Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Geologic Storage of Carbon Dioxide with Monitoring and Verification

Volume 2

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Geologic Storage of Carbon Dioxide with Monitoring and Verification

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Volume 2

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2005

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First edition 2005

Library of Congress Cataloging in Publication Data
A catalog record is available from the Library of Congress.

British Library Cataloguing in Publication Data
A catalogue record is available from the British Library.

ISBN: 0-08-044570-5 (2 volume set)

Volume 1: Chapters 8, 9, 13, 14, 16, 17, 18, 24 and 32 were written with support of the U.S. Department of Energy under Contract No. DE-FC26-01NT41145. The Government reserves for itself and others acting on its behalf a royalty-free, non-exclusive, irrevocable, worldwide license for Governmental purposes to publish, distribute, translate, duplicate, exhibit and perform these copyrighted papers. EU co-funded work appears in chapters 19, 20, 21, 22, 23, 33, 34, 35, 36 and 37. Norwegian Research Council (Klimatek) co-funded work appears in chapters 1, 5, 7, 10, 12, 15 and 32.

Volume 2: The Storage Preface, Storage Integrity Preface, Monitoring and Verification Preface, Risk Assessment Preface and Chapters 1, 4, 6, 8, 13, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33 were written with support of the U.S. Department of Energy under Contract No. DE-FC26-01NT41145. The Government reserves for itself and others acting on its behalf a royalty-free, non-exclusive, irrevocable, worldwide license for Governmental purposes to publish, distribute, translate, duplicate, exhibit and perform these copyrighted papers. Norwegian Research Council (Klimatek) co-funded work appears in chapters 9, 15 and 16.

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Carbon Dioxide Capture for Storage in Deep Geologic Formations, Volume 2
D.C. Thomas and S.M. Benson (Eds.)

Chapter 34

KEY FINDINGS, TECHNOLOGY GAPS AND THE PATH FORWARD

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Options for large-scale geological storage of CO_2 emissions have proceeded from concept development and capacity inventories in the 1990s to systematic site characterization and strategies for injection, long-term monitoring and risk assessment in recent years. To date, the only purpose-built CO_2 storage facility is the 1 million tonne/year Sleipner–Utsira project in the Norwegian North Sea. Although the project is deemed successful, it is doubtful that numerous projects of the scale or considerably larger such projects will be permitted without extensive technical due diligence.

In the constellation of industry, academic and government programs addressing geological CO_2 storage, the role assumed by the CCP Storage Monitoring and Verification (SMV) program over 2000–2004 is unique. The risk-based approach adopted entailed identifying technical gaps and addressing them by leveraging the existing natural and industrial analog knowledge base and developing new R&D avenues. Whereas some projects were based on a specific asset or storage venue type, the applications developed are universally applicable. The present chapter outlines the key findings of the SMV program and identifies needs for further R&D needed to support pilots, demonstration and commercial projects.

The SMV program was comprised of some 30 projects organized along four technical areas.

1. “Integrity”—assessing the competence of natural and engineered systems to retain CO_2 over extended periods
2. “Optimization”—strategies for improving the efficiency and economics of CO_2 transportation and storage
3. “Monitoring”—identification of techniques suitable for tracking CO_2 movement within (performance) and outside (leakage or seepage) the injection target
4. “Risk Assessment”—development of concepts, protocols and methodologies to quantify probability and impact of CO_2 leakage from storage sites.

INTEGRITY

The SMV integrity studies included characterization of naturally charged CO_2 systems, a survey of the natural gas storage industry, evaluations of reservoir and cap rock property responses to CO_2 injection and the stability of well materials in the presence of carbonated water. Key findings are given below.

