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Key messages from active CO_2 storage sites

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Abstract

An extensive programme of modelling, monitoring and verification activities was deployed at a set of active storage sites worldwide including Sleipner, In Salah, Ketzin, Weyburn, K12-B and Snøhvit (EU CO2ReMoVe project). All investigated storage sites were well managed and did not have a negative impact on humans or the environment. Time-lapse seismic and pressure monitoring are key in verifying the deep subsurface performance of the storage sites. Evidence gathered during the site characterisation and operational phases is key to handover responsibility of the storage site to governmental authorities after injection has definitely ceased, which is the focus of the follow-up EU project CO2CARE.

Keywords: CO_2 storage, operational and post-operational performance, monitoring; verification

1. Introduction

As part of the EU CO2ReMoVe project an extensive 6 year programme of modelling, monitoring and verification activities was executed for a unique set of active storage sites worldwide including Sleipner (offshore Norway), In Salah (Algeria), Ketzin (Germany), Weyburn (Canada), K12-B (offshore

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Netherlands) and Snøhvit (offshore Norway). The project, which ended in February 2012, aimed to provide tools for conducting safe and effective CO_2 storage based on real experience. The researchers in the project focussed on testing these tools in real CO_2 storage projects. CO2ReMoVe developed, combined and tested tools for performance prediction, risk assessment and monitoring starting from the premise that CO_2 storage has inherent uncertainties which need to be reduced. A detailed summary of the results can be found in [1].

Evidence gathered during the pre-operational and operational phases is key to handover responsibility of the storage site to governmental authorities after injection has ceased, which is the focus of the follow-up 3 year EU project CO2CARE [2] scheduled to end in December 2013.

The results presented here are of importance for the technical implementation of modelling and monitoring activities at storage sites, the permitting procedures for starting and closing site operations and for the future development of an industrial standard for CO_2 storage, e.g. an ISO CCS standard. The findings are relevant for a broad group of stakeholders from industry, government and the public at large.

This paper provides a concise summary of the key messages from the modelling, monitoring and verification research programme centred around a global portfolio of active storage sites (Table 1) and provides an outlook on an approach for necessary actions to transfer responsibility for a storage site to a state authority. The key messages are directed in particular to safety and effectiveness, practicability and standardisation of underground CO_2 storage.

Table 1. Active CO_2 storage sites studied in CO2ReMoVe; * site is also in investigation in CO2CARE

Site name	Reservoir	Depth top (m)	Annual injection estimate (Mt)	Location
In Salah	Sandstone (saline aquifer)	~1,950	0.6	Algeria
Sleipner*	Sand (saline aquifer)	~800	0.9	Norwegian Sea
Snøhvit	Sandstone (saline aquifer)	~2,700	0.4	Barents Sea
Ketzin*	Sandstone (saline aquifer)	~630	0.01	Germany
K12-B*	Sandstone (depleted gas reservoir)	~3,800	0.01	North Sea
Weyburn	Limestone/dolostone (depleted oil reservoir)	~1,370	2.4	Canada

2. Operational performance

2.1. Plume migration and containment

Results from CO2ReMoVe are showing that CO_2 can be stored safely and effectively and build confidence that the stored CO_2 will continue to be safely contained in future. At Sleipner 16 years of CO_2 injection, monitoring and performance assessment indicates that CO_2 has been contained within the storage reservoir with negligible pressure increase. Multiple repeat 3D seismic surveys give high resolution imaging of the reservoir and provide a detailed picture of plume development (Fig. 1). Combined with a robust geological characterisation of the overburden the seismic datasets show convincing evidence that no CO_2 has migrated from the reservoir. At Snøhvit downhole monitoring and 4D seismic confirm retention of CO_2 in the reservoir albeit with a higher than expected pressure response (Figs. 1 & 2).

