2nd MEETING OF THE RISK ASSESSMENT NETWORK

Report Number: 2007/10

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INTERNATIONAL ENERGY AGENCY

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ACKNOWLEDGEMENTS AND CITATIONS

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 BP and the University of Regina. The organisers acknowledge the financial support provided by EPRI for this meeting and the hospitality provided by the hosts LBNL.

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

John Gale, IEA Greenhouse Gas R&D Programme (Chairman)
Sevket Durucan, Imperial College
Anna Korre, Imperial College
Rick Chalaturnyk, University of Alberta
Malcolm Wilson, Energy INet
Tony Espie, BP
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Hans Aksel Haugen, Statoil
Larry Myer, Lawrence Berkeley National Laboratory
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The report should be cited in literature as follows:

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Further information on the network activities or copies of the report can be obtained by contacting the IEA GHG Programme at:

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Summary Report of

2nd Risk Assessment Network Meeting

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

Organized by IEA GHG, and LBNL.
With the support of EPRI

INTERNATIONAL RESEARCH NETWORK ON RISK ASSESSMENT

SECOND WORKSHOP
Berkeley, California, USA

Executive Summary

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

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

1. Site characterization is a key component in ensuring that the storage sites selected can effectively contain CO_2 for 1000's of years. Risk Assessment (RA)is one tool that can be used in the early screening of storage sites. RA and site characterization work in an iterative manner, over different project stages from preliminary screening to permitting to implementation.
2. Risk assessment studies can provide guidance on likely seepage rates from storage sites but they cannot define the impacts of leakage. Environmental Impact Assessments (EIA) can provide the framework for assessing the long term impacts of leakage. However, there is little research work underway currently that is addressing specifically the effects of CO_2 leaks and their potential impacts that could allow an EIA to be compiled. This is a major research gap.
3. A communication exercise with regulators has been undertaken to gauge their expectations for risk assessment and to make them aware of the current status of RA. As a result of this process regulators are better informed on both the role that RA can play and its current technical status.
4. However, RA is only part of the message that needs to be given to regulators; remediation is another important issue as well. Also, we need to get the message over that we are not promoting innovatory technology to avoid over regulation.
5. RA can also be considered as part of a Risk Management framework. RA is the means of identifying, estimating or calculating and evaluating potential risks. Risk management on the other hand deals with assessing, monitoring & remediating risks to conform to risk acceptance levels.
6. Natural analogues could be used to build confidence in CCS. By building up a database of events from natural and industrial analogues comparable to those that could occur from a CO_2 storage reservoir you can build a risk matrix that allows you to compare and communicate the risks of CCS in a way that is readily understandable to those outside the CCS community.

7. Four recently reported RA cases studies on potential geological storage sites were reviewed; three were based on aquifers and one on an oil field operation. It should be emphasized that several of these cases were not full blown risk assessments but were really scoping studies. The results of such studies should therefore be treated with some care when communicated outside of the technical community. The aquifer based assessments generally suffered from a lack of data, which is not unsurprising, which required a lot of assumptions to be made. The oil field case was much better characterized which allowed a more detailed risk assessment process to be undertaken. The oil field study gives us some confidence that CO_2 can be retained in that formation for 1000's years the same degree of confidence cannot be drawn from the aquifer studies.
8. The RA case studies completed to date have contributed significantly to the learning process for undertaking such studies which will be of benefit in the future and help to allow us to better define the data requirements needed to complete a good robust risk assessment.
9. More RA studies are needed to help develop confidence in the techniques and models used as well in the results they generate.

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

- On the issue of site selection we need to define how much characterization is needed to allow a formal risk assessment to be completed
- We need to ask the question whether a full blown quantitative risk assessment is required to give regulators confidence that a storage site is secure? Or could a simpler screening assessment be sufficient to generate confidence in CO_2 storage?
- Also now that we have some experience of using FEP databases for risk screening and scenario development can we design a screening process involving a simpler FEP database?
- There is a desire by regulators and project implementers alike to see the development of a RA standard or protocol. We need to decide how best to proceed to develop such a protocol or standard
- Similarly we need to process to peer review models and benchmark RA tools and approaches. We also need to decide how best to proceed to develop a benchmarking process.

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

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

SECOND WORKSHOP OF THE INTERNATIONAL RESEARCH NETWORK ON RISK ASSESSMENT

1. Introduction

The International Risk Assessment Network was launched at a meeting held in the Netherlands organised by the IEA Greenhouse Gas R&D Programme (IEA GHG) and hosted by TNO-NITG[1]. The Risk assessment network compliments two other international research networks that IEA GHG operates relating to geological storage of CO_2. These networks cover monitoring and well bore integrity. It is considered that these three networks together focus upon one of the key technical issues that need to be addressed for CO_2 capture and storage to be widely implemented, that of containment. It will be essential to gain both governmental and public support for the technology to demonstrate that the CO_2 injected into geological formations can be effectively contained. To resolve this issue it is considered that no single activity or action will satisfactorily answer the question alone. However, a number of different activities when taken together should be able to resolve it. These activities include:

- The development of a regulatory process for CCS that requires an operator to demonstrate "due diligence" in the selection of an appropriate site for CO_2 storage. The regulatory process would include: site characterisation, geological/geochemical modelling and development of a simulation tool for long term prediction of the fate of injected CO_2. In addition, potential seepage/fugitive emission pathways will be identified and remediation plans incorporated into the operational plans.
- The monitoring of CO_2 injection projects to determine actual seepage rates to the surface, if they occur. Knowledge of the flux to the surface will allow an estimate of both the local health/safety risks possible ecological consequences to be determined.

Taken together this work should help to build a reference manual of data on reservoir integrity/security and actual seepage of CO_2 that should build confidence that the CO_2 can be contained effectively in the geological formations into which it has been injected.

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

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

[1] Netherlands Organization for Applied Scientific - Netherlands Geological Survey

2. Aims and Objectives of Second Workshop

The workshop aimed to provide:

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

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

3. Workshop Programme and attendees

The programme for the workshop is oultined in Table 1.

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

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

Table 1 Workshop Programme

Day 1 (5th October 2006)	
08.30 to 08.40	Welcome to LBNL and, fire briefing/safety issues, Larry Myer LBNL
08.40 to 08.50	Meeting aims and context, John Gale IEA GHG
Session 1– Invited Presentations, Chair: John Gale, IEA GHG	
08.50 to 09.20	Site Characterization - summary of a workshop, Jens Birkholzer, LBNL and Elizabeth Scheehle, USEPA
09.20 to 09.50	Well Bore Integrity Network – feedback and current state of knowledge, Charles Christopher BP
09.50 to 10.10	Statistics on "Unexpected Occurrences", Preston Jordan, LBNL
10.10 to 10.30 Break	
Session 2 – Feedback on Actions From Last Meeting, Chair: John Gale IEA GHG	
10.35 to 10.50	Review of Inaugural meeting and actions set, John Gale, IEA GHG
10.50 to 11.10	Data Management and Risk Analysis Feedback, Ton Wildenborg, TNO-NITG
11.10 to 11.30	On shore ecological impacts assessment, Jonathan Pearce, BGS
11.30 to 12.10	Regulatory needs for risk assessment, Mike Stenhouse, Monitor Scientific (including discussion).
12.10 to 13.00	Regulatory framework development under the CO2GeoNet project. Anne Korre, Imperial College (including discussion).
13.00 to 14.30 Lunch	
Session 3-Risk Management for CCS, Chair: Ton Wildenborg.	
14.00 to 14.20	The role RA as part of a Risk Management framework Ton Wildenborg, TNO-NITG.
14.20 to 14.40	Open discussions on RA regulatory feedback.
14.40 to 15.00	Risk Assessment of a CO_2 storage site and risk-driven decision process. Natalia Quisel, Schlumberger.
15.00 to 15.45	Discussion Session on RA and RM.
15.45 to 16.00 Break	
Session 4 -Building confidence in CCS, Chair: Malcolm Wilson, EnergyINet	
16.00 to 16.15	Outline of the plan for international collaboration: Norio Shigetomi, Mitsubushi Research Institute Inc.
16.15 to 16.45	Development of international collaboration for building confidence in the long-term effectiveness of CO_2 geological storage; Hiroyasu Takase, Quintessa Japan.
16.45 to 17.15	Open discussion on plans for international collaboration.
17.15 to 17.30	Resume of Day 1 John Gale, IEA GHG/Malcolm Wilson EnergyINet.
Close Day 1	

Table 1 Workshop Programme (Cont'd)

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

4. Results and Discussion

4.1 Technical Presentations

The first session of technical presentations were aimed to bring the network members up to date with related activities relevant to risk assessment such as: site characterization, well bore integrity and incident statistics from relevant industries. The second set of presentations provided the members with feedback on the tasks set in motion at the end of the inaugural meeting. Presentations in Session 3 considered the inclusion of risk assessment in risk management frameworks. The final session, considered a Japanese proposal to establish an international collaborative activity to help build confidence in CO_2 capture and storage.

4.1.1 Related activities relevant to risk assessment

Jens Birkholzer provided the delegates with an overview of an international symposium that US Environmental Protection Agency (EPA) had organized with Lawrence Berkley National Laboratories (LBNL) in March 2006[2]. One of the main concerns of the US EPA in relation to CO_2 storage is the potential for large releases of CO_2 from a storage reservoir and its possible impact on groundwater quality. US EPA has sponsored two studies with LBNL to first study the potential for large releases of CO_2 and the second; to model the impact on groundwater quality. Neither of these pieces of work was complete at the time of the event but results should be available by the time of the next meeting of the network in August, 2007.

The site characterization symposium had over 150 participants from 11 countries with 47 oral and 28 poster presentations given. The symposium aimed to address the various aspects associated with the selection and characterization of geological sites for the CO_2 storage. These aspects covered included:

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

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

"The collection, analysis and interpretation of data and the application of knowledge to judge, with a degree of confidence, if an identified site will store a specific quantity of CO_2 for a defined period of time and meet all health, safety, environmental requirements."

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

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[2] The proceedings and presentations from this workshop can be found at http://www-esd.lbl.gov/CO2SC/

1. The ***injectivity*** component which includes the wells and any pressure build up due to injection,
2. The ***storage capacity*** component to ensure sufficient volume,
3. The ***containment effectiveness*** component which involves long term sealing properties.

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

a) Should characterization of a site occur only prior to CO_2 injection or should it continue (and be refined) throughout the injection phase, and during later monitoring and verification stages?

b) Should we define three phases of site characterization as; pre-injection ,injection, and post injection or should it be; pre-injection, injection/post injection, and site verification

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

- Approval would be based on limited characterization and documentation,
- Monitoring of the CO_2 movement would provide important information on site characteristics,
- Monitoring during injection and post injection phases would verify site suitability,
- Remediation plans need to be in place in case things go wrong.

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

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

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

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

- Large-scale characterization of seals for saline formations
  - Thickness, continuity, uniformity, long-term integrity

- Static and dynamic conditions
- Effective tools/procedures/protocols were needed for characterization of pathways (faults, wells) and their leakage potential
- Predicting plume extent and storage capacity, considering multi-phase flow with heterogeneity and dissolution, plus displacement of water
  - Upscaling strategies for multiphase (fingered) flow
  - Simultaneously predict flow, mechanical, and chemical changes
  - Impact on regional groundwater systems
- Definition of standards for site characterization
  - when, how much data, degree of confidence, HSE requirements, compliance period

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

"There is no such thing as the <u>perfect</u> storage site, but we can identify sites with acceptable levels of risk that are fully fit for purpose"

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

Jens concluded by making the following points:

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

The following questions were raised:

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

Q. Do we need to develop a new tool to measure fault properties and identify leakage?
A. Not necessarily, we can monitor the fault to see if it leaks

Q. How do we define what is an effective tool when there is no standard to measure them against?
A. The tools we have can define the boundaries of leakage but they cannot be precise, as long as we know where the limits lie we can use existing tools

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

Several members of the audience also made comments;

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

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

Tony Espie – Detailed quantitative RAs depend on the hazard of what you are doing. In the nuclear case you are trying to keep a few molecules out of the system for thousands of years, CO_2 storage is at the other end of the spectrum we want to keep as much out of the atmosphere as possible for as long as we can. For that reason semi-quantitative and quantitative RAs will suffice. For example the USEPA might not need a full blown RA from a regulatory standpoint. If something did happen, it is important that we are able to remediate.

Charles Christopher's detailed presentation was deferred until the next meeting but it was pointed out that a detailed analysis of a well in Texas was underway. This well had now been taken out of service but has had wet CO_2 flowing though it for 30 years. By undertaking experiments on old wells it is hoped to gain a better understanding of well cement degradation by CO_2 which will allow the calibration of laboratory experiments and lead to the development of models for well failure that could be used in risk assessments.

Preston Jordan gave a presentation on what can be quantifiably learnt about the risks of geological storage to workers from data on existing industrial analogues. The presentation considered public domain data from the US and the world on worker safety. The data sets accessed are outlined in the table overleaf:

United States Bureau of Labor Statistics (BLS)	**International Association of Oil & Gas Producers (OGP)**
Survey of Occupational Injuries and Illnesses	Safety Performance Indicators
Census of Fatal Occupational Injuries	
Quarterly Census of Employment and Wages	

The BLS statistics contain data for all industries in the United States (allowing inter-industry comparisons) and all companies (regardless of size), but the analogue upstream oil and gas industry is not clearly broken out. The OGP data set breaks down the global upstream oil and gas industry by functional sector (drilling, exploration, production, and other), and geographic location (continent and onshore versus offshore), but includes data only from large upstream oil and gas companies and their service providers. Using these data sets, the study compared the rate and consequences of reported incidents involving more than first aid in the upstream oil and gas industry to other industries, and considered the how safety rates in the geological storage industry in the United States would differ from those in the oil and gas industry .

The main conclusions that could be drawn were:

1. Drilling has the highest incident and lost time case rate of the functional sectors
2. Based on United States Bureau of Labor Statistics data for the upstream oil and gas industry, worker safety incidents in the CO_2 storage industry in the United States will almost certainly be less common than in the median industry, but less than that in the highway, street and bridge construction industry for instance.
3. Based on International Association of Oil and Gas Producers data, both worker safety incidents and incident consequences in the CO_2 storage industry in the United States will be lower than in the upstream industry to the extent that the CO_2 storage industry is more onshore and requires proportionally less drilling and includes more exploration-type activities (such as monitoring and verification).

4.1.2 Reports from task groups from previous meeting

At the inaugural meeting of the risk assessment network[3] it was agreed to undertake 4 pieces of work before the group met again. These 4 pieces of work were:

1. To build an inventory of data sets on storage projects and risk assessments

[3] IEA Greenhouse Gas R&D Programme, Launch Meeting of the Risk Assessment Network, Report No. 2006/5 January 2006

2. To assess the impacts of seepage of CO_2 from storage sites onshore
3. To assess the regulatory needs for risk assessment
4. To assess risk assessment frameworks and terminology

The task group leaders reported back in each case.

Task 1 - Ton Wildenborg provided a report on the progress made on compiling the data base. The group had met after the inaugural meeting and developed an excel spreadsheet containing16 geological storage sites. The list is contained in the table below. The list includes all those storage projects that were undertaking detailed characterization and monitoring work that could build up data sets that could be used for risk assessment studies.

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

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

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

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

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

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

It was noted that the early demonstration projects are operated within existing oil and gas regulatory frameworks. However, these frameworks do not necessarily require consideration of long-term, post-closure issues. Storage will be onshore in North America in particular and Europe to some degree.

It was felt that a modified environmental impact assessments (EIA) could provide a framework for assessing long-term impacts of potential leaks[4]. The EIA could include the following

- A description of the site selection and characterisation.
- A description of the project, including anticipated injection mass & rates, engineering design, and the project duration.
- Simulations of CO_2 behaviour over the long term, history-matched to monitoring data obtained during and after injection.
- A description of long-term monitoring options if required.
- Appropriate remediation plans.
- An assessment of the risks for & consequences of leakage, for a range of realistic possible future site scenarios.
- A closure plan.
- Together these components seek to demonstrate that future risks are as low as reasonably practicable (ALARP).

The possible impacts of low level CO_2 seepage from a storage site, in no particular order, should it occur are:

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

The review has shown that there is currently little research addressing specifically the effects of CO_2 seepage from depth and their potential impacts.

The study also identified a number of gaps which included:

- No target species have been identified.
- No thresholds or limits to CO_2 exposure for any species have been identified.
- Little data on the long term, low-level exposure of CO_2 on terrestrial ecosystems or on any single or potential target species is currently available.
- No data on recovery rates are available.
- Almost no data available on the effects of CO_2 seepage on groundwater quality are available.

[4] IEA Greenhouse Gas R&D Programme, Permitting Issues for CO_2 Capture and Geological Storage Report No. 2006/3, January 2006.

- Little information is available concerning co-injected species, or those mobilised during migration.

It was felt that the gaps identified constrain: the capabilities of risk assessments to accurately identify important risks, also the formulation of appropriate, cost-effective monitoring protocols and remediation plans. In addition, the integration between considerations of potential impacts of CO_2 leaks on terrestrial ecosystems and performance assessments.

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

1. Scenario definition:
   - Define relevant scenarios to reflect the storage context (geographical location, local environment, land use, etc)
2. Characterisation:
   - Define surface and subsurface ecosystems in terms of flora and fauna.
   - Identify indicator species (most susceptible, those with biggest change).
3. Impacts:
   - Identify impacts of CO_2 on indicator species & total ecosystem.
   - Define appropriate thresholds and safety criteria.
   - Identify recovery rates.
   - Scope impacts on ground waters via modelling and experiments.
4. Monitoring:
   - Develop floral and faunal monitoring techniques
5. Integration:
   - Improve system models by integrating key processes and indicators in an iterative manner.

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

Task 3 – Mike Stenhouse presented the results of another project supported by IEA GHG entitled the Role of Risk Assessment in Regulation of Geological CO_2 Storage Projects. The objectives of the project were to:

1. Establish whether there are existing (regulatory) provisions for authorizing CO_2 storage projects and whether these are sufficient/adequate for future implementation of large-scale geologic CO_2 storage projects
   – Are there any 'disconnects' between regulator and implementer in terms of timeline?
2. Identify key gaps associated with RA and its role in regulatory oversight

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

- Retention timescales,
- CO_2 seepage fluxes
- RA methodologies,
- RA modeling approaches,
- Role of monitoring in RA,
- Comprehensiveness of RA,
- Risk communication to stakeholders,
- Need for a technical standard/protocol,
- Potential gap /RA needs.

Note: the briefing document can be found in the report of the study[5].

Regulators from 10 countries agreed to participate. The countries involved were: Australia, Canada, France, Germany, Japan, The Netherlands, New Zealand, Norway, U.K., and U.S.A. These were supplemented with implementers who are involved in major CO_2 storage projects.

The feedback received indicated that regulators were in favor of:

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

The knowledge gaps identified by regulators included:

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

The feedback received indicated that the implementers were in favor of:

- Regulatory framework specific to CCS projects, which addresses timeframes and CO_2 leakage rates / fluxes
- Flexibility in modeling approaches
- A link between monitoring and RA results - for confirmation
- Some form of RA protocol or standard

[5] IEA Greenhouse Gas R&D Programme, Role of Risk Assessment in Regulatory Frameworks for CCS, Report no. 2007/2, February 2007.

Whilst the knowledge gaps identified by implementers included:

- Experience with different types of storage site
- Quantitative information from natural analogues
- Fundamental data
  - PVT behavior of CO_2 and impurities
  - Thermodynamic, kinetic data
  - Coupling between geochemical and geomechanical processes
- Well bore seal longevity
- Benchmarking of RA modeling approaches

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

It was felt that when it comes to the approval of CO_2 storage projects, in the short-term, these will continue to be approved on a case-by-case basis. Also research work currently being carried out on CCS-related projects (Sleipner, Weyburn, Frio etc.), including RA results/predictions, will help guide regulators. Monitoring during injection and post-injection phases will play a major role in regulatory acceptance of long-term safety. The link between monitoring and confirmation of RA predictions is very important. Both groups felt that some form of technical standard or protocol for addressing long-term safety in CCS projects was important. The Technical standard or protocol should have a basic *framework* (flexible). It should build on existing documents, e.g. Best Practice Manual, SACS Project, national standards for risk analysis. In addition, benchmarking studies are needed to enhance confidence in different modeling approaches but these needs to be carefully planned. Monitoring will provide a quantitative resolution capability to match needs by Confirming RA predictions and quantification of migration of CO_2 for GHG inventory purposes. The development of coupled geochemical-geomechanical-fluid transport models is essential to the development of long term predictions for CO_2 storage that regulators can be confident with.

After the presentation there was a considerable debate regarding the need for a qualitative or quantitative RA. There was a feeling from industry that a qualititative analysis, coupled with effective monitoring and remediation plans would be sufficient to build confidence. Other felt that quantitative assessments provide regulators with more confidence and many countries would require them. Also consequence analyses would be required to develop flux data because regulators were looking for that information. The response from industry was that it was impractical to attempt to define numbers based on the uncertainties involved and it was better to tell the regulator what could be realistically achieved. Others cautioned that we do not need complex RAs that give numbers that are not robust, rather we need to be able to undertake a subjective analysis on whether a reservoir would be suitable or not. This was reinforced by others who stressed that in the early stages we need to provide regulators with sufficient information to allow them to be able to discriminate between sites and make a decision to grant a permit. It was also felt that the precautionary principle could be applied to CCS. RA is only part of the message that needs to be given to regulators; remediation is one part as well. We need to get the message over that we are not promoting innovatory technology. There was some concern with the precautionary principle in that it is difficult to draw the boundaries of the box. We need to stress the point that getting as much CO_2 out of the atmosphere as soon as we can is the key issue.

Task 4 – Anne Korre presented the results from the final task, which was to report back on the work being undertaken by CO2GeoNet on risk assessments frameworks for CO_2 storage. The programme consists of three tasks:

Task 1:	Development of an inventory of tools used in risk and performance assessments
Task 2:	Development of guidelines for terminology use
Task 3;	Development of a conceptual framework – based on the inputs from Tasks 1 and 2.

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

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

The aims of Task 3 are:

- To identify the strengths/weaknesses of existing/under development methodologies for CO_2 storage performance and risk assessment,
- To determine the complimentary functionality or niche for each,
- Identify gaps where improvements can be implemented,
- To harmonize the use of tools and methods under a unified conceptual framework.

The risk assessment framework can be visualized in three tiers;

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

Tier 2 would involve exposure assessments, these would be used for storage licensing, monitoring and verification and remediation planning. Here you would use process level models, coupled models, systems models etc., Data requirements would be very site specific with perhaps input of data from surrogate sites to compliment the data sets. This tier would produce quantitative risk assessments, CO_2 fluxes and timescales.

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

These risks will then be communicated and be incorporated into the risk management plan for the project.

We will need to develop standards for site characterization and risk assessment for each lifetime stage of a project.

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

4.1.3 Risk assessment as part of a risk management framework

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

Ton Wildenborg opened the session with a presentation, entitled; the role of RA as part of a Risk Management framework. He asked the question what is risk assessment? He defined it as a means of identifying, estimating or calculating, and evaluating potential risks of CO_2 storage to human health and safety, the environment and assets. RA can be considered as problem oriented.

Risk = Probability of Hazard $\times$ *Consequence of Hazard (impact)*

Seepage of CO_2 from a CO_2 storage reservoir can best be regarded as a hazard, because it has the potential to be harmful. But we need to define who or what it is harmful to. Is it the pollution of drinking water, or a threat to peoples lives, or will it cause a change in biodiversity? First we have to define the consequence and then start calculating.

Risk assessment fits into a risk management framework as illustrated by the diagram overleaf:

RISK			
	RISK ASSESSMENT		
		RISK ANALYSIS	
			SOURCE
			RISK
		RISK EVALUATION	
	RISK TREATMENT		
		RISK AVOIDANCE	
		RISK OPTIMISATION	
		RISK TRANSFER	
		RISK RETENTION	
	RISK ACCEPTANCE		
	RISK COMMUNICATION		

We can identify the source of seepage using appropriate techniques like FEPs or scenario analyses, then quantify the hazard through performance modeling. We can assign probabilities to events and knowing leakage rates we can determine consequences. However, in a probabilistic approach we can define all the processes but a fair degree of expert judgment is then required.

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

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

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

Natalie Quisel of Schlumberger discussed a risk driven decision process for a CO_2 storage site. A storage operation comprises three phases,

- The pre-operational phase (1-2 years), which includes site selection, site characterisation and field design activities,
- The operational phase (3-50 years) which involves site construction, site preparation, injection and monitoring activities,

- The post operational phase, which will involve a site retirement programme and environmental monitoring.

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

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

In a risk driven decision making process the goal is containment of the injected $CO_{2.}$ From a storage reservoir the key risks of loss of containment are wells and faults. Initially you undertake a performance assessment to assess the risk of loss of containment and then you select the best risk mitigation option based on cost and benefits.

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

It is felt this approach can play a role in developing standards for CO_2 containment in storage reservoirs.

4.1.4 Building confidence in CO_2 storage

The final session involved two presentations aimed at establishing international collaboration in building confidence in CO_2 storage.

Kenshi Itaoka opened the session by discussing how natural analogues could be used to build confidence in CCS. He pointed out that there were two issues to consider first the long timeframes associated with CO_2 storage. Secondly, there were issues relating to the general uncertainty of geological formations, difficulties in data acquisition and uncertainties in the behavior of the injected CO_2 and difficulties in verifying the amount of CO_2 injected.

He pointed out the degree of risk is difficult to interpret and the uncertainties were difficult to estimate. However, natural analogues could play a role here. There are several ways that natural analogues could be used to build confidence in CO_2 storage which include:

- Helping geologists to understanding the leakage and trapping mechanism,
- Verification of numerical models and risk assessment procedures,
- Interpretation and risk management,
- Helping to communicate the safety of CO_2 storage.

By building up a database of events from natural and industrial analogues comparable to those that could occur from a CO_2 storage reservoir you can build a risk matrix that allows you to compare and communicate the risks of CCS in a way that is readily understandable. This work is on going.

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

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

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

However he went on to comment that:

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

He then described an exercise that was currently underway to demonstrate the integrated safety assessment approach using a sub-seabed CO_2 storage reservoir as a case study. In the coming year it is planned to refine this methodology and to develop a more comprehensive example to assess the applicability of the methodology.

4.2 Case Studies

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

1. The quality of the data set used
2. The methodology used
3. The inherent assumptions made
4. Their results

The group then split into 4 to consider the cases in detail. The breakout groups then reported their findings back to the whole group. The breakout groups were asked to review the studies that had been completed and comment back on the following issues:

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

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

4.2.1 Case Study 1 - the Latrobe Valley CO_2 Storage Assessment

Summary

This case study was presented by Andy Rigg, CO2CRC. The prospective Latrobe Valley storage site in Australia lies in the Gippsland Basin in the southern state of Victoria. The Gippsland basin straddles both on and offshore. Onshore the Gippsland Basin contains the world's thickest coal seams which represent Australia's cheapest power and Australia's largest CO_2 emissions sources. Whilst off shore it contains Australia largest and most productive oil fields. The problem is that new brown coal developments in Latrobe Valley will increase emissions by up to 50Million tonnes/year. One potential solution in a carbon constrained world is to inject those emissions offshore in the Gippsland Basin. The CO_2 would be injected into existing oil and gas fields (once depleted) and deeper saline formations. Injection could take place at several sites along regional migration pathways, sequentially & simultaneously, ramping up volume to 50 Mt/y. One field the Kingfish Field could inject: 15 Mt/y for 40 years and was the subject of the risk assessment presented.

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

- It has a complex stratigraphic architecture which slows vertical migration and increases residual gas trapping,
- The reservoir contains a sequence of non-reactive reservoir units, each with high injectivity,
- There is a geochemically reactive, low permeability reservoir just below the regional seal to provide additional mineral trapping,
- There are several pressure depleted oil fields to provide storage capacity coupled with transient flow regime that enhances containment pressure,
- There are long migration pathways beneath a good regional seal ,
- The Kingfish Field, in conjunction with other sites (e.g. the Fortescue, northern gas fields); indicate that the Gippsland Basin has sufficient capacity to store very large volumes of CO_2.

The study was based on a prospective CO_2 storage site and used a qualitative risk assessment approach. Exploration wells were found to the biggest risk to loss of containment.

Breakout group report

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

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

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

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

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

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

As discussed earlier, if two expert panels were given the same data they could come up with (somewhat) different conclusions

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

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

4.2.2 Case Study 2 - the Mountaineer CO_2 Storage project

Summary

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

FEP	Description
CO_2 storage (pre closure)	High injection rates and over pressuring may affect storage reservoirs and containment units
CO_2 properties	CO_2 solubility and aqueous specification
CO_2 transport	Advection of CO_2 due to injection Buoyancy driven flow/migration Displacement of formation fluids
Geosphere	Reservoir geometry variations and heterogeneity
Wells, drilling and completion	Durability of well casings and cement
Well, seals and abandonment	Degradation of borehole materials used to abandon injection well.

To address this issue the project included:

- A SCADA system to monitor the injection pressures,
- Reservoir sampling included to determine extent of reaction of brine with CO_2,
- Monitoring programme expanded to assess CO_2 migration within the reservoir,
- Well integrity to be monitored and well design changed to utilize acid resistant materials wherever possible.

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

Breakout group report

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

Comments on approach used. The assessment used the FEPs analysis for CO_2 storage. The assessment was designed to address the Risk assessment of an experimental injection rather than a full scale project. It did not address capture or transport issues. It used the Quintessa database to identify FEPs. A qualitative FEPs screening, was carried out at three levels of screening carried out by three independent reviewers. This identified six main items. The approach was systematic and the analysis comprehensive. However it must be noted that there was some subjectivity in the final selection.

General issues relevant to Risk Assessment and CO_2 storage Confidence Building. The audience is important in the design of the risk assessment results communication strategy, not in the design of the RA technical approach. Confidence building involves a lot more than the technical risk assessment. The impact on confidence when performing ‘what if’ scenarios that are not supported by the FEP analysis

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

4.2.3 Case Study 3 – Weyburn

Summary

Malcolm Wilson presented the Weyburn case study. Performance assessment was applied as the initial phase of an overall risk assessment process to evaluate the long-term fate of CO_2 injected into the Weyburn reservoir. The role of performance assessment within Phase 1 of the IEA GHG Weyburn CO_2 Monitoring and Storage Project was to identify the risks associated with geological storage and assess the ability of the Weyburn reservoir to securely store CO_2. The performance assessments were utilized to identify and increase the understanding of crucial processes for CO_2-EOR and will form a critical component of the final risk assessment in Phase 2 of the Project.

To assist in identifying the processes that could be relevant to the evolution or performance of the Weyburn reservoir, a list of FEPs was developed. Compositional reservoir simulations, supporting early performance assessment studies, were conducted over a time period of 5000 years, starting from the end of EOR and were conducted to provide an initial understanding of CO_2 migration; the process and parameters that may be important to modeling its long-term fate. These early studies highlighted the importance of processes such as CO_2 diffusion in the oil phase, phase saturation distribution at the end of EOR, groundwater velocities within the reservoir zone, and the strong interplay between the coupled processes of pressure-driven flow, density-driven flow and diffusion. Next a series of large-scale reservoir simulation simulations were carried out covering the entire 75 pattern EOR system and allowed the long-term performance assessment to be carried out for a period of 5000 years following the end of EOR.

Deterministic and stochastic approaches were adopted to assess the fate of CO_2 within the reservoir. Cumulatively, after 5000 years, the total amount of CO_2 removed from the EOR area is 26.8% of the initial CO_2-in-place (~ 21 MT) at the end of EOR, of which, 18.2% moves into the geosphere below the reservoir; 8.6% migrates laterally in the Midale reservoir outside the EOR area; 0.02% moves to the geosphere above the reservoir, and no CO_2 enters the potable aquifer over the 5000-yrs period. For the abandoned well leakage assessment, the estimated maximum cumulative leakage of CO_2 for an estimated 1,000 wells was ~0.03 MT or 0.14% of the total CO_2-in-place at the end of EOR over the 5,000 year period. The mean cumulative leakage was estimated to be less than 0.001% of the CO_2-in-place at the end of EOR.

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

All the performance assessment studies conducted within Phase 1 of the IEA GHG Weyburn CO_2 Monitoring and Storage Project have shown clear support for the conclusion that the geological setting at the Weyburn Field is highly suitable for long-term subsurface storage of CO_2. These studies have highlighted the significant capacity of the geosphere region surrounding the reservoir to effectively store CO_2 and prevent its migration to the biosphere.

Break out group report

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

<u>Comments on approach</u>. Generally robust. Limitations include:

- Inability to couple rock property changes due to geochemistry,
- Inconvenient well leakage calculations,

- Density calculation for water with dissolved CO_2.

Comments on assumptions used. Generally conservative and robust. If the CO_2 were to pass the cement, it will then migrate to other areas (overlying aquifers, atmosphere). For wells it was assumed that all regulations followed and all wells were known.
Overall it was considered that there were; no undetected features in reference scenario, no possibility of a severally fractured conduit zone, and no geochemical reactions that could reduce cap rock integrity.

Confidence in results. Qualitative containment of CO_2 has a high degree of confidence. Pathways are less certain. Impacts add another layer of uncertainty

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

- The reservoir performance
    - CO_2 will not reach the surface within 5000 years
    - Low permeability restricts impact of open boreholes
- Confident about well locations

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

How do the results help us build confidence in long term storage of CO_2?
It is felt that the results help convince technical, regulators, and the public. They also can help determine main parameters for future simplifications or refinements of RA/PA methods and models. By considering the worst case scenario we can rule out public concerns over issues like indoor air contamination.

Future actions to improve Confidence include;

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

4.2.4 Case Study 4 – The Schweinrich study

Summary

Sara Erikkson presented the outline of the Schweinrich study carried out by BGR and Vattenfall. The study was part of a larger study to investigate opportunities to store CO_2 captured from a 1600 MW lignite fired power plant in North Eastern Germany. The plant would produce 400MtCO_2 over its service life of 40 years. The study involved a regional mapping exercise to screen relevant regional occurrences of saline aquifers. This assessment identified the Schweinrich structure as having the most potential as a suitable CO_2 store in that region. A pre-feasibility study was then undertaken which relied on existing data with a further more detailed study to be undertaken later.

2D seismic data was available as well as well logs and mineralogical data this allowed 3D geological modeling to be undertaken. The aquifer was found to have a thickness of 270-380m with a passive anticlinal structure and was sealed by a thick clay sequence. Mineralogical analyses indicated the reservoir was moistly quartz with few reactive minerals present. The cap rock was a thick (several hundred metre) claystone sequence containing several overlying aquifers. The storage capacity was estimated at between 500 and 840 Mt CO_2. Reservoir simulations predicted that 10 wells would be needed to inject the CO_2; injection would result in a formation pressure increase and displacement of formation waters.

In summary the study identified that potential for one large onshore structure capable of storing sufficient CO_2. The pre-feasibility study highlighted a number of areas where further data was required. This data included:

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

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

Breakout group report

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

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

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

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

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

What can we communicate? This was only a scenario analysis and we need to take care when communicating results. We must be wary of presenting quantitative numbers and we need to add caveats clearly when presenting results from these types of studies.

Confidence building. The study identified the issues that need to be addressed in a structured appraisal programme.

4.2.5 Discussion Session

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

1. There was a general feeling that more work was needed on RA for CCS. Also that it was critical for early studies that as much data was assembled as possible to make sure the results are as credible as possible. Also we need to develop guidelines for RA and agree how benchmarking can occur.
2. There is a need to develop a RA for a full scale CCS project; the projects discussed above are only preliminary activities. It was felt that we should not oversell the RA results from these small studies but these cases are helping with tool development etc.,
3. There was concern that some of the studies the scenarios developed were not supported by the FEP analyses; the development of unrealistic scenarios does not help to build confidence in RA. The scenario referenced was leakage through a fractured cap rock.
4. The comment was made that you cannot prove that a cap rock is not fractured; you cannot ignore such a scenario even though FEPS may not support this process. This point was further emphasized by several speakers
5. Modeling well failure was currently difficult and there was a lack of consistency between the studies on this issue. There were cases where leakage from open hole bore holes had been modeled but the permeability of the reservoir will not allow quick flow of CO_2 back out of the reservoir.
6. The issue of subjectivity of expert panels was raised again. Construction of expert panels with broad experience is very important – should we bring in non-experts as well to gauge their response.
7. The issue of using worst case scenarios was raised and debated. In general, it was felt important to model worst case scenarios because if the scientific community doesn't do it, others will, possibly with serious consequences. Also worst case scenarios can help build confidence, as in the Weyburn case where it was shown there was no risk of ambient air quality problems arising from leakage of CO_2.
8. The point was made that it was currently difficult to assess the impact of seepage on groundwater quality because there was no data available.
9. Sensitivity studies are valuable to identify key risk parameters to model.
10. A question related to bench marking was raised – in future will RA models need to be certified and who will certify them? A peer review /benchmarking process will be required. In response to this question, industry felt that we were over playing the issue because currently we can engineer CO_2-EOR projects and natural gas storage (NGS) projects without the need for peer reviewed or certified RA techniques – why is CCS so different? The key difference was considered to be the long tern mature of CO_2 storage which may warrant the reinforced of regulations – regulations for EOR and NGS only deal with short term issues. It was also felt that regulations for EOR and NGS were set years ago and now there is a higher degree of environmental consciousness that could warrant stricter

regulations. In the USA, regulations for EOR were framed around resource recovery not with environmental security in mind.

11. The point was made that CCS was new and that when we generate data from several RA studies we might decide we won't need stricter permits than we currently. Also it was felt that we know more about oil and gas fields than we do about aquifers.
12. The question was raised; are we trying to oversell RA? The key need for RA was to screen out high risk sites, then identify lower risks sites for storage we can follow by monitoring. We want to avoid an early failure from a CCS operation due to poor initial screening.

5. Summary and Key Conclusions

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

The CCS community is aware that there is a need to fully characterize storage sites to ensure that the sites selected can effectively contain CO_2 for 1000's of years. Site characterization will be a step wide process, with initial pre-screening an important aspect because it will allow poor sites to be screened out early and allow efforts to be concentrated on those sites that have the best potential. Risk assessment is one tool that can be used in the early screening of storage sites. Risk Assessment and site characterization work in an iterative manner, over different project stages from preliminary screening to permitting to implementation. There will be increasing data requirements as you proceed to each stage.

Risk assessment studies can provide guidance on likely seepage rates from storage sites but they cannot define the impacts of leakage. Environmental Impact Assessments (EIA) can provide the framework for assessing the long term impacts of leakage. However, it has been shown that currently there is little research work underway that is addressing specifically the effects of CO_2 leaks and their potential impacts that could allow an EIA to be compiled. This is a major research gap.

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

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

RA can also be considered as part of a Risk Management framework. RA is the means of identifying, estimating or calculating and evaluating potential risks of CO_2 storage to human health and safety, the environment and assets. RA can be considered as problem oriented. Risk management on the other hand deals with assessing, monitoring & remediating risks to conform to risk acceptance levels. Risk management is therefore solution oriented. When we look at the results of risk assessments in relation to CCS we should put more emphasis on the 'solution' instead of the 'problem' when we communicate the risks involved.

Natural analogues could be used to build confidence in CCS. There are several ways that natural analogues could be used to build confidence in CO_2 storage which include:

- Helping geologists to understanding the leakage and trapping mechanisms,
- Verification of numerical models and risk assessment procedures,
- Interpretation and risk management,
- Helping to communicate the safety of CO_2 storage sites.

By building up a database of events from natural and industrial analogues comparable to those that could occur from a CO_2 storage reservoir you can build a risk matrix that allows you to compare and communicate the risks of CCS in a way that is readily understandable.

Four RA cases studies were reviewed; three were based on aquifers and one on an oil field operation. It should be emphasized that several of these cases were not full complete risk assessment studies but were really scoping studies. The results of such studies should therefore be treated with some care when communicated outside of the technical community. The aquifer based assessments generally suffered from a lack of data, which is not unsurprising. This resulted in a lot of assumptions being made. The oil field case was much better characterized which allowed a more detailed risk assessment process to be undertaken. All the assessments used expert panels which involve a degree of subjective analysis. Expert panels need to be drawn from as wide a group of individuals as possible whereas the groups involved in these assessments tended to be drawn internally from the research organizations involved. The oil field study gives us some confidence that CO_2 can be retained in that formation for 1000's years but the same degree of confidence cannot be drawn from the aquifer studies. The studies have, however, contributed significantly to the learning process for undertaking such studies which will be of benefit in the future and help to allow us to better define the data requirements needed to complete a good robust risk assessment. More RA studies are needed to help develop confidence in the techniques and models used as well in the results they generate.

6. Next Steps

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

1. Site selection how much characterization is needed to do a formal risk assessment?
2. Do we need full blown quantitative risk assessments or would simpler screening assessments be enough to generate confidence in CO_2 storage?

3. Having had experience of using FEPs can we design a screening process involving a simpler FEP database?
4. How and when do we begin to develop a RA standard or protocol?
5. How we develop a benchmarking system for RA tools and approaches?

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

Appendix 1. Delegates List

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

Jens T. Birkholzer	Lawrence Berkeley National Laboratory
Grant S Bromhal	US DOE/NETL
Preston Jordan	LBNL
Andrea Cortis	LBNL
Yingqi Zhang	Lawrence Berkeley National Laboratory
Jennifer Lewicki	LBNL
Dorothy S Peterson	Potomac-Hudson Engineering, Inc

1. Venue and Dates

2nd RISK ASSESSMENT NETWORK MEETING
Lawrence Berkeley National Laboratory
California, USA
Thursday 5th to Friday 6th October 2006-09-26

Workshop Programme

Workshop Overview

The meeting will present scene setting overviews of other IEA GHG international networks and current research activities relevant to the Risk Assessment Network. There will also be the opportunity to review the developments made by the four working groups since the Inaugural meeting of the network held in August 2005. The second day will look at the current status of knowledge on performance assessment and try to identify new initiatives the network should be aware of. Finally the meeting should plan the future direction of the network

Organised by:
IEA Greenhouse Gas R&D Programme and LBNL
With the support of EPRI

Workshop Agenda

Day 1 (5th October 2006)	
08.00 to 08.30	Registration
08.30 to 08.40	Welcome to LBNL and, fire briefing/safety issues, Larry Myer LBNL
08.40 to 08.50	Meeting aims and context, John Gale IEA GHG
Session 1– Invited Presentations, Chair: John Gale, IEA GHG	
08.50 to 09.20	Site Characterization- summary of a workshop, Jens Birkholzer, LBNL and Elizabeth Scheehle, USEPA
09.20 to 09.50	Well Bore Integrity Network – feedback and current state of knowledge, Charles Christopher BP
09.50 to 10.10	Statistics on "Unexpected Occurrences", Preston Jordan, LBNL
10.10 to 10.30 Break	
Session 2 – Feedback on Actions From Last Meeting, Chair: John Gale IEA GHG	
10.35 to 10.50	Review of Inaugural meeting and actions set, John Gale, IEA GHG
10.50	Data Management and Risk Analysis Feedback, Ton Wildenborg, TNO-NITG
11.30	On shore ecological impacts assessment, Jonathan Pearce, BGS
11.30 to 12.10	Regulatory needs for risk assessment, Mike Stenhouse, Monitor Scientific (including discussion).
12.10 to 13.00	Regulatory framework development under the CO2GeoNet project. Anne Korre, Imperial College (including discussion).
13.00 to 14.30 Lunch	
Session 3-Risk Management for CCS, Chair: Ton Wildenborg.	
14.00 to 14.30	The role RA as part of a Risk Management framework Ton Wildenborg, TNO-NITG.
14.30 to 15.00	Open discussions on RA regulatory feedback.
14.30 to 15.00	Risk Assessment of a CO_2 storage site and risk-driven decision process. Natalia Quisel, Schlumberger.
15.00 to 15.45	Discussion Session on RA and RM.
15.45 to 16.00 Break	
Session 3-Building confidence in CCS, Chair: Malcolm Wilson, EnergyINet	
16.00 to 16.15	Outline of the plan for international collaberation: Norio Shigetomi, Mitsubushi Research Institute Inc.
16.15 to 16.45	Development of international collaberation for building confidence in the long-term effectiveness of CO2 geological storage; Hiroyasu Takase, Quintessa Japan.
16.45 to 17.15	Open discussion on plans for international collaberation.
17.15 to 17.30	Resume of Day 1 John Gale, IEA GHG/Malcolm Wilson EnergyINet.
Close Day 1	

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

Second International Risk Assessment Network Workshop

John Gale
IEA Greenhouse Gas R&D Programme

Lawrence Berkeley National Laboratory

San Francisco, USA

5th to 6th October 2006

Building Confidence in CCS

- To move the technology forward to implementation we need to:
  - Identify technical barriers
  - Identify ways of addressing these barriers
- Provide information on what we know to build confidence
  - Transparent and open manner

Research Networks

IEA GHG Networks

CAPTURE

- International Network for CO_2 Capture
- Oxy-fuel Combustion Network
- International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae

STORAGE

- Risk Assessment Network
- Monitoring Network
- Well Bore Integrity Network

How Safe is CCS?

- Design storage facility for zero leakage
  - Site characterisation
- Monitoring programme
  - Current results indicate zero leakage during operational phase
- Well bore integrity?
  - Some uncertainties but developing our knowledge
- Performance assessments
  - Predict long term fate of injected CO_2
- Remediation strategy
  - IEA GHG study recently completed to begin to address this issue

Environmental impacts of CCS?

- CO_2 capture
  - Initial study underway
    - Need further work
- Onshore storage
  - Reported at this meeting
- Offshore storage
  - Initial study to identify issues/gaps in knowledge underway

Confidence Building

- Bring results from network and study activities together:
  - Briefing papers
  - Information sheets
  - Topical Report
- Aim to deliver positive (but unbiased) messages on CCS safety

Aims of this meeting

- Provide some reference material from related activities
- Present status of actions from last meeting
  - Four teams to address a number of key issues
    - Data management/quality
    - Ecosystem data
    - RA frameworks/terminology – CO2GeoNet
    - Regulatory feedback
  - Case study reviews
    - 4 different cases
    - Assess status of knowledge
    - What we can confidently say about performance assessments
  - Frameworks/Risk Management
  - Building confidence in CCS
  - Next Steps

EPA's Activities on CO2 Geological Storage: Ongoing Research Projects and a Report on the International Symposium on Site Characterization

E. Scheehle, A. Karimjee, B. Kobelski, B. Smith, US EPA

J. Birkholzer, S. Benson, C.-F. Tsang, LBNL

EPA Regulatory Goals

- Protect human health and the environment
- Ensure that decisions are cost-effective and fully protective
- Conduct high quality scientific, economic, and policy analyses at early stages so that decision makers are well informed
- Apply new and improved methods to protect the environment
  - build flexibility into regulations from the very beginning
  - create strong partnerships with the regulated community and other interested parties through public outreach and involvement
  - use effective non-regulatory approaches

EPA Activities

- Internal EPA Geologic Sequestration Workgroup co-chaired by Offices of Water and Air and including 30 members from HQ Offices, EPA Regions and Labs
  - Initial focus on technical and regulatory issues, risk assessment, communication and outreach

- Recent EPA Activities
  - Involvement in International efforts (CSLF, IPCC, etc.)
  - Research Projects with LBNL
  - GHG Inventory and Accounting
  - Conferences and Workshops
  - Guidance for Experimental Wells for DOE pilot projects

EPA Sponsored Research at LBNL

- Large Releases of CO_2 (2005 – 2006)
  - To evaluate the possibilities and consequences of large releases from a CO_2 storage reservoir
- CO2 Geological Storage and Groundwater (just started)
  - To evaluate geochemical impact of CO_2 leakage into USDW's (Task A)
  - To evaluate impact of CO_2 storage on large-scale groundwater systems (Task B)
  - Co-funded by NETL

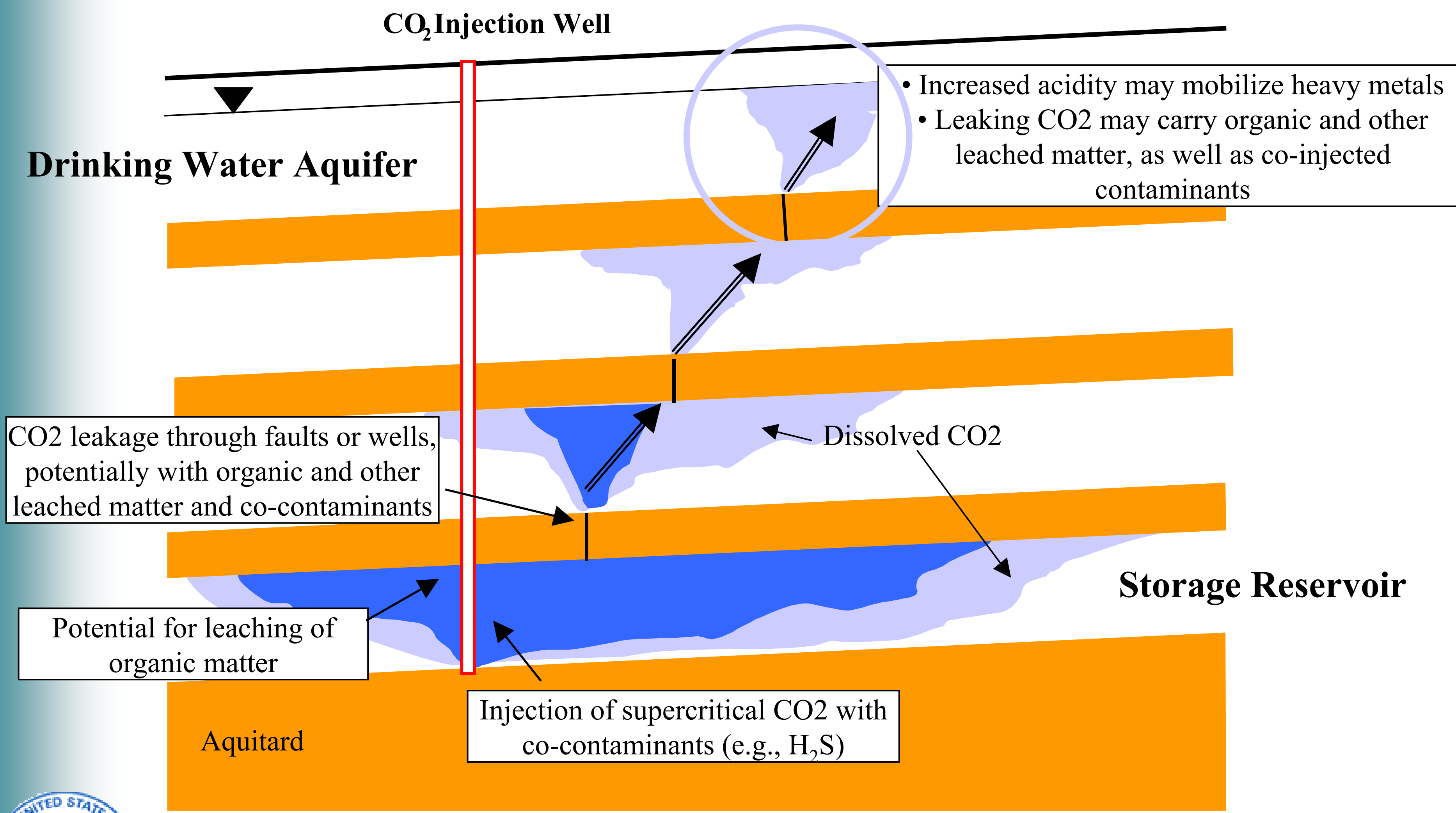
➤ Research projects address key technical gaps relevant for regulators

Large Releases of CO2

- Survey of natural and industrial analogs of CO2 releases to identify the relevant features, events and processes (FEPs) involved[1]
- Development of potential release scenarios for risk assessment[2]
- Simulations of hydrological and geomechanical processes that could initiate CO2 release and promote its acceleration[3]
- Literature survey to identify potential co-contaminants in CO2 captured from current and future coal-burning power plants[4]

[1]Lewicki et al., Environmental Geology, in press
[2]Birkholzer et al., GHGT-8
[3]Rutqvist et al., GHGT-8
[4]Apps, LBNL-59731

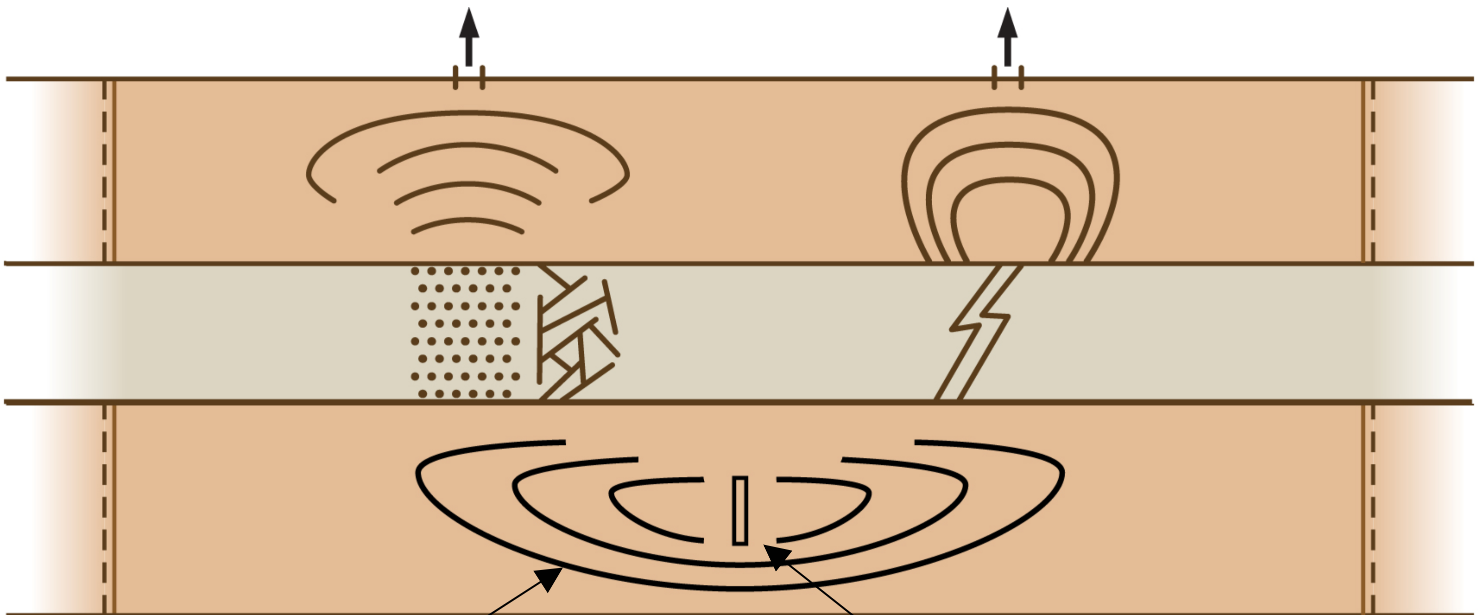
Groundwater Quality Concerns



Regional Groundwater Systems

Need understanding of displaced water movements; in particular, those into USDW's

Need to evaluate the effects on: groundwater table, discharge and recharge zones and rates, and properties and characteristics of USDW's



Need understanding of increase and extent of water pressure buildup, both in the storage formation and shallower aquifers separated by aquitards

Amounts of CO2 to be injected underground will be very large

EPA Sponsored Meetings

- Geologic Modeling and Reservoir Simulation
  - Workshop, April 6-7, 2005 in Houston, TX
  - Assess modeling capabilities for site characterization, risk assessment, and simulating long-term storage
- Risk Assessment & Management
  - Workshop September 28-29, 2005 in Portland, OR
  - Share information and solicit expert input from a wide range of stakeholders including researchers, industry, NGOs, and regulators.
- Site Characterization for CO2 Geological Storage
  - International Symposium, March 20-23, 2006 in Berkeley, CA
  - Address various aspects associated with selection and characterization of potential sites for CO2 geological storage

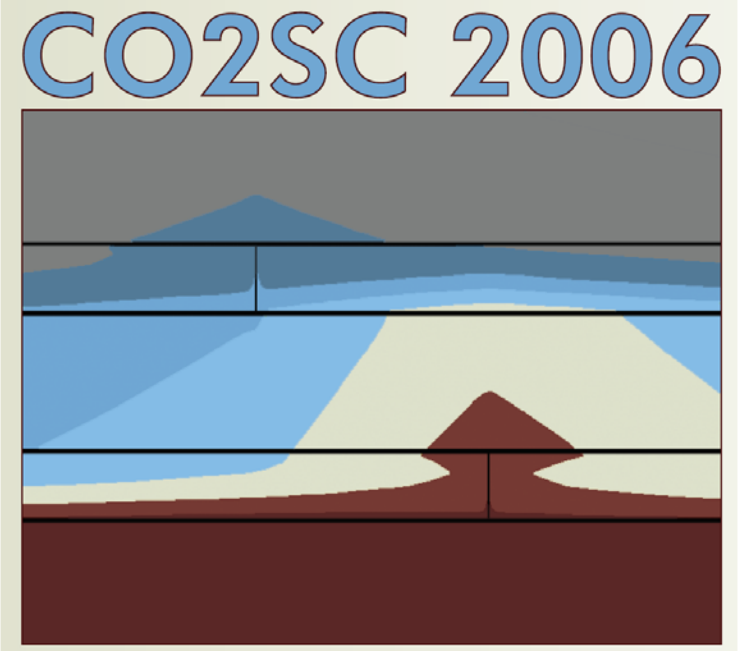
CO2SC 2006

International Symposium on Site Characterization for CO2 Geological Storage

LBNL, March 20-23, 2006

Sponsored by EPA

- About 80 Contributions
- 26 International Papers
- 11 Countries
- 47 Oral Presentations
- 28 Poster Presentations
- More than 150 Participants



Organizing Committee: J. Birkholzer, C.-F. Tsang, S. Benson (LBNL), A. Karimjee, B. Kobelski (EPA)

Topics and Sessions

The CO2SC Symposium addresses various aspects associated with selection and characterization of potential sites for the geological storage of CO2

- General Framework
- Characterization Methods and Technology
- Regional and Project Case Studies
- Characterization of Leakage Pathways
- Fundamental Processes
- Screening and Ranking Tools
- Regulatory and Social Issues
- Panel Discussion
  (S. Benson, S. Bachu, R. Finley, F. Molz, L. Orr, J. Tombari)

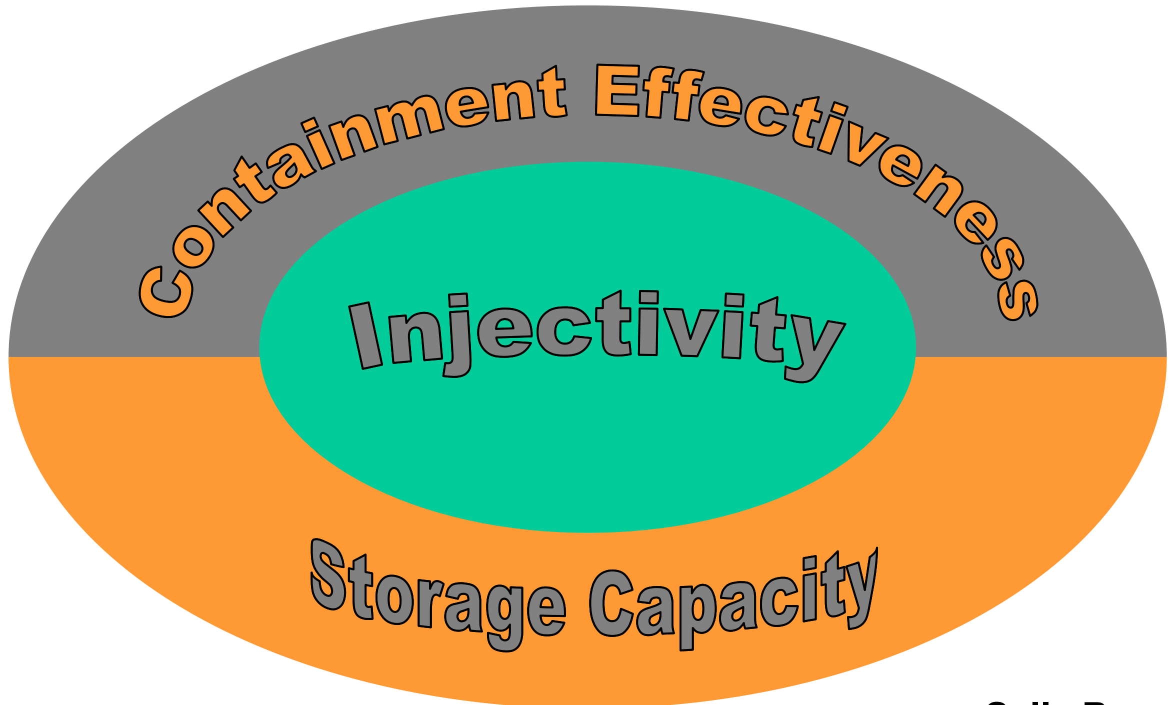
Technical Sessions

Site Characterization Definition

The collection, analysis and interpretation of data and the application of knowledge to judge, with a degree of confidence, if an identified site will store a specific quantity of CO_2 for a defined period of time and meet all health, safety, environmental requirements."

