Summary Report of

2nd Risk Assessment Network Meeting

Date: 5th to 6th October 2006
Lawrence Berkeley National Laboratory,
California, USA

Organized by IEA GHG, and LBNL.
With the support of EPRI
INTERNATIONAL RESEARCH NETWORK ON RISK ASSESSMENT

SECOND WORKSHOP
Berkeley, California, USA

Executive Summary

The International Risk Assessment Network was launched in August 2005 by the IEA Greenhouse Gas R&D Programme. This report provides a summary of the second meeting of the network hosted by Lawrence Berkeley National Laboratory in California, USA between the 5th and 6th October 2006. The workshop aims were to: review of the current status of risk assessment using case studies, assess the role of risk assessment in the framework of risk management, assess how best to communicate the results of RA studies to a broader non technical audience.

The meeting continued the progress made at launch network meeting in developing our understanding of the status of risk assessment in its application to CCS and developing the role that risk assessment can play. The main conclusions from the meeting can be summarized as follows:

1. Site characterization is a key component in ensuring that the storage sites selected can effectively contain CO₂ for 1000’s of years. Risk Assessment (RA) is one tool that can be used in the early screening of storage sites. RA and site characterization work in an iterative manner, over different project stages from preliminary screening to permitting to implementation.

2. Risk assessment studies can provide guidance on likely seepage rates from storage sites but they cannot define the impacts of leakage. Environmental Impact Assessments (EIA) can provide the framework for assessing the long term impacts of leakage. However, there is little research work underway currently that is addressing specifically the effects of CO₂ leaks and their potential impacts that could allow an EIA to be compiled. This is a major research gap.

3. A communication exercise with regulators has been undertaken to gauge their expectations for risk assessment and to make them aware of the current status of RA. As a result of this process regulators are better informed on both the role that RA can play and its current technical status.

4. However, RA is only part of the message that needs to be given to regulators; remediation is another important issue as well. Also, we need to get the message over that we are not promoting innovatory technology to avoid over regulation.

5. RA can also be considered as part of a Risk Management framework. RA is the means of identifying, estimating or calculating and evaluating potential risks. Risk management on the other hand deals with assessing, monitoring & remediating risks to conform to risk acceptance levels.

6. Natural analogues could be used to build confidence in CCS. By building up a database of events from natural and industrial analogues comparable to those that could occur from a CO₂ storage reservoir you can build a risk matrix that allows you to compare and communicate the risks of CCS in a way that is readily understandable to those outside the CCS community.
7. Four recently reported RA cases studies on potential geological storage sites were reviewed; three were based on aquifers and one on an oil field operation. It should be emphasized that several of these cases were not full blown risk assessments but were really scoping studies. The results of such studies should therefore be treated with some care when communicated outside of the technical community. The aquifer based assessments generally suffered from a lack of data, which is not unsurprising, which required a lot of assumptions to be made. The oil field case was much better characterized which allowed a more detailed risk assessment process to be undertaken. The oil field study gives us some confidence that CO₂ can be retained in that formation for 1000’s years the same degree of confidence cannot be drawn from the aquifer studies.

8. The RA case studies completed to date have contributed significantly to the learning process for undertaking such studies which will be of benefit in the future and help to allow us to better define the data requirements needed to complete a good robust risk assessment.

9. More RA studies are needed to help develop confidence in the techniques and models used as well in the results they generate.

The meeting has raised a number of issues that warrant further consideration at future network meetings. These include:

- On the issue of site selection we need to define how much characterization is needed to allow a formal risk assessment to be completed
- We need to ask the question whether a full blown quantitative risk assessment is required to give regulators confidence that a storage site is secure? Or could a simpler screening assessment be sufficient to generate confidence in CO₂ storage?
- Also now that we have some experience of using FEP databases for risk screening and scenario development can we design a screening process involving a simpler FEP database?
- There is a desire by regulators and project implementers alike to see the development of a RA standard or protocol. We need to decide how best to proceed to develop such a protocol or standard
- Similarly we need to process to peer review models and benchmark RA tools and approaches. We also need to decide how best to proceed to develop a benchmarking process.

In addition, the meeting has identified that within the RA community there is a need to try and harmonize the terminology used to allow the community to effectively communicate amongst itself let alone to outside bodies.

In summary, it was clear that we have gained a lot of knowledge from the RA cases completed to date, but that learning is far from complete and we need more case studies to be undertaken to build our confidence in the tools, models and approaches used. Also the RA studies to date have only been undertaken on storage reservoirs, we also need studies on the full CCS chain to help convince the public that the whole system is safe not just the storage reservoir.
SECOND WORKSHOP OF THE INTERNATIONAL RESEARCH NETWORK ON RISK ASSESSMENT

1. Introduction

The International Risk Assessment Network was launched at a meeting held in the Netherlands organised by the IEA Greenhouse Gas R&D Programme (IEA GHG) and hosted by TNO-NITG\(^1\). The Risk assessment network compliments two other international research networks that IEA GHG operates relating to geological storage of CO\(_2\). These networks cover monitoring and well bore integrity. It is considered that these three networks together focus upon one of the key technical issues that need to be addressed for CO\(_2\) capture and storage to be widely implemented, that of containment. It will be essential to gain both governmental and public support for the technology to demonstrate that the CO\(_2\) injected into geological formations can be effectively contained. To resolve this issue it is considered that no single activity or action will satisfactorily answer the question alone. However, a number of different activities when taken together should be able to resolve it. These activities include:

- The development of a regulatory process for CCS that requires an operator to demonstrate “due diligence” in the selection of an appropriate site for CO\(_2\) storage. The regulatory process would include: site characterisation, geological/geochemical modelling and development of a simulation tool for long term prediction of the fate of injected CO\(_2\). In addition, potential seepage/fugitive emission pathways will be identified and remediation plans incorporated into the operational plans.
- The monitoring of CO\(_2\) injection projects to determine actual seepage rates to the surface, if they occur. Knowledge of the flux to the surface will allow an estimate of both the local health/safety risks possible ecological consequences to be determined.

Taken together this work should help to build a reference manual of data on reservoir integrity/security and actual seepage of CO\(_2\) that should build confidence that the CO\(_2\) can be contained effectively in the geological formations into which it has been injected.

One issue that needs to be considered is the need for a risk assessment study. The use of Risk Assessment (RA) is common practise in many industries, such as the power sector and nuclear industries. To date the RA network has shown that the application of risk assessment tools and techniques to CCS is at an early stage and careful thought needs to be given to the results that this work is generating. RA studies will potentially be of significant interest to the regulatory bodies that will consider potential CCS projects but regulators will need to be aware of potential limitations in the development of the RA so that they do not over regulate operators in early. The status of RA for CCS projects is the focal point of this second RA network meeting.

This report provides a summary of the second meeting hosted by Lawrence Berkeley National Laboratory in California, USA between the 5\(^{th}\) and 6\(^{th}\) October 2006.

---

\(^1\) Netherlands Organization for Applied Scientific - Netherlands Geological Survey
2. Aims and Objectives of Second Workshop

The workshop aimed to provide:

1. Overviews of other relevant international research network activities that impact on the risk assessment network, in particular the well bore integrity network.
2. Provide feedback from the working groups on key topics that had been set up from the previous meeting.
3. A review of the current status of risk assessment using case studies
4. Assess the role of risk assessment in a the framework of risk management
5. Assess how best to communicate the results of RA studies.

In addition, one objective of the meeting was to identify new areas for the network to study.

3. Workshop Programme and attendees

The programme for the workshop is outlined in Table 1.

The first day of the workshop was structured into 5 sessions of technical presentations; the results of each of these sessions are summarized in section 4.

