO_2 in the reservoir and to enhance the gas recovery rate. The total amount of CO_2 re-injected by September 2013 was approaching 89 thousand tonnes. Since the start of injection no CO_2 leakage out of the storage complex has occurred as documented by various monitoring campaigns and it can be demonstrated that the wells penetrating K12-B are seal-tight.

Extensive knowledge about the site behavior and safe long term containment of the injected CO_2 could be generated by a suite of measurements and model simulations.



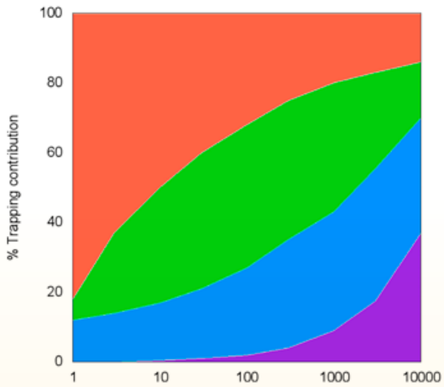
Measurements and models to ensure safe CO_2 injection operations at K12-B.

Long-term stability

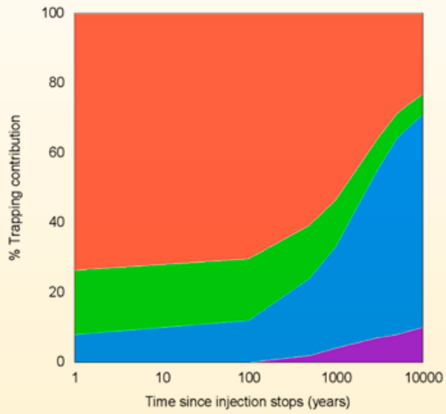
There are four mechanisms contributing to the stabilisation of a CO_2 storage site, acting on time-scales ranging from months to tens of thousands of years:

- Structural/stratigraphic trapping where buoyant CO_2 is trapped beneath an impermeable caprock
- Residual trapping where CO_2 is trapped in the pores of the reservoir by reservoir brine
- Dissolution, a longer-term process where CO_2 dissolves into the reservoir brine and thereby becomes gravitationally stable
- Mineral trapping where CO_2-rich aqueous solutions react with reservoir minerals to form new carbonate minerals thereby essentially converting the CO_2 into new rock.

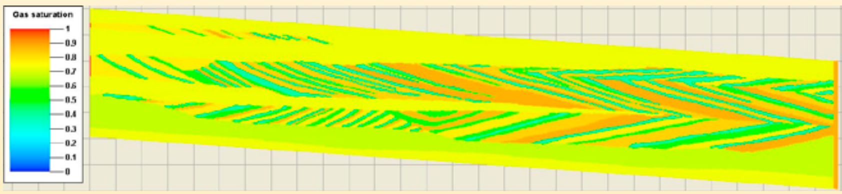
CO_2CARE has reviewed many storage site stabilisation scenarios and has established that the relative contribution and importance of these processes is very dependent on the storage site geology. It is clear that projections of long term trapping processes are very variable, especially concerning how the remaining amounts of buoyant CO_2 (which poses the greatest leakage risk) decrease with time.



Conceptual diagrams for trapping processes in different storage site situations. Red: Structural/stratigraphic trapping – potential leakage risk; Green: CO_2 residually trapped in pore space – very low leakage risk; Blue: CO_2 dissolved in brine – extremely low leakage risk; Purple: CO_2 trapped as mineral phase – no leakage risk.

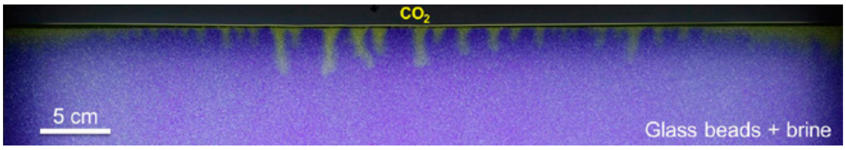


The assessment of long-term storage stability depends heavily on predictions performed with numerical tools. These show an impressive diversity with respect to the quantitative contributions of stabilisation mechanisms, and decisions made by the modeller about the tools used and the model input parameters (such as how much geological complexity to include) have a strong influence.



