3rd RISK ASSESSMENT NETWORK MEETING

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The IEA Greenhouse Gas R&D Programme supports and operates a number of international research networks. This report presents the results of a workshop held by one of these international research networks. The report was prepared by the IEA Greenhouse Gas R&D Programme as a record of the events of that workshop.

The international research network on Risk Assessment is organised by IEA Greenhouse Gas R&D Programme in co-operation with Imperial College, London. The organisers acknowledge the financial support provided by EPRI for this meeting and the hospitality provided by the hosts Imperial College, London.

A steering committee has been formed to guide the direction of this network. The steering committee members for this network are:

Sevket Durucan, Imperial College
Anna Korre, Imperial College
Rick Chalaturnyk, University of Alberta
Malcolm Wilson, Energy INet
Tony Espie, BP
Elizabeth Scheehle, US EPA
Ton Wildenburg, TNO
Hans Aksel Haugen, Statoil
Larry Myer, Lawrence Berkeley National Laboratory
Jonathan Pearce, British Geological Survey
John Gale, IEA Greenhouse Gas R&D Programme (Chair)
Brendan Beck, IEA Greenhouse Gas R&D Programme

The report should be cited in literature as follows:


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THIRD WORKSHOP OF THE INTERNATIONAL RESEARCH
NETWORK ON RISK ASSESSMENT

Executive Summary

The IEA Greenhouse Gas R&D Programme (IEA GHG) has been working on the topic of risk assessment for a number of years now. The cornerstone of the IEA GHG Programme’s risk assessment work is the IEA GHG International Risk Assessment Network. The Network was formally launched in 2005 in the Netherlands after two preliminary meetings in the UK in 2004 and in Canada in 2005. The purpose of the network is to bring together the key groups working on risk assessment for CO2 storage from around the world and to address what the regulators are expecting in regard to CCS assurance and whether risk assessment can provide the answers they require. This report provides a summary of the third risk assessment workshop hosted by Imperial College in London, UK between the 15th and 16th August 2007.

The main outcomes from the workshop were:

1. An initial attempt was made to define a set of common terms for use by the international risk assessment community and some progress was made, however this was only the start of the process. The next step in this work is to circulate a questionnaire to people within the industry to try and build consensus on the terms to use and their definition. One suggestion was to set up a Wikipedia style website to act as a forum to build an agreed pool of terms.

2. A key issue that the workshop attempted to resolve was on the requirements for site characterization. This is a common theme running throughout the Risk Assessment Networks and was explored in this meeting but not resolved. The issue remaining is determining how much site characterization is enough to satisfy all the stake holders involved in a CCS project.

3. There was a lot of discussion in this network about whether to use quantitative, qualitative, or simple analytical methods to analyze CCS risk. The debate concluded that whilst, there might be a desire to have a fully quantitative risk assessment process, currently it would not be possible for anything more than a semi-quantitative or predominantly qualitative process to be used for CO2 storage simply because we do not know enough about the underground yet to allow us to define probabilities of geological events with confidence.

4. Following the session on the FEP risk assessment process it was concluded that this process is just one tool of many and the general feeling was that it might be better suited as an auditing tool rather than the primary tool for risk assessment.

As well a continuing to work on some of the unresolved issues above there were also a number of additional issues/questions raised over the course of the workshop that need to be addressed. These include:
• Risk assessment guidelines? – are they required and if so, what is the best way of formulating them?
• How confident are we in the modelling results we are generating for CCS projects?
• How long do we need to monitor for after the cessation of CO2 injection?
• What use is the accident/worst case scenario risk assessment approach to the overall risk assessment process?

These questions will be addressed in future network meetings
THIRD WORKSHOP OF THE INTERNATIONAL RESEARCH NETWORK ON RISK ASSESSMENT

1. Introduction

The IEA Greenhouse Gas R&D Programme (IEA GHG) has been working on the topic of risk assessment for a number of years now. From early discussions on the topic, the key message was that to gain public acceptance of CO₂ capture and storage, two key areas will need to be demonstrated: that the technology is safe and that its environmental impact is limited. Safety can be demonstrated to some extent through monitoring programmes at CO₂ injection operations that are currently underway. However, whilst early results from these injection operations indicate leakage is not occurring, such programmes do not necessarily provide confidence in the long-term i.e. 1000’s years after injection has ceased.

The IEA GHG felt that risk assessment studies can assist the development of monitoring programmes for injection sites, relying on predictions of the long-term fate of the injected CO₂ and assessing the potential for leakage in both the short and long-term. To gain public acceptance of CO₂ capture and storage (CCS) the regulators and public will also need to have confidence in the predictions made by the risk assessment studies. To gain such confidence it will be necessary to understand the different approaches being used and the assumptions underlying the results. The results should be produced in an open and transparent manner, so that the results are understood and the implications for ecosystems and human health can be fully appreciated.

The cornerstone of the IEA GHG Programme’s risk assessment work is the IEA GHG International Risk Assessment Network. The Network was formally launched in 2005 in the Netherlands after two preliminary meetings in the UK in 2004 and in Canada in 2005. The purpose of the network is to bring together the key groups working on risk assessment for CO₂ storage from around the world and to address what the regulators are expecting in regard to CCS assurance and whether risk assessment can provide the answers they require. The 2nd meeting of the Risk Assessment Network was held in the USA in 2006.

This report provides a summary of the third meeting hosted by Imperial College in London, UK between the 15th and 16th August 2007.
2. Aims and Objectives of Second Workshop

The workshop aimed to provide:

- Overviews of the current status of CCS risk assessment and further develop a number of risk assessment principles
- An assessment of whether it is preferable to use quantitative, qualitative, or simple analytical methods to analyze CCS risk
- A review risk assessment terminology
- An assessment of site characterization needs for RA
- A review of FEP risk assessment methodology

In addition, the workshop provided an overview and status of the well bore integrity based on the work of the International Wellbore Integrity Network also organised by IEA GHG.

3. Workshop Programme

The programme for the workshop is outlined in Table 1.
# Table 1 Workshop Programme

<table>
<thead>
<tr>
<th>Time</th>
<th>Session/Activity</th>
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</thead>
<tbody>
<tr>
<td><strong>Day 1 (15th August 2007)</strong></td>
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<tr>
<td>08.30 to 09.00</td>
<td>Registration</td>
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<tr>
<td>09.00 to 09.15</td>
<td>Welcome; John Gale, IEA GHG</td>
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**Session 1: Site Characterisation-How much is enough?**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session/Activity</th>
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<tbody>
<tr>
<td>08.45 to 09.05</td>
<td>OSPAR/London Convention; Tim Dixon BERR</td>
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<tr>
<td>09.05 to 09.25</td>
<td>Sleipner Case Study; Helga Hansen, Statoil</td>
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<tr>
<td>09.25 to 09.45</td>
<td>FutureGen; Tom Grieb</td>
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<tr>
<td>09.45 to 10.15</td>
<td>Panel Discussion</td>
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<tr>
<td>10.15 to 10.30</td>
<td>Break</td>
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**Session 2: Site Characterisation**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session/Activity</th>
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<tbody>
<tr>
<td>10.30 to 10.50</td>
<td>IEA GHG Site Characterization guidelines and IPCC SRCCS; Brendan Beck, IEA GHG</td>
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<tr>
<td>10.50 to 11.10</td>
<td>Site Characterization Needs for Risk Assessment; Mike Stenhouse, Monitor Scientific</td>
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<tr>
<td>11.10 to 11.30</td>
<td>US Perspective; Anhar Karimjee, USEPA</td>
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<tr>
<td>11.30 to 11.50</td>
<td>Australian Perspective; John Kaldi, CO2CRC</td>
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<tr>
<td>11.50 to 13.00</td>
<td>Panel Discussion</td>
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<tr>
<td>13.00 to 14.00</td>
<td>Lunch</td>
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**Session 3: Terminology**

<table>
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<tr>
<th>Time</th>
<th>Session/Activity</th>
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<tbody>
<tr>
<td>14.00 to 15.00</td>
<td>Introduction and Presentation of Work; Anna Korre, Imperial College</td>
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<tr>
<td>15.00 to 16.00</td>
<td>Panel Discussion</td>
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<tr>
<td>16.00 to 16.15</td>
<td>Break</td>
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**Session 4: Report from Well Bore Integrity Network**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session/Activity</th>
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<tbody>
<tr>
<td>16.15 to 16.30</td>
<td>The Role of Wellbore Integrity in Risk Assessment for Geological Sequestration; George Guthrie, Los Alamos National Laboratory</td>
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<tr>
<td>16.30 to 16.45</td>
<td>Part 2; Rick Chalaturnyk, University of Alberta</td>
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<tr>
<td>16.45 to 17.00</td>
<td>Discussion</td>
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<tr>
<td>17.00 to 17.15</td>
<td>Confidence Building Through Argumentation; Notio Shigetomi, Mitubishi Research Institute</td>
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<tr>
<td>17.15 to 17.30</td>
<td>Confidence Building Through Argumentation; Hiroyasu Takase, Quintessa</td>
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Close Day 1
### Day 2 (16th August 2007)

#### Session 5: Expectations on Different Parts of the CCS Cycle

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter(s)</th>
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</thead>
<tbody>
<tr>
<td>09.00 to 09.30</td>
<td><strong>Introduction - Strawman Proposal</strong></td>
<td>Tony Espie, BP</td>
</tr>
<tr>
<td>09.30 to 09.50</td>
<td><strong>Risk Assessment Expectations</strong></td>
<td>Claudia Vivalda, Schlumberger</td>
</tr>
<tr>
<td>09.50 to 10.10</td>
<td><strong>Concerns and Alternatives to Non-Probabilistic Risk Assessment</strong></td>
<td>Julio Freedman, Lawrence Livermore National Laboratory</td>
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<tr>
<td>10.10 to 10.30</td>
<td><strong>Does Probabilistic Risk Assessment of Long-Term Geological Storage Make Sense?</strong></td>
<td>Jeroen van de Sluijs, Copernicus Institute, Utrecht University</td>
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<tr>
<td>10.30 to 10.45</td>
<td>Break</td>
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<tr>
<td>10.45 to 11.15</td>
<td><strong>Keep it Simple</strong></td>
<td>Lars Olof Hoglund, Kemakta Consultants</td>
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<tr>
<td>11.15 to 12.30</td>
<td>Panel/Strawman Discussion</td>
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<tr>
<td>12.30 to 13.30</td>
<td>Lunch</td>
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#### Session 6: FEP's - Features, Events, Processes

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.30 to 14.00</td>
<td><strong>Using the FEP Approach in Auditing the Comprehensiveness of a Site-Specific Research Programme for CO₂ Storage</strong></td>
<td>Ton Wildenburg, TNO</td>
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<tr>
<td>13.30 to 14.00</td>
<td><strong>Using not Abusing FEP's</strong></td>
<td>Steve Benbow, Quintessa</td>
</tr>
<tr>
<td>14.00 to 14.30</td>
<td><strong>Weyburn Experience of FEP's</strong></td>
<td>Rick Chalaturyk, University of Alberta</td>
</tr>
<tr>
<td>14.30 to 15.00</td>
<td><strong>Methodological Developments to Define Safety Criteria</strong></td>
<td>Olivier Bouc, BRGM</td>
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<td></td>
<td><strong>Certification Framework</strong></td>
<td>Curtis Oldenburg</td>
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<tr>
<td>15.00 to 15.15</td>
<td>Break</td>
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<tr>
<td>15.15 to 16.15</td>
<td>Panel Discussion</td>
<td></td>
</tr>
<tr>
<td>16.15 to 17.00</td>
<td><strong>Wrap up</strong></td>
<td>John Gale, IEA GHG</td>
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</tbody>
</table>

Close Day 2
4. Presentations Summaries and Discussion

4.1. Developments in Risk Assessment

4.1.1. OSPAR/London Convention – Tim Dixon – BERR

Tim Dixon from the UK Department of Business, Enterprise and Regulatory Reform presented an overview of the amendments that have recently been made to the London and OSPAR conventions. The London Convention and Protocol and the OSPAR convention govern various activities in the marine environment and up until now have prohibited most offshore CCS applications. Due to the desire for offshore CCS and the acknowledgement that the conventions were both written without CCS in mind there has been a drive from a number of countries to amend them to allow CCS. It was noted that a number of participants of this network were involved in the amendment process.

The amendments to the OSPAR convention to allow CCS occurred in Annexes II and III of the convention and were accepted by consensus on the 6th of June 2007. However, they will only come into force when they are ratified by 7 Parties. It should also be noted that before a country can ratify they require a CCS regulatory system to be in place domestically. It is also important to note that OSPAR is legally binding unlike the London convention and protocol which are only guidelines.

In conjunction with the amendment to the OSPAR convention they also produced the OSPAR Guidelines for Risk Assessment and Management of Storage of CO₂ in Geological Formations which includes the Framework for Risk Assessment and Management (FRAM). OSPAR ruled that it is a requirement to use these guidelines when permitting CCS projects in order to reassure parties of the safety of the CCS process. Although the amendments themselves require ratification, the OSPAR guidelines must be used as of the 15th of January 2008 for all CO₂ storage projects with the exception of EOR.