The extensive monitoring and verification programme at In Salah has shown that the CO_2 is currently contained within the storage complex. Satellite interferometry has detected mm-scale surface displacements associated with subsurface pressure changes and these have been confirmed by 3D seismic information (Fig. 1). Extensive shallow monitoring including soil gas and well fluid sampling, surface flux, shallow aquifer and ecosystem monitoring have noted no anomalies with the exception of a very small short-term emission from an old (1980s) appraisal well. This has now been fully remediated.

At Ketzin a very comprehensive deep- and shallow-focussed research monitoring programme has tested a large number of tools and performance assessment methods. Again, no migration out of the storage complex has been detected.

At Weyburn, 4D seismic has proved its worth not just for imaging plume development in the reservoir but also, via accurate measurement of time-shifts at top reservoir level, for providing a robust upper bound on the maximum amounts of CO_2 that could have migrated into the overburden [3]. Shallow and atmospheric monitoring systems have also been deployed, building on earlier surveys acquired from 2001 to 2005. Results confirm that no CO_2 from the oil reservoir has been detected at surface which refutes widely-publicised leakage claims made in 2011 [4].

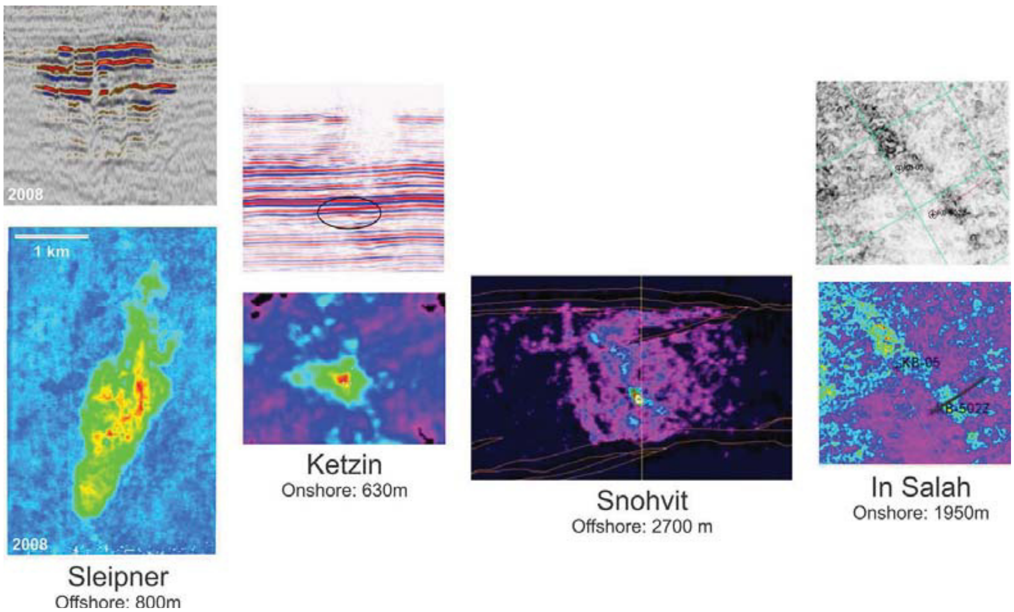

Fig. 1. Key deep-focused seismic monitoring tool: Results from 3D time-lapse seismics at 4 storage locations

2.2. Uncertainty

Baseline and repeat seismic surveys provide understanding of the reservoir heterogeneity and resulting plume migration in the reservoir. These surveys are particularly instructive for aquifer storage which is generally marked by a low level of a priori reservoir knowledge such as Sleipner, Snøhvit and Ketzin. The importance of having a series of possible reservoir descriptions covering this initial uncertainty instead of a single reservoir description has been clearly demonstrated in ensuing history-matches.