Detailed section (3m long x 0.5m high), through a numerical flow model of CO_2 injected into a cross-bedded sandstone. Note the fine-scale complexity of CO_2 distribution which influences the longer-term trapping mechanisms.

CO_2CARE has also carried out experimental work to establish the time-scale that these important processes work on. Dissolution is a key stabilisation process because it removes buoyant CO_2 from the system, the reservoir brine becoming denser as CO_2 dissolves in it. This is nicely demonstrated by a laboratory experiment with a Hele-Shaw cell comprising two plates of glass placed about 1 mm apart, with the intervening space filled with very small glass beads and brine. Gaseous CO_2 introduced at the top of the cell quickly dissolves in the uppermost layer of brine and reduces the brine pH, turning it yellow. Within a few minutes dense plumes of CO_2 saturated brine start to sink, demonstrating the onset of the stabilisation process. The time-scale for this process to start in real reservoirs might range from years to hundreds of years, depending on the site specific properties.



Photograph of the upper part of the Hele-Shaw cell after 90 minutes showing sinking plumes (yellow) of CO_2 saturated brine.

Risk management

In the context of closing and abandoning a CO_2 storage site, Risk Management includes all of the measures required to demonstrate its long-term safety. This is a pre-condition of transferring responsibility for the abandoned site from the Operator to the Competent Authority (CA) on a national level.

In order to provide a well-structured procedure for risk management within Project Life Cycle Phases 4 'Operation' and 5 'Post-Closure/Pre-Transfer', a set of Site-Closure Milestones (SCM) have been developed which are implemented within the different project phases. The milestones are closely linked to the requirements of the EC Storage Directive and describe key actions or key moments in time during site closure and transfer, which ensure that all conditions for transfer of responsibility are fulfilled when the set of milestones is passed.

The correspondence between SCMs and timeline is summarised below. It is important that the milestones must be passed one after another. For instance, the final evaluation of the absence of leakage must be undertaken after conformance of modelling and monitoring data has been established i.e. the behaviour of the storage complex is shown to be understood by the Operator.

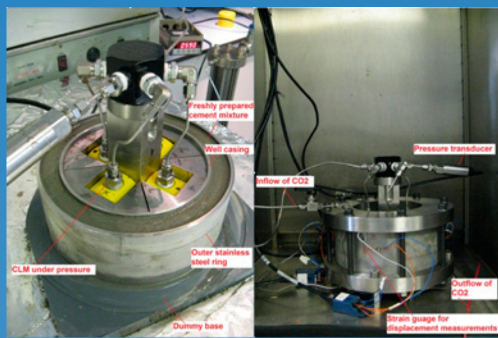
As these milestones are defined at a high level, they have to be complemented with more specific risk management and technical criteria that can be applied on an operational level. These additional criteria and the decision making methodology for CO_2 storage site abandonment are described and tested in two public reports, available on the CO_2CARE project website.

In one of these reports a decision-support system has been created using defined high-level (main requirements) and low-level technical criteria. The system provides instructions for operators on how to act in case of irregularities after site closure, with three risk levels — green, orange and red. This has been evaluated on the K12-B site in the context of reservoir pressure management.

Well abandonment

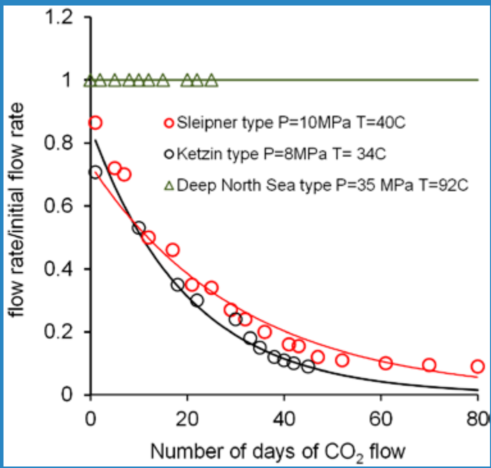
Knowledge of the wellbore geomechanical history is important in order to assess the wellbore flow conditions at the time of closure. This can be elucidated by means of laboratory experiments and numerical modelling.

