

# *EUG XI*



Theme EVO

Environment and Oceanography



# *EUG XI*



Symposium EVO1

Greenhouse Gas Storage

Convenors

Shelagh Baines  
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# EVO1 Greenhouse Gas Disposal

## Wednesday PM Session

### EVO1 : WEpm25 : F5

#### Why Do We Need Geological Storage of CO<sub>2</sub>?

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To meet targets for greenhouse gas emission reduction set by the Kyoto Protocol, many countries are considering a range of near-term options for emissions abatement. These abatement options include fuel switching, energy efficiency improvements and use of renewable sources of energy. However, to meet the goal of the UN Framework Convention on Climate Change, namely stabilisation of greenhouse gas concentrations in the atmosphere at a level, which avoids dangerous interference with the climate, it is likely to be necessary to make deeper reductions in emissions. Other measures will be needed to deliver these reductions - for example, geological storage of CO<sub>2</sub>. Geological storage of CO<sub>2</sub> will not replace the other options mentioned above but it is expected that it will be used in combination with them.

Geological storage of CO<sub>2</sub> would be used to sequester CO<sub>2</sub> captured from anthropogenic sources, such as power plant and large industrial plants. There are a number of reservoirs suitable for geological storage of CO<sub>2</sub>, including depleted oil and gas fields and deep saline aquifers. In these cases, there would be a net cost for storage. Other options combine CO<sub>2</sub> storage with enhanced recovery of fossil fuel, such as CO<sub>2</sub>-enhanced production of oil bed methane and CO<sub>2</sub>-enhanced oil recovery. In these cases, storage costs (i.e. not including CO<sub>2</sub> capture and transmission costs) would be offset by the increased production.

The storage of gases and fluids in geological reservoirs is not a new concept, it has occurred naturally for million of years. Following more than a century of petroleum production, thousands of oil and gas fields are approaching the ends of their economically productive lives. Such fields would be useful as stores for CO<sub>2</sub> because they are known to have held gases and liquids for millions of years, just what is needed to combat climate change. Some oil and gas fields have already been adapted to provide buffer storage for natural gas distribution systems, demonstrating in practice that such fields can be converted from production to storage sites. Similarly, there are many cases throughout the world where naturally occurring CO<sub>2</sub> from volcanic activity has been stored in sedimentary rocks for millions of years. These natural occurrences of trapped CO<sub>2</sub> give confidence that, in carefully selected reservoirs, CO<sub>2</sub> can be stored safely for thousands of years.

The aim of this paper is to review the need for geological storage, outline the options that are available and provide confidence that CO<sub>2</sub> can be safely stored by reference to examples of naturally occurring and artificial stores of CO<sub>2</sub>.

### EVO1 : WEpm26 : F5

#### The Case for Underground Carbon Dioxide Sequestration in Northern Europe

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Carbon dioxide sequestration (storing anthropogenic CO<sub>2</sub> away from the atmosphere until any greenhouse crisis has passed), can help mitigate industrial CO<sub>2</sub> emissions caused by fossil fuel combustion. Carbon can be sequestered by planting forests and, theoretically, by disposal in the deep oceans. However, amounts of CO<sub>2</sub> sequestered by afforestation are difficult to quantify, an important drawback in the likely context of international carbon trading. Moreover, as global warming continues, European forests appear to be increasingly susceptible to damage by storms and fire. Ocean storage has similar weaknesses with the additional factor of poorly understood environmental side-effects. In any case there is a lack of ocean storage potential around much of Europe as many countries have only distant and indirect access to intermediate and deep ocean waters. By contrast, major opportunities exist for subsur-

face CO<sub>2</sub> sequestration using current, proven technologies. CO<sub>2</sub> sequestered in this way can be precisely quantified at the point of injection and its subsequent underground fate closely monitored by geophysical means.