Peter Cook, CO2SC 2006

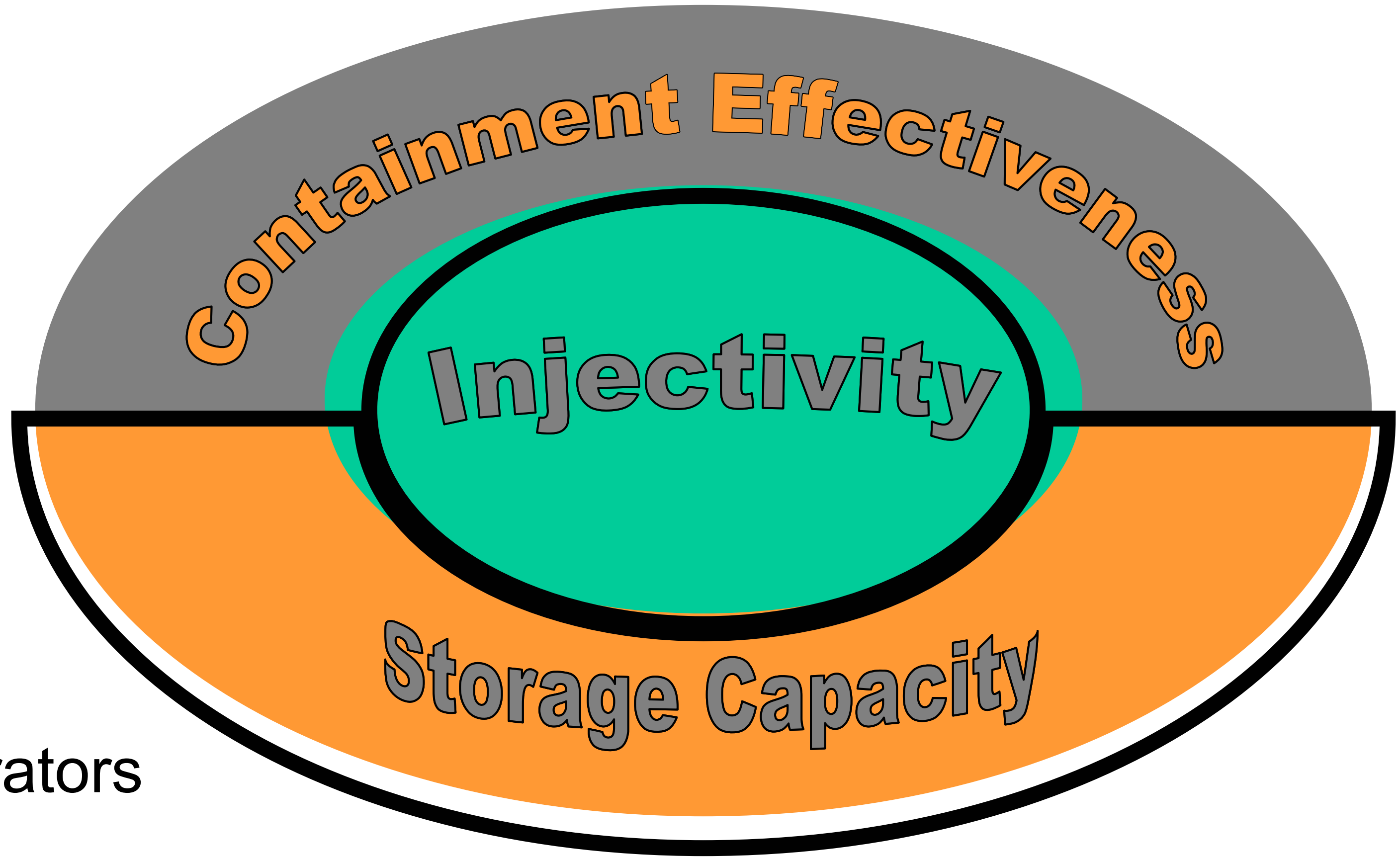
Components of a Storage System



Sally Benson, CO2SC 2006

- ***I**njectivity: Pressure Buildup, Number of Wells*
- *Storage **C**apacity: Sufficient Volume*
- ***C**ontainment Effectiveness: Long-Term Seal*

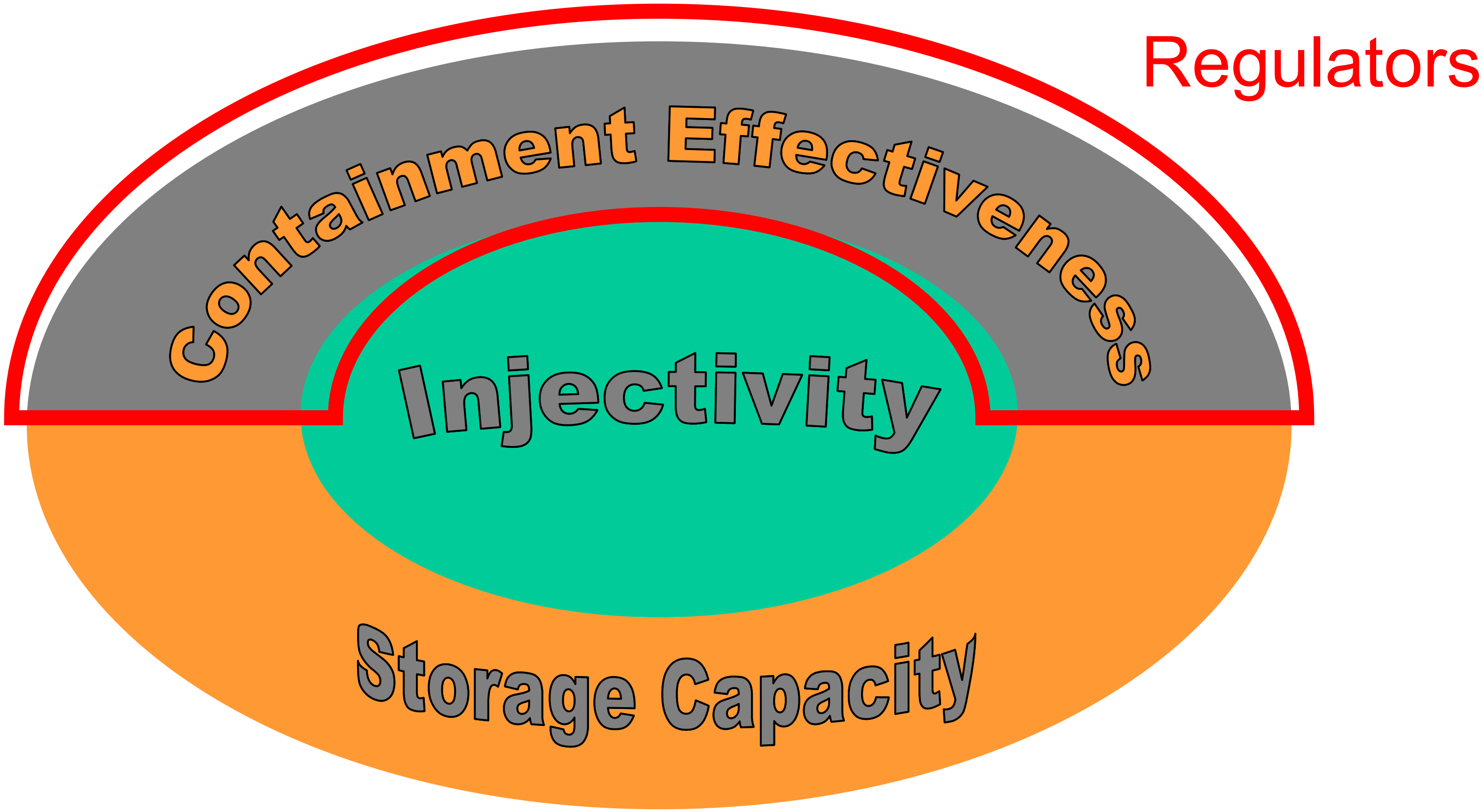
Components of a Storage System



Operators

Not everyone thinks the same things are most important.

Components of a Storage System

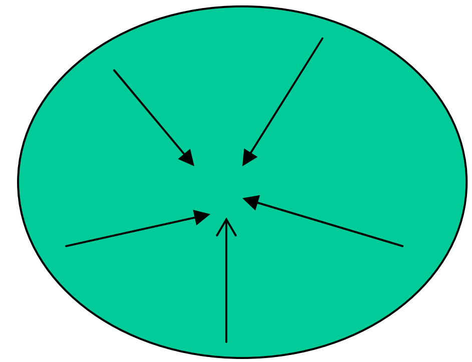


Not everyone thinks the same things are most important.

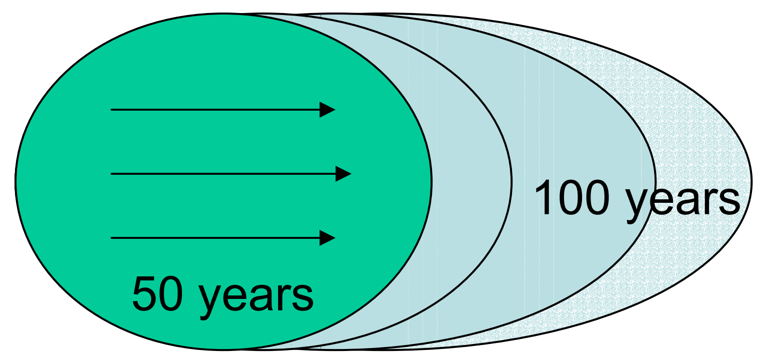
Not all characterization data is needed for a permit.

Characterization is Site-Specific

- Oil and gas
  - Current and future abandoned wells
- Saline formations
  - Seal adequacy over ~ 100 km^2
    - Closed trap vs. open trap
    - Stacked reservoirs
- Coal beds
  - Injectivity
  - Containment
    - Adsorption



Closed Trap



Open Trap

Fit for purpose characterization is needed.

Site Characterization – When?

- Would characterization of a site occur only prior to CO_2 injection, or should it continue (and be refined) throughout the injection phase, and during later monitoring and verification stages?
- Should we define three phases of site characterization?
  - pre-injection
  - injection
  - post injection
- Alternatively, should “site characterization” be the pre-injection phase and is the injection/post injection phase a “site verification” phase?

From Peter Cook, CO2SC 2006

Site Characterization – When?

- Staged approach (learning by doing) would have important ramifications for permitting[1]:
  - approval would be based on not too extensive characterization and documentation
  - monitoring CO2 movement would provide important information on site characteristics[2]
  - monitoring during injection and post injection phases would verify site suitability
  - remediation plans need to be in place if things go wrong

[1]Lindeberg, Can the Risk for CO2 Escape from Geological Storage be Quantified?, Review Lecture, GHGT-8

[2]Doughty, Site Characterization for CO2 Geological Storage and Vice Versa – The Frio Site as a Case Study, CO2SC 2006

Site Characterization – How Much?

- Resources will be scarce at full deployment of CCS (limited budget, experts, regulators, data, schedule)
- Which data are must-have versus nice-to-have for permitting a site (type and amount of data)?
- It is relatively easy to work at what can be done; it is more difficult to work out what is not necessary
- Pilot projects and early large-scale projects can help determine minimum set of information (do more than necessary, as a basis for prioritizing next time)
- Pilots must not become de facto standards, or unduly raise expectations
- Regulators expect complete, but not overwhelming information

Site Characterization Methods

- Geology, geology, geology!
- Lots of characterization technology available, more in the pipeline (some specific for CO_2 storage)
- Regional scale geochemistry is missing from saline formation characterization
  - Age of water
  - Connectivity and compartmentalization assessment
- Avoid specifying particular technologies
  - Different needs
  - Varying effectiveness
  - Stifle innovation

Regional and Project Case Studies

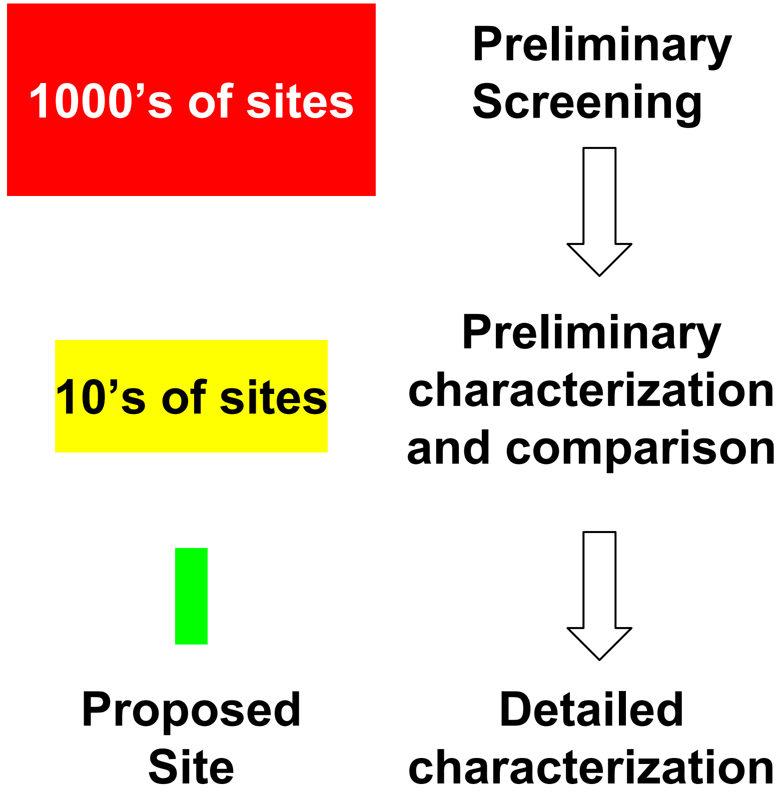
- Very important base of experience
- Learn from surprises
- Develop best practices
- Establish minimum set of information
- Site Characterization Network was suggested
  - Information sharing
  - Repository of case studies

Leakage Pathways

- Need for data on fault and well leakage properties (geometry and permeability of flow paths)
- Need for fundamental understanding and quantitative assessment of self-enhancing and self limiting processes controlling leakage up faults and wells
- Need for better understanding of geochemical and geomechanical changes to caprock

Screening Tools

- Quick and reliable methods for selecting storage options
- Comparative assessment of attributes
- Detailed characterization on most promising options
- Several tools available with different perspectives
  - Preliminary Screening
  - Risk Assessment
  - Economic
  - Geologic/Geographic
- Will these play a role in permitting (as standards)?



Key Gaps and Needs

- Large-scale characterization of seals for saline formations
  - Thickness, continuity, uniformity, properties, long-term integrity
  - Static and dynamic conditions
- Effective tools/procedures/protocols for characterization of fast paths (faults, wells) and leakage potential
- Predicting plume extent and storage capacity considering multi-phase flow with heterogeneity and dissolution, plus displacement of water
  - Upscaling strategies for multiphase (fingered) flow
  - Simultaneously predict flow, mechanical, and chemical changes
  - Impact on regional groundwater systems
- Definition of standards for site characterization
  - when, how much data, degree of confidence, HSE requirements, compliance period

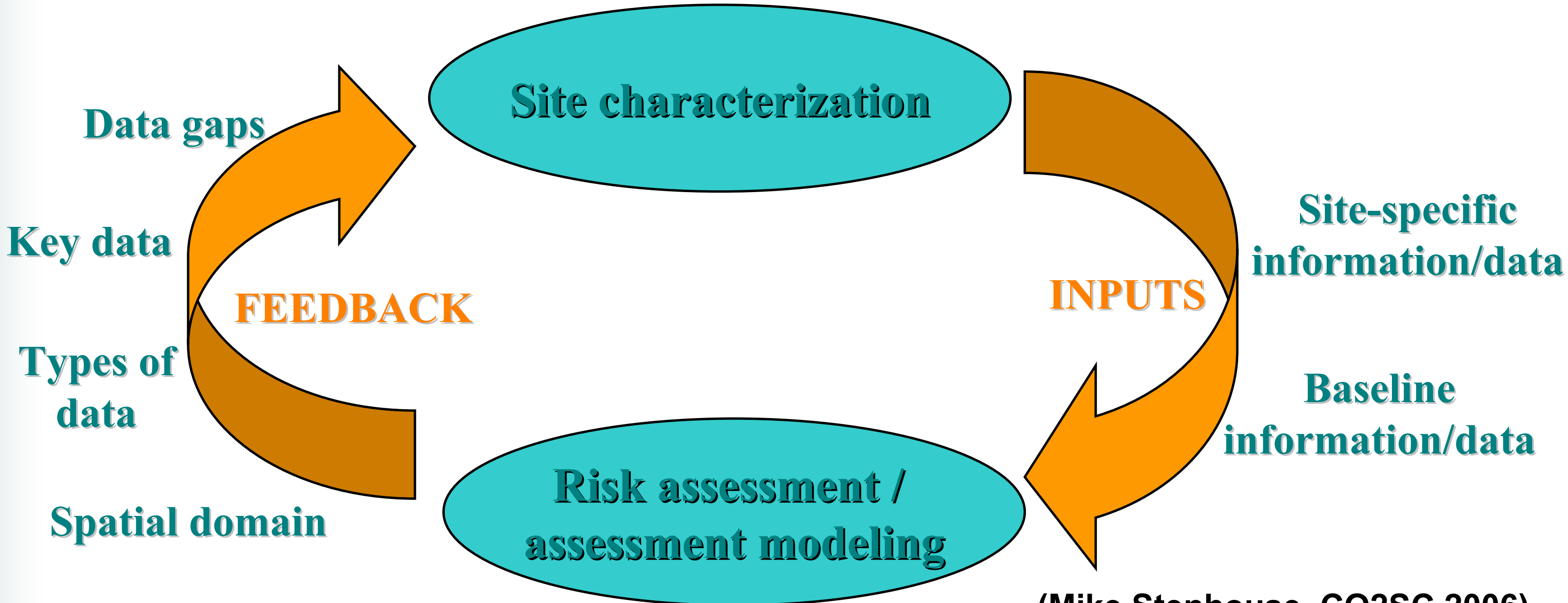
Site Characterization and Risk

There is no such thing as the perfect storage site, but we can identify sites with acceptable levels of risk that are fully fit for purpose ***(Peter Cook, CO2SC 2006)***

- Government ("The Regulator") defines the level of acceptable risk
- Industry ("The User") decides what level of risk to carry in moving a project forward
- Individuals ("The Community") may perceive acceptable risk of storage different from regulator and industry

➢ Risk may be interpreted, defined and communicated in different ways (cost, value of credits, impact on HSE)

Site Characterization and RA



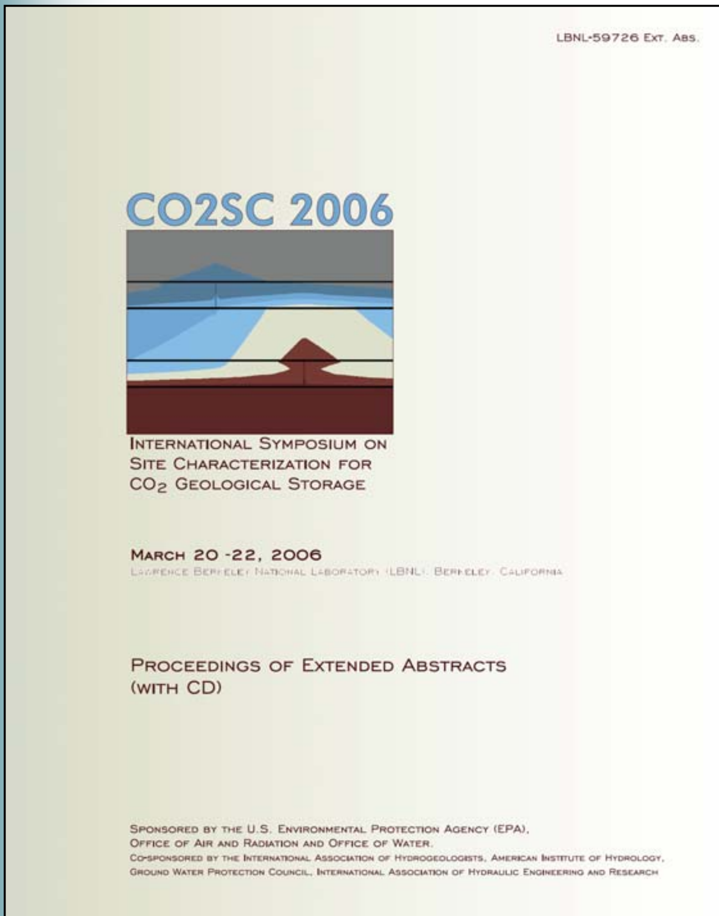
(Mike Stenhouse, CO2SC 2006)

- Risk Assessment (RA) expresses risk formally as the product of consequence of a FEP times its probability
- RA and site characterization work in an iterative manner, over different stages from screening to permitting to implementation
- Will site characterization ever provide level of detail needed to conduct a formal risk assessment?

Main Conclusions

- A carefully selected site can be safe (i.e.; it will meet acceptable levels of risk)
- Geology rules
- Site characterization, as the basis for permitting, needs to be defined and mutually agreed upon (standards)
  - How much information is necessary?
  - When does site characterization conclude?
- Sophisticated characterization and screening tools are available, more under development
- Pilots and early large-scale projects are important base of experience (learning by doing)

Publications



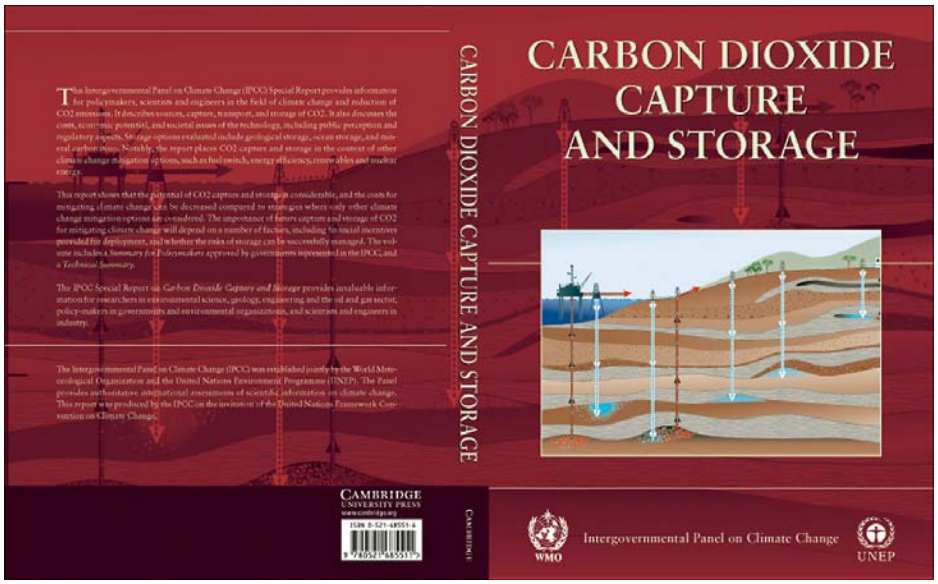
- **Proceedings Book with Extended Abstracts (LBNL-59726)**
- **Revised Proceedings available at http://www-esd.lbl.gov/CO2SC/**
- **Most presentations available at http://www-esd.lbl.gov/CO2SC/**
- **Special Issue Journal of Environmental Geology (15 manuscripts in review)**

The written and visual information contained in this document does not represent the verbal information with which it was presented. Therefore please use caution when citing or considering the information in this document. If you have any questions, please contact the presenting author, Preston Jordan, at pdjordan@lbl.gov or (510) 486-6774. Thank you.

Risk Assessment for Geological Storage of CO_2: What Can Be Learned About Worker Safety From Industrial Analogues

Preston Jordan and Sally Benson
Earth Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California 94720

What Do We Know About the Risks of Geological Storage of CO_2?



http://www.ipcc.ch/activity/csspm.pdf

" With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas."

Motivating Question

What can be quantifiably learned about the risks of geological storage of CO_2 from data on existing industrial analogues?

Data Sources

1. *United States Bureau of Labor Statistics*
2. *International Association of Oil & Gas Producers*

Worker Safety Datasets for Oil and Gas Exploration and Production

United States Bureau of Labor Statistics (BLS)	International Association of Oil & Gas Producers (OGP)
Survey of Occupational Injuries and Illnesses	Safety Performance Indicators
Census of Fatal Occupational Injuries	
Quarterly Census of Employment and Wages	

Dataset Comparison

United States Bureau of Labor Statistics (BLS)	International Association of Oil & Gas Producers (OGP)
Includes all industries	Includes only upstream industry
Includes all companies	Includes only member companies
Upstream industry **not** clearly broken out: in Whole, or by Sectors	Upstream industry clearly broken out: in Whole, and by Sectors

Safety Measures

- Incidents requiring more than first aid
  - BLS: Total Recordable Case (TRC) rate
  - OGP: Total Recordable Incident Rate (TRIR)
- Incidents causing any following day absence
  - BLS: Days Away Case (DAC) rate
  - OGP: Lost Time Injury Frequency (LTIF)
- Fatalities
  - BLS: Fatality (F) rate
  - OGP: Fatal Accident Rate (FAR)

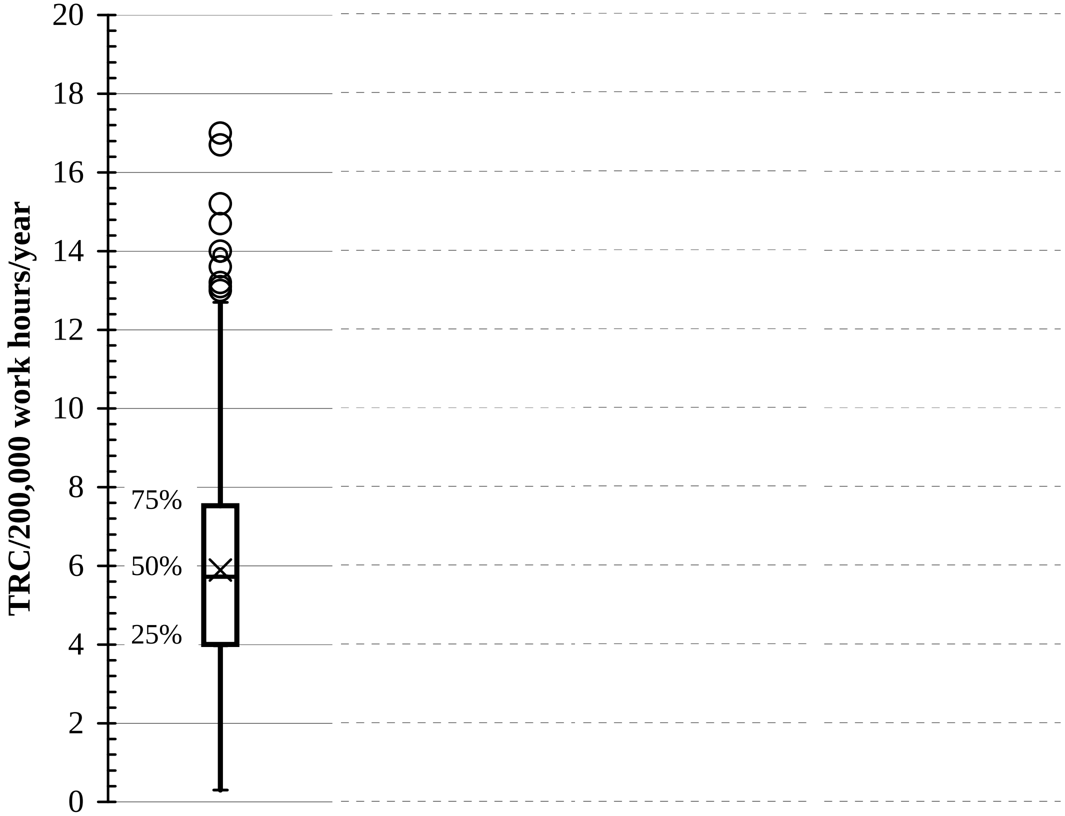
BLS Industry Classes in Oil and Gas Exploration and Production

NAICS code	Industry name
54136	Geophysical surveying and mapping services
23891	Site preparation Contractors
213111	Drilling oil and gas wells
213112	Support activities for oil and gas operations
21111	Oil and gas extraction
2371	Utility system construction
486	Pipeline transportation
4862	Pipeline transportation of natural gas

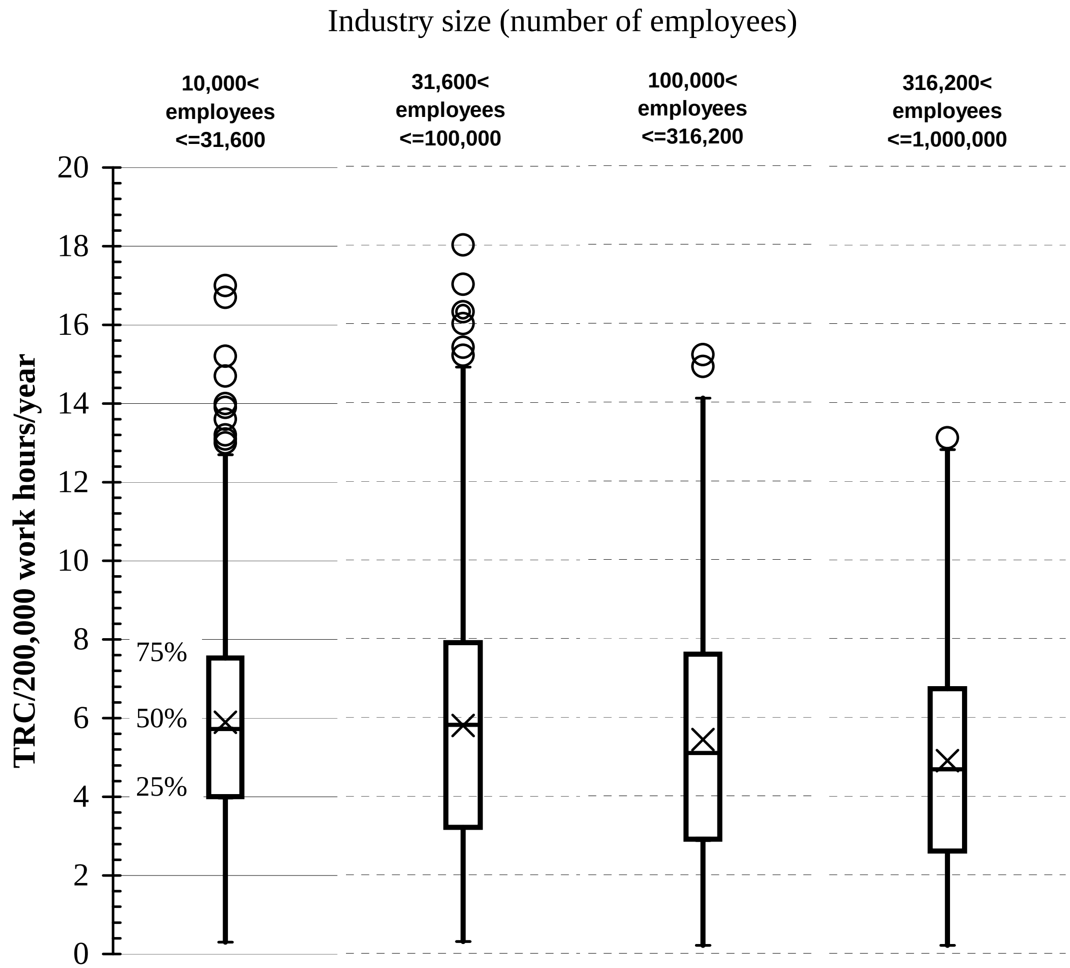
NAICS = North American Industrial Classification System

BLS Total Case (TRC) Rates (2003-2004)

BLS Total Case (TRC) Rates (2003-2004)

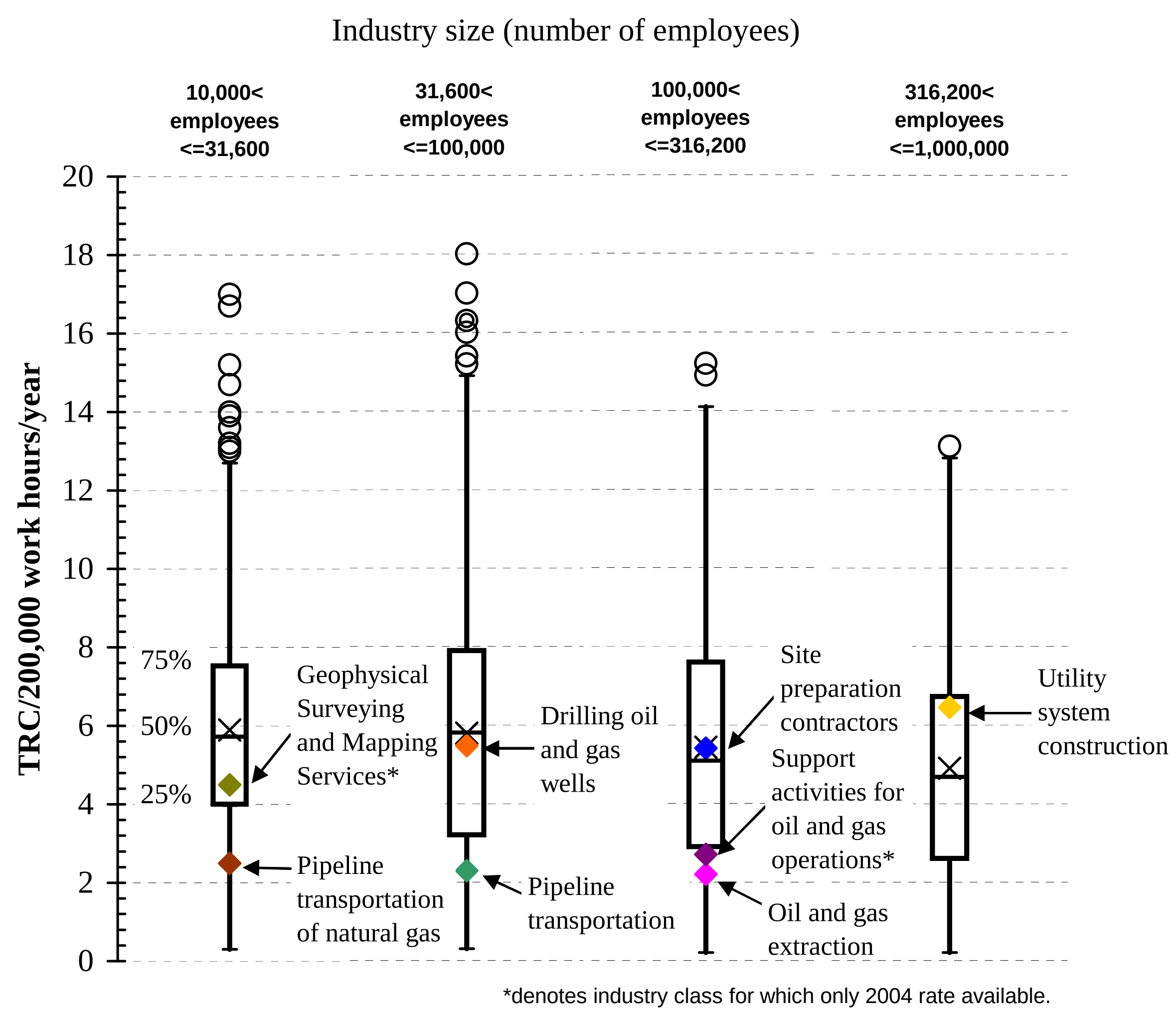


BLS Total Case (TRC) Rates (2003-2004)

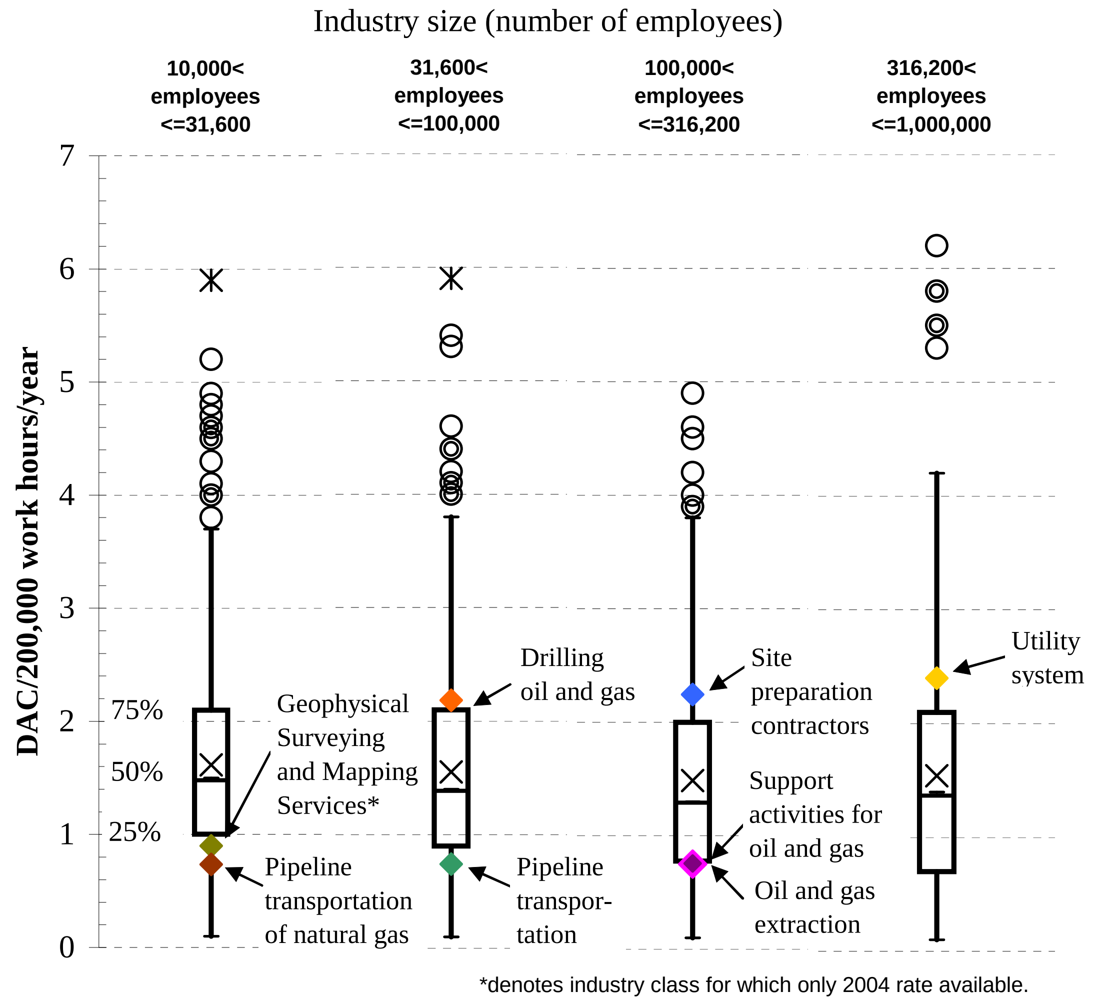


*denotes industry class for which only 2004 rate available.

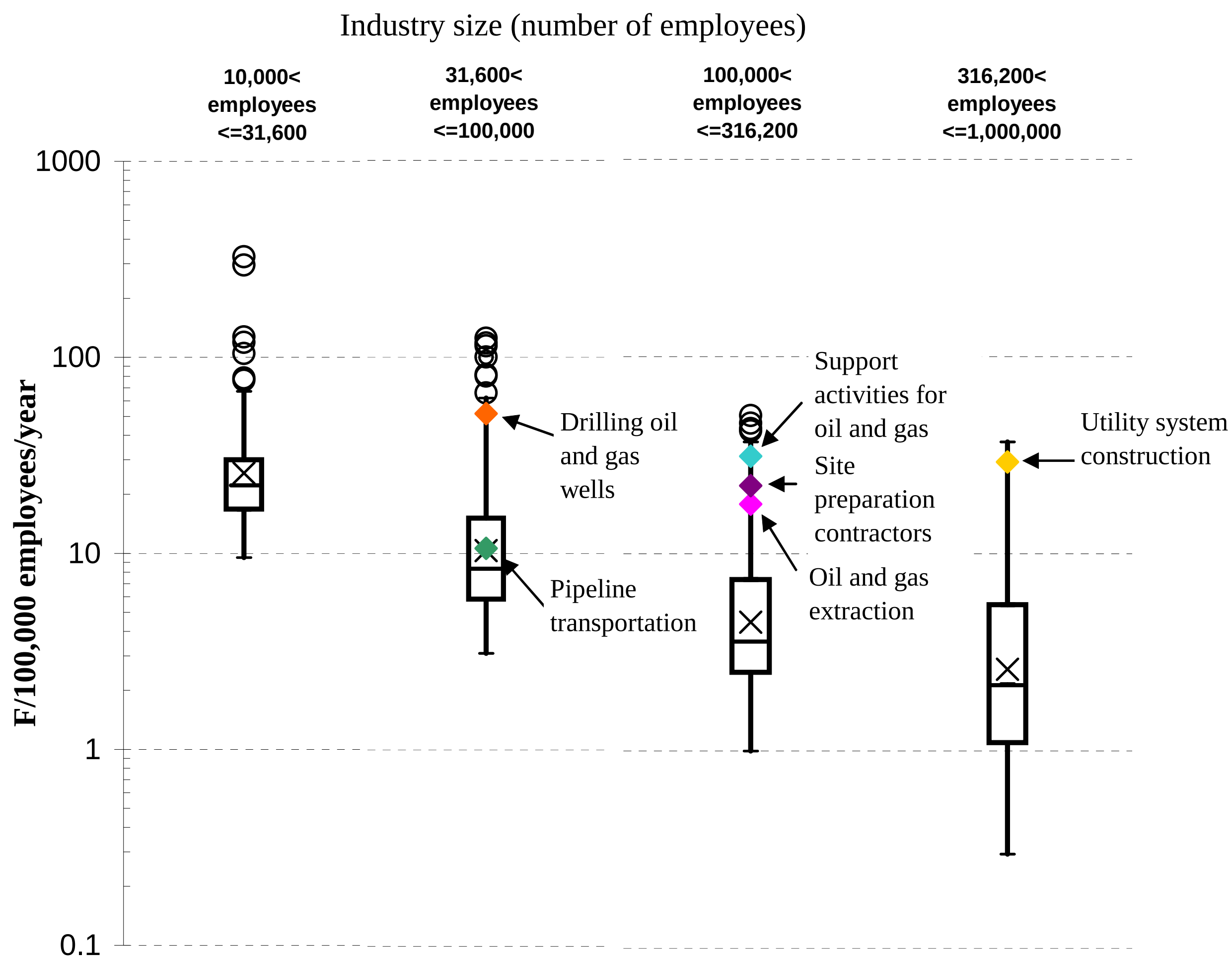
BLS Total Case (TRC) Rates (2003-2004)



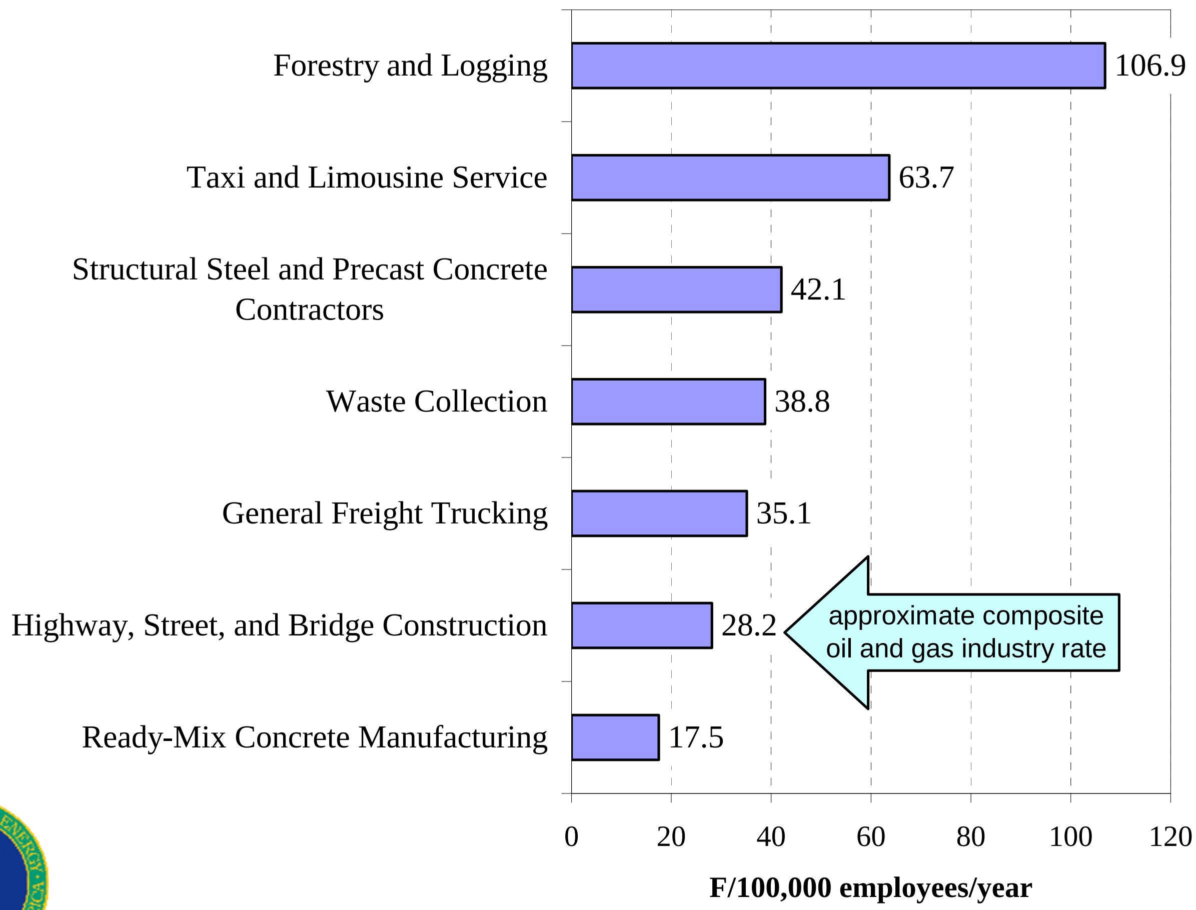
BLS Days Away Case (DAC) Rates (2003-2004)



BLS Fatality (F) Rates



Comparison of BLS Fatality (F) Rates for Selected Industries (2003-2004)



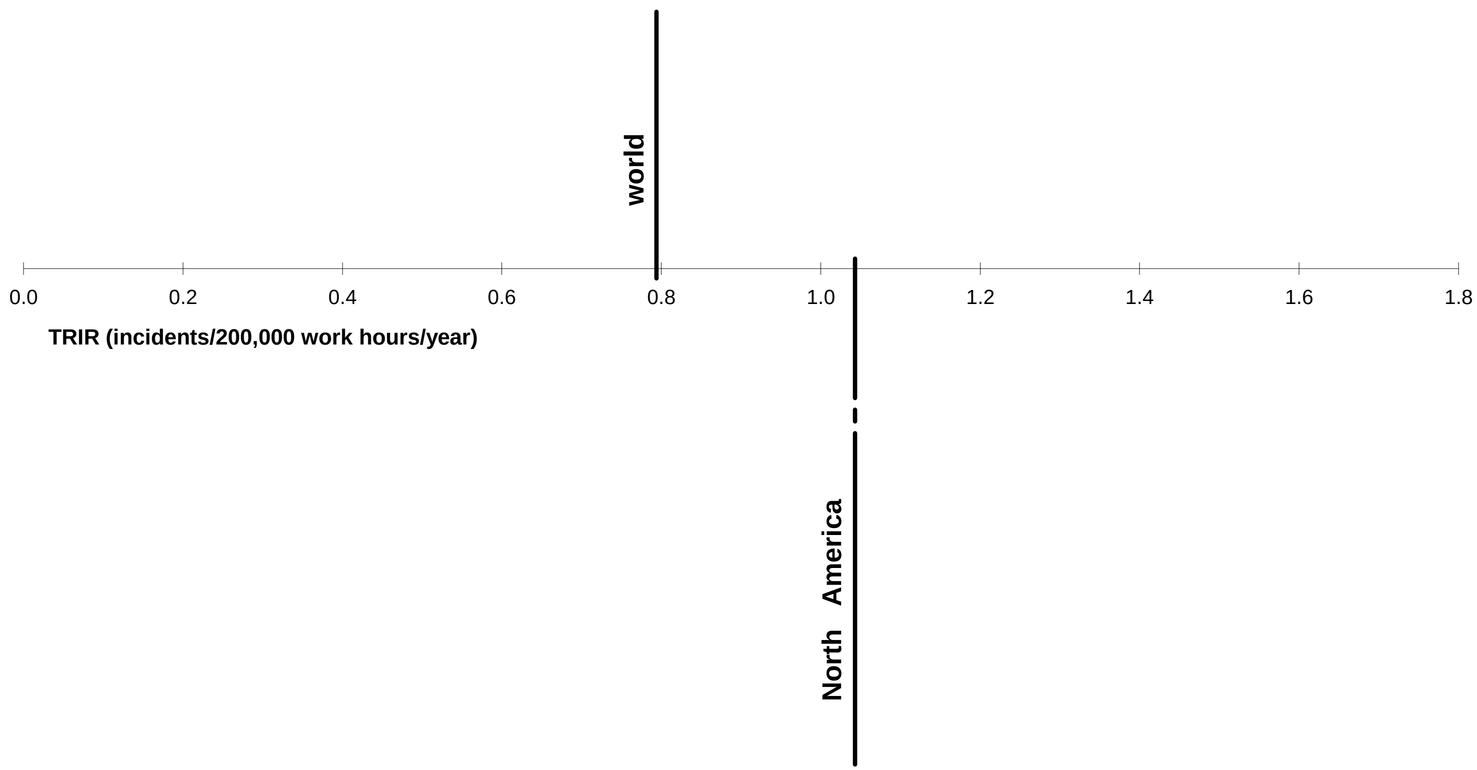
BLS E&P Industry Rates and Consequences

Compared to all industry classes, classes in upstream industry have:

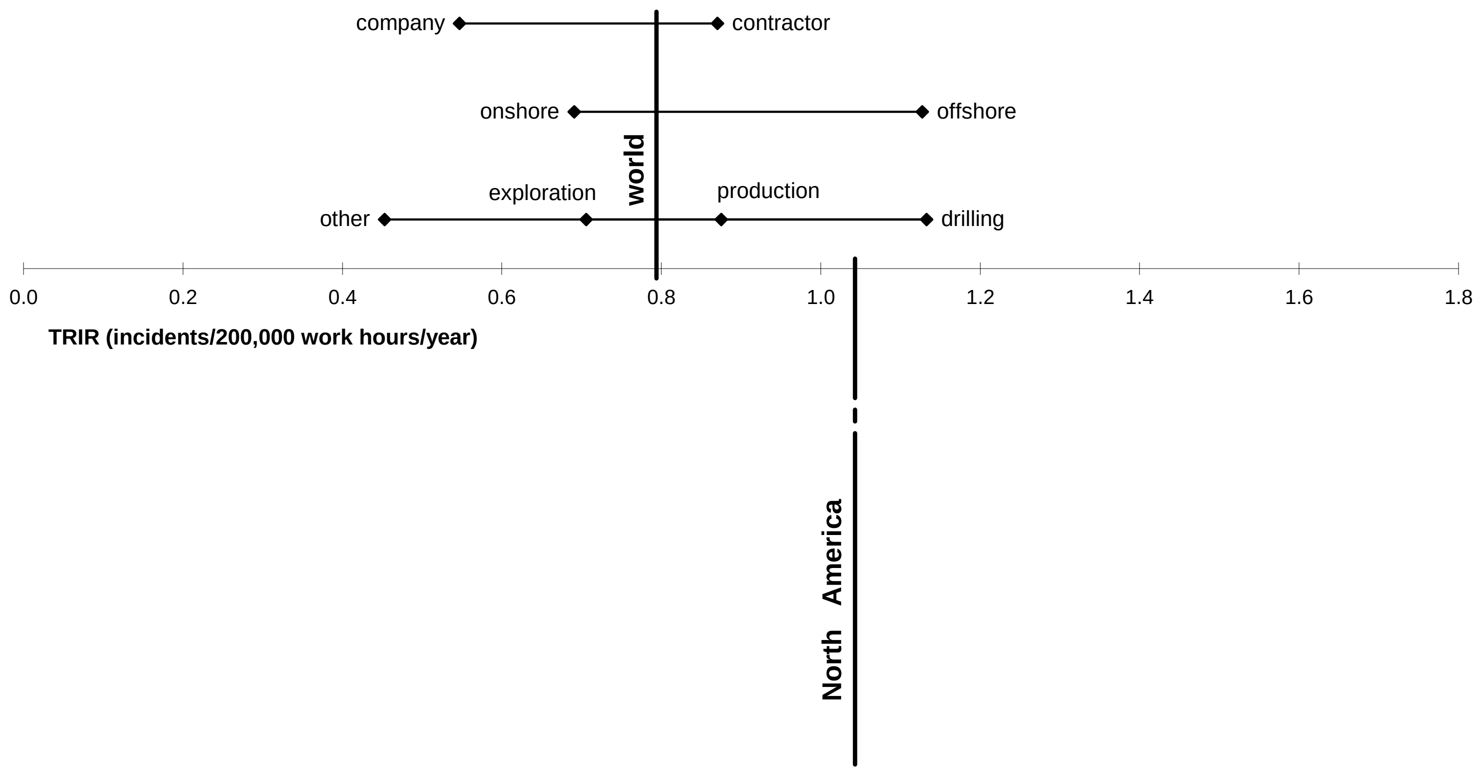
- Incident (TRC) rates typically significantly below or at median
- Lost time (DAC) rates typically near either 25th or 75th percentile
- Fatality (F) rates typically significantly above 75th percentile

Therefore incidents are rarer than in industry in general, but incident consequences are more severe.