The Guidelines:

- Provide generic guidance when issuing permits,
- Must be applied as fully as possible by countries,
- Focus on injection and storage,
- Requires countries to report CCS activities to OSPAR,
- Include the FRAM.

The guidelines are intended to be based on common sense and practicalities to ensure they were workable, practical and non-restrictive.

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1 The OSPAR convention applies to Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, and the European Community.
The amendments to the London Protocol to allow CCS were adopted in November 2006 and came into force in February 2007. Guidelines for Assessment of CO2 Streams for Disposal into Sub-Seabed Geological Formations not completed at time of amendment.

The guidelines will be derived from the London Convention’s Risk Assessment and Management Framework (2006). This is the same framework on which the OSPAR FRAM was based.

This London Convention Framework contains:

- Problem Formulation – define bounds, scenarios etc
- Site Selection and Characterisation
- Exposure Assessment – processes and pathways for environmental exposure
- Effects Assessment – of exposure on marine environmental
- Risk Characterisation – integrates exposure with effects and likelihood
- Risk Management – monitoring and mitigation

When producing the London Guidelines a contradiction arose with the need to follow existing waste guidelines. These guidelines look to minimise flow of waste into the environment however a caveat had to be added to explain that this principle doesn’t follow in the case of CCS.

Questions:
Q) Who do you anticipate will be the first country to use the OSPAR and London Guidelines?
A) Possibly the UK or Norway as they are moving ahead the quickest on demonstration plants. UK CCS regulations are due to come out as a draft in November of this year. The UK is also looking to see how it can help with regulation building in other countries. The EU regulations may also help fast track the process in member countries.

John Gale made the comment that he is impressed by speed of amendments (which took 3-4 years to be finalized) and it will be interesting to see how quickly other protocols such as the Barcelona convention in the Mediterranean are also amended.

4.1.2. Sleipner case study – Helga Hansen – Statoil
In the second presentation of the session Helga Hansen from Statoil discussed the risk evaluation process that took place prior to injection at Sleipner. Outcomes were also presented from a workshop Statoil held in 2006 that discussed the past, present and future risk associated with the CO2 injection on Sleipner.

CO2 storage at Sleipner was an integral part of the development plan at the site so it was included in the original Plan for Development and Operation (PDO) in 1991 so no separate application for CO2 storage was required. This PDO did not require any quantitative risk evaluation of the site but did mention possible risk associated with the CO2 storage. These risks included:

- Problems with injectivity and potential over-pressurisation of the formation
- Wet CO2 corroding the casing in the production wells
Hydrate formation in the Utsira Formation which was deemed highly unlikely

In addition to highlighting possible risks in the PDO, Statoil did perform an evaluation of a number of other issues prior to injection. The main issues were injectivity, migration of CO2 to the Sleipner wells, and the caprock integrity.

In 2006 Statoil invited a number of international CCS experts to a workshop in order to perform a risk evaluation of the Sleipner project. The aim of the workshop was to identify risks of CO2 escape and effects on neighbouring wells and licences, identify mitigating measures, and to evaluate whether the risk associated with the project was within acceptable limits.

This analysis was performed for the current injection rate and at increased injection rate of ten times the current level. Again, no quantitative evaluation was done but rather a qualitative method was used with the experts classifying the severity of the risks.

The project was then divided into three separate categories; the formation, the caprock, and the wells (including the injection and production wells). The results can be put into two categories; risks at current injection rates and, risks increased injection rates of ten times current injection rates.

The results for current injection rates are as follows:

<table>
<thead>
<tr>
<th>Project component</th>
<th>Risk</th>
<th>Possible risk scenario</th>
</tr>
</thead>
</table>
| Formation         | Medium| • CO2 migration under the caprock or internal shale layers and into adjacent wells  
|                   |       | • Low risk of migration under the caprock to up-dip sands and then to the seabed |
| Caprock           | Medium| • Leakage through undetected faults or fractures            
|                   |       | • A low risk of fractures being created                     |
| Wells             | Medium| • CO2 reaches adjacent exploration wells                    
|                   |       | • A low risk of injection system failure                    |

The results for increased injection rates are as follows:

<table>
<thead>
<tr>
<th>Project component</th>
<th>Risk</th>
<th>Possible risk scenario</th>
</tr>
</thead>
</table>
| Formation         | Medium| • Injection induced degradation of reservoir                
|                   |       | • Migration below the caprock or internal shale layers to neighbouring licence blocks |
|                   |       | • Low risk of reduction/misinterpretation                   |
| Caprock           | Medium| • Same as current injection rates                           |
| Wells             | Medium| • Same as current injection rates                           |

In conjunction with the above results, a number of key conclusions were drawn from the workshop:

- The risk of CO2 release from Utsira Formation is considered low and acceptable
- Increased injection rates would accelerate the identified risks
A selection of mitigating measures to reduce risk and improve control of the CO₂ plume are available and have been proposed.

Questions:
Q) When the project was divided into wells, formation, caprock. Did you look at the interaction of the risks between these categories? For example; formation subsidence would affect the caprock or undetected faults or fractures.
A) No real interaction was looked at although it was known that there could be some interaction. The division was performed to simplify the process.

Q) How could you achieve a ten times increase in injection rate?
A) The increased rate was used in this theoretical process for other projects that may have higher injection. If you were to actually increase injection you would have to do a new risk assessment.

Q) If CO₂ breaks the caprock, will the CO₂ bubble to the surface or pool at the bottom of the ocean?
A) It probably won’t reach the ocean floor, but rather be trapped in overlying formations where there is already evidence of accumulated gas.

Q) How did the CO₂ move through the shale levels in the formation?
A) The shale is not continuous. There is often communication around thick levels of shale.

Q) Could you directly measure the fracture grading in the formation?
A) Not directly. High resolution seismic was used to look at the caprock.

Q) What is the smallest volume of CO₂ movement that could you see in seismic? 10Mt?
A) Not sure yet.

Q) Will Statoil do more quantitative analysis in conjunction with seismic?
A) No, there is a focus on seismic and wells, but currently they are giving us confidence in the integrity of the storage.

Q) How good is the temperature control in the well?
A) There is a desire to do measurements for temperature and pressure in the well, but the well is very sensitive.

Q) Will Statoil perform baseline monitoring of the sea floor/environment for the London Convention or for OSPAR?
A) No, although work ongoing in Trondheim to model the sea and sea floor at high pressures. The pressure tank will be used to find more about the effects of CO₂ and pH changes on marine environment. Pressure vessel goes to 20bar.

Q) Are there plans to increase the injection rate at Sleipner?
A) Currently we are injecting 1.4Mt per year and there are no plans to increase this although there are discussions about using Sleipner for other projects such as Castor but this would require another well and more risk analysis.

4.1.3. FutureGen case study – Tom Grieb
In April 2007, the FutureGen Alliance completed the Final Risk Assessment Report for the FutureGen Project Environmental Impact Statement (EIS). Tom Grieb from Tetra Tech presented the results. The risk assessment analysis took three months to complete and was performed for all four of the potential FutureGen sites which are all situated in rural communities with low populations in the vicinity.

The FutureGen risk assessment was comprised of a number of different components:
- Conceptual site models
- Human health and ecological risk analysis
- Pre-injection RA
- Post-injection RA
- Risk Screening and Performance Assessment (Characterization)

The FutureGen project has finalised their human health and ecological risk analysis with the final draft of their environmental impact assessment (EIS) being completed. The FutureGen EIS looked at long term storage and analysed four gases; CO₂, NH₃, Radon and H₂S. FutureGen also models aspects of the subsurface and surface, however the modelling provided by the sites wasn’t extensive. The human health and ecological risk analysis was then compared to other examples of active and proposed CCS sites at Weyburn, and the Latrobe valley site and Gorgon sites in Australia, however none of these site are yet to fully complete their EIS.

From the analysis it was found that the largest risk associated with this site was upward migration of CO₂ through undocumented deep wells, followed by upward gradual release through the caprock. However it was concluded that overall, the likelihood and consequence of release of CO₂ above the plume footprint are not significant although H₂S releases from abandoned, undocumented, or poorly constructed wells could lead to potential human health risks.

At the conclusion of the FutureGen study, a number of possible uncertainties in their risk assessment results were identified:
- Uncertainties in release rates and their probabilities – wide ranging variables
- Analysis based on affected population remaining constant – this could change over the lifetime over the project
- Design of FutureGen facilities and sequestration methodology evolving – final site won’t be selected until end of 2007.
- Exposure and toxicity parameters conservatively chosen
- Peer-reviewed health effect levels not available for CO₂ for all durations

As a result of the FutureGen risk assessment analysis, a number of conclusions have been drawn. Firstly there are potentially serious risks from release of CO₂ to workers in
immediate vicinity of pipeline or well-head, in the event of a puncture or rupture. This does not relate to population in the area but rather only to the workers. H₂S releases from pipeline or wellhead could result in health effects to local population at distances up to several kilometres from the release point. The higher the H₂S content in the gas stream the more severe the risk profile. It was found that the likelihood and consequence of releases of CO₂ from above plume footprint are not significant. Lastly it was found that H₂S releases from abandoned, undocumented, or poorly constructed wells lead to potential human health risk. Ultimately the conclusion was that the risks associated with CO₂ are minimal compared to those associated with any H₂S in the stream.

Following the conclusion of the FutureGen risk assessment process, the team gave a number of final impressions about the risks associated with CCS and the FutureGen risk assessment process:

- Potential risks of transport and sequestration in the selected saline formations are quantifiable and manageable
- Transport of compressed gas is a significant consideration
- Well integrity is a key issue
- From the literature we reviewed there was an emphasis on frequencies not probabilities in CCS investigations
- Analogue approach suitable for site risk assessments and basis of developing regulatory framework
- Recommend risk-based MMV program
- Public support for local FutureGen site selection

Questions:
Q) FutureGen used an 8km spacing for safety valves, is this standard? Some are known to have used 30km spacing.
A) This is specified in the design but it is not standard. The analysis was replicated for different scenarios, such as more valves in built up areas.

Q) Won’t H₂S absorb quicker than the CO₂ in the subsurface?
A) Yes it will. The H₂S risks mentioned here are during transport and injection rather than leakage from the subsurface.

Q) Did other CO₂ pipelines looked at have similar H₂S content?
A) No, most had lower.

Q) What was the conclusion about the possible affects on groundwater.
A) There was found to be low probability of injected gas coming into contact with ground water.

Q) What caused the video rupture?
A) Backhoe. Most likely cause “whoops” factor – quite high, higher than corrosion.

Q) What were the demographics of the expert group who reviewed the project?
A) All technical, geologists, risk assessors. No NGOs or farmers but this is going on in other parts of the project. Different groups will review the results.

Q) How have you used the safety distance? Did you recommend safety distances?
A) Right now there is not specified distance – 100s of 1000s of pipelines in use now. So there should already be safety distances. They did make recommendations for distances but unsure.
A) Malcolm. Pipeline with 4% H₂S requires a 400m clearance
A) Really there is no general answer.

4.2. Site characterisation – How much is enough?

4.2.1. Site characterisation and the IPCC SRCCS – Brendan Beck – IEA GHG
The first presentation of this session looked to set the scene by outlining how the IPCC Special Report on Climate Change deals with site characterisation. Brendan also outlined some work the IEA GHG is doing in the area of site characterisation guidelines.

The IPCC SRCCS defines the key goals for site characterisation as:
- To assess how much CO₂ can be stored at a potential storage site
- To demonstrate that the site is capable of meeting required storage performance criteria.

These goals require the collection of the wide variety of geological data, much of which will be site-specific. Most data will feed into geological models that will simulate and predict the performance of the site.

Generally the storage site and surroundings need to be characterized by geology, hydrogeology, geochemistry and geomechanics focusing primarily on the trapping mechanisms present. This will include a very good analysis of the sealing horizons and strata above. Site characterization data fed into a three-dimensional geological model. The general site characterization data should include:
- Geological site description from wellbores and outcrops,
- Information on subsurface geological structure, including faults & fractures,
- Formation pressure measurements to map rate and direction of groundwater flow,
- Water quality samples to demonstrate the isolation between deep and shallow groundwater.

It is also noted that oil and gas fields will often be better characterized than saline formations given the history of subsurface exploration associated with these activities.

Brendan then went on to outline the more specific site integrity factors and data requirements that the report identifies in a number of areas including:
- Stratigraphic factors,
- Geomechanical factors,
- Geochemical factors,
- Anthropogenic factors.
Following the outline of the IPCC SRCCS site characterization coverage, Brendan briefly discussed some work that the IEA GHG is doing on Site Characterization Guidelines and their Best Practice Database.