On the second day 4 cases studies were presented in summary and then the group broke into 4 breakout sessions to discuss the case studies in detail. The results of the break out discussions were then reported back to the full group
## Table 1 Workshop Programme

### Day 1 (5th October 2006)

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>08.30 to 08.40</td>
<td>Welcome to LBNL and, fire briefing/safety issues, Larry Myer LBNL</td>
</tr>
<tr>
<td>08.40 to 08.50</td>
<td>Meeting aims and context, John Gale IEA GHG</td>
</tr>
<tr>
<td>08.50 to 09.20</td>
<td>Site Characterization - summary of a workshop, Jens Birkholzer, LBNL and Elizabeth Scheehle, USEPA</td>
</tr>
<tr>
<td>09.20 to 09.50</td>
<td>Well Bore Integrity Network – feedback and current state of knowledge, Charles Christopher BP</td>
</tr>
<tr>
<td>09.50 to 10.10</td>
<td>Statistics on &quot;Unexpected Occurrences&quot;, Preston Jordan, LBNL</td>
</tr>
<tr>
<td>10.10 to 10.30</td>
<td>Break</td>
</tr>
<tr>
<td>10.35 to 10.50</td>
<td>Review of Inaugural meeting and actions set, John Gale, IEA GHG</td>
</tr>
<tr>
<td>10.50 to 11.10</td>
<td>Data Management and Risk Analysis Feedback, Ton Wildenborg, TNO-NITG</td>
</tr>
<tr>
<td>11.10 to 11.30</td>
<td>On shore ecological impacts assessment, Jonathan Pearce, BGS</td>
</tr>
<tr>
<td>11.30 to 12.10</td>
<td>Regulatory needs for risk assessment, Mike Stenhouse, Monitor Scientific (including discussion).</td>
</tr>
<tr>
<td>12.10 to 13.00</td>
<td>Regulatory framework development under the CO2GeoNet project. Anne Korre, Imperial College (including discussion).</td>
</tr>
<tr>
<td>13.00 to 14.30</td>
<td>Lunch</td>
</tr>
<tr>
<td>14.00 to 14.20</td>
<td>The role RA as part of a Risk Management framework, Ton Wildenborg, TNO-NITG.</td>
</tr>
<tr>
<td>14.20 to 14.40</td>
<td>Open discussions on RA regulatory feedback.</td>
</tr>
<tr>
<td>14.40 to 15.00</td>
<td>Risk Assessment of a CO2 storage site and risk-driven decision process. Natalia Quisel, Schlumberger.</td>
</tr>
<tr>
<td>15.00 to 15.45</td>
<td>Discussion Session on RA and RM.</td>
</tr>
<tr>
<td>15.45 to 16.00</td>
<td>Break</td>
</tr>
<tr>
<td>16.00 to 16.15</td>
<td>Outline of the plan for international collaboration: Norio Shigetomi, Mitsubushi Research Institute Inc.</td>
</tr>
<tr>
<td>16.15 to 16.45</td>
<td>Development of international collaboration for building confidence in the long-term effectiveness of CO2 geological storage; Hiroyasu Takase, Quintessa Japan.</td>
</tr>
<tr>
<td>16.45 to 17.15</td>
<td>Open discussion on plans for international collaboration.</td>
</tr>
<tr>
<td>17.15 to 17.30</td>
<td>Resume of Day 1</td>
</tr>
</tbody>
</table>

**Close Day 1**
Table 1  Workshop Programme (Cont’d)

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day 2 (6th October 2006)</strong></td>
<td></td>
</tr>
<tr>
<td>08.30 to 08.50</td>
<td>Introduction to Day 2, John Gale IEA GHG.</td>
</tr>
<tr>
<td>08.50 to 09.00</td>
<td>Brief introductions to RA cases to be reviewed. The cases are:</td>
</tr>
<tr>
<td></td>
<td>• Latrobe Valley case - Andy Rigg, CO2CRC</td>
</tr>
<tr>
<td></td>
<td>• Mountaineer case - Joel Sminchak, Battelle.</td>
</tr>
<tr>
<td></td>
<td>• Weyburn case - Malcolm Wilson, EnergyINet.</td>
</tr>
<tr>
<td></td>
<td>• Schweinrich - Rob van Eijs, TNO-NITG and Sara Eriksson, Vattenfall</td>
</tr>
<tr>
<td>09.00 to 12.00</td>
<td>Breakout Group discussions on case studies.</td>
</tr>
<tr>
<td>12.00 to 12.30</td>
<td>Preparation of breakout group presentations.</td>
</tr>
<tr>
<td>12.30 to 13.30</td>
<td>Lunch</td>
</tr>
<tr>
<td>13.30 to 15.00</td>
<td>Presentation of breakout group findings.</td>
</tr>
<tr>
<td>15.00 to 15.30</td>
<td>Break</td>
</tr>
<tr>
<td>15.30 to 16.15</td>
<td>Open discussion on current state of knowledge on RA/Performance assessment.</td>
</tr>
<tr>
<td>16.15 to 17.00</td>
<td>Discussion on future actions and next steps for network. Malcolm Wilson, EnergyINet.</td>
</tr>
<tr>
<td>17.00 to 17.15</td>
<td>Meeting Close.</td>
</tr>
<tr>
<td>Close Day 2</td>
<td></td>
</tr>
</tbody>
</table>
4. Results and Discussion

4.1 Technical Presentations

The first session of technical presentations were aimed to bring the network members up to date with related activities relevant to risk assessment such as: site characterization, well bore integrity and incident statistics from relevant industries. The second set of presentations provided the members with feedback on the tasks set in motion at the end of the inaugural meeting. Presentations in Session 3 considered the inclusion of risk assessment in risk management frameworks. The final session, considered a Japanese proposal to establish an international collaborative activity to help build confidence in CO2 capture and storage.

4.1.1 Related activities relevant to risk assessment

Jens Birkholzer provided the delegates with an overview of an international symposium that US Environmental Protection Agency (EPA) had organized with Lawrence Berkley National Laboratories (LBNL) in March 2006\(^2\). One of the main concerns of the US EPA in relation to CO2 storage is the potential for large releases of CO2 from a storage reservoir and its possible impact on groundwater quality. US EPA has sponsored two studies with LBNL to first study the potential for large releases of CO2 and the second; to model the impact on groundwater quality. Neither of these pieces of work was complete at the time of the event but results should be available by the time of the next meeting of the network in August, 2007.

The site characterization symposium had over 150 participants from 11 countries with 47 oral and 28 poster presentations given. The symposium aimed to address the various aspects associated with the selection and characterization of geological sites for the CO2 storage. These aspects covered included:

- General Framework
- Characterization Methods and Technology
- Regional and Project Case Studies
- Characterization of Leakage Pathways
- Fundamental Processes
- Screening and Ranking Tools
- Regulatory and Social Issues

At the outset of the meeting a definition for site characterization was offered by Peter Cook from the CO2CRC which was:

“The collection, analysis and interpretation of data and the application of knowledge to judge, with a degree of confidence, if an identified site will store a specific quantity of CO2 for a defined period of time and meet all health, safety, environmental requirements.”

It was felt that there were three components to a storage system which included:

\(^2\) The proceedings and presentations from this workshop can be found at http://www-esd.lbl.gov/CO2SC/
1. The **injectivity** component which includes the wells and any pressure build up due to injection,
2. The **storage capacity** component to ensure sufficient volume,
3. The **containment effectiveness** component which involves long term sealing properties.

The point was made that from an operator, that not everybody thinks the same things are the most important. Also, from a regulatory perspective not all the characterization data is needed to gain a permit. Site characterization can be considered as site specific and when the timing for site characterization was considered a number of questions were raised. These included:

   a) Should characterization of a site occur only prior to CO\textsubscript{2} injection or should it continue (and be refined) throughout the injection phase, and during later monitoring and verification stages?
   
   b) Should we define three phases of site characterization as; pre-injection, injection, and post injection or should it be; pre-injection, injection/post injection, and site verification.

It was muted that a staged approach for site characterization would have important ramifications for permitting such as:

- Approval would be based on limited characterization and documentation,
- Monitoring of the CO\textsubscript{2} movement would provide important information on site characteristics,
- Monitoring during injection and post injection phases would verify site suitability,
- Remediation plans need to be in place in case things go wrong.

The issue then becomes how much characterization is enough. We need to define which data is required compared to what would be ideal to have, because resources will be limited. It was felt that it was an easy task to define what can be done, but not as easy to determine what is necessary. Pilot projects and demonstration projects can help by determining the minimum information requirements, and to develop best practice.

Quick and reliable methods for selecting storage options will be needed to help screen possible storage sites and allow the comparative assessment of site attributes. The detailed characterization need only then be carried out on the most promising options. Several tools are currently available with different perspectives these include:

- Preliminary Screening,
- Risk Assessment,
- Economic,
- Geologic/Geographic.

Key gaps identified that need to be addressed for effective site characterization were:

- Large-scale characterization of seals for saline formations
  - Thickness, continuity, uniformity, long-term integrity
– Static and dynamic conditions

• Effective tools/procedures/protocols were needed for characterization of pathways (faults, wells) and their leakage potential

• Predicting plume extent and storage capacity, considering multi-phase flow with heterogeneity and dissolution, plus displacement of water
  – Upscaling strategies for multiphase (fingered) flow
  – Simultaneously predict flow, mechanical, and chemical changes
  – Impact on regional groundwater systems

• Definition of standards for site characterization
  – when, how much data, degree of confidence, HSE requirements, compliance period

With regard to site characterization and risk it was proposed by Peter Cook that;

“There is no such thing as the perfect storage site, but we can identify sites with acceptable levels of risk that are fully fit for purpose”

As far as risk is concerned: governments define the level of acceptable risk through regulations, operators decide what level of risk they can carry by taking a project forward. Individuals may perceive risk in a different context to the regulators and operators. Risk can be communicated in a number of ways; either as a cost, a value for credits, or in its impact on health and safety. A Risk assessment expresses risk formally as the product of consequences of a feature, event or process (FEP), multiplied by its probability. Risk assessment and site characterization work in an iterative manner, over different stages from screening to permitting to implementation. However the question was raised, whether site characterization will ever provide the level of detail needed to conduct a formal risk assessment?

