REPORT ON

MONITORING WORKSHOP

Organised by IEA Greenhouse Gas R&D Programme and BP
with the support of EPRI and the US DOE/NETL

Monday 8th to Tuesday 9th November 2004

Seymour Center, University of California Santa Cruz, California USA

MONITORING WORKSHOP

Executive Summary

A workshop has been held in California, U.S.A. to establish a new international research network covering the monitoring of injected CO_2 in geological storage formations. The inaugural meeting of the Monitoring Network was held at the Seymour Centre, University of California Santa Cruz, California, USA, on the 8th and 9th November 2004. The workshop was organised by IEA Greenhouse Gas R&D Programme and BP with the support of EPRI and the US DOE/NETL. The international workshop, which was attended by nearly 60 delegates, aimed to bring together the main research groups currently active in the field of monitoring CO_2 injected into geological formations and to discuss and critique the work that is currently underway.

The purpose of monitoring injected CO_2 is to address the three requirements for the safe and effective storage of CO_2 in geological formations. These requirements are:

- Worker and public safety
- Local environmental impacts to groundwater and ecosystems
- Greenhouse Gas mitigation effectiveness

The objective of the workshop was to get a common understanding of the current state of the art, to identify the techniques available, and to assess their limitations. This was achieved by using the results available from projects that are currently monitoring injected CO_2. The aim was then to develop a view of where the technology needs to go from here, in order to develop stakeholder confidence that injected CO_2 can be monitored and verified and any leakage quickly detected.

Some of the key messages from the workshop were:

- There is a substantial tool box of monitoring techniques already available for use. This tool box includes techniques for monitoring in situ CO_2 movement and monitoring for surface and well-bore leakage. Actual experience of their use provides additional confidence in their applicability and the particular limitations of the techniques available have been identified.
- Seismic surveying has proven itself capable of monitoring CO_2 movement in the subsurface at Sleipner and Weyburn. Seismic surveying of the overburden should also identify if leakage is occurring from a CO_2 storage formation.
- Monitoring of pilot projects can provide valuable information on the advantages and limitations of particular monitoring techniques and allows comparison to modelling results. Even monitoring experiences at small projects like the Frio and Nagaoka projects can provide enormous amounts of information.

- Monitoring costs will not add substantially to the operational costs of an injection project.
- For successful monitoring of an injection site it was essential to have detailed baseline conditions at the surface and in the subsurface prior to injection; to know as much about the reservoir as possible at the beginning. For oil fields, there will be information already available from exploration and production activities and this could result in lower overall costs of monitoring at these sites. However, for deep saline aquifers, characterization and monitoring will be most probably required from scratch. One of the benefits of a baseline study is the ability to identify naturally occurring fluxes of CO_2, distinguishing such CO_2 from what is injected and identifying other noise around the site that may mask a leakage or seepage signal.

The workshop identified a number of key research issues:

- Because there is such an extensive tool box of monitoring techniques, new injection projects need guidance on what to measure and where. Such information can be provided by a safety and risk assessment of the injection site if this were undertaken early in the project lifetime.
- As there are plenty of techniques available for monitoring injected CO_2, it became evident, through the discussions at the workshop, that some techniques would be more appropriate in certain locations due to their suitability to particular climate and local environmental conditions. The production of some form of "auditing" chart was suggested to enable the right combination of techniques to be selected for a particular project.

A number of actions were agreed which included:

- IEA GHG will add the Monitoring Network to the dedicated Networks site on www.co2captureandstorage.info. The presentations from the workshop will be in a delegates-only area of the site but a public domain summary report will be produced and placed in the public section of the site.
- The second meeting of the network will be in Autumn 2005.

MONITORING WORKSHOP

1. BACKGROUND

If deep reductions in anthropogenic greenhouse gas emissions are to be achieved, the introduction of CO_2 capture and storage in geological reservoirs is likely to be necessary. The technology would be deployed alongside other mitigation measures such as renewables, energy efficiency and fuel switching. There are a number of potential geological reservoirs that can be used to store captured CO_2. These geological reservoirs include depleted and disused oil and gas fields, deep saline aquifers and deep unminable coal seams. Geological storage of CO_2 is not a new technology. However, it is acknowledged that all the technical issues related to geological storage have not yet been fully resolved and that the outstanding issues must be addressed before the technology can be accepted by the policy makers and public for wide scale implementation.

One key issue that needs to be addressed is the integrity of the formation containing the injected CO_2 and the resultant safety of CO_2 storage and environmental impact issues should leakage occur. They are two ways of addressing the integrity of reservoir and the potential for leakage. First is to monitor the CO_2 injected at pilot scale and demonstration sites, like Frio, Sleipner, Weyburn, Rangely, West Pearl Queen and Nagaoka. The monitoring data can provide information on the fate of the CO_2 after injection coupled with physical evidence of migration out of the reservoir in the near term (next 50 years). Secondly, modelling coupled with risk assessment studies can predict the long term fate (1000's years) of the injected CO_2 and the long term migration potential. Of course monitoring studies also assist the modelling and risk assessment process by providing calibration points for predictions in the early years which can help to build confidence in the longer term predictions.

The monitoring of injected CO_2 therefore has a key role to play in the development of stakeholder confidence in CO_2 capture and storage as a mitigation option. There are many monitoring projects now underway in Norway, USA, Canada, Algeria and Japan and many more are planned. In the current and planned monitoring projects a wide variety of monitoring techniques are being used. It is important to bring together the results of these different monitoring projects as well as the practical experiences of the project operators to identify what has worked well and what has not and why. Such an activity can help to build confidence in monitoring technology as well as help to guide new projects in the selection of their monitoring techniques. To this end, the IEA Greenhouse Gas R&D Programme and BP have formed an international research network on monitoring to help facilitate the exchange of information between those organisations actively involved in monitoring injected CO_2 across the globe.

2. MONITORING WORKSHOP

2.1 Workshop aims and objectives

This international workshop aimed to bring together the main research groups currently active in the field of monitoring of CO_2 in geological formations, to discuss and critique the work that is currently underway.

The objective of the workshop was to get a common understanding of the current state of the art, what techniques are available now, and what their limitations are. From that understanding, the aim was then to develop a view of how the technology needs to develop in order to establish stakeholder confidence that injected CO_2 can be monitored and verified and any leakage quickly detected.

2.2 Workshop attendees

The workshop was attended by 57 delegates, from 38 different organisations and 7 different countries. The attendance list is given in Annex 1 for reference.

2.3 Workshop programme and structure

The two day workshop was designed to allow technical presentations and time for open discussion. The presentations were focused into five topics covering the different aspects of monitoring currently underway and future activities. The topics were:

1. Opening perspectives and overviews
2. Surface/leakage monitoring
3. Geophysical monitoring – aquifers
4. Monitoring CO_2 injection into oil fields
5. New monitoring projects/future activities

The discussion sessions aimed to answer the following questions:

1. Are there any limitations in the techniques currently used?
2. Are new techniques being developed?
3. Are there any barriers to the use of these techniques?
4. What further research is needed to improve confidence in the monitoring results?