CO_2CARE investigated the sealing characteristics of the injection well casing-cement interface for a range of CO_2 and brine fluxes under a range of test conditions. A custom designed and instrumented experiment was used to study the effect of reactive transport due to flow of CO_2 through the well infrastructure. Freshly prepared oilfield cement was set between a full scale well casing and a stainless steel ring simulating reservoir stiffness. Well pressure during casting the cement and later during the experiments representative of different field conditions was applied on the casing by a central loading mechanism made of four precision controlled hydraulic jacks. Initial permeability of the microannulus formed by stress relief on the cement was measured while flowing brine through the wellbore.



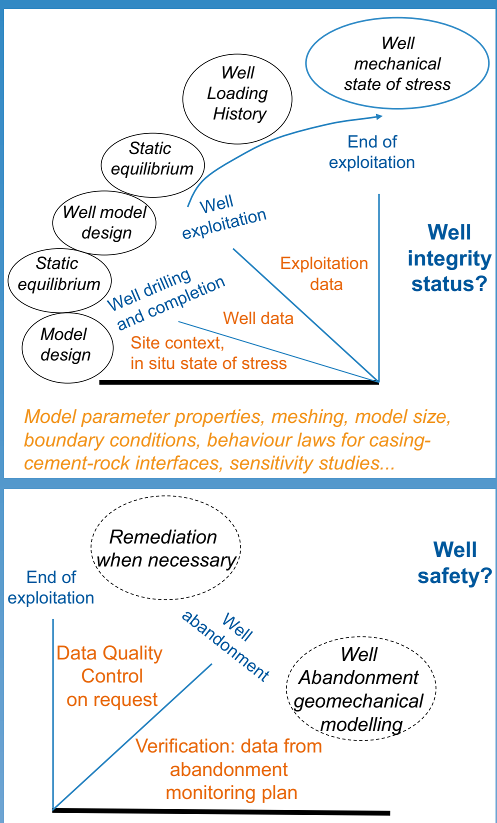
Details of the experimental set up for the study of near wellbore processes.

Long-term experiments of continuous CO_2 flow through the wellbore casing and cement interface were run under three different reservoir conditions: a) Sleipner type shallow reservoir conditions (well pressure: 10 MPa, T = 40°C, Salinity = 3.5%), b) Ketzin type shallow and high salinity reservoir conditions (well pressure: 8 MPa, T = 34°C, Salinity = 25%) and c) Deep, North Sea hydrocarbon reservoir type high temperature and high pressure conditions (well pressure: 35 MPa, T = 92°C, Salinity = 12.5%). Results under shallow depth and moderate temperature conditions have shown progressive reduction in the flow rate, attributed to the carbonation reactions between cement, stainless steel casing and CO_2, indicating a tendency to self-seal. On the other hand, no change in CO_2 flow rate (or permeability of the cement-casing interface) was observed at conditions representative of deep North Sea type high temperature and high pressure reservoirs, indicating the dominant effect of subsurface environmental conditions.



Observed behaviour of the cement casing interface during continuous flow of CO_2 under different reservoir temperature and pressure conditions.

A workflow to model wellbore mechanical behaviour at full-scale was developed in CO_2CARE, to assess well integrity prior to site closure. The aim is to identify any possible weakness zones at end of storage operation to be able to develop appropriate specific actions to secure the well abandonment.



Modelling workflows for well mechanical history (top) and abandonment design and completion (bottom).