IEA GHG are looking to develop a set of site characterization guidelines to help fast track the development of CCS projects by creating standardized approach to CCS site characterization. The guidelines will be generic to saline aquifers and hydrocarbon fields and will be target oriented rather than being prescriptive. The guidelines will not be regionally focus but rather apply globally. They will then be available for general distribution to encourage uptake of the guidelines in practice. Before the drafting of the guidelines commences a review will be undertaken of the current work in this area to ensure that work is not duplicated.

The guidelines will be underpinned by the IEA GHG Best Practice Database which is being developed in conjunction with the EU CO2ReMoVe project. The database will ensure the most up-to-date practices are available to the project developers and to regulatory bodies. The database has been set up and is ready to go live as soon as a ‘critical mass’ of information has been gathered.

4.2.2. Site characterization needs for risk assessment – Mike Stenhouse

The second presentation of this session looked specifically at site characterization needs for risk assessment and vice versa and focused specifically on the long term fate of the CO₂. Initially the question was posed; why do risk assessment? The answer given was that risk assessment forms a major part of the confidence building process among stakeholders both technical and public. The goal of risk assessment is to build a sufficiently broad consensus across the stakeholders to proceed to implement a storage project.

There are a number of different requirements to ensuring confidence in a project and these will change depending on the stakeholder in question. A consensus in the technical community that the system (storage system and geosphere) is sufficiently well understood to quantify the ways in which it can evolve with time. Public confidence requires trust that the CO₂ storage community will perform high quality and honest work and is aided by open access to all important information. In both cases, demonstration of robust storage system would enhance confidence.

There are also different risk assessment requirements for the different phases of a CCS project.

- Site Selection: the role of risk assessment would be to screen and compare sites. During Site Characterization: risk assessment will provide guidance as to what data and information will be required.
- Permitting Phase: risk assessment will form the major part of the safety submission.
- Injection phase: The major role of risk assessment will be to refine models with comparison of model using existing data.
• Post injection: Risk assessment will help with the long term predictions which require a robust prediction process

Risk assessment and site characterization is an iterative process that requires an active feedback loop to assess and reassess data as it is acquired. It is important to note that baseline data is imperative to differentiate between natural and project based observations.

Specific RA needs from site characterization include the conceptual model of storage system and most importantly data. The conceptual model will reflect the current understanding of the reservoir, the sealing system, leakage pathways, hydrology, hydrochemical and geochemical inputs and wellbore characteristics. The conceptual model will be founded on the current data available and will have to evolve as new data is acquired.

The major question surrounding site characterization of CCS site is deciding when enough is known. There are a number of considerations to take into account when deciding:

• Knowledge increases with additional information and data, but by how much and is the knowledge useful? It is also important to note that certainty doesn’t necessarily increase with knowledge.
• Cost of acquiring site characterization information including both direct cost and the indirect or hidden costs.
• Value of information. Reduced uncertainties may make it easier to convince stakeholders of overall safety. Reduced uncertainties could reduce probability of ‘negative’ surprises by decreasing undetected faults and features.
  o The Probability of conceivable surprises should be possible to bound based on detection limits for characterization techniques.
  o RA can help assess what site properties affect storage integrity
• Stop characterization once the “net gain” of the additional information is zero or negative. A comparison must be made between the value of the increased information and the cost of acquiring it.
• Who decides the value or ‘gain’ of additional information?

All site characterization information and data must have a useful purpose and this is to improve the understanding of the site and or contribute to the risk assessment needs.

To wrap up the presentation Mike made two key conclusions. Firstly, technical and public confidence is needed as a basis for proceeding with CO₂ storage projects. Technical confidence and good science are prerequisites, but openness and, transparency are also required and can be achieved through the involvement of all stakeholders whenever possible. Secondly, risk assessment can contribute significantly to technical and public confidence as it provides a useful framework for guiding site characterization activities at all stages in the development of a geological CO₂ storage project. As well as identifying what information and data feed directly/indirectly into assessment modelling,
RA can also guide decision makers on what information/data are *not* crucial to assessment predictions.

Questions:
Q) The presentation implied that knowledge converges to a finite required amount. Oil and gas doesn’t occur this way. Oil and gas estimates often end up well beyond the original estimates. It is not possible to say when enough is enough? Only after a number of years of dynamic performance can you start to properly understand the site.
A) I agree – The presentation described an idealized concept for site characterization knowledge. It is broadly recognised that as you collect data it often leads to lesser relative understanding of the site. You have to look at something like this as one method of deciding when you have enough information
A) Understanding is not the objective; the objective is to reduce the risk to the point where it is acceptable.

Comment) This is very much a question based on where you can make real assessment of risks. One option would be to analyse the worst-case scenarios and if they are acceptable then you can justify large sums of money to develop the project.

Comment) A lot of the risk can be handled by mitigation optimisation

Comment) I can see some scenarios, such as diffuse leakage through a fault which I would question if you can mitigate at all.
A) If no other mitigation option is possible then you always have the choice to ultimately stop injection at the site.

4.2.3. **The US perspective – Anhar Karimjee – US EPA**
Anhar presented the US perspective of risk assessment and site characterization for CCS projects. In the US, there is a demand for transparent and easily understood risk assessment and it will be important to consider the target audience when developing these approaches. It is understood in the US that site characterization is critical but it can be costly, the key question is “What information is critical and when do we need to have it?” – How much do you need to start injection, how much can you leave to learn as you go? There are currently changing attitudes in the US in regard to climate change and with this change there have been growing interest in CCS.

**CCS and US Climate Policy**
- Senators Lieberman and McCain requested that EPA estimate the economic impacts of S. 280, the Climate Stewardship and Innovation Act of 2007.
  - The enabling technologies in this analysis for electricity generation are Carbon Capture & Storage (CCS) and Nuclear Power.
- In 2007 alone, there have been at least nine bills presented to congress that are relevant to CCS.
- In addition to the work being done for the federal government, there is also a lot of work going on at state government level in regard to CCS. This has however
led to concerns that the US could be divided into a patchwork of different CCS regulation.

In order to establish what regulatory options are appropriate the risks of the process must be identified and evaluated. The method of quantifying risk can vary and be either qualitative or quantitative or a combination of the two. It was proposed that the mean risk, i.e. the most likely outcome, should form the basis of the analysis rather than the worst case scenario. If scientific opinion is divided about the most likely outcome then multiple risk estimates should be presented. Once regulatory options are identified, the relative costs and benefits of each option must be estimated i.e. what will it cost to implement and how will health and environmental risks be reduced?

The costs of regulatory development will change with the level of analysis required. More costly regulations require more extensive analysis. An estimate as to the costs is outlined below:

- <$100M: Preliminary cost analysis
- $100M-$1B: Formal “Regulatory Analysis” including cost-benefits and uncertainty analyses
  - describe uncertainties qualitatively
  - conduct sensitivity analysis
  - identify key parameters where probabilistic analysis may be needed
- >$1B: Regulatory Analysis+
  - conduct formal probabilistic analysis of relevant uncertainties

It is estimated in the US that the cost for CCS regulations may end up in the $100M-$1B range.

Two examples were given of risk assessment approaches in the US. One was for the treatment of waste water where the EPA conducted a relative risk assessment of wastewater disposal options and the other where the EPA performed a vulnerability assessment for CCS.

The EPA is becoming more active with workshops and has recently sponsored two focused specifically on site characterization. The first was the International Symposium on Site Characterization for CO2 Geological Storage in March 2006 and the second was the EPA Technical “Area of Review” Workshop in July 2007.

In conclusion:
- CCS is a key climate mitigation technology
- There is a high demand for transparent and easily understood risk assessment approaches
- Key Challenges Remain
  - Demonstration
  - Appropriate Regulations
  - Public acceptance
Questions:
Q) In regard to the cost of data acquisition a system model was presented earlier for the Weyburn project saying it would only cost a few million dollars, but Weyburn has so many wells and to recreate that data from scratch would cost \( \frac{1}{2} \) to 1bn dollars.
A) This is true, only the additional costs not the total project costs were presented here.

Q) All the site characterization proposed seems to be for the geosphere and not the biosphere – soil gas, ecosystem, and airborne surveys. With no biosphere characterization can evaluate impacts in the future.
A) EPA is considering biosphere characterization and other level 2 attributes in the RA approach but they are currently further along with their geological characterization work.

Q) It was said that the EPA did a study on a US cap and trade system, do you know what the cap was or if it was tight?
A) Not sure what the cap was but it was thought to be neither tight or loose but rather medium.

4.2.4. The Australian Perspective – John Kaldi – CO2CRC
John presented the Australian perspective to CCS risk assessment specifically looking at the methods for quantitative risk assessment and its applications for site characterization. John the presented an update for the Otway Basin project including the future aims and objectives of the project.

The CO2CRC are currently working on a quantitative risk assessment methodology. As part of this process they are looking to develop “best practice” for running quantitative risk-based CCS project analysis underpinned by methods adopted in CO2CRC site characterisation, and monitoring and verification workflows.

John also took the opportunity to present an update on the CO2CRC Otway Basin pilot project announcing that the injection well was drilled at the site earlier this year with injection expected to commence late 2007. John also used the pilot as an example of how site selection could occur outlining some of the factors that led to the choice of the site. A brief explanation was then give to the as to some of the site selection decisions for other CO\(_2\) storage sites.

John then went on to outline some of the issues still remaining with risk assessment for site characterization. This included the composition of the injected gas, the characterisation of existing and future wells, whether the site characterisation requirements will differ for onshore and offshore storage, and what phases of a project site characterisation relate to? Does it only relate to prior injection or does it continue throughout the lifetime of the project? These are all questions that will need to be address in order to achieve a consistent and replicatable methodology for site selection that is adequate for all the stake holders involved in the process.
In conclusion John summarised with a number of key points:

- There is no such thing as the perfect site; they will be fit for purpose….each with own risk assessment criteria
- We need to agree what is meant by “site characterisation”, including when it concludes – the title of the section
- We need to have an agreed methodology for storage capacity assessment
- “Characterisation” is site specific, onshore/ offshore specific and storage type specific; it is therefore essential that we identify commonalities and don’t just look for differences
- Easy to work out what we can do; more difficult to work out what we don’t need to do – otherwise the task will overwhelm us!
- Geology is only one of the features that determines suitability of a site for CO₂ storage

Questions:
Q) Did the monitoring well get completed in terms of all the equipment being set up?
A) Not yet, right now we are waiting for the weather to improve.

Q) How do involve the public at this stage of the Otway project?
A) The CO2CRC ran community meetings from early on in the project. This included open houses, show and tells, and school lectures to kids. We found the best approach was to send the CO2CRC students who are excited about this technology to these sessions rather than the older staff. We found the land owners are quite aware, they knew what their royalty rights were from oil and gas, for them it is just another project but with information they can feel ownership over the benefits. We stress that you need lots on engagement throughout the project.

Q) The CO2CRC definition of site characterization mentions the storage of CO₂ for a “defined period of time”, can you elaborate?
A) We will let the regulators will decide what this period of time is.

Q) How do you combine the qualitative (expert panel, public opinion) and quantitative assessment?
A) We work to ensure that the expert panels used involve a large array of different technical and non-technical disciplines.

Q) What is the aim of the Otway Basin Project?
A) The aim is to demonstrate that it can be done to plan, to budget in the Australian environment and with Australian technology.

Discussion:
Q) What is the area that is subject to site characterisation? Air or surface?
A) The EPA has used a fixed radius in the past but for CCS we will have to use modelling to determine an area. The policy makers need support to make a proper decision; they need to know what is practical. There is a need to determine what is actually possible and what isn’t.
A) Weyburn used a 10km x 10km project boundary but this could be reduced

Q) Are there any scale up issues of the projects from pilot scale?
A) The FutureGen project goal is to sequester 50Mt over the lifetime of the project. The FutureGen area for site characterization is 1.5mile for all four sites for CO₂ and 40+ miles further for pressure monitoring. You have to invest in monitoring now so you have the data in 20-30 years.

Q) It was good to see consistency across the presentations in this session. In regard to costs, do we have any grasp of the financial uncertainty or hidden costs?
A) There are hidden costs in the site characterisation for Weyburn you are unlikely to have that detail of existing data in any other project.
A) What you need to do is develop an uncertainty plan and find where the uncertainties are.
A) We are good at estimating risk in known experience but are very bad in new scenarios. Also we have no way of apportioning risk over the long time frame.

4.3. Terminology

4.3.1. CO₂ storage risk assessment terminology: Introduction and presentation of work – Anna Korre – Imperial College

Terminology has previously been highlighted as a key issue in the area of risk assessment which led to Imperial College undertaking a body of work in this area for IEA GHG. The objective of this work has been is to develop and propose internationally harmonised generic and technical terms used in CO₂ storage hazard/risk assessment, which will help facilitate the mutual use and acceptance of the assessment of CO₂ storage projects between countries, saving resources for both governments and the industry.