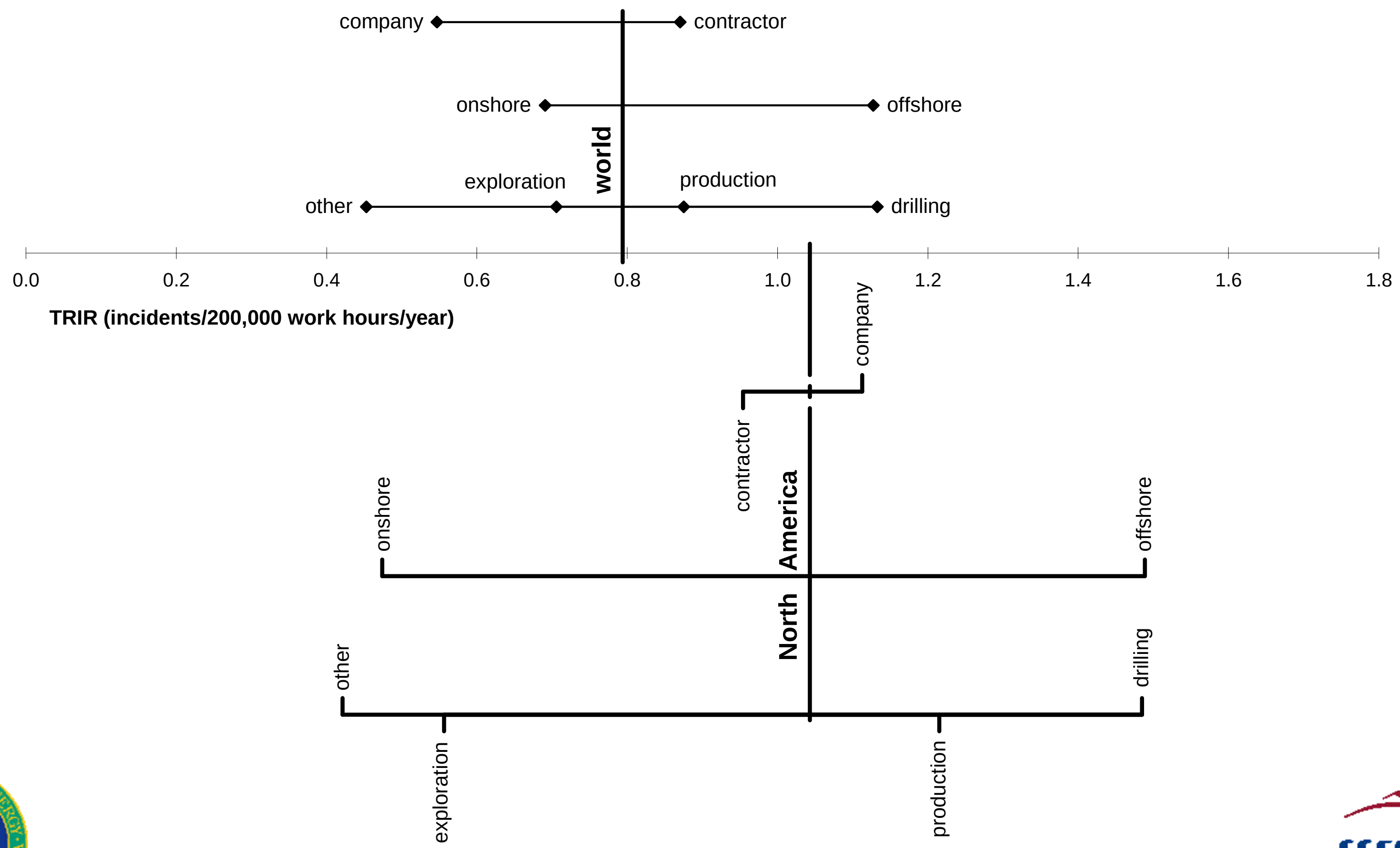
OGP Total Incident Rates (TRIR) (2003-2004)



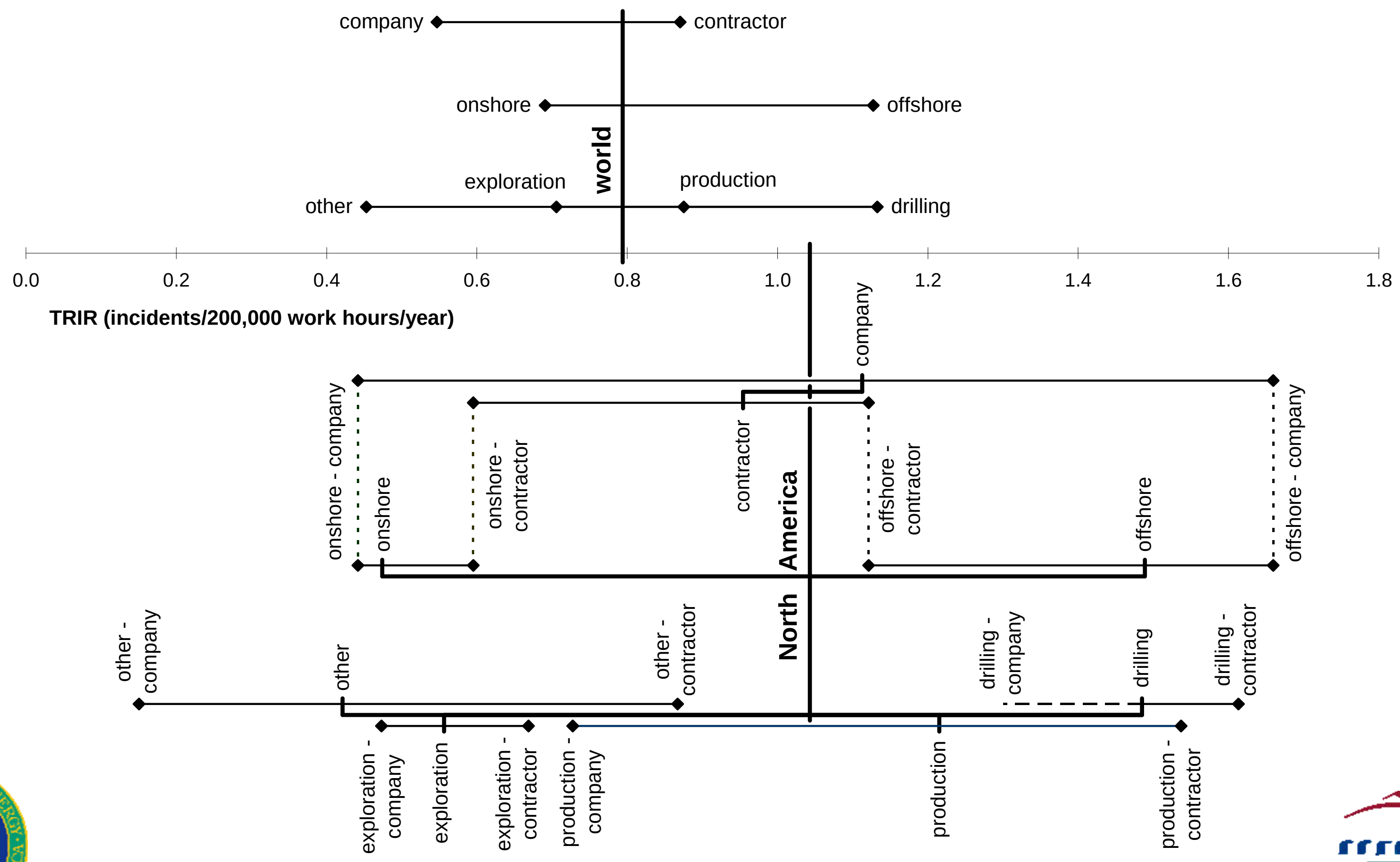
OGP Total Incident Rates (TRIR) (2003-2004)



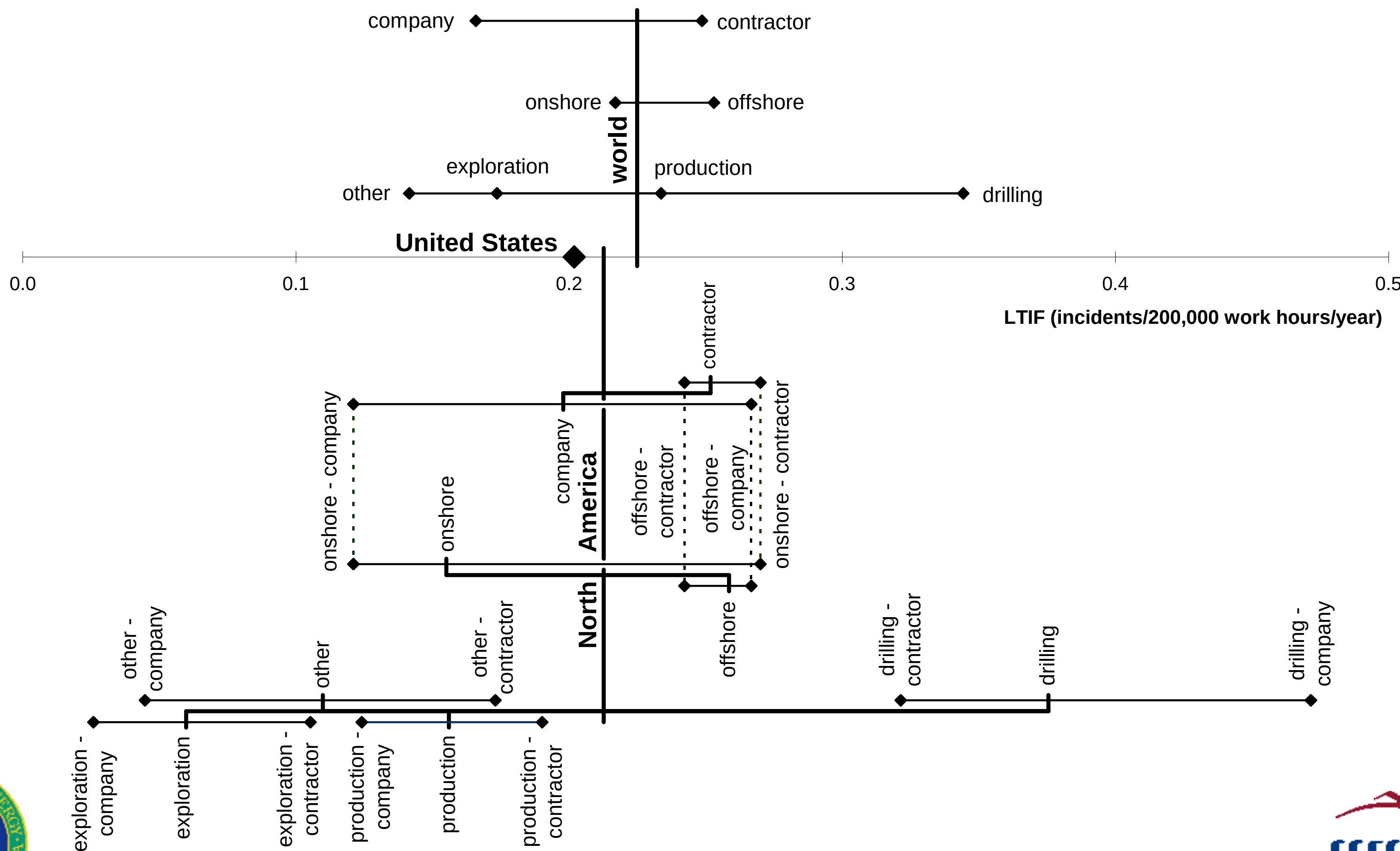
OGP Total Incident Rates (TRIR) (2003-2004)



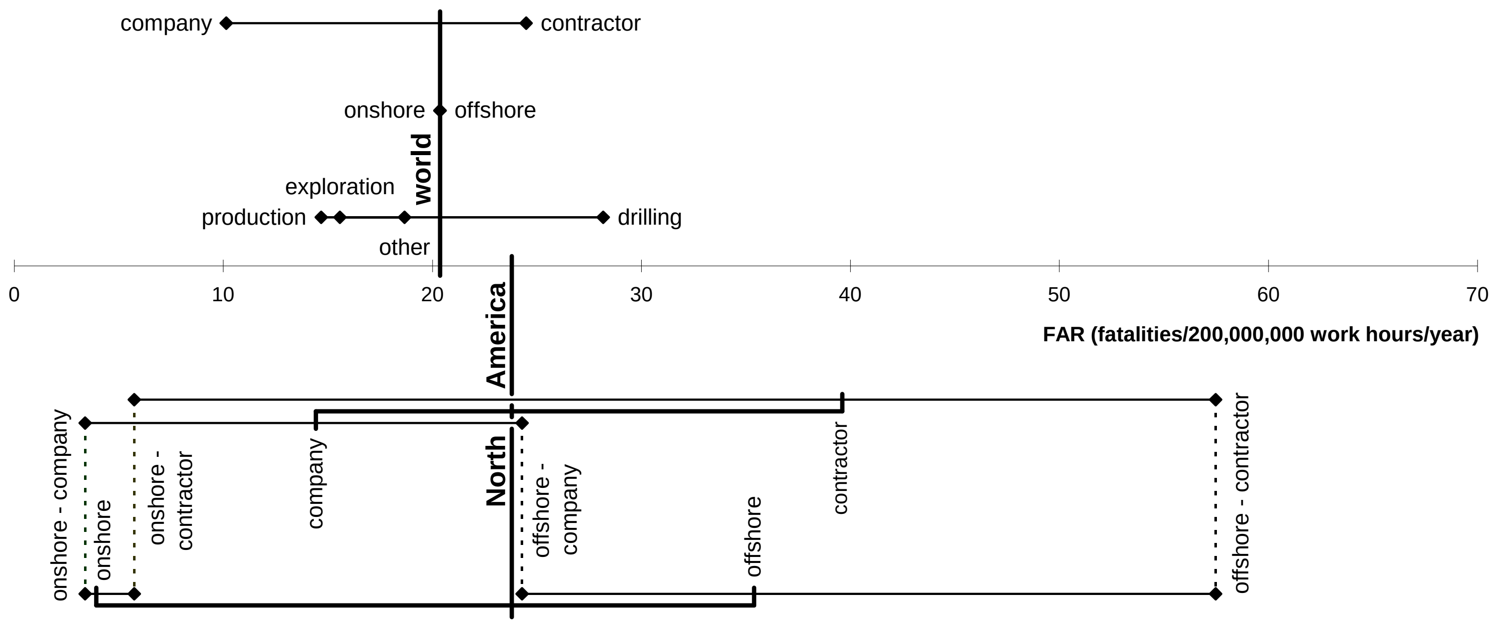
OGP Total Incident Rates (TRIR) (2003-2004)



OGP Lost Time Incident Rates (LTIF) (2003-2004)



OGP Fatality Rates (FAR) (2003-2004)



OGP North America – Onshore Versus Average

- Onshore less than 50% of the average incident rate
- Onshore less than 75% of the average lost time case rate
- Onshore about 15% the average fatality rate*

*10 employees were killed in a single air transportation accident offshore in 2004. Therefore the offshore and average fatality rates are likely not such high multiples of the onshore rate in periods not including 2004.

OGP North America – Drilling Influence on Average

- Drilling has the highest incident and lost time case rate of the functional sectors
- 13% of work hour basis for incidents, but 17% of incidents
- 19% of work hour basis for lost time cases, but 31% of lost time incidents
- Fatality rate by functional sector not reported

Implications for CO_2 Storage Worker Safety in North America

- CO_2 storage incident rate likely to be lower than upstream industry to extent it is more onshore and less drilling intensive
- CO_2 storage incident rate therefore likely to be much lower than overall industry
- Incident consequences still more severe than overall industry

Example rate differences between CO_2 Storage and North America Upstream

- If CO_2 storage is onshore with
  - 50% of the proportion of drilling work,
  - 75% of the production (injection) work,
  - and 200% of the exploration (monitoring) work of the upstream industry,
- Then for CO_2 storage workers
  - the incident rate will be 40%,
  - the lost time rate will be 60%, and
  - the fatality rate will be 15%

compared to the North American upstream averages.

Data management and risk analysis – Inventory of datasets (WG I)

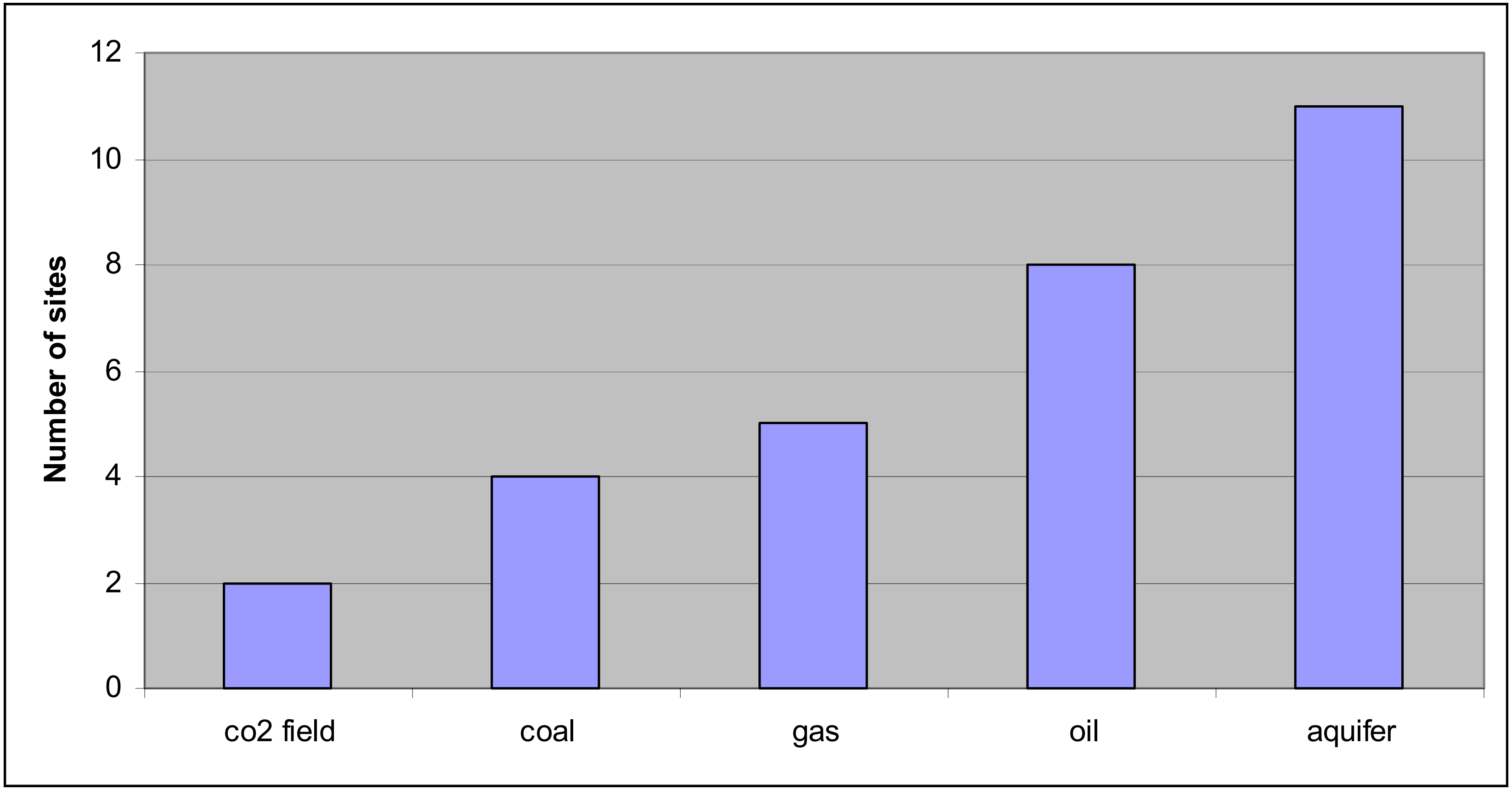
Risk Assessment Network Meeting
Berkeley, 5 and 6 Oct 2006

TNO | Knowledge for business

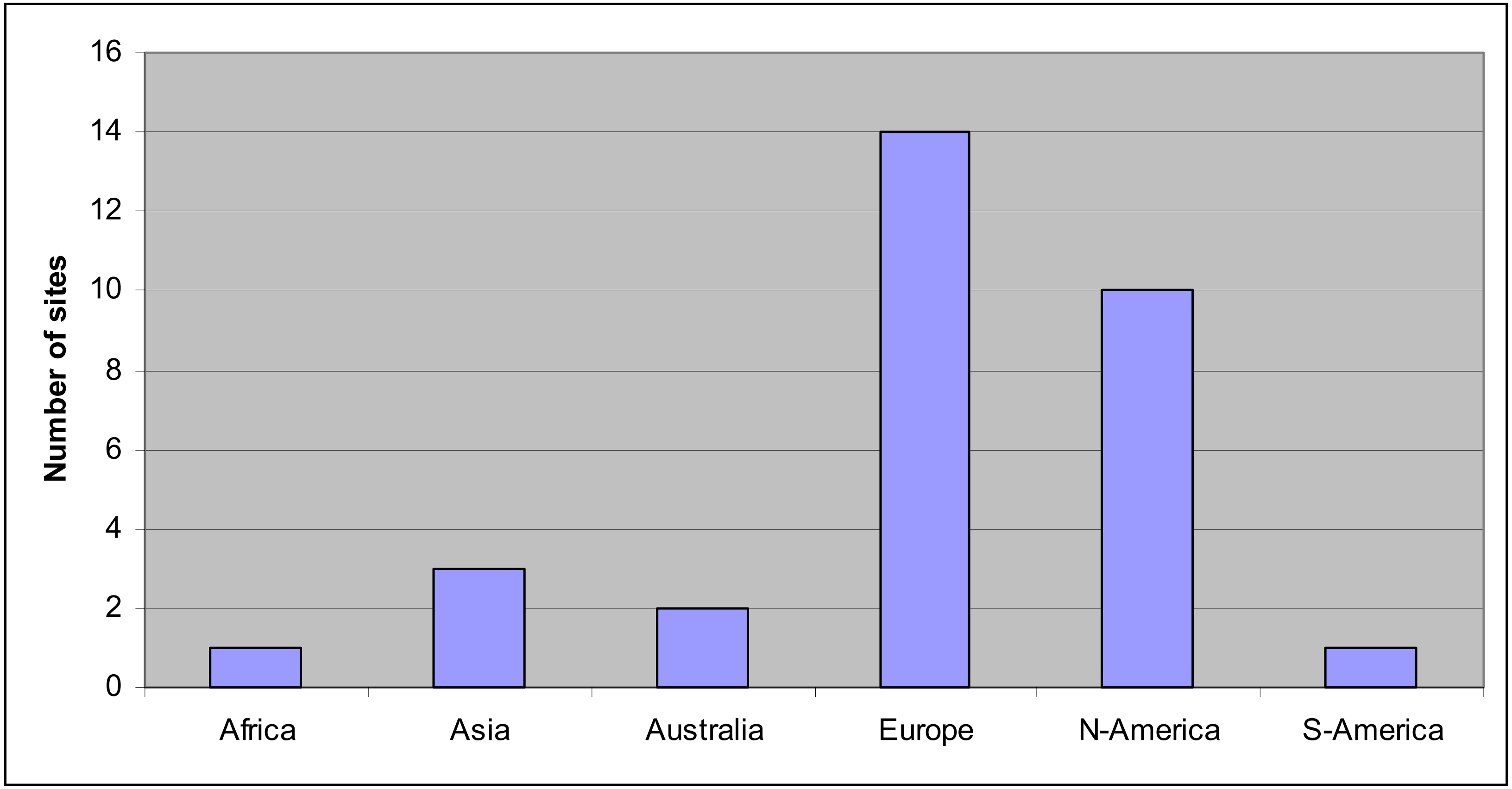
Contents

- Activity:inventory of ra datasets during and at the end of the launch meeting, proposal for contents of site database
- Status: adapted overview of datasets (xls-format) and structure of db
- Plan: update list during and after workshop

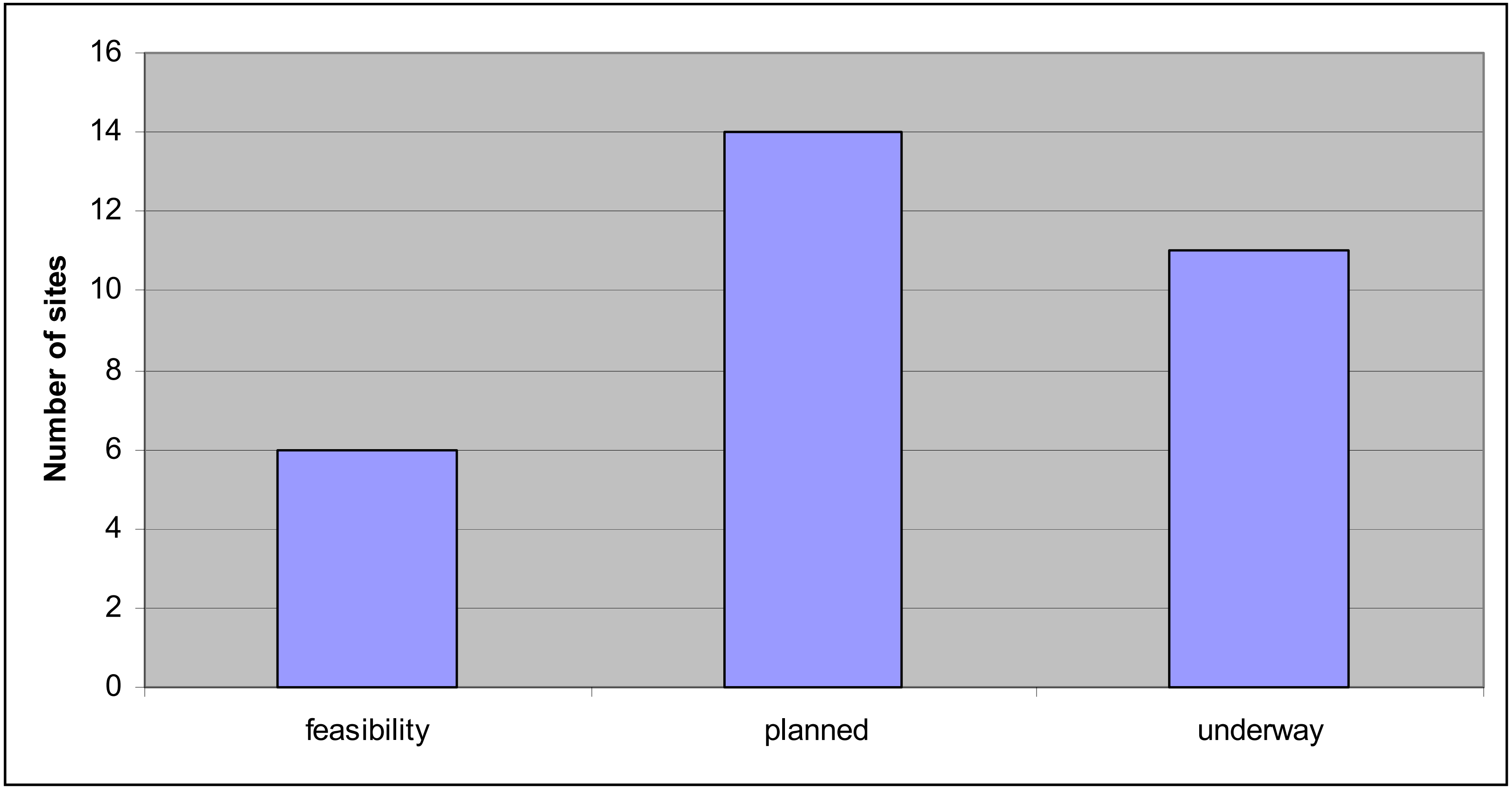
Sites and storage options incl. natural analogues (24-08-2005)



Geographical spread of sites (inventory 24-08-2006)



Status of sites in inventory (24-08-2005)



Inventory (launch meeting)

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

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

www.bgs.ac.uk

Potential impacts of leaks from onshore CO_2 storage projects on terrestrial ecosystems – a review.

Jonathan Pearce & Julie West

Kingsley Dunham Centre
Keyworth
Nottingham NG12 5GG
Tel 0115 936 3100

NATURAL ENVIRONMENT RESEARCH COUNCIL

Outline

- Rationale
- Remit
- Safety case/ Environmental Impact Assessments
- Possible impacts
- Current research
- Gaps
- Proposed research
- Role of network
- Conclusions

Rationale

- Should specific long-term performance criteria be added to those already defined through other HSE legislation?
- If performance criteria are considered appropriate:
  - Should they be generic or site-specific?
  - How relevant could generic safety criteria be?
  - What form would they take?
- If such performance criteria are not required:
  - How can operators and regulators judge site performance and what aspects of ecosystems to monitor?
  - How do operators and regulators know when to intervene, what to remediate, how to remediate?
  - How do the operators and regulators address public concerns about long-term safety of the site?

Rationale

- Early demonstration projects are operated within existing oil&gas regulatory frameworks.
- These frameworks do not necessarily require consideration of long-term, post-closure issues.
- Considerable storage will be onshore in North America and Europe.
  - Several early demonstrations are onshore.

- Modified environmental impact assessments could provide a framework for assessing long-term impacts of potential leaks (Zakkour, IEAGHG report 2006/3).

Remit

- At the Utrecht meeting (August 2005) of this network, the Environmental Impacts working group recommended:
  - A review of data requirements for environmental impact assessments
  - Compile and review existing research
  - Provide a state-of-the-art report

- IEAGHG R&D programme have funded this study.

- Our remit is the onshore environment.

EIA could include…

- A description of the site selection and characterisation.
- A description of the project including anticipated injection mass & rates, engineering design, and the project duration.
- Simulations of CO_2 behaviour over the long term, history-matched to monitoring data obtained during and after injection.
- A description of long-term monitoring options if required.
- Appropriate remediation plans.
- **Assessment of the risks for & consequences of leakage, for a range of realistic possible future site scenarios.**
- A closure plan.
- Together these components seek to demonstrate that future risks are as low as reasonably practicable (ALARP).

Possible impacts

- CO_2 leaks could:
  - Affect human and animal health.
  - Inhibit crop growth or, in high concentrations, cause root asphyxia with resulting plant death.
  - Change biological diversity and species composition.
  - Change subsurface biogeochemical processes
    - pH, microbial populations and nutrient supply.
  - Alter groundwater quality (acidification, mobilisation of heavy metals in aquifers, etc) with implications for water resources.

- There is little research addressing specifically the effects of CO_2 leaks from depth.

Gaps

- No target species are identified.
- No thresholds or limits to CO_2 exposure for any species.
- Few data on long term, low-level exposure of CO_2 on terrestrial ecosystems or on any single or potential target species.
- No data on recovery rates.
- Almost no data available on the effects of CO_2 leakage on groundwater quality.
- Little information is available concerning co-injected species, or those mobilised during migration.

Gaps – so what?

- These gaps constrain:
  - The capabilities of risk assessments to accurately identify important risks
  - The formulation of appropriate, cost-effective monitoring protocols and remediation plans.
  - The integration between considerations of potential impacts of CO_2 leaks on terrestrial ecosystems and performance assessments.

Possible capabilities needed

- Tools to monitor impacts on target organisms in all environments need to be developed.
- These tools need to be responsive to changes in ecosystems.
- They should be tailored to the different challenges to be found in terrestrial environments.
- Confidence in risk assessments will be increased if biogeochemical processes and their effects can be satisfactorily represented.

Current research

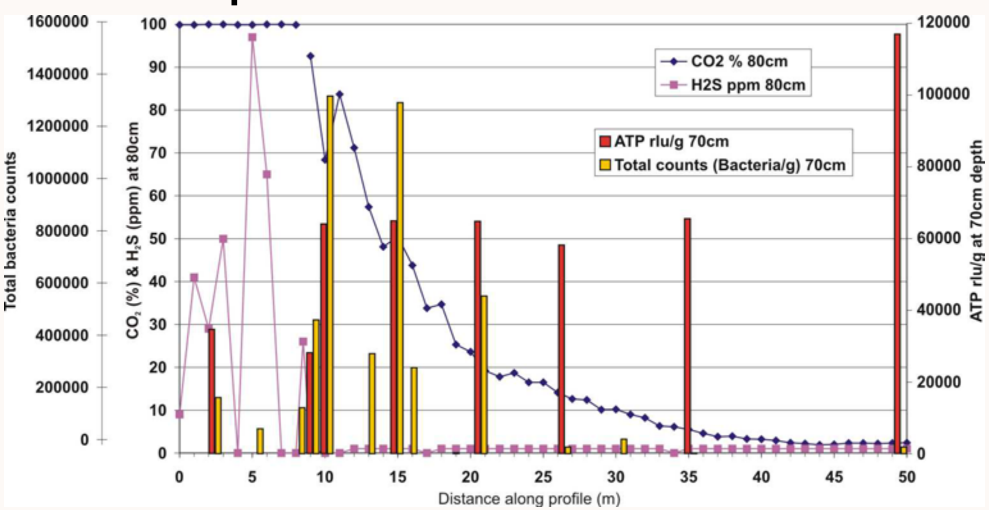
- CO_2GeoNet Joint Research Project:
  - *JRAP04: 'Ecosystem responses to CO_2 Leakage -Model Approach'*
  - Looking at both marine and terrestrial systems including freshwater
  - Budget €400k over 2 years, starting July 2005
  - 6 partners: BGS (Coordinators: UK), BGR (Germany), BRGM (France), NIVA (Norway), OGS (Italy) and University Rome "La Sapienza" (Italy).
  - The project has links with DTI (UK), Nottingham University (UK) and RITE (Japan).

Current research

- The aim is to provide holistic integrated site investigation tools to assess the long-term potential risks of geological storage on subsurface, terrestrial and marine ecosystems.
  1. Development of a system model for assessment of near-surface long-term impacts
     – Quintessa via separate UKDTI funding
  2. Feasibility studies to set up European Test Facilities.
  3. Development of a Decision Support Tool.
  4. Dissemination.

Current research - Latera

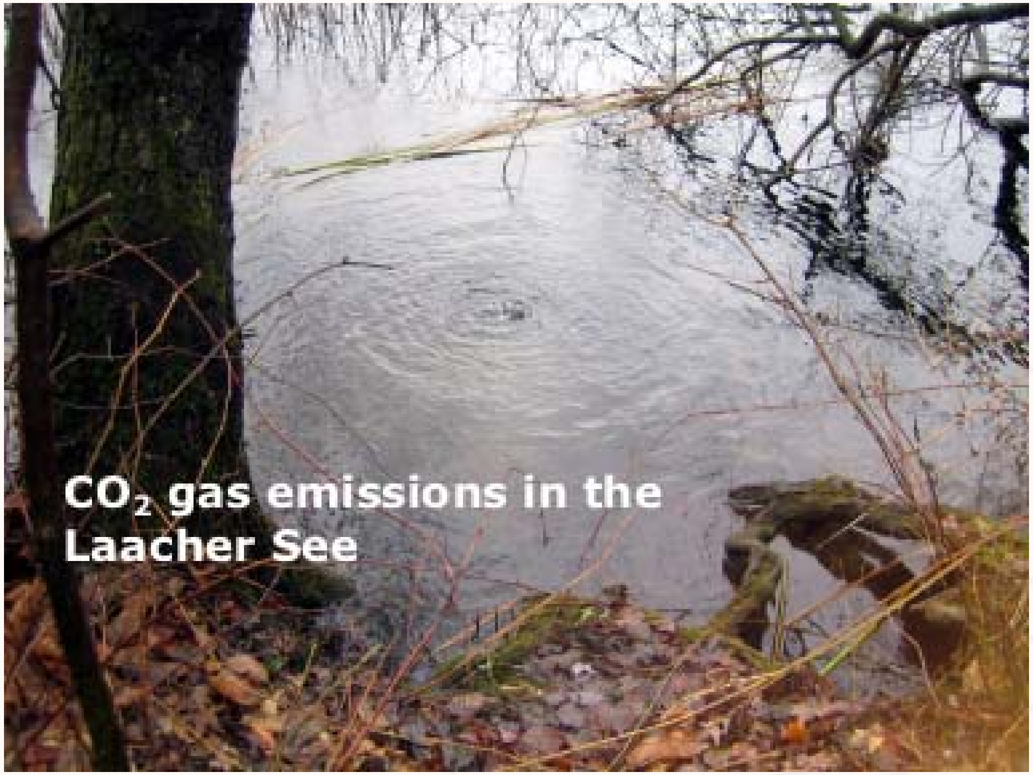
- Geothermal region with many CO_2 (& H_2S) vents
- Studying microbiological, botanical & mineralogical impacts across vents



GeoNet

Current research - Laacher See

- Protected area with strong tourist interest
- 3000 tonnes per year CO_2 released
- BGR performing microbiological and ecological studies, relating these to CO_2 flux and gas compositions.



Current research – system model

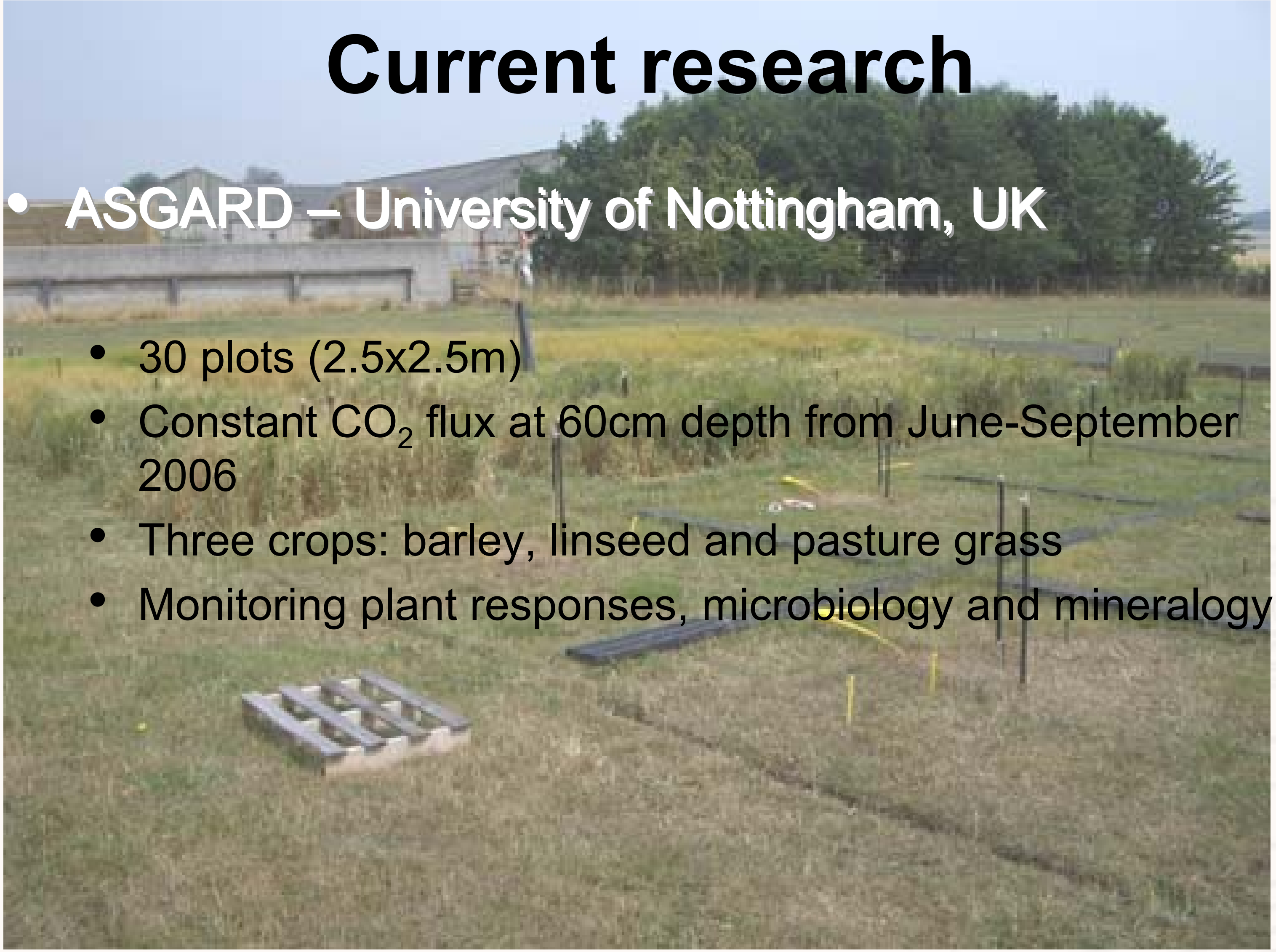
- Quintessa developing a generic system model
- The system-level model will have sub-models for the deep geosphere, near-surface regions, and representative ecosystems and will include a large number of chemical, biological and microbiological processes.
- The overall ambition for the Latera system-level model is to:
  - Reproduce realistic fluxes.
  - Provide an overall mass balance for the system.
  - Calculate the effect on groundwater acidity.
  - Calculate soil gas concentrations for different assumptions about key near-surface processes.
  - Calculate the contribution of vented CO_2 to atmospheric concentrations.
  - Calculate potential impacts to flora/fauna and humans.

Quintessa

GeoNet

Current research

- ASGARD – University of Nottingham, UK
  - 30 plots (2.5x2.5m)
  - Constant CO_2 flux at 60cm depth from June-September 2006
  - Three crops: barley, linseed and pasture grass
  - Monitoring plant responses, microbiology and mineralogy



Current research

- Prof. Tranvik, Uppsala University
  - Studying natural CO_2 supersaturation of lake waters, leading to biomineralisation and CO_2 export to atmosphere
- Biomonitoring - Tarkowski et al., GHT8.
  - Preliminary work to isolate soil microorganisms to monitor CO_2 leakage

A proposed research plan

1. Scenario definition:
   - Define relevant scenarios to reflect the storage context (geographical location, local environment, land use, etc)
2. Characterisation:
   - Define surface and subsurface ecosystems in terms of flora and fauna.
   - Identify indicator species (most susceptible, those with biggest change).
3. Impacts:
   - Identify impacts of CO_2 on indicator species & total ecosystem.
   - Define appropriate thresholds and safety criteria.
   - Identify recovery rates.
   - Scope impacts on groundwaters via modelling and experiments.
4. Monitoring:
   - Develop floral and faunal monitoring techniques
5. Integration:
   - Improve system models by integrating key processes and indicators in an iterative manner.

Role of network

- Is there current or planned research we have not included…?
- Any comments on the draft report (especially environmental impacts working group)
  - Send to John Gale by 13th October
- The network could consider:
  - Ways to address the research gaps identified and how to coordinate research internationally
  - How to integrate findings from this research with performance assessment

Conclusions

- Some key gaps in our understanding of potential impacts of CO_2 leaks have been identified.
- Current research has been identified that begins to address these gaps.
- A broad research plan is proposed
  - This needs to be duplicated for different ecosystem types and regulatory environments
- Data should be integrated with performance assessments
- Role of this network:
  - Comment on report
  - Identify opportunities
  - Provide integration and comparison

Acknowledgements

- IEAGHG - funding
- EPRI – access to Susan Rice report
- Christian Bernstone, Vattenfall and CO_2Store partners – access to Schweinrich report
- Sara Eriksson, Vattenfall – access to SEA report

Role of Risk Assessment in Regulation of Geological CO_2 Storage Projects

Mike Stenhouse

Monitor Scientific LLC, Denver, Colorado

IEA GHG Risk Assessment Network Meeting

Lawrence Berkeley National Laboratory

October 5, 2006

MONITOR SCIENTIFIC

Acknowledgements

- IEA GHG R&D Project Manager
  - John Gale
- Project Team
  - Wei Zhou, Malcolm Wilson, Matt Kozak
- Participants (in questionnaire)
  - See later slide

Monitor Scientific

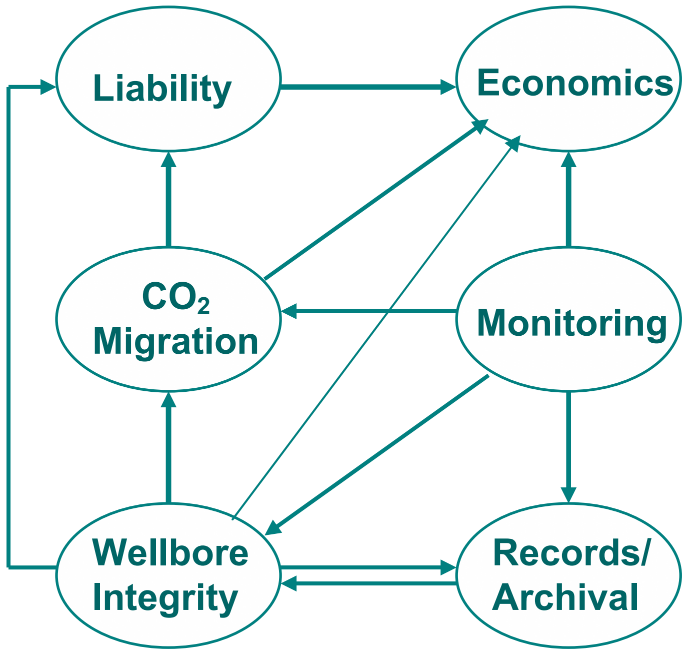
Outline of Presentation

- Introduction / Background
- Objective of IEA GHG Project
- Strategy
  - Briefing Document
  - Questionnaire
- Briefing Document
- Responses (questionnaire)
- Summary / Recommendations

Monitor Scientific

Background

- Regulatory issues (previous IEA GHG R&D project)
- Key issues (interlinked):
  - Liability
  - Economics
  - CO_2 migration away from reservoirs (subsurface)
  - Monitoring
  - Wellbore integrity
  - Record archival



Discuss in the context of regulatory drivers…..

Two Key Regulatory Drivers

- **Greenhouse gas (GHG) mitigation**
  - **CO_2 remains underground - requires *effective reservoir storage***
  - **Need to be able to account for any CO_2 released back to the atmosphere**
- **Health, safety and environmental (HSE) impacts**
  - **Need to be assured that CO_2 is not released back to the surface / near-surface environment causing harm - also requires *effective reservoir storage***

Timescales of two drivers are potentially different

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Regulatory Issues: Main Conclusions

- No regulatory hurdles specific to geologic CO_2 storage that have not been addressed in other types of projects, with the exception of CO_2 migration and GHG mitigation / accreditation
  - *Only the relevant timeframes are different*
- *Adaptation of existing scheme*, ideally one that is widely-used, appears preferable to developing entirely new scheme
- *Flexible* regulatory framework is preferable in order to be able to adapt to, and take advantage of, the benefits of increased knowledge from collective understanding and experience of CCS projects

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Perceived Role of Risk Assessment

Stage of Project Development	RA Role	Input Data
Preliminary site characterization - site selection	Screening	Generic data
Detailed characterization	Guidance	SC data primarily; generic data to fill gaps
Permitting phase	Major	SC data primarily
Injection phase	Testing predictions	SC and monitoring data
Post-injection phase	Major?	SC and monitoring data

RA = risk assessment; SC = site characterization

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Current Study - Objectives

- To establish whether there are existing (regulatory) provisions for authorizing CO_2 storage projects and whether these are sufficient / adequate for future implementation of large-scale geologic CO_2 storage projects
  - Are there any '**disconnects**' between regulator and implementer in terms of timeline?
- To identify key gaps associated with RA and its role in regulatory oversight
  - ===> RA needs

Strategy for Conducting Project

- Initial e-mail contact with potential participants, introducing project
  - Advance warning of questionnaire (~ 2 months)
- Preparation of Briefing Document
- Preparation of Questionnaire
  - Slightly different for regulator and implementer
- Distribution of questionnaire
  - Follow-up (e-mail, telephone) as necessary
- Collate / interpret responses
  - Provide conclusions / recommendations

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Briefing Document - Topics

- Timescales
- CO_2 leakage flux / rate
- RA methodologies
- RA modelling approaches
- Role of monitoring in RA
- Comprehensiveness of RA
- Risk communication to stakeholders
- Need for technical standard / protocol
- Potential gaps / RA needs

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Briefing Document - Sample Extracts [1]

- Timeframes for RA analysis
  - Two timeframes are relevant to CCS depending on the needs of the regulator, whether for *GHG reduction inventory control*, or for HS&E impacts, with an overall timeframe for RA of several thousand years
  - While a value for each timeframe would help to define the upper limit for RA predictions, such values do not need not be specified explicitly, as long as the RA addresses all relevant risks.

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Briefing Document - Sample Extracts [2]

- **Leakage / Flux Rates of CO_2**
  - **Leakage flux/rate of CO_2 and cumulative CO_2 leakage are likely outputs from RA predictions and, as such, could be part of the regulatory requirement for CCS projects. However, any regulatory requirement for such leakage rates/fluxes must be based on a good scientific understanding, *ultimately linked to specific hazards*.**

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Briefing Document - Sample Extracts [3]

- **RA and Natural Analogues**
  - **Natural Analogues (NA) serve a number of purposes linked to RA, the most quantitative purpose being the *validation of predictive modeling results*. In the absence of quantitative information, NA examples can be used to *support risk communication with stakeholders*, by identifying geological environments that are suitable for long-term CO_2 storage, and, on the other hand, by explaining why bad sites leak.**
- **Stakeholder / Public Acceptance**
  - **Stakeholder acceptance, in particular public acceptance, is considered key to developing CCS projects in a timely manner, and RA is a critical component of public acceptance. All indications suggest, however, that science-based information is not sufficient to satisfy public concerns, and other avenues of communication, *e.g.*, natural and industrial analogues, are needed to support the science-based approach, particularly when *RA techniques are not easy to communicate*.**

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Briefing Document - Sample Extracts [4]

- Role of RA in geological CO_2 storage
  - Risk/Safety Assessment, as the quantitative method of demonstrating safety, is likely to be a key part of any authorisation for CCS projects. While it should be a major component in any submission for a permit / licence application, RA is unlikely to be the only means of demonstrating or assuring safety.

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Questionnaire Feedback - Summary

- Regulators from 10 countries agreed to participate
  - Australia, Canada, France, Germany, Japan, The Netherlands, New Zealand, Norway, U.K., U.S.A.
- Responses so far from 8 of those countries - going for 100%!
- Supplemented with implementers who are involved in major CO_2 storage projects
- ***Substantial comments*** provided supporting Yes/No answers

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Questionnaire Participants

REGULATOR	IMPLEMENTER
Australian Greenhouse Office	CO2CRC, Australia
Environment Canada	Natural Resources, Canada
BC Ministry of Energy and Mines (Canada)	BRGM, France
Alberta Utilities and Energy Board (Canada)	GFZ, Germany
Ministry of Industry, France	RITE, Japan
Federal Ministry of Economics and Technology, Germany	TNO, Netherlands
Safety Department, METI, Japan	Statoil, Norway
Minjstry of Housing, Spatial Planning and the Environment, Netherlands	BP, U.K.
New Zealand Climate Change Office	CO_2 Capture Project (CCP)
Norwegian Petroleum Directorate	Chevron Texaco
DEFRA, SEPA, U.K.	Southwestern DOE Partnership (USA)
U.S. EPA (Federal and State representatives)	

- ***Without responses and feedback from the questionnaire, the project could not have been completed***

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Regulator Feedback

- Regulators were in favour of:
  - Need for specific regulatory framework for CCS projects
    - Likely to exist 2008 at earliest
  - RA part of authorization process
  - Flexibility in methodology and modelling approach
  - Link between RA results and monitoring
    - Confirmation of predictions
    - As means of ensuring safety (HSE impacts)

Risk Assessment / Knowledge Perceived Gaps - Regulator

- Nature of long-term risks
  - Timeframe
- Storage capacity verification
  - Ability of monitoring techniques to quantify extent of any leakage / migration
- Wellbore / caprock integrity
- Effects of fluid movement
  - Regional vs. localized displacement
- Specific environmental impacts
  - Groundwater, ecosystems

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Implementer Feedback [1]

- Implementers in favour of:
  - Regulatory framework specific to CCS projects, which addresses timeframes and CO_2 leakage rates / fluxes
  - Flexibility in modelling approaches
  - Link between monitoring and RA results - for confirmation
  - Some form of RA protocol / standard

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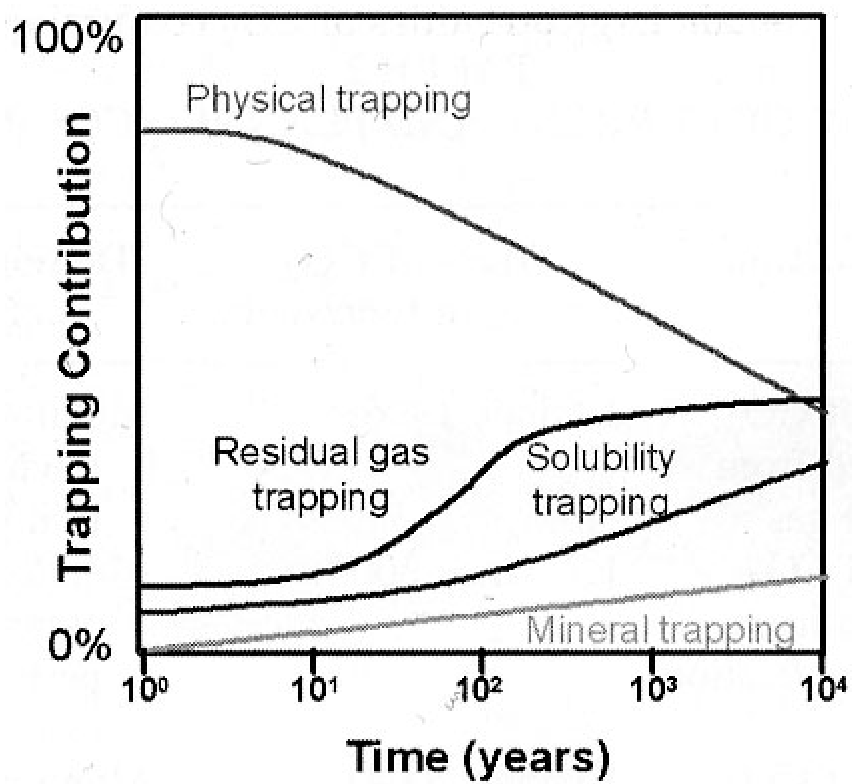
Risk Assessment / Knowledge Gaps - Implementer

- Experience with different types of storage site
- Quantitative information from natural analogues
- Fundamental data
  - PVT behaviour of CO_2+ impurities
  - Thermodynamic, kinetic data
  - Coupling between geochemical and geomechanical processes
- Wellbore seal longevity
- Benchmarking of RA modelling approaches

Geological CO_2 Storage - Trapping Mechanisms



Sally Benson [2005]

- Physical trapping *cf.* hydrocarbons
- Residual trapping (small pores)
- Solubility trapping (CO_2 dissolution)
- Mineral trapping (CO_2 reactions with rock-water system)

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Authorization of CO_2 Storage Projects - Summary

- In the **short-term**, CO_2 storage projects will continue to be approved on a **case-by-case basis**
- Research work currently being carried out on CCS-related projects (Sleipner, Weyburn, Frio etc.), including RA results/predictions, will help guide regulators
- Monitoring during injection and post-injection phases will play a major role in regulatory acceptance of long-term safety
  - Link between **monitoring and confirmation of RA predictions** important
- Some form of **technical standard / protocol** for addressing long-term safety in CCS projects considered important by both regulators and implementers

MONITOR SCIENTIFIC

Existing Regulations / Relevant Laws

Country	Existing Relevant Laws	Comment
Australia	Combination of petroleum, environmental and safety legislation	Different legislations apply to different aspects of CO_2 storage
Canada	Environmental assessment	
Saskatchewan	CO_2 EOR, Acid-Gas injection	Specific framework 2008
Alberta	CO_2 EOR, Acid-Gas injection	No regulations for CCS
B.C.	Environmental assessment	Legislation 2008
France	Mining Act, Water Law (pilot projects)	Laws apply to pure CO_2
Germany	Mining Law	CCS legislation date open
Japan	None (except R&D projects)	Legislation 2011-2016
Netherlands	Mining Act, EIA	Long-term aspect not covered
Norway	Petroleum Law, Environmental Protection Law	Mostly covered by petroleum legislation
U.K.	Petroleum Act, Pollution-Control Act (petroleum)	CCS legislation date open
U.S.A.	Underground Injection Control (UIC)	Assessing implications of adapting UIC --------????

RA Gaps / Needs?

- **Technical standard / protocol** - basic *framework* (flexible)
  - Build on existing documents, e.g. Best Practice Manual, SACS Project, national standards for risk analysis
  - Appropriate output for IEA RA Network?
- **Benchmarking studies** to enhance confidence in different modelling approaches
  - Need to be carefully planned
- **Monitoring**: provide quantitative resolution capability to match needs:
  - Confirmation of RA predictions
  - Quantification of migration of CO_2 for GHG inventory purposes
- **Coupled modelling**
  - geochemical-geomechanical-fluid transport

Monitor Scientific

Risk Assessment Framework for CO_2 Geological Storage

Anna Korre
Imperial College London

CO2 GeoNet Project

Integrating Risk Assessment Tools in a Consistent Framework for CO2 Geological Storage Performance Assessment

Co-ordinator: Imperial College London (IMPERIAL)

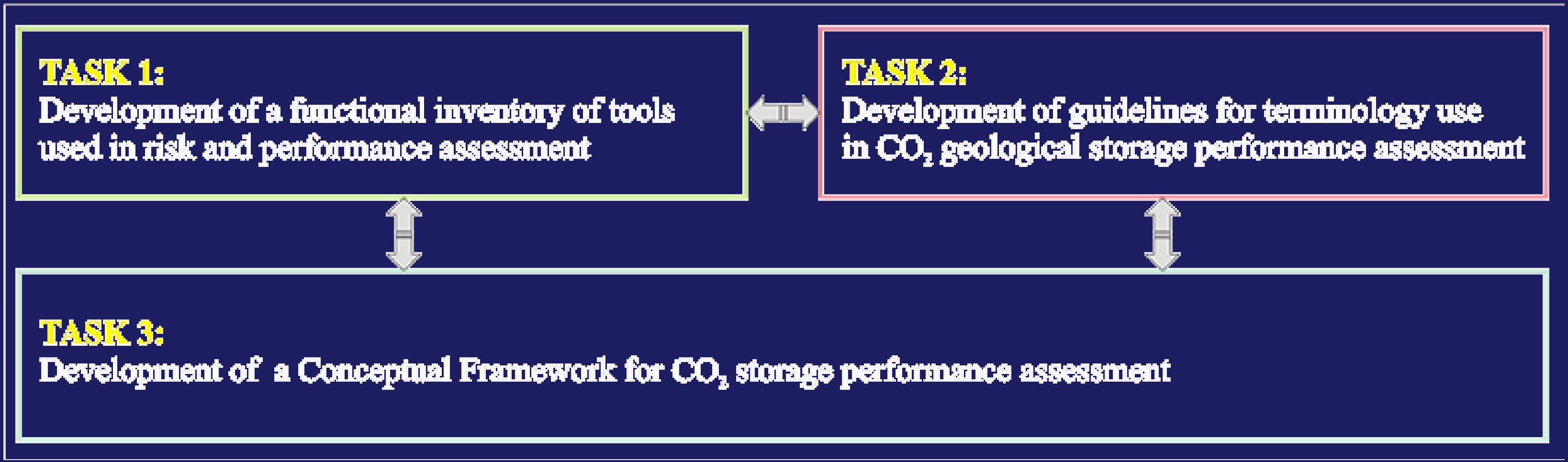
Partners: Netherlands Organisation for Applied Scientific Research (TNO)

Bureau de Recherches Geologiques et Minieres (BRGM)

Institut Français du Pétrole (IFP)

Methodology

The work programme consists of three interrelated tasks.



Task 1 Risk and performance assessment inventory contents

1. **SCENARIO DEVELOPMENT**
   The scenarios approach
   Assessment basis (FEPs databases)
   Scenarios construction methodologies

2. **MODEL DEVELOPMENT**
   Conceptual models development
   Process level modelling
   Modelling tools (software codes)
   System level models

3. **PROBABILISTIC ANALYSIS**
   Treatment of uncertainties
   Probabilistic performance assessment
   Sensitivity analysis
   Expert judgment elicitation

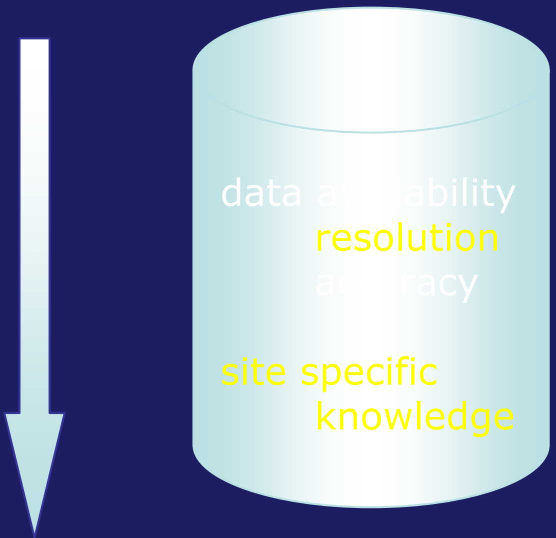
Task 3 Development of a consistent conceptual framework for CO_2 storage performance assessment

The aims of this task are to:

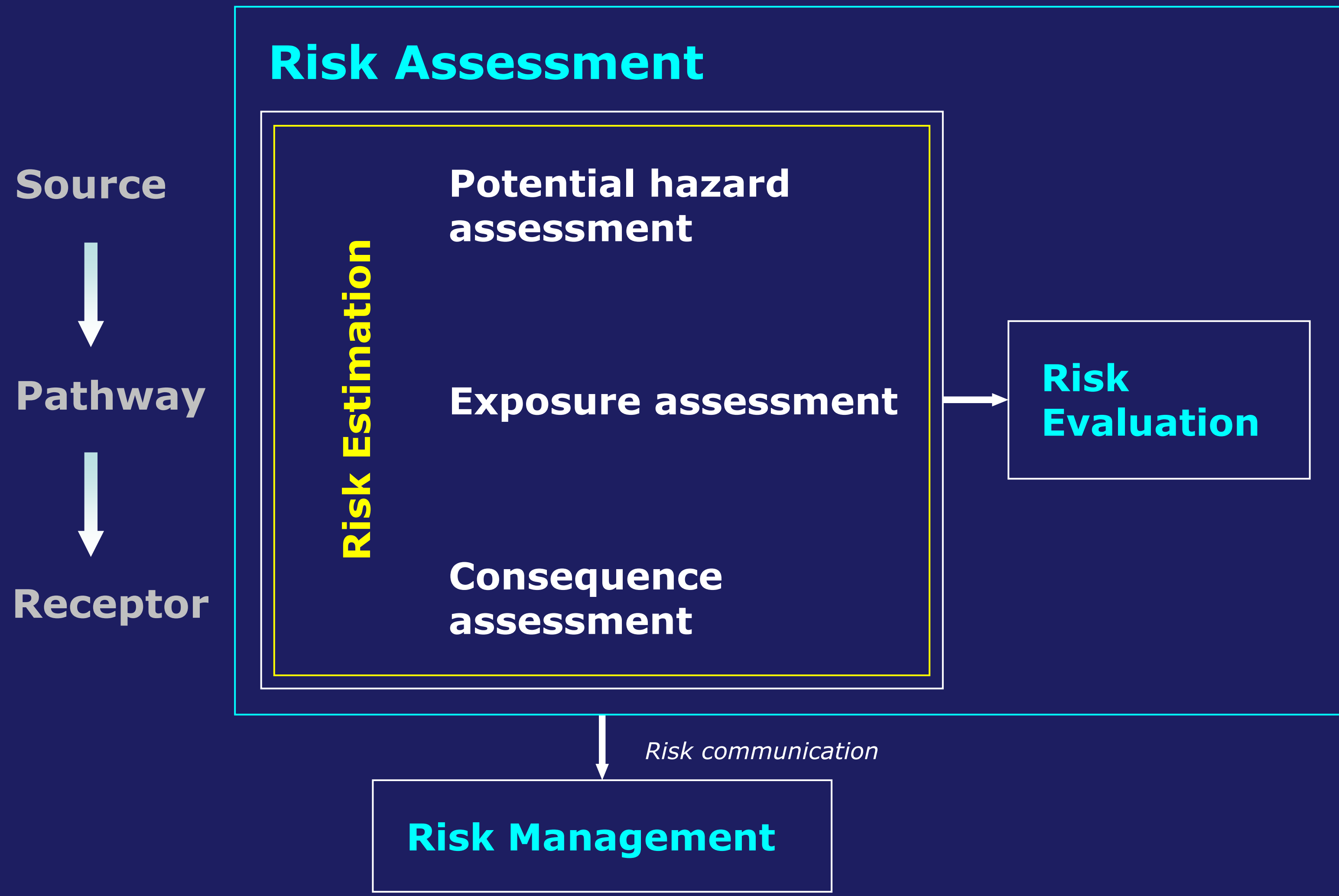
- identify the strengths/weaknesses of existing/under development methodologies for CO_2 storage performance and risk assessment;
- determine the complimentary functionality or niche for each;
- identify gaps where improvements can be implemented; and
- harmonise the use of tools and methods under a unified conceptual framework.

Relevance of risk assessment to the lifetime stages of a CO_2 storage project

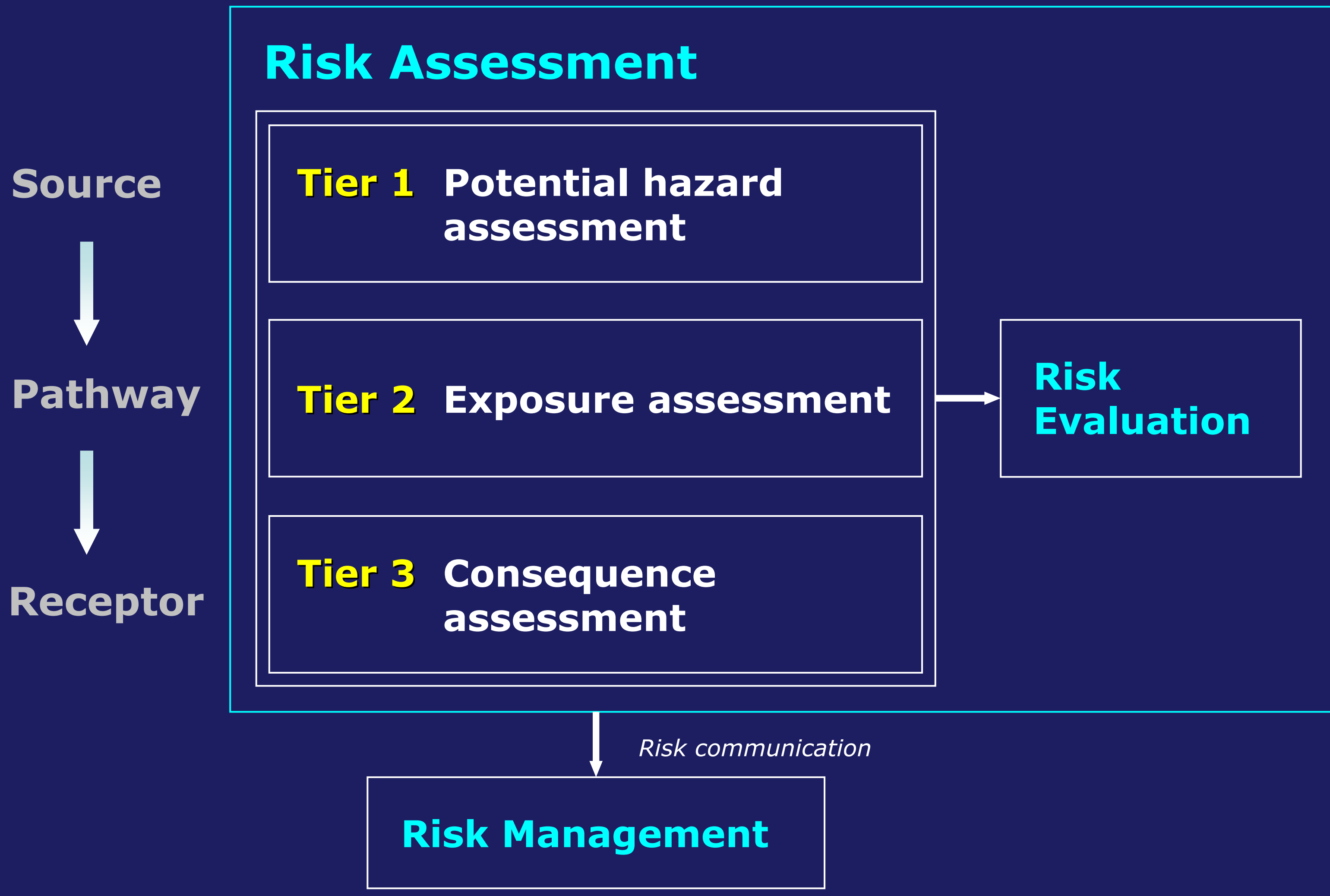
- **A.** **Site Selection**
- **B.** **Storage Licensing**
- **C.** **Storage Monitoring and Verification**
- **D.** **Potential Leakage Mitigation Plan**



Conceptual CO_2 storage risk assessment framework



Conceptual CO_2 storage risk assessment framework



Conceptual CO_2 storage risk assessment framework

A. **Site Selection**
B. Storage Licensing
C. Storage Monitoring and Verification
D. Potential Leakage Mitigation Plan

Tier 1

Potential Hazard Assessment

Scenario analysis tools
FEPs analysis tools
Conceptual model development tools

Data requirements:
modest, use of generic data

→

Risk evaluation

Risk likelihood
(likely, …, unlikely) and
Significance
(negligible, marginal, significant)

Conceptual CO_2 storage risk assessment framework

A. Site Selection
B. Storage Licensing
C. Storage Monitoring and Verification
D. Potential Leakage Mitigation Plan

Tier 1

Potential Hazard Assessment

Scenario analysis tools
FEPs analysis tools
Conceptual model development tools
Treatment of uncertainties
System level modelling

Data requirements:
generic data
coarse site specific data
(aggregation, audit)

Risk evaluation

Risk and significance
qualitative,
semi-quantitative

Performance: CO_2 flux
Ecosystem acceptable levels(?)