Jens concluded by making the following points:

1. Carefully selected sites can be safe (i.e. they will meet acceptable levels of risk)
2. Site characterization, as the basis for permitting, needs to be defined and mutually agreed upon (standards). Inherent questions include:
   • How much information is necessary?
   • When does site characterization conclude?
3. Sophisticated characterization and screening tools are available, but more are under development,
4. Pilots and early large-scale projects provide an important base of experience (learning by doing).

The following questions were raised:

Q. Are tools available to identify faults?
A. Yes, tools are available that can identify faults but these cannot tell us if a fault will seep or give us information on the faults properties

Q. Do we need to develop a new tool to measure fault properties and identify leakage?
A. Not necessarily, we can monitor the fault to see if it leaks
Q. How do we define what is an effective tool when there is no standard to measure them against?
A. The tools we have can define the boundaries of leakage but they cannot be precise, as long as we know where the limits lie we can use existing tools.

Q. Do we know enough to set a RA standard?
A. There are still a lot of questions to be answered, so probably not yet.

Several members of the audience also made comments;

Sally Benson – regulations are moving towards setting safety standards the role of RA is to make progress on geological characterization to feed into these standards.

Anne Korre – RA is necessary because we need to know what level of confidence we need to aim for.

Tony Espie – Detailed quantitative RAs depend on the hazard of what you are doing. In the nuclear case you are trying to keep a few molecules out of the system for thousands of years, CO₂ storage is at the other end of the spectrum we want to keep as much out of the atmosphere as possible for as long as we can. For that reason semi-quantitative and quantitative RAs will suffice. For example the USEPA might not need a full blown RA from a regulatory standpoint. If something did happen, it is important that we are able to remediate.

Charles Christopher’s detailed presentation was deferred until the next meeting but it was pointed out that a detailed analysis of a well in Texas was underway. This well had now been taken out of service but has had wet CO₂ flowing through it for 30 years. By undertaking experiments on old wells it is hoped to gain a better understanding of well cement degradation by CO₂ which will allow the calibration of laboratory experiments and lead to the development of models for well failure that could be used in risk assessments.

Preston Jordan gave a presentation on what can be quantifiably learnt about the risks of geological storage from data on existing industrial analogues. The presentation considered public domain data from the US on worker safety. The data sets accessed are outlined in the table overleaf:
United States Bureau of Labor Statistics (BLS)  
Survey of Occupational Injuries and Illnesses  
Census of Fatal Occupational Injuries  
Quarterly Census of Employment and Wages

International Association of Oil & Gas Producers (OGP)  
Safety Performance Indicators

The UBS statistics contains data for all industries and all companies. The OGP data set only contains information on the upstream oil and gas industry. The upstream oil and gas industry is contained with the UBS statistics but is not clearly broken out. The study then went on to compare the number of reported incidents which involved first aid, absences from work and fatalities.

The main conclusions that could be drawn were:

1. Drilling has the highest incident and lost time case rate of the functional sectors
2. Based on United States Bureau of Labor Statistics data for the upstream oil and gas industry, worker safety incidents in the CO₂ storage industry in the United States will be almost certainly be less common than in industry in general, but the consequences of these incidents in terms of lost work time and fatalities will likely be higher than in industry in general.
3. Based on International Association of Oil and Gas Producers data, both worker safety incidents and incident consequences in the CO₂ storage industry in the United States will be lower than in the upstream industry to the extent that the CO₂ storage industry is more onshore, requires less drilling and includes a higher proportion of exploration-type activities (such as monitoring and verification).

4.1.2 Reports from task groups from previous meeting

At the inaugural meeting of the risk assessment network³ it was agreed to undertake 4 pieces of work before the group met again. These 4 pieces of work were:

1. To build an inventory of data sets on storage projects and risk assessments
2. To assess the impacts of seepage of CO₂ from storage sites onshore
3. To assess the regulatory needs for risk assessment
4. To assess risk assessment frameworks and terminology

The task group leaders reported back in each case.

**Task 1** - Ton Wildenborg provided a report on the progress made on compiling the data base. The group had met after the inaugural meeting and developed an excel spreadsheet containing 16 geological storage sites. The list is contained in the table below. The list includes all those storage projects that were undertaking detailed characterization and monitoring work that could build up data sets that could be used for risk assessment studies.

The data set had not been developed further since that meeting. Several of the sites in the data set were to be discussed during the case study section of the meeting; namely Weyburn, Schweinrich and Mountaineer.

<table>
<thead>
<tr>
<th>Site</th>
<th>Storage medium</th>
<th>Country</th>
<th>Institute</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>In Salah</td>
<td></td>
<td>Algeria</td>
<td>BP</td>
<td>planned</td>
</tr>
<tr>
<td>Gorgon</td>
<td></td>
<td>Australia</td>
<td>Chevron</td>
<td>confidential</td>
</tr>
<tr>
<td>Weyburn</td>
<td>oil field</td>
<td>Canada</td>
<td>PTRC</td>
<td>planned</td>
</tr>
<tr>
<td>Apache Middale</td>
<td>oil field</td>
<td>Canada</td>
<td>PTRC</td>
<td>planned</td>
</tr>
<tr>
<td>Pennwest</td>
<td></td>
<td>Canada (Alberta)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Montmiral</td>
<td>CO2 field</td>
<td>France</td>
<td>PTRC</td>
<td>planned</td>
</tr>
<tr>
<td>Schweinrich</td>
<td>aquifer</td>
<td>Germany</td>
<td>PTRC</td>
<td>planned</td>
</tr>
<tr>
<td>Nagaoka</td>
<td>gas field</td>
<td>Japan</td>
<td>PTRC</td>
<td>planned</td>
</tr>
<tr>
<td>K12-B</td>
<td>aquifer</td>
<td>Netherlands (offshore)</td>
<td>Statoil</td>
<td></td>
</tr>
<tr>
<td>Sleipner</td>
<td>oil field</td>
<td>Norway (offshore)</td>
<td>BP</td>
<td>confidential</td>
</tr>
<tr>
<td>Forties</td>
<td>oil field</td>
<td>UK (offshore)</td>
<td>Statoil</td>
<td></td>
</tr>
<tr>
<td>SACROC</td>
<td>CO2 field</td>
<td>USA</td>
<td>Statoil</td>
<td></td>
</tr>
<tr>
<td>McElmo dome</td>
<td>aquifer</td>
<td>USA</td>
<td>Statoil</td>
<td></td>
</tr>
<tr>
<td>Frio</td>
<td></td>
<td>USA (West-Virginia)</td>
<td>Statoil</td>
<td></td>
</tr>
<tr>
<td>Mountaineer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Task 2** – Jonathan Pearce reported on a review undertaken by BGS for IEA GHG on the potential, impacts of seepage from onshore geological storage projects on terrestrial ecosystems. The rationale behind the study was to address whether specific long-term performance criteria be added to those already defined through other HSE legislation? If performance criteria are considered appropriate should they be: generic or site-specific? Underlying these questions were issues such as

- How relevant could generic safety criteria be?
- What form should the performance criteria take?

If such performance criteria are not required then the following questions need to be reconciled:

- How can operators and regulators judge site performance and what aspects of ecosystems to monitor?
- How do operators and regulators know when to intervene, what to remediate, how to remediate?
- How do the operators and regulators address public concerns about long-term safety of the site?

It was noted that the early demonstration projects are operated within existing oil and gas regulatory frameworks. However, these frameworks do not necessarily require consideration of long-term, post-closure issues. Storage will be onshore in North America in particular and Europe to some degree.
It was felt that a modified environmental impact assessments (EIA) could provide a framework for assessing long-term impacts of potential leaks\(^4\). The EIA could include the following:

- A description of the site selection and characterisation.
- A description of the project, including anticipated injection mass & rates, engineering design, and the project duration.
- Simulations of CO\(_2\) behaviour over the long term, history-matched to monitoring data obtained during and after injection.
- A description of long-term monitoring options if required.
- Appropriate remediation plans.
- An assessment of the risks for & consequences of leakage, for a range of realistic possible future site scenarios.
- A closure plan.
- Together these components seek to demonstrate that future risks are as low as reasonably practicable (ALARP).

The possible impacts of low level CO\(_2\) seepage from a storage site, in no particular order, should it occur are:

- Affect human and animal health.
- Inhibit crop growth or, in high concentrations, cause root asphyxia with resulting plant death.
- Change biological diversity and species composition.
- Change subsurface biogeochemical processes
- Alter pH, microbial populations and nutrient supply.
- Alter groundwater quality (acidification, mobilisation of heavy metals in aquifers, etc) with implications for water resources.

The review has shown that there is currently little research addressing specifically the effects of CO\(_2\) seepage from depth and their potential impacts.

The study also identified a number of gaps which included:

- No target species have been identified.
- No thresholds or limits to CO\(_2\) exposure for any species have been identified.
- Little data on the long term, low-level exposure of CO\(_2\) on terrestrial ecosystems or on any single or potential target species is currently available.
- No data on recovery rates are available.
- Almost no data available on the effects of CO\(_2\) seepage on groundwater quality are available.
- Little information is available concerning co-injected species, or those mobilised during migration.