The North Sea is surrounded by major point sources of CO<sub>2</sub>, including power plants, integrated steel plants, cement manufacturing plants, oil refineries and petrochemical complexes. Thick, porous and permeable sandstone and carbonate reservoir rocks are abundant beneath the North Sea. These reservoirs are commonly sealed by mudstones whose seal efficiency is demonstrated by the presence of oil and gas fields. An assessment of this storage potential will form part of the EU-funded GESTCO project.

CO<sub>2</sub> is currently being sequestered for environmental reasons in the Utsira Sand (a saline aquifer of late Tertiary age) beneath the Sleipner West platform in the central North Sea. In the EU / industry funded SACS project time lapse seismic reflection data are being used to monitor the subsurface distribution of the CO<sub>2</sub> within the reservoir. Images of the CO<sub>2</sub> bubble are remarkably clear and offer the potential to assess its current detailed geometry. Independent calculations of the volume of CO<sub>2</sub> in the subsurface, based on the time-lapse data are in general agreement with the well injection figures, further supporting the efficacy of the monitoring technique. Further time-lapse seismic acquisition is planned, which coupled with reservoir modelling studies, offers the potential to monitor the future migration and dispersion of the bubble. Other geophysical methods, including multi-component seismic and microgravimetric monitoring are also being assessed for their suitability as monitoring tools. In addition, the regional reservoir characteristics of the Utsira Sand, such as total pore volume and storage efficiency are being evaluated, to assess its suitability for further sequestration projects elsewhere.

### EVO1 : WEpm27 : F5

#### Progress Report- CO<sub>2</sub> Capture Project (CCP) Joint Industry Project

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Global Warming will have a profound impact on the fossil fuels energy business, both in terms of increased costs, but also may result in new, profitable business opportunities for the business and our professionals. The subject joint industry project (JIP), led by BP, including participants such as Chevron, Norsk Hydro, Statoil, Shell, Suncor and Texaco, has now completed roughly one year of intensive work planning efforts. Detailed work plans have now been developed for this ~\$20 MM USD, 3.5 year technology development effort. The JIP's business objectives include the following: (a) significantly reduce the cost of CO<sub>2</sub> separation for capture of CO<sub>2</sub> from exhaust stacks, and (b) further develop downhole sequestration, monitoring and verification (SMV) technology for CO<sub>2</sub>, and demonstrate to the public, governments, and environmental non-government organizations that the technology is safe and effective.

Five technology development teams have been created in the areas of pre-combustion carbonization, oxygen fuels, post-combustion, developing a common economic model, and CO<sub>2</sub> sequestration. The teams have participants made up from the JIP members and contractors. These technical teams have completed a review and evaluation phase and are now implementing a detailed R&D program.

Significant R&D ongoing in the geologic storage or sequestration, monitoring and verification (SMV) technology area. However, the CCP JIP's SMV Team found there were significant technical areas that need further development. These areas will be the focus of the SMV Teams funding program, and these include: (a) Long-Term Monitoring and Verification Tools (seismic, gravity, airborne, etc.) and (b) Environmental Risk Assessment, Mitigation and Remediation Methodologies.

Third-party technology providers have now been engaged to develop the JIP's high priority technology gaps. This paper will highlight the lessons learned, the process to engage the technology providers, and the initial R&D programs that are already underway. Finally, the paper will share some of the early results of the R&D program.

### EVO1 : WEpm28 : F5

#### Disposal of CO<sub>2</sub> in Deep Aquifers: Geochemical Investigations of Water-Rock-CO<sub>2</sub> Interactions at the Sleipner (North Sea) as Part of the SACS Project

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The Sleipner project is the world's first commercial-scale underground storage of CO<sub>2</sub> for mitigation of emissions to the atmosphere. The Sleipner West gas field began production in 1996. The unwanted CO<sub>2</sub> by-product is being injected into a deep saline aquifer, the Utsira sandstone formation, about 800 m below the bed of the North Sea. Over 2 million tons of CO<sub>2</sub> have been injected since 1996. A research project named SACS (Saline Aquifer CO<sub>2</sub> Storage), jointly funded by the EU, industry and national governments, is currently investigating the fate of the stored CO<sub>2</sub>. As CO<sub>2</sub> is a reactive 'acidic' gas, one aim is to assess the nature, magnitude and rates of chemical reactions between CO<sub>2</sub>, formation fluid, rock and caprock. An assessment can then be made about how these affect storage capacity, longevity, and safety (see Czernichowski-Lauriol et al., 1996).