- The suitability of natural systems to retain CO_2 over extended periods of time is predictable using 3D structural and stratigraphic models combined with fluid migration history analysis.
- The basin to reservoir scale geohydrologic model and simulation of CO_2 storage in the Forties Field serves as a prototype for systematic assessment of prospective geological storage sites.
- A survey of the natural gas storage industry, comprising >600 facilities operated over 90 years in North America and Europe, documents few gas migration incidents and an excellent HSE record. Site selection, operation and leak detection, intervention and remediation techniques used by the gas storage are applicable to CO_2 storage.
- Assessments of rock response to CO_2 injection through core flood experiments, geomechanical models and geochemical/geomechanical simulations identify and begin to quantify risks for failure through fracturing and fault reactivation.

- Experiments demonstrate that well materials currently in use are subject to rapid degradation through carbonic acid attack, particularly in the case of flowing water.

The importance of integrated geological characterization of prospective CO_2 storage sites from the systems scale to the reservoir scale is highlighted by the SMV integrity studies. There is a particular need to obtain reservoir and cap rock samples for geomechanical and geochemical testing under CO_2-flooded reservoir conditions and matching of observed behavior using simulations. Further work with natural gas storage and EOR analogs will likely reveal additional details of geologic features and operational parameters necessary for appropriate selection and safe operation of CO_2 storage facilities. Well integrity issues are clearly becoming more of a concern than geological integrity issues. Development of new, resistant materials and sealants and modification of existing construction and completion protocols are essential. Novel technologies for rehabilitation of old wells and leakage detection and intervention are essential needs for CO_2 storage facility development in depleted oil and gas fields.

OPTIMIZATION

The SMV optimization studies sought to leverage industry experience of gas injection, identify operational parameters that ensure rapid and secure CO_2 immobilization and realize cost reduction opportunities in CO_2 capture, transportation and injection. Key findings include the following.

- A survey of the CO_2 EOR experience, centered on the Permian Basin for ~ 3 decades, shows that performance issues are mostly attributable to inadequate reservoir characterization. Leakage and other untoward incidents have not been reported (although monitoring for CO_2 leakage is not in widespread use). The development of acid gas (CO_2 and H_2S form gas processing) injection programs in North America and elsewhere demonstrates that more hazardous gases can be safely injected and stored given appropriate pre-injection characterization, well construction design and testing, controlled injection testing and long-term monitoring.
- Injection of CO_2 into depleted gas fields is promising as infrastructure is in place and gas containment is proven. Experiments and models demonstrate that CO_2 compatibility with remnant hydrocarbon gases is predictable and that, given the high compressibility of CO_2, storage capacity may approach five times that of the original hydrocarbon charge.
- Injection of CO_2 into saline formations comprises the largest volume opportunity for CO_2 storage although compared to oil and gas reservoirs, reservoir data and infrastructure are often lacking and economic offsets are unavailable. Nevertheless, well-planned saline formation CO_2 injection projects could minimize costs and maximize storage through efficient well placement and operating parameters. Two independent reservoir simulations that variously incorporated multiple water–CO_2 interaction phenomena (e.g. buoyant flow, solubility trapping, pore space capillary trapping and mineralization) show that injection at the base of the aquifer slows the progress of CO_2 migration to the top of the reservoir and contact with abandoned wells. A considerable proportion of the CO_2 is immobilized in the decadal timeframe and the vast majority in the millennial timeframe. Immobilization of CO_2 via mineralization is probably minor and effective over the 10,000 + year timeframe.
- The success of CO_2 injection into coal beds for the purpose of enhanced coal bed methane recovery (ECBM) and permanent CO_2 storage relies on appropriate coal characterization, production history (primary production and N_2 injection) and facility installation and operation.
- Opportunities to reduce CO_2 capture cost by injecting less than pure CO_2 streams ($\sim 5\%$ SO_x, NO_x) into aquifers or CO_2 EOR fields are unlikely to damage clastic reservoir or substantially affect oil production. The effects of such contaminants, particularly in the presence of water, on surface equipment (pipelines, compressors, etc.), however, is a concern.
- Costs associated with long distance pipeline transportation of CO_2 from the capture point to storage reservoir may determine the economic and technical feasibility of a CO_2 storage facility. New experimental and theoretical data on water solubility in CO_2 and predicted corrosion/erosion rates demonstrate that existing specifications for expensive alloy steels currently in place may be relaxed given some circumstances, particularly in offshore, northern water environments.