Conceptual CO_2 storage risk assessment framework

A. Site Selection
B. Storage Licensing
C. Storage Monitoring and Verification
D. Potential Leakage Mitigation Plan

Tier 2

Exposure Assessment

Process level modelling tools
- fluid flow codes; geochemical codes; geomechanical codes, …
- ecosystem modelling codes(?)

System level models
Treatment of uncertainties,
natural heterogeneity (geological model)

Data requirements:
- site specific data, surrogate data from analogue sites
- (data audit)

→

Risk evaluation

Risk and significance
- quantitative

Performance: CO_2 flux
- (volume, timescale)

Receptor based thresholds (?)

Conceptual CO_2 storage risk assessment framework

A. Site Selection
B. Storage Licensing
C. **Storage Monitoring and Verification**
D. **Potential Leakage Mitigation Plan**

Tier 3

Consequence Assessment

Ecosystem modelling
- ecotoxicity assessment,
- biodiversity impact assessment,
- dose - response curves

Data requirements:
- experimental data from laboratory and field studies

→

Risk evaluation

Receptor based thresholds (?)

Conceptual CO_2 storage risk assessment framework

Source

Pathway

Receptor

Risk Assessment

Tier 1 Potential hazard assessment

Tier 2 Exposure assessment

Risk Evaluation

Risk communication

Risk Management

A. Site Selection
B. Storage Licensing

B. Storage Licensing
C. Storage Monitoring and Verification
D. Potential Leakage Mitigation Plan

C. Storage Monitoring and Verification
D. Potential Leakage Mitigation Plan

Relevance of ...

- Site characterisation
  - standards for site characterisation (?)
  - standards for site selection (?)
- **Risk Assessment**
  - **standards for risk evaluation**

at the lifetime stages of a CO_2 storage project

A. Site Selection
B. Storage Licensing
C. Storage Monitoring and Verification
D. Potential Leakage Mitigation Plan

Value of Information

- **Risk Management**
  including risk communication

The role of RA as part of a Risk Management framework

Risk assessment network meeting, Berkeley

TNO | Knowledge for business

What is risk assessment (RA)?

- Identifying, estimating or calculating and evaluating potential risks of CO_2 storage to human health and safety, the environment and assets

- RA is problem oriented

Risk = Probability of Hazard × Consequence of Hazard (impact)

Hazard and risk

- Leakage of CO_2 from the reservoir can best be regarded as a hazard
    - Hazard is the potential for harmful effects.
- But harmful to who or what?
    - Is it the pollution of drinking water?
    - Is it the threat of peoples life's?
    - Is it the change in biodiversity?
- So first define the canary and than start calculating

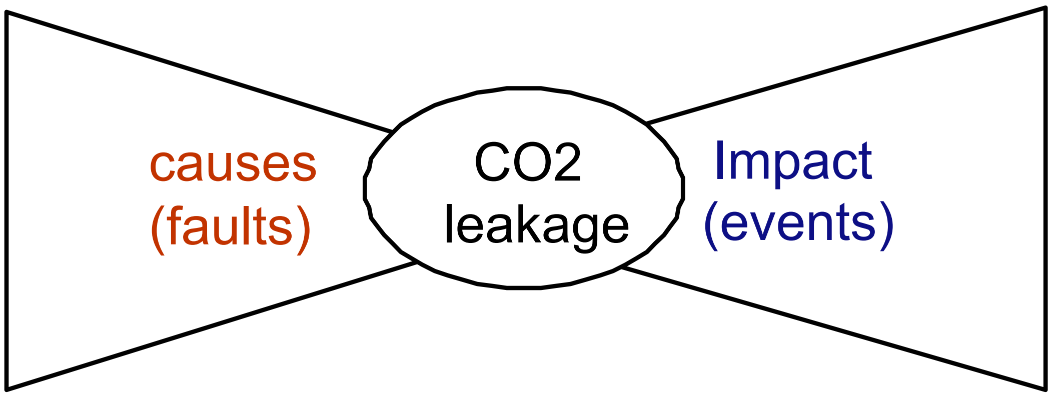
Risk = Probability of Hazard × Consequence of Hazard (impact)

RA in the risk management framework

- **RISK MANAGEMENT**
  - **RISK ASSESSMENT**
    - **RISK ANALYSIS**
      - **SOURCE IDENTIFICATION**
      - **RISK ESTIMATION**
    - **RISK EVALUATION**
  - **RISK TREATMENT**
    - **RISK AVOIDANCE**
    - **RISK OPTIMISATION**
    - **RISK TRANSFER**
    - **RISK RETENTION**
  - **RISK ACCEPTANCE**
  - **RISK COMMUNICATION**

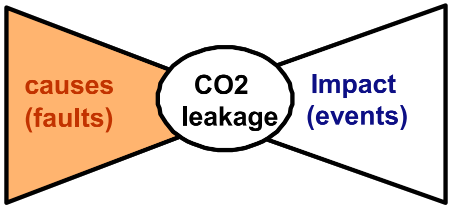
Two important components

- **SOURCE IDENTIFICATION**

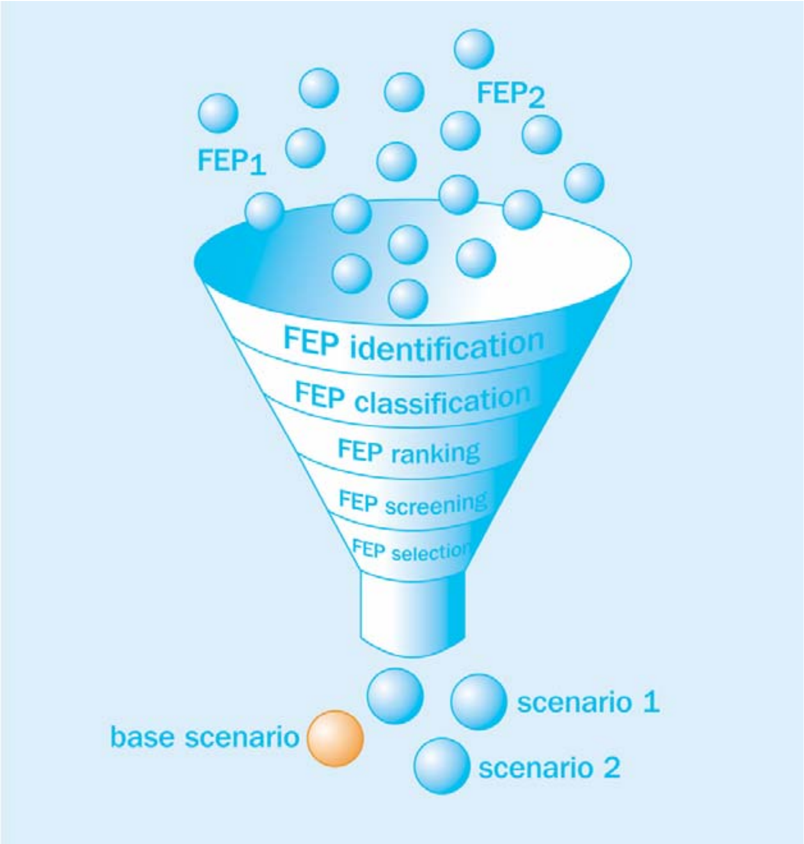


- **RISK ESTIMATION (impact)**

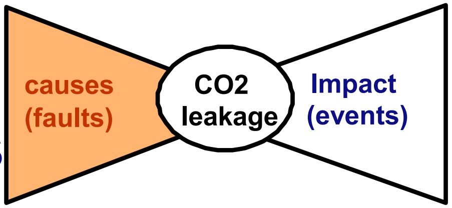
Source identification
Do we know all leakage paths?

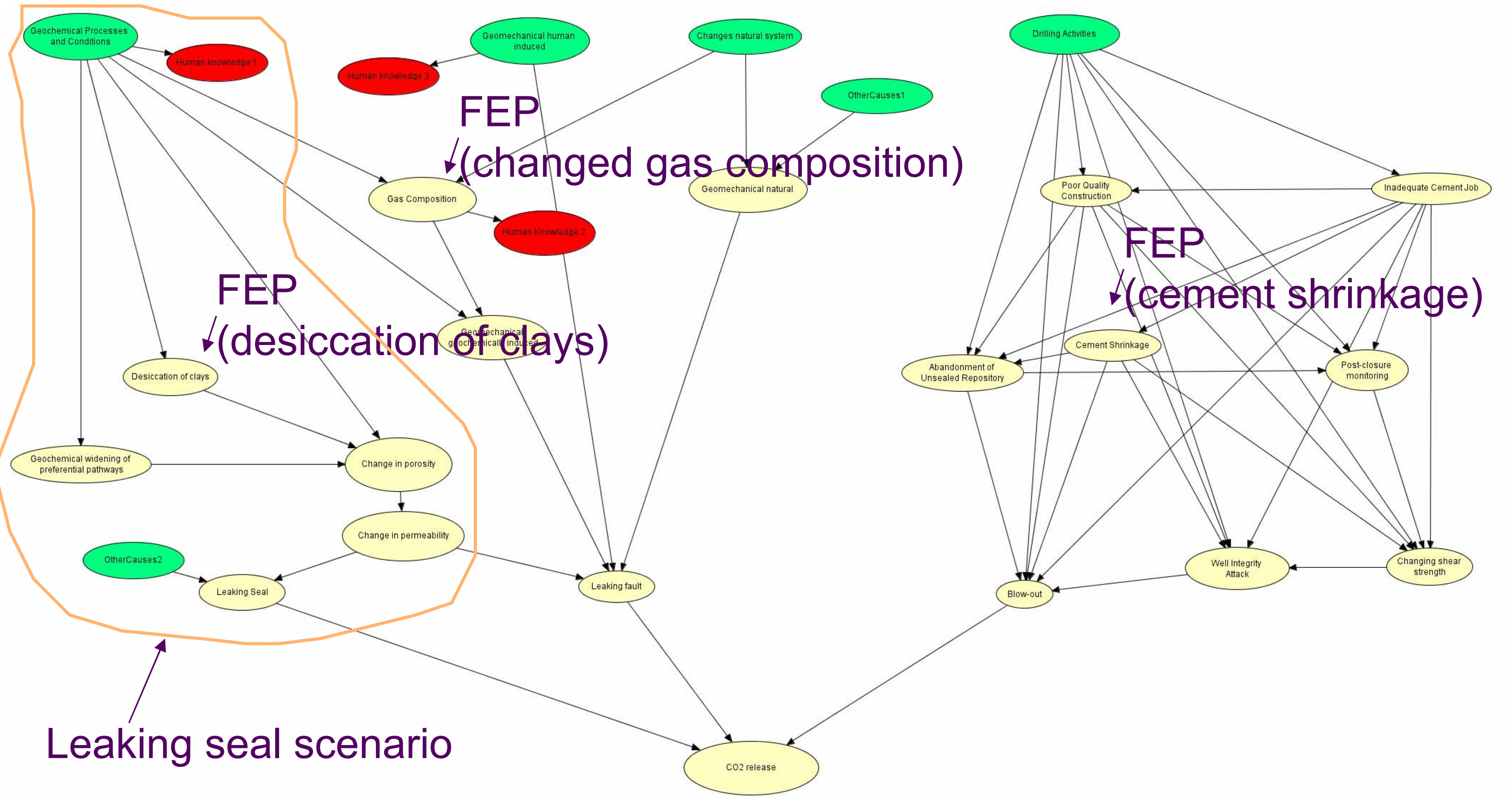


- FEP analysis
- Scenario's

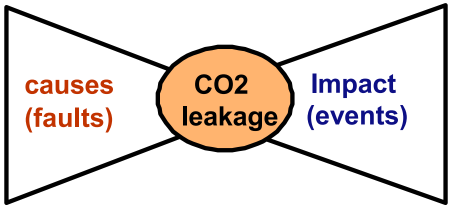


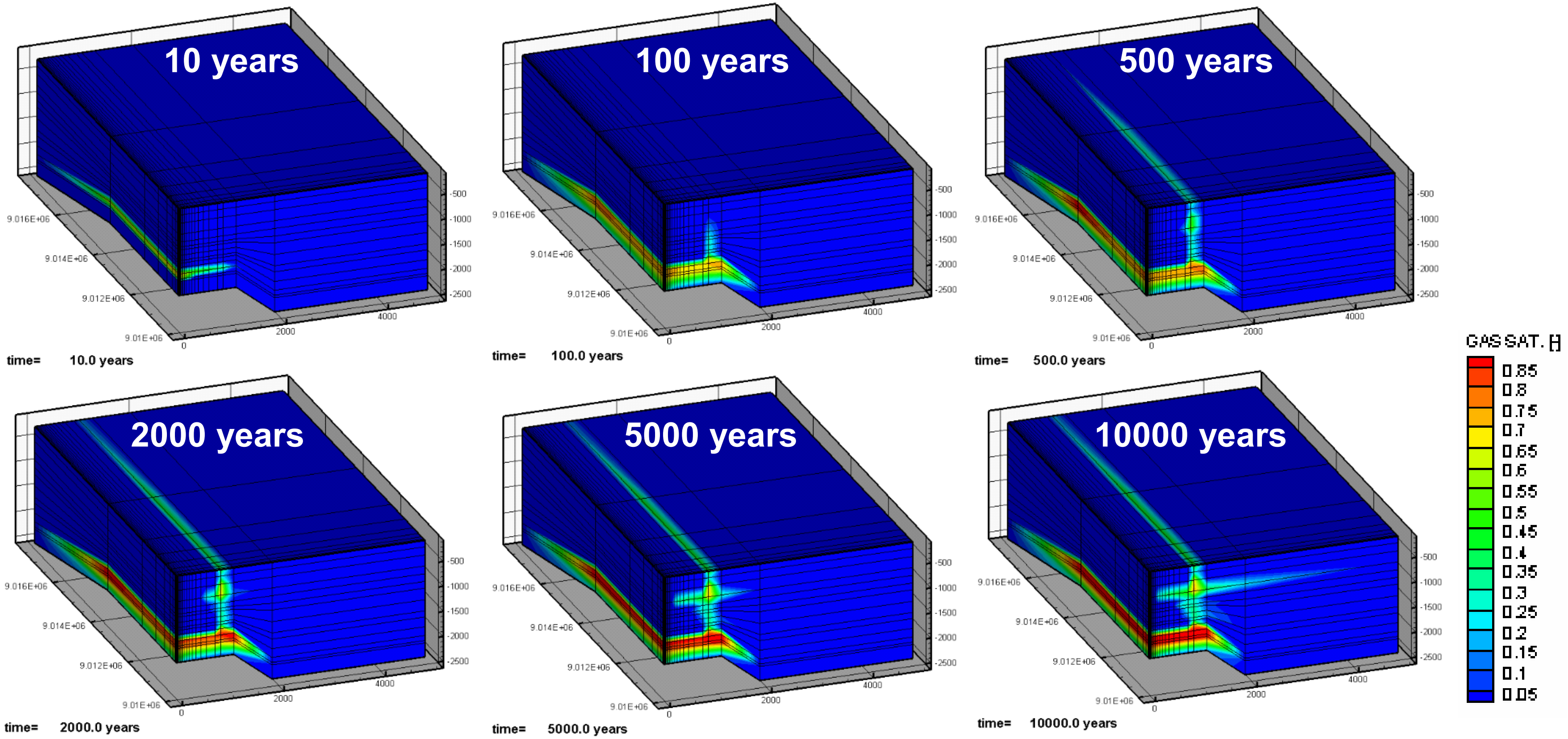
Scenario: Description of a possible future
Evolution of the project, specified by a set of FEPs



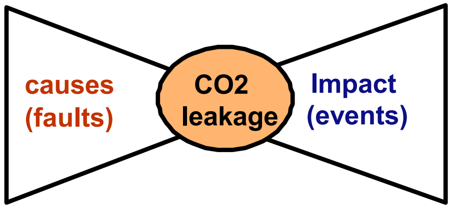


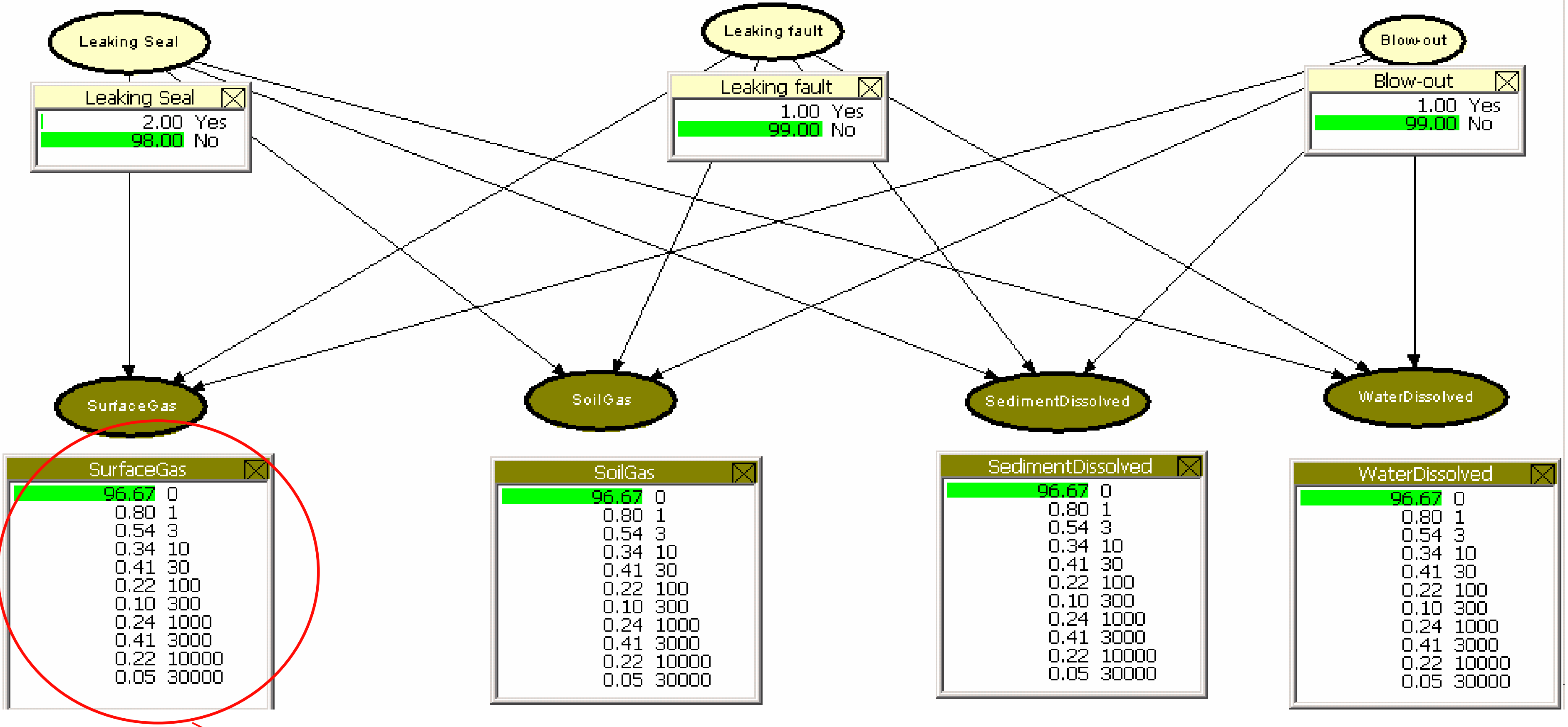
Quantification of the hazard (CO_2 leakage)





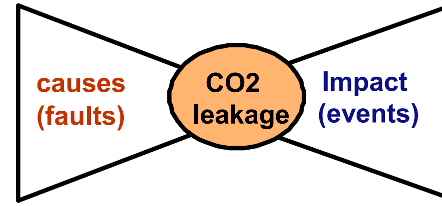
Probability (%/year) of occurrence BBN networks

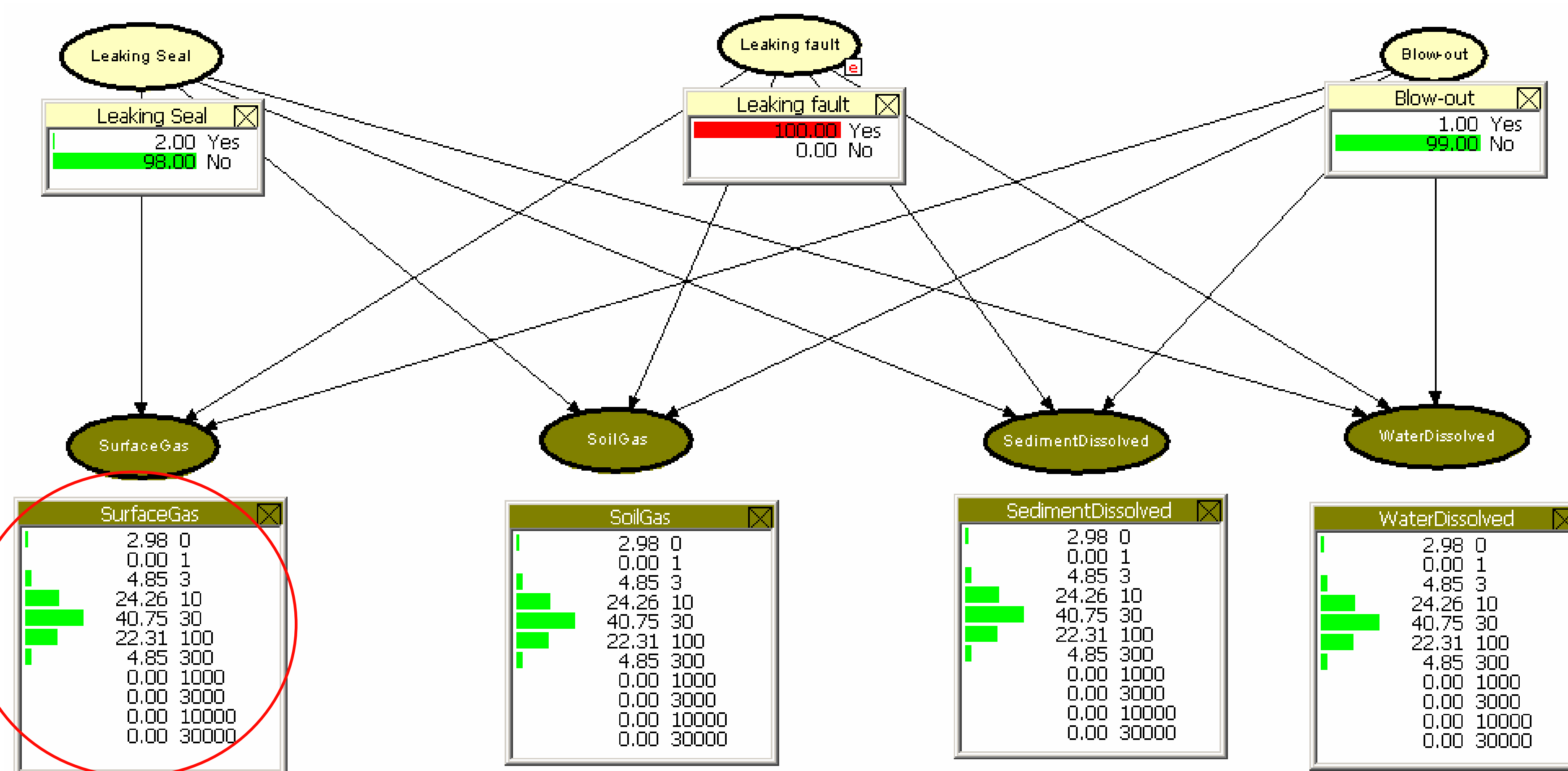




Histogram of excedance probabilities for ppm concentrations

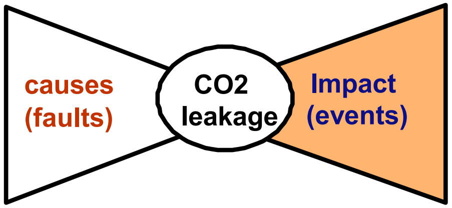
Knowing that the fault is leaking



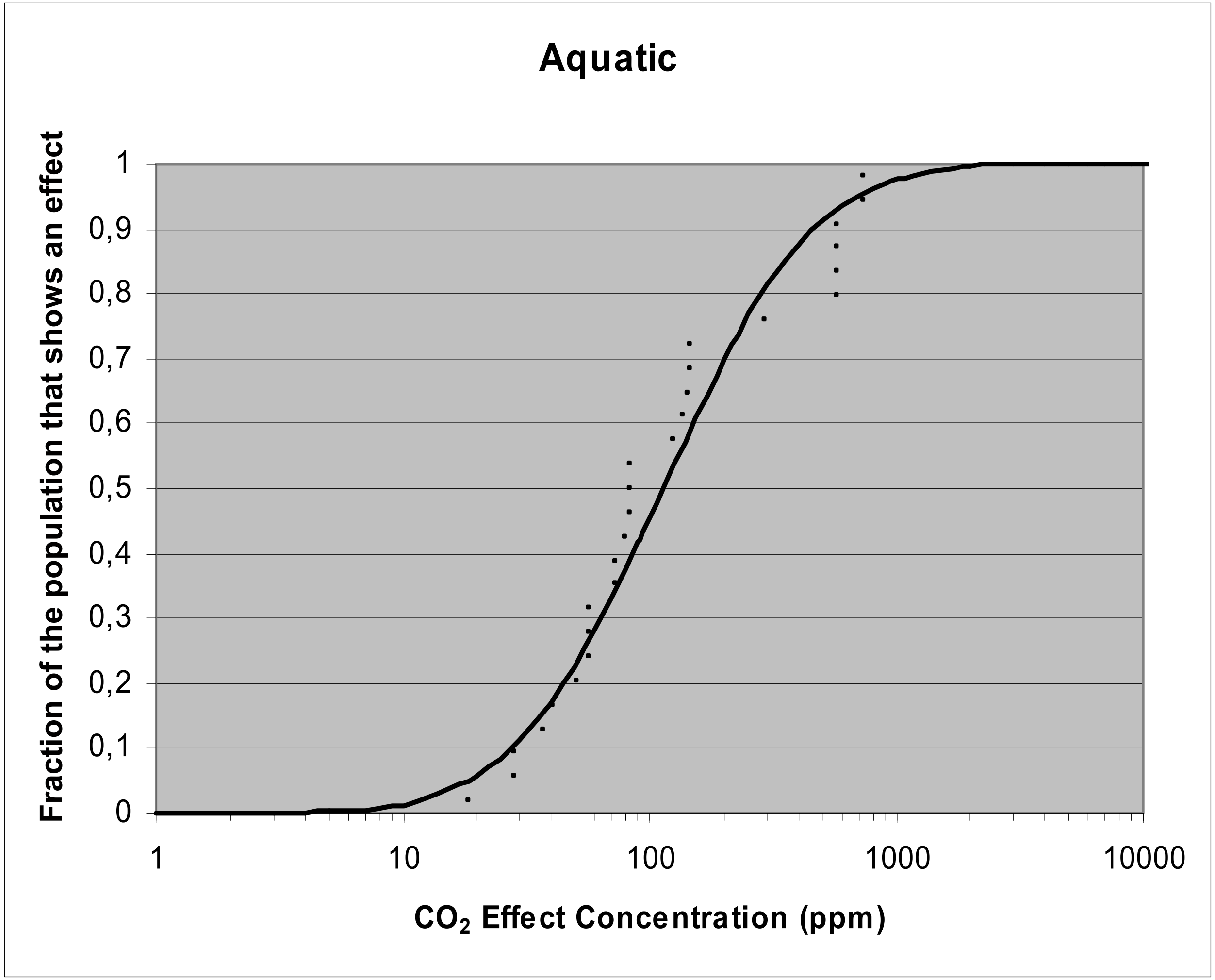


Histogram of excedance probabilities for ppm concentrations

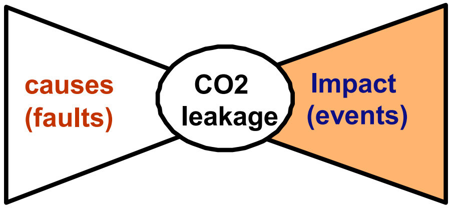
Consequences of CO_2 leakage – aquatic environment

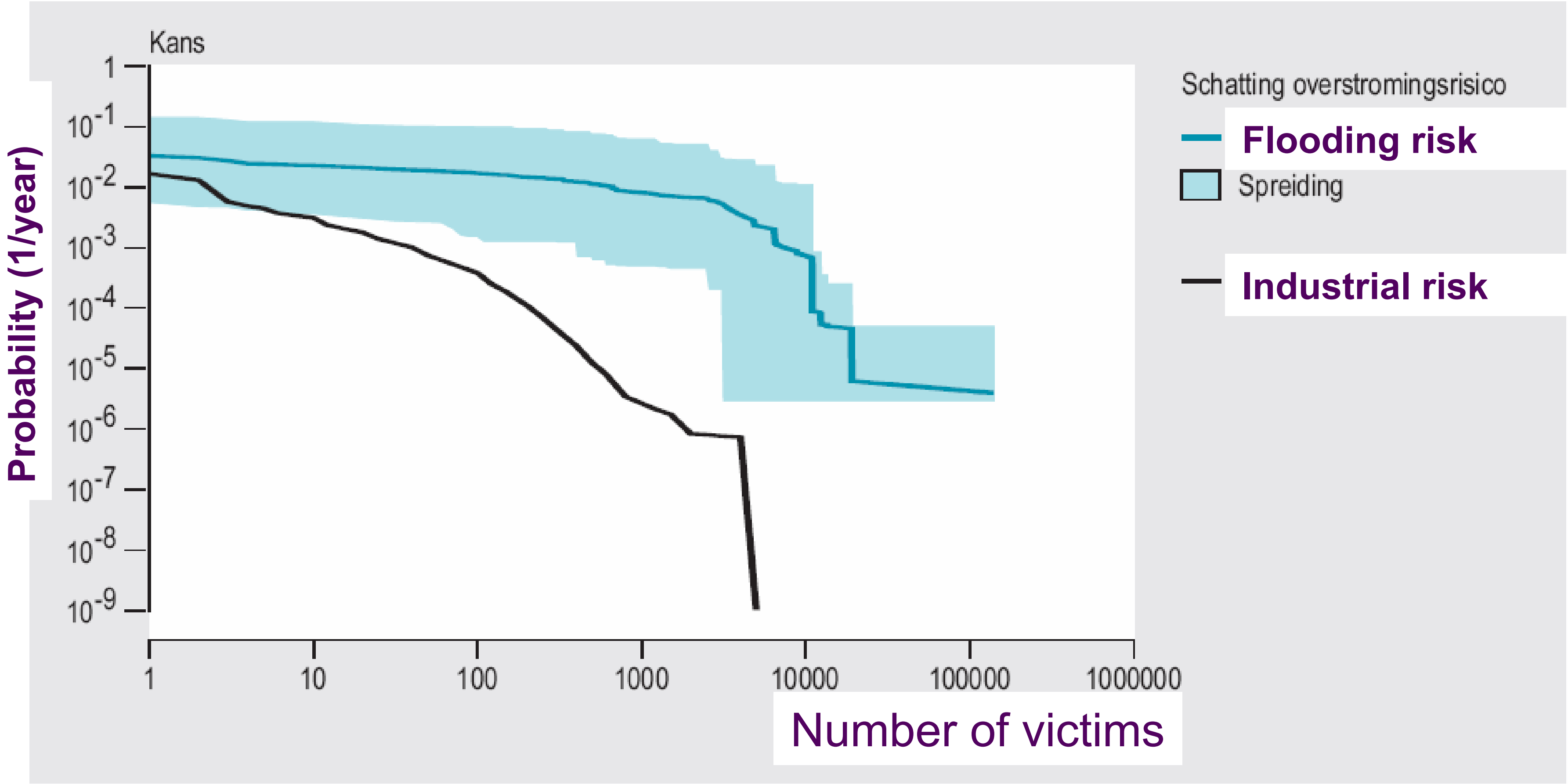


- **Species sensitivity distribution** (SSD) of aquatic fauna



Comparison with other risks (Fn functions)



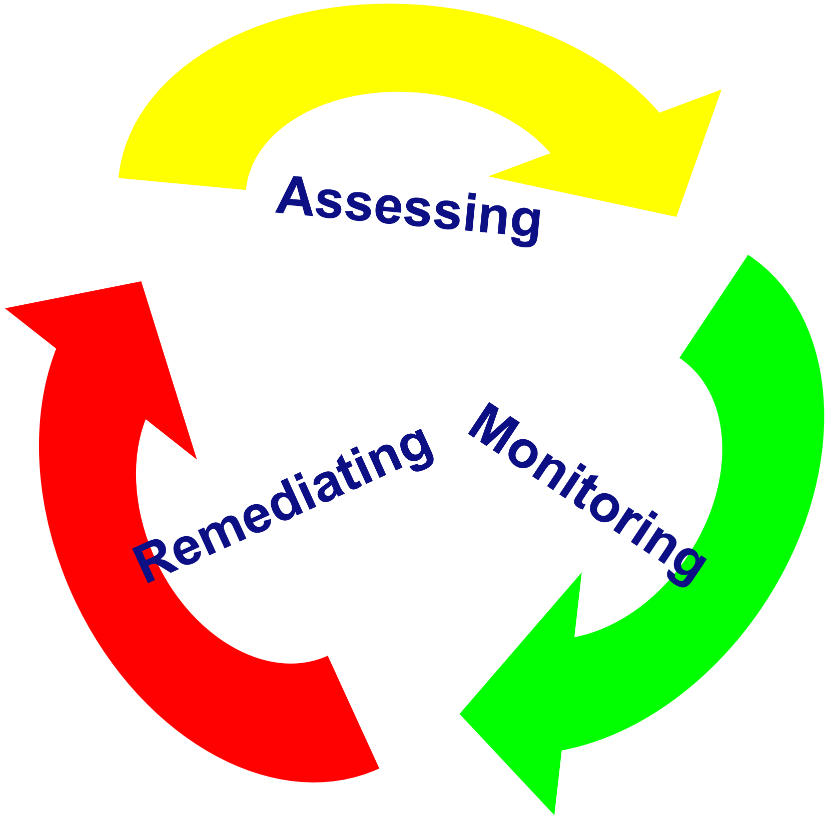


Some remarks on QRA

- You can not quantify all processes
- The experts make a distinction between high risk and low risk scenarios
- The experts do calculations on the impact of certain scenarios on leakage rates
- The experts make an estimation (no statistics yet) on the probability of the scenarios
- The experts conclude on the uncertainty of impacts and probabilities
- The results will be evaluated against governmental regulations

Risk management (RM)

- RA is an integral par of risk management
- Risk management deals with assessing, monitoring & remediating risks to conform to risk acceptance levels
- RM is solution oriented



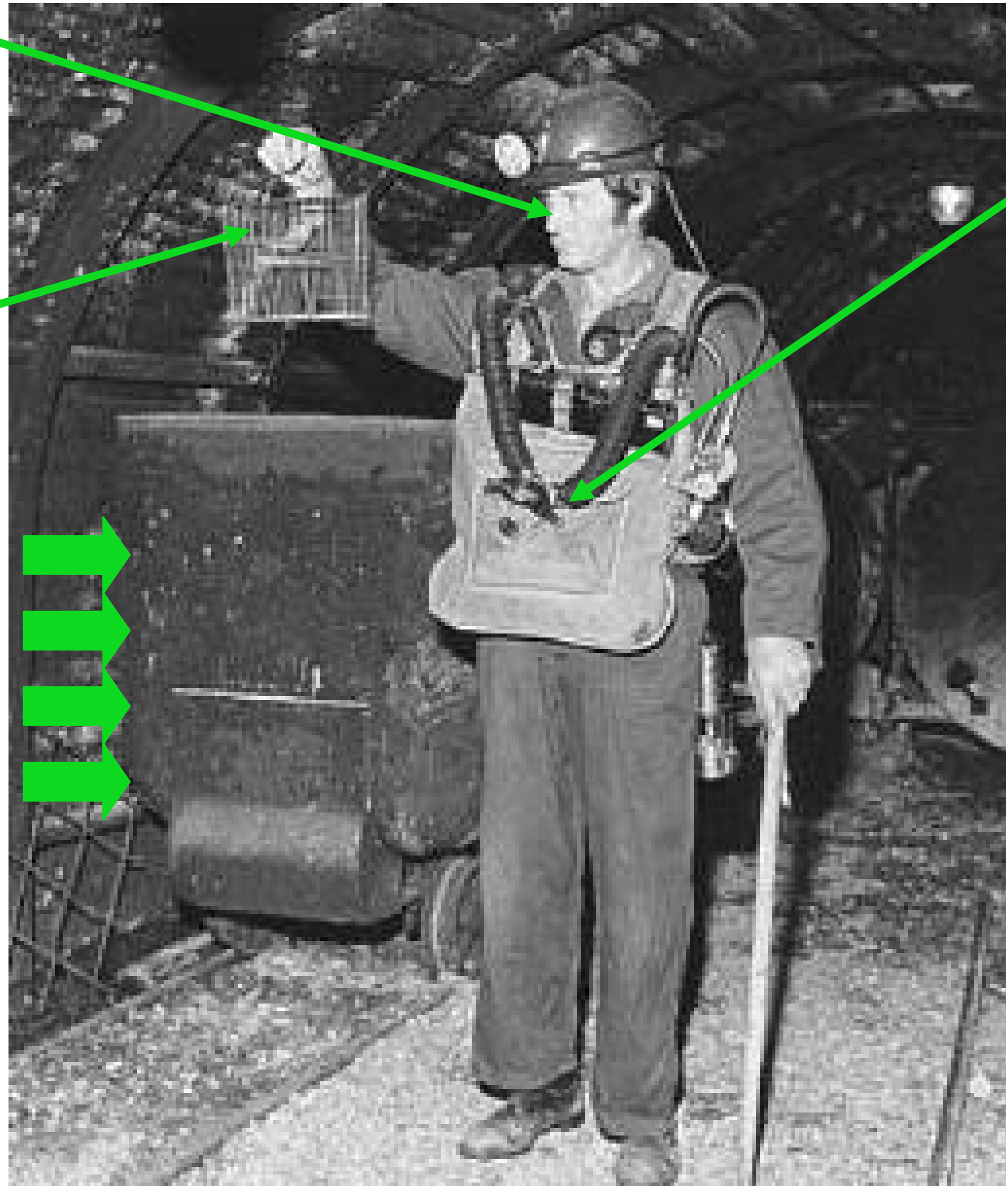
Risk management (RM)

Risk taker

remediation

Monitoring tool

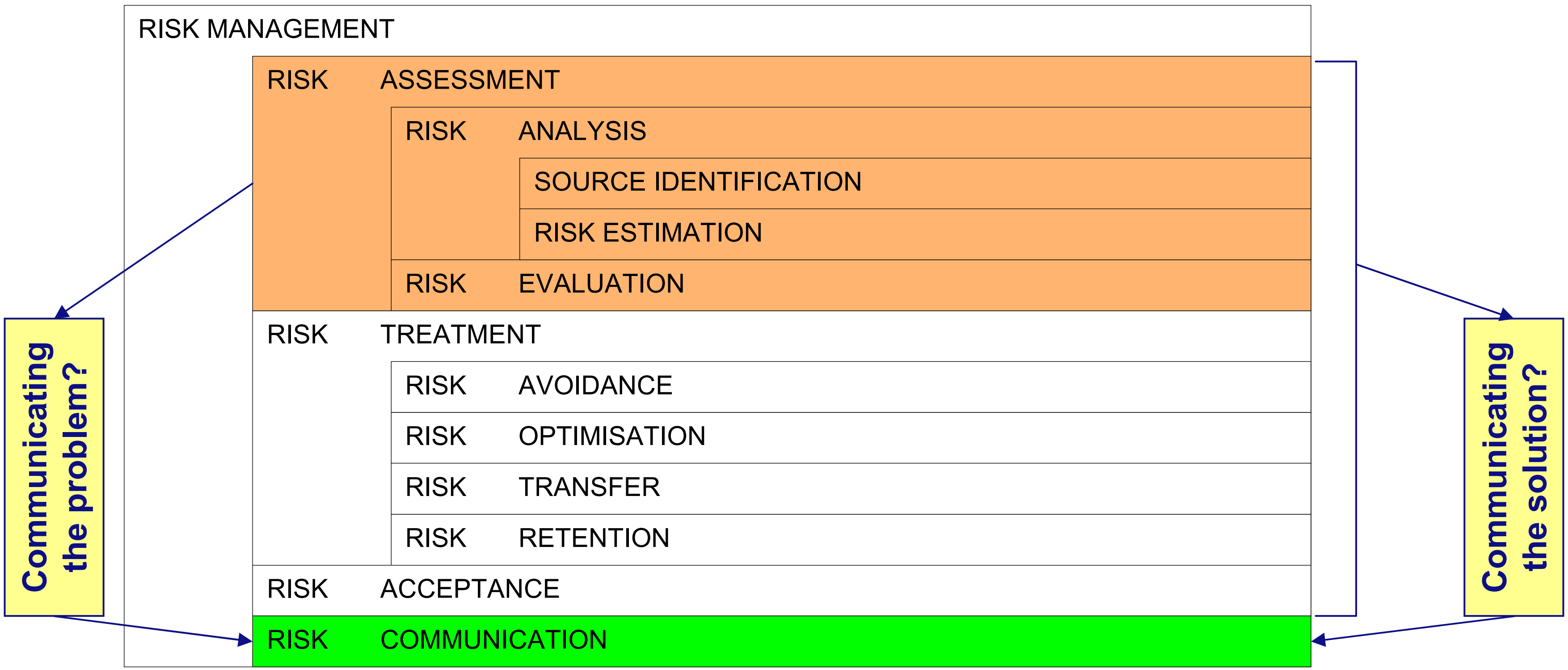
Hazard



How to communicate results?

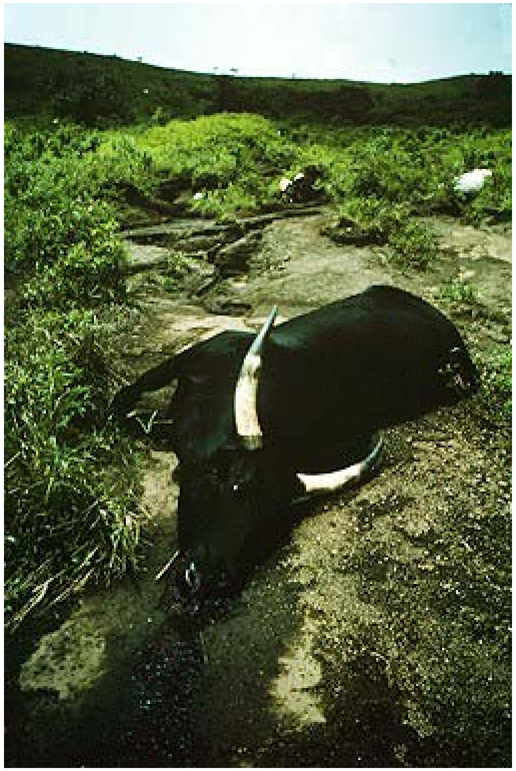
- Present results of risk assessment in relation to the management of risks in the successive phase of the CCS lifecycle
- Putting more emphasis on the ‘solution’ instead of the ‘problem’

Risk management: ISO, 2002



When you communicate this -> the perception can be..

Hazard



risk

mitigation

- Putting more emphasis on the ‘solution’ instead of the ‘problem’

Risk assessment of a CO2 storage site and risk-driven decision process

Laurent Jammes, Jean Desroches, Natalia Quisel (SCHLUMBERGER)
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2nd MEETING of the
RISK ASSESSMENT
NETWORK
October 5th, 2006

Optimizing Infrastructure Solutions

Outline

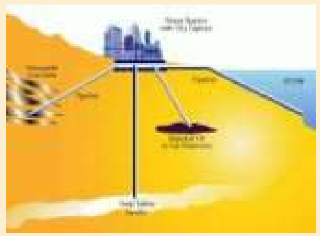
- Background: CO_2 storage site life
- Why, What and How
- A risk driven decision process
- Concluding remarks

CO2 Storage Workflow

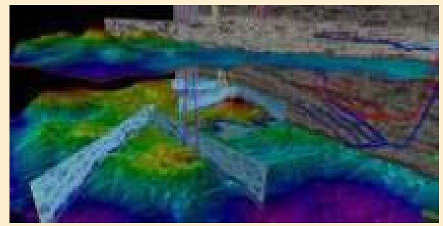
Pre-Operation Phase

~ 1-2 year

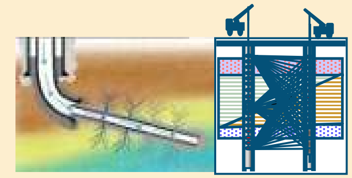
Site Selection



Site Characterization (SCP)



Field Design

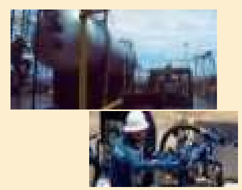


Operation Phase

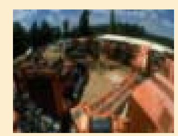
~ 10-50 years

Site Construction

Site Preparation

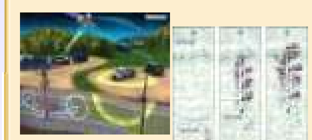


Injection



Monitoring (M&V)

- **Operation**

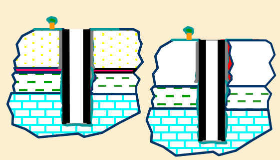


- **Verification**

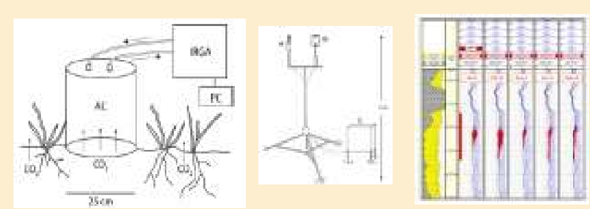
Post-Injection Phase

~ 100+ years

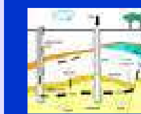
Site Retirement Programme (SRP)

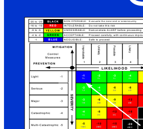


- **Environmental**



Performance & Risk Management System (PRSM)
Communication and Public Acceptance





Optimizing Infrastructure Solutions

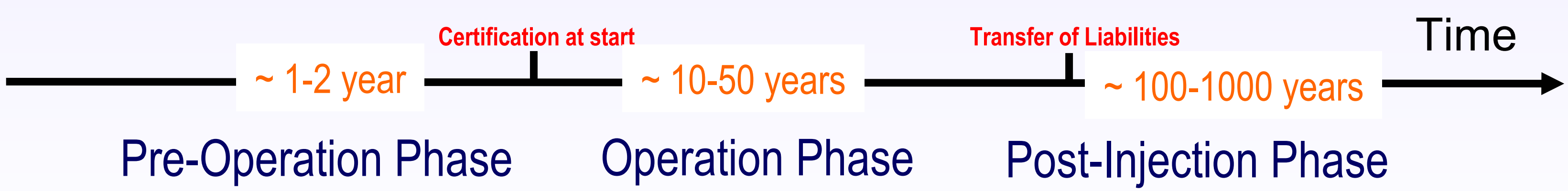
Why? Safety control

Concerns:

- Certification and permitting process
- Cost-effective risk treatment

Particular focus on:

- Sealing integrity with time
- Risk mitigation planning

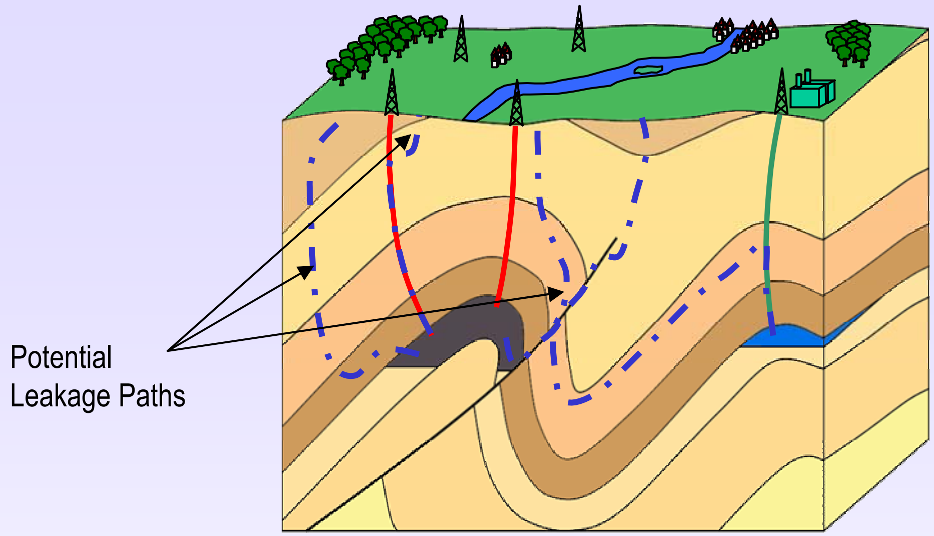


What? Risk-driven decision process

Goal: containment

Risk: leakage (well, reservoir)

Storage system
- ☑ Uncertainties
- ☑ Material degradation



Performance Assessment of storage system
(assess the risk of insufficient containment)

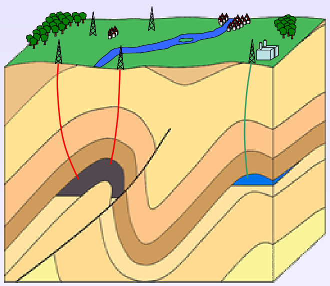
Decision Support

Selection of action for best risk mitigation (best cost/benefit)

Decision

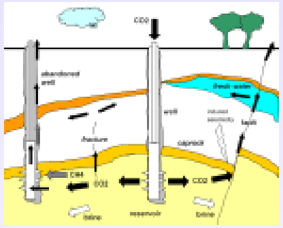
How? Risk Assessment Workflow

Functional analysis → Identify, quantify failure mechanisms → Construction, quantification of leakage scenarios → Risk ranking and performance evaluation → Risk-based decision support

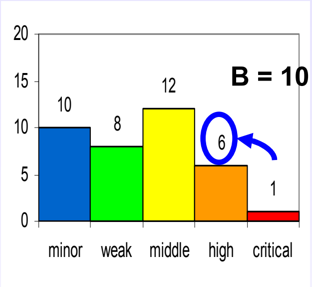


Exhaustive inventory of features and potential hazards

Knowledge
Data & Models
Uncertainties



(from Damen et al, 2003)



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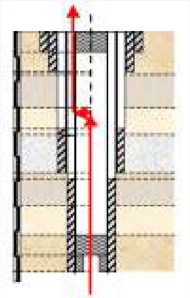
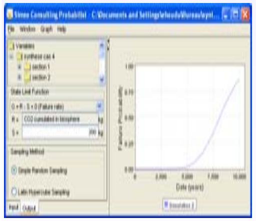
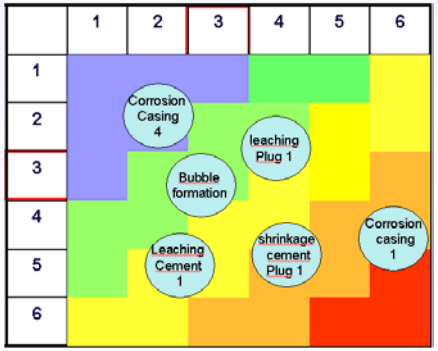




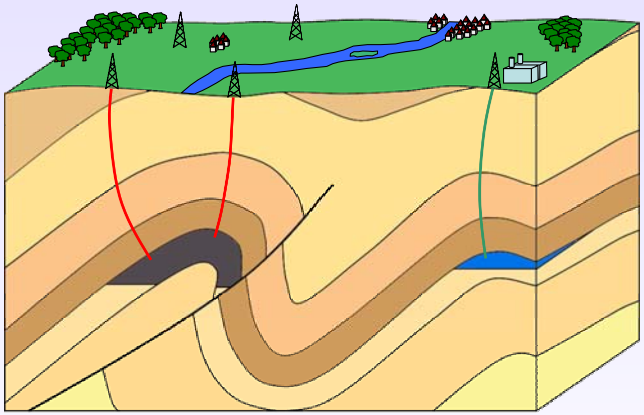


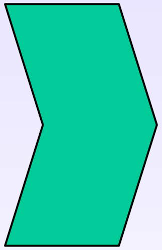
Oxand Optimizing Infrastructure Solutions

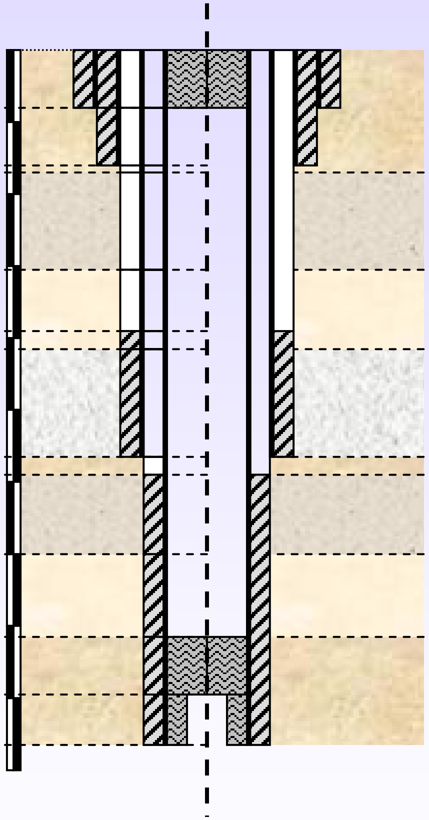
Schlumberger

Functional analysis

System components



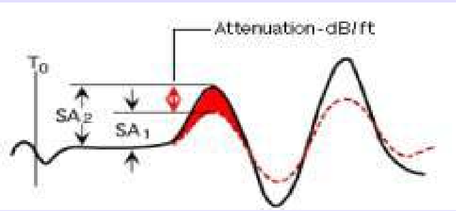


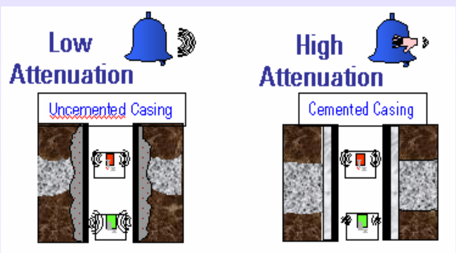


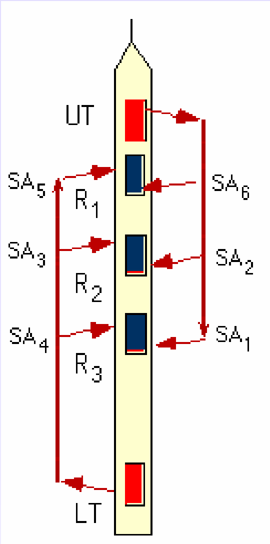
Identify, quantify failure mechanisms

Well Integrity Characterization

Sonic

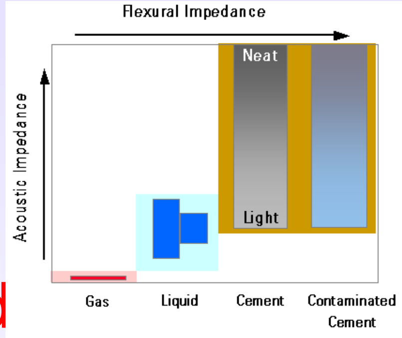


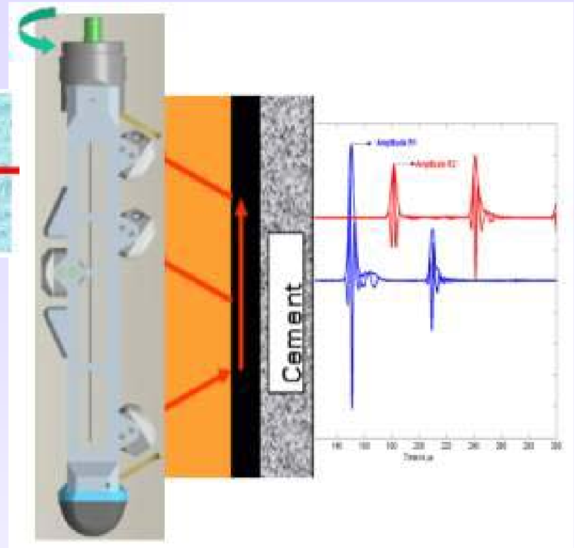




Cement Bond

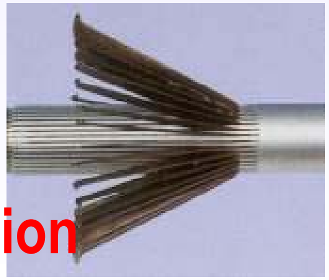
Ultrasonic





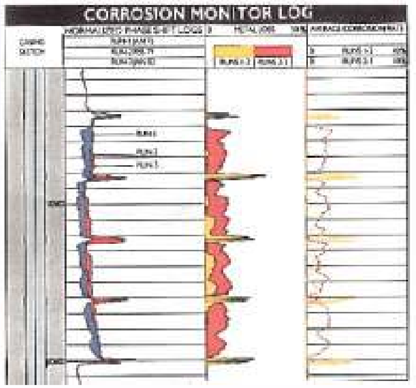
Cement / Corrosion

Multi-finger Caliper



Corrosion

Electromagnetic



Corrosion

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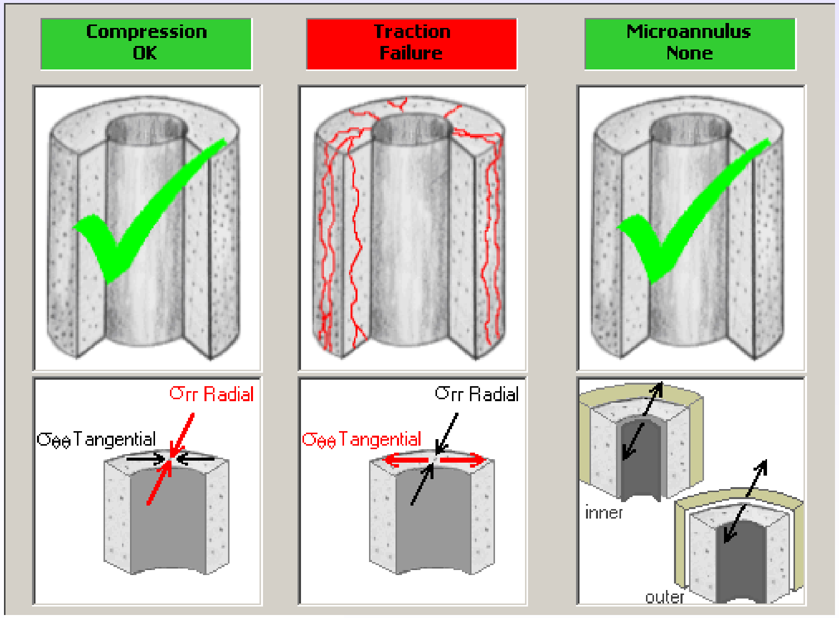
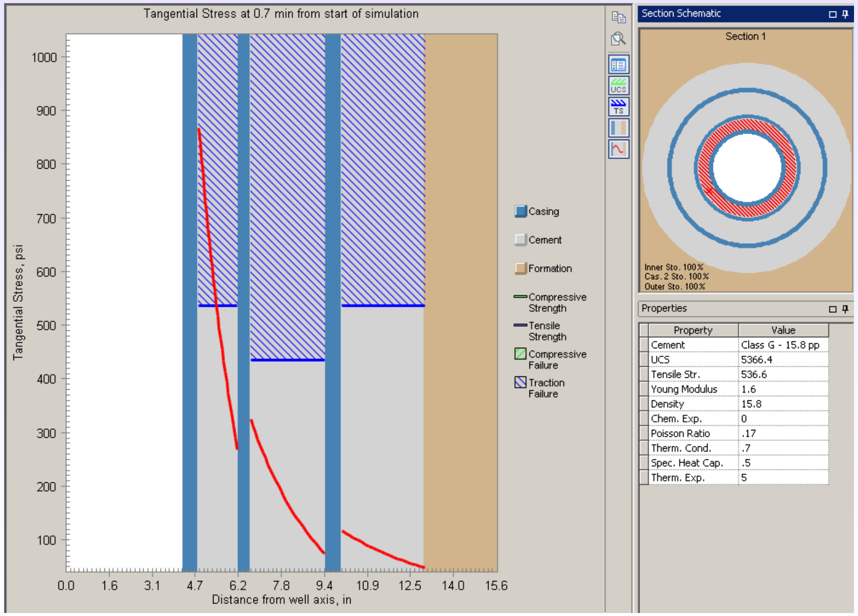
Identify, quantify failure mechanisms