It was felt that the gaps identified constrain: the capabilities of risk assessments to accurately identify important risks, also the formulation of appropriate, cost-effective

monitoring protocols and remediation plans. In addition, the integration between considerations of potential impacts of CO$_2$ leaks on terrestrial ecosystems and performance assessments.

Finally a research plan was proposed to take this issue forward. The plan includes the following elements:

1. Scenario definition:
   - Define relevant scenarios to reflect the storage context (geographical location, local environment, land use, etc)
2. Characterisation:
   - Define surface and subsurface ecosystems in terms of flora and fauna.
   - Identify indicator species (most susceptible, those with biggest change).
3. Impacts:
   - Identify impacts of CO$_2$ on indicator species & total ecosystem.
   - Define appropriate thresholds and safety criteria.
   - Identify recovery rates.
   - Scope impacts on ground waters via modelling and experiments.
4. Monitoring:
   - Develop floral and faunal monitoring techniques.
5. Integration:
   - Improve system models by integrating key processes and indicators in an iterative manner.

In response to a question asked, Jonathan said we want to avoid quoting headline seepage rates. He also added that EIAs were probably the best route for assessing the impacts of long term leaks.

**Task 3** – Mike Stenhouse presented the results of another project supported by IEA GHG entitled the Role of Risk Assessment in Regulation of Geological CO$_2$ Storage Projects. The objectives of the project were to:

1. Establish whether there are existing (regulatory) provisions for authorizing CO$_2$ storage projects and whether these are sufficient/adequate for future implementation of large-scale geologic CO$_2$ storage projects
   - Are there any ‘disconnects’ between regulator and implementer in terms of timeline?
2. Identify key gaps associated with RA and its role in regulatory oversight

The study involved an initial round of contact establishment to get people buy in to the project. The production of two documents: a briefing document on the status of risk assessment for CCS and a follow up questionnaire. The distribution of these documents to the participants; followed by follow-up calls and finally the collation of the results. The briefing document contained current details on the state of knowledge on:

- Retention timescales,
- CO$_2$ seepage fluxes
- RA methodologies,
- RA modeling approaches,
• Role of monitoring in RA,
• Comprehensiveness of RA,
• Risk communication to stakeholders,
• Need for a technical standard/protocol,
• Potential gap /RA needs.

Note: the briefing document can be found in the report of the study\textsuperscript{5}.

Regulators from 10 countries agreed to participate. The countries involved were: Australia, Canada, France, Germany, Japan, The Netherlands, New Zealand, Norway, U.K., and U.S.A. These were supplemented with implementers who are involved in major CO\textsubscript{2} storage projects.

The feedback received indicated that regulators were in favor of:
• The need for a specific regulatory framework for CCS projects, unlikely to exist before 2008 at earliest
• For RA to be part of the authorization process
• Flexibility in methodology and modeling approach
• Link between RA results and monitoring
  – To allow confirmation of predictions
  – As means of ensuring safety (HSE impacts)

The knowledge gaps identified by regulators included:
• The nature of long-term risks
  – In particular the retention/seepage timeframes
• Storage capacity verification
  – Ability of monitoring techniques to quantify extent of any migration or seepage
• Wellbore/caprock integrity
• Effects of fluid movement
  – Regional versus. localized displacement
• Specific environmental impacts
  – Groundwater and ecosystems

The feedback received indicated that the implementers were in favor of:
• Regulatory framework specific to CCS projects, which addresses timeframes and CO\textsubscript{2} leakage rates / fluxes
• Flexibility in modeling approaches
• A link between monitoring and RA results - for confirmation
• Some form of RA protocol or standard

Whilst the knowledge gaps identified by implementers included:
• Experience with different types of storage site
• Quantitative information from natural analogues
• Fundamental data
  – PVT behavior of CO\textsubscript{2} and impurities
  – Thermodynamic, kinetic data

Coupling between geochemical and geomechanical processes
- Well bore seal longevity
- Benchmarking of RA modeling approaches

Generally it can be seen that there was a good connection between the responses of the regulators and implementers.

It was felt that when it comes to the approval of CO₂ storage projects, in the short-term, these will continue to be approved on a case-by-case basis. Also research work currently being carried out on CCS-related projects (Sleipner, Weyburn, Frio etc.), including RA results/predictions, will help guide regulators. Monitoring during injection and post-injection phases will play a major role in regulatory acceptance of long-term safety. The link between monitoring and confirmation of RA predictions is very important. Both groups felt that some form of technical standard or protocol for addressing long-term safety in CCS projects was important. The Technical standard or protocol should have a basic framework (flexible). It should build on existing documents, e.g. Best Practice Manual, SACS Project, national standards for risk analysis. In addition, benchmarking studies are needed to enhance confidence in different modeling approaches but these needs to be carefully planned. Monitoring will provide a quantitative resolution capability to match needs by Confirming RA predictions and quantification of migration of CO₂ for GHG inventory purposes. The development of coupled geochemical-geomechanical-fluid transport models is essential to the development of long term predictions for CO₂ storage that regulators can be confident with.

After the presentation there was a considerable debate regarding the need for a qualitative or quantitative RA. There was a feeling from industry that a qualitative analysis, coupled with effective monitoring and remediation plans would be sufficient to build confidence. Other felt that quantitative assessments provide regulators with more confidence and many countries would require them. Also consequence analyses would be required to develop flux data because regulators were looking for that information. The response from industry was that it was impractical to attempt to define numbers based on the uncertainties involved and it was better to tell the regulator what could be realistically achieved. Others cautioned that we do not need complex RAs that give numbers that are not robust, rather we need to be able to undertake a subjective analysis on whether a reservoir would be suitable or not. This was reinforced by others who stressed that in the early stages we need to provide regulators with sufficient information to allow them to be able to discriminate between sites and make a decision to grant a permit. It was also felt that the precautionary principle could be applied to CCS. RA is only part of the message that needs to be given to regulators; remediation is one part as well. We need to get the message over that we are not promoting innovatory technology. There was some concern with the precautionary principle in that it is difficult to draw the boundaries of the box. We need to stress the point that getting as much CO₂ out of the atmosphere as soon as we can is the key issue.

**Task 4** – Anne Korre presented the results from the final task, which was to report back on the work being undertaken by CO2GeoNet on risk assessments frameworks for CO₂ storage. The programme consists of three tasks:
Task 1: Development of an inventory of tools used in risk and performance assessments
Task 2: Development of guidelines for terminology use
Task 3: Development of a conceptual framework – based on the inputs from Tasks 1 and 2.

Progress on tasks 1 and 3 were reported at the meeting, work on Task 2 will be reported at the next meeting (Imperial College, London, UK, August 2007).

Task 1 the inventory includes three sets of techniques firstly those that involve scenario building, such as FEP’s and other scenario construction methodologies. Secondly models, such as conceptual models, process level models, modeling tools, and system level models. Thirdly, probabilistic analyses involving the treatment of uncertainties, probabilistic performance assessment, sensitivity analyses and expert judgment elicitations.

The aims of Task 3 are:

- To identify the strengths/weaknesses of existing/under development methodologies for CO₂ storage performance and risk assessment,
- To determine the complimentary functionality or niche for each,
- Identify gaps where improvements can be implemented,
- To harmonize the use of tools and methods under a unified conceptual framework.

The risk assessment framework can be visualized in three tiers;

Tier 1 represents the potential hazard assessment, here you can use scenario analyses, FEPs or simple analytical models to select sites; data requirements will be limited and perhaps generic data could be used. The risks identified would merely represent grades of likelihood or similar ranking like negligible, marginal or probable. Tier 1 would also be used for site licensing again using scenario based tools and conceptual or system level models to assess the risks. Coarse site specific data would be required at this stage. In this case you would make qualitative or semi-quantitative assessments of risk and derive indicative flux rates.

Tier 2 would involve exposure assessments, these would be used for storage licensing, monitoring and verification and remediation planning. Here you would use process level models, coupled models, systems models etc., Data requirements would be very site specific with perhaps input of data from surrogate sites to compliment the data sets. This tier would produce quantitative risk assessments, CO₂ fluxes and timescales.

Tier 3 is the consequence assessment which uses ecosystem modeling requiring experimental data from laboratory and field studies to determine risks to ecosystems. Tier 3 data will be used in monitoring and verification and remediation planning.

These risks will then be communicated and be incorporated into the risk management plan for the project.
We will need to develop standards for site characterization and risk assessment for each lifetime stage of a project.