The full programme for the two day workshop is shown in Table 1 for reference.

Table 1. Monitoring Workshop Programme

Day 1	**Monday 8th November 2004**
Opening Session	
08.30 to 08:45	Welcome, Safety Briefings Meeting objectives John Gale, IEA GHG
Session 1 – Opening Perspectives and Overviews	
08.45 to 09.15	Monitoring needs, a regulatory perspective - *Martha Krebs. West Coast Regional Carbon Sequestration Partnership*
09.15 to 09.45	Overview of status of monitoring technologies - *Sally Benson, LBNL*
09.45 to 10.15	Monitoring strategies and cost comparisons - *Larry Meyer, LBNL*
10.15 to 10.40	**Break**
Session 2 – Surface/leakage monitoring	
10.40 to 11.00	CO_2 Fluxes to the Atmosphere, and in Soil Gas: Detection of a Deep Source Masked by Near-surface Noise - *Ron Klusman, USDOE/NETL*
11.00 to 11.20	Surface monitoring techniques as applied at Weyburn and elsewhere – *Jonathan Pearce, BGS*
11.20 to 11.40	Monitoring and verification of CO_2 leakage from underground storage formations - *William Pickles, LLNL*
11.40 to 12.00	Preliminary Evaluation of the Ability of Airborne Reconnaissance Techniques to Find Abandoned Wells - *Rick Hammack, USDOE/NETL*
12.00 to 13.00	**Break**
Session 2 – Surface/leakage monitoring cont'd	
13.00 to 13.20	Leakage and seepage in the near surface environment: an integrated approach to monitoring and detection - *Curt Oldenburg, LBNL*
13.20 to 14.20	Discussion session on approaches adopted. Key issues to be addressed include: • Are there any limitations in the techniques currently used? • Are new techniques being developed? • Are there any barriers to the use of these techniques? • What further research is needed to improve confidence in the monitoring results?
Session 3 – Geophysical monitoring - aquifers	
14.20 to 14.40	Review of geophysical monitoring results from the SACS project *Ola Eiken, Statoil*
14.40 to 15.00	Verifying the volumes of injected CO_2 – experience from the SACS project - *Gary Kirby, BGS*
15.00 to 15.20	**Break**
15.20 to 15.40	Geophysical Monitoring of CO2 Sequestration at An Onshore Saline Aquifer in Japan *Ziqiu Xue, RITE*
15.40 to 16.00	Initial results from the Frio Brine Injection project *Mark Holtz, Texas BEG*
16.00 to 17.00	Discussion session on approaches adopted. Key issues to be addressed include: • Are there any limitations in the techniques currently used? • Are new techniques being developed? • Are there any barriers to the use of these techniques? What further research is needed to improve confidence in the monitoring results?
17.00	Close of Day 1

Table 1. Monitoring Workshop Programme, cont'd

Opening Session - Day 2	
08.30 to 09.00	Review of Day 1 and plan for Day 2 *John Gale IEA GHG and Charles Christopher, BP*
Session 4 – Monitoring CO_2 injection into Oil fields	
09.00 to 09.20	Tracer Results from the West Pearl Queen Field Pilot Sequestration Site *Arthur Wells, USDOE/NETL*
09.20 to 09.40	What worked and what didn't – experiences from the Weyburn Monitoring Project, *Malcolm Wilson, PTRC*
09.40 to 10.00	Review of seismic results from the Weyburn Monitoring project *Don White, GSC*
10.00 to 10.20	Geochemical monitoring at Weyburn *Kyle Durocher, ARC*
10.20 to 10.40	**Break**
10.40 to 11.30	Discussion session on approaches adopted. Key issues to be addressed include: • Are there any limitations in the techniques currently used? • Are new techniques being developed? • Are there any barriers to the use of these techniques? What further research is needed to improve confidence in the monitoring results?
Session 5 – New monitoring projects/future activities	
11.30 to 11.50	The In-Salah project – monitoring plans *Iain Wright, BP*
11.50 to 12.10	Teapot Dome - baseline monitoring results and future monitoring programmes *Julio Friedmann, LLNL*
12.10 to 12.30	The EnergyINET project, *David Keith, University of Calgary*
12.30 to 13.30	**Break**
Session 6 - Workshop Review	
13.30 to 14.00	The Mountaineer project – monitoring plans *Neeraj Gupta, Battelle*
14.00 to 15.00	Facilitated discussion to cover the following points: What have we learnt? How confident are we in the results obtained to date? where are the gaps? What are the future research needs?
15.00 to 15.20	**Break**
Session 7 - Closing Session	
15.20 to 16.20	Way forward and Next steps Including discussion on establishment of an international research network
16.20 to 16.30	Closing Remarks

3. SUMMARY OF MONITORING NETWORK MEETING

3.1 Overview and perspectives of monitoring CO_2 injection

3.1.1 Public acceptance of CO_2 Capture and Storage

Introducing new energy technologies is hard; there are risks for both producers and consumers. Risks can be financial, environmental, health and safety related or due to more complex issues like the interdependencies among end use sectors. Risks can often be quantifiable unless there are uncontrollable externalities like wars.

There are several policy options available, for use by governments, to assist the introduction of CO_2 capture and storage. Research and development is probably the easiest to commit to although it can be controversial but demonstration and deployments can be difficult.

It is accepted that public outreach is critical to the introduction of any technology. Engagements in transparent exchanges with the "public" will assist in highlighting their concerns. In turn such exchanges provide targeted information about the possible role, benefits and risks of CO_2 storage and ensure that the right information that is being supplied.

It must be acknowledged that there are a range of public 'audiences', from the regulators and legislatures (decision makers), to the media, local government and business leaders (who can all influence opinion). Also, there are the national and international environmental groups although they may be less responsive than local environmental groups. Then finally the general public, the opinion of which has been scoped through general surveys undertaken in the UK and U.S.A. These surveys have helped to identify some of the (initial) concerns of the general public, but they have not necessarily been those of 'Backyard'. Despite the surveys and media coverage to date, it will be real projects that will bring the challenge of real people with real backyards (The NIMBY[1] Lobby). The one critical issue that the public will expect to be answered will be how long will the CO_2 remain stored? (1000, 2000 or 10 000 years?). As far as addressing the critical issue of the period required for storage integrity, the question is, who will decide that the answers are good enough? The time is now considered right to begin a transparent, but independent process that will allow the public to be satisfied with the answer to this question.

3.1.2 Sensitivity and resolution of monitoring

The most important aspect of monitoring for the public will be the sensitivity and resolution of methods for leakage detection. There are three requirements for safe and effective geological storage, firstly public and worker safety,

[1] NIMBY stands for Not In My Backyard

secondly local environmental impacts to groundwater and ecosystems and thirdly, greenhouse gas (GHG) mitigation effectiveness. The level of leakage will have different impacts on these three requirements; for example, a very small level of leakage over a long time period may only effect GHG mitigation.