Early opportunities for geological CO_2 storage, particularly in regimes without carbon taxes or restrictions, will focus on settings with enhanced resource recovery potential. Existing enhanced recovery projects, particularly EOR are promising, but need more study related to storage security in more diverse reservoir/cap rock types (e.g. clastic as opposed to carbonates prevalent in the Permian Basin). Separation of CO_2 and other impurities during gas processing to meet pipeline specifications and its subsequent injection into saline aquifers would add a relatively small incremental cost. Credits might be obtained for associated SO_x and NO_x disposal. Accurate reservoir characterization and predictions of CO_2 behavior in the subsurface will, along with establishing best practices for facility operations and abandonment, ease the regulatory approval of CO_2 storage projects and ensure good performance and long-term safety. The poor geographic match between industrial CO_2 sources and suitable geologic sinks in many areas of the World will require new thinking on transportation systems. Adapting existing operation practices to extend the use of conventional materials such as carbon steel in pipelines and identifying alternative transportation schemes (e.g. shipping) will determine the technical and economic viability of many CO_2 capture and storage schemes.

MONITORING

The SMV monitoring program evaluated a broad range of existing and novel technologies that might be used to improve the cost effectiveness and safety of geological CO_2 storage. These technologies ranged from remote detection of injected CO_2 effects on the surface to direct detection near the surface to alternatives for subsurface imaging of CO_2 movement. Key findings are given below.

- Existing monitoring techniques vary widely in resolution and cost. Successful application depends on site-specific geologic and geographic features and required resolution level over time.
- The satellite-based InSAR technique may have the resolution necessary to detect ground movement from CO_2 injection if topographic effects are minimized. Remote geobotanical acquisition produces detailed surface images but relies on indirect effects of CO_2 on plant life or soils that, unless extreme, must be surveyed over an extended period of time.
- Near-ground direct CO_2 laser spectroscopy detection techniques are already in commercial use. Their ability to detect CO_2 depends on the rate, magnitude and type (diffuse or point) of seepage and local topography and atmospheric conditions.
- Conventional time lapse (4D) seismic techniques have a proven ability to image CO_2 movement in the subsurface but are expensive, logistically difficult over the long term and in some areas restricted due to environmental impacts. Non-seismic geophysical methods may have the resolution to detect subsurface CO_2 movement inexpensively over long periods without little impact on the surface.
- Addition of natural and synthetic tracers to injected CO_2 could be used to monitor the movement of injected CO_2 within target reservoirs. This would allow for detection of leaks from well bores and faults and in predicting gas break through in time to adjust operating parameters. The Mabee Field case study identified an isotope of Xe as the ideal noble gas tracer based on distinctiveness from natural reservoir and atmospheric noble gases and cost/availability.

An ideal monitoring system for a given CO_2 storage project would include the necessary resolution based on local subsurface and surface features, cost effectiveness and robust and stable operation with minimal environmental impact. Meeting these criteria would probably require some redundancy (subsurface imaging, tracers and surface collection and detection) with reliance of different techniques over short and long terms. Updating and calibration of reservoir simulations to match monitoring results will be necessary to verify CO_2 storage for carbon credits and ultimately facility abandonment. Development of inexpensive, instrumented monitoring wells and dual use wells (injection and post-injection monitoring) may be a cost effective, long-term solution to reservoir surveillance.

RISK ASSESSMENT

Risk assessment methods have long been applied to familiar hazards. The SMV risk assessment program includes a HSE perspective on handling and storage of CO_2 and other industrial materials, simulations showing the behavior of CO_2 in the vadose zone and atmosphere, strategies for early detection, intervention and remediation of CO_2 leakage and the development of two comprehensive methodologies tailored to geologic CO_2 storage. Key findings include the following.