Well Integrity changes with time

Response of wells to injection/production operation

- Micro-annulus
- Fractures in the cement sheath





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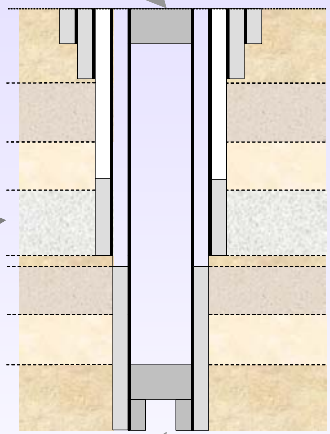
Identify, quantify failure mechanisms

Modeling Degradation and CO_2 Transport

Cement behavior

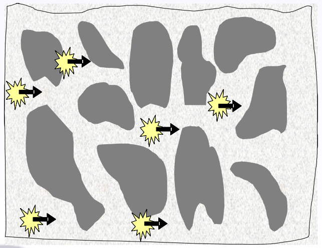
Cement leaching
Physico-mechanical coupling
Initial state



Steel behavior

Steel corrosion
Steel stability

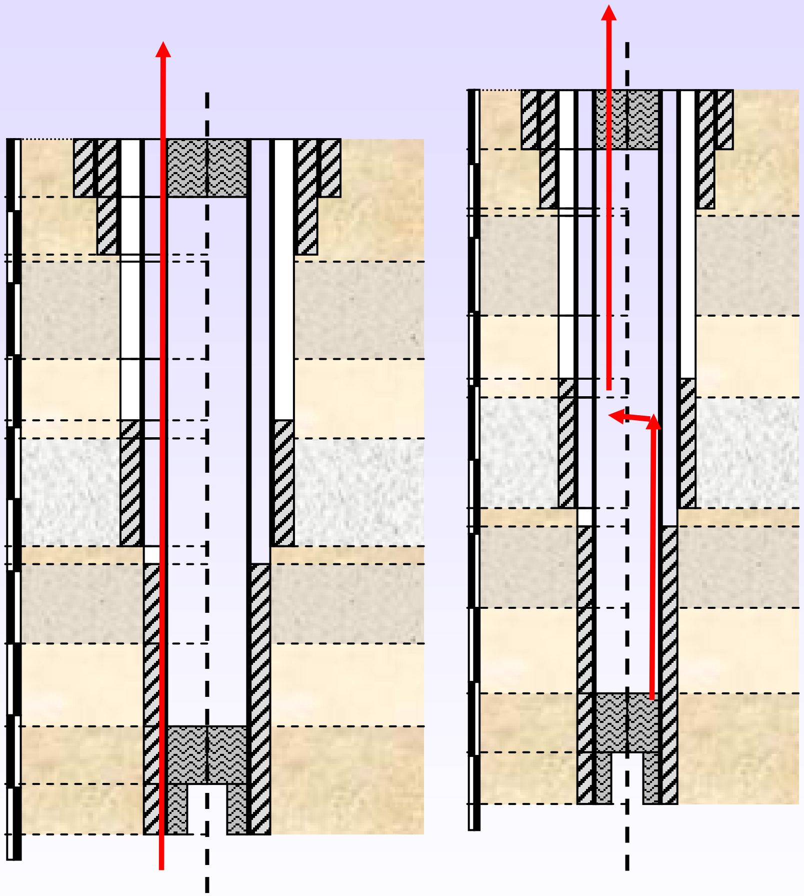
Cap rock and Reservoir

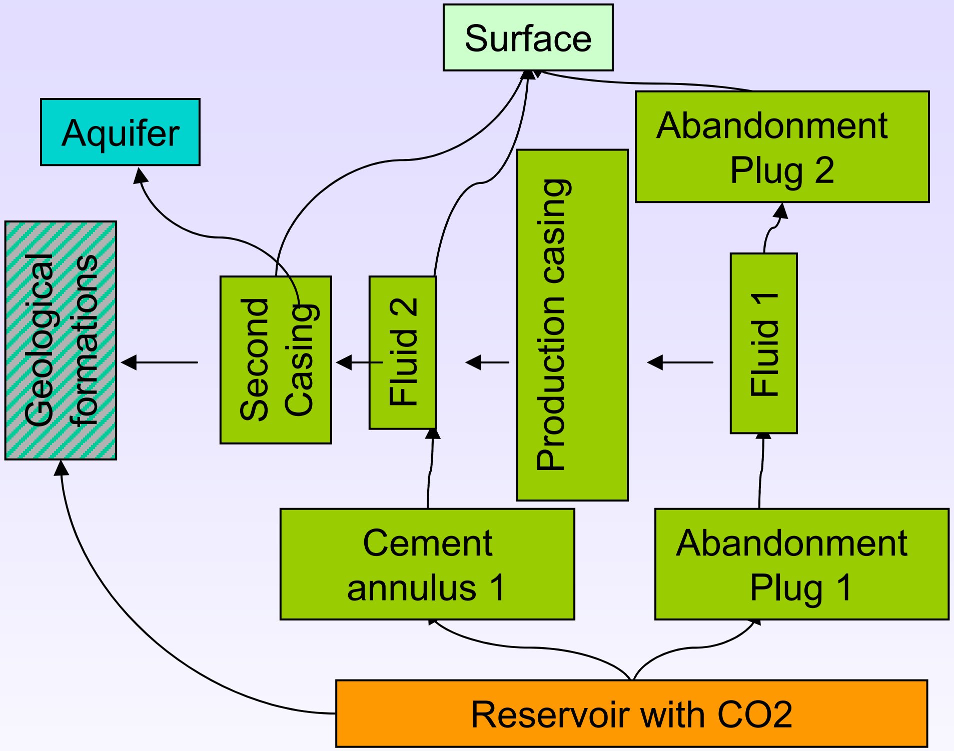


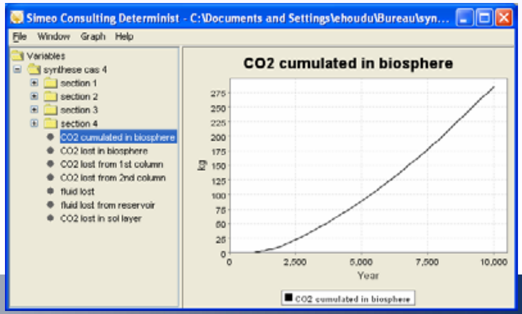
Transport phenomena
(advection + diffusion)
Gas migration
Porosity, capillary pressure

Estimation of Leakage Rates

For each failure scenario :







Multi-Risk Integration

Consequence grid

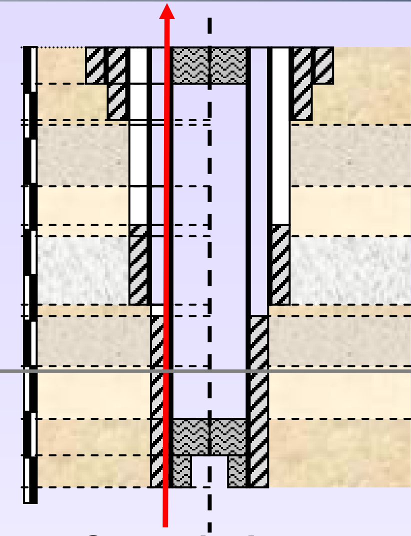
Stakes / Level	F Financial	A Injection stops	B Government	C SAFETY			Market
				People	Pollution	Environment	
1 : Minor	> 500 M$	< 1 day					
2 : Low							
3 : Serious	1 - 5 M$	> 2 days		1 poisoned person	Temporary exceeding of regulation threshold (> 0,038 % CO_2 in volume)		5%< market share lost
4 : Major							
5 : Critical							
6 : Extreme							

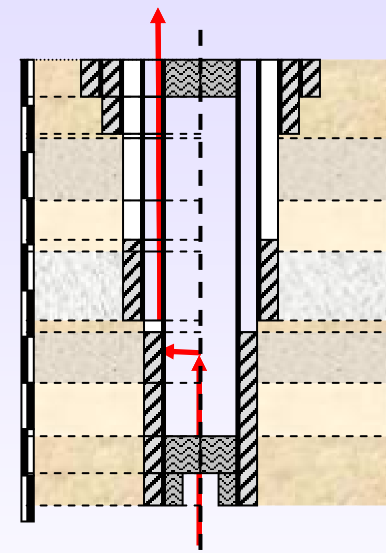
Risk ranking and performance evaluation

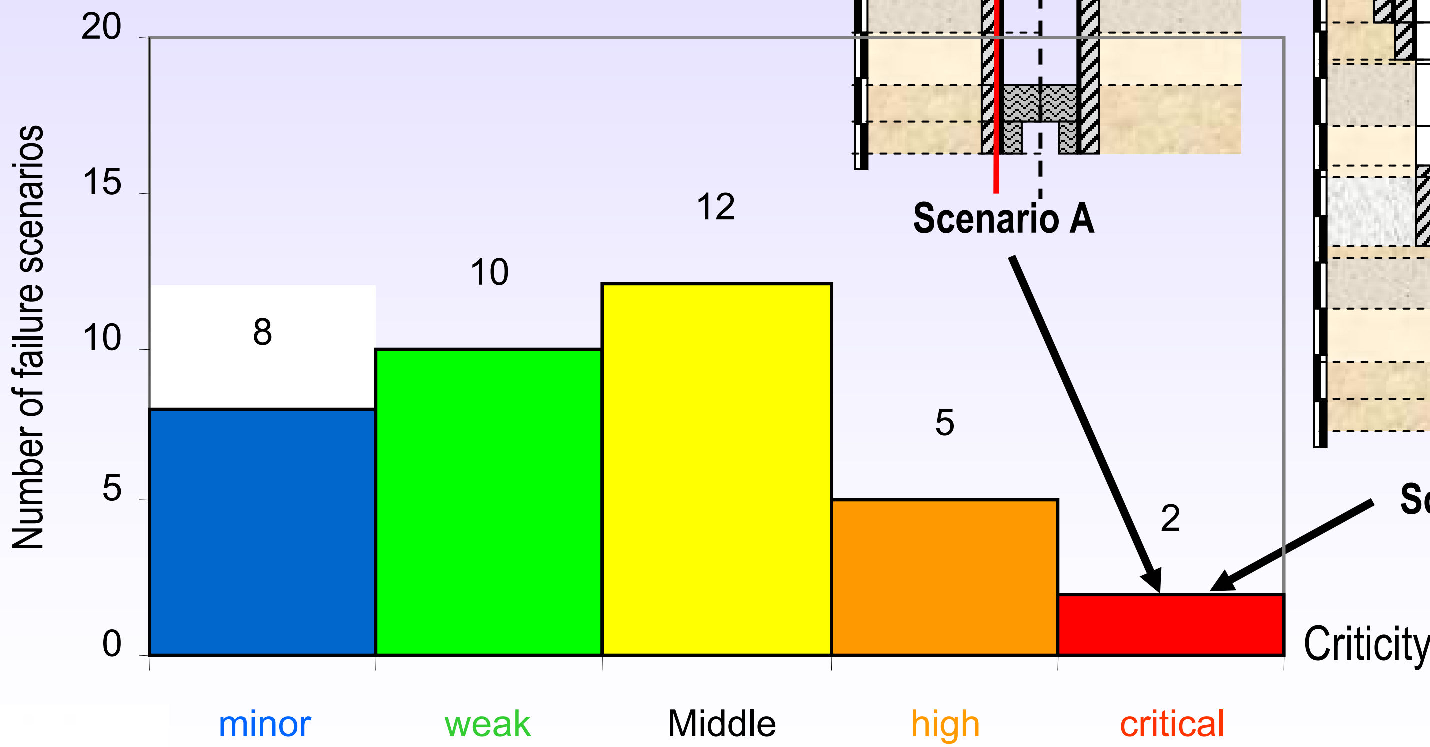
Risk Mapping as a decision support

Objectives:

- ☑ Rank failure scenarios
- ☑ Eliminate critical scenarios
- ☑ Choose solutions for best risk mitigation







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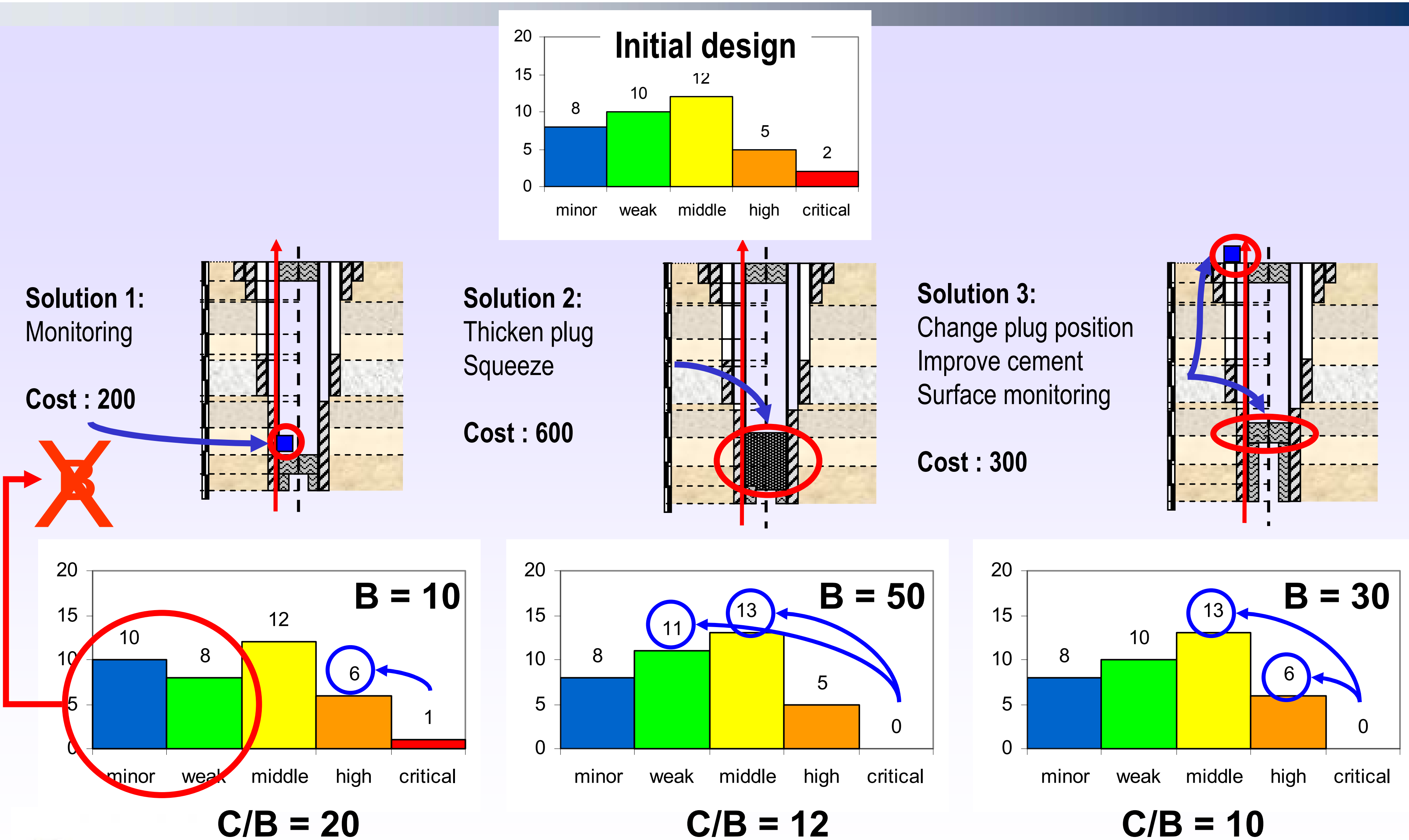
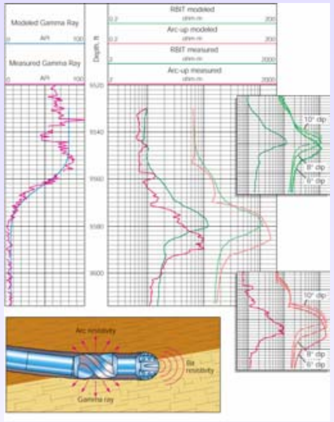
Action Selection – A Guide to Decision

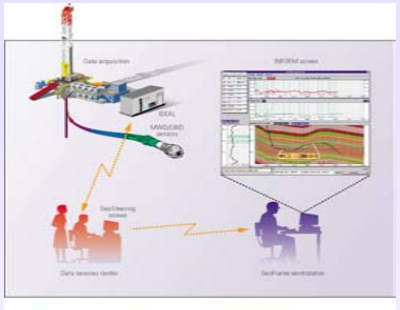


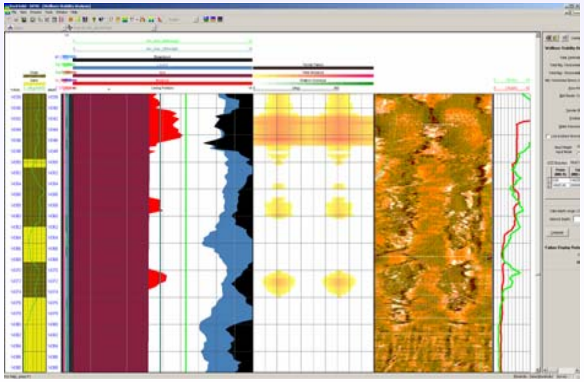
Optimizing Infrastructure Solutions

Decision – Well Construction Technologies

- Optimum positioning of wells to minimize exposure to CO_2
  - Horizontal wells to maximize injection rate
- No formation damage while drilling
- Injection Well Completion
  - CO_2-Resistant cement
  - Casing & Completion metallurgy / protection







Decision – Well Abandonment / Work over

Plug design

Material

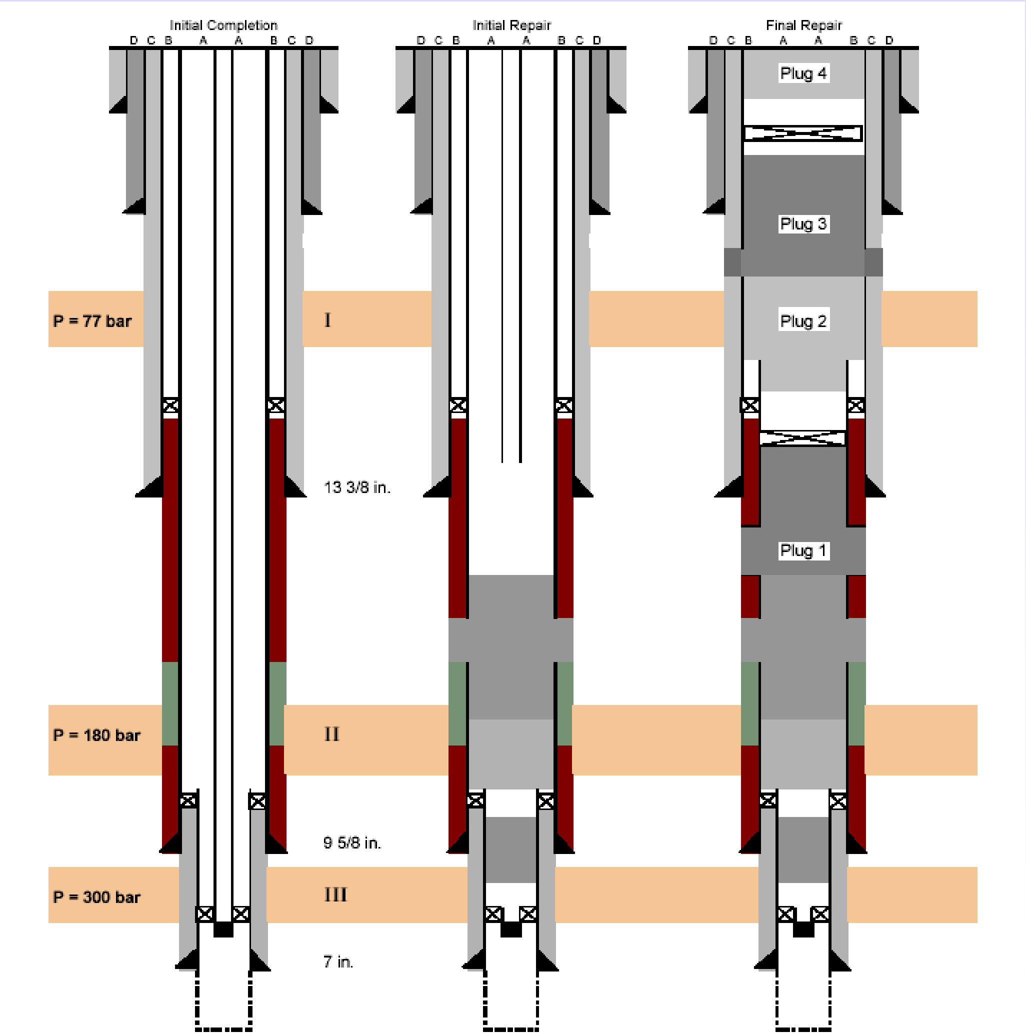
Placement

Monitoring

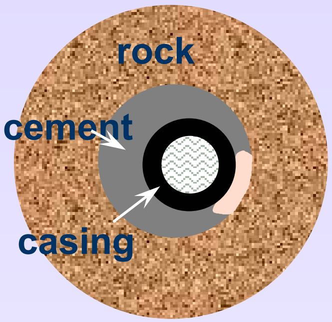
Squeeze Jobs

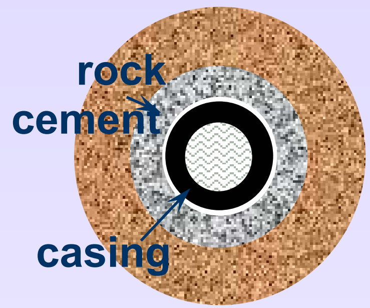
Placement of a special material to seal long and thin discontinuities

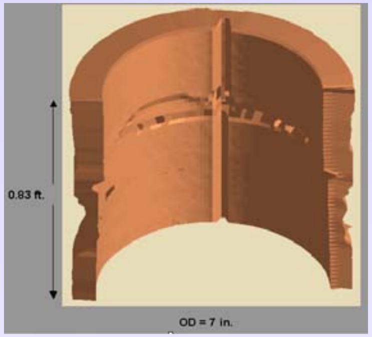
CO2-Resistant Materials

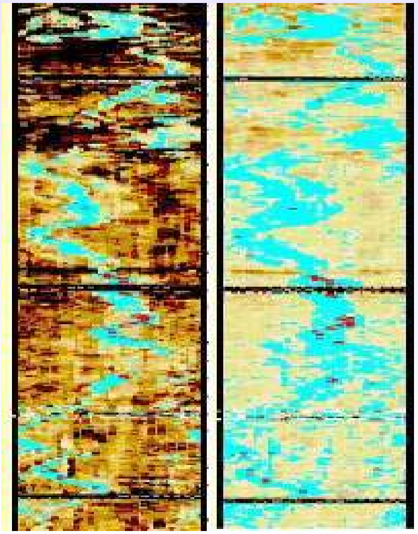


Decision – Well Integrity Monitoring

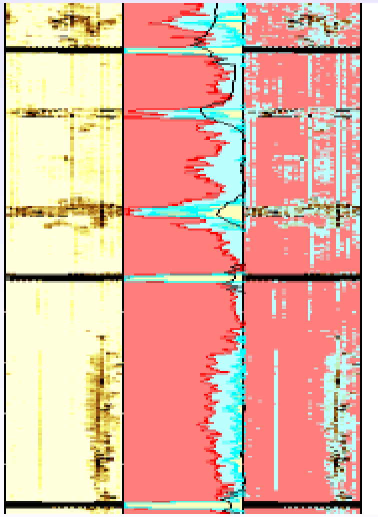




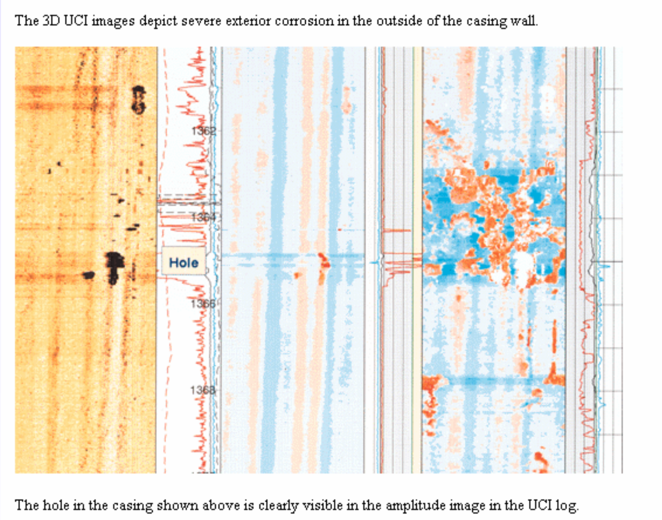




Channeling



Debonding
steel/cement interface



Corrosion

Summary

- **Decision** methodology for action selection based on risk assessment for risk mitigation
- **Knowledge and best practices**: expertise to provide fit for purpose solutions
- **Integrated approach**: could play a key contribution to establishing standards for CO_2 storage containment

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Outline of the plan for international collaboration

Development of International Collaboration for Building Confidence in the long-term Effectiveness of CCS

Norio SHIGETOMI

Mitsubishi Research Institute, Inc.

2nd Meeting of the Risk Assessment Network
5-6 October, 2006
Lawrence Berkeley National Laboratory, California, USA

Contents

- Background
- Objective
- Schedule

Background

- The Ministry of Economy, Trade and Industry of Japan (METI) promotes CCS project activities.
- Physical leakage (seepage) is the key issue for CCS project activities.
- To accelerate CCS project activities, confidence building will be needed.
- Confidence building is applicable to methodologies for CDM project activities.
- METI proposed development of international collaboration for building confidence in long-term effectiveness of CCS at the 30th IEA GHG Executive Committee on September 12-13 2006.
- IEA GHG Executive Committee had approved the proposal for development of international collaboration at the 30th meeting.

■Summary for recommendation by the CDM Executive Board -1

A. Policy or legal issues:

- Acceptable levels of long-term physical leakage (seepage) risk and uncertainty (e.g. less than X% seepage by year with a likelihood of Z %);
- Project boundary issues (such as reservoirs in international waters, several projects using one reservoir, etc) and national boundaries (approval procedures for projects that cross national boundaries);
- Long-term responsibility for monitoring the reservoir and any remediation measures that may be necessary after the end of the crediting period (i.e. liability);
- Accounting options for any long-term seepage from reservoirs (e.g. new modalities and procedures such as those for LULUCF).

■Summary for recommendation by the CDM Executive Board -2

B. Issues of a largely technical and methodological nature:

- The development of criteria and a step-wise guidance for the selection of suitable storage sites with respect to the release of greenhouse gases, and how this relates to applicability conditions for methodologies;
- Guidance on the development of adequate and appropriate monitoring methodologies for physical leakage (seepage) from the storage site;
- Guidance related to the operation of reservoirs (e.g. well sealing and abandonment procedures) and remediation measures and how these may need to be addressed in baseline and monitoring methodologies.

Objective

To accelerate CCS (and CCS-CDM) project activities, confidence building will be needed.

↓

Recommendations regarding confidence building based on discussions and papers presented at the workshop will be published as an IEA report.

↑

- International workshop
- Discussion by e-mail and so forth

Schedule

- Discussion of the need for international collaboration and planning of its implementation at the 2nd meeting of the IEA GHG Risk Assessment Network .

- Discussion of the current status and the need for confidence building at a workshop on October 24 2006 in Tokyo.

- An international workshop in Tokyo in January or February 2007 where:
  - Members of IEA GHG R&D Programme are encouraged to present their experience and plans for confidence building.
  - Key issues relating to confidence building in CCS are discussed by the members and a set of generic recommendations are to be formulated.

- Recommendations regarding confidence building based on discussions and papers presented at the workshop will be published as an IEA report.

Building confidence of CCS using knowledge from natural analogues

Kenshi Itaoka and Koji Yamamoto

Mizuho Information and Research Institute (MHIR), Tokyo, Japan

The 2nd Meeting of the Risk Assessment Networt

October 5-6, 2006, Lawrence Berkeley National Laboratory

Contents of the presentation

- How natural analogues can help building confidence for CCS decision making (building confidence in long term effectiveness and safety).
- Our ongoing natural analogue study
- Promotion of international collaboration.

How natural analogues can help building confidence for CCS.

Characteristics of CCS risk

- Super long-term risk and high uncertainty
- Natural risk and manmade risk
  - Intrinsic uncertainty of the geological systems
  - Difficulty of the data acquisition
  - Uncertainty of the behavior of injected CO_2
  - Difficulty of the verification

Different types of the risk

Manmade risks

No or little unknown uncertainty but there is known uncertainty.

The probability should be minimized.

Natural risks.

Broad unknowns and known uncertainty. The damages should be minimized.

Issues of building confidence for CCS effectiveness of confinement: risk of seepage

Natural analogue

1. Risk: difficult to interpret
   - Very long-term risk
     - Unfeasibility of long-term monitoring
     - Reliance on numerical modeling for prediction but difficulty in the verification
   - Probability × consequence
     - *The fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years* (IPCC SR)
2. Known uncertainty: difficult to estimate
   - Intrinsic uncertainty of the geological systems: complexity
   - Behavior of injected CO_2
   - Error of obtained information
3. Unknown uncertainty: ??
   - Intrinsic uncertainty of the geological systems: heterogeneity (unknown factors)

How natural analogue can be used for building confidence?

- Understanding the leakage and trap mechanism
  - ► Effectiveness of the four trap mechanisms: proof of confinement
  - ► Effects of the heterogeneity of the earth crust on CO_2 behavior
- Verification of numerical models and risk assessment procedures
  - ► Long-term behavior of the CO_2 can be observable and comparable to the simulation results
  - ► Reduction of uncertainty of parameters of models.
  - ► Test of monitoring methodology.
- ★ Interpretation and risk management
  - ► Help interpretation of stochastic events and their consequence.
  - ► Comparison of natural analogue sites and a CCS site give basic idea of the character, magnitude and impact of the leakage risk.
- ★ Risk communication
  - ► Communication of how safe and how risky.
  - ► Risk of the CO_2 leakage can be measurable and comparable to the assessed results

Risk types and management options

- Manmade pathways (poor well completion, abandoned wells, etc.)- *Engineering solutions*
    - Technology development and strict design guideline for new wells
    - Finding old wells
    - Mitigation techniques
- Natural pathways ← Natural analogue
    - ► Slow migration in the seal formation-*"main stream" leak risk*
        - Site selection
        - Monitoring the migration to find unidentified pathways
        - Modelling based assessment of the leak-rate and total escapable volume considering trap mechanisms to ensure that they are acceptable level
    - ► Unknown/unpredictable pathways, creation of new pathways *-that may not happen in the monitoring term*
        - Explore the pathways as much as possible
        - Site selection with assessed leak risk based on the known conditions
        - <u>Natural analogue based risk assessment</u> to know how common, how significant effects.

Events comparable to natural/industrial phenomena

- Examples
  - CO2 release from failed wells
  - CO2 release through reactivated faults
  - Seismic, volcanic, and other tectonics related activities
  - Activities caused by other external natural force (glacier, meteorite impact,
- Critical points of the risk assessment
  - Geological, mechanical and chemical conditions that govern the initiation and termination of the leakage and its rate
  - Frequency/Impact on the human health and eco-system
- Risk management options from the analogue study
  - Compare the conditions (geological/geochemical/geomechanical, etc.)
  - Identify that the relationship between the conditions and probability/consequences
  - Choose the management options
    - Accepting the risk
    - Monitoring to detect the leakage
    - Some remediation options, etc.

For risk interpretation and management

Risk matrix of the CO_2 leakage events based on natural analogue (if site is in the same condition…)

Consequence →

Probability ↑

	Detectable but no effects on human health and environment	Anxiety, discomfort, impact on env. recoverable in short time	Damage on human health and life, long-term impact on env.	Massive loss of life, unrecoverable change of eco-system
More than once in the project term (<50 yrs)	Monitoring, damage reduction measures	Prevention measures or design chang	Not allowable (abort the project)	
More than once in the reserve period（<1000 yrs)	Acceptable with monitoring of leakage			
Geological evidence of the phenomena	Acceptable without any countermeasures			
Theoretically possible				

Condition of
nmoth Mt.

Condition of
Matsushiro

Condition of
Dieng

For risk interpretation and management

Risk matrix of the CO2 leakage events based on the industrial analogue

Consequence →

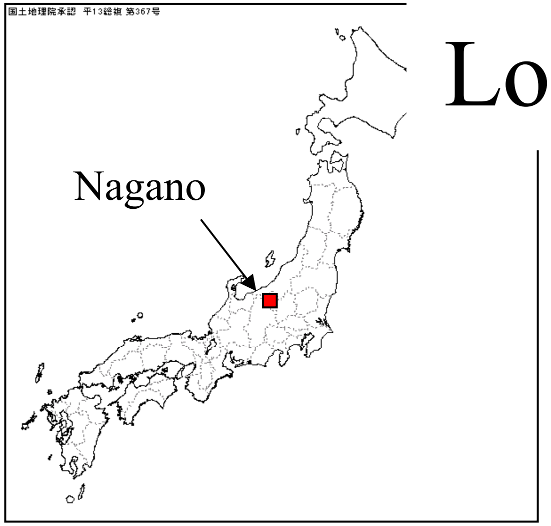
Probability ↑

	Detectable but no effects on human health and environment	Anxiety, discomfort, impact on env. recoverable in short time	Damage on human health and life, long-term impact on env.	Massive loss of life, unrecoverable change of eco-system
Usually happen in each field	Prevention measures or design change		Not allowable (abort the project)	
Often heard in the industry (once per year)	Monitoring, damage reduction measures			
One or a few records in the industry	Acceptable with monitoring of leakage			
Not heard in the industry	Acceptable without any countermeasures			

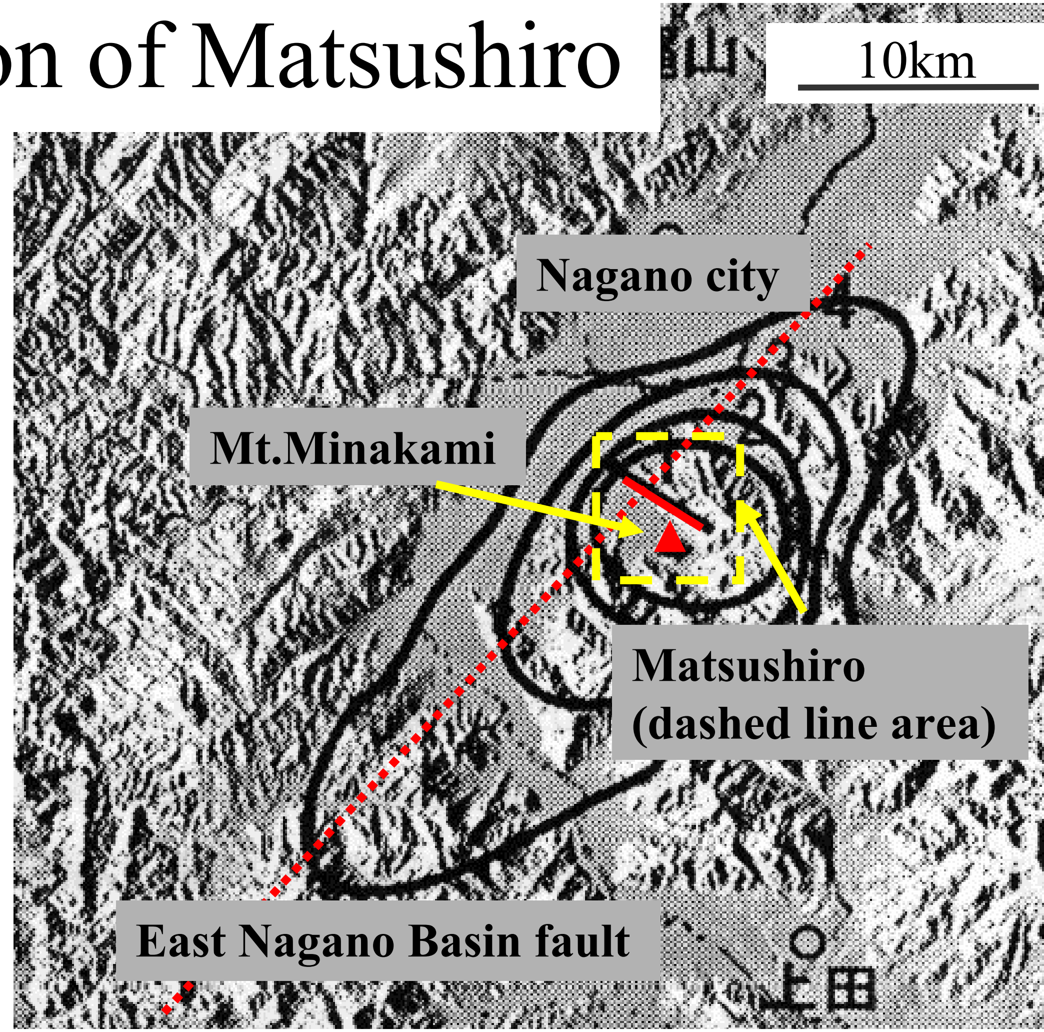
Our natural analogue study ongoing

Objective

- Study of natural analogues
  - ►To identify key mechanisms and processes relevant to long-term stability and potential seepage associated with CO_2 geological sequestration
- Faults
  - ►One of the major potential cause of CO_2 seepage
  - ►Difficult to characterize by laboratory tests



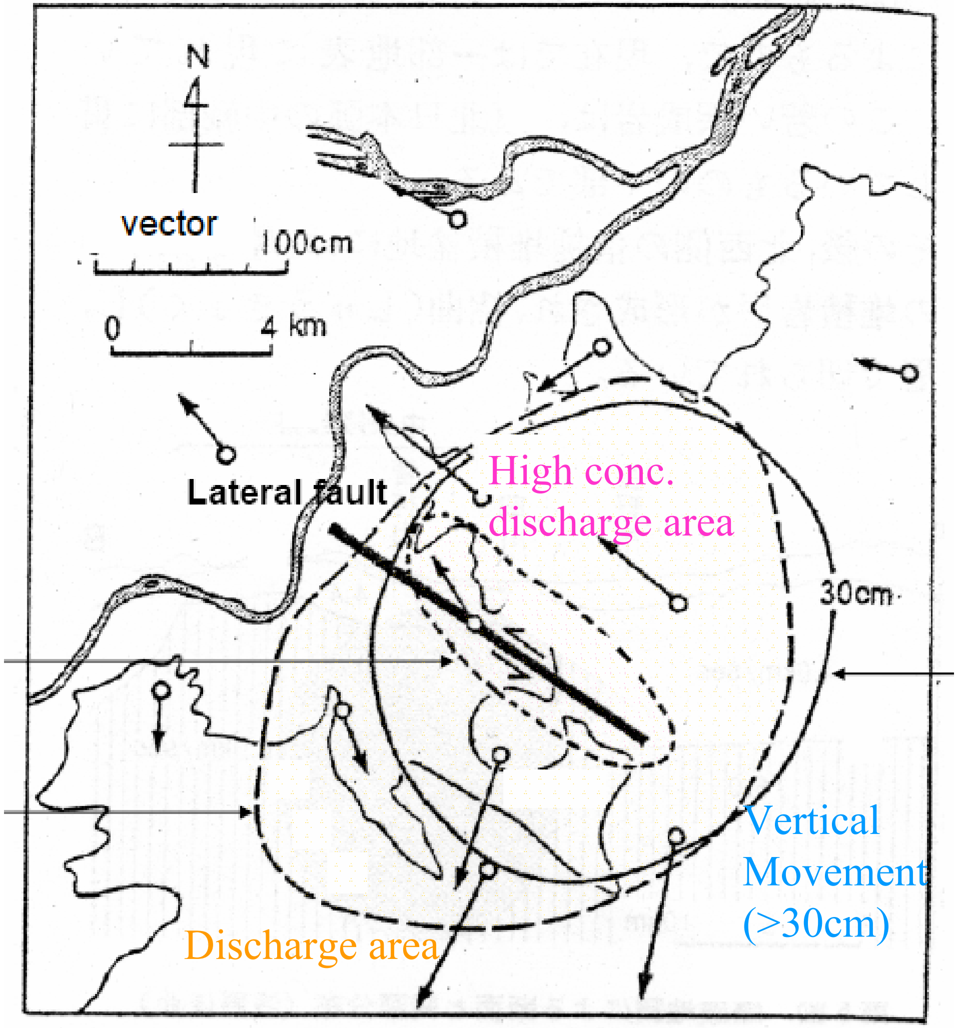
Location of Matsushiro

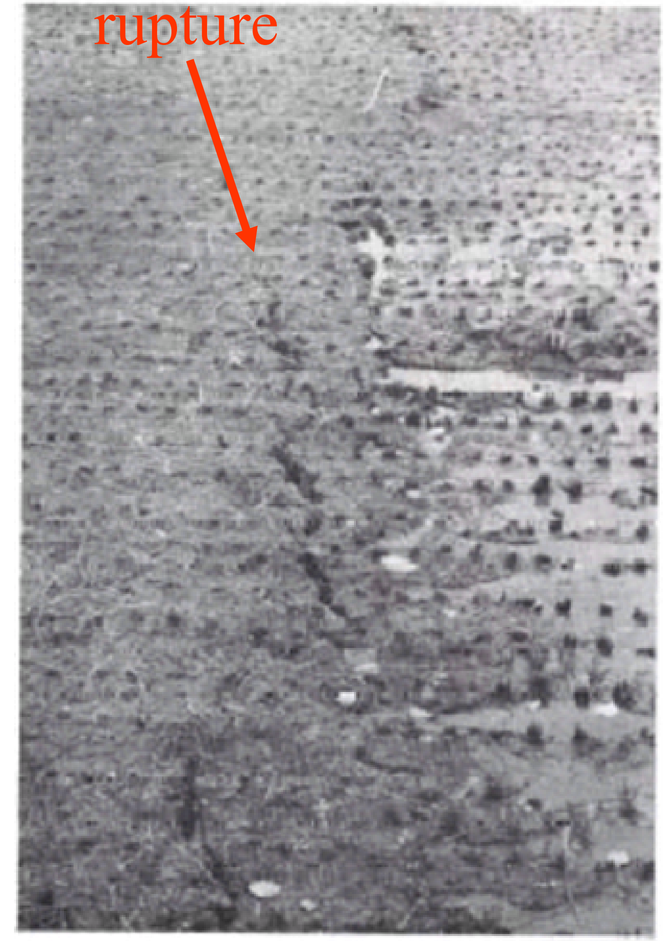


Location: suburb of Nagano city
Land use: agricultural, residential
Geology: NE-SW major reverse fault and conjugated strike-slip fault
fan sediment(surface), volcanic rock(basement), lava dome

Characteristics of Matsushiro

- Major reverse fault and conjugated strike-slip fault
- A little CO_2 is emitted from ground.(present) .
- Earthquake Swarm(1965-1967)
  - ►60,000 earthquakes were felt and additional 600,000 unfelt tremors were recorded during five-year period (JMA,1968)
  - ►Total energy released was M6.4, the energy of the maximum single earthquake was M5.4
  - ►During the swarm, ten million tons of CO_2 bearing water discharged at the surface through newly created surface ruptures





Nakamura(1971)

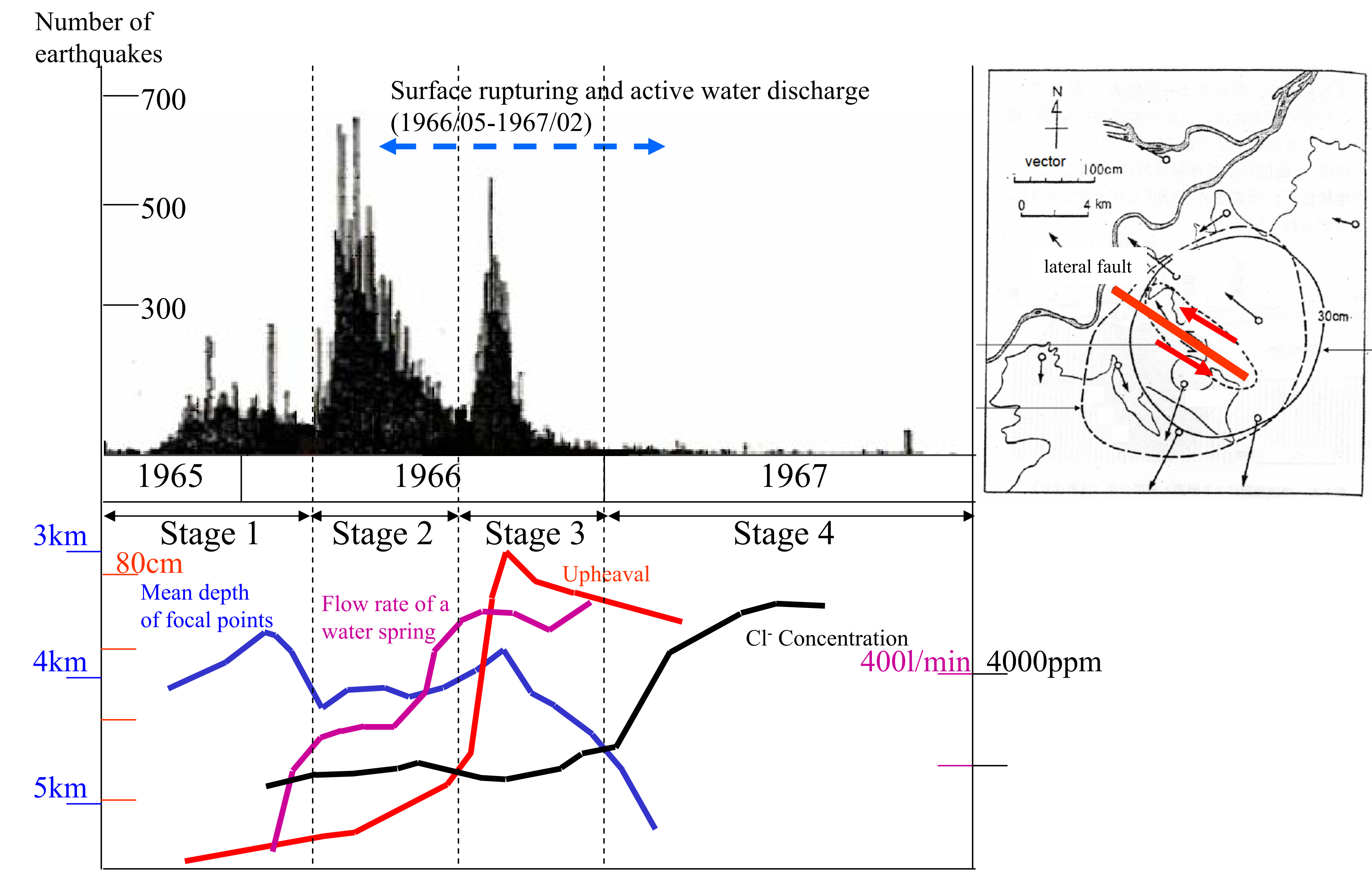
One probable cause of the swarm:

- water intrusion from great depth
- dilatancy reactivated the fault system

Matushiro and Mammoth Mt.

Geological conditions and Phenomena

	Matsushiro	Mammoth Mt.
Geology	Hypabyssal rocks, surface is covered by sediment	Volcanic rock
Structure	Uplift zone near a volcano	Outer rim of a caldera
Hydrogeology	Much rain fall,	Snow fall,
Stress state	Compressional (Strike-slip fault)	Extensional (Normal fault)
Fault	Single fault with a conjugate fault	Complex system
Relation to earthquake	During the seismic activity	After the earthquake (?)
Long-term	Stop immediately (?)	Continue for more than ten years
Fluid	CO2 saturated brine	Free gas
Impact	No casuality, influence on the eco-system not detected	Tree kill, a skier overwhelmed



Time series change of seismicity, uplift, spring discharge, and salinity (1965-1967). (After JMA 1968, Tsukahara and Yoshida 2005)

Hypothesis and approaches

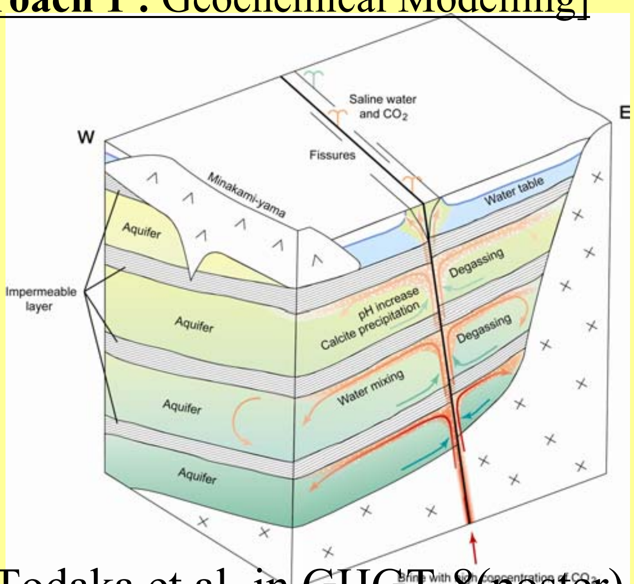
Geochemistry

- Supply of CO_2 bearing water from deep formations
  - → Dissolution of carbonate cap by increased acidity ⇕ Pore pressure increment and reactivation of faults (enhancement of permeability and earthquakes)
  - → Degassing from water
  - → Creation of Carbonate cap / Fluid pressure release due to outflow, degassing and dilatancy of faults
  - → Stabilization (current state)

Geomechanics

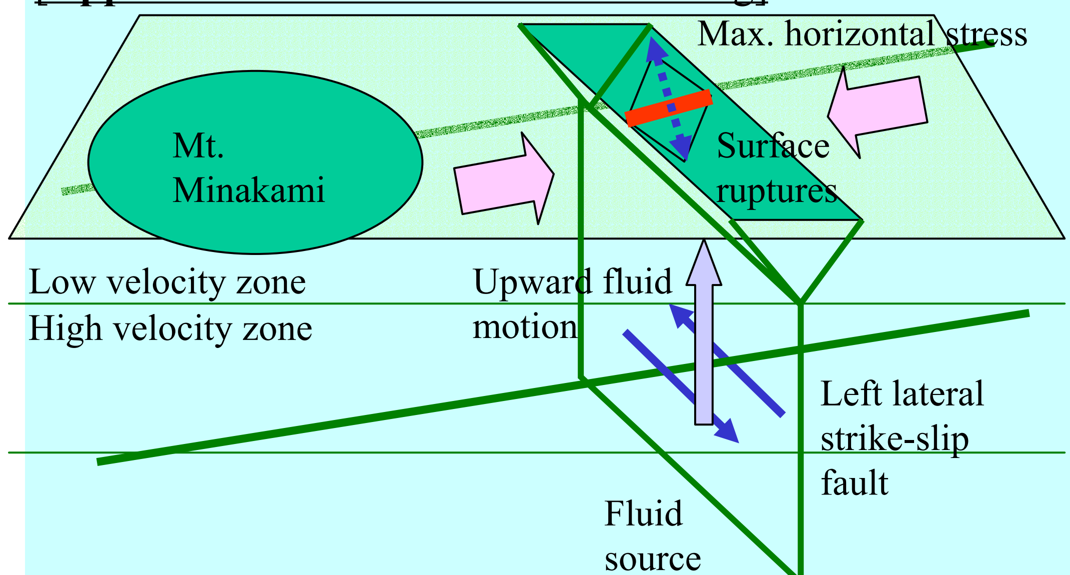
[Approach 3 : Geochemical survey]
- -Soil gas concentration
- -CO2 flux

[Approach 1 : Geochemical Modelling]



See Todaka et al. in GHGT-8(poster)

[Approach 2 : Geomechanical Modelling]



Summary and future work

- Matsushiro site is a promising natural analogue for studies of fault - fluid interaction related to CO_2 injection, including both mechanical and chemical interactions
- Geochemical survey, geomechanics coupled flow modelling, geochemistry coupled flow modelling are being conducted
- Resistivity survey, drilling and fluid sampling, and further modelling work will be done this year
- Risk assessment and management guideline for CO_2 seepage through faults will be established using this natural analogue

Promotion of international collaboration

Need International collaboration

- There are many existing studies
  - ►NASCENT, NACS, GEODISC
- Need more applications of knowledge from natural analogue to various stages of risk assessment and building confidence.
- Sharing collection of application of natural analogue would help building confidence for CCS in the world.

Development of international collaboration for building confidence in the long-term effectiveness of the geological storage of CO_2

Hiroyasu Takase
Quintessa Japan

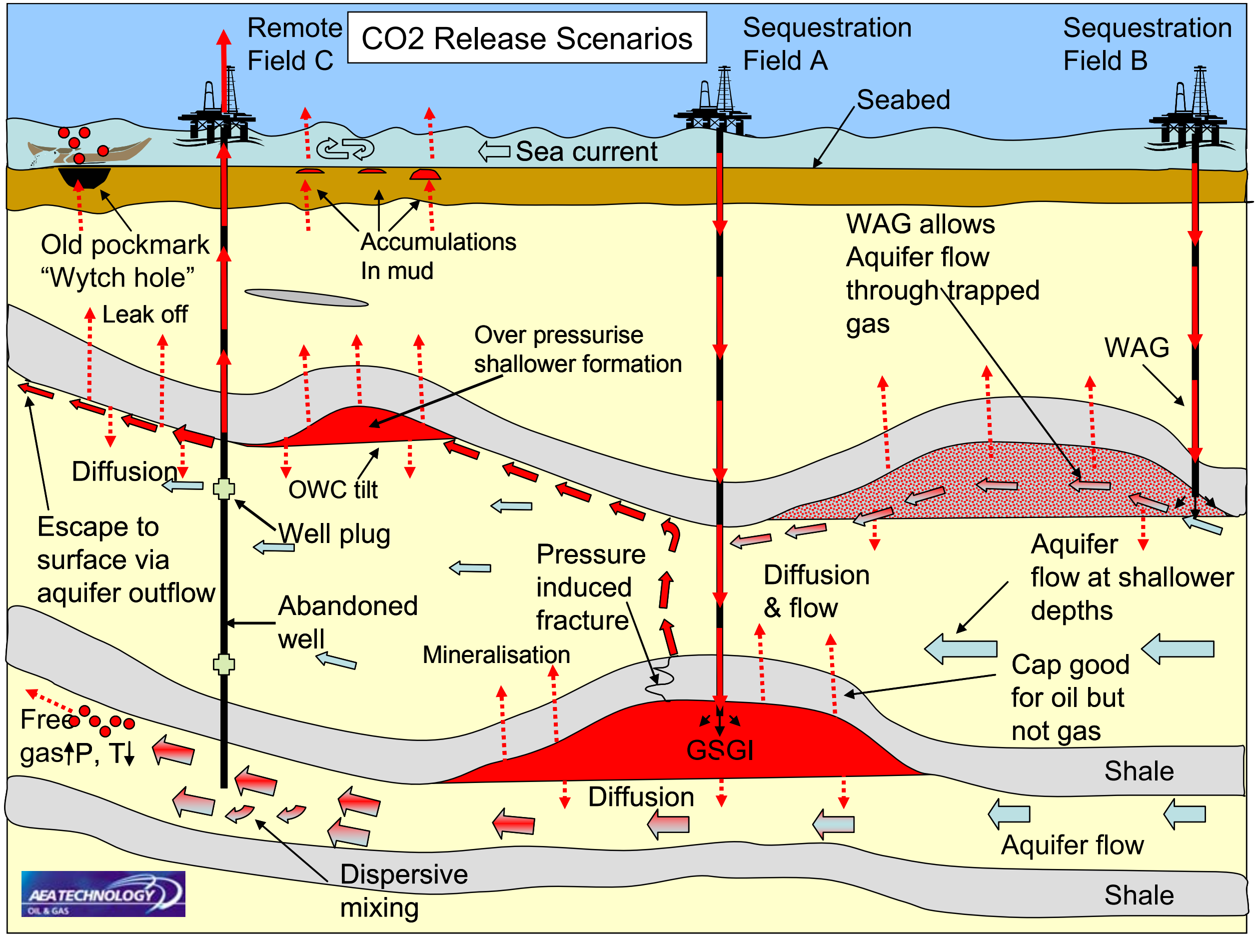
Contents

- Background & Objectives
- Examples
- What can we gain from an international collaboration?

Background & Objectives

FEPs relating to long-term effectiveness of CCS

- Impossible to describe completely the evolution of an open system with multiple potential migration paths for CO_2



Objectives of confidence building

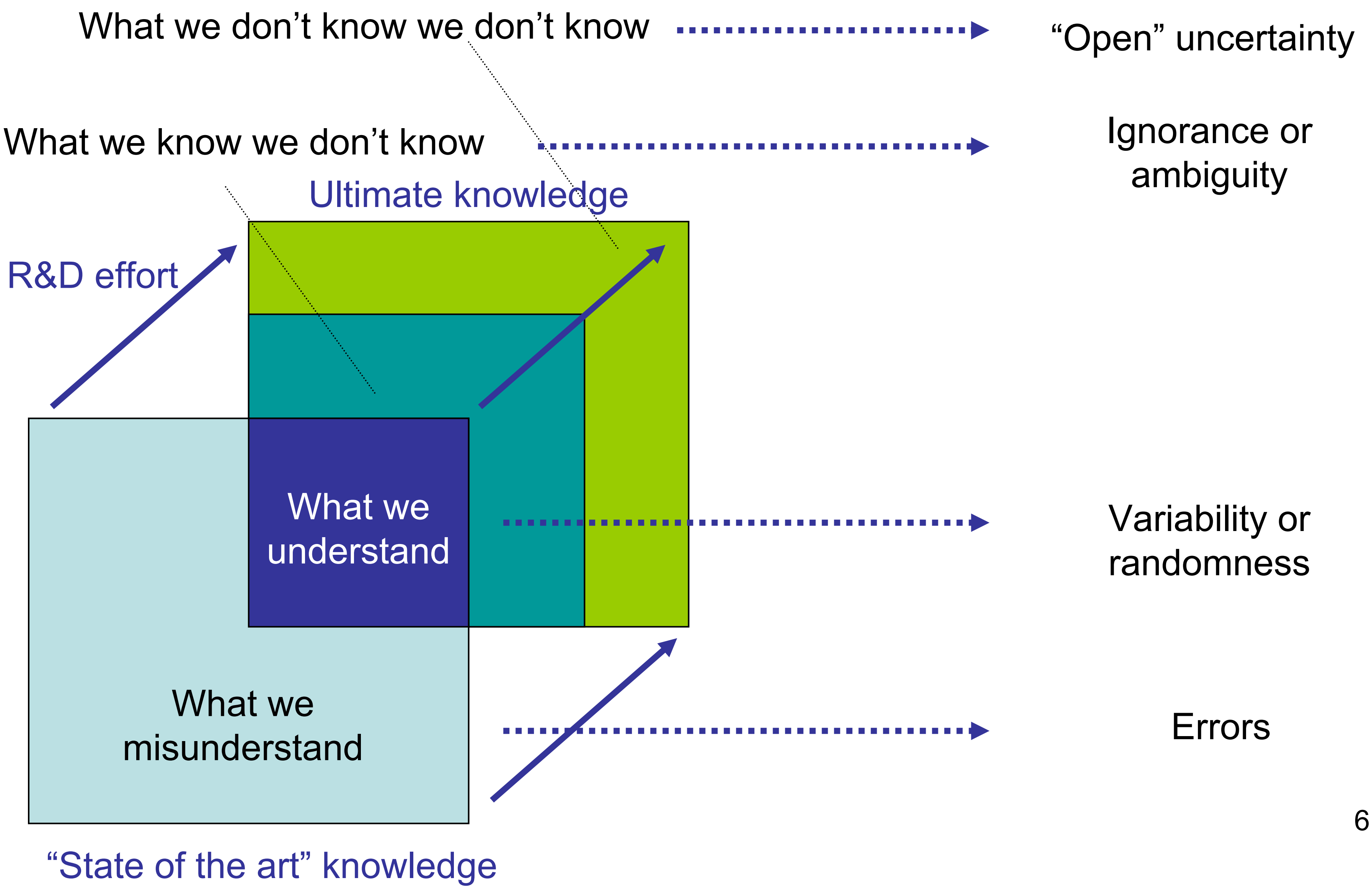
- A number of arguments to support effectiveness of confinement.
- Strategy for dealing with uncertainties that could compromise effectiveness.
- Assessment of our confidence in performance of the system in the presence of uncertainty.