There are many purposes for monitoring CO_2 following injection. Detecting plume location and leakage from a storage formation may not always be necessary from a regulatory perspective[2] but for many projects it will be useful information to communicate with the public. It will also give confidence if the results from monitoring match those obtained from modelling. Monitoring could also have a key role in providing assurance and accounting for monetary transactions and validation of emissions reductions. It could provide a form of accounting by monitoring injection rates versus potential leakage.

There are many techniques for monitoring, from wellhead and formation pressure monitoring, to well logs, to seismic geophysics, and this is good because it indicates how big the tool box is. The different techniques have different sensitivities and a selection can be made depending on what is required for a particular project. It is likely that it will be a combination of monitoring techniques that will be used at any one site. The decision on the technique will be dependant on what is it that the project will need to monitor or what the objectives of the regulators may be. The capabilities of the tests can be assessed by looking at scenarios of active projects. The key question for monitoring could be whether it is possible to obtain a cumulative amount of CO_2 that had leaked and could it be detected? Scenarios can show that even at low rates CO_2 rates can be detected within 50 years. More demonstrations are needed to improve monitoring techniques.

The ease of detecting leakage will depend on its nature. If leakage occurred across the whole footprint of the CO_2 plume, it might be difficult to identify CO_2 above the typical ecosystem flux. However, if leakage was concentrated through certain features (like an abandoned well bore or a fault) a flux higher than the "natural" ecosystem flux could be expected and the impact on vegetation etc. could be identifiable.

3.1.3 Monitoring costs

The cost of monitoring will not be a major factor in the total cost of a CO_2 storage project based upon a life time of 55-85 years approximately.

There are some components that will be required even for the most basic of monitoring packages with the option of additional measurements for an enhanced monitoring package. The monitoring of a site could be split into three phases: Pre-operational, Operational and Closure monitoring.

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[2] Injection programmes currently operating in the USA and Canada do not require in-situ monitoring of the injected gases or fluids. However it is currently uncertain whether this approach would be adopted in other regions of the world or whether even in North America in the future in-situ monitoring might become part of regulatory requirements.

For EOR some pre-operational monitoring will already have been completed and available for use by the operators of a storage project. As it is likely that there will have been no previous activity for a saline aquifer, the pre-operational monitoring will need to be more thorough and therefore comparatively more expensive; simply it will need to be done from scratch. It is estimated that the price for pre-operational monitoring could be $0.9million for EOR as opposed to $5.7million in the case of saline aquifers. This cost range is indicative and will depend highly on a number of site specific factors.

Once monitoring begins for the operational phase the price ratio changes. EOR has a fixed size survey with a cost estimated at $34million; whereas saline aquifers would be less at $23million because the size of the survey grows in time in relation to the growth of the plume. The costs for saline aquifers can be further split into two options: high residual gas saturation (HRG) and low residual gas saturation (LRG). In the case of HRG, CO_2 will be easily trapped in the pore spaces of the storage formation because the residual gas saturation is high (25%) and the plume will tend to be relatively compact and retained in the vicinity of the injection wells. This smaller plume will result in lower surveying costs. In fact, HRG saline aquifers could have a total cost for monitoring over the three phases that could be cheaper than that for EOR. LRG is likely to be the greatest expense in terms of monitoring because of the eventual size of the plume, with CO_2 migrating until it dissolves, along with the high cost of pre-operational monitoring. Again, these costs are indicative and will depend highly on a number of site specific factors.

The costs of a basic monitoring programme given a discount rate of 10% could be <$0.05 - 0.10 per tonne CO_2. Whereas an enhanced monitoring package which may be necessary for satisfying occupational health and safety concerns would be available at 40 – 60% over basic package. The most expensive technique is the seismic surveys but they are the best technology available.

Well measurements can provide many data sources (flow rate, temperature and pressure information) that seismic surveys cannot. However, how many wells do you want to drill in a saline formation? When the lack of wells can be seen as a benefit compared to the case in EOR.

At the moment the different monitoring techniques provide information in overlying maps but developing the technology to merge/integrate information together is the focus.

3.2 Leakage monitoring

3.2.1 Surface Monitoring Techniques

Surface flux measurements in the USA

Surface flux analyses have been undertaken at several CO_2-EOR fields in the USA (Rangely – Colorado, Teapot Dome - Wyoming and South Liberty - Texas). Surface fluxes have been measured using flux chambers that sit on the ground and using gas sampling tubes set into 10m deep hole. The results show that CO_2 in soil gas has two distinct origins, ancient CO_2 migrating up from the deep earth and biogenic CO_2 resulting from soil respiration and decomposition of roots. Generally, recently formed biogenic CO_2 is isotopically lighter than ancient CO_2 - i.e. biogenic CO_2 contains less ^{13}C than ancient CO_2. Thus, by carefully measuring the $^{12}C/^{13}C$ ratio in soil gas CO_2 one can determine its origin. If one is not careful, biogenic CO_2 can mask the results. In a large open system, this type of monitoring will be searching for a small, deep-sourced signal in the presence of substantial near-surface biological noise, but it can be done. The climate around the monitoring site is also important and due attention needs to be given to the different climatic conditions of a site when developing monitoring plans.

Even in a desert environment, photosynthesis can cause changes in the atmospheric CO_2 and there can be significant differences between the CO_2 flux of summer and winter. At the Rangely test site soil gas monitoring results have shown that the summer CO_2 flux can look random with no obvious pattern. In comparison, even though the biological CO_2 flux from photosynthesis does not reach 0 in the winter, the lower values show more detail in the NW part of the test site. Clearly, it will be important to understand any interference (natural or man-made[3]) that may effect or confuse the CO_2 measurements at each storage site.

At Rangely leakage of deep sourced methane has been identified, however, it cannot be confirmed that deep sourced CO_2 leakage is also occurring because the CO_2 has a similar $\delta^{13}C$ to the methane. It cannot be discounted that some of the deep sourced methane that is leaking has been converted to CO_2 by biological processes in the soil. It is, therefore, necessary in any monitoring exercise to measure a range of gaseous species not just CO_2.

After measuring the total CO_2 flux in soil gas samples at Rangely on a seasonal basis, and carefully correcting the measurements for contributions from biogenic sources, the total amount of CO_2 leakage from the petroleum reservoir is estimated to be less than 0.01% of the CO_2 stored over 15 years of operation.

[3] For example, natural interference can refer to the biological process of photosynthesis, vegetation and surface water cover or climatic variations. Man-made interference can refer to the development of the site, extra roads, buildings etc which may disturb the original monitoring locations.

Results from the Weyburn monitoring project

Surface flux measurements have been undertaken at the Weyburn CO_2 flood in Saskatchewan, Canada and the results compared with measurements taken in other countries as part of the NASCENT[4] project. The monitoring at the Weyburn site has been repeated and undertaken at the same time every year to get the best results. However, if monitoring occurs over an extended timeframe for example 50 years, the effects of climate change could have a big effect on the sampling results. Weyburn has used a continuous rather than batch gas sampling approach. This monitoring approach has worked well for the Weyburn project and the project emphasised the importance of obtaining the baseline conditions (initial dataset).