The objective of the geochemical work within the SACS project is to characterise the initial geochemical conditions within the Utsira formation and assess the changes that would be caused by CO<sub>2</sub> injection. Present work is based on laboratory experiments for timescales up to 24 months. Numerical modelling is then used to interpret the experimental data by considering thermodynamic, kinetic and transport processes. Further studies will be able to assess longer-term effects by making predictions using geochemical codes 'validated' on experimental test cases and by considering new field observations at Sleipner and the results of studies on natural CO<sub>2</sub> accumulations.

Baseline geochemical conditions were discussed by Pearce et al. (2000). New data increase confidence in the assumption of widespread, relatively constant Utsira porewater composition throughout the formation. A synthetic Utsira fluid together with Utsira rock samples from Sleipner are being used to carry out batch and core-flood experiments under in-situ conditions of temperature and pressure. The experiments are being undertaken in pairs: one pressurised with CO<sub>2</sub> and an 'experimental blank' pressurised with nitrogen. Modelling of the experiments is being performed using a variety of standard geochemical codes and chemical simulators developed for the SACS project. These include (i) EQ3/6 (Wolery, 1995), (ii) the 'UTSIRA' geochemical simulator specially developed using a simulator generation package (Kervévan and Baranger, 1998), (iii) a coupled code linking the UTSIRA simulator to the hydro-transport code MARTE used to model groundwater flow in porous media (Kervévan et al., 1998), (iv) the reaction-transport code DIAPHORE which was developed for the modelling of water-rock interactions during diagenesis of oil reservoirs (Le Gallo et al., 1998). Comparison of experimental results with modelling results from various approaches is useful. This ensures adequate interpretation of the experiments, and increases confidence in our understanding of chemical reactions induced by CO<sub>2</sub> injection and in the validity of the numerical tools.

Czernichowski-Lauriol I, Rochelle CA, Bateman KA, Pearce JM, Sanjuan B & Blackwell P. *In: Deep Injection Disposal of Hazardous and Industrial Waste (J. A. Apps and C. F. Tsang, eds.)*, Academic Press, 565-583, (1996).

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Le Gallo Y, Bildstein O & Brosse E. *Journal of Hydrology*, **209**, 366-388, (1998).

Pearce JM, Czernichowski-Lauriol I, Rochelle CA, Springer N, Brosse E, Sanjuan B, Bateman K & Lanini S. *Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies, Cairns, Australia*, (2000).

Wolery TJ. *EQ3/6 version 7. 2b report, Lawrence Livermore National Laboratory*, (1995).

# EVO1

## Greenhouse Gas Disposal

### EVO1 : WEpm29 : F5 Reactive Transport Modeling of Geologic CO<sub>2</sub> Sequestration: Identification of Optimal Target Formations Based on Geochemical, Hydrologic, and Structural Constraints

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Geologic sequestration represents a promising strategy for isolating CO<sub>2</sub> waste streams from the atmosphere. Scientific viability of this approach hinges on the relative effectiveness of CO<sub>2</sub> migration and sequestration processes in the subsurface, while its successful implementation relies on our ability to predict sensitivity of this migration/sequestration balance to key physical and chemical characteristics of potential target reservoirs. By quantifying this sensitivity, we can establish geochemical, hydrologic, and structural constraints on maximizing sequestration performance that can be used to identify those formations most likely to provide optimal storage capacity and isolation security. We are integrating kinetically-controlled reactive-transport and multiphase-flow simulators (NUFT, GIMRT), supporting geochemical software and thermodynamic/kinetic databases (SUPCRT92, GEMBOCHS), and recent equation-of-state and viscosity formulations for CO<sub>2</sub> (Span and Wagner, 1996; Fenghour et al., 1998) to develop a unique modeling capability for identifying optimal target formations in this manner.