→ Adequate level of confidence to support decision at hand (rather than a rigorous quantitative “proof”)

↓

Iterative process of decision making

Types of uncertainty



Variability and Ignorance

Variability

- Stochastic nature of the phenomena.
- Spatial heterogeneity is an important class of variability.
- Probabilistic framework, e.g., geostatistics, is usually used to describe variability.
- Variability cannot be reduced by investigation.

Ignorance

- Ambiguity in our knowledge due to imprecise and/or imperfect information.
- (Subjective) probabilistic approach or Fuzzy set theory is usually used to describe ignorance.
- Ignorance could be reduced by further investigation.

"Duality" between confidence building and uncertainty management

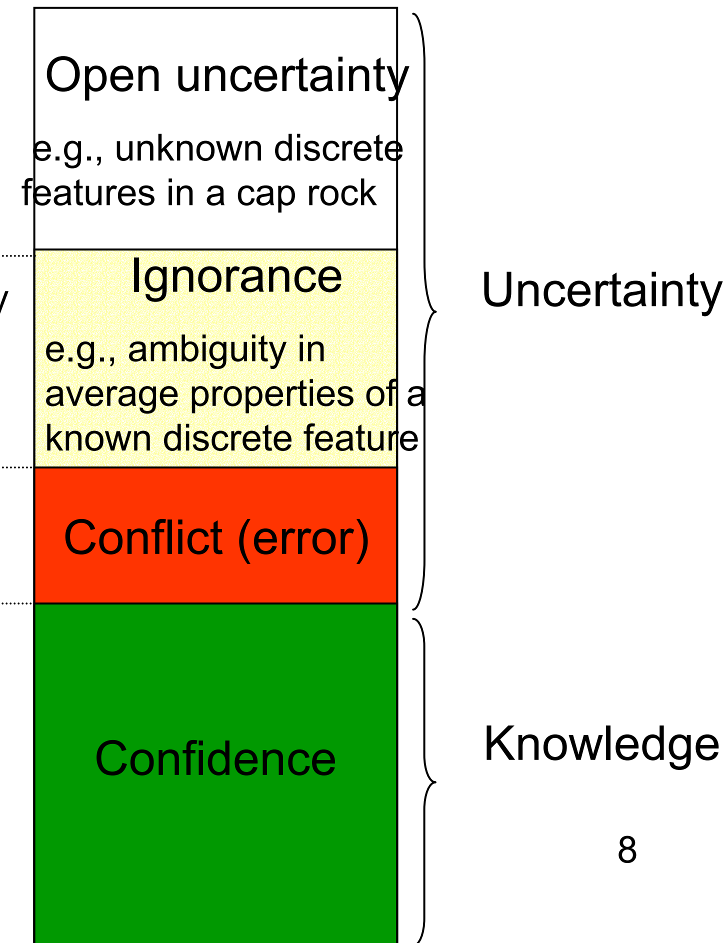
Confidence building / Uncertainty management

- "What if" analysis to bound size of impact
- Evidence to maximize chance of realizing discrete features
- Defense in depth concept to minimize impact of unknown discrete features

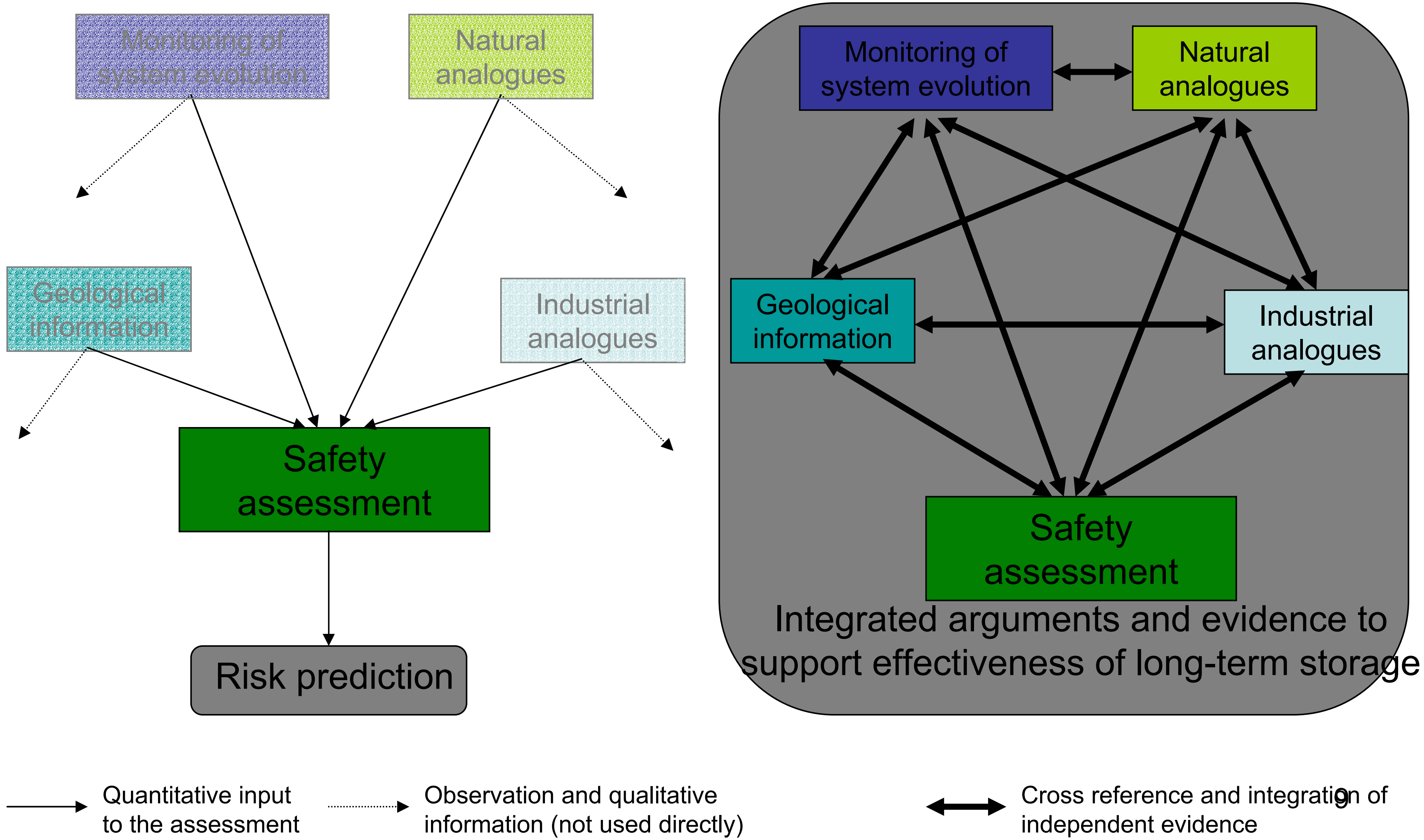
- Possibility theory, Fuzzy set theory, subjective probability
- Acquisition of new data / information
- Design change

- Verification / validation

Variety of imprecise and imperfect evidence



Advantage of using multiple lines of reasoning



Summary

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

Example
Exercise of Integrated Safety Assessment
for a sub-seabed reservoir

Objectives of exercise

- Comprehensive identification of scenarios leading to environmental risks

  review of mechanisms leading to risks originating from a sub-seabed CO_2 sequestration.

- Development/assessment of a set of robust arguments

  multiple lines of reasoning for safety of sub-seabed CO_2 sequestration supported by a variety of available evidence such as geological survey, reservoir simulation, risk assessment, monitoring, similar experience at analogous host formations, etc.+ feed back to planning

Approach

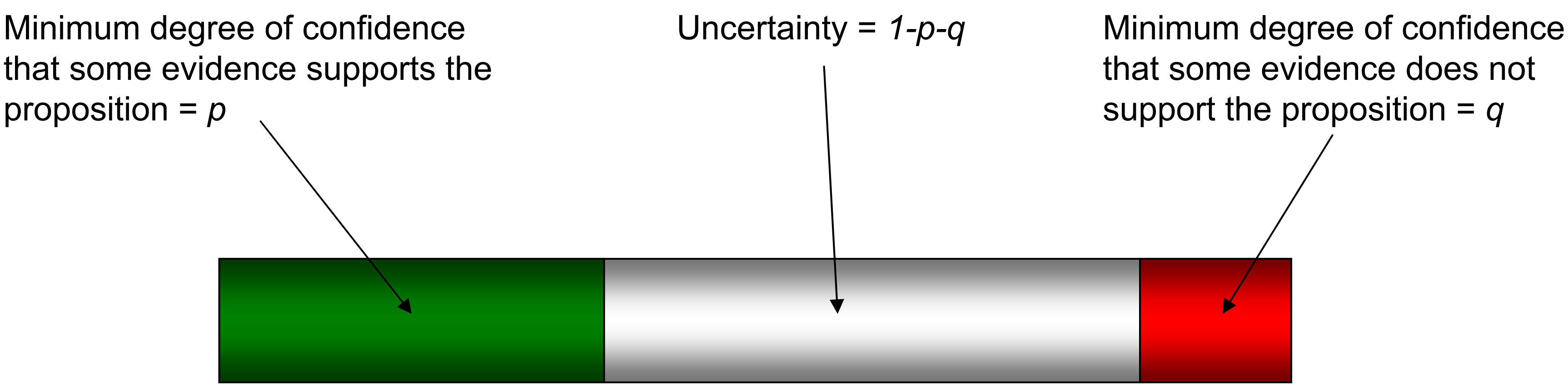
- International FEP database
- ✓ FEP database collated by IEA is used so that comprehensiveness and consistency with international development is guaranteed.
- ✓ Influence diagram is generated to illustrate chains of FEPs leading to impact on environment.
- ✓ Fault tree analysis is carried out to identify possible mechanisms and key factors for risks.
- Evidential Support Logic (ESL)
- ✓ A variety of available evidence such as geological survey, reservoir simulation, risk assessment, monitoring, similar experience at analogous host formations, etc. is used to strengthen arguments for confinement.
- ✓ Plausibility of countermeasures against possible mechanisms for risks is assessed from a holistic point of view using ESL.

Evidential Support Logic (ESL)

- A generic mathematical concept to evaluate confidence in a decision based on the evidence theory and consists of the following key components (Hall, 1994).
- First task of ESL is to unfold a “top” proposition iteratively to form an inverted tree-like structure (Process Model). The subdivision is continued until the proposition becomes sufficiently specific and evidence to judge its adequacy becomes available.
- Degree of confidence in the support for each lowest-level proposition from corresponding information (*i.e.* evidence) is estimated and propagated through the Process Model using simple arithmetic.

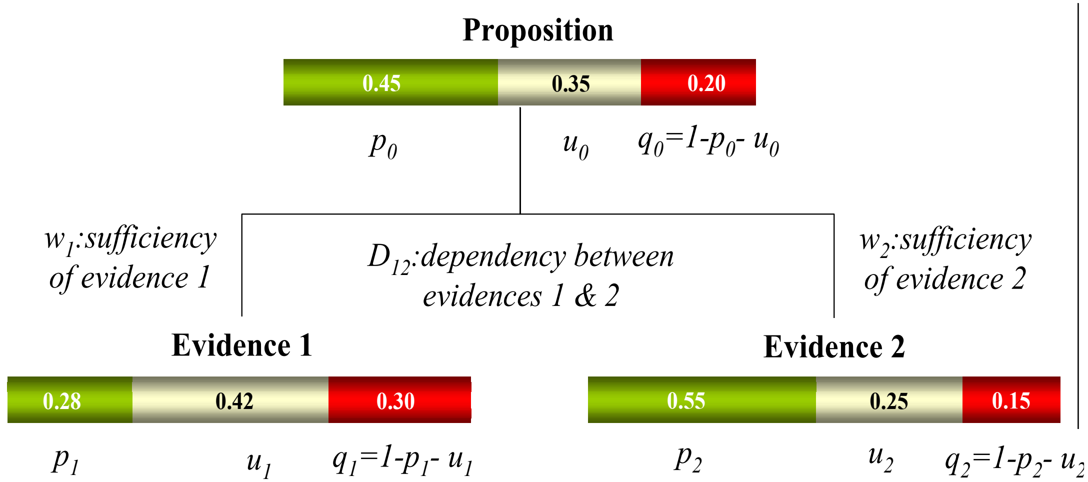
Subjective Interval Probability

- Degree of confidence that some evidence supports a proposition can be expressed as a subjective probability.
- Evidence concerning a complex system is often incomplete and/or imprecise, so it may be inappropriate to use the classical (point) probability theory.
- For this reason, ESL uses Interval Probability Theory.



Mathematics to Propagate Confidence

- "Sufficiency" of an individual piece of evidence or lower level proposition can be regarded as the corresponding conditional probability, *i.e.,* the probability of the higher level proposition being true provided each piece of evidence or lower level proposition is true.
- A parameter called "dependency" is introduced to avoid double counting of support from any mutually dependent pieces of evidence.



$$p_0 = w_1 \; p_1 + w_2 \; p_2 - \rho_{12} Min(w_1 \; p_1 \;, w_2 \; p_2 \;)$$

$$q_0 = w_1 \; q_1 + w_2 \; q_2 - \rho_{12} Min(w_1 \; q_1 \;, w_2 \; q_2 \;)$$

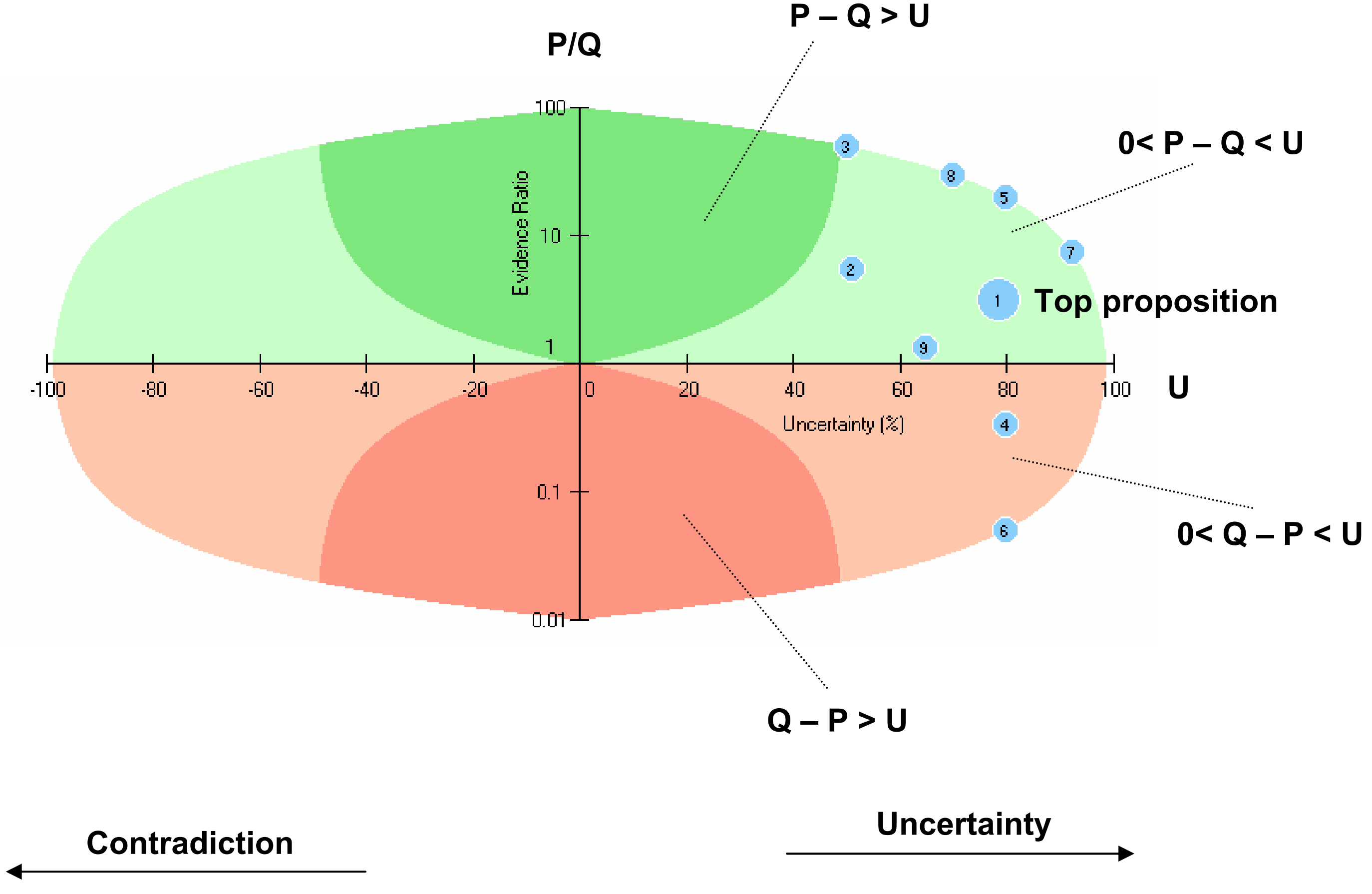
where $\rho_{12} = \frac{(1 - D_{12})(w_1 \; p_1 \; w_2 \; p_2 \;)}{Min(w_1 \; p_1 \;, w_2 \; p_2 \;)} + D_{12}$

Presentation of Assessment Result
- Ratio plot -

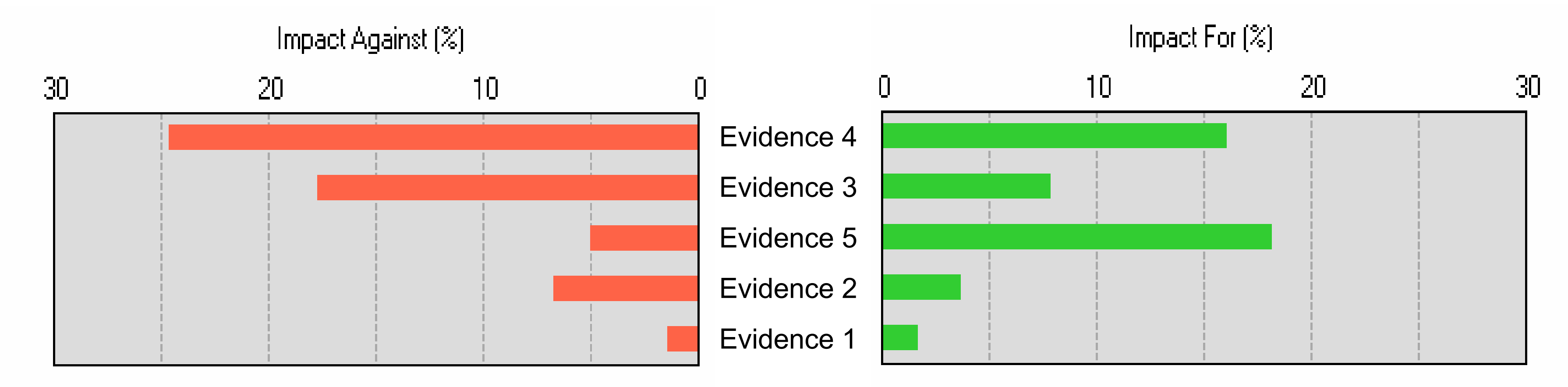
Confidence in argument for the proposition, *P*

Confidence in argument against the proposition, *Q*

Uncertainty, *U*



Sensitivity Analysis
- Tornado Plot -



Relative importance of acquiring new evidence by geophysical survey, monitoring, reservoir simulation, etc., is evaluated by increasing *P* (“impact for”) or *Q* (“impact against”) by one unit and investigate how it propagates to the top proposition

Example of “key” safety argument

- Influence of Thief Beds -

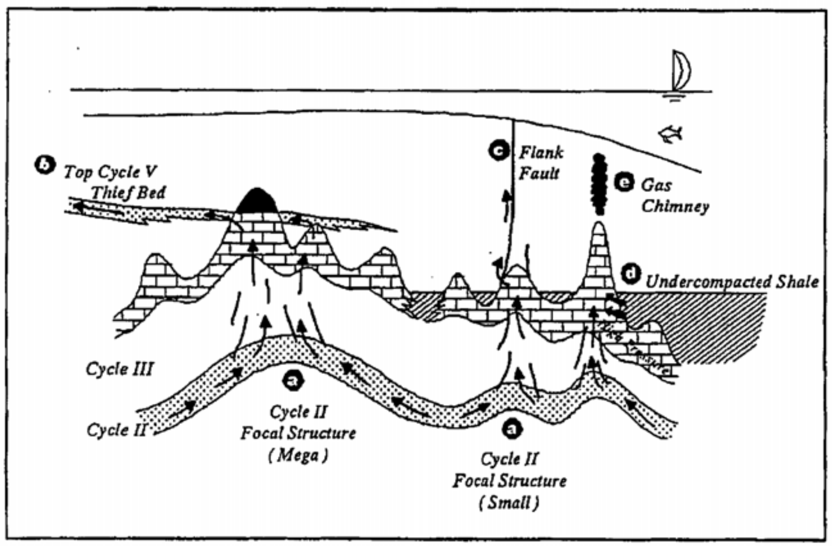
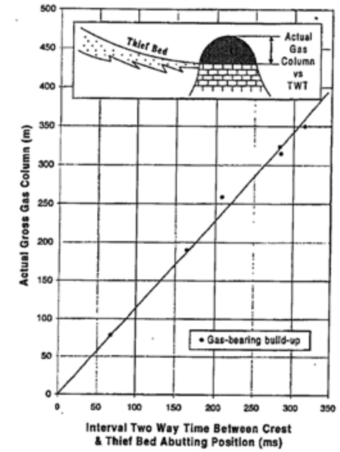


Fig. 2 Schematic view of main risk factors



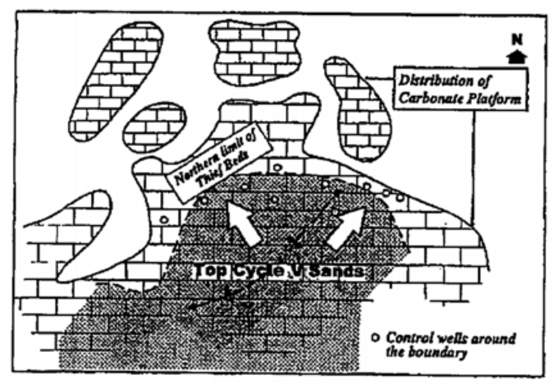


Fig. 7 North limit of sandy thief beds (Top Cycle V)

From Nakashima & Chow (1998)

Example

Process Model for Release through Thief Beds

- No unacceptable release through thief beds in the cap rock
  - Non-existence of thief beds in the cap rock
    - Borehole investigation in the target area
    - Geophysical investigation in the target area
    - 3D Facy modelling
  - Sealing capability of the cap rock in the adjacent natural gas field
    - Stability of natural gas reservoir where no thief beds are detected by the same method
    - Confirmation by routine monitoring at the natural gas field where no thief beds are detected by the same method
  - Numerical simulation of release through thief beds in the cap rock
    - Reservoir simulator (Continuum multi-phase Darcy model:Dterministic)
    - System assessment model (Dterministic: Stochastic)
  - Monitoring during and after CO2 injection in the target area
    - 4D seismic monitoring
    - Microseismicity
    - Gravity
    - Airborne remote sensing
    - Gas/fluid sampling at the sea bed
    - Side scan sonar

Assessing Experts’ Confidence by ESL

- Confidence in each Process Model was evaluated by applying ESL.
- For this purpose, a group of experts ranging from geologists, civil engineers and safety assessors was formed and each Process Model was reviewed.
- The experts evaluated their degree of belief on each argument supported or disqualified by the evidence, together with estimation of sufficiency of each argument in judging the proposition at the higher level.
- Whenever members of the expert group had different opinions, the minimum value was used as a consensus. By applying this rule, the variation of the experts’ view is regarded as a component of uncertainty.

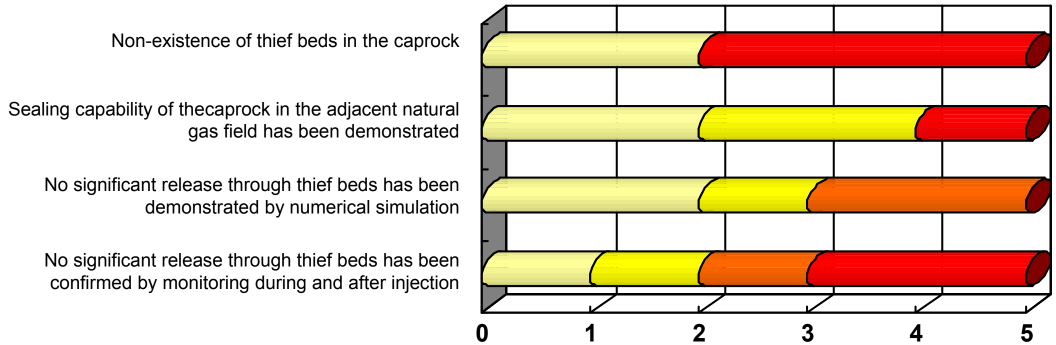
Result of expert elicitation

Sufficiency of each argument

Date: Feb 13the, 2006
Respondent to the questionnaire: 5

LEVEL 1

Proposition: No unacceptable release through thief beds in the caprock



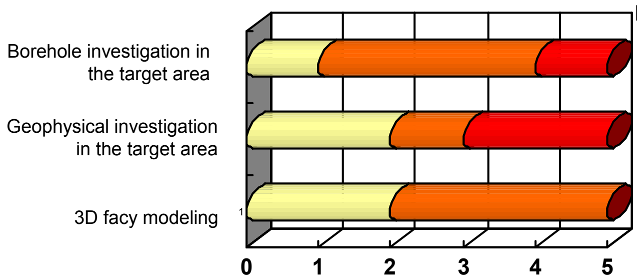
Highest	Ave.
0.9	0.66
0.9	0.5
0.7	0.5
0.9	0.66

(Point)

- Very low (0.1)
- Low (0.3)
- Moderate (0.5)
- High (0.7)
- Very high (0.9)

LEVEL 2

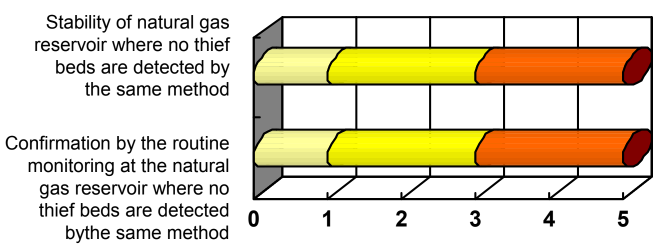
Sub-proposition: Non-existance of thief beds in the caprock



Highest	Ave.
0.9	0.66
0.9	0.62
0.7	0.54

(Point)

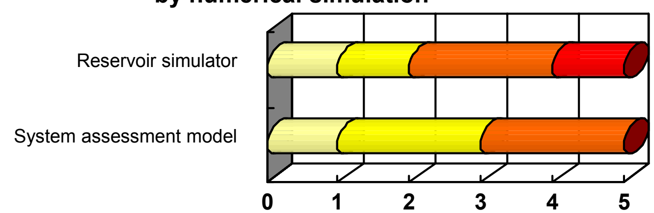
Sub-proposition: Sealing capability of thecaprock in the adjacent natural gas field has been demonstrated



Highest	Ave.
0.7	0.54
0.7	0.54

(Point)

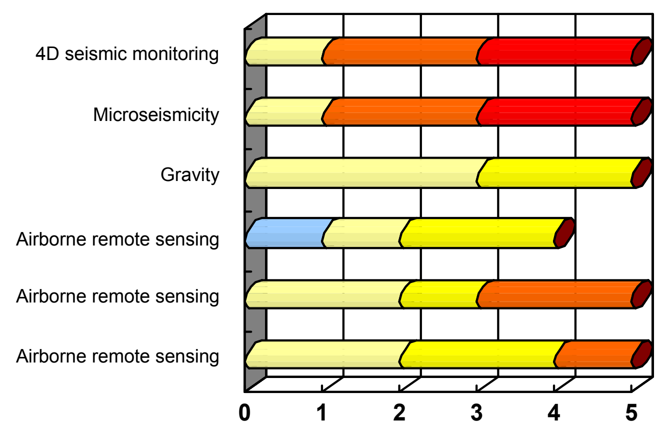
Sub-proposition: No significant release through thief beds has been demonstrated by numerical simulation



Highest	Ave.
0.9	0.68
0.7	0.54

(Point)

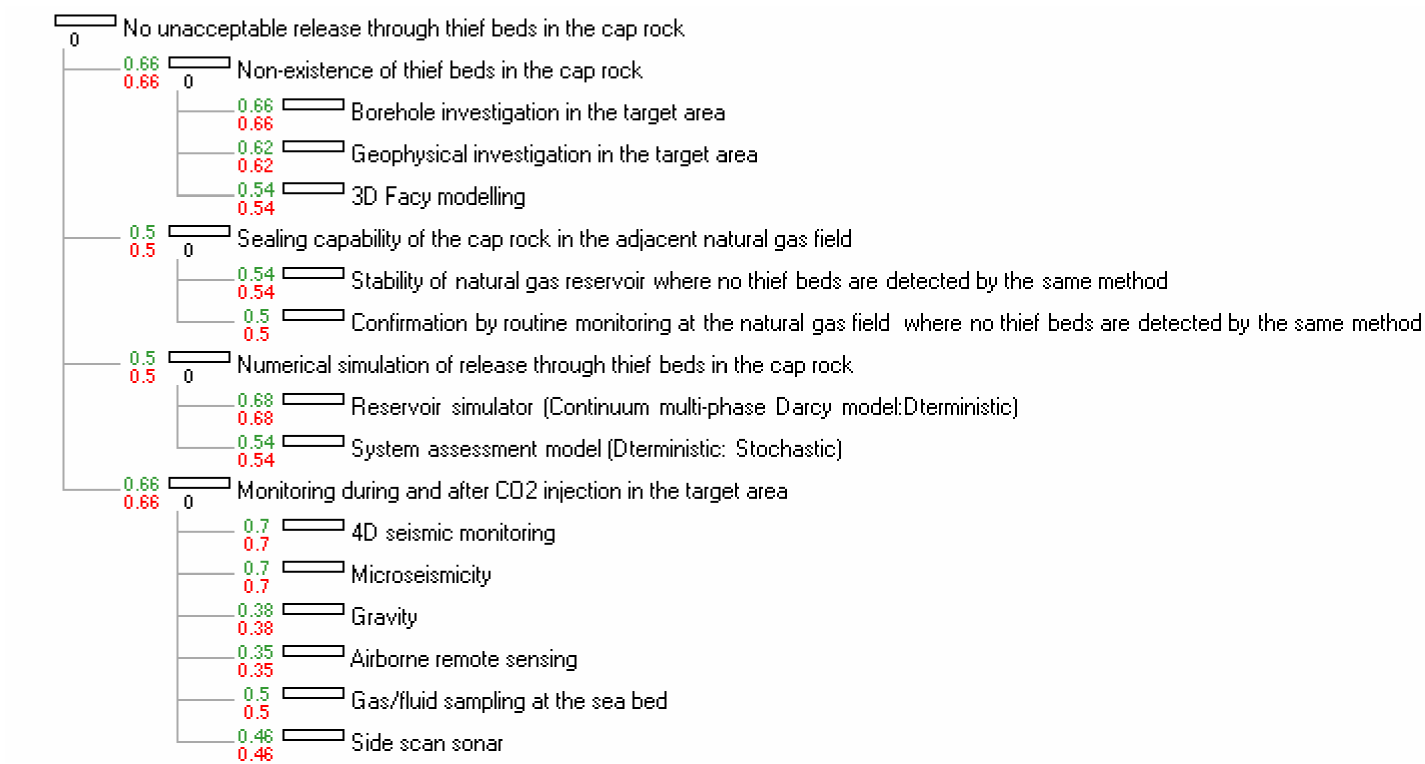
Sub-proposition: No significant release through thief beds has been confirmed by monitoring during and after injection



Highest	Ave.
0.9	0.7
0.9	0.7
0.5	0.38
0.5	0.35
0.7	0.5
0.7	0.46

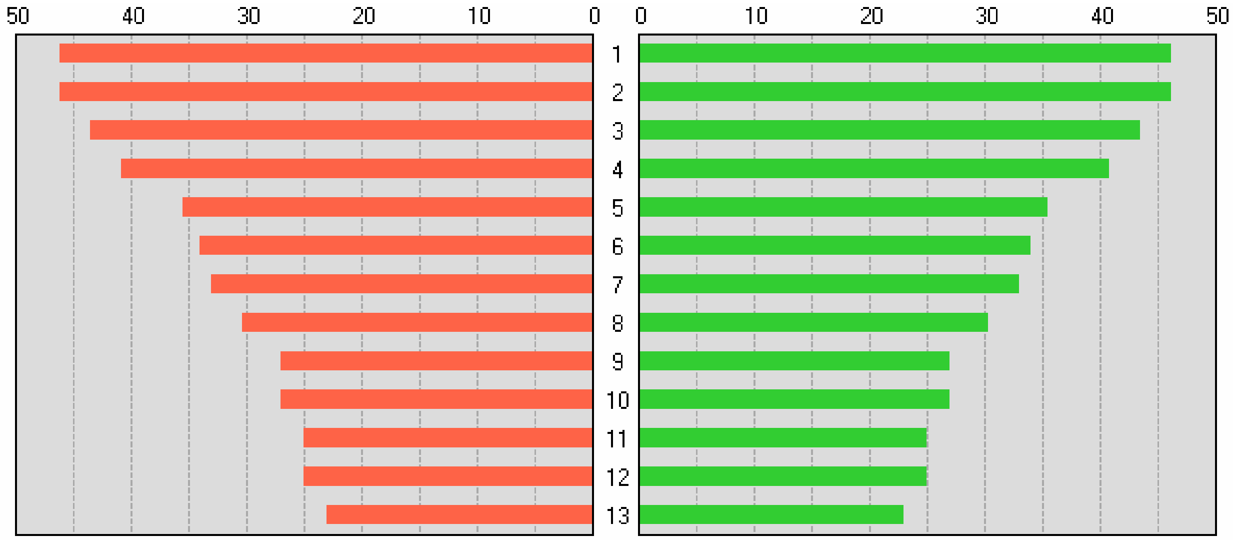
(Point)

Process Model with Sufficiency Input (Average Values)



Sensitivity Analysis

Impact against



Impact for

1 : 4D seismic monitoring

2 : Microseismicity

3 : Borehole investigation in the target area

4 : Geophysical investigation in the target area

5 : 3D Facy modelling

6 : Reservoir simulator (Continuum multi-phase Darcy model:Dterministic)

7 : Gas/fluid sampling at the sea bed

8 : Side scan sonar

9 : Stability of natural gas reservoir where no thief beds are detected by the same method

10 : System assessment model (Dterministic: Stochastic)

11 : Gravity

12 : Confirmation by routine monitoring at the natural gas field where no thief beds are detected by the same method

13 : Airborne remote sensing

FY2006

- The exercise will be continued focusing on;
- ✓ Formulation of the methodology and procedure including expert elicitation as a guideline
- ✓ More comprehensive “walk-through” example to assess applicability of methodology and to identify issues for further R&D

What we gain from
an international collaboration?

A way forward

- Advantages of international collaboration -

- Experience of building confidence at various CCS projects in different nations can be regarded as case studies.
- Variety of methodologies used in a number of CCS projects can be shared as a technical inventory by other nations.
- Collection of natural and industrial analogues world-wide can be employed as a generic database of evidence.
- Description of basic concepts and terminology in confidence building and a set of recommendations provides a broad international guideline.

LATROBE VALLEY CO_2 STORAGE ASSESSMENT (LVCSA)

(with focus on the RA activity)

A Team Effort

Presented by Andy Rigg

Cooperative Research Centre for Greenhouse Gas Technologies
(CO2CRC)

Outline

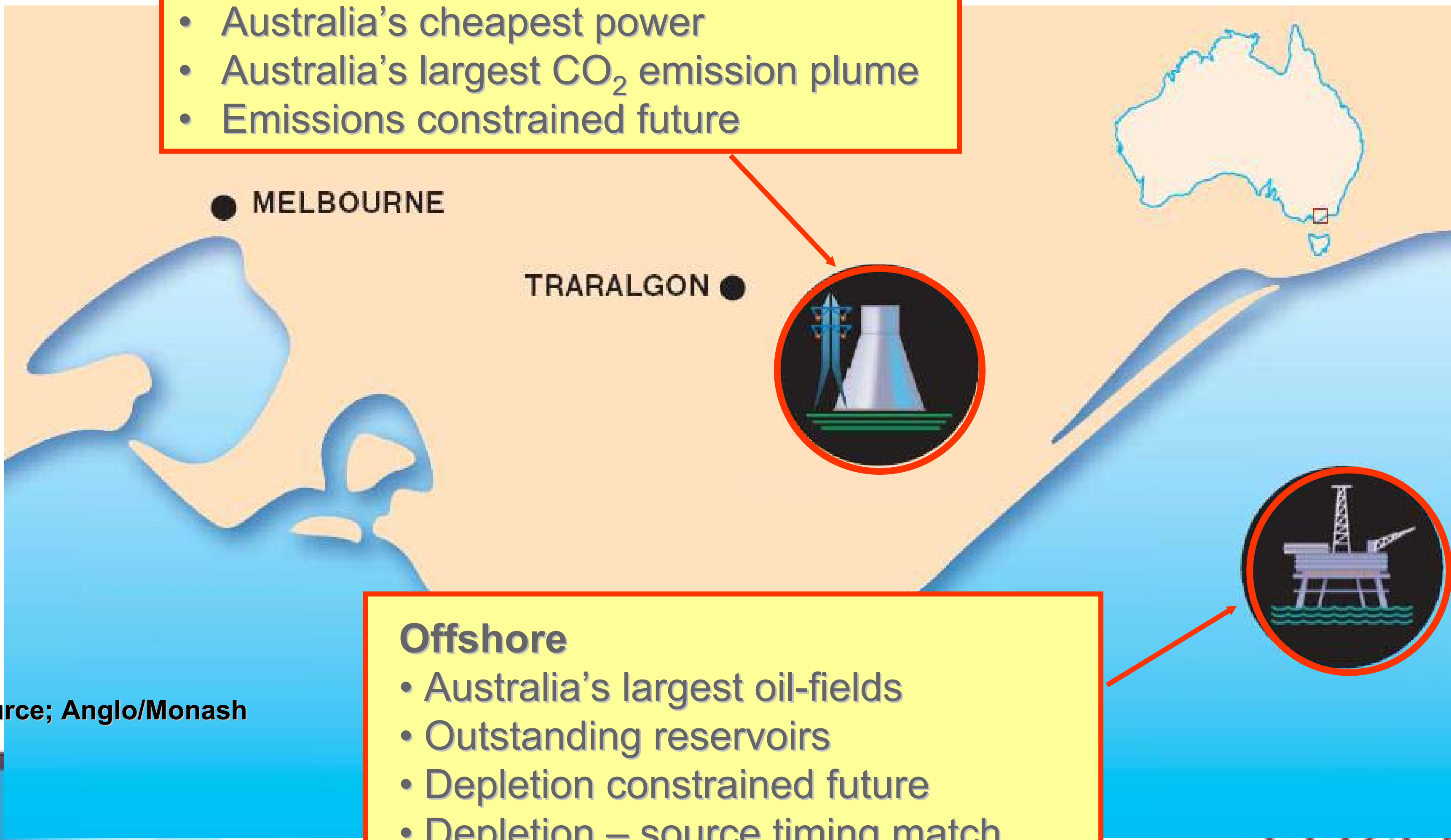
- Background to LVCSA; overview, outcomes, and tasks; concept
- Earth Science Studies
- Reservoir Modelling
- Storage Risk Assessment
  - GEODISC, CO2CRC background in RA
  - LVCSA Containment
    - ➢The quality of the data set used
    - ➢The methodology used
    - ➢The inherent assumptions that were made
    - ➢The results
- (Infrastructure Risk Assessment)

Broad task areas

- Geological/hydrological analysis and modelling
- Interaction with Bass Strait producers
- Risk assessment and storage assurance
- Development of infrastructure plans
- Techno-economic studies

Gippsland Basin Source – Sink Fundamentals

Onshore
- World's thickest coal
- Australia's cheapest power
- Australia's largest CO_2 emission plume
- Emissions constrained future



Source; Anglo/Monash

Offshore
- Australia's largest oil-fields
- Outstanding reservoirs
- Depletion constrained future
- Depletion – source timing match

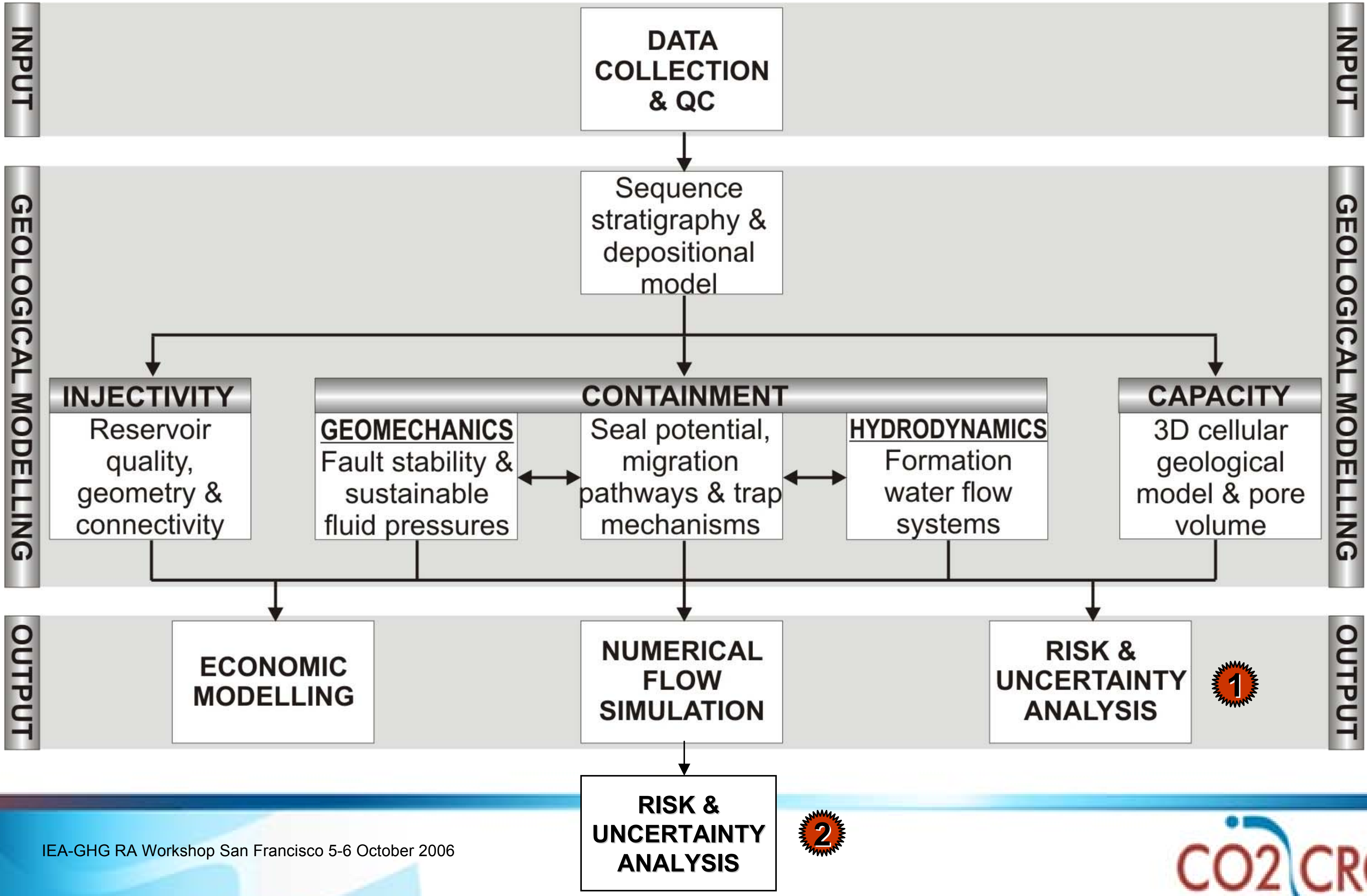
LVCSA Introduction

- The Problem
  - New brown coal developments in Latrobe Valley, Victoria
  - CO_2 emissions up to 50 Million tonnes/year
- Potential Solution
  - Offshore Gippsland Basin
  - Existing oil and gas fields (once depleted)
  - Deeper saline formations
- Injection Scenarios
  - Injection at several sites along regional migration pathways, sequentially & simultaneously, ramping up volume to 50 Mt/y

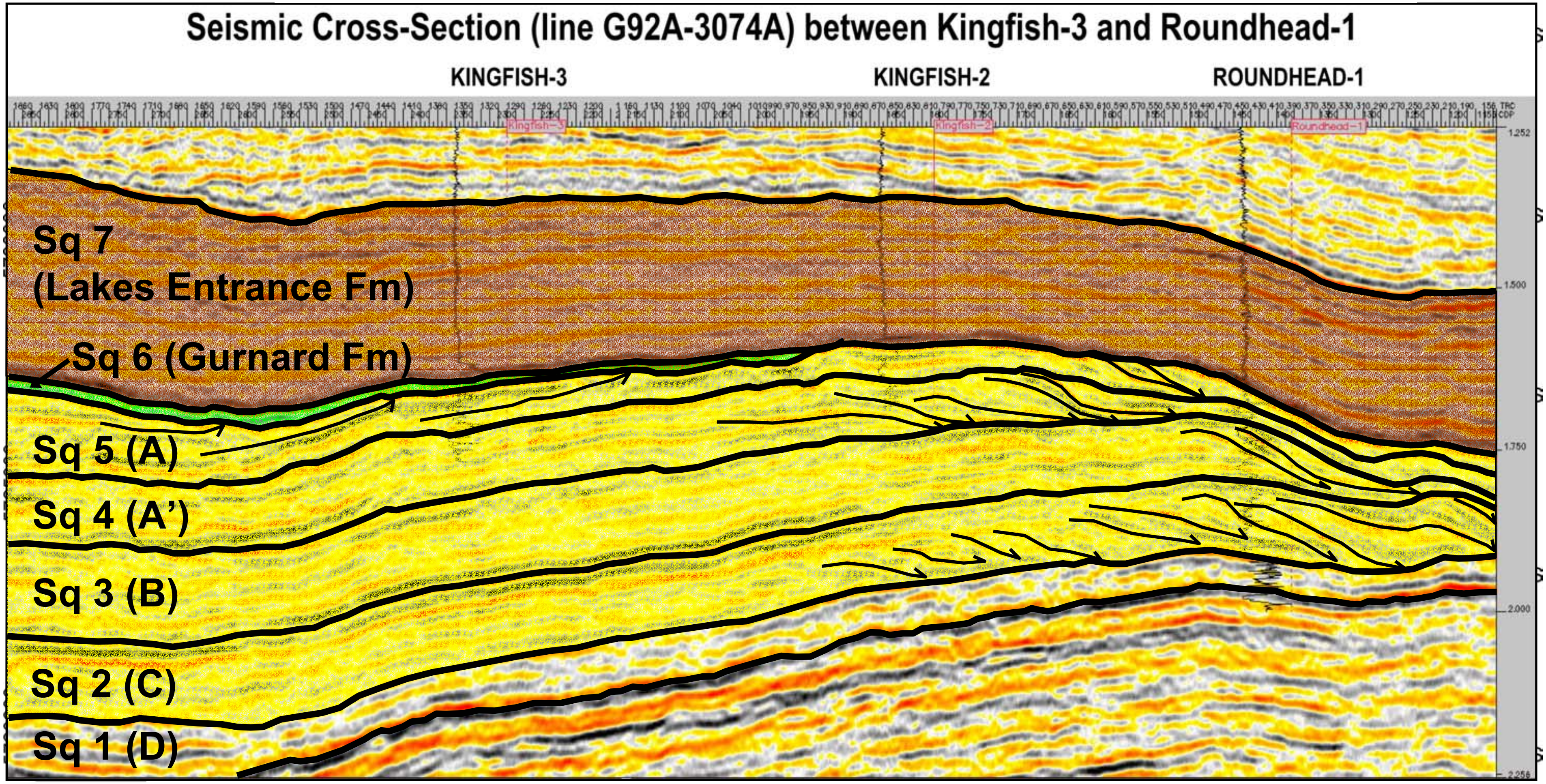
1. Kingfish Field: 15 Mt/y for 40 years ← **This presentation**
2. Fortescue Field: 15 Mt/y for 40 years
3. Basin centre & northern gas fields: 20 Mt/y for 40 years

CO2CRC

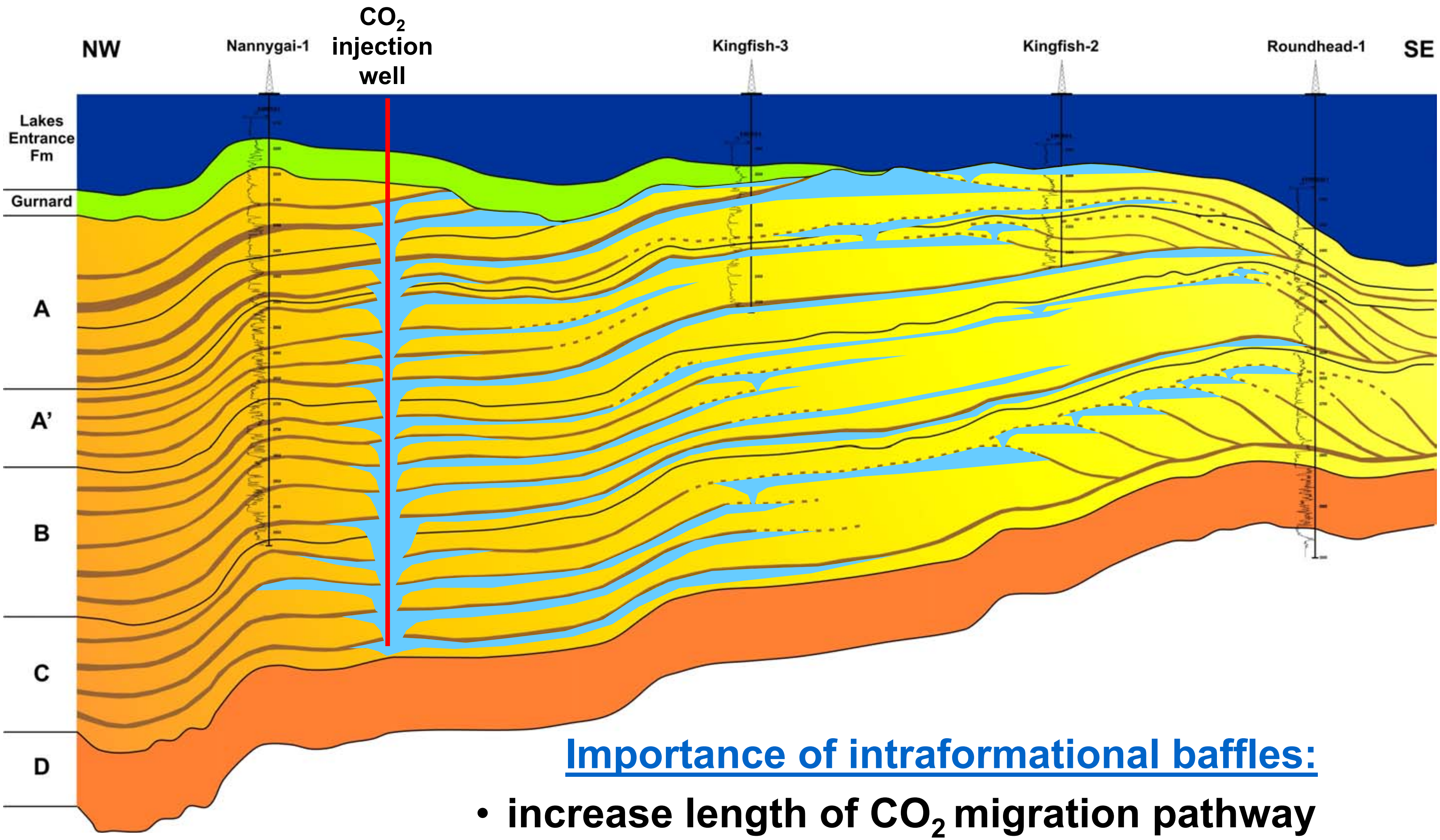
Storage Site Characterisation-Workflow



Sequence Stratigraphy



Containment: Migration Pathways Concept



Importance of intraformational baffles:

- increase length of CO_2 migration pathway
- increase volume of pore space moved through

= greater residual gas trapping & dissolution

Geoscience Conclusions

Suitability of Kingfish Field/Gippsland Basin as geosequestration site:

- Complex stratigraphic architecture which slows vertical migration and increases residual gas trapping
- Non-reactive reservoir units with high injectivity
- Geochemically-reactive, low permeability reservoir just below regional seal to provide additional mineral trapping
- Several pressure-depleted oil fields to provide storage capacity coupled with transient flow regime that enhances containment
- Long migration pathways beneath competent regional seal
- Kingfish Field, in conjunction with other sites (e.g. Fortescue, northern gas fields), indicate that Gippsland Basin has sufficient capacity to store very large volumes of CO_2.

Kingfish 3D Model outline

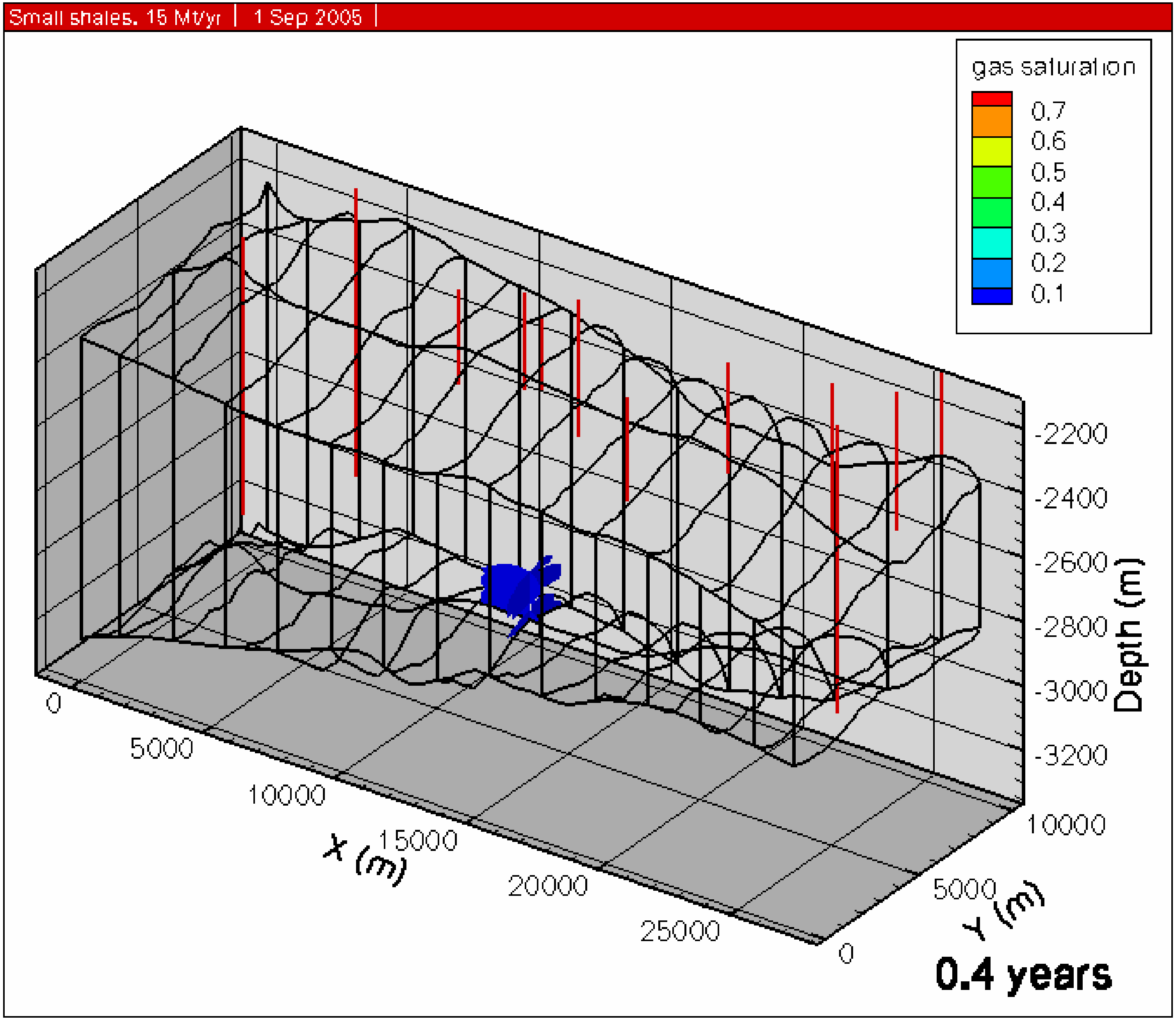
• Surfaces from 3D seismic

• Permeability averaged over each formation using porosity-perm transforms on logs

• Vertical permeability via object modelling of shale distributions

•Lateral spacing 500 m, vertical spacing ~ 10 m,
•91000 grid blocks

• Injection based on 1 Mt/yr per well



Kingfish Deep

- 15 Mt/y for 40 years
- Post-injection small shales 0–40 yrs

Gippsland QRA Context
Input Information

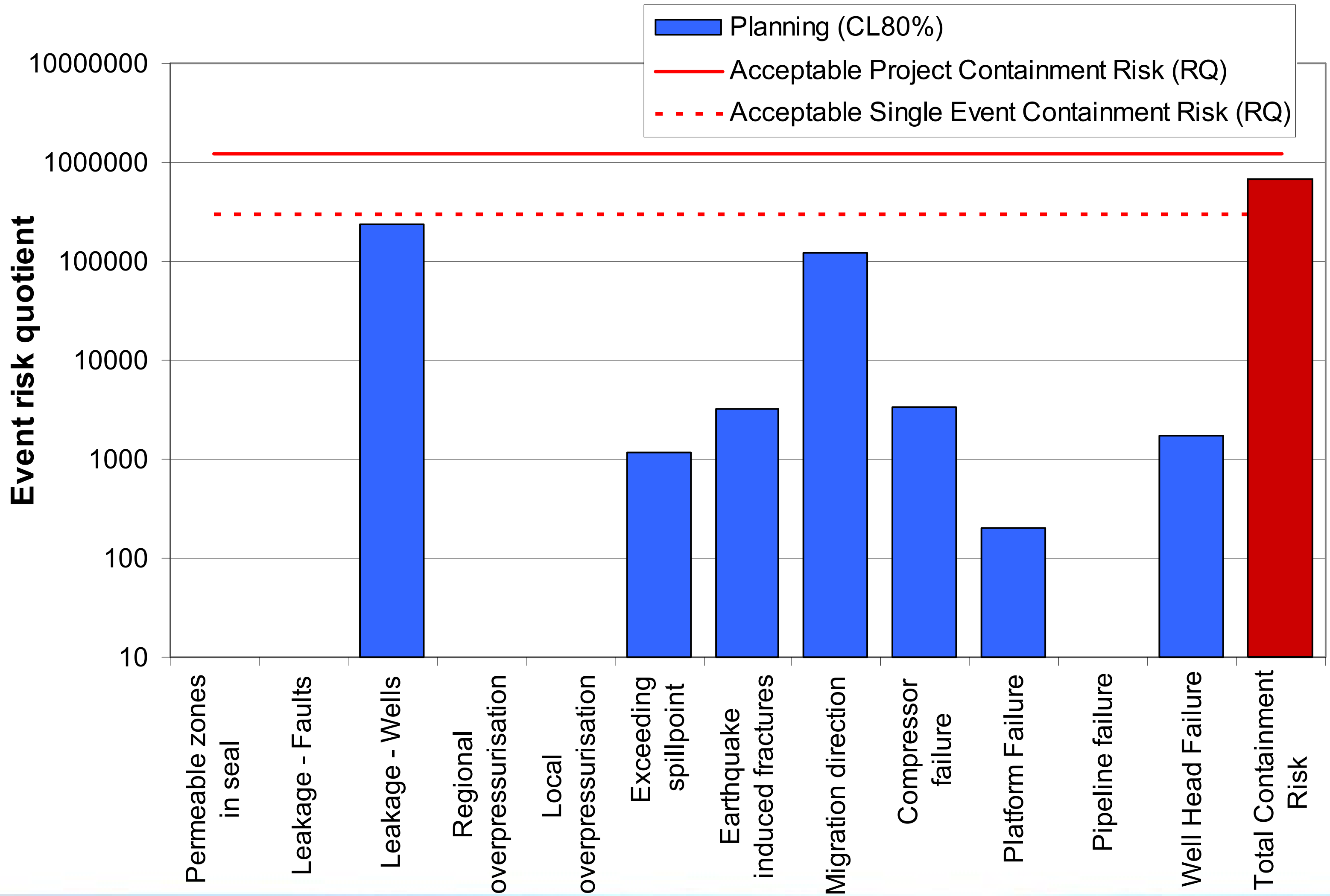
- Start injection 2015
- Injection in 3 stages
  - Initially (T_0) 15 Mtpa injection for 40 years below Kingfish oil reservoir; total injected 600 Mt
  - Subsequent (T_0+7 years) 15 Mtpa injection for 40 years below Halibut/Fortescue oil reservoirs; total injected 600 Mt
  - Subsequent (T_0+15 years) 20 Mtpa injection for 40 years in the Central Deep; total injected 800Mt
- Total injection to year 2070 amounts to 2000 Mt (= amount extracted)
- 2 injection models
  - Kingfish (repeated for Halibut/Fortescue); 15 near vertical wells
  - Central Deep; 20 near vertical wells

Containment; leakage from existing exploration wells

Location	Probability of Being present (Annual)	Probability of Being present (1000 years)	Loss Rate (t/yr/item)	No. of Items	Loss Duration (years)	Comments
Kingfish		Possible (10^{-2})	200	14	500	It is considered possible that each well will leak over 1000 years. Rate may vary for each well.
Central Deep		Possible (10^{-2})	200	15	500	It is considered possible that each well will leak over 1000 years. Rate may vary for each well.