Results have indicated that monitoring for a range of gases (CO_2, HC, O_2, N_2, Rn, Tn, He) can give clues on whether there are conduits for gas migration, determining their presence can be indicative of a deep source, even identifying the source as a reservoir or whether the CO_2 is present from biogenic production. Other sources of information are essential to give a clear picture, soil gas monitoring alone is not enough. Other sources of information include: surface and sub surface geology, faults/fractures and linements to best target where to sample. Identification of potential release pathways helps to improve the risk assessment process and can help calibrate risk assessment results.

Surface flux analyses indicate that the CO_2 analysed at Weyburn is of biogenic origin. Overall, there is no evidence of CO_2 leakage from depth at Weyburn.

The study identified that it maybe necessary to have denser sampling, as one concern would be that a leak could be missed even if it occurs within a few meters of a sample site. Further work would be beneficial on the evaluation of potential gas migration pathways and on carbon isotope work.

Other improvements will be automatic continuous monitoring stations but the locating of these stations will be crucial and dependant on supporting information. The testing of such equipment can be done at sites of natural seepage, such as those investigated in the NASCENT project.

Further research required to improve confidence in monitoring results will include the integration with other techniques and the development of risk maps. However, the cost of using these techniques and the length of time it takes to get the results are potential barriers.

Geobotanical hydrospectral remote sampling

Geobotanical sensing can involve both airborne and satellite imagery. Airborne hyperspectral remote sensing methods allow early detection and spatial mapping of CO_2 leakage over whole regions. The technique has been tested at

[4] Natural Analogues to the storage of CO_2 in the geological environment

Mammoth Mountain in California and at the Rangely CO_2-EOR field in Colorado. CO_2 can potentially leak from the subsurface by percolating up faults, cracks and joints and become concentrated in the soil. CO_2 concentrations of up to 50% have been observed at Mammoth Mountain to significantly affect local plant and animal ecologies.

Vegetation Stress Techniques or Geobotanical Remote Sensing can be used firstly, to create a baseline dataset, and then for mapping known or buried abandoned well heads, subtle or hidden faults cracks and joints and then signs of CO_2 leakage. It uses very high spatial resolution imagery with pixel size of 3x3m. This high resolution can be used to look for habitat changes due to CO_2 seepage as the shape of the habitat is likely to change. At Rangely the airborne sensing has indicated three distinct habitat regions which appear to have not changed (based on comparison with earlier aerial photographs) for 23 years. Whereas results at Mammoth Mountain where CO_2 leakage is known to have occurred, changes in habitat distributions are clearly seen. For reference, injection of CO_2 has been underway at the Rangely field for the last 15 years, which would infer that CO_2 seepage has not occurred and affected these habitats. However, results have shown that desert environments confuse plant analysis by this method. Sagebrush can look dead in some branches whilst remaining alive in others. Drought tolerant plants will cause problems and for this reason this method is not very well suited to such areas.

Airborne reconnaissance to identify abandoned wells

In the early days of oil and gas production, wells were not completed to any particular standard. Airborne reconnaissance can be used to identify potential leakage pathways from old wells before injection has started. Once identified these old wells could be remediated and sealed. Unmanned vehicles used for this type of survey can have up to 9hr flight times.

Three methods are used to identify abandoned wells:

1. Magnetics can identify steel cased wells.
2. Uncased and improperly plugged wells can be identified by the volatile components.
3. Electromagnetic surveys can locate saline incursions into freshwater aquifers.

When this technique was used to search for steel cased wells in the Powder River Basin, the well locations were compared to the locations recorded by the Wyoming Oil and Gas Commission. In this example, the wells indicated by old datasets are off-centre and slightly mislocated. Clearly, caution should be taken when using historical information. In some cases the wells listed did not exist at all.

Seeps of radon can be used to detect uncased wells. Wells with Radon and CH_4 anomalies should be re-plugged first; those that do not show an anomalously high Radon and CH_4 concentration will probably not leak CO_2 immediately.

Aerial reconnaissance to search for existing wells and faults allows uncharted or mis-located, improperly sealed wells to be mapped quickly, accurately, and inexpensively. Further, the airborne techniques allow a large geographical area to be evaluated quickly when compared to ground-based searching. This is important when one considers that the underground CO_2 plume from a sequestration site may extend over 10's of square miles.

Offshore shallow gas monitoring

A new application of marine acoustic and seismic surveying is being developed to monitor offshore shallow gas build up in sediments and the water column. This technique has been demonstrated to monitor shallow methane accumulations in the Black Sea. Monitoring of seeps of natural gas in offshore locations infers that CO_2 seeps could also be identified using the same techniques. The seeps of natural gas offshore leave pockmarks on the sea floor; these could become leakage pathways if they occur over CO_2 storage sites.

An integrated approach to monitoring and modelling

Even for small CO_2 fluxes, subsurface CO_2 concentration can be high. Diffuse seepage leads to passive dispersion in the surface layer. Surface atmospheric conditions are effective at dispersing CO_2 seepage although it can be less effective, for example, in areas of low-wind or if the CO_2 flux is particularly high.

There are some conventional monitoring techniques that are very well established, such as accumulation chambers linked to IRGA (infrared gas analyzers) or eddy correlation towers and truck mounted LIDAR (LIght Detection And Ranging), that can be used to measure surface fluxes. Accumulation cells are good for measuring fluxes at small features, whereas Eddy correlation and LIDAR techniques are better for measuring the average flux over larger areas. Some of the techniques would be used constantly and others at intervals. The length of time of monitoring, before/during/after injection, is currently highly speculative, although the goal should be to have a comprehensive understanding of the ecological system prior to injection.

The ability to conduct monitoring of the site will be determined by seasonal features and climate conditions. Sampling can also be limited in cases, such as at the Frio site because of vegetation cover or surface water, or original monitoring sites maybe covered by later additions to the site such as roads. Therefore, plenty of time should be given to study the variable climatic conditions throughout the year without the influence of other factors. Monitoring approaches may have to be developed to take into account a site's particular requirements and future infrastructure developments (such as roadways) around a monitoring site.

3.2.2 Discussion

Comments raised by the delegates in open discussion included:

Monitoring shows due diligence, a way of showing the public that project operators care. However, there are lots of noxious materials injected without monitoring, why does CO_2 storage require such efforts?

Some may argue that monitoring methods are too late and remediation methods could have been put in place before CO_2 reaches the surface. In the case of Rangely, methane flux has been detected but there is no evidence of CO_2 leakage from the injection site.

It is agreed that for monitoring to be successful a firm baseline of the conditions around the site will be required. It will be essential to determine the naturally occurring CO_2 versus that which has been injected. Then the surface monitoring technologies will need to be chosen depending on the location. Structured tests will be required to ensure that the monitoring results can be compared between sites.

As far as what to measure and where, answers maybe available from risk assessments completed for a site so they should be done hand in hand. Especially as the issues for a site will be very site specific.