Confidence in this modeling approach requires demonstrated success in simulating the observed behavior of natural systems. Hence, our initial modeling efforts have focused on simulating CO<sub>2</sub> injection at the unique Sleipner facility, where properties of the target aquifer and its bounding cap rock are well constrained and location of the migrating CO<sub>2</sub> plume after three years of injection has been established. Preliminary results suggest that local permeability structure of the target formation controls CO<sub>2</sub> movement by all migration processes (immiscible displacement, gravity segregation, and viscous fingering) and the potential effectiveness of all sequestration processes (structural, solubility, and mineral trapping). For typical sandstone aquifers, at least 90% of the injected CO<sub>2</sub> migrates as an immiscible plume; hence, potential structural trapping represents the dominant sequestration mechanism. Intra-aquifer shales retard vertical and promote horizontal CO<sub>2</sub> migration, thus expanding the volumetric extent of CO<sub>2</sub>-aquifer interaction, and thereby increasing the potential effectiveness of solubility and mineral trapping. Relative impermeability of clay-rich inter-bedded and cap-rock shales may be enhanced by carbonate precipitation at the CO<sub>2</sub>-shale interface, thus improving cap-rock integrity - the most important constraint on long-term isolation performance.

Span R & Wagner W, *J. Phys. Chem. Ref. Data*, **25**, 1509-1596, (1996).

Fenghour A, Wakeham WA & Vesovic V, *J. Phys. Chem. Ref. Data*, **27**, 31-44, (1998).

### EVO1 : WEpm30 : F5 Long-Term Mineral Storage of CO<sub>2</sub> in Aquifers and Reservoirs: Trapping Mechanisms Offered by Sandstones Rich in Anhydrite or Gypsum

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One of the mechanisms expected to increase the capacity of sequestration offered by permeable rocks with respect to CO<sub>2</sub> is trapping of the gas to form carbonates. The concept was investigated and discussed, notably, by Gunter *et al.* (1999). In order to precipitate carbonate, the host rock of sequestered gas must contain one or several precursor minerals capable of being dissolved in presence of the interstitial water enriched in CO<sub>2</sub>, and also capable of providing elements that can be incorporated into carbonate minerals (e.g., Ca, Mg, Fe). Moreover, the carbonate precipitation must be possible in terms of thermodynamics.

Two minerals that deserve a priori to be considered as possible precursors in such a process are gypsum CaSO<sub>4</sub>·2H<sub>2</sub>O and anhydrite CaSO<sub>4</sub>. Our presentation aims at giving an insight into the capacity of these minerals to be de-stabilized by a formation water acidified by CO<sub>2</sub>, in the general context of CO<sub>2</sub> sequestration in sandstone. It investigates the following questions : i) what are the stability

domains of carbonates, sulphates and sulphides in the ranges of temperature and pressure relevant to CO<sub>2</sub> sequestration? ii) What is the stability of these minerals in presence of a sandstone-formation water enriched in CO<sub>2</sub> (different concentrations of CO<sub>2</sub> and different salinity values were explored) ? iii) What is known about kinetic rates involved (intrinsic rate and reactive surface areas), and what is the implication for the long-term reactivity of the geological systems (several hundreds of years, and more)?