- This is a change in approach from previous GEODISC work; each type of well is evaluated separately
- Exploration wells are assumed not to be remediated prior to or during storage of CO_2
- Each exploration well will need to be evaluated separately
  - As to age, casing depths, method of abandonment
  - Period of time during and post injection in the CO_2 plume, likely time of resistance to CO_2 degradation, likely pathway for CO_2 leakage out of site and/or to sea floor
  - As to the impact of possible water displacement/leakage from exploration wells during injection and before arrival of CO2 plume

Kingfish



Planning (CL80%)
Acceptable Project Containment Risk (RQ)
Acceptable Single Event Containment Risk (RQ)
Event risk quotient
10000000
1000000
100000
10000
1000
100
10
Permeable zones in seal
Leakage - Faults
Leakage - Wells
Regional overpressurisation
Local overpressurisation
Exceeding spillpoint
Earthquake induced fractures
Migration direction
Compressor failure
Platform Failure
Pipeline failure
Well Head Failure
Total Containment Risk

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Performance and Safety Screening for the Mountaineer CO_2 Storage Site Using Features, Events, and Processes Database

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2nd Risk Assessment Network Meeting
October 5-6, 2006 • Berkeley, California

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- BP – *Charles Christopher*
- Schlumberger – *T.S. Ramakrishnan, Nadja Mueller, John Tombari, and others*
- Ohio Geological Survey: *Larry Wickstrom, Mark Baranoski, Ron Riley*
- Regional Geologists: *Bill Rike, John Forman, Amy Lang*

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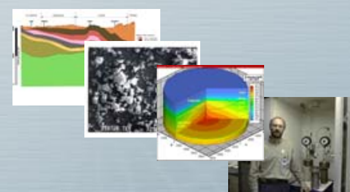
Mountaineer Project Background

a.k.a. "Ohio River Valley CO_2 Storage Site"

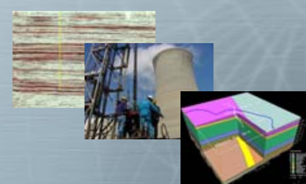
Overall Objective- Provide an understanding of the viability of carbon sequestration as greenhouse gas reduction technology by performing an integrated demonstration of CCS in Ohio R. Valley.

✓ **Phase I- Regional capacity evaluation.**

✓ **Phase II- CO_2 injection modeling, economic & engineering assessment, geochemical experiments.**



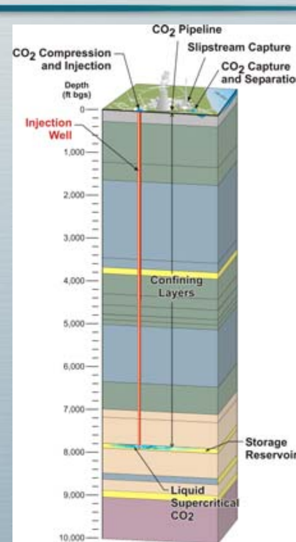
✓ **Phase III- Test well drilling, seismic, reservoir testing, rock coring at Mountaineer Power Plant. Design and feasibility study.**



Potential Future Effort- Small-scale carbon capture and storage (CCS) at power plant, injection, storage monitoring.

Mountaineer Project Plans / Assumptions

- **Develop pilot-scale integrated carbon capture and storage system.**
- **Capture and injection of <0.5% plant emissions into deep saline formation (rate depends on slipstream capture specs ~20-100 metric ton CO_2/day).**
- **Several years of continuous injection & monitoring.**
- **Entire system to be contained on plant site.**



Conceptual Model- Site Location / Environmental Setting

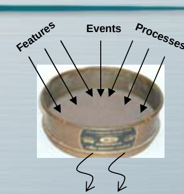
- 1300 MW AEP Mountaineer Power Plant, New Haven, WV, on the Ohio River along U.S. Route 62.
- The closest West Virginia town to the study area is New Haven (population 1,559), which is less than a mile upriver.

Conceptual Model- Site Location / Environmental Setting

- AEP is the largest employer in the area and power generation is the main industry. 72.4 % of the workforce have a high school degree and 8.8% have a college degree or better. Median household income is $27,134. The poverty rate is 19.9%.
- Infrastructure is fairly well-developed along the river, but less extensive away from the river valley. Land use is a mixture of agricultural, industrial, and residential.
- The AEP Philip Sporn Power Plant is directly south of the Mountaineer Plant. An underground coal mine is present west of the site. The nearest residential areas are approximately half a mile north.

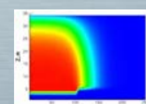
Risk Assessment Methodology

Features, Events, and Processes (FEP) Performance and Safety Screening



- Systematic, qualitative screening
- High-level effort to identify potential risk items for the project

Integrated Numerical Modeling Approach



$$\bar{S}_g = \frac{1}{\pi r^2 \phi h}\int_{r=0}^{r=r_1} 2\pi r \phi h S_g \, dr$$

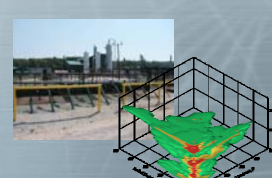
- Integrated assessment framework to address risk and consequence
- Quantitative methods

- Comprehensive site characterization provides knowledge base and site-specific parameters for risk assessment.

Performance and Safety Screening for the Ohio River Valley CO_2 Storage Site Using Features, Elements, and Processes Database

1. **Apply systematic screening procedure to the Ohio River Valley Carbon Dioxide Storage site for geologic storage of CO_2.**

2. **Identify potential performance and safety risk items.**



3. **Provide guidance on injection system design, monitoring program, reservoir simulations, and other risk assessment efforts.**

Features, Events, and Processes (FEP) Database for Geologic Storage of CO_2

- "***Generic FEP Database for the Assessment of Long-Term Performance and Safety of the Geological Storage of CO_2***" **developed by Quintessa (Savage et al., 2004).**

- **Database includes possible features, events, and processes that should be considered in a storage project.** (Only addresses *geologic storage*, capture and transport are not included.)

- **This systems analysis approach has been used for several applications, most notably radioactive waste disposal. Used for CO_2 storage evaluation at Weyburn Project (Stenhouse, 2002).**

- **High level systematic analysis to focus quantitative risk analysis.**

Screening Methods

FEP Screening Methods for this Study-

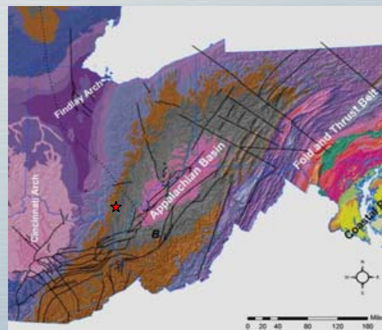
A stepwise approach was utilized to identify the FEPs that should be considered for the Ohio River Valley CO_2 Storage Project:

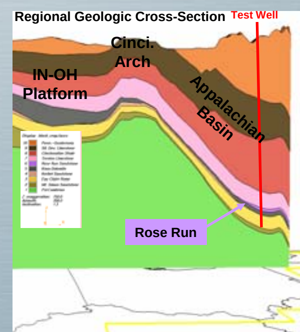
1. **Compile site-specific conceptual model.**
2. **Level 1 screening for non-applicable/unlikely items.**
3. **Level 2 screening based on general site conditions or site characterization results.**
4. **Level 3 screening using site testing and/or system specifications.**
5. **Providing recommendations on addressing remaining FEPs into system design, monitoring, and analysis.**

Note- database for geologic storage only.
Capture and transport are not covered.

Conceptual Model- Site Location / Environmental Setting

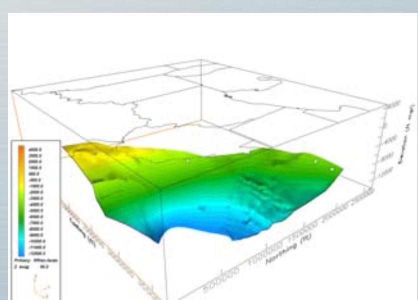
- Geologic Setting
- Appalachian Basin (mature basin)
- Thick sequences of Paleozoic sedimentary rocks
- Saturated with dense brines 100,000+ mg/L

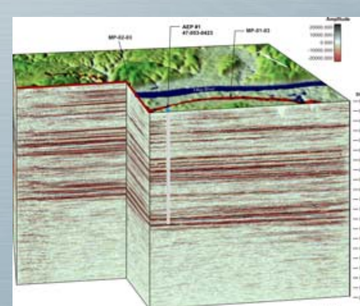




Conceptual Model- Geologic Setting

- Thick sequences of Paleozoic age sedimentary rocks, mature basin.
- Stable setting, no major faulting in survey area, little seismic activity.
- Target reservoirs = Rose Run Sandstone and Copper Ridge Dolomite.
- Both formations pinch out in subsurface. Stratigraphic trapping mechanisms. No direct path to near surface/USDWs.
- Thick, extensive, and diverse series of containment units.





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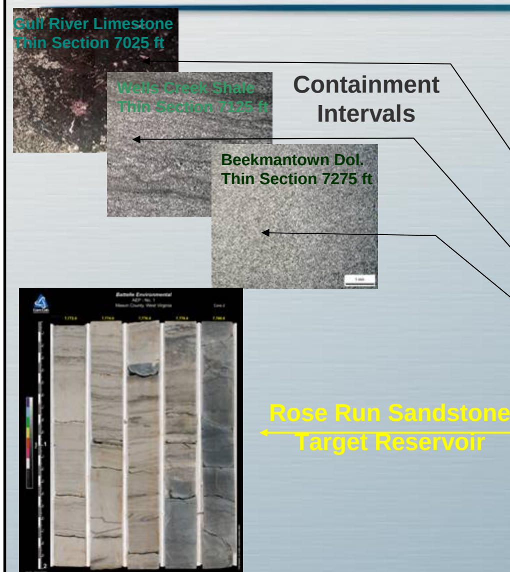
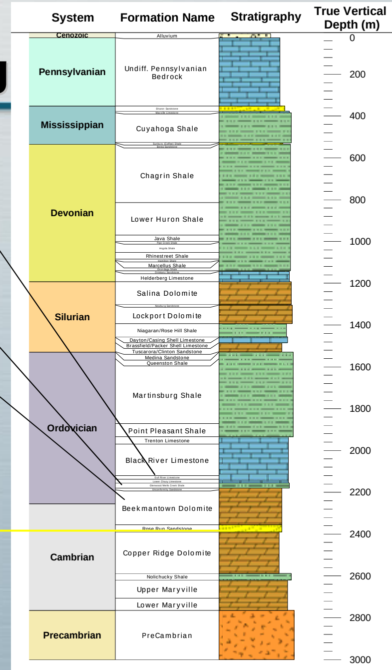
Conceptual Model-
Local Geologic Setting





FEP Screening Categories

(Savage et al., 2004)

Category	Class	Description	# Items
Assessment Basis	0	Assessment Basis	8
External Factors	1.1	Geological Factors	7
	1.2	Climatic Factors	8
	1.3	Future Human Actions	10
CO2 Storage	2.1	CO_2 Storage Pre-Closure	10
	2.2	CO_2 Storage Post-Closure	5
CO2 Properties, Interactions, and Transport	3.1	CO_2 Properties	3
	3.2	CO_2 Interactions	19
	3.3	CO_2 Transport	7
Geosphere	4.1	Geology	16
	4.2	Fluids	3
Boreholes	5.1	Drilling and Completion	5
	5.2	Borehole Seals and Abandonments	5
Near Surface Environment	6.1	Terrestrial Environment	8
	6.2	Marine Environment	5
	6.3	Human Behavior	6
Impacts	7.1	System Performance	1
	7.2	Impacts of Physical Environment	8
	7.3	Impacts on Flora and Fauna	5
	7.4	Impacts on Humans	4

Example FEP Screening Items

- **Total of 143 items covering wide range of FEPs that could affect performance or safety of geologic storage.**
- **Everything from neotectonics to record-keeping.**

FEP Items- Examples

Description	Explanation
Drilling Activities	Events related to any type of drilling activity in the vicinity of the CO2 sequestration system. These may be taken with or without knowledge of the disposal and may include activities such as: - exploratory and/or exploitation drilling for natural resources; - attempted recovery of residual hydrocarbon resources; - drilling for water resources; - drilling for site characterization or research; - drilling for further disposal; and - drilling for hydrothermal resources.
Effects of Pressurization of reservoir on caprock	A storage reservoir will experience enhanced pressure due to injection of CO2. This may exceed original 'natural' pressurisation due to hydrocarbon emplacement, or clay mineral transformations during diagenesis.
Dissolution in formation fluids	The process of dissolution of CO2 in formation fluids. The rate of dissolution depends on factors such as the interfacial area between the CO2 and the formation fluids and temperature. Savage et al., 2004

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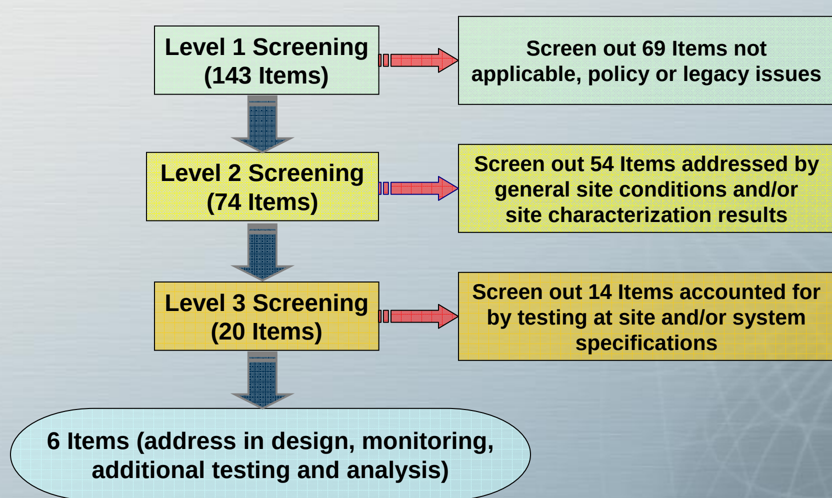
FEP Screening Process



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Example- Level 1 Screening

Screen out 69 Items not applicable, policy or legacy issues

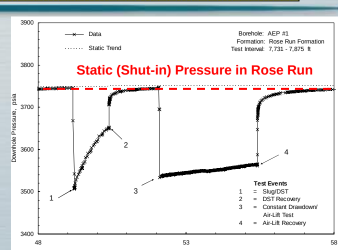
- **Example- Marine features**
- **Response- Not applicable...not a marine setting.**

FEP#	Description	Explanation	Response
6.2.3	Marine Sediment	Features and processes associated with sediments in the marine environment. This includes both the physical and chemical characteristics of the sediments, along with sedimentation and resuspension processes.	Not applicable

Example- Level 2 Screening

Screen out 54 Items addressed by site conditions or site characterization results

- **Example- Depth necessary to retain CO_2 at supercritical pressure?**
- **Response-**
  - **-Target reservoirs are more than 2,200 m deep.**
  - **-Reservoir testing shows pressures over 25 MPa (3700 psi) in storage intervals**

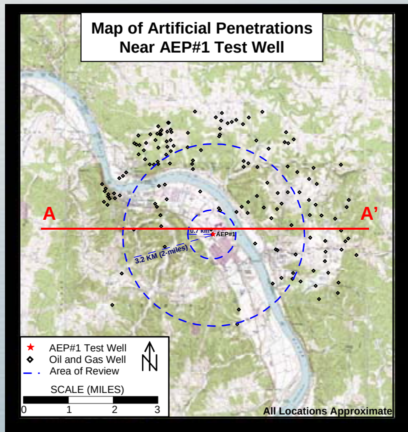


FEP#	Description	Explanation	Response
4.1.14	Formation Pressure	The pressure of fluids within the pores of a formation, normally hydrostatic pressure, or the pressure exerted by a column of water from the formations depth to the sea level prior to the injection of CO2. The critical pressure of CO2 is 7.38 mega-Pascals. The average underground hydrostatic pressure increases with depth by approximately 10.5 mega-Pascals per kilometre for aquifers that are in open communication with surface water. Applying this average gradient, the critical pressure of CO2 will be reached at a depth of around 690 metres. However, aquifers or hydrocarbon reservoirs that are sealed off from the rest of the sub-surface may be under- or overpressured. Savage et al., 2004	Storage reservoirs are over 2200 m deep, easily meeting the critical pressure of CO2.

Example- Level 3 Screening

Screen out 14 Items accounted for by testing at site and/or general system specifications

- **Item= Existing Artificial Penetrations**
- **Response = Few deep wells nearby, mostly Devonian Shale gas wells less than 4,000 ft deep.**



Geologic cross section showing well depths near AEP#1 (in blue).

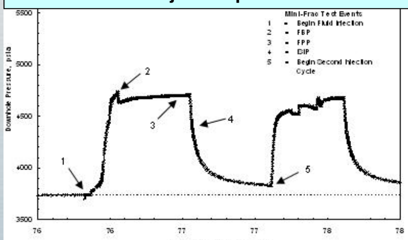
FEP Items Retained for Further Analysis

Category	FEP Item	Description	Response
CO_2 Storage	CO_2 Storage Pre-Closure	High injection rates and over pressuring may affect storage reservoirs and containment units	The injection pressure will be kept under fracture gradients (as determined from fracture testing of reservoir and caprocks). Modeling indicates that injection will not overpressurize the storage reservoir.
CO_2 Properties, Interactions, and Transport	CO_2 Properties	CO_2 solubility and aqueous speciation	Storage will not rely on CO_2 dissolution as most CO_2 is anticipated to remain as a supercritical liquid in place due to highly saline formation fluids. These processes have been addressed with geochemical analysis of brine samples from the well and equilibrium models that predict the effect of introducing CO_2 to the formation fluids.
	CO_2 Transport	-Advection of CO_2 due to injection -Buoyancy-driven flow/migration -Displacement of formation fluids	Movement of the injected CO_2 will be contained in the storage reservoirs as confirmed by injection modeling. The need for a separate monitoring well is being considered for the project, which would be able to monitor migration of injected fluid.
Geosphere	Geology	Reservoir geometry variations and heterogeneity	These features were accounted with stochastic injection simulations to see how they may affect storage over a range of potential conditions such as thickness, permeability variations, and layering.
Boreholes	Drilling and Completion	Durability of well casing and cements	Special cements and tubing are planned for the final well completion, and additional monitoring of the well materials will be built into the project. Injection well design will include interannulus fluid and a surface monitoring system that will automatically detect any damage to the well materials.
	Borehole Seals & Abandonments	Degradation of borehole materials used to abandon the injection well	Acid-resistant cement mixtures were used to complete the proposed injection well. System monitoring will be used to detect any degradation in well materials and well workover may be included to see if well materials altered during the project.

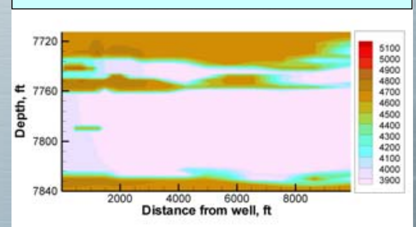
Results & Implications- Item 1

CO_2 Storage	CO_2 Storage Pre-Closure	High injection rates and over pressuring may affect storage reservoirs and containment units	The injection pressure will be kept under fracture gradients (as determined from fracture testing of reservoir and caprocks). Modeling indicates that injection will not overpressurize the storage reservoir.

Mini-fracture Tests in Rose Run Sandstone
-Used to define injection pressure limits



Reservoir Simulations indicate Injection will not Cause Unacceptable Increase in Reservoir Pressure



Implications- Include automated (SCADA) monitoring system with injection well to track injection pressures.

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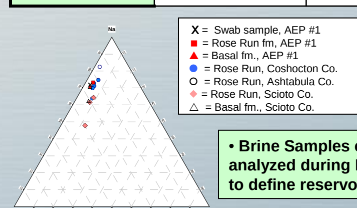
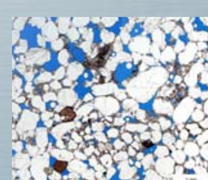
Results & Implications- Items 2&3

CO_2 Properties, Interactions, and Transport	CO_2 Properties	CO_2 solubility and aqueous speciation	Storage will not rely on CO_2 dissolution as most CO_2 is anticipated to remain as a supercritical liquid in place due to highly saline formation fluids. These processes have been addressed with geochemical analysis of brine samples from the well and equilibrium models that predict the effect of introducing CO_2 to the formation fluids.
	CO_2 Transport	-Advection of CO_2 due to injection -Buoyancy-driven flow/migration -Displacement of formation fluids	Movement of the injected CO_2 will be contained in the storage reservoirs as confirmed by injection modeling. The need for a separate monitoring well is being considered for the project, which would be able to monitor migration of injected fluid.



- **Brine Samples collected and analyzed during Reservoir testing to define reservoir conditions**



- **Detailed examination of pore space to define trapping mechanism**

Implications- Obtain samples from reservoir to see how injection CO_2 interacts with in-situ brines.

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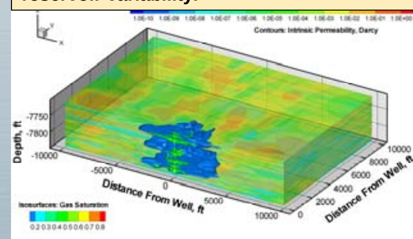
Results & Implications- Item 4

Geosphere	Geology	Reservoir geometry variations and heterogeneity	These features were accounted with stochastic injection simulations to see how they may affect storage over a range of potential conditions such as thickness, permeability variations, and layering.

CO_2 Exploration Wells Suggest Rose Run is a regional Unit, but some degree of heterogeneity is expected.

Reservoir Simulations incorporate reservoir variability.



Implications- Assess CO_2 movement in target reservoir with monitoring program.

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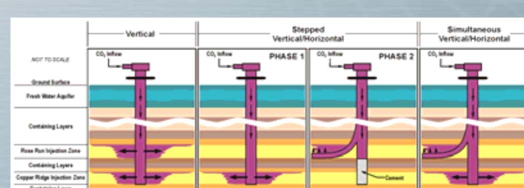
Result and Implications- Items 5&6

Boreholes	Drilling and Completion	Durability of well casing and cements	Special cements and tubing are planned for the final well completion, and additional monitoring of the well materials will be built into the project. Injection well design will include interannulus fluid and a surface monitoring system that will automatically detect any damage to the well materials.
	Borehole Seals & Abandonments	Degradation of borehole materials used to abandon the injection well	Acid-resistant cement mixtures were used to complete the proposed injection well. System monitoring will be used to detect any degradation in well materials and well workover may be included to see if well materials altered during the project.

Well design to incorporate resistant materials and capability to test some well materials.



Implications- Monitor well integrity, utilize acid-resistant cement, and other material for well completion.

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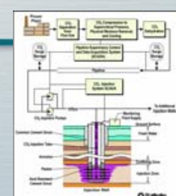
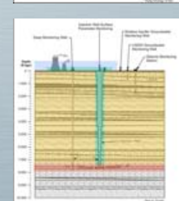
Conclusions

- *FEP Database Applications*- The "Generic FEP Database for the Assessment of Long-Term Performance and Safety of the Geological Storage of CO_2" is a useful tool for evaluating a site specific CO_2 storage project.
- *Systematic Approach*- Database is an exhaustive list of features, events, and processes that could affect a project. The systematic analysis reduces chances of omitting items which could affect a project.
- *Ohio River Valley CO_2 Storage Project*- It was discovered that the database aided in focusing remaining system design, monitoring, additional risk analysis, and storage application efforts.

Path Forward

- Integrate FEP results into design and feasibility activities.
- Incorporate FEP suggestions into well completion, monitoring, and injection system construction work.
- Evaluate system performance in relation to items identified in the screening process.





The End

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Geological Characterisation of the Saline Aquifer Structure "Schweinrich", a Suitable Candidate Site for Industrial Scale CO_2-Storage in Germany ?

Robert Meyer, Franz May and Paul Krull (BGR)
Bert van der Meer, Kees Geel and Eric Kreft (TNO)
Pierre Durst and Irina Gaus (BRGM)
Rickard Svensson and Christian Bernstone (Vatenfall)

Introduction / Project Scenario

- **Main objective:** To investigate opportunities to store CO_2 captured from a 1,600 MW lignite power plant (service life time of 40 years, 400 Mt CO_2)
- R&D work of CO2STORE (co-founded by the European Commission, 5th framework)

  experience from former projects ⇒ 4 case studies in Europe + Sleipner http://www.co2store.org/

- Schwarze Pumpe Power plant (Vattenfall) = CO_2 source (400 Mt CO_2)
- Investigation area = NE-Germany
- Regional site screening
- Ranking and site selection
- Site characterisation (BGR, TNO, BRGM and Vattenfall)

Pre-feasibility study

- relying on existing data only
- How far we can get before a commercial site exploration ?

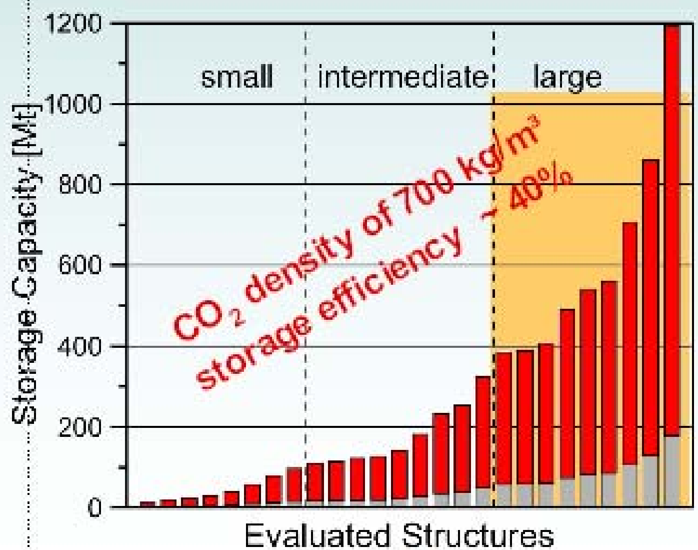
Site Screening and Identification

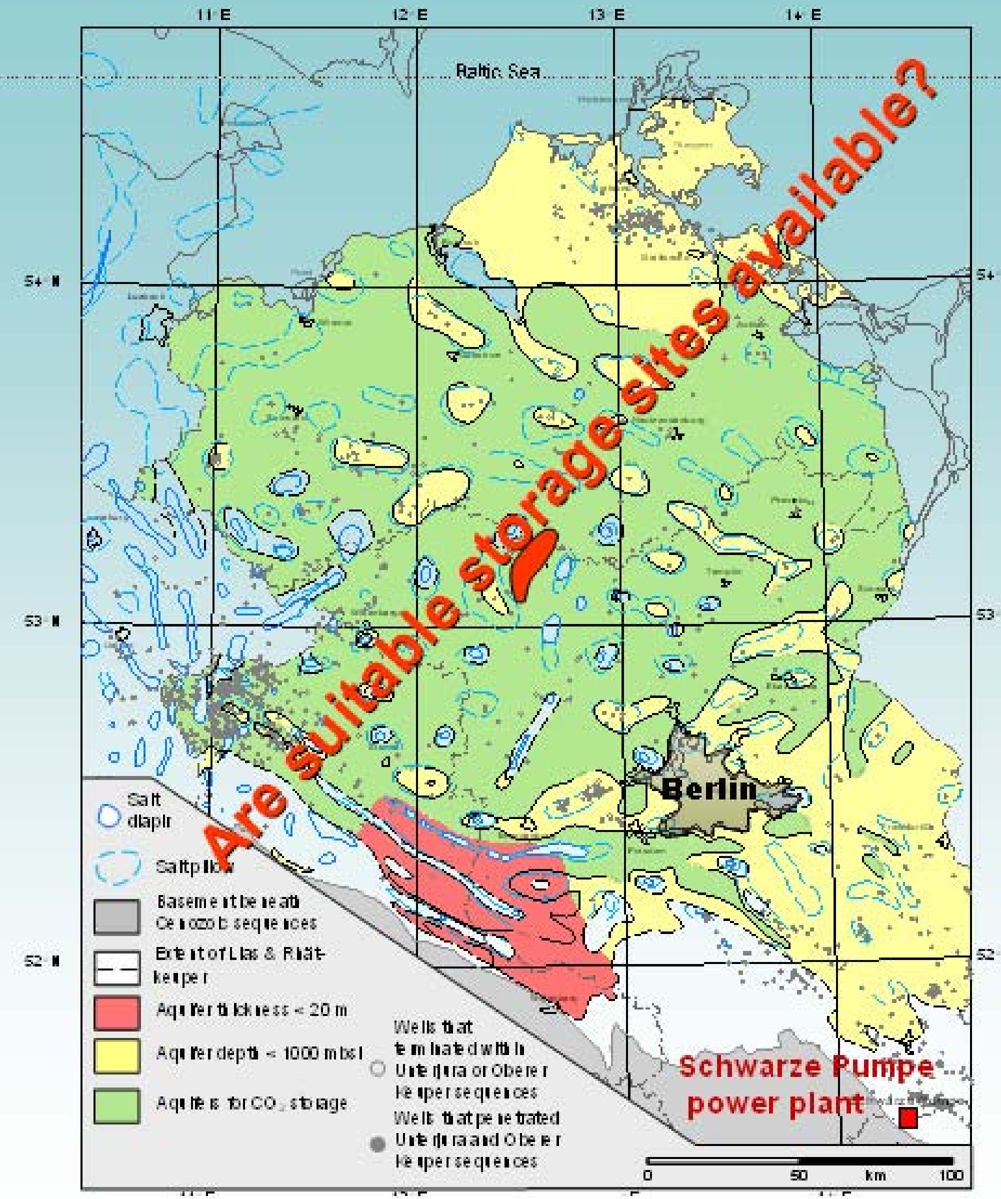
Procedure:

- Mapping the regional occurrence and relevant properties of saline aquifers (GIS)

Criteria

- open aquifer & closed structures (anticlines)
  - depth: 900 to 4000 m
  - thickness of reservoir > 20 m
  - porosity > 20%
  - presence of reserve aquifer
  - suitable cap rock





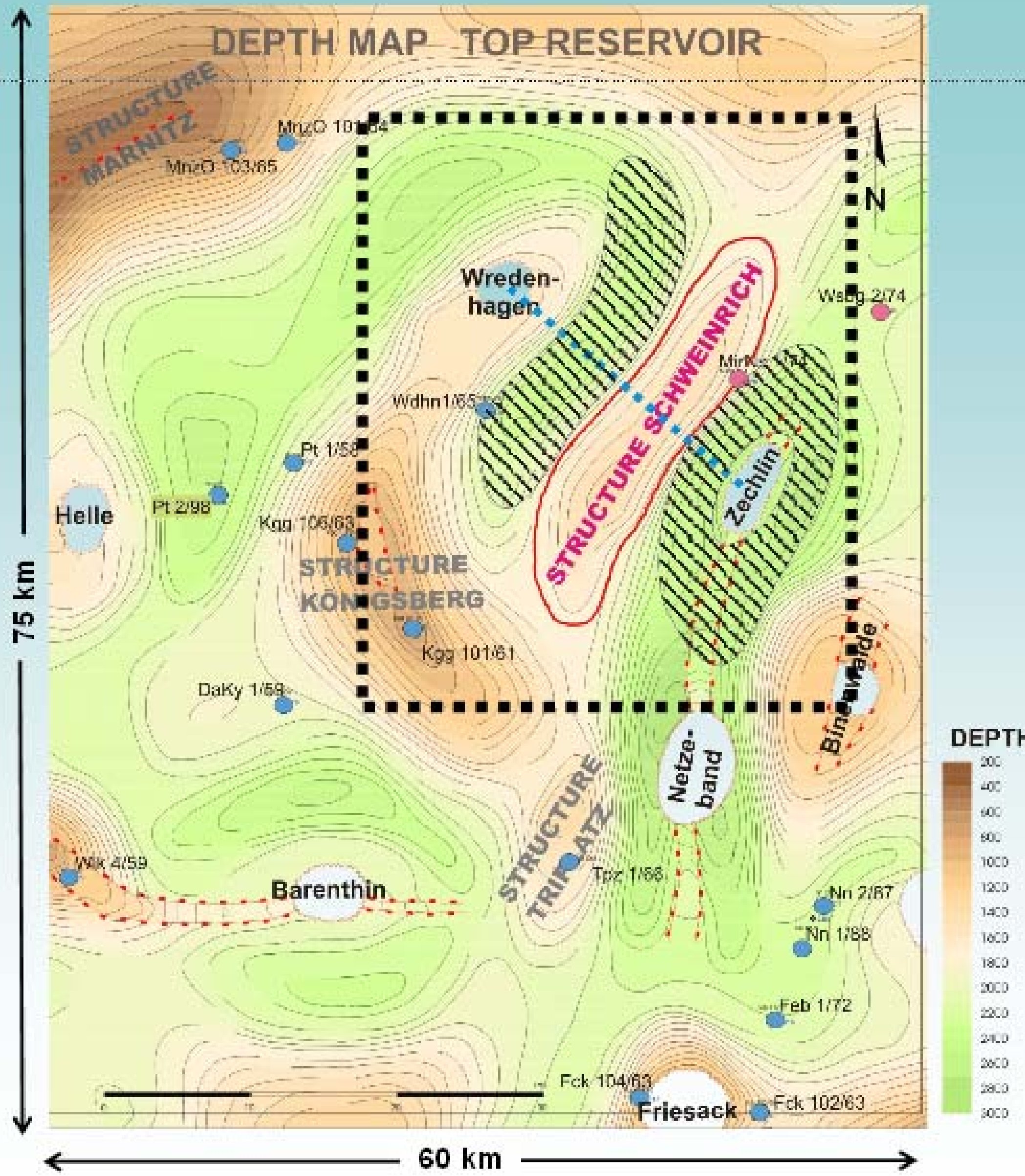
Site Characterisation

available data: 2D seismic lines and wells

- structural geological framework
- mapping the depth and thickness of reservoir
- petrophysical properties (well logs)
- well core analysis (mineralogy, geochemistry)

- 3D geological modelling (TNO + BGR)
  ⇒ pore volume/storage potential
  ⇒ reservoir simulations (TNO)

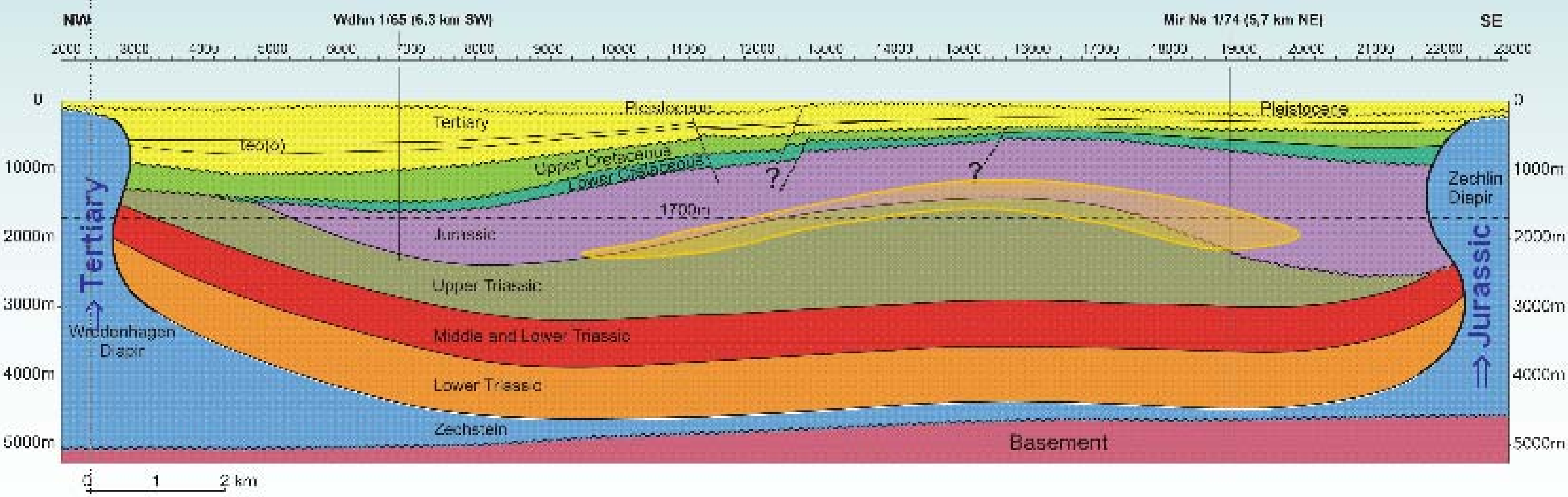
⇒ Surrounding area also included in the site characterisation !



Site Characterisation

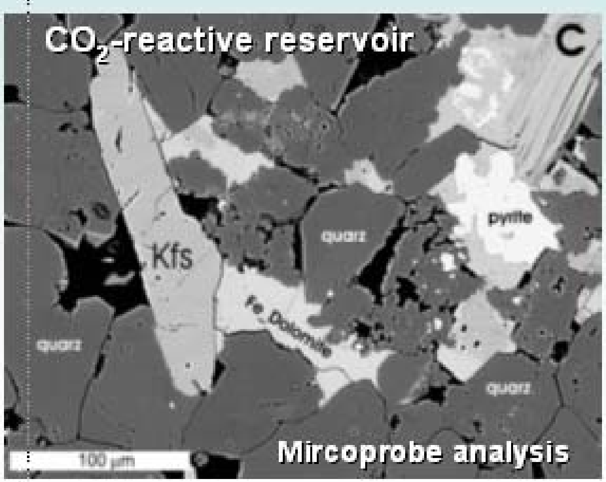
Structure Schweinrich

- passive anticlinal structure (turtle structure)
- aquifer stores below 1,300 m / spill points at 1,700 m
- gross thickness 270 – 380 m
- sealed by a thick clay sequence
- tectonic settings / faults in the overburden ...?



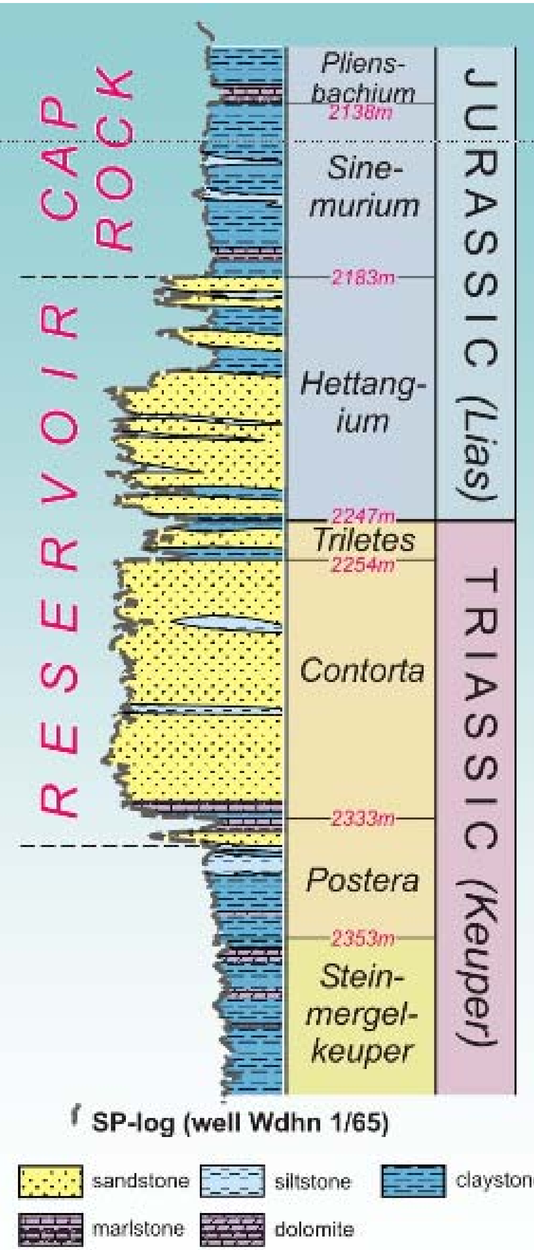
Reservoir characterisation

- sampling and mineralogical and geochemical characterisation
- XRD, microprobe, cathode luminescence, AAS)
  - CO_2-reactive minerals
  - Fe-bearing minerals and carbonates in the cap rock (!)
- porosity measurements ⇒ calibrating well log interpretation
- ….



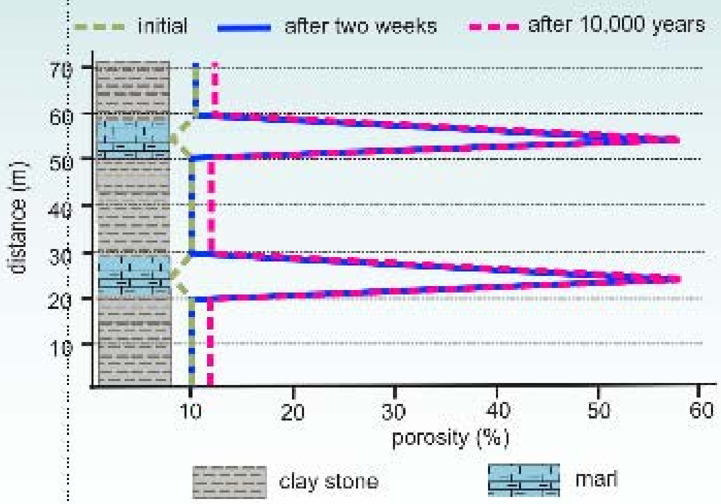
Reservoir Rock
Mineralogical comp. [weight-%]

Quartz	80 - 95
Illite	0 – 10
Kaolinite	0 - 3
Albite/Plagioclase	<1 - 4
K- feldspar	1 - 5
Siderite	0 – 2
Rutil / Anatase	0 - 0.5
Fe-oxohydroxide	< 0.5
TC	0.03 – 0.49
TOC	0.03 – 0.21



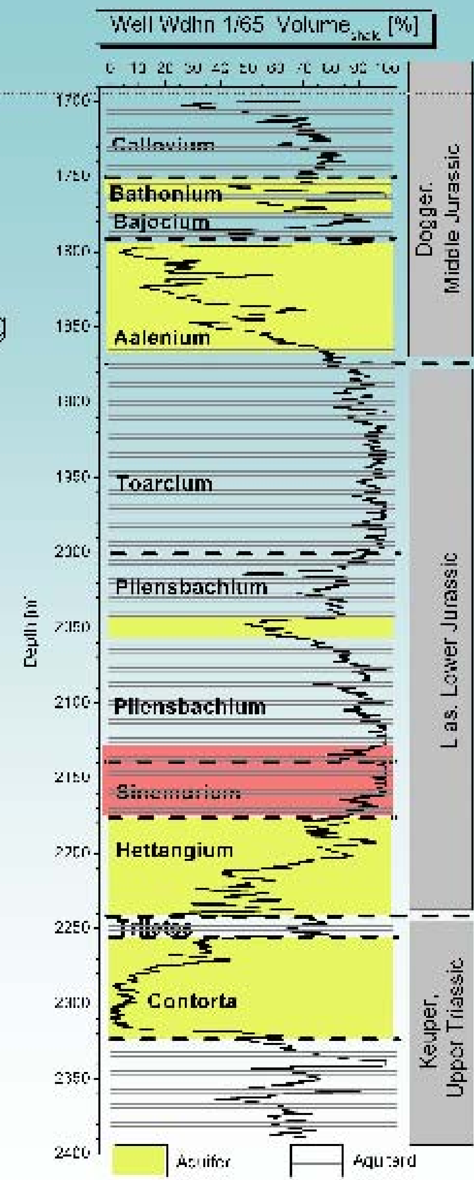
Cap Rock and Overburden

- several hundred meters thick claystone sequence above the reservoir
- reserve aquifers in the overburden
- cap rock composed of claystones with interstratification of marls
- geochemical/mineralogical analysis ⇒ input data for geochemical modelling



Cap Rock, mineralogical composition [weight-%]

Quartz	10 - 20
Illite and ML	(15) - 50
Kaolinite	(5) - 30
Chlorite	5 - 9
Albite/Plagioclase	4 - 8
K- feldspar	1 - 6
Calcite	0 – 3 (11)
Dolomite / Ankerite	0 (15)
Siderite	0 – 3 (26)
Rutil / Anatase	0.5 – 1
Hematite	2 – 5
TC	0.2 – 1.1 (5.4)
TOC	0.2 – 1.1

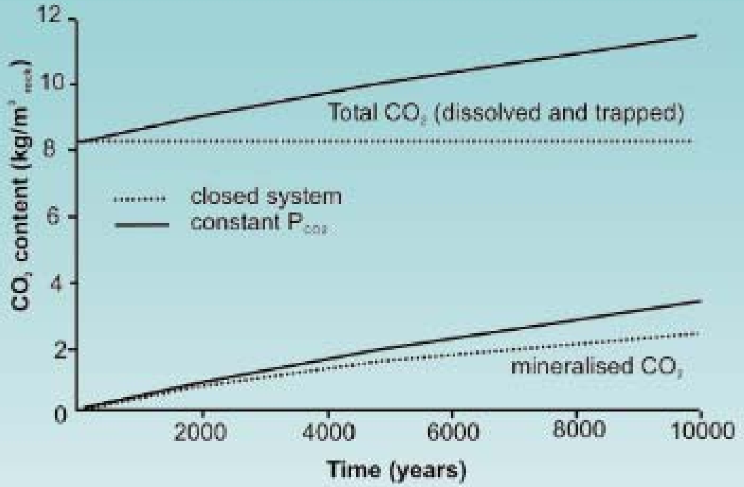


CO_2 – brine – rock interactions

Predictive geochemical modelling (BRGM)

→ geochemical sensitivity

- potential for CO_2-dissolution
- potential for CO_2-precipitation in mineral form



Issues addressed to geochemical modelling:

- likely impact of CO_2/brine/rock reactions
- likely geochemical CO_2-impact on reactivated faults crossing the cap rock
- risk of degassing or overpressurisation due to salting out effect

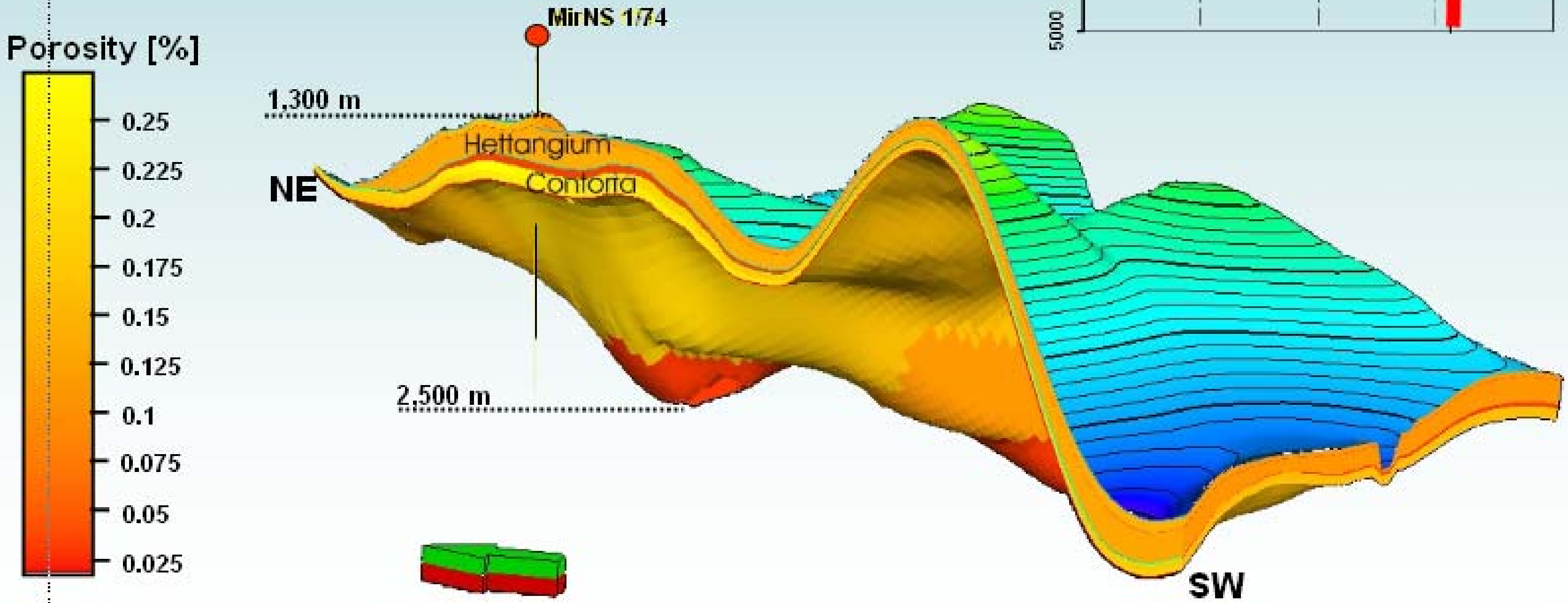
Predictions / Findings:

- Initial CO_2 solubility 29,4 g/l_{fluid} → 8,24 kg/m^3_{rock}
  - max. sequestration capacity: 11,5 kg/m^3_{rock}
  - negligible impact (poro/perm) on claystones but rapid dissolution in carbonate rich layers (marls)
  - salting out and overpressurisation only occurs CO_2-rich fluid ↔ evaporites (very unlikely in the reservoir)

Storage capacity

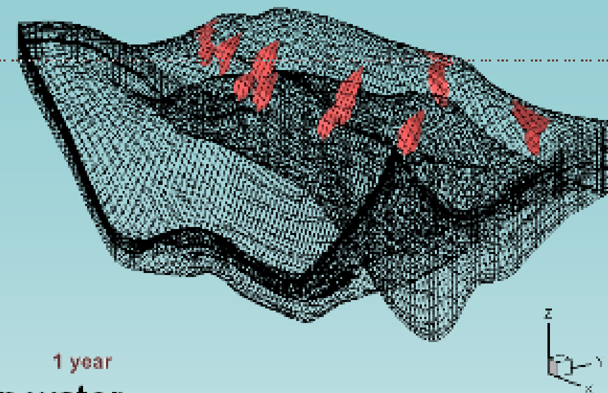
3D geological model (*Petrel*)

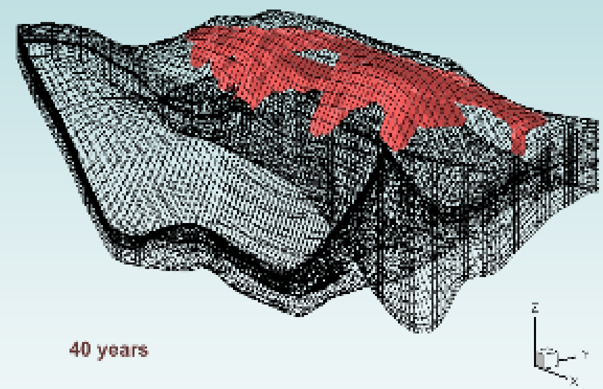
- different geological interpretations
  - Triletes clays = CO_2-permeable ⇒ 1 spill point
  - Triletes clays = CO_2-impermeable ⇒ 2 spill points
- total storage volume of 500 to 840 Mt supercritical CO_2 (40 % storage efficiency)
- basis for reservoir simulations

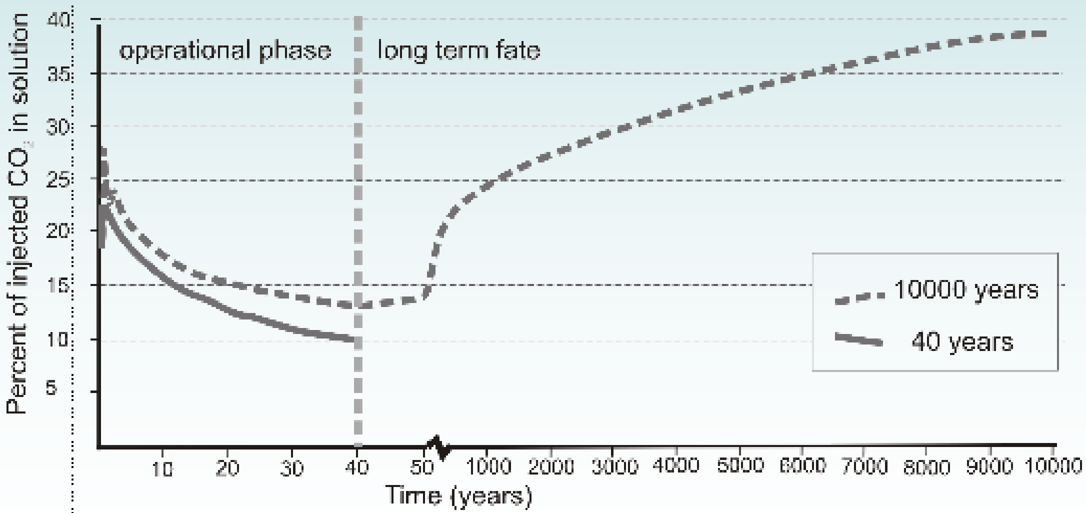


Reservoir Simulations

- test the operational phase
  (40 years, 10 wells, 400 Mt of $CO_2 \approx$ 550 Mio m^3)
- predict the long term dissolution and migration
- increase in formation pressure / displacement of formation water
  $\Delta P \approx V_{Aquifer}$, permeability, compressibility, etc., …







400 Mt CO2 ≈ 550 Mio m³

Results and Open Questions…

… this is a pre-feasibility study before a commercial site exploration -

- ***how far we got / advance using the available data (or generally available data)***
- ***which methods are important and which key issues have been identified***

• successful characterization of one large candidate CO_2-storage site
(structural framework, reservoir properties, geochemical sensitivity and available pore volume)

⇒ Structure Schweinrich seems to provide a sufficiently large storage potential (> 400 Mt CO_2)

• pre-feasibility study revealed gaps in our data:

- tectonic inventory (structural integrity of the storage system)
- geomechanical analysis, tectonic stress regimes, tolerable pressure capacity)
- commercial site exploration is indispensable (new wells and 3D seismic) !

• 400 Mt of CO_2 are an enormous volume / considerable scale up compared to Sleipner, In Salah

• indications about the major controlling factors/issues which might limit the storage capacity

- predictions of formation pressure increase and propagation referring to geomechanical issues (formation fracture pressure, fault reactivation)
- injection well planning (position/perforation)
- securing a sound reservoir aquifer with supra-regional extend and a suitable cap rock

Report

The Latrobe Valley CO_2 Storage Assessment

Cooperative Research Centre for Greenhouse Gas Technologies

November 2005

CO2CRC Report No: RPT05-0220

CSIRO

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THE UNIVERSITY OF NEW SOUTH WALES

CO2CRC

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CRC for Greenhouse Gas Technologies

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Curtin University
Geoscience Australia
Monash University
University of Adelaide
University of Melbourne
University of New South Wales

Core Industry & Government Participants

Australian Coal Assoc. Research Program
BHP Billiton
BP Developments Australia
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Shell
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Supporting Participants

Australian Greenhouse Office
CanSyd
Meiji University
The Process Group
University of Queensland
URS
WA Dept. of Industry & Resources
Whistler Research

CRC AUSTRALIA

The Latrobe Valley CO_2 Storage Assessment

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CO2CRC

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Australian School of Petroleum

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Hooper, B, Murray, L and Gibson-Poole, C (eds.), 2005. *The Latrobe Valley CO_2 Storage Assessment.* Cooperative Research Centre for Greenhouse Gas Technologies, Canberra. CO2CRC Publication No RPT05-0220, November 2005. 15pp.

Contents

The Latrobe Valley CO_2 Storage Assessment

The Latrobe Valley brown coal deposits within Victoria's Gippsland Basin are a world class resource characterised by very large reserves of very low-cost coal. They provide Australia's lowest cost electricity but, because the coal has a high moisture content, they also produce a relatively large volume of CO_2 per unit of electricity. Carbon capture and storage (CCS) technology could, however, provide a means of drastically reducing the CO_2 emissions associated with the use of the Latrobe Valley's brown coal.

The adjacent offshore Gippsland Basin is the site of large mature petroleum fields which have securely trapped and stored large volumes of oil and gas for many millions of years. As some of these fields start to approach depletion, the offshore reservoirs offer the potential for secure storage of CO_2 from the Latrobe Valley (Figure 1).

Figure 1. Location of Gippsland Basin and the Latrobe Valley.

In July 2004, the Department of Transport and Regional Services (DoTaRS) awarded a grant to Australian Power and Energy Limited (APEL) - now Monash Energy - to undertake the Latrobe Valley CO_2 Storage Assessment (LVCSA), drawing on the expertise of the CO2CRC. The scope for the assessment was developed in late 2004 and evaluation by CO2CRC researchers commenced in early 2005.

The LVCSA provides a medium to high-level technical and economic characterisation of the volume and cost potential for secure geosequestration of CO_2 produced by the utilisation of Latrobe Valley brown coal. It identifies key issues and challenges for implementation and provides a reference framework for the engagement of stakeholders, including the identification of items that will require further focused verification studies.

The project is by definition an early assessment of the risks and uncertainties of a major infrastructure investment. It is intended to provide strong indications of the potential viability of such a project leading to higher levels of definition as more scoping and development proceeds.

The outcomes agreed by Monash Energy with DoTaRS for the LVCSA were:

- Definition of the capacity of the Gippsland sedimentary basin to provide a high integrity storage site for CO_2 sourced from the Latrobe Valley over the long term.

- Definition of the costs of providing transportation, injection and monitoring / verification of CO_2 from the Latrobe Valley from commencement through until around 2050.

- Evaluation of the potential synergies and challenges of implementing the CO_2 storage project while oil and gas operations continue through to ultimate field depletion.

- Definition of an optimum CO_2 storage infrastructure roll-out plan including preferred injection locations.

- Definition of the specific uncertainties associated with implementation and specification of the work necessary to ensure that these are mitigated to the extent necessary.

- Collaboration during the assessment between Monash Energy, the CO2CRC, the Federal and Victorian Governments and, ideally, key oil and gas producers operating in the area of prospective CO_2 storage.

- A framework for engagement with community stakeholders.

CO2CRC, through their researchers at the Australian School of Petroleum, CSIRO and the University of New South Wales, worked to address these outcomes under the following scope:

1. Broad characterisation of regional storage potential within the Gippsland Basin presumably leading to the identification of the offshore Basin as the preferred storage repository.

2. Identification and description of prior storage studies, relevant petroleum studies, data coverage and availability for the offshore Gippsland basin.

3. Identification, ranking and qualitative and quantitative characterisation of preferred injection site(s) and horizons - including storage capacity and storage security.

4. Reservoir simulation to predict migration path, ultimate long-term destination and form, of CO_2 injected at the preferred injection site(s) for each of the volume scenarios.

5. Interaction with oil and gas developments, including synergies and potential cost savings as well as any potential adverse impact on oil and gas recovery.

6. Storage assurance – identification of potential risks and uncertainties to be addressed in subsequent project approvals technical evaluations.

7. Preliminary specification of the compression, pipeline and injection infrastructure required linking Latrobe Valley coal utilisation developments to the preferred injection site(s) and horizons, for each of the volume cases.

8. The estimation of the corresponding capital and operating costs for each of the volume cases.

9. The identification of key potential impacts, risks and uncertainties, associated with the development and operation of the infrastructure, to be addressed in subsequent technical, safety and environmental evaluations for project approvals.

10. Summary of the potential of geosequestration to facilitate ongoing development of Latrobe Valley coal resources, together with an identification of the key challenges and requirements for project approvals evaluations.