It could be argued that monitoring is too expensive and modelling is enough with remediation work undertaken when required. Of course public reaction may change this decision but perhaps it should not be the case that this level of public response is pre-empted in the first instance. If there is to be any type of tax on CO_2 though, accounting will be necessary as it is more than likely that storage will be based upon the net storage rather than the gross storage and monitoring will help in this assessment.

There is plenty of experience within the USA for wastewater injection (includes storm water), is the amount of CO_2 to be injected unprecedented therefore making it necessary for monitoring? Use modelling where necessary to identify problems and remediate where necessary.

Monitoring is too expensive; it may miss the problem and should be used as a very last resort if public perception or specific regulation requires it.

3.3 Monitoring experience from saline aquifer projects

3.3.1 Monitoring in offshore Saline Aquifers

Results from the Sleipner project

Monitoring of the injected CO_2 at the Sleipner gas field in the North Sea has been underway since 1999. To date some 7 million tonnes have been injected into the Utsira formation, a deep saline aquifer above the gas field. Statoil have reviewed their monitoring options at Sleipner, an observation well was considered to be too expensive, whilst well seismic was considered to be too complicated and also too expensive. Repeat seismic surveys were therefore considered to be the most promising option. Four seismic surveys have now been completed at Sleipner. They have clearly defined the outer boundary of the CO_2 plume, and also no leakage has been identified. Results indicate that the leakage detectability threshold will be dependent on the CO_2 distribution and could range from a few tonnes to a few thousand tonnes.

Time lapse gravity surveying offers a lower cost complementary technique to seismic surveying. A baseline gravity survey was completed at Sleipner in 2002 and a repeat survey will be completed in 2005. Data on the suitability of this technique for monitoring injected CO_2 will therefore be available in late 2005/early 2006.

Verifying injected CO_2 volumes using seismic monitoring

The SACS project has also attempted to verify the volumes of injected CO_2 at Sleipner based on the seismic data. Initial attempts to calculate the CO_2 volumes within the aquifer, showed that some of the parameters used in the calculation had a huge impact on the ratio of calculated to known volume of CO_2 (range 63% - 231%). Therefore, uncertainty in the variables needs to be re-addressed, especially the in-situ temperature and nature of dispersal, whether it is fine scale homogeneous mixing or whether it is extreme and patchy mixing. This work is continuing.

3.3.2 Monitoring Onshore Saline Aquifers

Results from Japanese Onshore Saline Aquifer Study - Nagaoka project[5]

In comparison to the offshore location of the SACS project, the Nagaoka project undertaken by RITE[6] and ENAA[7] looks at the geophysical monitoring of CO_2 injection in an onshore saline aquifer in Japan. The CO_2 is being injected into a thin permeable zone of the reservoir at 20-40 tonnes per day. The CO_2 injection started on July 2003 and will end January 2005. The total amount of

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[5] Since the Monitoring meeting in Santa Cruz (November 2004) the Japanese Onshore Saline Aquifer Study has been named the Nagaoka Project.
[6] Research Institute of Innovative Technology for the Earth
[7] Engineering Advancement Association of Japan

injected CO_2 will be about 10,000 tonnes. The pilot-scale demonstration allowed an improved understanding of the CO_2 movement in a porous sandstone reservoir. The results presented were based on experiences from cross well seismic tomography and comparison with well log data. Laboratory scale tests had indicated the potential for cross well seismic tomography as a tool for monitoring injected CO_2. The laboratory results were confirmed by the field experiment which demonstrated a p-wave reduction near the injection well as the CO_2 migrated past it. The presence of CO_2 was also identified by induction, sonic and neutron logging at the observation well. The seismic wave velocity showed a response to the injected CO_2 and has identified the mechanisms of how the CO_2 has displaced the formation water.

Results from Frio project

The Frio formation in Texas was chosen for an injection trial because there was extensive pre-injection characterisation data (3-D seismic, wireline logs from wells, core analyses and hydrological data was already available). Injection at the Frio site began on the 4th October 2004 and continued for 10 days, in which time 1,600 tonnes of CO_2 were injected. Post injection monitoring will continue until March 2005. Monitoring techniques being tested at Frio include: tracer injection, vertical seismic profiling (VSP) and cross well seismics, cross well electromagnetic, reservoir saturation tool (RST) logging as well as surface sampling for soil gas and groundwater contamination. The results from the monitoring will be combined and compared with an extensive programme of modelling that is running in parallel with the injection test. Modelling identifies the parameters that appear to control CO_2 injection and post injection migration. Physical measurements made can then confirm the correct values for these parameters.

There were some monitoring techniques that were not applied to the Frio project. They were not chosen because either it was estimated that they would be unlikely to collect useful measurements, they would interfere with the success of another experiment or they were simply cost prohibitive in the case of this project (although this may not be true of larger budget projects).

3.4 Monitoring experience from EOR projects

3.4.1 Results from monitoring at the West Pearl Queen site

Perfluorocarbon tracers (PFT's) were used to follow CO_2 migration and quantitatively estimate the CO_2 leak rate to the surface at a depleted petroleum well in the West Pearl Queen Field in New Mexico. Three tracers were co-injected with CO_2 including perfluoro-trimethylcyclohexane (PTCH), perfluoro-1,2-dimethylcyclohexane (PDCH) and perfluoro-dimethylcyclobutane (PDCB). The tracers were injected independently in 3, 12 hour slugs consisting of 500 ml each about a week apart along with the injected CO_2.

The concentration of each tracer detected in soil gas was small but relatively uniform over several months. The concentration of each of the three tracers in soil gas was approximately the same for each of the three tracers over the entire length of the experiment. The very small, but relatively constant concentration of tracer in soil gas indicates that the tracers were emanating from a very small leak from a large sink of tracer, ie. the petroleum reservoir. It appears that leakage occurred around the well bore. This is not surprising since the wells at the site are from the 1980's and had been previously over pressured, which could have caused small fractures in the annulus. The overall leak rate was estimated to be less than 0.1 % per year. A ground penetrating radar (GPR) survey of the caliche layer just below the sandy soil was conducted at the site. The GPR survey revealed areas of faulting to the north-west and thinning of the caliche to the south and south-west that coincide with leakage zones identified by the soil-gas monitors.

3.4.2 Results from monitoring at the Weyburn site

The Weyburn CO_2 Monitoring and Storage project consisted of 70 research projects and subdivisions which equated to 7 research areas. The project had CAN$20 million fund which will be difficult for other projects to duplicate. A key factor of the project was to fit in with the oil field operations and timing that would suit EnCana, the field operator. There were also difficulties with the local climate conditions where there is freeze/thaw and wet/dry cycles, subsequently, not all monitoring techniques were available. The monitoring has been undertaken over a four year period but how long is enough for some techniques?

As with other monitoring projects, the importance of the baseline survey stood out in its value to all subsequent work at Weyburn. There was also extensive information available for the field from 1000 wells, 600 cores, and all production injection history from 1955. Essentially all this information was available in the public domain. A good understanding of the long term storage capability of the cap rock was another significant result of the monitoring project at Weyburn. Tests showed that there was no communication through the cap rock and the preliminary risk assessment indicated that it was a good location for storage.