Uncertainty about site performance arises from a combination of geological variability, incomplete information, variable in observational quality, imperfect understanding of processes and subjectivity in expert judgement. However, uncertainty does not equate with unsafe or ineffective CO_2 storage, nor necessarily represent a risk. Risks can be managed by identifying uncertainties that might threaten good performance and adopting suitable avoidance or mitigation strategies for such risks. Uncertainties and their implications for risk can be determined by expert judgement informed by a range of information, including monitoring data, past experience and outputs from different performance assessment tools. Throughout a project it is essential to maintain a dialogue between stakeholders to ensure consistent understanding of uncertainty and its implications for risk, and to agree on the approach to risk management. To meet these goals, a structured, documented and auditable approach for identifying and assessing risks was developed [5, 6]. The approach uses a decision tree, which is implemented in a software tool called CO2TESLA-Excel [6]. The decision tree is used to record and propagate judgements about the various kinds of evidence for the future behaviour of a storage site. This evidence includes direct observations, such as those made in a monitoring programme, and outputs from a wide range of modelling tools, such as reservoir simulators, systems models and geomechanical models. These models can be managed simultaneously through integrated performance assessment workflows [7, 8, 10, 11, 12, 14].

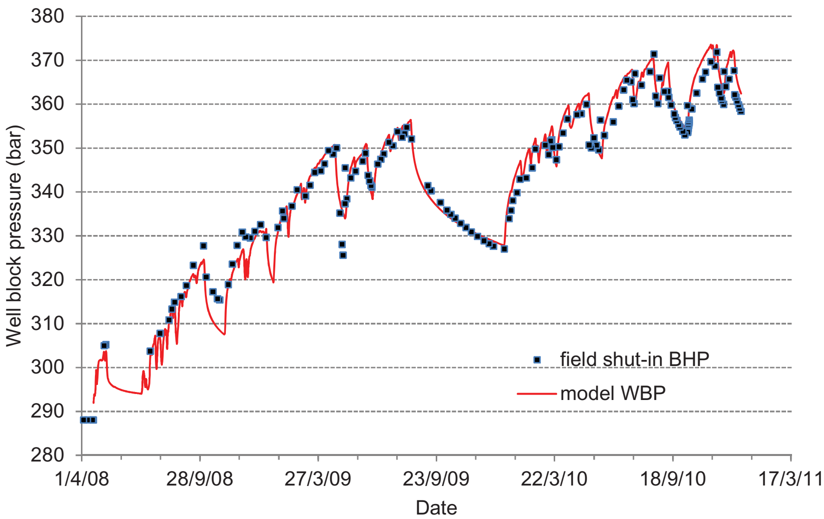

Fig. 2. Key deep-focused pressure monitoring tool: Results for Bottom Hole Pressure at Snøhvit [7]

2.3. Monitoring and verification

Gathering of robust monitoring baseline datasets is essential for effective performance verification. The Weyburn project has proved the value of baseline measurements in helping to refute leakage claims. For shallow-focussed monitoring in particular, comprehensive baselines are crucial for capturing the full range of natural variation. This task can be significant, and future measurement exceptions may be incorrectly interpreted as leakage if the baseline is not measured over a sufficiently long period of time.

The verification activities in CO2ReMoVe show that even when CO_2 is stored safely and effectively monitored site performance always deviates to a variable degree from predictions [10, 11, 14]. A key requirement is to establish what constitutes an acceptable deviation and to demonstrate convergence of prediction and observations with time. At Sleipner performance predictions are likely to be robust despite minor mismatches of prediction and measurement This is because both the basic processes and the nature of the uncertainties are understood [6]. Operating in the fourth year of CO_2 injection, Ketzin is effectively early in its injection history but takes advantage of the on-going phase of data integration to reduce uncertainties in the understanding of the CO_2 plume propagation in a complex saline aquifer. Nevertheless the scope for significant deviations is limited and the monitoring data are proving effective at restricting uncertainty. It is essential that a monitoring and site management plan is flexible over time in order to take into account new insights on the storage complex that are likely to emerge as more information becomes available. For example, at In Salah the 3D seismic acquisition programme was guided by new information from satellite interferometry which also suggested the addition of shallow aquifer monitoring rather than just surface sampling. These experiences confirm that site management plans must be flexible for updating if necessary.