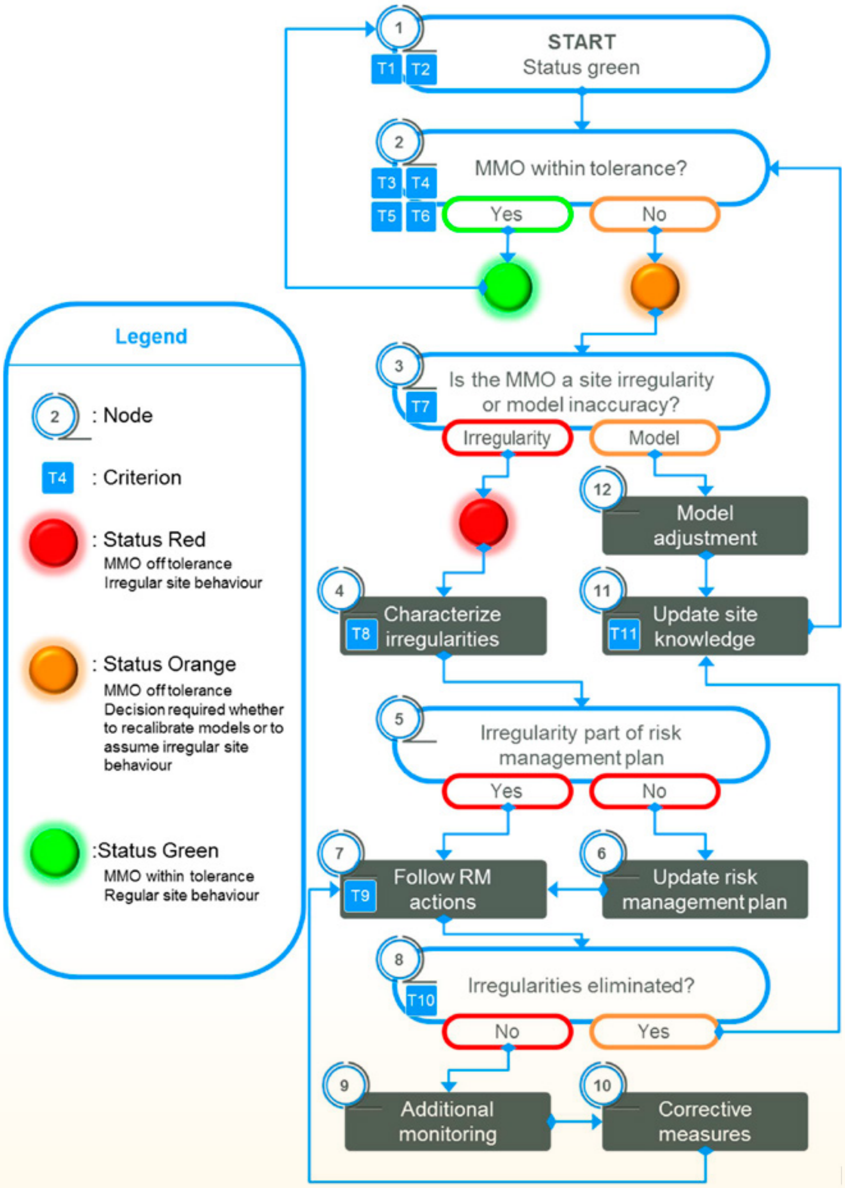
Site-Closure Milestone chart leading to the transfer of responsibility according to the EU Storage Directive.

Site-Closure Milestone (SCM)	Description	Sub-phase	Phase/ Moment
0	Specify models and monitoring selected for conformity check	Final Operation	Phase 4 (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	(Phase 5) 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 (e.g. for a minimum period of five years)		
9	Optional final update of risk management plan		
10	Evidence of absence of leakage presented to Competent Authority		
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	Optional verification of other 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