Target groups of users of the harmonised terms are CO₂ storage and environment professionals and political actors at all levels. The harmonised terms may also be used as a basis for preparing other publications primarily aimed at public information and CO₂ storage education. It is not a goal to standardize risk assessments globally, as that is considered to be neither appropriate nor feasible.

Historically there have been two types of risk assessment; first public-health risk assessment and second engineered-systems risk assessment. As their names suggest, the first focuses on the health effects and the second relates to the immediate and delayed effects due to the failure of systems. In both cases, risk assessment involves a search for “causal links” or “causal chains” verified by “objective” analytic and experimental techniques.

In conjunction with risk assessment regulators also apply risk management the difference being; risk assessment is the use of the factual base to define the health effects of exposure of individuals or populations to hazardous materials and situations, where as risk management is the process of weighing policy alternatives and selecting the most
appropriate regulatory action, integrating the results of risk assessment with engineering data and with social, economic, and political concerns to reach a decision.

Imperial College has used work done by NRC and IPCS/OECD to define four steps which risk assessment contains some or all of:

- **Hazard identification**: The determination of whether a particular agent is or is not causally linked to particular adverse effects.
- **Dose-response assessment**: The determination of the relationship between the magnitude of exposure and the probability of occurrence of the effects in question.
- **Exposure assessment**: The determination of the extent of exposure before or after application of regulatory controls.
- **Risk characterization**: The description of the nature and often the magnitude of risk, including attendant uncertainty.

Anna went on to address a number of specific generic terms. Only a selection of the full terminology set were addressed; these included data-oriented terms such as hazard, agent, risk, effect, and source, and action-oriented terms such as hazard assessment, risk assessment, risk management, and risk analysis. The set of terms presented are part of a greater set of 200 terms that Imperial currently have.

Anna wrapped up her presentation explaining what is next for the CO₂ storage RA terminology development work that they are doing at Imperial. All the terms identified and the definitions will be circulated widely (e.g., through IEA GHG RA network, the research community and industry) for review and comments.

Questions and Discussion:
Q) Is this the right group to be engaging on this? If it is we are looking for long term support from the people here to ensure it.
Q) Because this is terminology could we use Wikipedia or a similar style of mechanism to get open and transparent discussion?
A) Wikipedia style approach sounds very possible.
A) Wikipedia is one approach but so it engaging with a working group. The document that is being produced by Imperial will be able to be used as a guide and will evolve with the industry. If we invest some effort now in this it will be an investment for the future.
A) The Wikipedia becomes very attractive. Getting the information in one place is the first and significant step.

Q) The RA that was done for the four areas including Otway calls it quantitative although it includes expert panel attaching numbers to things. Would you call this Qualitative, semi qualitative, semi quantitative?
A) If there is opinion involved in the process then it is qualitative.

Q) What are we looking to achieve? A lot of the definitions used come from very complex projects and relate to specific fields and people. There are a lot of definitions already out there.
A) The goal is to achieve consistency in the way we communicate with each other and the world.

Q) Have the terminology in the OSPAR document been reviewed as it looks like it will be a fairly influential document?
A) This has not been done by Imperial, yet but they will definitely be looking at it and use it in the preparation of the documents that are going to be circulated

Q) There is a project that the DTI funded in the 80’s which looked at evidence based analysis.
Q) The nuclear industry did safety assessment and performance assessment is a subset of this. This document came out in the 70s when there was a need to deal with nuclear waste.

C) Part of this process is assembling generic data but the other part is looking at specific CCS terms and how we get them, either from oil and gas or from elsewhere, or our own definition. Closure, abandonment, post-closure have all been pulled from different parts of the industry.

Q) Are we ever going to get to a stage that we will all be using the same terminology?
A) We can try and then it is all out on the table and we know what terms are equivalent.

Q) How long does the list of terms need to be? 200,000 or 20?
A) There was discussion of 50 + 50. Currently Imperial has 200 but this needs to be cut down. Then we will be open for suggestions for things that may need to be added.

Q) The IPCC SRCCS has a glossary, can we use this as the basis for further work?
A) That glossary was just an amalgam of sources and there was no attempt at trying to achieve consensus.
A) IPCC defines risk assessment as “part of a risk management system”
A) London convention and OSPAR both have glossaries and they both come from the IPCC special report.

Q) In the presentation a definition of risk management was given but there was no mention of mitigation.
A) Mitigation would fall into emissions and exposure control.

Q) Risk perception is also an area to look at, as well as probabilistic, non-probabilistic etc.
A) Not all the work done by Imperial was presented today.

Q) Why do people hesitate at performance assessment. Most people these days are try to prove that their system will perform as they expect. Does this not point to performance assessment? There is no talk of X molecules of CO₂ at Y meters which would indicate risk assessment?
A) A risk assessment process can be carried out in separate tiers with tier 1 being potential hazard assessment, tier 2 being exposure assessment, and tier 3 is consequence assessment.

A) Nobody is pushing toward exposure assessment at the moment. If we go by these tiers then we will need to specify exposure limits, in particular with the sub surface. The IPCC numbers 1% over 100 years... that’s a performance target.

A) Everyone here is technical and not from health or environment so it is fitting that we discuss technical.

A) This is a concern at the EPA as well. We are not calling it risk assessment because we don’t want to give the impression that we can do a quantitative probability assessment. We are using a new term: vulnerability assessment. OMB is extremely politicised organisation and can’t be trusted and so is a bad example, they are reacting to politics.

A) This may be the case but Imperial wants to be prepared for tough questions

A) It is a good idea be prepared but don’t over sell yourself. We need to manage expectations.

Q) The implication from the discussions is that a certain amount of leakage is acceptable?

A) Perhaps we should talk containment underground rather than containment in a specific formation. Then we don’t have to deal with exposure.

Q) How will the data be processed once we give our answers to the terminology survey?

A) It will be presented as a report with review by a small group of experts with the background of all the experts provided in the appendix. It is through this review process that the results will be derived.

Q) We are dealing with many people in the IGCC and pipelines and chemical industry, and all have to deal with other industries so you are not going to get convergence but rather a glossary or translation book.

Q) Glossary is a good idea but we can’t make the expectations of storage security so high that in the future we are excluding projects that we need to overcome climate change.

Q) Uncertainty analysis can be reviewed as its own industry with its own terminology.

A) True, this has been considered by Imperial.

Q) What about possible links to the CSLF?

A) George Guthrie and Tim Dixon can provide this network with a link with the CSLF.

Wrap-up) It seems we are in general agreement to go forward and we will send out an abridged list of terms amongst the network before looking into the Wikipedia option. John Gale will look into organising an organising committee.
4.4. Report from the Wellbore Integrity Network

In this session Rick Chalaturynyk from the University of Alberta and George Guthrie for Los Alamos National Laboratory gave an update on the ongoing work of the Wellbore integrity network.

The wellbore integrity network has a number of guiding aims regarding the bringing together of experts in the field and ultimately improving the understanding of the long term performance on well seals, past present and future. To date the wellbore integrity network has worked very well and achieved a lot, in particular since the second meeting where some aggressive objectives were set for what the network hopes to achieve.

The overarching concern is that a CO₂ storage site in an oil or gas reservoir could contain upward of 2000 well penetrations. This means researchers need to better understand the chemistry that occurs in the well and model the implications that these wells may have on site integrity. Current models are unable to deal with this number of wells but it is imperative that people can come up with new models that can because it is not feasible to perform pre-emptive remediation to 2000 wells as this will ruins any cost/benefit analysis for the project.

One of the most interesting findings coming from the network is the comparison of lab results to the observed results from the field. Based on lab experiments there will be rapid degradation of the cements (Portlands) used to plug the well but in practice there are field observations of wells that have been exposed for 90+ years and show very good performance. The question is, how do you reconcile this contradiction? In one case you might say that Portland it fine but in another case you might need very expensive CO₂ resistant materials.

How do we go from performance in the lab to performance in the field? There many variables in the field that we don’t completely understand, different cements, different cap rocks. Two approaches are using analogues or using scientific information. These must then combine into probabilistic model.

Another interesting observation involved a sample of well sealing cement taken from the SACROC field. The sample seemed to indicate that there had been some corrosion of the cement at the contact point with the CO₂. It did however indicate that this dissolved cement particles were then forced into the overlying cement creating a very good, impermeable seal.

Conclusions
- Existing wells represent potentially important leakage pathways
- A semi-analytical model allows Monte Carlo simulations for risk assessment
- A comprehensive experimental programme is needed to determine important properties of existing wells.
The next IEA GHG wellbore integrity workshop will be held in Paris in March 2008 and will be hosted by Schlumberger. This is come shortly before the joint network meeting in May in the USA.

Discussion:
Q) How do your wellbore integrity experiments work?
A) The wellbore integrity experiments use reservoir pressure and temperature with a flow CO₂ or CO₂ brine through a made sample which matches result in the field.

Q) How many wells have sustained casing pressure?
A) At Weyburn the safest thing to say is that cases of sustained casing pressure are going up.

Q) Should we avoiding formations with 2000 wells rather than trying to find solutions?
A) Yes perhaps, but reservoirs without wells have their own risks? More wells mean more data?

Q) What is your hypothesis why the degradation rates of cement are quick in the lab and slow in the field.
A) Lab experiments are generally batch experiments which didn’t necessarily match the field.

Comment) From a risk assessment standpoint I would have originally said CO₂ resistant cement but not the cement seems to have been redistributed in the well and sealed possible better, although this is one well of one million wells in the basin.

Comment) Maybe we should be concentrating on doing the cement properly. Perhaps we should be looking at cement work rather than the chemistry.

Comment) If you look at SACROC the hypothesis says that fluid flows through a crack to bring material. The resolution to find this is very high. We have to do all our sampling and experiments in a non destructive way before you can fully rely on your results.

4.5. Confidence Building through Argumentation

In the final set of two presentations, Notio Shigetomi from the Mitsubishi Research Institute and Hiroyasu Takase from Quintessa presented some of the work they are doing on confidence building. The two pieces of work that were presented were a workshop that was ran on confidence building and an interactive tool to help pool knowledge on CCS risks.

The workshop was titled confidence building in the long-term effectiveness of CO₂ capture and geological storage and was held in Tokyo in early 2007 in conjunction with the IEA GHG. The objectives of the conference were twofold:
1. To exchange state-of-the-art information, knowledge, expertise and insights on CO₂ capture and geological storage and,
2. To have in-depth discussion among experts in order to build confidence on CO₂ capture and geological storage amongst experts and policy makers.

At the conference four key confidence building questions were identified:
1. Whose confidence do we need?
2. What kind of logics and arguments do we need?
3. Do we have enough evidence for those logics and arguments?
4. How do we communicate with stakeholders?

The second piece of work was the collaborative knowledge networking tool called KNetwork. The KNetwork tool is based around the principle of argumentation – the use critical discussion to arrive at intellectual consensus. The discussion would commence with the proponents posting their hypothesis on the web based KNetwork tool. This could then be accessed by experts via the internet who could pose arguments to the original hypothesis with the proponent and other experts posting counter-arguments. Each argument would then have to be assessed as to how it “links” to the other information presented. It is thought that the critical discussion that it facilitated by the KNetwork tool would help achieve an intellectual conclusion.

Questions:
Q) What is the process of peer review and what is the next step to developing this database?
A) Depends on the interest and the participation. The tool will be ready on the web next month.

4.6. Expectations on different parts of the CCS cycle

4.6.1. BP Introduction – Tony Espie – BP
This session was kicked off by Tony Espie from BP who gave an overview of the BP Alternative Energy Risk Assessment process for CCS. BP is extremely active in the area of CCS having one project in operation at In Salah, three further projects announced (although not all of them may proceed) and three others unannounced. With that many projects in the pipeline BP feel they need to streamline the development processes to focus on what needs to be done rather than what would be nice to have. BP sees this project development as the only way to make serious developments in CCS. It is with this experience that we will build a large enough data set to be able to understand the system.

At In Salah, the primary focus of the risk assessment was on:
- Capacity
- Impact on hydrocarbon operation
- Injectivity

With a secondary focus on:
- Seal capacity (thick regional seal)
• Faulting (no faulting observed above reservoir)
• Well integrity – considered but still needs to be close out.

It is interesting to note here that for the In Salah the reservoir engineering is more of an issue than long term storage. This is due to the fact that the nearest village to the site is 100 miles away and there is no site vegetation so there will be no damage if leakage. The only real risk that relates to leakage is risk to the employees.

At In Salah, BP used a pragmatic, reservoir engineering approach to project development. They only performed minimal qualitative risk assessment but rather decided, given the unique setting of the project, that they can live with the downsides of not getting the geological characterisation 100% correct.

Currently BP are working on the Australia-NZ Standard for Risk Assessment which sets out a very generic and structured process that applies better to CCS than the chemical industry process. The often quoted analogy with the chemical industry breaks down for CCS because of the vast uncertainties in a CCS system. This is a general concern with numerical models which can be let down because of the uncertainties.