In the discussion there was some concern that if you were a regulator you would not want to base your decision on Tier 1 but Tier 2. It was felt that regulators would undertake a cost benefit analysis between the amount of regulation and associated costs, compared to the benefits (i.e. permanence). There was concern raised regarding the use of terms such as likely and unlikely and we need to identify an order of magnitude of risk in words so people will understand what is meant. It was recognized that this was an iterative process and the level of data requirements will increase with time. There was considerable debate about the term quantitative and what it really meant, it was clear from this and the preceding discussion that the people were using the definition differently. We need to be clear amongst ourselves what we are talking about before we communicate outside the group. The question was raised what was a reasonable time for this staged process and 2-3 years was considered appropriate. From a regulators perspective the comment was made that they want simple tools that give good guidance in a reasonable time frame rather than overly complex models that are based on lots of assumptions and the outputs from which are unclear.

4.1.3 Risk assessment as part of a risk management framework

There were two presentations in this session relating to the topic of risk management framework.

Ton Wildenborg opened the session with a presentation, entitled; the role of RA as part of a Risk Management framework. He asked the question what is risk assessment? He defined it as a means of identifying, estimating or calculating, and evaluating potential risks of CO2 storage to human health and safety, the environment and assets. RA can be considered as problem oriented.

\[
\text{Risk} = \text{Probability of Hazard} \times \text{Consequence of Hazard (impact)}
\]

Seepage of CO2 from a CO2 storage reservoir can best be regarded as a hazard, because it has the potential to be harmful. But we need to define who or what it is harmful to. Is it the pollution of drinking water, or a threat to peoples lives, or will it cause a change in biodiversity? First we have to define the consequence and then start calculating.

Risk assessment fits into a risk management framework as illustrated by the diagram overleaf:
We can identify the source of seepage using appropriate techniques like FEPs or scenario analyses, then quantify the hazard through performance modeling. We can assign probabilities to events and knowing leakage rates we can determine consequences. However, in a probabilistic approach we can define all the processes but a fair degree of expert judgment is then required.

Ton concluded that RA is an integral part of risk management. Risk management deals with assessing, monitoring & remediating risks to conform to risk acceptance levels. Risk management is solution oriented.

He closed by saying we should present results of risk assessment in relation to the management of risks in the successive phase of the CCS lifecycle and put more emphasis on the ‘solution’ instead of the ‘problem’ when we communicate the risks involved.

In the ensuing discussion it was felt that reference to the Lake Nyos event in the positive context was not a good approach. Also the approach generates numbers that cannot be qualified. However it was noted that the Dutch regulators are looking for numbers, 10% risk of leakage etc., but the concern was that if we generate numbers with big error bars was it worth generating the numbers in the first place. The Delphi approach was suggested as an alternative method but there was concerns that we were trying to assign probabilities to things we know little about which could cause unpleasant surprises.

Natalie Quisel of Schlumberger discussed a risk driven decision process for a CO₂ storage site. A storage operation comprises three phases,

- The pre-operational phase (1-2 years), which includes site selection, site characterisation and field design activities,
- The operational phase (3-50 years) which involves site construction, site preparation, injection and monitoring activities,
• The post operational phase, which will involve a site retirement programme and environmental monitoring.

A performance and risk management system will be required through all three phases coupled with risk communication to the public.

Controlling safety throughout the project lifetime is essential for the permitting process but also for cost effective risk treatment. In both cases particular focus should be made on the sealing integrity with time and risk mitigation planning.

In a risk driven decision making process the goal is containment of the injected CO₂. From a storage reservoir the key risks of loss of containment are wells and faults. Initially you undertake a performance assessment to assess the risk of loss of containment and then you select the best risk mitigation option based on cost and benefits.

In the case of wells we can assess the integrity of a well with a variety of techniques. Also we know cements can degrade with time but this can be modelled. By knowing the costs of techniques to remediate leaks you can build a consequence grid. Risk mapping can then be used as a decision support tool to guide your decision on which remediation option to choose. You can use the same approach to optimise the positioning of injection wells in a field to minimise formation damage.

It is felt this approach can play a role in developing standards for CO₂ containment in storage reservoirs.

4.1.4 Building confidence in CO₂ storage

The final session involved two presentations aimed at establishing international collaboration in building confidence in CO₂ storage.

Kenshi Itaoka opened the session by discussing how natural analogues could be used to build confidence in CCS. He pointed out that there were two issues to consider first the long timeframes associated with CO₂ storage. Secondly, there were issues relating to the general uncertainty of geological formations, difficulties in data acquisition and uncertainties in the behavior of the injected CO₂ and difficulties in verifying the amount of CO₂ injected.

He pointed out the degree of risk is difficult to interpret and the uncertainties were difficult to estimate. However, natural analogues could play a role here. There are several ways that natural analogues could be used to build confidence in CO₂ storage which include:

• Helping geologists to understanding the leakage and trapping mechanism,
• Verification of numerical models and risk assessment procedures,
• Interpretation and risk management,
• Helping to communicate the safety of CO₂ storage.

By building up a database of events from natural and industrial analogues comparable to those that could occur from a CO₂ storage reservoir you can build a risk matrix that
allows you to compare and communicate the risks of CCS in a way that is readily understandable. This work is on going.

Hiroyasu Takase provided the second presentation in the session. He focused on the issue of how to build confidence in CCS. The objectives of building confidence were:

- To build a number of arguments to support effectiveness of confinement.
- To develop a strategy for dealing with uncertainties that could compromise effectiveness.
- To make an assessment of our confidence in performance of the system in the presence of uncertainty.

These will lead to an adequate level of confidence to support the decision at hand (rather than a rigorous quantitative “proof”)

However he went on to comment that:

- Due to complexity of the CCS system, it is impossible to fully understand/describe the system.
- Development of a CCS concept is an iterative process and a decision at any stage requires a number of arguments that give adequate confidence to support it (rather than a rigorous proof).
- Confidence building and uncertainty management requires an iterative process of identification, assessment and reduction of uncertainty.
- A framework of multiple lines of reasoning based on a variety of evidence can contribute more to overall confidence building than an approach focusing just on quantitative risk assessment.
- An integrated strategy is therefore needed to manage various types of uncertainties.

He then described an exercise that was currently underway to demonstrate the integrated safety assessment approach using a sub-seabed CO₂ storage reservoir as a case study. In the coming year it is planned to refine this methodology and to develop a more comprehensive example to assess the applicability of the methodology.

4.2 Case Studies

The second day of the meeting was devoted to understanding the current status of risk assessment analyses. This was achieved by considering in detail, in break out groups, 4 published risk assessment case studies. To begin the process the four case studies were presented in outline to the whole group for reference. A ‘champion’ for each project was appointed who presented the work, in some cases additional experts also attended to assist in the break out group discussion. Each case study presenter was asked to comment on:

1. The quality of the data set used
2. The methodology used
3. The inherent assumptions made
4. Their results
The group then split into 4 to consider the cases in detail. The breakout groups then reported their findings back to the whole group. The breakout groups were asked to review the studies that had been completed and comment back on the following issues:

- How robust was the data base used?
- How robust was the approach used?
- How robust were the assumptions used?
- How confident can we be in the results?
- What we can confidently say about the performance assessments,
- How we can use the results to build confidence in the long term storage performance.

Each case study is summarized first and then the feedback from the break out groups presented:

4.2.1 Case Study 1 - the Latrobe Valley CO2 Storage Assessment

**Summary**

This case study was presented by Andy Rigg, CO2CRC. The prospective Latrobe Valley storage site in Australia lies in the Gippsland Basin in the southern state of Victoria. The Gippsland basin straddles both on and offshore. Onshore the Gippsland Basin contains the world’s thickest coal seams which represent Australia’s cheapest power and Australia’s largest CO2 emissions sources. Whilst off shore it contains Australia largest and most productive oil fields. The problem is that new brown coal developments in Latrobe Valley will increase emissions by up to 50 Million tonnes/year. One potential solution in a carbon constrained world is to inject those emissions offshore in the Gippsland Basin. The CO2 would be injected into existing oil and gas fields (once depleted) and deeper saline formations. Injection could take place at several sites along regional migration pathways, sequentially & simultaneously, ramping up volume to 50 Mt/y. One field the Kingfish Field could inject: 15 Mt/y for 40 years and was the subject of the risk assessment presented.

The study had showed that the Kingfish Field/Gippsland Basin was considered very suitable as a geological storage site for the following reasons:

- It has a complex stratigraphic architecture which slows vertical migration and increases residual gas trapping,
- The reservoir contains a sequence of non-reactive reservoir units, each with high injectivity,
- There is a geochemically reactive, low permeability reservoir just below the regional seal to provide additional mineral trapping,
- There are several pressure depleted oil fields to provide storage capacity coupled with transient flow regime that enhances containment pressure,
- There are long migration pathways beneath a good regional seal,
- The Kingfish Field, in conjunction with other sites (e.g. the Fortescue, northern gas fields); indicate that the Gippsland Basin has sufficient capacity to store very large volumes of CO2.
The study was based on a prospective CO₂ storage site and used a qualitative risk assessment approach. Exploration wells were found to be the biggest risk to loss of containment.