Emissions measurement (as is required by the ETS) is very challenging as a combination of point and areal measurements is likely to be needed. CO2ReMoVe has developed possible systems for both offshore and onshore scenarios. Even so, direct quantification of subsurface leakage or seepage is likely to be impossible and selected measurements might need to be integrated with leakage simulations to provide quantitative estimates.

3. Post-operational performance

Evidence gathered during the pre-operational and operational phases is key to transferring responsibility of the storage site to governmental authorities after injection has ceased. This establishes the central research theme of the EU project CO2CARE. The European Commission has defined three main criteria for transferring the responsibility for the storage site to the state. These aim to assure the long-term safety and effectiveness of the storage site, and are briefly discussed below.

3.1. Absence of any detectable leakage

As discussed in Section 2.1, with the exception of the small event at an old appraisal well which was successfully remediated, no leakage was detected at the storage sites discussed above. Any irregularities related to containment failure need to be monitored so that adequate corrective measures can be taken.

CO2CARE advocates the following requirements for verifying the absence of leakage:

- Pressure evolution in conformance with the reservoir models;
- No detectable indication of leakage by monitoring measures applied within the scope of the monitoring plan;
- Evidence for the location of the CO_2 plume within the storage reservoir by periodic seismic surveys or other appropriate measures;
- Verified well integrity (mechanical deformation, degradation of cement or casing, bonding quality).

3.2. Conformity of actual behaviour of the injected CO_2 with modelled behaviour

Striving for a perfect fit of modelled and monitored behaviour is not realistic as verification activities in CO2ReMoVe show that monitored site performance almost always deviates from initial predictions. This is due to a number of inherent uncertainties: the full geological complexity is not known; the dynamic model cannot capture the full resolution of the (imperfectly understood) static model; complex fluid flow properties are not fully understood; the monitoring tools have limited resolution and inversions of the monitoring data can be non-unique. The principal question is to what extent model and measurement may deviate.

Thus, establishing that CO_2 behaviour “conforms to predictions”, as required by the EC CO_2 Storage Directive, involves: (1) recognizing at the start of a project that predictions will be uncertain; (2) predicting a range of possible future behaviours, taking into account uncertainties; (3) establishing that all behaviours within this range are acceptable; and (4) showing that actual behaviour lies within this range.

3.3. Storage site is evolving towards a situation of long-term stability

In CO2ReMoVe the long-term evolution of the In Salah storage site was investigated using a combination of various kinds of reservoir simulations [10, 11, 12, 13, 14] and system-scale models [9]. The outcome was that none of the simulations called into question the overall long-term security of CO_2 storage at this site [6].

Monitoring during the operational phase may be used to further constrain predictions of long-term site behaviour. Building on the performance assessment workflow in CO2ReMoVe [10], the EU CO2CARE project suggested the following requirements:

- Pressure evolution is matching model prediction;
- Plume movement is matching model predictions;
- Optional verification of other parameters/features related to the storage concept.

4. Practicability and standardisation

Pressure and plume envelope verification is central to monitoring and verification for industrial-scale sites. Different monitored parameters can be used to verify performance depending on site characteristics. At Sleipner plume migration and overburden imaging are the most important parameters. At In Salah reservoir pressure, microseismicity and surface displacements are key and at Snøhvit pressure and plume migration were the central monitored parameters. As discussed above, pre-injection baseline surveys, especially in the near surface, are also essential to provide the basis for emissions measurement should this ever be necessary. At Weyburn, an onshore enhanced oil recovery site, surface monitoring for leakage is also important for public acceptance purposes.

These requirements commonly mean that a rather limited portfolio of monitoring tools is needed to provide assurance at a given storage site. At Sleipner time-lapse seismic monitoring and seabed imaging established the central elements of the monitoring portfolio and proved that a robust site characterisation has been performed. Assurance of CO_2 storage at Snøhvit was provided by time-lapse seismic and continuous pressure monitoring. Additional monitoring techniques must be put in place if some irregularity is being observed or suspected.