The Australia-NZ Standard for Risk Assessment includes:
• Identification of key risks and event scenarios
• Quantification of risks
• Evaluation of risks (with stakeholder input)
• Process modification to eliminate excess risk
• Monitoring and intervention strategy to manage remaining risk

BP has already developed a structured risk framework that they use internally. There are however some gaps in the current risk assessment process. These include:
• The criteria that are used for evaluation for example capacity.
• Bust between capacity and rate.
• The robustness of current quantitative Risk Assessment Tools and processes

BP have used the work they are doing with Australia and New Zealand and combined it with their internal experience to develop an approach to assessing CCS projects. Firstly you must design to minimise risk, this means effective site selection criteria and site characterisation. Secondly you must assess the risks that can’t be avoided. This would require a risk register and modelling to help understand controls on storage and potential downsides of injection. Thirdly you must manage the risks using monitoring and verification.

This was used for the DF-1 Peterhead project where BP assumed a worst case scenario and looks at the consequences on the marine environment. The scenario looked at was a sub-sea pipeline failure which release 4Mt of CO2 over the course of a year. This scenario was then modelled with the results show that pH due to the leak is around 0.1 at the sea bed which is one third of the North Seas natural annual fluctuation of 0.3. The pH change
at the surface is even less significant. From this study it was deemed that a worst case scenario would have minimal to no effect on the marine environment.

It was also mentioned here that BP have not found FEPs particularly useful in their risk assessment process, and they haven’t thrown up anything unexpected. BP feels that deducting key hazards from 100s of FEPs is a challenge and is better done through reliance on existing experience.

In conclusion, BP are moving into a stage of industrial scale CCS deployment and therefore are boiling down the key requirements for CCS rather than concentrating on all the possibilities and what would be nice to have. However, even at this well developed stage BP feel they are not really in a place to do quantitative analysis and at best can do semi-quantitative risk assessment.

### 4.6.2. Risk assessment expectations – Claudia Vivalda – Schlumberger

Claudia Vivalda from Schlumberger then presented on risk assessment expectations. Prior to joining Schlumberger Claudia worked specifically on risk assessment so she brings significant expertise and experience to the topic.

Generally a CCS cycle is broken up into a number of distinct phases which can be seen in the diagram below. Each phase relates differently to the risk assessment process with different risk assessment objectives and methods. The table overleaf outlines how risk assessment can be applied through each phase using tools that are in use throughout industry today. The methods are aimed at answering the four key questions of risk assessment; these are what can go wrong, how likely is it, what are the consequences, and how confident are we about our answers?

Determining confidence requires an uncertainty analysis to be performed. The objective of the uncertainty analysis is to determine how the uncertainty in the initial conditions affects the results. There are two main types of uncertainty that need to be addressed. These are:

- Aleatory uncertainty which is the inherent variation associated with the physical system or the environment and can never be completely removed.
- Epistemic uncertainty which is due to lack of knowledge of quantities and processes of the system or the environment and so are reducible.

Claudia also talked about the places that uncertainties can be hidden in a project and the need to remember the full range of uncertainties in risk assessment even if we choose not to address them all. The main challenges relating to uncertainties are their representation, aggregation, propagation, and interpretation.

There is much debate about the use of expert judgement in risk analysis. By definition expert judgment is a qualitative risk assessment method but until quantitative methods are development it is often the only option available. When using expert judgement you are looking to build on what people know already, usually on the technical side. Although expert judgement is inherently qualitative, the transparency and reliability of the process
<table>
<thead>
<tr>
<th>Phase</th>
<th>Objective</th>
<th>Method Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site selection</td>
<td>Maximize performance, minimize risks. Qualitative Risk Assessment</td>
<td>Risk register, what-if analysis, Analytical Hierarchy Process, experts’ elicitation, FEP analysis, RIS, QUE method</td>
</tr>
<tr>
<td>Characterization</td>
<td>Know what is important, to have the risks under control at the best performance. Iterative process. From Qualitative to Quantitative Risk Assessment</td>
<td>•Qualitative: same methods as site selection + others to be identified/developed •Quantitative: to be identified/developed</td>
</tr>
<tr>
<td>Design</td>
<td>Assure a robust design vis-à-vis the performance requirements and risks avoidance. Qualitative and/or Quantitative Risk Assessment of the engineered system.</td>
<td>•Qualitative: see above + FMECA, HAZID, HAZOP, etc •Quantitative: FT/ET, Petri Nets, Markov chains, etc. for the engineered system. To be identified/developed for the geological system.</td>
</tr>
<tr>
<td>Construction</td>
<td>Build the system as designed, do not introduce additional risks or notify them if unavoidable, minimize operation risks. Qualitative/Quantitative Risk Assessment.</td>
<td>e.g. risk register, HARC, what-if analysis</td>
</tr>
<tr>
<td>Preparation</td>
<td>No induced risks, proceed according to the procedures. Qualitative risk assessment.</td>
<td>•Qualitative/Quantitative: risk register, risk avoidance procedures, HAZOP</td>
</tr>
<tr>
<td>Injection Note: one of the most important phases for risk control</td>
<td>Optimize operations to achieve the foreseen performance and to keep the risks under control. Update qualitative and quantitative risk assessment. Risk management.</td>
<td>•Qualitative/Quantitative: risk register update, RCM</td>
</tr>
<tr>
<td>Decommissioning Note: here in particular we need to ensure the work is well done because you will not be around to fix it.</td>
<td>Optimize plugging design to minimize long term risks, minimize operation risks, and minimize geological system risks. Qualitative and Quantitative Risk Assessment.</td>
<td>•Qualitative: risk register, what-if analysis, Analytical Hierarchy Process, experts’ elicitation, FMECA, HAZID, HAZOP, etc •Quantitative: FT/ET, etc. for the engineered system. To be identified/developed for the geological system.</td>
</tr>
<tr>
<td>Surveillance</td>
<td>Monitor/survey what is important, to have the risks under control. Update Qualitative and Quantitative Risk Assessments.</td>
<td>Approach: region/site specific. No universal recipe at the current state of the art.</td>
</tr>
</tbody>
</table>
can be improved through a formalized expert judgment process. The nuclear industry uses a four step process:

- Identifying the elicitation issues and information needs
- Selecting the experts
- Training the experts
- Carrying out the elicitation sessions – maybe we need to explore more robust methods of assembling expert judgment. Beyond workshop.

In conclusion it is believed that for the first years of a project, a site customized procedure for risk assessment should be able to reasonably answer the four questions initially raised, e.g. what wrong, how often, what consequences, what confidence using a combination of qualitative and quantitative methods. Simulation models should be built taking into account quantitative risk assessment needs and all the uncertainties should be considered even if they are not quantifiable. Finally there is a need for a set of models that when combined together can be used to build the “risk model” of a specific site – CO₂ storage is not in a system that we can fully control? What we know about the system is through simulations.

Questions:
Comment) This comment was made in regard to the two previous presentations. When you are dealing with CO₂ storage it is the long-term risk which is unique. The two options you have are to continue monitoring and verification for ever or to decide when you stop. During your operational period you build confidence and use short-term operation for further long-term prediction. At some moment some state authority will ask how they can take over liability for the site.

4.6.3. Concerns and alternatives to non-probabilistic risk assessment – Julio Freedman – Lawrence Livermore National Laboratory – Presented by John Gale

The next presentation in this session was written by Julio Friedmann from Lawrence Livermore National Laboratory and was on the concerns and alternatives to non-probabilistic risk assessment, unfortunately Julio was unable to attend the event in person so John Gale from the IEA GHG presented his slides on his behalf.

Julio is putting forward a new approach for risk assessment which is based around the identification of hazards rather than risks. The change in approach was brought about through the concern that there are too many uncertainties related to traditional risk assessment. The outcomes of this hazard based process are called operation protocols and place an emphasis on earth and atmospheric hazards.

The reasons for using operational protocols are that they should help operators & regulators make decisions based on sound technical constraints across a range of geological circumstances. Protocols for CCS should also help stimulate development of both commercial projects and evolving regulations. And finally they should guide
operators in terms of selecting and maintaining site effectiveness, esp. regarding key hazards and risks.

The focus for operational protocols should be hazards first, risks second. Hazards are easily mapped & understood, providing a concrete basis for action whereas risks are often difficult to determine. With risk defined as probability multiplied by consequence, it can be difficult to define either of these terms from first principles. Also there is a current dearth of large, well-studied projects prevents empirical constraint.

Hazards are defined as a set of possible features, mechanisms, and conditions leading to failure at some substantial scale with substantial impacts. The table below lists a number of hazards and associated features, mechanisms, and conditions.

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Atmospheric release</th>
<th>Groundwater degradation</th>
<th>Crustal deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature, Mechanism, or Condition</td>
<td>Well leakage</td>
<td>Well leakage</td>
<td>Well failure</td>
</tr>
<tr>
<td></td>
<td>Fault leakage</td>
<td>Fault leakage</td>
<td>Fault slip/leakage</td>
</tr>
<tr>
<td></td>
<td>Caprock leakage</td>
<td>Caprock leakage</td>
<td>Caprock failure</td>
</tr>
<tr>
<td></td>
<td>Pipeline/ops leakage</td>
<td></td>
<td>Induced seismicity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsidence/tilt</td>
</tr>
</tbody>
</table>

Taking this example of a hazard list, a process of prioritization can be done for any site with a combination of expert knowledge, scientific evidence and experience. Part of protocol design is to provide a basis for this kind of local prioritization for a small number of classes/cases. After the prioritization is complete the results can be used to tailor the monitoring programme. The monitoring suite design and integration should focus on the hazards. In the case of the Illinois basin, the protocol should focus on ground water hazards, and in particular wells.

A two-phase technical program can help provide insight needed to develop CCS protocols. First, simulations should provide constraints on CCS operating conditions and second, a field program must be used to substantiate these constraints. The program should focus on earth & atmospheric hazards of greatest relevance and provide.

The E&A hazards and need for protocols leads to a few important questions
- What is the technical basis for developing a risk hierarchy? How can that basis be improved?
- If wells represent the greatest risk, how can that risk be quickly characterized, quantified, and managed?
- If geomechanics represent substantial risks, what are the minimal data necessary to properly characterize those risks
- What science is necessary to understand the potential risks to fresh groundwater?
- What is the least monitoring necessary to serve the needs of all stakeholders?
The full list of E&A hazards suggests a need to rank, quantify, and respond to risk elements to inform operators and regulators on what actions to take for preparing a site.

Given the lack of empirical data, other approaches are needed.

- **Use of analogues:**
  - Industrial analogues (NG storage)
  - Natural analogues (HC systems, CO₂ domes)

- **Simulation:**
  - Key features & processes
  - Must be accurate, but not unduly complex

- **Lab experimentation:**
  - Focus on most relevant problem
  - Experimental design is key

- **Scenario development:**
  - Max/min cases can be defined and tested

- **Risk assessment methodology:**
  - Requires integration of results
  - Some probabilistic methods as appropriate

4.6.4. “Useless arithmetic” or “the best of our knowledge”? – Does probabilistic risk assessment of long-term geological storage of CO₂ make sense? – Copernicus Institute, Utrecht University – Jeroen van der Sluijs

The next presentation in this session was from Jeroen van der Sluijs from the Copernicus Institute at Utrecht University. Jeroen looked at when and how probabilistic risk assessment can be used in conjunction with the long-term storage of CO₂.

Probabilistic risk assessment is used widely in a number of different fields. The strength of this risk assessment approach is as follows.

- Integrative and quantitative approach
- Allows ranking of issues and results, explicit treatment of uncertainties, and optimisation
- Can be used to both enhance safety and manage operability.
- Results and decisions can be communicated on a clearly defined basis – as it has been used for a number of decades, it is well understood
- Its use is beneficial even if the models generated are not (fully) quantified
- Lack of accuracy of the data does not hamper the use of probabilistic approaches as comparative tools to rank alternatives

There are however, a number of weaknesses also associated with the approach that must be acknowledged such as:

- It can be complex, time consuming, and data-intensive
- It unavoidably requires mixtures of ‘subjective’ (expert judgement) and ‘objective’ data (observations, measurements) which limits scientific rigor of result.
- There is large potential for misunderstanding of scientific status of the outcomes possibly resulting in an undue sense of certainty
• Models of open (uncontrolled) systems can never be validated, only ‘confirmed’ by non-contradiction between observation and prediction (Oreskes et al. 1994)
• There are dangers of standardization & benchmarking too early

Probabilistic risk assessment has been used to assess the reliability of these industrial installations. There are however some key differences which set apart the geological CO₂ storage from industrial installations which will affect the validity of probabilistic risk assessment.
• Natural reservoirs are much less defined and significantly more heterogeneous than industrial storage
• A natural CO₂ storage reservoir is not an engineered system
• Geological CO₂ storage is looking at a much longer time horizon - the longer the time horizon, the more open the system is
• Geological CO₂ storage involved significantly larger volumes of CO₂
• There is much more past experience for industrial gas storage
• Geological CO₂ storage requires a much larger dependency on expert judgement

All these factors combined amplify the weaknesses of probabilistic risk assessment for geological CO₂ storage.