For examining these questions, the reaction-transport numerical model Diaphore was used (Le Gallo *et al.*, 1998). This geochemical software solves the conservation equations of the elements considered in the system. They are determined by the choice of minerals taken into consideration. The conservation equations integrate: i) the coupling between transport of water and elements, and heterogenous reactions (dissolutions, precipitations) represented with kinetic rates and a feedback on the rock fabric (porosity, permeability, surface areas); ii) the exchanges at equilibrium between the aqueous solution and a multi-component gas phase.

The sandstone composition was deduced from published data for the Rotliegendes Sandstones (Lower Permian) of Northern Netherlands (e.g., Amthor and Okkerman, 1998): quartz, alkali-feldspars, minor plagioclase, dolomite, calcite, anhydrite (alternatively, gypsum), kaolinite and illite. The contribution of halite was not envisaged, as the formation waters tested presented values, for total dissolved salts, lower than the solubility threshold of anhydrite (or gypsum). As a consequence, the elements considered were Si, Al, Na, K, Ca, Mg, Fe, S, C, O, H and Cl. Compositions tested for the gas phase included various mixings of CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>O and H<sub>2</sub>S.

Amthor, J.E. & Okkerman, J., *AAPG Bulletin*, **82**, 2246-2265, (1998).

Gunter, W.D., Perkins, E.H. & Hutcheon, I., *Applied Geochemistry*, in press, (2000).

Le Gallo, Y, Bildstein, O & Brosse, E, *Journal of Hydrology*, **209**, 366-388, (1998).

### EVO1 : WEpm33 : F5 Geologic Sequestration of CO<sub>2</sub> in Carbonate Rocks: Preliminary Results from Coupled Multiphase Flow, Transport, and Reaction Simulations

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CO<sub>2</sub> sequestration in deep saline aquifers is potentially a low cost and long term way to reduce CO<sub>2</sub> emissions on a global scale. Relatively little is known, however, about the physical and chemical behavior of CO<sub>2</sub> when injected into a variety of subsurface formations and how this behavior influences their sequestration capacity. A lack of field studies of subsurface CO<sub>2</sub> injection is the primary reason for our limited understanding, although the situation is now being improved as a result of ongoing injection of CO<sub>2</sub> into the Utsira Aquifer at Sleipner in the North Sea. A second important field study will be carried out at Weyburn, Saskatchewan in Canada where the injection of CO<sub>2</sub> into a carbonate reservoir as part of an enhanced oil recovery (EOR) project will be used to study CO<sub>2</sub> behavior and sequestration capacity in this setting. In addition to the need for field studies, however, there is also a need for more sophisticated multiphase flow, transport, and reaction simulators which take into account the coupled physical and chemical dynamics associated with CO<sub>2</sub> injection. A modern treatment of geochemical processes (aqueous complexation, kinetically-controlled mineral dissolution and precipitation, and multiphase partitioning) is necessary in order to accurately represent the attenuation of the CO<sub>2</sub> plume.

In this work, we present preliminary coupled multiphase flow and geochemical reaction simulations of CO<sub>2</sub> injection into a carbonate-dominated reservoir similar to that found at Weyburn. Since carbonate minerals themselves contribute relatively little to the trapping of CO<sub>2</sub>, it is important to analyze the effect of various included silicate minerals in the rock on the chemistry of the formation waters and the porosity and permeability of the formation.

### EVO1 : WEpm34 : F5 Evaluation of Long Term Geological CO<sub>2</sub> Storage: Controls on the Presence of CO<sub>2</sub> in Naturally Occurring Accumulations