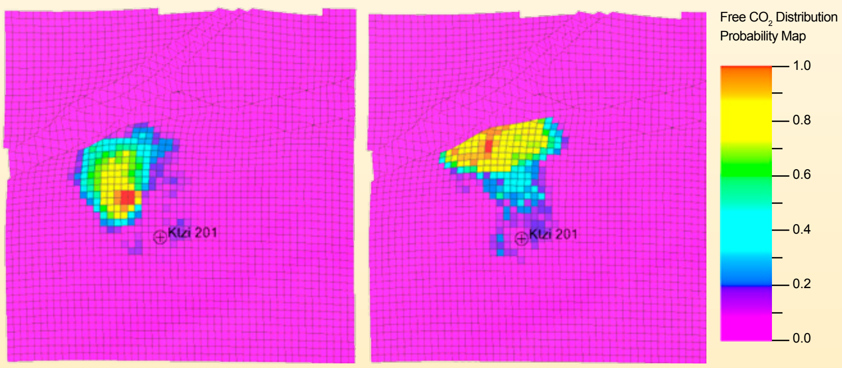
A quantitative risk assessment of the Ketzin site was carried out to assess CO_2 plume behaviour during the post-closure period, especially in the far-field region where the uncertainty in the reservoir heterogeneity is very high. Research used the most recent and history matched static model developed by GFZ as the basis for the risk assessment. In order to model these uncertainties, 25 statistical realisations of fluvial channel distributions, that represent some of the possible far-field heterogeneities, were created and implemented in the flow simulations.

The results obtained from the flow simulations were summarised in a free CO_2 distribution probability map, which describes the likely location of the CO_2 plume at a given time. Multiple probability maps were created for different post-closure time periods (up to 500 years) from the end of injection in August 2013. Examples of free CO_2 distribution probability maps at the top layer of the reservoir for 20 and 500 years after the end of injection are illustrated.

Such maps are useful to establish possible areas for monitoring and risk management activities during the post-closure period.



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; note that the Storage Directive exclusively refers to 'significant irregularities' instead of 'irregularities'.



Free CO_2 distribution probability maps (area 5 km by 5 km) in the top layer of the reservoir at Ketzin, showing the most likely far-field plume behaviour in year 2033 (left) and year 2513 (right).

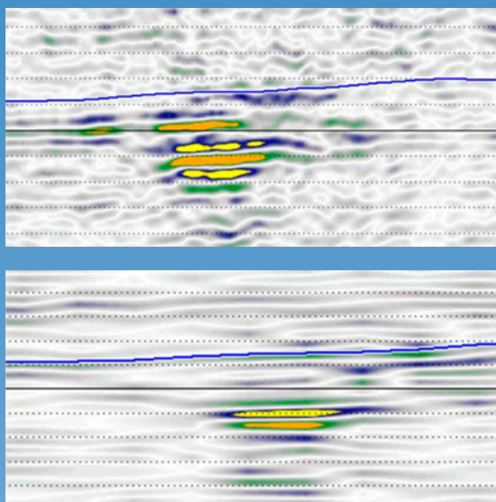
Numerical models based on this workflow can incorporate a wide range of effects including geomechanical and geochemical processes. Appropriate model parameters have to be evaluated from field or laboratory measurements, key ones being the evaluation of initial *in situ* stresses prior to well drilling and constitutive laws of the different materials rock, cement and casing at interfaces.

In scenarios focussing on pressure variations and assuming a good well cementing, results of the full-scale wellbore modelling show that materials remain below their damage/failure envelope, indicating that significant mechanical degradation of the wellbore during storage operations is unlikely.

Reservoir management

Depending on storage site characteristics, tracking of the plume in the storage reservoir may be a key post-injection monitoring requirement. Time-lapse 3D seismic reflection data provide full spatial coverage of the reservoir but it is important to minimise monitoring costs at all times, particularly in the post-injection phase as the site starts to stabilise.

Pilot site monitoring data, such as those acquired at Ketzin, show that quite small quantities of CO_2 can be detected, even when using sparse, cost efficient acquisition geometries. The real seismic data have shown that 22 000 tonnes of CO_2 can clearly be imaged. Seismic modelling indicates that a similar amount can be satisfactorily imaged using a much less expensive survey specification with only 10% of the number of seismic source points.