Jeroen described three different ways that you can look at uncertainty, these are the deficit view, the evidence evaluation view and the complex systems, or post-normal view. He also outlines the different dimensions of uncertainty,
• Technical uncertainty (inexactness)
• Methodological uncertainty (unreliability)
• Epistemological uncertainty (ignorance)
And,
• Societal uncertainty (limited social robustness)

A process that can be used to help identify and quantify uncertainty is the NUSAP approach which stands for: Numeral, Unit, Spread, Assessment, and Pedigree. Looking at the final two components, assessment uses expert judgement to assess unreliability and pedigree evaluates the strength of a piece of data by looking at a number of factors including the background history by which the number was produced and the underpinning and scientific status of the number. Pedigree can be evaluated using a pedigree matrix to document and to communicate the level of certainty and reliability of pieces of information or criteria.

When assessing uncertainty it is also important to assess the quality of your model. It is important to note that models are tools and not truths; you should concentrate on whether it is fit for purpose. Untrue tools can be very useful for example, the London underground map. A model is not good or bad but there are ‘better’ and ‘worse’ forms of modelling practice. Models are ‘more’ or ‘less’ useful when applied to a particular problem. By performing model quality assessment you can provide insurance against pitfalls in process and insurance against irrelevance in application. It is also important to note that as a model become more complex then the data error becomes larger even though the model error decreases. This means that an optimum must be found.
Taking into account the pros and cons of probabilistic risk assessment, valid and invalid uses can be defined for geological CO₂ storage. Valid uses of probabilistic risk assessment of geological CO₂ storage:

- Comparative assessment of different reservoirs and storage options
- “Validation” of simpler methods – use complex methods to test simple methods
- Gain insight in key-characteristics that determine reservoir safety
- Gain insight in what factors should be monitored for early detection of leakage risks
- Improvement of operational practices
- Support of safer designs
- Informed debate with regulators and society (but it is essential to make pedigree of results explicit!)

Uses of probabilistic risk assessment that are not so straightforward with the present state of knowledge are:

- Demonstration of compliance to a quantified safety requirement
- Comparison to other (e.g. industrial) risks

And finally invalid uses of probabilistic risk assessment of geological CO₂ storage with the present state of knowledge are:

- Demonstration of safety
- Interpreting outcomes as absolute

Following this analysis of probabilistic risk assessment and its application to geological CO₂ storage a number of conclusions can be drawn:

- Specific characteristics of CO₂ storage amplify all generic weaknesses of probabilistic risk assessment
- Probabilistic risk assessment currently has a strong dependence on expert judgement – we need to document the experts decision process
- There is a need for systematic reflection on knowledge quality – and on the numbers that we use.
- There is a need for systematic elicitation and documentation of the arguments behind each judgment by each expert
- You must be very open and very transparent about uncertainty and pedigree of results
- You must be explicit about all assumptions on which outcomes are conditioned
- You must avoid mismatch between regulatory requirements and the limited level of rigor that state-of-the-art science can realistically achieve
- There are some alternatives risk assessment options for regulators to consider including the Precautionary Principle and the Maximum Credible Accident or Worst Case Scenario approach.

4.6.5. **Keep it simple! – Performance Assessment applied to Geological Carbon Dioxide Capture – Lars Olof Hoglund – Kamakta Consultants**
Lars Olof’s presentation looked at performance assessment for geological CO₂ storage and stressed the need to keep it simple.

First of all the principles of a performance assessment methodology were described stressing the need to keep it simple. The methodology should be simple but robust, based on fundamental and well-established scientific principles, e.g. mass-balances or thermodynamics. Using these fundamental mechanistic approaches allows reliable extrapolation in time; this is not the case with lumped knowledge.

Use an iterative approach, avoiding unnecessary detail in the first rounds of iteration. Only go into more detail with issues that you judge to have potential global impact. Discard processes/features/scenarios that are obviously irrelevant or can be discarded based on simple estimates. It is important to be quantitative where ever possible – try to pin down some numbers that can be refined.

Always document exactly what you are doing and why you are doing it. It doesn’t take too much extra time but it can save years if you need to come back to the work you have done. Issues to document include:

- What has been studied (purpose and scope of investigation, the studied site and storage system etc)
- Which assumptions that were made
- Quantitative parameterization – why you used the numbers and what are their sources?
- Judgments made based on the quantitative results
- Sensitivity of results to parameter uncertainty – parameter uncertainty is less than conceptual uncertainty
  - Is the uncertainty expected to be of importance?
- Who made the judgments

Try to keep the overall aim in focus – what are we really trying to do? Are we trying to get the exact number of kilograms of CO₂ are entering the atmosphere or counting how many salmon die or are we trying to save the earth? The results of your assessment must be compared with field and laboratory observations, using any deviations to improve the understanding of the system. Results should also be compared to observations of natural analogues to address long-term and/or large scale processes. These comparisons work as feedback to the design and help improve and optimise the process.

There are some issues of potential importance that should be kept in mid when generating a performance assessment methodology.

- Scale-effects may be important. What is not observed in small scale experiments/applications may well occur in large scale applications. An example of this is rock heterogeneity at different scales which will affect the mechanical impacts of CO₂ pressure or the buoyancy effect.
- Impact on groundwater systems. Effects due to dissolution and hydrolysis of CO₂ can include pH effects, dissolution/precipitation of minerals and mobilisation of heavy metals. There is also the issue of displacement of saline groundwater which may impact water a long way away. This can result in huge volumes
displaced by injected CO$_2$, high pressure gradients created, and possible impacts on fresh groundwater aquifers.

- In all cases risk assessments should be used to address possible effects. This process should include identifying:
  - Which processes/features may be critical?
  - What are the potential consequences?
  - Would the consequences be acceptable? – if they are…no problem.
  - What would be required for this to happen? Is this reasonable?
  - Can it be avoided/minimised?

In conclusion it was highlighted that CCS will be required to meet the significant mitigation requirements to avoid serious climate change, particularly for the growth emissions in India and China. It was stressed that we should not wait for the perfect solution and complete knowledge of all details about CCS, because by this time it may be too late to contribute to the solution. Instead we should be prepared for the certain surprises that will arise in the development of CCS. The performance assessment methodology can be applied to address, foresee and possibly avoid some of these difficulties.

Discussion:
Q) The approach of working backwards from a possible event is good but it requires judgement of the likelihood of it happening. For example Lake Nyos would have been deemed very very unlikely to occur but it did kill 1800.
A) True but we have more knowledge than in the natural system. If the Lake Nyos was monitored and understood then we could probably have predicted it.

Q) In terms of communicating to the public the maximum credible accident approach works. This has to be the way forward for building confidence.
A) Yes. You may not know what the worst case is.

Q) Whatever scenario you choose, it is very hard to come up with a significant accident with CO$_2$, so it is hard to come up with a worst case scenario.
A) Worst case scenarios are often extrapolated by non technical people to something that is not very realistic.

Comment) We need to look at the risk of not doing CCS as well and compare these to the risks associated with it.

Comment) The experience from Sleipner indicates that the probability that anything escapes from the Utseria formation is likely to go downwards because of dissolution. Risk profile can improve over time although this is over thousands of years.

Comment) People can’t comprehend 1000+ years.
Comment) Listening to the conversation we don’t have a definition of risk. What is it that we are worried about? People, climate change, fish? Maybe we don’t have just one single type of risk?

Comment) Changing levels of pH as an example and playing devils advocate. Why did the pH change occur? You have to be very careful to identify all the risks and measures.

Comment) The BP rupture model would not pass the credibility test because it wouldn’t happen.

Comment) If you have a lot of projects or the ocean behaves differently than we think then the results may be worse than we think.

Session Conclusions
To wrap up this session John Gale summarised the major conclusions. He stated that we have achieved a consensus of sorts. The question from the session was; What are we really trying to do? The answer; what we are really trying to do is stop global warming and CCS technology should be looked at and assessed in this context.

There is a drive from regulators to describe impacts but this would require us to define flux rates and multiply it out but we can’t do this yet so we shouldn’t focus on it. We should instead concentrate on the fact that climate change is the big issue.

If we are going to experience leakage it will be from the engineered system – pipelines, well, infrastructure. We do have history on this so to some extent we can history match and use past experience. This in turn would allow us to use a quantitative analysis. The engineering design will be the same irrespective of the storage site. We are able to predict with some degree of confidence the likelihood of the risk for this part of the process.

In regard to the storage reservoir; we don’t feel that we are going to experience any serious leakage from the storage reservoir. We can’t really quantify that any further at this stage because we don’t really have the analytical data to support it. We can however run worst case scenario. We can also try to minimise the risk of the event occurring. In the early days we may have to over engineer, by isolating the project to reduce risk. This could be done by placing the project out at sea, like Sleipner, or in uninhabited places, like In Salah. The best we can do at this stage is a semi-quantitative process while we keep working on the models and on a full quantitative process.

Comment) Would this be enough for regulators and public? What more can we offer them?

Comment) If you have a 1 in 100000 chance of an event happening, people don’t understand that, people buy lottery tickets. We must put this information out so that people are not scared about it. Before we have a realistic evaluation we need 50+ years of experience. The regulators are going to listen to the voters so it is important to inform the voters properly. This is the way that they approached it in Australia.
Comment) Without large scale injection we are going nowhere, modelling is not going to get us any further.

Comment) You need the money for the CO₂ from somewhere. But people are not going to pay if we can’t prove to the spender that we know where it is going otherwise this is going to devalue storage to five from twenty five.

Comment) Public don’t trust industry. We also need to know how long we monitor before hand over.

Comment) In Nuclear they foresee monitoring for 300+ years. We want to avoid this.

Comment) Once there is a convergence of the model and the monitored data, that is when we can hand over the site.

Comment) There is another piece missing from this discussion. In nuclear there are limits to nuclear exposure. What we are missing is how much leakage is acceptable. At the moment we have 100% leakage. We want to go to the regulators and the public and convince them that CCS is good.

Comment) Leakage is acceptable up to 500ppm in the atmosphere.

Comment) To be honest with CCS it can be impossible to get the CO₂ back out of the reservoir again, even if we wanted to.

4.7. **FEPs – Features, events, processes**

4.7.1. **Using the FEP approach in auditing the comprehensiveness of a site-specific programme for CO₂ storage – Ton Wildenburg – TNO**

This presentation looked at how FEPs or Feature, Event, and Processes analysis can be used in an auduting capacity for the De Lier project in the Netherlands. The De Lier project currently involves the capture of CO₂ from a refinery and the use of the CO₂ in greenhouses in the region. The CO₂ is almost pure as it comes from the refinery however the CO is only required in the summer months because in winter the CO₂ required is generated from the diesel engines used to heat the greenhouses. It has been proposed that during the winter months the CO₂ could be diverted into a geological storage reservoir.

The objective of the feasibility study was to evaluate the feasibility of safe and effective storage of CO₂ in the depleted De Lier gas field near the village of De Lier. The emphasis of this study was on the integrity of containment or hazards rather than on the consequences of a potential leak.

The eight specific studies involved were:

1. Well integrity
2. Subsurface model
3. Caprock and fault integrity
4. Spill risk
5. Reservoir compatibility
6. Monitoring programme
7. Surface design, including risks and mitigation
8. Qualitative hazard assessment

Study number eight, qualitative hazard assessment, is relevant to this network. The objective of this study is to try and achieve qualitative consensus on possible leakage scenarios of CO₂ out of containment and to evaluate the comprehensiveness of the initial programme of technical studies.

To assess the hazards and risks initially the bowtie concept was used however for this study only one half of the bowtie was addressed with the focus on hazards rather than consequences.

The FEP process was then used as part of a greater scenario-based assessment method. The scenario based assessment process includes:
1) Definition of the assessment basis
2) FEP analysis
   • Identifying any potential risk posed to your storage site.
   • Ranking the risks identified
3) Scenario formation
4) Development of dedicated models for simulation of safety scenarios
5) Risk evaluation against HSE effects

The first step, defining assessment basis, in this case relates to the De Lier reservoir and surroundings. The assessment basis will include the geographical and geological setting, the containment concept, the assessment target, the temporal and special scale and the assessment procedure.

The second step is FEP identification. Currently the FEP database contains 657 FEPs. TNO’s first step then was to narrow down this list, removing any redundant FEPs or FEPs that didn’t relate to this particular project. This pre-selection process brought the list of FEPs down to 200. These 200 were then grouped according to what they related to. The groups were:

<table>
<thead>
<tr>
<th>Chemical reactions</th>
<th>CO₂ behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faults and fractures</td>
<td>Fluid Flow</td>
</tr>
<tr>
<td>Human flaws</td>
<td>Injection</td>
</tr>
<tr>
<td>Mineral dissolution and precipitation</td>
<td>Natural changes of the system</td>
</tr>
<tr>
<td>Petrophysics</td>
<td>Anthropogenic activities</td>
</tr>
<tr>
<td>Rock mechanics</td>
<td>Seal integrity</td>
</tr>
<tr>
<td>Thermal processes</td>
<td>Well Integrity</td>
</tr>
</tbody>
</table>
The list of 200 grouped FEPs were then circulated via email to 13 experts who were asked to identify their top 20 FEPs that could impact this project. After combining the top 20 FEPs from each expert, 67 unique FEPs were identified in total.