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It is likely that nature, in the form of evidence from the geological record, can reveal how the subsurface will respond to CO<sub>2</sub> injection since many geological traps naturally have received large quantities of CO<sub>2</sub> during their burial (diagenetic) history. Sites should be selected primarily on the basis of (1) the natural ability of the host rock to react with CO<sub>2</sub> to produce new carbonate minerals (2) the long term integrity of the cap rock to withstand elevated concentrations of reactive CO<sub>2</sub>. Natural CO<sub>2</sub> in sedimentary basins is due mainly to organic source rock heating during burial or release from deeply buried non-organic sources in the crust. Some traps retain the CO<sub>2</sub> while others lose it to the mineral phase through natural sequestration. We have deduced that there are two main controls on natural CO<sub>2</sub> sequestration. First, CO<sub>2</sub> can only be sequestered if the addition of CO<sub>2</sub> takes the geochemical system away from equilibrium and if the rock contains a non-carbonate mineral source of alkaline earth elements such as calcium in anorthite feldspar, Ca-zeolite or Ca-smectite. Such rocks include lithic arenites and some arkosic sandstones; especially those derived from volcanoclastic sources. Clean sandstones and limestones are characteristically incapable of sequestering CO<sub>2</sub>. Second, the process of CO<sub>2</sub> sequestration involves aluminosilicate dissolution and carbonate precipitation. These processes can be slow even on a geological timescale. It is also significant that typical rates of dissolution (and precipitation) of aluminosilicate minerals are approximately one million times slower than equivalent processes for carbonate minerals. The timescale of attainment of equilibrium is important and the fact that some geological traps have enriched CO<sub>2</sub> that is presently out of equilibrium with the host rock and its formation water suggests caution in any deep disposal schemes. The main conclusions to the study of the accumulation and natural reaction of CO<sub>2</sub> are thus: (1) Naturally elevated CO<sub>2</sub> is derived mainly from inorganic sources such as deep-seated igneous processes deep in sedimentary piles or in the crust. (2) Natural CO<sub>2</sub> sequestration will only occur if the rock contains the appropriate (and quite specific) mineralogy. (3) Natural CO<sub>2</sub> sequestration will only occur if there has been sufficient time (> 50 kA minimum). (4) The most reactive minerals include Ca and Mg aluminosilicates such as plagioclase, zeolite, smectite and chlorite. (5) Clean sandstones, limestones and dolomites will not naturally sequester CO<sub>2</sub> (unless there has been naturally slow diffusion of alkaline earth elements from, for example, mudstones). (6) In the absence of non-carbonate mineral sources of alkaline earth elements, elevated CO<sub>2</sub> may cause extensive carbonate mineral dissolution, with loss of rock strength, increased pore throat aperture sizes in cap rocks and thus loss of seal integrity.

### EVO1 : WEpm35 : F5 Analysis of CO<sub>2</sub> Leakage along Faults from Natural Reservoirs in the Colorado Plateau, United States

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Numerous natural reservoirs of CO<sub>2</sub> occur in the Colorado Plateau region of the United States, and are natural analogs for deep geologic sequestration. Many of these reservoirs are fault-bounded structures, about which but little is known of the long-term subsurface behaviour of CO<sub>2</sub>. We examine evidence for long-term leakage from natural CO<sub>2</sub> reservoirs in southeastern Utah. CO<sub>2</sub>-charged springs, geysers, and seeps are localised along fault zones throughout the region, and have deposited travertines, some of which may be as old as 200,000 years. These are either natural springs which can be demonstrated to have had a long history, or are springs that were induced by recent drilling. The faults cut siltstones, shales, and sandstones,

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and their outcrop appearance suggests they should be effective barriers to cross-fault flow (fine grained, clay-rich fault gouge). However, abundant large calcite veins cut the faults, suggesting that fluid pressures in the past were high enough to rupture the faults. The spring waters are highly saline and high in Na, Cl, Ca and dissolved CO<sub>2</sub>. Modelling of the water chemistry indicates that the water is either saturated or supersaturated in aragonite, calcite, dolomite, fluorite and gypsum, all of which are observed in the veins along the faults, and that the water from both areas is likely to have come from organic decomposition of a sequence of marine evaporates at depth. Preliminary isotopic data from calcite veins show that the veins are highly enriched in <sup>13</sup>C. This can only be explained if the veins have a fluid source in Palaeozoic marine rocks. The heavy δ<sup>13</sup>C values provide further evidence for thermal decomposition of organic material or development of methane. Structural analyses of the system show that the faults sole into Pennsylvanian salt beds 2-3 km deep. This suggests that the spring waters are sourced in Palaeozoic rocks and flow along the faults to the surface. Past evidence for rupture of the fault seals indicates that reservoir pressures may exceed lithostatic pressure, causing the reservoir to leak repeatedly over time. These data indicate that injection of CO<sub>2</sub>-rich fluids into geologic reservoirs must be carefully designed and monitored to avoid slow seepage or fast rupture to the biosphere.