**Breakout group report**

Strengths and weaknesses of datasets used: only publicly available data was used in the assessment. 3D seismic data was available over the field itself, but larger coverage would have been useful. Data from cored wells within the Kingfisher field was available, but there was a lack of deep well control data. There was also a lack of pressure data, the latest pressure information was unavailable, and therefore the assessment relied on 15-year old extrapolation data. It was felt that whilst the lack of data increases uncertainty over containment and modelling results, in terms of public concern this is unlikely to be important. Overall the data set was good but could be improved upon.

It was noted that access to commercially-sensitive information could be an issue in active oil/gas fields.

Comments on approach used. The RISQUE approach used requires expert input. The experts are used to identify risk events but could also be used to comment on data quality. The experts used, only had experience from research organisations but should be extended to experts with extensive oil & gas experience. It might be interesting to compare the results from different expert panels, drawn from groups with different expertise.

The point was made that when considering the performance assessment that it should be clear that this was a research exercise, not a RA for seeking a permit/licence. A formalised FEP approach was not used due to lack of time and financial resources but might not have been done anyway. The RISQUE approach allows rapid assessment, scenario definition and identification of principle risks. The Performance Assessment (instead of RA) component was completed by 1 person over 2 months and expert panel met twice for review. However the approach does provides regulators with digestible summary of likely risks. If external stakeholders were involved, then a more formal FEP audit may have been required. The approach used may not identify all scenarios but key scenarios are probably included. Issues not included were:

- Coupling between risk events
- Wells were not evaluated individually
- There was a lack of empirical data for leakage rates in faults and wells
- Modelling has not been peer-reviewed

Comments on the assumptions used. Performance criteria (<1% leakage in 1000 years) was defined by the research group involved based on the IPCC SRCCS: however the question must be asked is this acceptable for stakeholders? Assumptions are needed due to lack of empirical leakage data. Many data requirements were not known such as intraformational seal distribution and properties, but were modelled. A sensitivity analysis was not carried out, this would have enabled the influence of critical assumptions to be identified. Overall the assumptions were considered to be robust based on the information/modelling tools available.
As discussed earlier, if two expert panels were given the same data they could come up with (somewhat) different conclusions.

**Confidence in the results.** The fact that the results are only based on publicly available data constrains confidence in some results. There was no access to well data, (production data or pressure data etc) and no operator participation. The internal expert panel did not necessarily have wide oil & gas expertise therefore the estimates of confidence may be different from other experts. Of course one could recommend you repeat the expert panel process with different experts.

**Comments on confidence building.** The RA was made publicly available with strong community engagement and there was broad support. Some issues from agricultural communities regarding water supply (storage was good, reducing groundwater draw down) were raised. Also the potential for onshore leakage was raised and then adequately addressed.

### 4.2.2 Case Study 2 - the Mountaineer CO₂ Storage project

**Summary**
The mountaineer case study was presented by Joel Sminchak, LBNL. The project is situated in the Ohio River valley in the USA and plans to inject a slip stream of gas from an existing power plant operated by AEP into a deep saline formation at a depth of 2500m. The project has undertaken a qualitative risk assessment based on FEPs and is developing a quantitative model based approach which was not reported here. The FEP analysis involved a three stage screening process which resulted in 6 key FEP’s identified, from a staring point of 143 possible FEP’s which were:

<table>
<thead>
<tr>
<th>FEP</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ storage (pre closure)</td>
<td>High injection rates and overpressuring may affect storage reservoirs and containment units</td>
</tr>
<tr>
<td>CO₂ properties</td>
<td>CO₂ solubility and aqueous specification</td>
</tr>
<tr>
<td>CO₂ transport</td>
<td>Advection of CO₂ due to injection</td>
</tr>
<tr>
<td></td>
<td>Buoyancy driven flow/migration</td>
</tr>
<tr>
<td></td>
<td>Displacement of formation fluids</td>
</tr>
<tr>
<td>Geosphere</td>
<td>Reservoir geometry variations and heterogeneity</td>
</tr>
<tr>
<td>Wells, drilling and completion</td>
<td>Durability of well casings and cement</td>
</tr>
<tr>
<td>Well, seals and abandonment</td>
<td>Degradation of borehole materials used to abandon injection well.</td>
</tr>
</tbody>
</table>

To address this issue the project included:

- A SCADA system to monitor the injection pressures,
- Reservoir sampling included to determine extent of reaction of brine with CO₂,
- Monitoring programme expanded to assess CO₂ migration within the reservoir,
- Well integrity to be monitored and well design changed to utilize acid resistant materials wherever possible.

Overall the project found the FEP process useful and the systematic approach through up issues that helped focus the design of the project.
**Breakout group report**

Comments on quality of data set. The RA was completed on a limited data set, but this was considered to be typical for a project at evaluation stage, and one in a non-petroleum environment. There was one full length well through the Precambrian formation of interest. Overall the quality of information was considered to be very good. However, there were few additional wells in the general region. Only two seismic lines were present, limited information on depositional system and on lateral continuity of the sandstone lenses.

Comments on approach used. The assessment used the FEPs analysis for CO₂ storage. The assessment was designed to address the Risk assessment of an experimental injection rather than a full scale project. It did not address capture or transport issues. It used the Quintessa database to identify FEPs. A qualitative FEPs screening, was carried out at three levels of screening carried out by three independent reviewers. This identified six main items. The approach was systematic and the analysis comprehensive. However it must be noted that there was some subjectivity in the final selection.

General issues relevant to Risk Assessment and CO₂ storage Confidence Building. The audience is important in the design of the risk assessment results communication strategy, not in the design of the RA technical approach. Confidence building involves a lot more than the technical risk assessment. The impact on confidence when performing ‘what if’ scenarios that are not supported by the FEP analysis

Overall the RA was considered to be appropriately designed for the scale of the project perceived.

**4.2.3 Case Study 3 – Weyburn**

**Summary**
Malcolm Wilson presented the Weyburn case study. Performance assessment was applied as the initial phase of an overall risk assessment process to evaluate the long-term fate of CO₂ injected into the Weyburn reservoir. The role of performance assessment within Phase 1 of the IEA GHG Weyburn CO₂ Monitoring and Storage Project was to identify the risks associated with geological storage and assess the ability of the Weyburn reservoir to securely store CO₂. The performance assessments were utilized to identify and increase the understanding of crucial processes for CO₂-EOR and will form a critical component of the final risk assessment in Phase 2 of the Project.

To assist in identifying the processes that could be relevant to the evolution or performance of the Weyburn reservoir, a list of FEPs was developed. Compositional reservoir simulations, supporting early performance assessment studies, were conducted over a time period of 5000 years, starting from the end of EOR and were conducted to provide an initial understanding of CO₂ migration; the process and parameters that may be important to modeling its long-term fate. These early studies highlighted the importance of processes such as CO₂ diffusion in the oil phase, phase saturation distribution at the end of EOR, groundwater velocities within the reservoir.
zone, and the strong interplay between the coupled processes of pressure-driven flow, density-driven flow and diffusion. Next a series of large-scale reservoir simulation simulations were carried out covering the entire 75 pattern EOR system and allowed the long-term performance assessment to be carried out for a period of 5000 years following the end of EOR.

Deterministic and stochastic approaches were adopted to assess the fate of CO₂ within the reservoir. Cumulatively, after 5000 years, the total amount of CO₂ removed from the EOR area is 26.8% of the initial CO₂-in-place (~21 MT) at the end of EOR, of which, 18.2% moves into the geosphere below the reservoir; 8.6% migrates laterally in the Midale reservoir outside the EOR area; 0.02% moves to the geosphere above the reservoir, and no CO₂ enters the potable aquifer over the 5000-yrs period. For the abandoned well leakage assessment, the estimated maximum cumulative leakage of CO₂ for an estimated 1,000 wells was ~0.03 MT or 0.14% of the total CO₂-in-place at the end of EOR over the 5,000 year period. The mean cumulative leakage was estimated to be less than 0.001% of the CO₂-in-place at the end of EOR.

In addition, probabilistic risk assessment techniques were pursued to investigate the potential application of these methods for geological storage projects. A full probabilistic risk analysis study of the 75-pattern area was not completed in Phase 1 of the IEA GHG Weyburn Project. However, to demonstrate the capability and potential of the probabilistic risk assessment methodology and its ability to identify key processes or parameters, a benchmarking and focused case study using the results from a single pattern reservoir simulation was undertaken. Benchmarking results showed that despite the differences in numerical/analytical approaches, both the reservoir simulator and probabilistic program generally agreed on the total amount of gas phase released, that the fractional gas release to the surface was considerably smaller than the fraction dissolved in place, and that the leakage rate to the surface through failed well seals was relatively small in terms of the overall effectiveness of the storage system.

All the performance assessment studies conducted within Phase 1 of the IEA GHG Weyburn CO₂ Monitoring and Storage Project have shown clear support for the conclusion that the geological setting at the Weyburn Field is highly suitable for long-term subsurface storage of CO₂. These studies have highlighted the significant capacity of the geosphere region surrounding the reservoir to effectively store CO₂ and prevent its migration to the biosphere.