There can be plenty of improvement through the next phase of Weyburn (Weyburn II) with more quantification especially in seismics.

There were several kinds of monitoring techniques used at Weyburn including a 3D survey prior to CO_2 injection. The project discovered that initial modelling of the injection did not match seismic results. The modelling techniques were readdressed so that a second run matched what had been seen.

The geochemical monitoring and modelling of the Weyburn project enabled a model of the geochemical reactions in the reservoir over a 5000 year period to be developed for use in the risk assessment process. The CO_2 was tracked using carbon isotope signature which allowed the tracking of dissolution.

The injection of CO_2 into the Weyburn field resulted in a drop of 50-60% in resistivity and an increase in conductivity allowing fluids that had previously been inaccessible to be accessed. This improved production which was the purpose of the project.

Within the storage formation, flow units were identified with different flow properties. Each flow unit was modelled giving 5000 year reaction models. The models showed that the CO_2 will react given enough time assuming that the container is secure.

Geochemistry modelling was also used to look into the scenario that CO_2 had leaked from the reservoir. Each layer was assessed to see what minerals were available that would react with fluids. The layers included those below the Midale in case of down flow of injected CO_2. The modelling concluded that there was considerable excess storage capacity (solubility, ionic, and mineral) in the Weyburn Midale reservoir and that much of the geosphere above and below the reservoir had a high mineral trapping potential.

Some of the new modelling techniques are not suitable because of the expense and others need to be arranged so they fit in around the local climate conditions.

3.4.3 Discussion

Comments raised by the delegates in open discussion included:

For heterogeneous reservoirs, good modelling is increasingly important to better understand the reservoir.

There are positives and negatives for projects injecting CO_2 into an oil field with EOR. Monitoring of the injection site will benefit from access to reservoir models already available from oil recovery operations. It is also likely that the oil companies will have had better access to the high tech seismics than those involved with looking at CO_2 storage. Access to observation well data maybe available through the field operator and the produced fluid composition will have been recorded.

However, the experience gained from the pilot projects studying EOR can also provide some lessons for future projects. The schedule for an oil field will be driven by the operator and any project involved with that field will have to accept this priority and fit in accordingly. Similarly, the operations will be driven by the success of EOR rather than the amount of CO_2 that can be stored, although it is accepted that CO_2 could be more effectively used for EOR than it currently is. Other difficulties experienced when monitoring a CO2 injection site could be the noise interference of the other field operations. It will also need to be decided who had ownership or liability for the wells used during assessment and monitoring, research institutes and universities could have difficulty in accepting these liabilities.

The EOR resource for CO_2 storage is smaller than that for aquifers but there is plenty of information available. Where does this leave us in terms of monitoring aquifers? It has been suggested that monitoring should be undertaken along side risk assessments but at the end of the day it will be what data the modellers require and how that information can be provided? Again the question arises as to whether qualitative models can provide enough confidence or whether quantitative modelling is required. Progress may require a meeting with both the modellers and the monitors in the room at the same time.

It will be important to identify what can be done to bridge the gap which is something that the regional partnerships[8] in the U.S.A. are trying to approach. Monitoring needs to be done to satisfy the appropriate people but who these people are and how this would be achieved needs to be looked at in more detail.

The project results available for current CO_2 injection projects Weyburn and Sleipner have huge datasets that can be used to answer the questions. However, there could be some concern that seismics are being asked to perform tasks that were never required by the oil industry. Seismic monitoring can not do quantitative measurements alone but it is only one form of geophysics and there are other methods available. Perhaps geochemistry should be used to identify the actual site of the leakage first. The movement of CO_2 underground will be less of a concern if it does not involve seepage. Is it possible to identify how much of the CO_2 would be mineralised and therefore permanently stored?

In terms of the language used, it was suggested that climate modellers refer to % leakage. This value will drop over time and be different between projects therefore this is a useful piece of information that could be provided by the projects.

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[8] US DOE initative

3.5 New monitoring projects and future plans

3.5.1 Development of the In Salah CO_2 storage project

On an industrial scale, In Salah provides a project larger than Sleipner but smaller than Weyburn and it will provide another source of data for modelling and monitoring studies. The operation is part of a project to transport gas to Italy and Spain at a rate of 900 million scf/day. CO_2 will be injected at 1 million tonnes/year.

A range of models will be used at the site from regional to well scale. It is clear though that industry will not want to get involved in projects that leak. There is no recovery of costs at the moment for CO_2 injection and again industry will not be involved in these projects if there are not credits associated with storage of CO_2. Projects such as In Salah could be used to set precedents for the regulation and verification of the geological storage of CO_2, allowing eligibility for GHG credits.

3D seismics were used to identify the faults in the reservoir but it has held hydrocarbons for a significant period of geological time. The In Salah project could also have difficulties for certain monitoring techniques because of the local climate. Temperatures of $60^{O}C$ can be reached.

3.5.2 Development of the Teapot Dome CO_2 storage project

The Teapot Dome test centre is situated in Wyoming close to a major CO_2 pipeline (the Salt Creek pipeline). There are over 600 active wells and all the information is in the public domain. The structure is very well characterised which is certainly very important in planning new work. Whilst accepting that leakage studies are not something industry may want to be associated with, this new project would like to monitor engineered leakage to assess and model leakage profiles. Baseline Electro Resistance Tomography (ERT) and VSP surveys are now being taken in situ as well as geochemical and surface monitoring baseline data. Expansive outcrops of the reservoir rocks of Teapot Dome are allowing detailed studies of the reservoir properties including information about fracturing to be developed in advance of CO_2 injection. Large scale CO_2 injection is planned to commence in 2005.

3.5.3 Development of Mountaineer CO_2 storage project

On a regional basis the Mt Simon sandstone still has the best potential for storage but storage needs to be made feasible at the lowest cost. Site characterisation is the most important part.

The development of a monitoring project as part of the Mountaineer project showed that the regulatory monitoring requirements for injection wells and the scientific monitoring to understand the fate and transport of injected CO_2 will need to be addressed. It will be necessary to avoid setting costly precedents for future full scale sites. Monitoring does not want to be part of regulatory process unless absolutely necessary. The features of the site and the constraints related to the industrial setting need to be considered. Finally, the monitoring should have enough resolution in relation to the amounts of CO_2 injected.

3.5.4 New developments in Canada

Four new pilot CO_2-EOR projects are planned in Alberta, Canada. These projects will start operation in late 2004. One of these new pilot projects (details of which were still to be announced at the time of the workshop) will include a detailed monitoring programme of the injected CO_2. The monitoring project was expected to start operation in late 2004/early 2005.

4. SUMMARY OF MONITORING TECHNOLOGY AND LIMITATIONS

One of the aims of the meeting was to address the current status of monitoring techniques, assess their limitations and further development needs. The results of the workshop discussions on these issues are summarised in Table 2.