The costs of deploying different technologies can be quantified, but is very site specific. Monitoring frequency is also a key issue. At Sleipner, expensive 3D time-lapse seismic has been deployed at roughly two year intervals, but these have generally been for research or other purposes. A far lower repeat frequency would likely be required purely for the purpose of storage assurance. It is also the case that low-cost technologies can be very effective. At In Salah, satellite measurements of mm-scale surface displacements in response to CO_2 injection were coupled and inverted with geomechanical models to assess the spatial extent of the subsurface pressure front.

The CO2ReMoVe project has investigated and tested a much wider range of monitoring techniques than a commercial CO_2 storage project, operating normally, is ever likely to use. Although not all techniques will be used widely at the industrial scale, pilot-scale monitoring has two important benefits: the reliability of our predictive models has been tested to a high level of detail and the wide range of monitoring techniques that have been tested allows a high degree of flexibility to respond to unexpected circumstances during site operation. Testing and validating a variety of alternative tools in early CO_2 storage projects will also allow for effective cost optimisation when CCS is rolled out on an industrial scale.

The question arises as to whether a set of standard procedures and performance acceptance criteria can be developed. Although CO_2 storage relies heavily on technology and practice in the oil and gas industry, CO_2 storage also poses significant new challenges. CO_2 storage projects like In Salah, or Weyburn require the integration of a wider range of datasets over a greater spatial extent compared to hydrocarbon developments; integration of reservoir and overburden data with potable aquifer, soil gas, microbiology and satellite data go well beyond normal practice in the oil and gas industry. Although the monitoring technologies can comprise existing standard oil field techniques and practices, specialist technologies and modelling of coupled processes are also needed as illustrated in [10].

CO2ReMoVe demonstrates that regulatory frameworks for CO_2 storage should not be technology-prescriptive. Geological storage sites are marked by a considerable variability in their characteristics from site to site. Technologies for monitoring stored CO_2 at one site may not work at all for others, so there cannot be a “one-size-fits-all” monitoring programme. In practice, two key deep-focussed monitoring techniques seem to stand out: down-hole pressure and temperature measurement, and time-lapse seismic imaging. These tools allow for the calibration and verification of reservoir pressure changes and also predictive simulations of CO_2 plume migration. As such, this combination can provide detailed information on processes in the storage reservoir and also give early warning of unexpected CO_2 behaviour: either unexpected migration within the Storage Complex or, more seriously, leakage out of the Storage Complex. The Sleipner, In Salah, Snøhvit, Ketzin and Weyburn projects all demonstrate in different ways that these two tools are very important for monitoring storage performance. On the other hand specific geological, logistical or surface conditions might preclude use of a specific preferred tool. In this case, suitable combinations of other tools might be acceptable through dialogue with regulators and other stakeholders to ensure common understanding and agreement of monitoring plans leading to a standard.

5. Conclusions

All of the investigated storage sites were satisfactorily managed and have not resulted in unacceptable impacts in terms of safety or to the environment. However, technologies for monitoring stored CO_2 at one site may not work at all for others, so there cannot be a "one-size-fits-all" monitoring programme. Time-lapse seismic and pressure monitoring appeared to be key in verifying the performance of the storage sites.

Simulation work focused on reservoir pressure and CO_2 saturation and explicitly evaluated multiple scenarios and uncertainties. This approach improved understanding of the sensitivities among performance metrics, leading to more robust conclusions about the effectiveness and safety of storage.

Inevitably predictions of the behaviour of stored CO_2 will be uncertain. Demonstrating that the behaviour of CO_2 conforms to predictions, as required by the EC Storage Directive, involves showing that observations lie within an envelope of predicted safe and effective behaviours.

Future standardization of CO_2 storage activities can thrive on oil and gas experience but must also consider specific characteristics of CO_2 storage including the larger extent of the spatial domain and application of specialist modelling and monitoring techniques.

Evidence gathered during the pre-operational and operational phases is key to transferring responsibility of the storage site to governmental authorities after injection has definitely ceased.

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