The next step in the process was the scenario formation workshop which brought the experts together in person to reach a consensus on the selected FEPs. The workshop also allowed the experts to combine the FEPs into meaningful cause-consequence relations and to review the completeness of the whole De Lier feasibility study. Following the workshop 42 FEPs remained for further (quantitative) assessment. Scenarios were also defined for three stages, pre-injection, injection and post injection.

Each of the stages included a flow chart that outlines the process and categorised each element. The scenarios for each stage are as follows:

Pre-injection:
- Effect of production on well, reservoir and seal

Injection:
- Pressure
- Temperature
- Compositional change

Post injections
- Pressurized reservoir
- Buoyancy
- Reactions

In conclusion, the FEP process was found to provide a structured way of how to define possible leakage scenarios within limited time. In this process it was found that splitting the time domain into pre-injection, injection, and post-injection made the scenario definition less complicated. It was also noted that most of the selected FEPs were included in the initial risk assessment programme. It was also noted that although this process does involved some expert judgement, a lot of quantitative analysis is also involved in this process. In the end it was found that parts of the FEP approach are really adding to this work and the whole assessment took two weeks so it isn’t too tedious.

In regards to the case study it was found that the field has over 50 wells penetrating it and in Dutch law there is no requirement for a well going to an underlying stacked field to have a cement lining as it passes through the overlying fields. These two factors combined with the close proximity to populated areas means the field was deemed to high risk and will not be pursued, however another site has been identified in the area.

Questions:
Q) How did you choose the experts? Could you be accused of bias in the selection of the expert panel? Were they CCS people? If not did you have to bring their level of knowledge up to a certain level before you could proceed?
A) The main bias is that they were people from the organisation developing the project. Technically they covered the range of experience required. You could say that an independent panel of experts should be used. Perhaps this could be a step to follow the internal review process.

Q) In regard to the expert workshop consensus building process, this is a very uncertain area with a lot of ignorance. Did you analyse where the experts disagree and the process used to reach consensus?
A) We have looked at all the FEPs and documented why they are excluded however it could have been done in a more systematic way. The process could be formalized. Lots of people think the FEP process is a tedious approach. In this case it worked. FEP is just a name; you could call it hazard identification instead. This is inline with many other industries such as oil and gas.

Q) In the Weyburn context, the concern is that with the experts TNO assembled end up answering the wrong questions. The questions will be posed by regulators and the public and if you only consult experts you will miss all these important questions.
A) Agreed, we weren’t ready to go public but there will have to be a dialogue. If the public do pose different problems then you will have to redo the FEPs process with the new issues. It could be an iterative process. This is not the end point, this could be used for the internal screening.

Q) People will argue that all these other stake holders should be part of this process.
A) The critical question is when do you bring other people in? In Australia we tried to sort out as many of the technical issues as possible before we went to the community. The community also involved EPA and government. You can’t bring the people in until you have answers for them.
A) In FutureGen the technical analysis was done as part of the EIS which then lead to public consultation.
A) The clarity of how you present it is very important.

4.7.2. Using (not abusing) FEPs – Steve Benbow – Quintessa
This presentation gave a background to the FEP process, showed some of the possible usage options and how FEPs could be applied to natural analogue systems.

There are many slightly different formal definitions for FEPs but basically they are:
- Feature – a physical component of a system or a physical entity that influences a system. This also involves concentrations and pressures.
- Event – a process influencing system evolution over a short time period compared to the time frame being considered
- Process – a dynamic interaction between “Features”, which may operate over any particular time interval of interest.

FEP databases are collections of FEPs and should not be used or described as modelling tools. They do however attempted to be more than just lists of FEPs. FEP databases can
be used in a number of applications. They can be used to aid model and scenario development, describing key scenarios and providing us with a language and terminology to use. They can act as auditing tools for system-level models. They provide a knowledge base for storage studies, giving an explanation of the FEP, sources, descriptions and links. They also stimulate discussions among experts. Project specific FEP databases indicate the range of phenomena that have been considered and build confidence in thoroughness and logic of a safety assessment.

For Weyburn, Quintessa came up with a generic FEPs database. The database was developed initially during the Weyburn Project between 2001 and 2004 and tried to create a core set of FEPs that broadly described the project. Initially this database contained between 100 and 200 FEPs. This database has since been expanded and is available from the IEA GHG website – www.co2captureandstorage.info/riskscenarios/riskscenarios.htm. Each FEP contains a description, its relevance to safety, references, links and an area where suggested improvements can be made.

FEP databases can be used in two ways, 1) the Bottom-up approach and 2) the Top-down approach.

In the bottom-up approach the database is used directly in the development of assessment models, e.g. process influence diagrams and interaction matrices. If the database is used as a starting point, then all possible FEPs and relationships must initially be considered which potentially results in huge complexity. There is also the issue of where to begin? If the bottom-up approach is used, there is a tendency to reach for probabilistic tools in order to cope with the complexity. This is fine if good PDFs are available for all likely FEPs and interactions, if they are not available there is a danger of “risk dilution”. Risk dilution is a situation where an increase in the uncertainty in the values of input parameters to a model leads to a decrease in calculated risk. This generally involves the risk being spread out in time or space. Examples of risk dilution are ignoring parameter correlations or when a PDF is inappropriately wide or biased to low consequence outcomes. There is also an issue with sampling, how many runs do we need to convince ourselves that we’ve covered all relevant possibilities? We must not only choose which relationships to include, but also how to include them.

In the Top-down approach the database is used as an audit tool and modelling aid to ensure all relevant FEPs are in the model and to document why other FEPs are screened-out. To help explain the top down approach better, the CO2GeoNet study of the Latera analogue was used. This was not a performance assessment but rather a modelling study. However the approach to modelling the system is similar to a performance assessment.

The objective of the study was to simulate:
- The CO₂ fluxes to the surface and near-surface aquifers
- The overall mass balance for the near surface part of the system
- The soil gas concentrations
- The potential impacts to flora

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The plan was to use this to develop a probabilistic assessment model and run it 1000 times so the model can not be too complex. To reduce the complexity a system-level model was produced.

The top down approach is used to identify the key subsystems and “project FEPs” using information from detailed site characterisation. These project FEPs were then audited using the larger FEP database to document “project-specific” details for relevant FEPs, give reasons for all screened-out FEPs, and to ensure that we've not missed anything. Following this process we can identify the “base case” and the scenarios that we want to model with the aim of covering the range of “interesting” possibilities, both central and worst cases. Only after this process is complete can we develop a model. The “knowledge” in the database can help us in creating the model however the database is only ever used to assist in developing models/scenarios and as an audit tool. It is never used as a “model generator”.

When developing a model it must be decided on an appropriate level of detail when modelling, full complex reservoir models should feed into simpler broader models. It may be suitable to model some aspects of the system in “less detail” than others (e.g. the ecosystem). “Less detail” means less detailed representation of processes and/or geometry. Other aspects may need to be modelled in more detail (e.g. the multiphase flow of CO2 and water). There is a balance to be struck as less detail can lead to less accuracy, but the model runs faster which means more scenarios are possible. More detail leads to greater accuracy but slower runs so fewer scenarios are possible. The outcome is that the least amount of detail should be used that still provides sufficient accuracy. The choice of detail level could also be limited by what is possible in our programming code chosen.

The two key models used in this example were the CO2 transport model and the ecosystem model which was intentionally fairly simple. The results of the two models mapped CO2 fluxes at the surface and the resulting effects on vegetation.

In conclusions it was found that FEPs are good to audit and allow us to talk about models, but should not be used to create them.

We have demonstrated our approach to using FEPs and FEP databases in the system level modelling approach:

- Example QPAC systems-level model was discussed
- System was broken down in to “subsystems” corresponding to key project FEPs
- Processes relevant to each subsystem are modelled in appropriate detail
- Subsystems are joined by common CO2 fluxes at the surface
- FEP audit reveals comprehensiveness of the model and identifies areas for consideration in future modelling studies.
The “FEP approach” is not “fancy” - it just gives us a logical way to structure our modelling study. It is important to note however that databases need to be kept up to date if they are to continue to provide a useful knowledge base.

Questions:
Q) Is the model a good tool?
A) It is a prototype tool, a reasonable stab at reproducing field results in terms of flux profiles and vegetation response.

Q) Did you use geomechanical and chemical modelling?
A) Not yet.
A) This is the first time to try and link the surface and the subsurface modelling and it pretty accurately matches what is happening in the field. Quintessa is happy with the results from this study to date.

4.7.3. Weyburn experience of FEPs – Rick Chalaturnyk – Alberta University
The final phase of IEA GHG Weyburn-Midale CO2 Storage and Monitoring Project is to go ahead 3 years after phase 1 finished. The final phase will contain both technical and non-technical components. The non-technical component will look at regulation, public communication, and fiscal policy. The technical component will look at geological integrity, wellbore integrity, storage monitoring methods (Geophysics and Geochemistry) and risk assessment.

Risk assessment forms the 4th theme of the programme and will look specifically at storage & trapping mechanisms, remediation measures, and HSE. There are a number of knowledge gaps that will act as a driver for this work programme. There is a need to find consensus on risk/performance methodologies suitable for site approval for operations and for earning (storage) credits. There is a need for appropriate risk assessment methods and risk mitigation measures for confirming the safety and reliability of geological storage of CO2. There is a strong need to rationalize the selection of cost and time-effective methodologies for risk assessment of the long-term fate of stored CO2. Finally there needs to be recognition that risk/performance assessment is critical for the development of future regulations and/or identifying and addressing gaps that may exits in existing regulatory frameworks

In the final phase there are a number of objectives.
- A number of risk assessment techniques will be used to complete a full field risk assessment of the Weyburn Storage site, Region B. This will include FEP analysis, Bow-Tie Method and URS Method
- A peer review of Phase I dataset in order to establish a collection of data and information for use in quantitative/semi-quantitative risk analysis – this is necessary to demonstrate traceability of the data and contribute to the transparency of the RA process.
- A peer review evaluation of the Base and Alternate Scenario’s developed in Phase I to ensure integration of the final geoscience/reservoir data into the performance
assessment model. There is a need to update and refine the geosphere model based on the latest interpretation of geological and hydrogeological information.

- Reconciling Reservoir/Geosphere/Biosphere Modelling Issues
- Perform FEP and Scenario Development for Midale
- Conduct a semi-quantitative risk assessment utilizing experts and Phase I work in order to frame the entire risk assessment process.
  - This will engage a multidisciplinary panel of experts and stakeholders for input
  - The goal is to complete even a qualitative risk assessment that identifies the major issues that include both likelihood and consequence and provide a framework for configuring the more detailed and comprehensive analysis tasks required for completion of a quantitative risk assessment.

Finally, one other technique for assessing risk in CO₂ storage projects that was developed in Australia and that is called the RISQUE Method. This technique addresses the need to compare relative risks between projects. This will enable the Weyburn project to be placed in the context of other international projects. The expert panel is a critical resource in the RISQUE method. The quality of information used in the assessment is dependent on the level of skill and knowledge of the expert panel and to a lesser extent, on the ability of the risk analyst to effectively guide the panel through the process. This will be done first and use it to drive more quantitative work later on. Spend the money solving the questions that need answering.

Questions:
Q) Now you are doing this for Weyburn, what are you going to do at Midale?
A) Nothing really, there is some stuff that they would like to do but they don’t have the resources. Midale is a field just east. Apache want to make money, Encana are in it for the storage.

4.7.4. Methodological developments to define safely criteria – Olivier Bouc – BRGM

In this presentation Olivier describes some of BRGM’s research about safety criteria for CO₂ Geological storage, in particular, qualitative/quantitative approach of risk scenarios. The findings are based on a 3 year cooperative research project which is funded by government, industry and a number of universities.

This study is looking to address safety criteria which are distinct from performance objectives. Safety criteria relate to the requirements to ensure near-zero local impacts on health, safety and the environment in the short, middle and long term. Qualitative assessment will be used for the generic criteria with quantitative when possible for the site specific criteria.

The aim of the study is to contribute to demonstrating safety of CO₂ geological storage by providing a simple workflow to evaluate safety in a licensing process. This will involve building long-term evolution scenarios, evaluating potential targets exposure
using simple models and ultimately determining safety criteria. It is important to note that this is not a risk assessment, but rather gives keys to control a risk assessment.

The first step in the process was to build scenarios which are where FEPs were used. The scenarios were based around an hypothetical storage site, in the Dogger Aquifer underneath the Paris basin, in France.