Table 2.	**Current state of the art**	**Assess limitations**	**New Technology/further developments**
Surface monitoring			
General	• Experience has shown that the development of baseline conditions at a site is an essential part of site characterisation for a CO_2 storage site. • Pathways can be identified near to the surface which could be potential leakage routes in the future. This can provide guidance for further monitoring. • Monitoring a range of gases can give clues as to whether potential pathways are conduits for gas migration. • Continuous monitoring has worked well at Weyburn and has been repeated and undertaken at the same time each year to provide consistent climatic conditions. It also provides real monetary value for surface monitoring. • From an existing operating site, extensive information is available for creating the baseline case. For Weyburn this information was available in the public domain and can significantly reduce the cost of monitoring.	Biological Interference: • Photosynthesis and soil respiration can cause changes in the levels of atmospheric CO_2 and can lead to significant differences between summer and winter. The lower biological interference during the winter can result in more detail being seen. • In a large open system, monitoring will be searching for small, deep-sourced signals in the presence of substantial near-surface noise. Local Climate Interference: • Sites where the local climate is both warm and wet can make surface monitoring very difficult, this was the experience at the Frio site. Weyburn experienced extreme conditions of freeze/thaw and wet/dry cycles, subsequently, not all monitoring techniques were available. Vegetation cover or surface water can unavoidably lead to biased sampling for some monitoring techniques. • Climate change could have a big effect on continuous monitoring. Over an extended timeframe (50 years of injection) the effects of climate change could impact on the monitoring results. Other factors: • Original monitoring sites can be lost with the development of the site. • Nitrogen fertilization from agricultural practices can modify the soil gas composition from that of unfertilized areas. • The Weyburn project was aware that any monitoring had to fit in with the commercial operations at the oil field.	Developments in methodology: • The baseline study will be essential to fully understand the noise at a site before CO_2 injection begins. • Surface monitoring technologies will need to be chosen depending on the location. Structured tests will be required to ensure that the monitoring results can be compared between sites. • Denser sampling should be a future development. Concern has arisen over leaks that could be missed even if they have occur within a few meters of a sample site. • Monitoring approaches may have to be developed to take into account a site's particular requirements. Technological developments: • Automatic continuous monitoring stations are a future technological development but the locating of these stations will be crucial and dependant on supporting information. Testing of this new technology can be done at sites of natural seepage, such as those investigated in the NASCENT project. • Further research to improve confidence will include integration with other techniques and development of risk maps.

	Current state of the art	Assess limitations	New Technology/further developments
Surface monitoring cont.			
Accumulation chambers/cells	• Surface leakage has been monitored at Rangely and Weyburn. Soil-gas flux measurements at Rangely indicate very low potential leakage rates (<0.01% per year), none at Weyburn. • Good for small features and delineating spatial trends. • Can be portable or fixed and automated	• The area covered by the chamber is small (~25cm diameter) so it will be essential to pin point the exact location of leakage sites to set up the monitoring station. This could be like looking for a needle in a hay stack. • Could miss a leak within a few meters of a sample site. • Diffuse leaks over a large area could be difficult to identify and quantify.	• Use in conjunction with other techniques. Can be used to fine tune after other techniques have located possible sites. • Link to RA to identify best sites to monitor • Need to monitor for other gases that can also indicate possible leakage pathways.
Eddy covariance	• Larger surface sampling area. The area of the footprint (m^2-km^2) is a function of the height of the tower and the meteorological conditions. Good for large areas with average flux measurement.	• As per accumulation chambers	• As for accumulation chambers
LIDAR	• Rapidly developing with good areal coverage	• Too early to define	• Too early to define
Electro magnetics	• This method of identifying abandoned wells has shown that historical data is not always accurate. The historical information of the location of wells does not always line up with the locations identified by this method. • Unmanned vehicles have been developed for this type of survey with up to 9hrs fly time. • Low cost technique • Seeps of radon can be used to detect uncased wells. Wells with radon and CH_4 anomalies should be re-plugged first.	• Current examples focus on large open areas that are not highly populated/urbanised. It may not be suitable for denser populated areas.	

	Current state of the art	Assess limitations	New Technology/further developments
Surface monitoring cont.			
Aerial reconisance	• Airborne techniques allow a large geographical area to be evaluated quickly when compared to ground-based searching. • Airborne hyperspectral remote sensing methods allow early detection and spatial mapping of CO_2 leakage from deep underground storage sites. • Vegetation stress techniques or geobotanical remote sensing can be used to create a baseline dataset. • Geobotanical sensing at Rangely showed no changes in vegetation patterns after 23 years of CO_2 injection. • It can also be used for mapping known or buried abandoned well heads, subtle or hidden faults and joints and signs of leakage • High spatial resolution can be achieved with a pixel size of 3x3m. This high resolution can identify habitat changes due to CO_2 leakage.	Biological Interference: • Desert environments can cause problems for this method. Drought tolerant plants may cause confusion. It is therefore not necessarily suited to these conditions. Local Climate Interference: • Rainfall can significantly change the images making them look much brighter. • Current examples focus on large open areas that are not highly populated/urbanised. It may not be suitable for denser populated areas, or areas with high air traffic density.	• Satellite could be next step
Tracers	• Perfluorocarbon tracers have been tested in a trial at West Pearl Queen. • Initial results look promising that the technique could detect very low leakage rates (i.e. <0.01% per year)	• Further more extensive trials are needed	• Too early to define

	Current state of the art	Assess limitations	New Technology/further developments
Sub-surface monitoring			
Seismic General	• Seismic has been demonstrated at Sleipner and Weyburn capable of monitoring the movement of CO_2 in reservoirs. • Using time-lapse surface seismic 1.4 million m^3 (2500 tonnes) of CO_2 is the minimum detectable. • Seismic can also determine movement of CO_2 out of a storage reservoir but does not have the resolution to detect low level leakage	• Saline aquifers are a much larger resource for CO_2 storage that EOR but there is a lot less information available. Therefore, determining the baseline conditions for saline aquifers is essential and likely to make the pre-operation costs more expensive than those for EOR. • Can be expensive, especially offshore • Not suitable for use in very deep thin reservoirs • Not suitable where Karst systems present. • Seismic's are being asked to perform tasks that were never required by the oil industry. • Seismic monitoring should not be used alone but as part of a suite of monitoring techniques. • The more expensive techniques such as seismic will not be undertaken by industry unless there are regulatory requirement or financial credits for storage.	• Seismic is being used by industry and as a result the technology is rapidly developing
Sub surface gravimetry	• Baseline tests at Sleipner • Good areal coverage with lower cost but lower resolution	• Too early to define	• Potentially less expensive than Sleipner but not yet proven
3D Seismics	• Tested at Sleipner & Weyburn • Detected movement of CO_2 in sub surface • Allows profiling of up to 5000 meters below the sea bed. Can also show effects in the water column. • 3D seismics at Weyburn did not match the initial modelling. This allowed a second run of modelling which matched that which had been seen.	• Not applicable in all situations • Costly • There is difficulty with verifying results of seismic tests. Changing the temperature of the reservoir has had a huge impact on the percentage known volume of CO_2 that is calculated.	• 3D seismics can identify the faults