**Break out group report**

**How robust is the dataset?** The dataset and the geological description were considered to be as good as it gets. There was good overall data on the status of wells in area; however the cement status in cases may be unknown. Impacts were limited to human health and groundwater due to lack of data on impact on ecological receptors. Site specific data on groundwater is now available, but was not during the initial assessment.

**Comments on approach.** Generally robust. Limitations include:
- Inability to couple rock property changes due to geochemistry,
- Inconvenient well leakage calculations,
• Density calculation for water with dissolved CO₂.

Comments on assumptions used. Generally conservative and robust. If the CO₂ were to pass the cement, it will then migrate to other areas (overlying aquifers, atmosphere). For wells it was assumed that all regulations followed and all wells were known. Overall it was considered that there were; no undetected features in reference scenario, no possibility of a severely fractured conduit zone, and no geochemical reactions that could reduce cap rock integrity.

Confidence in results. Qualitative containment of CO₂ has a high degree of confidence. Pathways are less certain. Impacts add another layer of uncertainty

What can we confidently say? We can be confident about:

• The reservoir performance
  – CO₂ will not reach the surface within 5000 years
  – Low permeability restricts impact of open boreholes
• Confident about well locations

We are less confident in: well bore integrity over 5000 years and the RA may not extend to other sites because of tightness of site, EOR, location (impacts)

How do the results help us build confidence in long term storage of CO₂?
It is felt that the results help convince technical, regulators, and the public. They also can help determine main parameters for future simplifications or refinements of RA/PA methods and models. By considering the worst case scenario we can rule out public concerns over issues like indoor air contamination.

Future actions to improve Confidence include;

• Verification,
• Development of Best Practices for RA for EOR projects,
• Remediation Analysis.

4.2.4 Case Study 4 – The Schweinrich study

Summary
Sara Eriksson presented the outline of the Schweinrich study carried out by BGR and Vattenfall. The study was part of a larger study to investigate opportunities to store CO₂ captured from a 1600 MW lignite fired power plant in North Eastern Germany. The plant would produce 400MtCO₂ over its service life of 40 years. The study involved a regional mapping exercise to screen relevant regional occurrences of saline aquifers. This assessment identified the Schweinrich structure as having the most potential as a suitable CO₂ store in that region. A pre-feasibility study was then undertaken which relied on existing data with a further more detailed study to be undertaken later.

2D seismic data was available as well as well logs and mineralogical data this allowed 3D geological modeling to be undertaken. The aquifer was found to have a thickness of 270-380m with a passive anticlinal structure and was sealed by a thick clay sequence. Mineralogical analyses indicated the reservoir was mostly quartz
with few reactive minerals present. The cap rock was a thick (several hundred metre) claystone sequence containing several overlying aquifers. The storage capacity was estimated at between 500 and 840 Mt CO₂. Reservoir simulations predicted that 10 wells would be needed to inject the CO₂; injection would result in a formation pressure increase and displacement of formation waters.

In summary the study identified that potential for one large onshore structure capable of storing sufficient CO₂. The pre-feasibility study highlighted a number of areas where further data was required. This data included:

- A tectonic inventory – to assess the storage integrity of the reservoir
- A geo-mechanical analysis to assess tectonic stress regimes and the tolerable pressure capacity
- 3D Seismic and exploration wells are essential

It was noted that the injection volumes involved in such an onshore structure would be a considerable scale up from In-Salah and Sleipner.

**Breakout group report**

It was reinforced again that this was not a full risk assessment. It was actually a scoping study to test of concepts and to learn by doing. However it was felt to be a good first step. The next step would be to acquire more data to do a performance assessment.

**Robustness of dataset.** The data set was limited but was considered typical for a saline formation in Europe. Existing “old” sub surface geological data was used, which was not designed for this purpose. There was no data on hydrology etc. There were major uncertainties about seal integrity and the basis for uncertainty ranges could not be evaluated

**Robustness of approach.** The approach was considered to be good based on data available. FEP analysis is too complex at this stage of a project. There was a disconnect in FEP detail and model needs at this stage of an assessment. It was felt that there was a need to develop a smaller FEP sub-set for this stage of a project. The set of scenarios developed were plausible, the use of base cases as well as worst cases gave balance. The modelling approach was appropriate.

**Robustness of assumptions.** Some of the assumptions may not have been physically feasible. In particular the well bore case. The worst case scenarios were simply assumed rather than taking probabilities of events into account.

**Confidence in results.** Scenario analysis is important to test feasibility. The study identified the need to collect more data to increase confidence, but achieved desired purpose.

**What can we communicate?** This was only a scenario analysis and we need to take care when communicating results. We must be wary of presenting quantitative numbers and we need to add caveats clearly when presenting results from these types of studies.
Confidence building. The study identified the issues that need to be addressed in a structured appraisal programme.

4.2.5 Discussion Session

Following the presentations of the breakout group comments an open discussion session was held for attendees to raise any issues or make comments on the presentations give. The comments/issues raised are outlined below.

1. There was a general feeling that more work was needed on RA for CCS. Also that it was critical for early studies that as much data was assembled as possible to make sure the results are as credible as possible. Also we need to develop guidelines for RA and agree how benchmarking can occur.

2. There is a need to develop a RA for a full scale CCS project; the projects discussed above are only preliminary activities. It was felt that we should not oversell the RA results from these small studies but these cases are helping with tool development etc.

3. There was concern that some of the studies the scenarios developed were not supported by the FEP analyses; the development of unrealistic scenarios does not help to build confidence in RA. The scenario referenced was leakage through a fractured cap rock.

4. The comment was made that you cannot prove that a cap rock is not fractured; you cannot ignore such a scenario even though FEPS may not support this process. This point was further emphasized by several speakers.

5. Modeling well failure was currently difficult and there was a lack of consistency between the studies on this issue. There were cases where leakage from open hole bore holes had been modeled but the permeability of the reservoir will not allow quick flow of CO2 back out of the reservoir.

6. The issue of subjectivity of expert panels was raised again. Construction of expert panels with broad experience is very important – should we bring in non-experts as well to gauge their response.

7. The issue of using worst case scenarios was raised and debated. In general, it was felt important to model worst case scenarios because if the scientific community doesn’t do it, others will, possibly with serious consequences. Also worst case scenarios can help build confidence, as in the Weyburn case where it was shown there was no risk of ambient air quality problems arising from leakage of CO2.

8. The point was made that it was currently difficult to assess the impact of seepage on groundwater quality because there was no data available.

9. Sensitivity studies are valuable to identify key risk parameters to model.

10. A question related to benchmarking was raised – in future will RA models need to be certified and who will certify them? A peer review /benchmarking process will be required. In response to this question, industry felt that we were over playing the issue because currently we can engineer CO2-EOR projects and natural gas storage (NGS) projects without the need for peer reviewed or certified RA techniques – why is CCS so different? The key difference was considered to be the long term nature of CO2 storage which may warrant the reinforced of regulations – regulations for EOR and NGS only deal with short term issues. It was also felt that regulations for EOR and NGS were set years ago and now there is a higher degree of environmental consciousness that could warrant stricter
regulations. In the USA, regulations for EOR were framed around resource recovery not with environmental security in mind.

11. The point was made that CCS was new and that when we generate data from several RA studies we might decide we won’t need stricter permits than we currently. Also it was felt that we know more about oil and gas fields than we do about aquifers.

12. The question was raised; are we trying to oversell RA? The key need for RA was to screen out high risk sites, then identify lower risks sites for storage we can follow by monitoring. We want to avoid an early failure from a CCS operation due to poor initial screening.

5. Summary and Key Conclusions

The meeting has continued the progress made at earlier network meetings in developing the role that risk assessment can play and furthering our understanding of the status of risk assessment in its application to CCS.

The CCS community is aware that there is a need to fully characterize storage sites to ensure that the sites selected can effectively contain CO\textsubscript{2} for 1000’s of years. Site characterization will be a step wide process, with initial pre-screening an important aspect because it will allow poor sites to be screened out early and allow efforts to be concentrated on those sites that have the best potential. Risk assessment is one tool that can be used in the early screening of storage sites. Risk Assessment and site characterization work in an iterative manner, over different project stages from preliminary screening to permitting to implementation. There will be increasing data requirements as you proceed to each stage.

Risk assessment studies can provide guidance on likely seepage rates from storage sites but they cannot define the impacts of leakage. Environmental Impact Assessments (EIA) can provide the framework for assessing the long term impacts of leakage. However, it has been shown that currently there is little research work underway that is addressing specifically the effects of CO\textsubscript{2} leaks and their potential impacts that could allow an EIA to be compiled. This is a major research gap.

A communication exercise with regulators has been undertaken to gauge their expectations for RA and to make them aware of the current status of RA. As a result of this process regulators are better informed on both the role that RA can play and its current technical status. Regulators are keen for a regulatory framework to be developed for CCS, which will occur after 2008, and for RA to be part of the approval process. It was accepted that there should be flexibility in the RA tools and approaches used, in the approval process, and there should be a link between RA and monitoring. Project implementers are looking for regulators to provide an RA protocol or standard (based around best practice) and on a bench marking process for RA tools.