### EVO1 : WEpm36 : F5 Geophysical Monitoring of Carbon Dioxide Injection and Sequestration using Electrical Resistance Tomography (ERT): Sensitivity Studies

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If geologic formations are used to store or sequester carbon dioxide (CO<sub>2</sub>), monitoring CO<sub>2</sub> injection will be required to confirm the performance of the reservoir system, assess leaks and flow paths, and detect the geophysical and geochemical interactions between the CO<sub>2</sub> and the geologic minerals and fluids. Electrical methods are well suited for monitoring processes involving fluids, as electrical properties are sensitive to the presence and nature of formation fluids. High resolution tomographs of electrical properties are now used for site characterization and to monitor subsurface migration of fluids (i.e., leaking underground tanks, infiltration events, steam floods, and to assess the integrity of engineered barriers). Surveys are commonly conducted utilizing vertical arrays of point electrodes in a crosswell configuration. Recent field results obtained using steel well casings as electrodes are promising. If 3D electrical resistance tomography (ERT) imaging can be performed using existing well casings as long electrodes, this reduces the need for additional drilling.

Using a model patterned after an oil field undergoing CO<sub>2</sub> flood, forward and inverse simulations of ERT surveys are being run to test the sensitivity of the method to detect the changes resulting from CO<sub>2</sub> migration. Factors considered include resistivity contrast, anomaly location (proximity to electrodes), anomaly size and shape, noise level and measurement configuration. CO<sub>2</sub> migration is simulated by changing the resistivity of a layer, producing an anomalous region. The anomalous region's resistivity ranges from 0.2 to 10 times that of the initial value. Its geometry ranges from a thin, horizontal finger to a planar, horizontal mass having vertical protrusions, simulating leakage of CO<sub>2</sub>.

Simulation results confirm that point electrode arrays offer the highest sensitivity and resolution, but their use requires monitoring wells with installed electrodes. Vertical and horizontal well casings can be used together as long electrodes to coarsely resolve changes vertically and horizontally; this approach does not require the use of additional monitoring wells. The tomographs tend to exaggerate the anomaly's volume, and underpredict the changes in resistivity, although the average resistance of the tomograph anomalies is close to the true average value. The fidelity of the images is largely independent of measurement noise but is strongly dependent on the regularization (smoothing) approach used by the inverse algorithm. The most easily resolved anomalies are those having the largest volume and contrast near the center of the probed region; the hardest are "finger-like" anomalies of low volume and contrast. Over the range of contrasts considered, conductive and resistive changes can be resolved equally well.

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

### EVO1 : WEpm37 : F5 Geological Sequestration of Carbon dioxide and Enhanced Coalbed Methane Recovery: The Campine Coal Basin (N-Belgium) and its Mined-Out Areas Have a Potential