	Current state of the art	Assess limitations	New Technology/further developments
Sub-surface monitoring cont.			
Cross well seismics	• Japanese trial, Weyburn and Frio • Observed CO_2 at observation well • Covers a relatively large cross section (Japan – 160m). • Following tests in Japan, researches were confident that the seismic wave velocity showed a response to the injected CO_2 and has identified the mechanisms of how the CO_2 has displaced the formation water.	• To early to define	• Not applicable in larger offshore fields
Observation wells	• Japanese test and Frio • Onshore existing wells can be utilised.	• Expensive, especially offshore too much for a research project. • Limited spatial information • Possible increased risk of leakage if new wells drilled through cap rock	• None
Produced Fluid and Gas	• Relatively inexpensive method to sample and analyze in-situ fluids, gas, and oil (if present). • Using in-situ P and T, can calculate reservoir fluid and gas compositions from surface samples (e.g. Weyburn). • U-tube technology allows sampling at in-situ P-T (e.g. Frio). • Can determine qualitative and quantitative effects of CO_2 injection on dissolution and/or precipitation processes with existing fluid, gas, oil, and minerals (e.g. Weyburn).	• Not all injection sites have good spatial coverage of monitoring or producing wells. • Drilling new monitoring wells for produced fluids and gases can be prohibitively expensive. • Field-wide P and T surveys are difficult, dataset can be incomplete. • Mass balance calculations can be complex, quantitative calculations associated with dissolution and precipitation of CO_2 contain some assumptions. • Can be difficult to overlay geochemical results with high-resolution seismic.	• In-line continuous gas measurements (e.g. Frio). • In-line gas detectors and downhole P, T instrumentation. • Need for “basic toolset” of geochemical parameters that can be measured quickly to assess subterranean CO_2 movement.

5. CONCLUSIONS

Major conclusions from the workshop:

- It is accepted that public outreach is critical. It allows the benefit of transparency whilst highlighting the concerns of the public. It provides targeted information about the possible role, benefits and risks of CO_2 storage and ensures that it is the right information that is being supplied.

- There are many techniques for monitoring and this is good because it indicates how big the tool box is.

- It is likely that a good monitoring strategy will include a combination of monitoring techniques that will be used at any one site. The decision on the techniques to be used will be dependant on what it is that the project will need to monitor or what the objectives of the regulators may be. The capabilities of the tests can be assessed by looking at scenarios of active projects.

- The cost of monitoring will not be a major factor in the total cost of a CO_2 storage project based upon a life time of 55-85 years approximately. The costs of basic monitoring given a discount rate of 10% could be <$0.05 - 0.10 per tonne CO_2. The enhanced monitoring package which would be necessary for occupational health and safety would be available at 40 – 60% over basic package. The most expensive technique is the seismic surveys.

- The monitoring of a site could be split into three phases: Pre-operational, Operational and Closure monitoring. For EOR monitoring some pre-operational will already have been completed and available for use by the operators of a storage project. As it is likely that there will have been no previous activity for a saline aquifer, the pre-operational monitoring will be more thorough and therefore more expensive; simply it will need to be done from scratch. However, the price ratio could change during the operation and closure phases. The cost will depend highly on a number of site specific factors.

- Soil gas flux measurements the Rangely EOR field and have indicated very low potential leakage rates (>0.01 % per year). However, near surface biological noise can mask the results of CO_2 flux measurements to the atmosphere. Thus, one must carefully measure the ^{12}C /^{13}C ratio in the CO_2 from soil-gas to distinguish between ancient CO_2 and biogenic CO_2. It is essential that baseline surveys are completed before injection to fully understand any interference to monitoring. It is both timely and expensive to return to a baseline conditions once injection has taken place.

- The local climate can have significant impact on the results of monitoring. In fact there will be some techniques that will not be suited to certain environments. An auditing tool to identify a suitable selection of techniques could be a good idea.

- Sampling can be biased through vegetation cover, seasonal climate conditions or surface water and original monitoring sites can be covered over during the development of the site (i.e. new roads). Therefore, in order to obtain a good baseline of the site, plenty of time should be allowed for monitoring before development begins to take place. The monitoring of a site will have to be developed to take in to account the sites requirements.

- Monitoring for other gases can be a way of identifying conduits for gas migration and determining their source through isotopic analysis.

- A continuous monitoring approach at the same time each year has been a successful approach at the Weyburn project. Denser sampling could help to find all leakage as it was identified that it could be possible to miss leakage even if a sample site was close by. Automated continuous monitoring stations will be a technological development.

- Aerial reconnaissance to search for existing wells and faults allows uncharted or mis-located, improperly sealed wells to be mapped quickly, accurately, and inexpensively. Further, the airborne techniques allow a large geographical area to be evaluated quickly when compared to ground-based searching. This is important when one considers that the underground CO_2 plume from a sequestration site may extend over 10's of kilometres.

- Monitoring of existing injection projects such as Weyburn and Sleipner provide access to actual results whilst providing an opportunity to identify areas of further work and highlighting limitations and uncertainties. Injection projects like Frio show the process of a project from site selection through to post-injection monitoring providing enormous amounts of information.

- Monitoring of a CO_2 injection site at an active oil field for EOR purposes will have positives and negatives. There should be vast amounts of information from cores and wells as well as a documented production history and the oil recovery operations will have access to high tech seismics. However, the schedule of the oil field will be driven by the operator and the operation will be driven by enhanced production rather than the storage of CO_2.

- There is still more that needs to be known about the conditions within the reservoir in the case of saline aquifers.

- Projects such as In Salah provide industrial scale examples of monitoring and modelling of CO_2 injection. However, at the moment there is no recovery of costs for CO_2 injection and industry will not be involved if there are not credits for storage. Neither will industry want to get involved with projects that will leak.

- Precedents for monitoring requirements of new CO_2 injection projects should not be set where they become cost prohibited.

6. FUTURE RESEARCH NEEDS

The workshop identified a number of future key research needs:

- Because there is such an extensive tool box of monitoring techniques, new injection projects need guidance on to what to measure and where. Such information can be provided by a safety and risk assessment of the injection site if this were undertaken early in the project lifetime.
- Once again because there are plenty of techniques available for monitoring injected CO_2 and it became evident, through the discussions at the workshop, that some techniques would be more appropriate to certain locations due to their suitability to particular climate conditions. The production of some form of "auditing" chart was suggested to enable the right combination of techniques to be selected for a particular project.

7. NEXT STEPS

A number of actions were agreed which included:

- IEA GHG will add the Monitoring Network to the dedicated Networks site on www.co2captureandstorage.info. The presentations and report of the workshop will be in a delegate's only area of the site but a public domain summary report will be produced and placed in the public section of the site.

- The second meeting of the network will be in autumn 2005, details will be sent out by the organising committee.

Appendix 1

Delegate List

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