- An initial survey of natural and industrial analogs to CO_2 handling, storage and HSE/regulatory implications has become a much-cited contribution to geologic CO_2 storage and provided guidance to the selection and execution of several of the subsequent SMV projects.
- The comprehensive risk assessment methodology developed by TNO included features, events and processes (FEP) development and application over a multi-compartment model. Testing of the model predicted no leakage over the 10,000 year timeframe (the consequence analysis was therefore not performed). Further testing is recommended.
- The INEL probabilistic methodology, in addition to its capability of predicting the likelihood and consequences of CO_2 leakage over multiple compartments, allows testing of well placement options and operation parameters for safe and effective CO_2 storage in coal beds.
- The concentration of CO_2 within the vadose zone and topographic lows with eventual atmospheric dispersion was simulated for specific sites. This simulation approach, in addition to its capability to identify site-specific risks of CO_2 concentration near the surface, provides an instructive visualization tool for regulators and the public.
- The impact of CO_2 injection on subsurface ecology showed that, depending on lithology and water chemistry, some classes of organisms will be favored at the expense of others. Whereas local extinction of useful organisms may not be an issue, possible operational parameters may be affected via microbial gas generation and porosity and permeability changes.
- Pre-injection assessment of potential leakage pathways and their impact on economic and HSE interests comprise the basis for early leakage detection, intervention and remediation planning.

The credibility of the “holistic”, risk-based approach to CO_2 storage encompassing the SMV integrity, optimization, monitoring and risk assessment studies is a key contribution to the science and technology of geological CO_2 storage. Logical steps in progressing risk assessment for CO_2 storage include standardization of FEPs, benchmarking of independently developed methodologies and quantifying and bracketing risks relative to familiar hazards. The development of technologies that prevent or allow response to leakage will facilitate project approval, safeguard economic and HSE interests and ensure verification and favorable liability release terms.

THE PATH FORWARD

Progress in advancing the technology and acceptance of geological CO_2 storage has accelerated in recent years to the point that several pilot/demonstration and a few commercial projects are underway or planned for the near future. By 2010, geologic storage is expected on the 10 million tonne/year scale. To reach the 1 billion tonne/year scale required to achieve mid-century stabilization targets, key technical issues related to storage capacity and security need to be resolved, and integrated evaluation protocols developed. Initiation of large-scale storage will be facilitated by the example of successful projects and creative approaches to source–sink matching and infrastructure development.

Key technical R&D needs include:

- integrated site evaluation protocols including accurate 3D structural/stratigraphic models and fluid flow paths/history that can be used for multi-compartment risk assessment;
- integration of experimental data and simulations to predict physicochemical rock response to perturbations from CO_2 injection and document the types and rates of CO_2 immobilization mechanisms;
- development of well technologies including resistant materials and construction/completion procedures, leakage intervention strategies and old well remediation;
- detailed leveraging of EOR and natural gas storage site characterization, operation and intervention/remediation protocols, optimization of oil production versus storage maximization;
- systematization of near and long-term monitoring and verification technology resolution with guidelines for site-specific suitability based on FEPs; validation of long-term CO_2 immobilization models and development of criteria for safe facility abandonment and liability release;
- benchmarking of CO_2 storage methodologies and quantification of storage risk relative to familiar hazards and those associated with climate change;
- economic tradeoffs, process integration and infrastructure considerations for CO_2 capture, transportation and storage.

There is good reason to be optimistic that geological CO_2 storage can substantially reduce atmospheric emissions in the next 10–50 years. Compared to geological storage, ocean storage presents serious environmental risks, mineral storage is slow and terrestrial storage is inefficient and probably temporary. Given the present and anticipated scale of anthropogenic CO_2 emissions, however, a portfolio approach to carbon mitigation that also includes conservation, renewables and nuclear energy will be required. The evolution of a hydrogen economy, the ultimate approach to carbon mitigation, will nevertheless require fossil fuel use and subsequent CO_2 storage. To make large-scale geologic CO_2 storage a reality, technical developments such as those outlined above need to be applied to moderate regulations and ensure public acceptance. Collaboration of industry, governments, academic institutions and environmental NGOs has begun in earnest and should continue to expand.