Seismic imaging of 22 000 tonnes of CO_2 in the reservoir at Ketzin. Image from the real 3D time-lapse data (top) and modelled image from sparse seismic data using strongly reduced acquisition parameters (bottom).

To sum up, CO_2CARE has carried out three years' research into some of the fundamental issues surrounding CO_2 storage site closure and abandonment.

The research has centred on two main scientific and engineering research topics: wellbore integrity and abandonment and reservoir management.

In developing procedures for safe and effective well abandonment we have compiled a major review of global well abandonment procedures and performance. We have carried out geomechanical and geochemical laboratory experiments and numerical modelling studies to evaluate post-injection and long-term processes at the wellbore. We have also developed monitoring techniques for rapid identification of leakage around a wellbore.

In reservoir management we have researched into processes crucial to long-term storage integrity such as capillary trapping, dissolution and geochemical trapping. Again numerical models have been supported by innovative laboratory experiments, run on time-scales from a few hours to several years. We have carried out studies into predicted and observed conformance in terms of plume migration at Sleipner and reservoir pressure evolution at Ketzin. We have field-tested innovative and cost-effective reservoir monitoring methodologies, such as cross-well resistivity and seismic interferometry, and established leakage detection thresholds for 3D time-lapse seismics. We have also researched into remediation measures such as pressure seals and injected flow retardant gels.

Key elements of CO_2CARE have been the cross-cutting themes enshrined in the EU Directive requirements for site abandonment: no detected leakage, conformance between predicted and observed behaviour, and long-term stabilisation.

In order to test these concepts we ran a detailed exercise examining hypothetical site closure cases for Sleipner, K12-B and Ketzin. For each site we developed a detailed 'dry-run' document setting out the technical case for closure. A stakeholder workshop, including national regulators and the industry, was held to review and assess the documents. Feedback from the workshop has contributed to best practice for site closure.

Finally, also included in the dry-runs, we have developed a comprehensive risk management framework for closure and abandonment. This includes procedures and criteria for site abandonment, decision-aid tools for transfer of responsibility (a traffic light system) and recommendations for post-closure monitoring strategies.

	Site (*offshore)	Operator/ CO_2CARE partner	Current status	Injected CO_2	Depth m
Europe	Sleipner*	Statoil	injection	14.5 Mt	800 - 1000
	K12-B*	GDF Suez (TNO)	injection	88 500 t	3800
	Ketzin	VGS/GFZ	post-injection monitoring	67 271 t	650
	Montmiral natural CO_2 reservoir	AirLiquide	temporarily inactive	-	2400
	Rousse	TOTAL	post-injection monitoring	51 000 t	4200
USA	Wallula	Battelle-PNNL	post-injection monitoring	1000 t	850
	Frio	Univ. Texas at Austin	post-injection monitoring	1600 t	1500
Asia-Pacific	Nagaoka	RITE	post-injection monitoring	10 400 t	1100
	Otway	CO_2CRC	injection	66 100 t	1500

CO_2CARE Timeline

- **Jan 2011** — **CO_2CARE launch**; Kick-off meeting at GFZ, Postdam, Germany
- **June 2011** — General Assembly (GA), Potsdam, Germany
- **March 2012** — Annual scientific conference and GA, London, UK
- **Aug 2012** — CO_2CARE Midterm Review, Brussels, Belgium
- **Sept 2012** — Kick-off meeting of Best Practice and Regulatory compliance
- **Apr 2013** — Annual scientific conference
- **May 2013** — Review of abandonment plan criteria completed
- **July 2013** — Regulators workshop for Best Practice
- **Nov 2013** — Best Practice Guidelines and summary brochure
- **Nov 2013** — Annual scientific conference
- **Dec 2013** — Report on remediation techniques for site abandonment; **End of the project**

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November 2013 - NERC-BGS (Debbie Rayner) - Science Services