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Both the virgin coal reserves and the mined-out areas (residual volumes) of the paralic Westphalian Campine coal basin show an interesting potential for different CO<sub>2</sub>-storage scenarios. Based on the distribution of coal reserves, coal rank and average gas content (up to a depth of -1500 m) at least six target zones with an increased coalbed methane concentration have been identified in the basin. The nature of these CBM anomalies may differ depending on the burial history of different sub-basins, the existence of which is related to the presence of an important transpressional fault zone. The estimated producible CBM-reserves in combination with CO<sub>2</sub>-sequestration (or with the use of propellant gases) in the target areas, varies between 53 and 98 billion m<sup>3</sup> of methane. At a 2:1 exchange ratio for methane replacement by CO<sub>2</sub> and a suggested 60% recovery only, the minimum geological sequestration capacity within the target areas is about 106 million m<sup>3</sup>, or ca 208 million tons (at standard conditions). If by the use of CO<sub>2</sub>-stripping, an enhanced CBM-recovery of 90% could be reached, the CO<sub>2</sub>-sequestration capacity by exchange would increase to about 312 million tons. Furthermore, as most coals seams in the studied basin are under-saturated in methane, additional storage capacity of about 86 million tons of CO<sub>2</sub> is postulated. This would mean a total minimum CO<sub>2</sub>-sequestration potential in the target areas of almost 400 million tons. At injection depths over 800 m, the CO<sub>2</sub> will be supercritical. This might well provide an even larger sequestration potential for the coals. The formerly mined-out areas should be considered in the CO<sub>2</sub>-ECBM production scenarios as well. The total pore space of the calculated human-induced pore volume of the fractured rock, plus the matrix porosity of the residual coal seams, together with the residual volume of the stonedrifts and blind shafts, varies between 35.5 and 60 million m<sup>3</sup>. The storage capacity in the mined-out areas might reach over 45 million tons of CO<sub>2</sub>. Initially, the abandoned deep coal mines might provide methane gas from de-stressed strata. Subsequently, they may also be used as storage room for the CO<sub>2</sub> deemed necessary for further ECBM production.

The Campine coalfield holds potential for setting up a CO<sub>2</sub>-industry. The coal basin is surrounded by important CO<sub>2</sub>-producers, including coal-fired power plants, cement works, and one of the world largest concentrations of chemical industry, among which fertiliser producers. The already present gas transportation pipeline network serves a steadily growing market of methane users.

### EVO1 : WEpm38 : F5 Subsurface Storage of Carbon Dioxide for the in Salah Gas Project, an Eight Field Gas Development in Central Algeria

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In Salah Gas is a joint venture between Sonatrach and BP that will produce 9 billion cubic metres of gas per annum from eight gas discoveries located in the Ahnet - Timmimoun Basin in Central Algeria. The eight fields are located 500 kilometres from existing gas export infrastructure at Hassi R'Mel so development of the fields requires major investment in new pipeline and gas processing infrastructure. The gas will be delivered to markets in Southern Europe.

Gas to be produced from the fields contains a significant fraction of carbon dioxide. To meet gas composition specifications for the gas transmission network it is necessary to remove a large proportion of this carbon dioxide in the processing facilities prior to export. Sonatrach and BP both have goals to reduce greenhouse gas emissions to the atmosphere so disposal of the carbon dioxide into the atmosphere is not an option. A review of alternative uses for the carbon dioxide was therefore undertaken, leading to selection of subsurface storage in Tournaisian aged reservoir sandstones adjacent to one of the eight fields as the preferred option.

A reservoir simulation model was built to aid design of the carbon dioxide storage scheme. 3D seismic data was used to define structural surfaces and also to guide the interpretation of reservoir thickness and quality. A full equation of state was used to capture the subsurface phase behaviour of the injected carbon dioxide. The model has been used to identify injection well locations that satisfy a number of criteria including: avoiding carbon dioxide breakthrough at gas production wells, accessing sufficient connected pore-volume to accommodate predicted volumes of carbon dioxide and minimising flow line distances to address cost saving challenges.

Prior to implementation of the carbon dioxide storage scheme additional 3D seismic data will be acquired and an improved reservoir model will be built. The improved model will be used for detailed design of the injection well locations and trajectories.

The impact of the scheme will be to reduce overall emissions from the In Salah Gas project by approximately 60 percent.