There was a clear feeling that RA is only part of the message that needs to be given to regulators; remediation is another important issue as well. Also, we need to get the message over that we are not promoting innovatory technology, to avoid over regulation.
RA can also be considered as part of a Risk Management framework. RA is the means of identifying, estimating or calculating and evaluating potential risks of CO$_2$ storage to human health and safety, the environment and assets. RA can be considered as problem oriented. Risk management on the other hand deals with assessing, monitoring & remediating risks to conform to risk acceptance levels. Risk management is therefore solution oriented. When we look at the results of risk assessments in relation to CCS we should put more emphasis on the ‘solution’ instead of the ‘problem’ when we communicate the risks involved.

Natural analogues could be used to build confidence in CCS. There are several ways that natural analogues could be used to build confidence in CO$_2$ storage which include:

- Helping geologists to understanding the leakage and trapping mechanisms,
- Verification of numerical models and risk assessment procedures,
- Interpretation and risk management,
- Helping to communicate the safety of CO$_2$ storage sites.

By building up a database of events from natural and industrial analogues comparable to those that could occur from a CO$_2$ storage reservoir you can build a risk matrix that allows you to compare and communicate the risks of CCS in a way that is readily understandable.

Four RA cases studies were reviewed; three were based on aquifers and one on an oil field operation. It should be emphasized that several of these cases were not full complete risk assessment studies but were really scoping studies. The results of such studies should therefore be treated with some care when communicated outside of the technical community. The aquifer based assessments generally suffered from a lack of data, which is not unsurprising. This resulted in a lot of assumptions being made. The oil field case was much better characterized which allowed a more detailed risk assessment process to be undertaken. All the assessments used expert panels which involve a degree of subjective analysis. Expert panels need to be drawn from as wide a group of individuals as possible whereas the groups involved in these assessments tended to be drawn internally from the research organizations involved. The oil field study gives us some confidence that CO$_2$ can be retained in that formation for 1000’s years but the same degree of confidence cannot be drawn from the aquifer studies. The studies have, however, contributed significantly to the learning process for undertaking such studies which will be of benefit in the future and help to allow us to better define the data requirements needed to complete a good robust risk assessment. More RA studies are needed to help develop confidence in the techniques and models used as well in the results they generate.

6. **Next Steps**

The meeting has raised a number of issues that warrant further consideration at future network meetings. These are listed below:

1. Site selection how much characterization is needed to do a formal risk assessment?
2. Do we need full blown quantitative risk assessments or would simpler screening assessments be enough to generate confidence in CO$_2$ storage?
3. Having had experience of using FEPs can we design a screening process involving a simpler FEP database?
4. How and when do we begin to develop a RA standard or protocol?
5. How we develop a benchmarking system for RA tools and approaches?

In addition, the meeting has identified that within the RA community there is a need to try and harmonize the terminology used to allow the community to effectively communicate amongst itself let alone to outside bodies.
Appendix 1. Delegates List

<table>
<thead>
<tr>
<th>Name</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferhat Taylan Yavuz</td>
<td>Universiteit Utrecht</td>
</tr>
<tr>
<td>John Kindinger</td>
<td>Los Alamos National Lab</td>
</tr>
<tr>
<td>Sujoy B. Roy</td>
<td>Tetra Tech, Inc.</td>
</tr>
<tr>
<td>Rajesh Pawar</td>
<td>Los Alamos National Laboratory</td>
</tr>
<tr>
<td>Andrew John Rigg</td>
<td>CO2CRC</td>
</tr>
<tr>
<td>Kaoru Koyama</td>
<td>Research Institute of Innovative Technology for the Earth</td>
</tr>
<tr>
<td>John Gale</td>
<td>IEA GHG</td>
</tr>
<tr>
<td>Olivier Bouc</td>
<td>BRGM</td>
</tr>
<tr>
<td>Kenneth T. Bogen,</td>
<td>Univ. Calif., Lawrence Livermore Natl. Lab.</td>
</tr>
<tr>
<td>Richard Rhudy</td>
<td>EPRI</td>
</tr>
<tr>
<td>Wolf Heidug</td>
<td>Shell International</td>
</tr>
<tr>
<td>F. Scott Truesdale</td>
<td>Tetra Tech, Inc.</td>
</tr>
<tr>
<td>Jean-Philippe Nicot</td>
<td>Texas Bureau of Economic Geology - The University of Texas at Austin</td>
</tr>
<tr>
<td>Tom Grieb</td>
<td>Tetra Tech, Inc.</td>
</tr>
<tr>
<td>Brian J. McPherson</td>
<td>University of Utah</td>
</tr>
<tr>
<td>W.C. Turkenburg</td>
<td>Copernicus Institute, Utrecht University</td>
</tr>
<tr>
<td>Joel Sminchak</td>
<td>Battelle</td>
</tr>
<tr>
<td>Budnitz, Robert J.</td>
<td>Lawrence Livermore National Laboratory</td>
</tr>
<tr>
<td>Christopher, Charles A</td>
<td>BP</td>
</tr>
<tr>
<td>Brent Lakeman</td>
<td>Alberta Research Council</td>
</tr>
<tr>
<td>Carolyn Preston</td>
<td>IEA GHG Weyburn-Midale CO2 Monitoring and Storage Project</td>
</tr>
<tr>
<td>Lisa S. Botnen</td>
<td>University of North Dakota - Energy &amp; Environmental Research Center</td>
</tr>
<tr>
<td>Malcolm Alan Wilson</td>
<td>EnergyINet c/o University of Regina</td>
</tr>
<tr>
<td>Jonathan Pearce</td>
<td>British Geological Survey</td>
</tr>
<tr>
<td>Curtis M. Oldenburg</td>
<td>Lawrence Berkeley National Laboratory</td>
</tr>
<tr>
<td>Sevket DURUCAN</td>
<td>Imperial College London</td>
</tr>
<tr>
<td>Anna KORRE</td>
<td>Imperial College London</td>
</tr>
<tr>
<td>Rob van Eijs</td>
<td>TNO</td>
</tr>
<tr>
<td>Natalia Quisel</td>
<td>Schlumberger</td>
</tr>
<tr>
<td>Sara Eriksson</td>
<td>Vattenfall Research and Development</td>
</tr>
<tr>
<td>Neeraj Gupta</td>
<td>Battelle</td>
</tr>
<tr>
<td>Dr Tony Espie</td>
<td>BP Exploration</td>
</tr>
<tr>
<td>Kenshi Itaoka</td>
<td>Mizuho Information &amp; Research Institute</td>
</tr>
<tr>
<td>Bill Mills</td>
<td>Tetra Tech, Inc.</td>
</tr>
<tr>
<td>Elizabeth Scheehle</td>
<td>US Environmental Protection Agency</td>
</tr>
<tr>
<td>Norio Shigetomi</td>
<td>Mitsubishi Research Institute, Inc.</td>
</tr>
<tr>
<td>Hidemitsu Shimada</td>
<td>JGC Corporation</td>
</tr>
<tr>
<td>Tsukasa Kumagai</td>
<td>JGC Corporation</td>
</tr>
<tr>
<td>Hiroyasu Takase</td>
<td>Quintessa Limited</td>
</tr>
<tr>
<td>Mike Stenhouse</td>
<td>Monitor Scientific LLC</td>
</tr>
<tr>
<td>Ilka von Dawligk</td>
<td>Vattenfall Research and Development AB</td>
</tr>
<tr>
<td>David W. Keith</td>
<td>University of Calgary</td>
</tr>
<tr>
<td>Yuri Leonenko</td>
<td>University of Calgary</td>
</tr>
<tr>
<td>Michael Cox</td>
<td>BP</td>
</tr>
<tr>
<td>Larry Myer</td>
<td>Lawrence Berkeley National Lab</td>
</tr>
<tr>
<td>Christian Hermanrud</td>
<td>Statoil</td>
</tr>
<tr>
<td>Makoto Akai</td>
<td>AIST</td>
</tr>
<tr>
<td>Name</td>
<td>Affiliation</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>Jens T. Birkholzer</td>
<td>Lawrence Berkeley National Laboratory</td>
</tr>
<tr>
<td>Grant S Bromhal</td>
<td>US DOE/NETL</td>
</tr>
<tr>
<td>Preston Jordan</td>
<td>LBNL</td>
</tr>
<tr>
<td>Andrea Cortis</td>
<td>LBNL</td>
</tr>
<tr>
<td>Yingqi Zhang</td>
<td>Lawrence Berkeley National Laboratory</td>
</tr>
<tr>
<td>Jennifer Lewicki</td>
<td>LBNL</td>
</tr>
<tr>
<td>Dorothy S Peterson</td>
<td>Potomac-Hudson Engineering, Inc</td>
</tr>
</tbody>
</table>