FEPs database workflow used can be seen in the flow chart below:

The Quintessa online FEPs database was used for the study and the workflow closely followed that used by Vattenfall and TNO in the CO2STORE project.

The results of the study defined 6 leakage scenarios

A) Well degradation
B) Caprock fracturing due to overpressure
C) Leakage through buoyancy
D) Leakage through fault
E) Reservoir water migration
F) Open hole leakage e.g. future drilling

Following the study they review the use of FEPs. They found that the method was not optimal as it was tedious and time consuming, and identified very little compared to investment, i.e. could have achieved the same results cheaper. They also found their results were very close to the results of the CO2STORE study.
More specifically they found some of the steps involved in the FEPs process to be unnecessary. Steps 1-3 are fine, Step 4 (grouping) they found questionable and very subjective and they also had concerns about Step 7 (Deducing scenarios from influence diagram). Ultimately they found that the same results could be achieved even without steps 4-7. They do however acknowledge that there are some restrictions to their criticism which are, this was only a test and their first use of the tool, they used a hypothetical site so had no real data, they did not bring together an actual expert panel, they used the Quintessa Database where the TNO may be more suitable for this method.

The main advantages of the FEPs process were its comprehensiveness and it systematic documentation of the evaluation process. They feel however that it may be better suited as an auditing tool rather than a scenario-building tool.

Questions:
Q) Did you consider using a correlated variable to address the uncertainty of compartmentalised models?
A) We are trying not to represent everything by probability functions. People are working on showing what we know using fuzzy logic. We don’t want to represent more than what we know. They will then look at how to propagate it through the model.

Sessions Conclusions:
To summarise this session on the used of FEPs in risk assessment John Gale noted that FEPs are a tool, one of many, and ultimately it will be a developer’s choice as to which tool they use. He also said that the consensus seems to be that FEPs are a very good audit tool and noted that we have learnt a lot from the application of FEPs until now.

4.7.5. **Geological CO₂ Storage Certification Framework – Curt Oldenburg**
The final presentation of the network meeting was from Curt Oldenburg who described the CCP2 study to develop a simple framework for evaluating leakage risk for certifying operation and decommissioning of geological CO₂ storage systems. They believe that having a simple, transparent, and accepted basis for regulators and stakeholders to certify that the risks of geologic CCS projects to HSE and resources are acceptable is critical to the large scale deployment of CCS.

Certification Framework Overview

- Theory and Philosophy of Certification Framework
  - Effective Trapping requirement – We don’t want to say 100% storage so we need a framework that will allow some CO₂ leakage.
  - The Certification Framework is based on CO₂ Leakage Risk
  - Compartment concept
  - Broad classes of features
  - Catalogue of model results
  - Model results are from sophisticated modelling of simplified systems
  - The Certification Framework is probabilistic in existence of flow pathways and deterministic in flow along the pathway

- Inputs are properties and definitions of the injection system
• Outputs are CO2 Leakage Risk numbers for impacts to various compartments

As part of the development, existing Underground Injection Control (UIC) regulations were looked at which address the injection of hazardous liquid waste. The requirement for this certification is projection that no migration will occur from the injection zone while the waste remains hazardous (or for 10,000 years). The main concern of the UIC regulations is the protection of underground sources of drinking water or USDW rather than migration to the surface. This is because these, Class I, wells inject below the USDW and the injected fluids are nearly always denser than native fluids. Under these conditions, the non-migration requirement is relatively easy to meet.

CO2 injection however differs from hazardous liquid waste injection in some key areas such as CO2 being less dense than the reservoir brine and CO2 will be injected in much larger volumes and higher injection rates. This means that CO2 has tendency to migrate upwards and the CO2 area of review may be very large.

Part of the Certification Framework is a method of leakage risk calculation which was shown using a hypothetical storage site to illustrate. The hypothetical site included a number of oil and explorations wells, a number of water wells, and a CO2 injection well. The wells and faults contained a mixture of active and non-active.

The project was simplified into a mixture of conduits (wells, faults and fractures) and compartments (Hydrocarbon and mineral resources, USDW, HSE (Health, Safety and the Environment), and ECA (Emissions credits and atmosphere). The simplified model also contained a CO2 source.

Using this as the basis for the analysis, the CO2 leakage risk is calculated using the multiplication of impacts and probability. Examples of impacts could be:
• Exceeding the concentration limit of a compartment e.g. 0.4% in air in an HSE compartment (indoors, local)
• Exceeding flux limits e.g. CO2 flux greater than 100 times background to the USDW compartment
• Exceeding time-integrated concentration or flux e.g. concentration of CO2 exceeds ten days of greater than 0.1% in an HSE compartment (outdoors, local)

Thresholds for individual compartments would pertain to the probability of occurrences of exceeding limits. The impacts would relate to defined limits and thresholds. The probabilities considered by the Certification Framework are the probabilities of conduits (wells, faults and fractures) intersecting the CO2 source and the compartments (Hydrocarbon and mineral resources, USDW, HSE and ECA).

In short, certification of a storage system will be allowed only if the CO2 leakage risk is below thresholds established for the probability that a limit will be exceeded for concentrations or fluxes at all compartments. When the CO2 leakage requirement is below all thresholds, the effective trapping requirement will be met.
Ongoing efforts relating to the Certification Framework include:

- Reservoir simulation catalog
- Case studies
- Fault and well flow model
- Fault intersection and characterization
- Above-ground CO₂ migration
- Interaction with regulators, guidance on impact thresholds and risk limits
- Uncertainty by fuzzy membership models
- Rapid Prototype in GoldSim

Lastly Curt wanted to make one last comment about probability. For years people have tried to avoid it and focus on impacts but there is a steady drum beat of demand for probabilistic risk assessment. It is something that is inevitable as we need to portray how likely things are.

Questions:

Q) Are you only looking at subsurface? We will have to deal with operational venting because no one wants to talk about it.
A) Our experience is only in storage

Q) What about the spill point?
A) We are assuming that the site was chosen to avoid meeting the spill point.

Q) This is a process for permitting but do you foresee that operators will have to measure the fluxes when they are operating?
A) We have been thinking that monitoring is a secondary overprint so no, we do not expect the operators to do this.

Q) Do you have a model for each part?
A) We have 2 models, one complex and one more simple. We have run 1000 iterations with generic data depth, etc. We are trying to push the Framework not the model.

Q) Do you want to benchmark this about actual projects?
A) Yes.

Q) Who would be doing this?
A) The developer or a consultant hired for the developer.

Q) If the developer does it then you can’t separate out the monitoring.
A) Yes, perhaps then the monitoring would have to be imposed as an overlay. It could turn out that the performance is so good that monitoring requirements are minimal.
5. Summary and Outcomes

Following the final presentations John Gale gave a brief outline of what we have achieved at this meeting and what further issues and questions have been identified for future focus.

In regard to risk assessment technology, Imperial College performing a study that tries to identify and define key terms that are integral to CCS risk assessment communication. The terms identified are drawn from CCS literature and associated industries. The next step in this work is to circulate a questionnaire to people within the industry to try and build consensus on the terms to use and their definition. One suggestion was to set up a *Wikipedia* style website to act as a forum to build an agreed pool of terms.

A key discussion from this workshop was around the process of site characterization. This is a common theme running throughout the Risk Assessment Networks and was explored in this meeting but not resolved. The issue remaining is determining how much site characterization is enough to satisfy all the stakeholders involved in a CCS project.

There was a lot of discussion in this network about whether to use quantitative, qualitative, or simple analytical methods to analyze CCS risk. The debate seemed to conclude that it would be ideal to have a fully quantitative risk assessment process but currently it would not be possible for anything more than a semi-quantitative or predominantly qualitative process to be used. This led to a discussion on the use of expert panels in risk assessment which was seen as a process that needs formalization.

Following the session on the FEP risk assessment process it was found that this process is just one tool of many and the general feeling was that it was better suited as an auditing tool rather than the primary tool for risk assessment.
6. Next Steps

There were also a number of additional issues/questions raised over the course of the network that need to be addressed. These include:

- Risk assessment guidelines? – are they required and if so, what is the best way of formulating them?
- How confident are we in the modelling results we are generating for CCS projects?
- How long do we need to monitor for after the cessation of CO₂ injection?
- What use is the accident/worst case scenario risk assessment approach to the overall risk assessment process?

Finally John announced the first Joint Network meeting that will involve the Risk Assessment Network, the Monitoring Network and the Wellbore Integrity Network. This meeting will be held in New York in June 2008. The 4th Risk Assessment Network meeting will be held in Australia and hosted by the CO2CRC. The date for this meeting has not been confirmed but will most likely be early 2009. The 5th Risk Assessment Network meeting will be in France, hosted by Schlumberger.
3rd Risk Assessment Network Meeting

15th—16th August 2007
Imperial College, London, UK

Organised by
IEA Greenhouse Gas R&D Programme.

Hosted by
Imperial College
15th August 2007 Day 1

08.00 to 08.30 Registration
08.30 to 08.45 Welcome Address; John Gale, IEA GHG

Session 1 – Developments in Risk Assessment

08.45 to 09.05  OSPAR/London Convention; Tim Dixon, BERR
09.05 to 09.25  Sleipner Case Study; Helga Hansen, Statoil
09.25 to 09.45  FutureGen; Tom Grieb, Tetra Tech
09.45 to 10.15  Panel Discussion

10.15 to 10.30 Coffee Break

Session 2 - Site Characterization - How much is enough?

10.30 to 10.50  IEA GHG site characterisation guidelines and IPCC SRCCS; Brendan Beck, IEA GHG
10.50 to 11.10  Site Characterization Needs for Risk Assessment; Mike Stenhouse, Monitor Scientific
11.10 to 11.30  US Perspective; Anhar Karimjee, US EPA
11.30 to 11.50  Australian Perspective; John Kaldi, CO2CRC
11.50 to 13.00  Panel Discussion

13.00 to 14.00 Lunch

Session 3—Terminology

14.00 to 15.00  CO2 Storage Risk Assessment Terminology: Introduction and Presentation of work; Anna Korre, Imperial College
15.00 to 16.00  Panel Discussion

16.00 to 16.15 Coffee Break

Session 4—Report from Well Bore Integrity Network

16.15 to 16.30  The Role of Wellbore Integrity in Risk Assessment for Geologic Sequestration; George Guthrie, LANL
16.30 to 16.45  Wellbore Integrity Part II; Rick Chalaturnyk, Weyburn
16.45 to 17.00  Panel Discussion

17.00 to 17.15  Confidence Building Through Argumentation; Norio Shigetomi, Mitsubishi Research Institute

Close Day 1
### 16th August 2007 Day 2

#### Session 4—Expectations on different parts of the CCS cycle

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<td>Introduction - Strawman proposal; Tony Espie, BP.</td>
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<td>09.30 to 09.50</td>
<td>Risk Assessment Expectations; Claudia Vivalda, Schlumberger</td>
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<td>09.50 to 10.10</td>
<td>Concerns and Alternatives to Non-Probabilistic Risk Assessment; Julio Freedman, Lawrence Livermore National Laboratory</td>
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<td>10.10 to 10.30</td>
<td>Does probabilistic risk assessment of long-term geological storage of CO2 make sense?; Jeroen van der Sluijs, Copernicus Institute, Utrecht University</td>
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<td>10.30 to 10.45</td>
<td>Coffee Break</td>
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<td>10.45 to 11.15</td>
<td>Keep it Simple; Lars Olof Hoglund Kemakta Consultants Co.</td>
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<td>11.15 to 12.30</td>
<td>Panel/Strawman Discussion; Tony Espie, BP</td>
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#### Session 5—FEPs - Features, Events, Processes

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<td>13.30 to 14.00</td>
<td>Using the FEP approach in auditing the comprehensiveness of a site-specific research programme for CO2 storage; Ton Wildenburg, TNO</td>
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<td>14.00 to 14.30</td>
<td>Using not abusing FEPs; Steve Benbow, Quintessa</td>
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<td>14.30 to 15.00</td>
<td>Weyburn Experience of FEPs; Rick Chalaturnyk, Weyburn</td>
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<td>15.00 to 15.30</td>
<td>Methodological developments to define safety criteria; Olivier Bouc, BRGM</td>
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<td>Coffee Break</td>
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<td>16.00 to 16.45</td>
<td>Panel Discussion</td>
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<td>16.45 to 17.00</td>
<td>Wrap up; John Gale, IEA GHG</td>
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### Close Day 2
# Attendee list for the 3rd Risk Assessment Network Meeting,
Imperial College London, 15th-16th August 2007

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<td>Claudia Vivalda</td>
<td>Schlumberger</td>
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<td>Malcolm Wilson</td>
<td>University of Regina</td>
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<td>Olivier Bouc</td>
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<td>Jeremy Colls</td>
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<td>David Savage</td>
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<td>John Gale</td>
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<td>Brendan Beck</td>
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<td>Guenter Borm</td>
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<td>Sarah Stiff</td>
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<td>Andrew Garnet</td>
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