The resulting work was grouped into the following broad themes:

1. Geological/hydrological analysis and modeling;

2. Interaction with the Bass Strait producers on development plans;

3. Risk assessment and storage assurance;

4. Development of infrastructure plans for transportation and injection;

5. Techno-economic studies; and

6. Communication.

The assessment is based around a series of generic storage volume cases, indicatively 2 million tonnes of CO_2 per year, 15 million tonnes per year and 50 million tonnes per year, which provide the basis for techno-economic assessment.

Understanding CCS

CCS comprises four main steps:

1. Capturing the CO_2 at the source, such as a power plant or industrial facility.

2. Transporting the captured CO_2, typically via a pipeline, from the source to the geological storage site.

3. Injecting the CO_2 deep underground into a geological reservoir.

4. Storing the CO_2 in the geological reservoir.

The capture of CO_2 from a stationary source, such as a power plant, involves separating and purifying CO_2 from the bulk of the flue gas stream rather than allowing it to be released to the atmosphere. The purified CO_2 stream is then available for geological storage.

The main sources suitable for CO_2 capture are: industrial processes; electricity generation; and, in the future, hydrogen production from fossil fuel sources. Industrial processes that lend themselves to CO_2 capture include natural-gas processing; ammonia production; and cement manufacture, however the total quantity of CO_2 produced by these processes is relatively small. A far larger source of CO_2, accounting for one-third of total CO_2 emissions in Australia, is fossil-fuelled electricity generation. Research is underway on the capture of CO_2 from this source.

Geological storage of CO_2 secures the gas deep underground in a geological reservoir. In addition to the careful selection of a suitable geological reservoir, a comprehensive monitoring system is required initially to ensure that the gas is safely contained.

Geological reservoirs into which CO_2 can be injected include depleted oil and natural gas fields, and deep saline formations. Since the stored CO_2 will be less dense than the water in and around the reservoir rocks, it needs to be stored in carefully studied sites where it will be geologically trapped to ensure that it does not reach the surface. The exact trapping mechanism depends on the geology. In depleted oil and gas fields, similar to those nearing depletion in the Gippsland Basin, a geological trap and a regional seal rock will contain the CO_2.

CO_2 is usually transported from a source, such as a power station, to the geological storage site in a compressed form via a pipeline. It is injected from a tanker, truck or pipeline deep underground into the geological reservoir. CO_2 geosequestration includes the capture, transport, injection and storage of CO_2 into deep geological formations.

Geological/hydrological analysis and modeling

Previous studies and data coverage

The LVCSA is not the first study to assess the geosequestration potential of the Gippsland Basin. The GEODISC™ program of the Australian Petroleum Cooperative Research Centre (APCRC) undertook a study of the geosequestration potential of the upper Latrobe Group stratigraphy in the vicinity of the northern gas fields (Marlin, Snapper, Barracouta) in the offshore Gippsland Basin. The study reviewed an injection rate of 10 million tonnes per year for 20 years, equating to a 200 million tonnes total storage volume. The GEODISC™ study comprised a PhD by Rob Root (in prep.) on the sedimentology, sequence stratigraphy and 3D geological model, plus reports by the National Centre for Petroleum Geology and Geophysics (now known as the Australian School of Petroleum) on the geomechanics, and reports by CSIRO on the hydrogeology and long-term reservoir simulation. The key results from these studies are publicly available[1].

[1] Root, R S, Gibson-Poole, C M, Lang, S C, Streit, J E, Underschultz, J R and Ennis-King, J, 2004. Opportunities for geological storage of carbon dioxide in the offshore Gippsland Basin, SE Australia: an example from the upper Latrobe Group. *In*: P J Boult, D R Johns & S C Lang (eds.) *Eastern Australasian Basins Symposium II*, Special Publication, 19-22 September 2004, Adelaide. Petroleum Exploration Society of Australia, pp. 367-388.

A second study was conducted by APEL and CSIRO in 2003/04. The area of interest was the nearshore western part of the offshore Gippsland Basin, with proposed injection into the Golden Beach Subgroup in the vicinity of the Dolphin and Perch oil fields. The APEL/CSIRO study reviewed a total storage volume of ~220–260 million tonnes, injected at a rate of ~11–13 million tonnes per year for 20 years.

By Australian standards, the Gippsland Basin is a mature basin and one of Australia's most prolific oil and gas provinces. Petroleum exploration has been active onshore since the 1920s and in the offshore region since the 1960s, thus there is a considerable amount of data that has been accumulated. In particular, as of 2001 there was over 80,000 kilometres of 2D seismic data, more than 25 3D seismic surveys, 160 exploration wells onshore, and 204 exploration and appraisal wells offshore. The average exploration well density throughout the basin is about one well in 125 kilometres[2], which increases to around one well in 50 kilometres[2] in the main producing areas.

The present offshore oil and gas production is generally in water depths of 40- 90 metres deep from reservoirs that are 1-2.5 kilometres below the sea floor.

Methodology

Safe and reliable containment of CO_2 in geological structures begins with a structured assessment of the characteristics and features of the target reservoir or location.

The methodology for evaluating a site for geological CO_2 storage is shown in Figure 2.

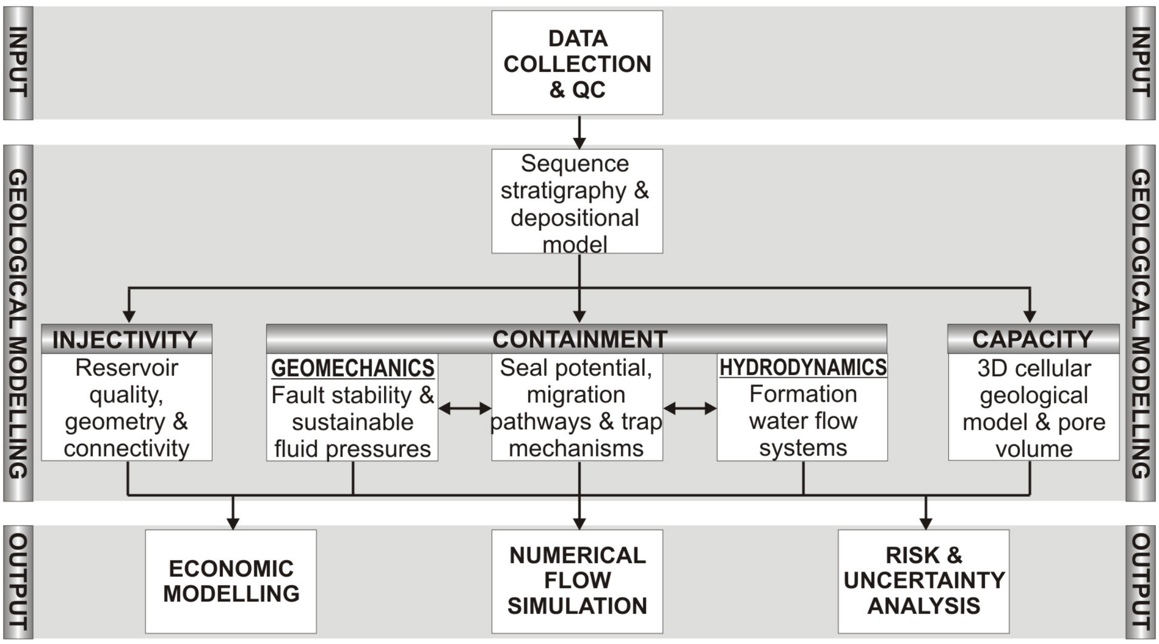

Figure 2. Workflow for CO_2 geological storage assessment[2].

[2] Gibson-Poole, C M, Root, R S, Lang, S C, Streit, J E, Hennig, A L, Otto, C J and Underschultz, J R, in press. Conducting comprehensive analyses of potential sites for geological CO_2 storage. In: E Rubin, D Keith & C Gilboy (eds.) *Greenhouse Gas Control Technologies: 7th International Conference on Greenhouse Gas Control Technologies*, 5-9 September 2004, Vancouver, Canada.

CO2CRC researchers studied the Gippsland sedimentary basin using this methodology and completed this technical work in the context of the LVCSA scope, namely:

- Regional evaluation
- Geology and geophysics interpretation
- Seal capacity study
- Geochemical evaluation
- Geomechanical analysis
- Hydrodynamic assessment
- Short-term (injection phase) numerical flow simulations
- Long-term (post-injection phase) numerical flow simulations
- Economic modeling
- Risk assessment

Site evaluation can be a complex and interdependent task requiring considerable iteration and interaction between key research groups and stakeholders. The outputs are quite sensitive to the geological parameters.

For instance, the required storage capacity is a critical feature of any CCS project, with proponents requiring considerable certainty to underpin large capital expenditures. Storage assessments can be predicted reasonably well at early stages of evaluation for some target sinks such as depleted oil and gas fields. However saline aquifer capacities can only be confirmed by numerical modelling which may not be available until some time into the evaluation. Further iterations may be required if it proves necessary to redirect attention to other horizons to achieve the capacity. New horizons are likely to display different injectivity conditions which in turn can have significant impacts on the capital cost of the project.

The capacity, containment and injectivity parameters form the basis for further assessment. Once these parameters have been determined, numerical flow and economic modelling, in addition to risk assessments, will dictate the acceptability of a storage site.

Geoscience characterisation

The Gippsland Basin is an east-west trending rift basin, located mostly offshore in south-eastern Australia, Victoria. It contains sediments over 10 kilometres thick from Early Cretaceous to Recent in age. CO2CRC researchers evaluated and ranked potential CO_2 storage sites in terms of their location, injectivity, containment, storage capacity and proximity to existing natural resources. Results indicated that the Gippsland Basin stratigraphy is highly favourable for CO_2 storage. In particular, the upper Latrobe Group sediments are of good to excellent reservoir quality and the Lakes Entrance Formation provides a substantial regional seal, which has proven its capability by the retention of hydrocarbons in the area for millions of years.

A number of regions in the basin were reviewed as part of the study (Figure 3) and a more detailed study was conducted over the Kingfish Field location, where it is expected that the field will be conventionally depleted within the period 2015 – 2025. Mindful of the sensitivity to CO_2 entering these significant oil and gas producing reservoirs, a deep injection strategy was chosen for the base case for scenario analysis. This involves injecting up to

15 million tonnes per year deep beneath West Kingfish into the intra-Latrobe Group stratigraphy (550-800 metres deeper than the main oil accumulation, at a depth of 2750-3000 metres below sea level). CO_2 is predicted to migrate upwards and eastwards towards the top of the Latrobe Group. The discrete nature of the stratigraphy and structure will ultimately control the rate at which this occurs. Free CO_2 that reaches the base of the Lakes Entrance Formation would subsequently accumulate in the depleted Kingfish Field structural closure. Although the spill point of the Kingfish structure is somewhat ambiguous, it is postulated that if the capacity of the Kingfish closure is exceeded, and if still mobile, CO_2 would then migrate westwards towards the structural closure of the Bream Field.

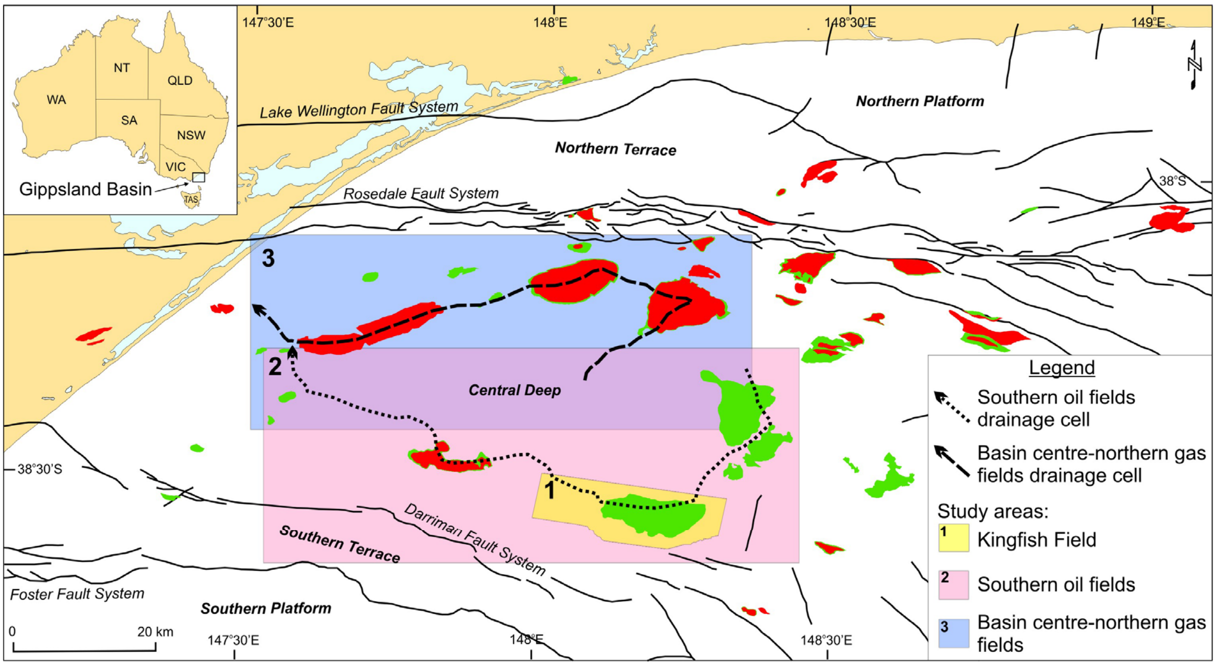

Figure 3. Study areas for the Latrobe Valley CO_2 Storage Assessment (tectonic elements after Power et al., 2001).

The detailed characterisation concluded that the reservoirs are of sufficient quality to allow injection. The complex intra-Latrobe stratigraphy may provide baffles and intraformational seals that could hinder and slow the migration of the CO_2, thus allowing other trapping mechanisms such as residual gas saturation to take effect. While permeabilities are much lower in the deeper stratigraphic horizons, drilling strategies were identified to mitigate cost increases. The seals evaluation work to date indicated that the Lakes Entrance Formation has sufficient seal capacity to successfully retain the CO_2. The geochemical assessment of the likely CO_2-water-rock interactions revealed that mineral reactions were unlikely in the low-reactive reservoir units during the short-term (injection period), thus the injectivity of the reservoir units would not be compromised. However, mineral reactions were possible in the Gurnard Formation at the top of the Latrobe Group (but still below the regional top seal), which would provide mineralogical storage of CO_2.

Most of the faults detected around the Kingfish Field are not in the predicted immediate CO_2 migration, and most do not cut the top seal. However, geomechanical assessment indicated that some have a potential for reactivation, and therefore pore pressure increases adjacent to faults would need to be carefully monitored.

The hydrodynamic analysis determined that the formation water flow has been affected by hydrocarbon production in the region. The Latrobe Aquifer System has been drawn-down and depressurised by decades of offshore petroleum production, onshore irrigation and mine de-watering. The locally steepened hydraulic gradients oppose the expected buoyancy-driven CO_2 migration direction, which may positively impact on the predicted migration direction and containment of CO_2 in the short-term (tens to hundreds of years). The injection of CO_2 into the offshore reservoirs is likely to offset some of the aquifer depressurisation, but detailed numerical analysis will be required to assess the extent of this impact.

Sensitivity studies conducted on short-term numerical simulation (25–40 years) determined that permeability and the maximum injection pressure affect the injectivity of CO_2. Lower permeabilities and lower injection pressures result in a reduction of the maximum injection rate of CO_2 that can be achieved. Thus, a greater number of wells are required to compensate for this effect. The long-term numerical simulations of the scenarios analysed verified that the first arrival of CO_2 at the oil-producing zone was 50 to 200 years after injection commenced (i.e. post-production of the Kingfish Field) and that a deep injection strategy results in greater CO_2 storage via residual gas saturation. However, further verification studies will be required in order to confirm that all possible scenarios have been considered to mitigate any earlier arrival of CO_2 at the oil-producing zone.

The Kingfish site, in conjunction with other similar sites within the basin (e.g. Fortescue, basin centre) will provide sufficient capacity for 50 million tonnes CO_2 per year storage for the 40 years injection duration. It is envisaged that the individual sites would be used sequentially, ramping up the volume of CO_2 stored to 50 million tonnes per year but timed such that existing hydrocarbon assets are not compromised.

CO2CRC researchers have documented and analysed the CO_2 storage potential of larger areas within the offshore Gippsland Basin as part of this assessment. The immediate modeling scenarios and assumptions completed under this study showed CO_2 storage potential in excess of 2 billion tonnes. More comprehensive studies of the basin's stratigraphy, particularly at deeper levels such as the intra-Latrobe Group sediments, will be required to confirm overall basin storage capacities. However, broad indications, based on the increase in capacity when using both the intra-Latrobe and top Latrobe stratigraphy at the Kingfish Field, suggest a basin-wide storage capacity of possibly 6 billion tonnes. The veracity of this figure would need to be confirmed by further studies.

Development of infrastructure plans

The availability of CO_2 for injection in the Gippsland Basin is hard to predict, as it is influenced by breakthroughs in science and engineering, community opinions on climate change and CCS, and government policy on a range of issues including carbon pricing. The basis for this assessment is that up to 15 million tonnes of CO_2 will be available for injection from the proposed Monash Energy facility in 2015. Case A is a 2 million tonnes per year injection scenario intended to represent a possible five-year demonstration facility, whereas Case B represents a Monash Energy facility type scenario (15 million tonnes per year). The large-scale injection scenario of Case C (50 million tones per year) required more complex definition (Table 1). A number of scenarios predicting the availability of CO_2 from subsequent facilities, including possible closures of ageing power plants, introduction of new gas-fired and low emission coal-fired power stations and low emission gas to liquids plants were considered. The conservative scenario considered in this assessment is that CO_2 will become available from two subsequent pre-combustion facilities. It was assumed that the amount of CO_2 available for injection will increase in step-wise increments up to 50 million tonnes per year.

Table 1. Description of volume cases assessed.

Case	Type	Volume Injected
Case A	Demonstration facility	2 million tonnes per year
Case B	Monash Energy facility	15 million tonnes per year
Case C	Large-scale injection	50 million tonnes per year

The depletion dates of existing oil and gas reservoirs are both commercially sensitive and uncertain to predict. Primarily due to the uncertain nature of predicting ultimate depletion dates, the Producers could only provide depletion date ranges for existing oil reservoirs. They indicated that the Kingfish Field and other southern oil fields, were likely to be available before the gas reservoirs starting with the Kingfish Field in the range 2015-2025. With this agreed strategy, CO2CRC researchers initially focused on the southern oil reservoirs in the offshore Gippsland Basin as opposed to the northern gas reservoirs considered in a previous study by the GEODISC™ Program.

Considering these uncertainties and an initial review of the geological modeling, the final roll-out plan was chosen to spread injection over three storage areas. CO_2 would first be injected at Kingfish at 15 million tonnes per year, then the Fortescue region at 15 million tonnes per year, then in the basin centre at 20 million tonnes per year. CO_2 can be injected at sustainable rates from a geological viewpoint that complements this source scenario (Figure 4).

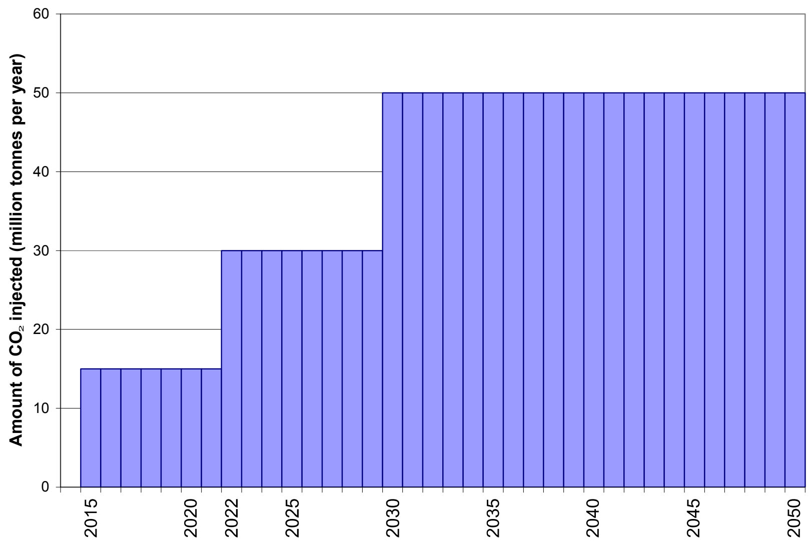

Figure 4. Scenario for the amount of CO_2 available for Case C1 over the study period.

Interaction with oil and gas producers in the region

The area of the offshore Gippsland Basin that is best suited for CO_2 storage is also the focus of oil and gas production, and is entirely subject to existing petroleum exploration and production tenements. Whilst oil and gas production will decline in the medium to long-term as the fields are progressively depleted, there will need to be close cooperation between petroleum producers and CO_2 injectors in the short to medium-term. The LVCSA was designed by Monash Energy to foster that cooperation from the outset by inviting the largest oil and gas producers in the region to collaborate in the study.

As part of that collaboration Esso and BHP Billiton assisted CO2CRC by providing access to confidential geoscience information and by providing constructive comment on the CO2CRC's injection scenarios, assessments and conclusions. It was at Esso's suggestion that the Kingfish Field was selected as the area for first injection, on the grounds that it will be the first depleted of the fields and therefore least susceptible to any possible adverse impact from CO_2 injection on oil production.

Although the likely depletion of the Kingfish Field is in approximate alignment with the earliest commencement of CO_2 injection, there can be no guarantee that oil production will have ceased when first CO_2 injection could commence. Consequently, the injection strategy adopted was designed to effectively eliminate the risk of injected CO_2 reaching the oil reservoirs before production has been completed. Under this strategy the CO_2 is injected at a depth at least 500 metres deeper than the oil-producing reservoir, from which point it would take a minimum of 50 years to migrate upward through the strata to reach the trap from which oil production has by then long ceased.

The adoption of this over-riding risk management strategy removed the need for any more detailed LVCSA evaluation of potential impacts of CO_2 injection on oil production but, planning for future proposals involving adjacent injection and production will require more detailed risk management strategies – and continuing cooperation between prospective injectors and existing producers.

Enhanced oil recovery (EOR) is often considered an excellent synergy between CO_2 storage and oil recovery providing improved recovery from existing fields. However, following discussion with Esso and BHP Billiton as part of this assessment, there is some doubt as to the economic viability of such an approach in the Gippsland Basin, particularly given the wholesale re-configuration to wellbores and facilities that would be required. Esso already expect to extract a significantly higher proportion of the oil in place than elsewhere in the world and many factors such as high permeability rock, light oil characteristics and reservoir geometry suggest developing an economic EOR project to be challenging. One of the significant challenges identified is the likely time delay of decades between CO_2 injection after the completion of primary oil production and any additional oil recovery after the reservoir becomes filled with CO_2.

Given the need for detailed evaluations using commercially sensitive data, it has not been possible to reach a conclusion on the viability of EOR in this assessment. Additional studies may resolve some of the issues identified and determine scenarios where EOR can be developed economically, however given the uncertainties, no economic benefits for EOR have been assumed for this assessment.

Risk assessment and storage assurance

The construction and implementation of a major CO_2 geosequestration project, such as that envisaged in the LVCSA, has associated risks like any other major infrastructure or production project. However, the hazards and associated risks can be clearly identified and addressed by project proponents. They can draw on the extensive international experience obtained from existing CO_2 pipelines, EOR operations and demonstration CCS projects to help identify uncertainties and mitigation measures.

A range of risk assessment processes were conducted to confirm the project as a safe and reliable project for long-term containment of CO_2 and to demonstrate the risk assessment process. Risk assessments were performed on the project infrastructure and the geological storage integrity.

Major projects such as the LVCSA are typically developed in stages and consequently the safety and risk assessments are conducted in ever increasing levels of sophistication as the project definition increases. Accordingly, two types of initial hazard study were performed on the LVCSA infrastructure, a preliminary risk assessment and a quantitative risk assessment.

The preliminary risk assessment identified key potential impacts, risks and uncertainties from the process, as well as several specific mitigation actions that had already been factored into the costings for the project. The screening analysis conducted under the LVCSA indicates that all issues associated with the proposed injection infrastructure have the potential to be managed within accepted safety levels.

A quantitative risk assessment of CO_2 compression and transport and the risk and consequence modeling of pipeline leaks identified potential hazards along with issues that will need to be addressed by project proponents. This more detailed risk assessment also confirmed that the risks from compression and pipeline infrastructure are low and manageable using well-known methods common to industry. There are no likely impediments to development based on risks imposed by the infrastructure of such a project.

The geological assessment of the target sites in the Gippsland Basin confirmed previous studies showing the sites to be excellent candidates for safe and reliable containment of CO_2. A quantitative risk assessment of the geosequestration sites, using the technique developed under GEODISC^{TM}, determined that the reservoir could contain CO_2 to an acceptable level. A CO_2 leakage rate of 1% over 1000 years is commonly used as an acceptable level for storage assurance and the targeted reservoirs within the offshore Gippsland Basin are predicted to be below this level. A plot of the results of the Kingfish Field (Figure 5) shows the components of containment risk. These provide guidance on the risk mitigation issues CCS proponents should focus on, namely pursuing a process for well maintenance and evaluation and further work to enhance data for reservoir modeling and flow prediction.

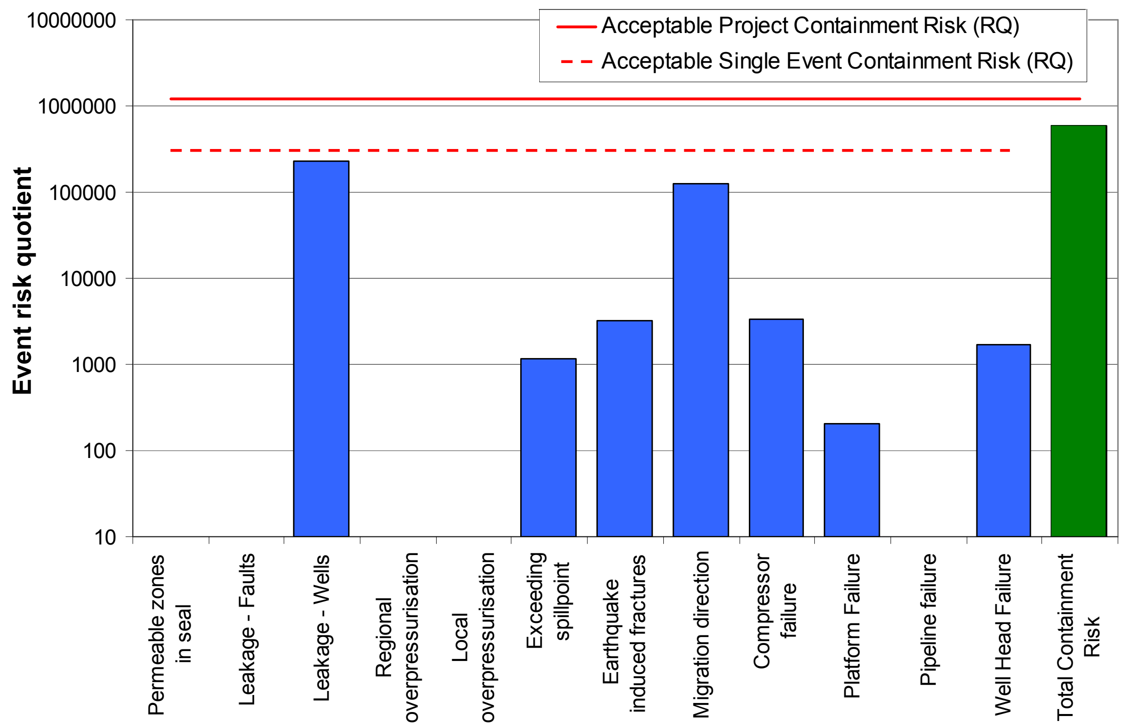

Figure 5. Kingfish event risk quotient (a measure of containment risk).

The risk assessment processes performed under the LVCSA provide strong indication that the Gippsland Basin can be a safe and effective storage site for CO_2 for thousands of years.

Techno-economic studies

Techno-economic modeling was used to define the costs of providing compression, transport, and injection for all the scenarios using an integrated capture and storage model developed to investigate CCS projects. It uses a cash flow modeling approach to design compression, transportation and injection components of any source-sink combination.

Specifically for this project, additional cost data on compressors, pipelines (onshore and offshore), platforms and wells were sought from engineering consultants and used to supplement data in the model. All costs are 2005 Australian dollars. The results from the model have an order of accuracy of ± 30% for any given set of source and sink characteristics.

Analyses were carried out for CO_2 injection rates for 2 million tonnes per year (Case A), 15 million tonnes per year (Case B) to 50 million tonnes per year (Case C). Offshore costs were based on an assumption of new stand-alone infrastructure, and on injection deep below the oil and gas fields, i.e. no integration with existing oil and gas production. The resulting cost estimates for cases considering injection of 15 million tonnes per year and 50 million tonnes per year are shown in Tables 2 and 3.

Table 2. Real (2005) capital and operating costs of CO_2 storage (not including Capture) in Australian dollars based on a permeability of 150mD.

Annual CO_2 flows	15 million tonnes per year	50 million tonnes per year
Capital costs	$1,199 m	$3,861 m
Compression[3]	$408 m	$1,163 m
Pipeline	$242 m	$750 m
Injection[4]	$516 m	$1,836 m
Oil well remediation	$34 m	$112 m
Operating costs /year	$62 – 71 m	$204 – 227 m

Table 3. Total capital and operating cost per tonne of CO_2 avoided in Australian dollars.

Annual CO_2 flows	Total cost
15 million tonnes per year	$10.9 per tonne
50 million tonnes per year	$10.5 per tonne

The unit costs of storage are comparable to those developed under GEODISC™ for the high volume cases. The costs include that of compression so care must be taken when comparing to other studies.

A 2 million tonne per year (Case A) was assessed in order to investigate the relationship between injection rate and cost per tonne. At this low rate it was considered to represent a small-scale demonstration plant and was modeled as such. As expected, the storage costs were determined to be relatively high at $34.2 per tonne of CO_2. The comparison of the costs for the three injection rates over a similar 40 year basis is shown in Figure 6.

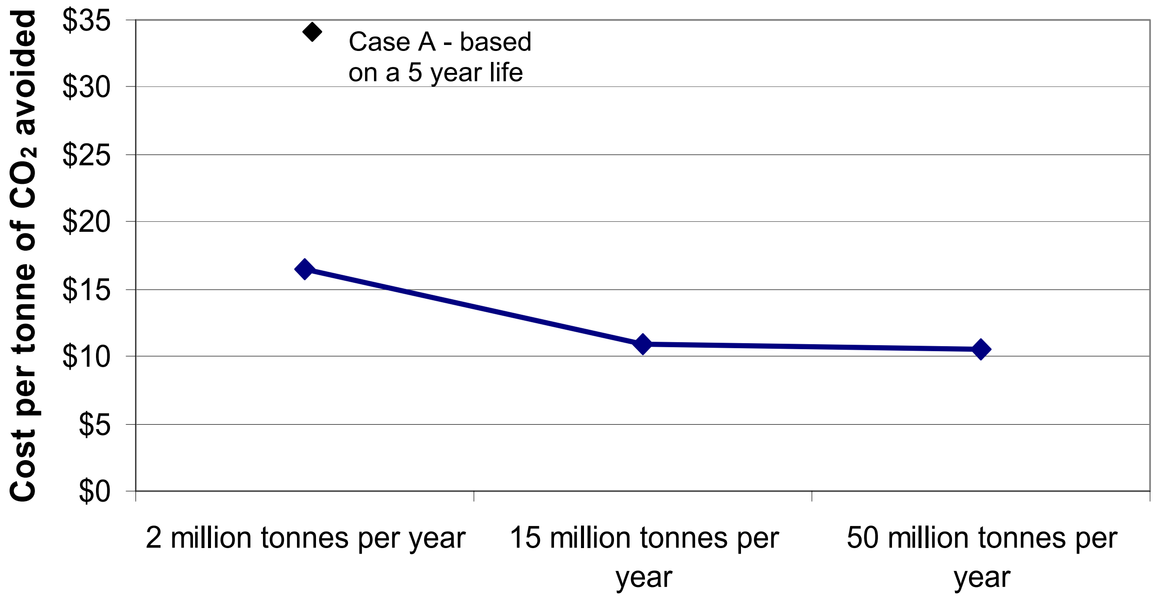

Figure 6. The relationship between injection rate and cost per tonne of CO_2.

[3] Compression comprises the cost of compressors and power plant to drive them.
[4] Injection comprises the cost of well drilling, platforms and remediation of old oil production wells.

The capital cost estimates and costs per tonne of CO_2 avoided are quite sensitive to project parameters such as project scope, injection depth, reservoir permeability, ramp-up time, policies on equipment sparing, methodologies for providing compressor drive power and project life.

Sensitivity studies were conducted on a number of parameters using Case B1 as the base (Figure 7). The analysis compared scenarios with: no spare compressors; a shallow staged injection concept for the top Latrobe Group at Kingfish and Fortescue; high permeability of 1000mD (as opposed to 150mD) for intra-Latrobe Group injection (purely for comparative purposes); and horizontal well injection. The most sensitive parameter is reservoir permeability, which affects the number of wells and hence the size and cost of offshore injection facilities.

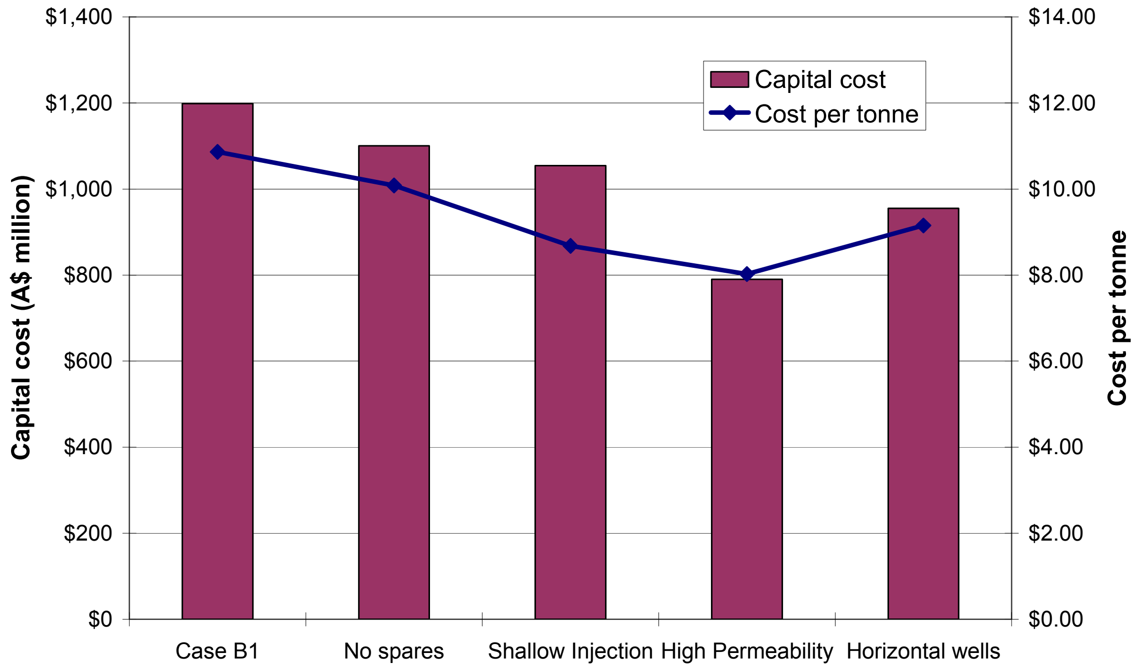

Figure 7. Sensitivity analysis.

Horizontal wells were considered to reduce costs by allowing increased reservoir penetration, moderating pressure interference and reducing the number of wells required. This showed the potential for reduced costs if long-run horizontal wells are used.

The base cases included a compressor sparing policy for greater reliability. Relaxing this requirement reduced costs which should be considered more closely in final designs.

A final sensitivity was run on a shallower injection for the B1 case. While not chosen as the base case because oil production may not have ceased before injection starts, a two-stage step-out of the Kingfish Field followed by the Fortescue Field could conceptually be employed to achieve Case B volumes for 40 years. Little reservoir modeling was performed on this shallow injection and it may not be viable for Case C due to storage constraints. Nevertheless, costs were reduced as shown in Figure 7.

Conclusion

The LVCSA provides strong indications that the Gippsland Basin has sufficient capacity to safely and securely store large volumes of CO_2 and may provide a viable means of substantially reducing greenhouse gas emissions from coal-fired power plants and other projects using brown coal in the Latrobe Valley.

The LVCSA has addressed the agreed outcomes and fulfilled the requirements of the Australian Government's Sustainable Regions Programme.

an emission free vision for the future

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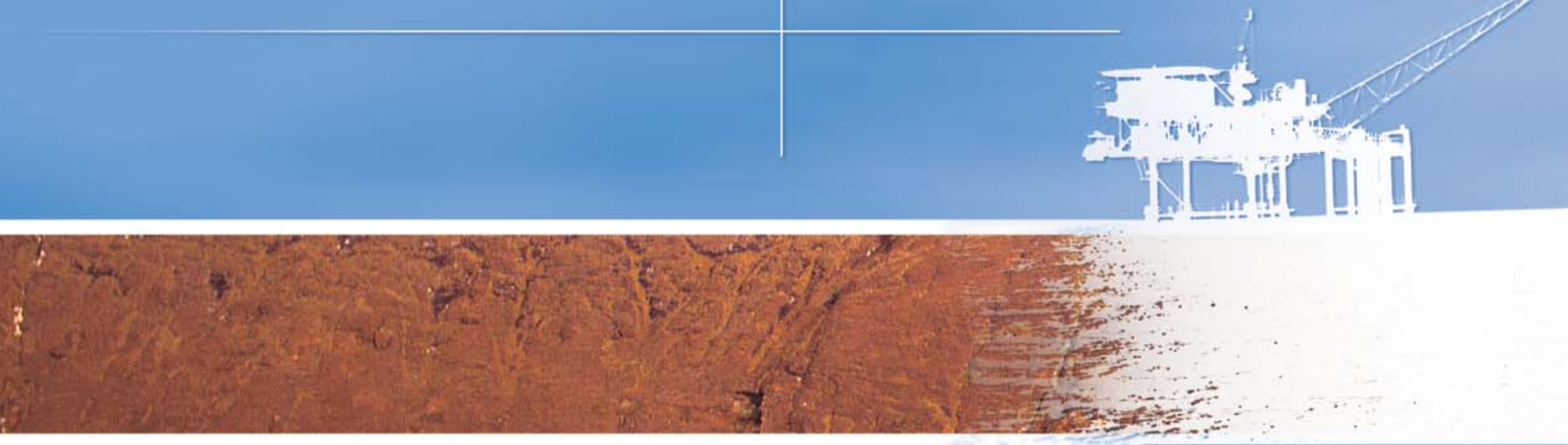

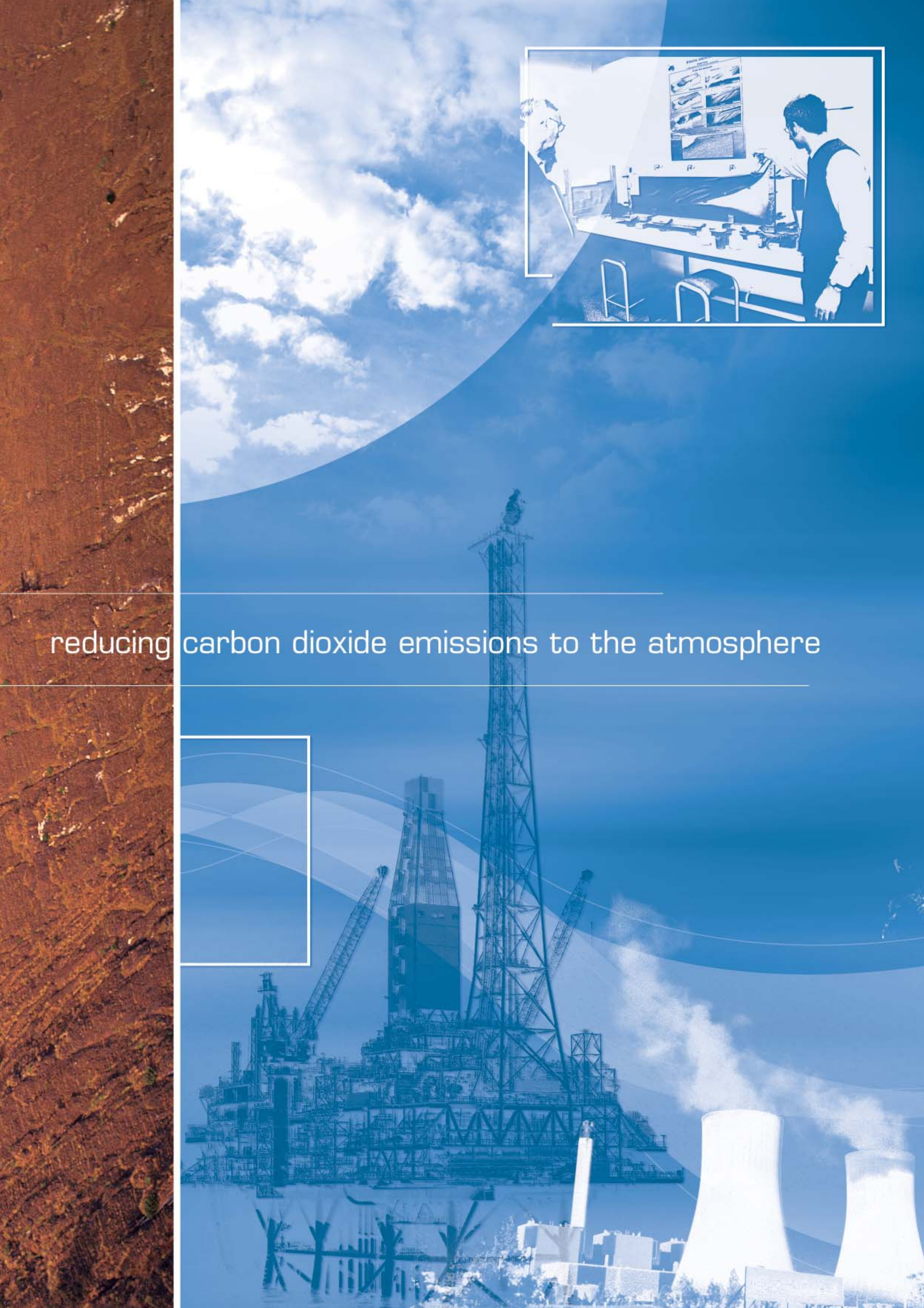

reducing carbon dioxide emissions to the atmosphere

From Andy's presentation

- Aims
  - high-level techno-economic study
  - Framework for stakeholder engagement
  - Pre-feasibility study
  - May initiate licence applications for coal to liquids from brown coal

Project

- 50 Mt per year
- Anglo/Monash open cast coal with drying, gasification to make diesel with CO2 capture
- Centralised capture/compression
- Transport (40km onshore, 100km offshore) to Bass Strait offshore oil fields and deeper saline aquifers
- Kingfish field: 15Mt per year for 40 years

Geology

- Offshore Gippsland basin, Tertiary and Cretaceous with oil and gas fields
- Kingfish Paleaocene and Eocene beach sand sediments with high permeabilities (up to 10D) and high productivities
  - 1 billion bbls
- Reservoir quality is very good
- Seal capacity
  - Supports 100m CO_2 column heights
  - Intraformational seals 517m height
  - Top seals 360 column
  - Regional 395 m column height

Storage concept 1

- Migration will be west to east, updip
- Seismically-mapped faults in intra units do not intersect migration pathway
  - 3 faults cut top seal
  - 7 intraformational faults
  - Most have medium to high reactivation potential
  - System is underpressured due to oil production
- When CO_2 reaches top (100-200yrs) of unconformity it will migrate east to west
- CO_2 moves under intraformational seals, leading to lots of residual gas trapping and solution trapping (25% after 200 yrs)
- Some mineral trapping in immature reservoir underneath regional seal
- Pressures always below initial reservoir (pre-production) pressures

Storage concept 2

- Hydrogeology
  - Onshore extraction
  - Offshore pressure sink due to depleted fields
  - This leads to strong hydrodynamic drive which balances east to west CO2 buoyancy-drive migration at top of Latrobe
- Capacity, >600Mt so enough for storage plan
- Injection will start at end of oil production but gas production will be ongoing at this stage

Modelling

- 1Mt/yr per well, for 15 wells
- Object modelling of shale interlayers within reservoir, small or large shales
- Surfaces from 3D seismic
- Permeabilities are averaged within formations
- CO2 predicted to reach top seal after 200 years
- Some potential for CO2 movement ot of field but remains trapped.

QRA for Kingfish

- Outcome: total containment risks are below the proposed performance criteria
- Discussion of terminology
  - Performance assessment or risk assessment
  - Consequences of impacts were not considered

Key lessons from techniques/frameworks used - Andy

- RA aims
  - Transparent process
  - Interface with wider community
  - Allow assessment of safe, measurable, verifiable and economically sound
- QRA using URS RISQUE method
  - Using expert panel, of 10 members, to identify risks events, likelihood and costs
  - Also includes cost-benefit analyses, impacts on communities
- Fits with Aus/NZ risk standards
- Qualitative descriptions of probability were transformed to mathematical probabilities
- No performance indicators when started:
  - Therefore defined by CO2CRC
  - Containment: CO2 retention is 99% after 1000 years
  - Effectiveness: Any CO2 reduction to amount stored should

Latrobe Valley

Evaluation of risk assessment

Strengths and weaknesses of datasets

- Only publicly available data
  - 3D seismic coverage over field, larger coverage would have been useful
  - Cored wells within Kingfisher field
  - Lack of deep well control
    - Addressed through shale object modelling
    - High uncertainty, lack of pressure data
  - Lack of well density
  - Latest pressure information is unavailable, therefore relied on 15-year extrapolation
    - This increases uncertainty in containment and modelling but in terms of public concern this is unlikely to be important.
- Access to commercially-sensitive information could be an issue in active oil/gas fields
- Data that was missing
  - Poroperm data to constrain reservoir simulations
  - Need to drill deep wells to confirm stratigraphy and shale distribution
  - Stress tensors are not well constrained therefore less confidence from geomechanical modelling

Strengths and weaknesses of datasets

- Lack of pressure profile
  - Could provide data on integrity of intraformational seals
- Modelling highlighted lack of data on seal distribution and sensitivity to pathways
- Well integrity
  - Currently only on classes of wells
  - Not evaluated individually
  - Some are open-hole, it is not known if these have self-sealed
- Experts could be used to comment on data quality as well as identifying risk events
- Have yet to consider timescales in terms of pressure evolution
  - Risk at highest during injection and have yet to identify pathways from wells during injection
  - Due to lack of detailed control of intraformational seal distribution and properties

Key lessons from techniques/frameworks used

- Experts only from research organisation but should be extended to experts with extensive oil&gas experience
- Could compare with additional expert panels
- Plot containment against effectiveness risk indices for a number of storage sites, allows interpretation of confidence in risks as well as comparison against acceptable risk targets
- Could perform sensitivity analyses to identify what drives confidence (e.g. expert opinion or parameter uncertainty…)
- RA focussed on long-term issues
  - Containment but little work on near-surface leakage or impacts
  - Well treatments as classes (exploration, production, injection)
  - Development of stand-alone risk screening
- Performance criteria is leakage from reservoir, this does not equate to marine or atmospheric flux

Key lessons from techniques/frameworks used

- Should be clear that this was a research exercise not a RA for seeking a licence.
- Not a formalised FEP approach
  – Due to lack of time and financial resources but might not have been done anyway
  – Use approach with which they were familiar
  – Allows rapid assessment, scenario definition and identification of principle risks
    - Performance Assessment (instead of RA) component completed by 1 person over 2 months and expert panel met twice for review
  – Provides regulators with digestible summary
- If external stakeholders were involved than a more formal FEP audit may be required
- May not identify all scenarios but key scenarios are probably included
- Coupling between risk events not included
- Wells were not evaluated individually
- Lack of empirical data for leakage rates in faults and wells
- Modelling has not been peer-reviewed

Inherent assumptions - general

- Performance criteria (<1% leakage in 1000 years): is this acceptable for stakeholders?
- Assumptions are needed due to lack of empirical leakage data
- Intraformational seal distribution and properties are not known and therefore modelled
- Two expert panels could come up with (somewhat) different conclusions
- Sensitivity analyses would have enabled the influence of critical assumptions to be identified
  - This was done for shale distributions

Inherent assumptions - specific

- Exploration wells, plugged and not re-entered or remediated
  - Assumed that they could leak, leakage rates are generic and are fixed
  - 200 t/yr/well for 14 wells over 500 years
- Production & injection wells will be evaluated and remediated prior to abandonment therefore likelihood for leakage is lower, no opportunity for remediation after abandonment
- No expected leakage through seal since a thick seal and retained oil for geological timescales
- Overpressurisation will be avoided by monitoring and could get some fluid migration into field due to depletion
- Seismic activity has been reviewed
  - Assume self-sealing of any reactivated fault with some short-term leakage
- Identification of seismically resolvable faults does not indicate potential migration to surface

Confidence in results

- Publicly available data constrains confidence in some results
  - No access to wells, production data or pressure data etc
  - No operator participation
- Internal panel experts did not necessarily have wide oil&gas expertise
  - estimates of confidence may be different from other experts
- Could repeat expert panel process with different experts
- Based on confidence in data, is it right to make assertions to non-experts about Gippsland containment?
  - *A priori* – an oilfield
  - It is recognised that well integrity remains the key issue.
- The impacts of faster vertical migration could be investigated
- Uncertainty ranges indicated from this approach for other sites possibly too narrow.

Confidence Building

- Explicit statements of known parameters, processes and their uncertainty, weaknesses
- This leads to a definition of how to address these weaknesses
  - Monitoring programmes could be developed to address weaknesses identified.
- The RA was made publicly available with strong community engagement
  - Broad support
  - Some issues from agricultural communities regarding water supply (storage was good, reducing groundwater drawdown)
  - Potential for onshore leakage was raised and then adequately addressed

Latrobe Valley

Evaluation of risk assessment

Strengths and weaknesses of datasets

- Mainly publicly available data
  - 3D seismic coverage over field, 2D ties to off-field wells; larger coverage would have been useful
  - Cored wells within Kingfish field
  - Lack of deep well control
    - Addressed through shale object modelling
    - High uncertainty, lack of pressure data
  - Lack of well density
  - Latest pressure information is unavailable, therefore relied on 15-year extrapolation from 2000 to injection start at 2015
    - This increases uncertainty in containment and modelling but in terms of public concern this is unlikely to be important.
- Access to commercially-sensitive information could be an issue in active oil/gas fields
- Data that was missing
  - Actual permeability data to constrain reservoir simulations
  - Need to drill deep wells to confirm stratigraphy and shale distribution
  - Stress tensors are not well constrained therefore low confidence in the geomechanical modelling

Strengths and weaknesses of datasets

- Lack of deep pressure profile across reservoirs and seals
  - Could provide data on integrity of intraformational seals
- Modelling highlighted lack of data on seal distribution and sensitivity to pathways
- Well integrity
  - Currently only risk assessed by classes of wells
  - Not evaluated individually
  - Some are open-hole, it is not known if these have self-sealed
- Experts could be used to comment on data quality as well as identifying risk events
- Have yet to consider timescales in terms of pressure evolution
  - Risk at highest during injection and have yet to quantify leakage rates during injection, immediately post injection and long term
  - Due to lack of detailed control of intraformational seal distribution and properties

Key lessons from techniques/frameworks used

- Experts only from research organisation but should be extended to experts with more extensive oil&gas experience
- Could compare results from additional expert panels
- Plot containment against effectiveness risk indices for a number of storage sites, allows interpretation of confidence in risks as well as comparison against acceptable risk targets
- Could perform sensitivity analyses to identify what drives confidence (e.g. expert opinion or parameter uncertainty…)
- RA focussed on long-term issues
  - Containment but little work on leakage into shallower horizons, near-surface leakage or impacts of either
  - Wells treated as classes (exploration, production, injection)
  - Development of stand-alone risk screening
- Performance criteria is leakage from reservoir, this does not equate to marine or atmospheric flux

Key lessons from techniques/frameworks used

- Should be clear that this was a high-level, research exercise not a RA for seeking a licence.
- Not a formalised FEP check-list approach
  - Due to lack of time and financial resources but might not have been done anyway
  - Used an approach with which they were familiar
  - Allows rapid assessment, scenario definition and identification of principle risks
    - Performance Assessment (instead of RA) component completed by 1 person over 2 months and expert panel which met twice for review
  - Provides regulators with digestible summary
- If external stakeholders were involved then a more rigorous FEP audit may be required
- May not identify all scenarios but key scenarios are probably included
- Coupling between risk events not included
- Wells were not evaluated individually
- Lack of empirical data for leakage rates in faults and wells (as is generally the case)
- Modelling has not been peer-reviewed other than by presentation to CO2CRC sponsor companies

Inherent assumptions - general

- Key performance criteria for containment (<1% leakage in 1000 years): is this acceptable for stakeholders?
- Assumptions are needed due to lack of empirical leakage data
- Intraformational seal distribution and properties are not known and therefore object modelled in simulations
- Two expert panels could come up with (somewhat) different conclusions
- Sensitivity analyses would have enabled the influence of critical assumptions to be identified
  - This was done for shale distributions

Inherent assumptions - specific

- Exploration wells, already plugged and not re-entered or remediated
  - Assumed that they could leak, leakage rates are generic and are fixed
  - 200 t/yr/well for 14 wells over 500 years
- Production & injection wells will be evaluated and remediated prior to abandonment therefore likelihood for leakage is lower, no opportunity for remediation after abandonment
- No expected leakage through seal since a thick seal and retained oil for geological timescales
- Overpressurisation will be avoided by monitoring
- Could get some fluid migration into shallow oil field due to depletion
- Seismic activity has been reviewed
  - Assume self-sealing of any reactivated fault with some short-term leakage
- Identification of seismically resolvable faults does not indicate potential migration to surface

Confidence in results

- Publicly available data constrains confidence in some results
  - No access to recent production wells, production data or pressure data etc
  - No significant operator participation in study but reviewed by them
- Internal panel experts did not necessarily have wide oil&gas expertise
  - estimates of confidence may be different from other experts
- Could repeat expert panel process with different experts
- Based on confidence in data, is it right to make assertions to non-experts about Gippsland Basin containment?
  - Positive*; A priori* – an oilfield
  - Negative; It is recognised that well integrity remains the key issue.
- The impacts of faster vertical migration could be investigated
- Uncertainty ranges indicated from applying this same approach for other sites (GEODISC) possibly too narrow.

Confidence Building

- Explicit statements of known parameters, processes and their uncertainty, weaknesses
- This leads to a definition of how to address these weaknesses
  - Additional well data needs to be obtained
  - Monitoring programmes could be developed to address weaknesses identified.
- The RA was made publicly available with strong community engagement
  - Broad support
  - Some issues from agricultural communities regarding water supply (storage was good, possibly reducing groundwater drawdown)
  - Potential for onshore leakage was raised and then adequately addressed

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Risk Assessment Case Study: Mountaineer CO_2 Sequestration Site

Joel Sminchak[1], Prasad Saripalli[2], Neeraj Gupta[1], Yiling Fang[2], and Mark Kelley[1]

[1]Battelle, Columbus, Ohio

[2]Pacific Northwest National Laboratory, Richland, Washington

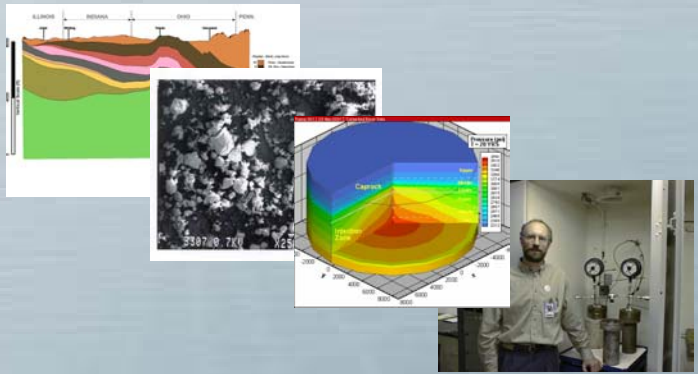
IEA Greenhouse Gas R&D Programme
2nd Risk Assessment Network Meeting
October 5-6, 2006 • Berkeley, California

Mountaineer Project Background

a.k.a. "Ohio River Valley CO_2 Storage Site"

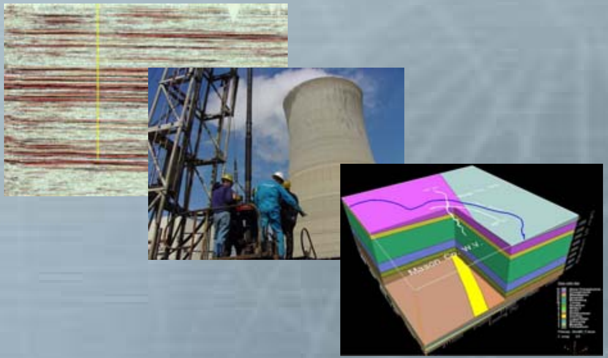
Overall Objective- Provide an understanding of the viability of carbon sequestration as greenhouse gas reduction technology by performing an integrated demonstration of CCS in Ohio R. Valley.

- ✓ **Phase I- Regional capacity evaluation.**



- ✓ **Phase II- CO_2 injection modeling, economic & engineering assessment, geochemical experiments.**

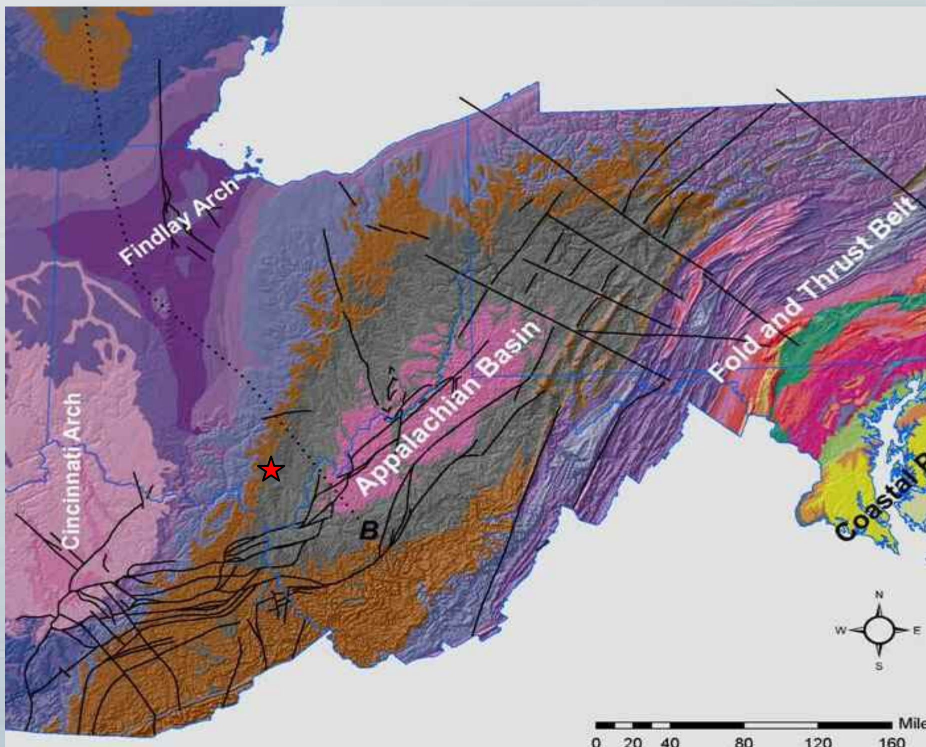
- ✓ **Phase III- Test well drilling, seismic, reservoir testing, rock coring at Mountaineer Power Plant. Design and feasibility study.**

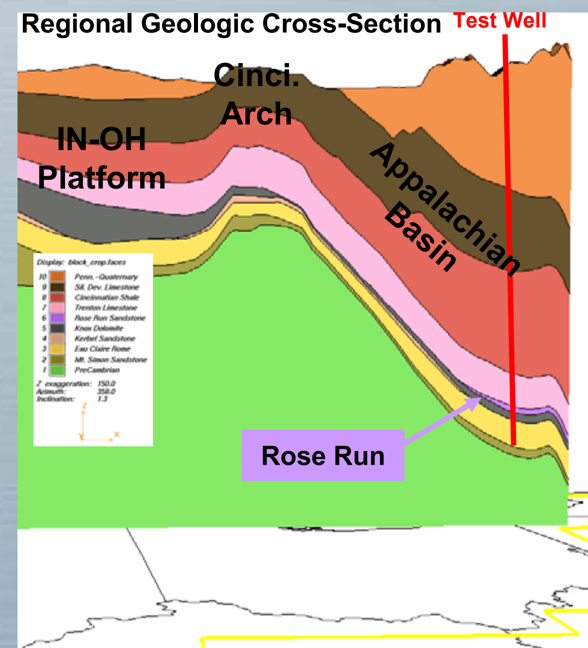


- ✓ **Potential Future Effort- Pilot-scale carbon capture and storage (CCS) at power plant, injection, storage monitoring.**

Site Location/Environmental Setting

- 1300 MW AEP Mountaineer Power Plant, New Haven, WV, on the Ohio River along U.S. Route 62.





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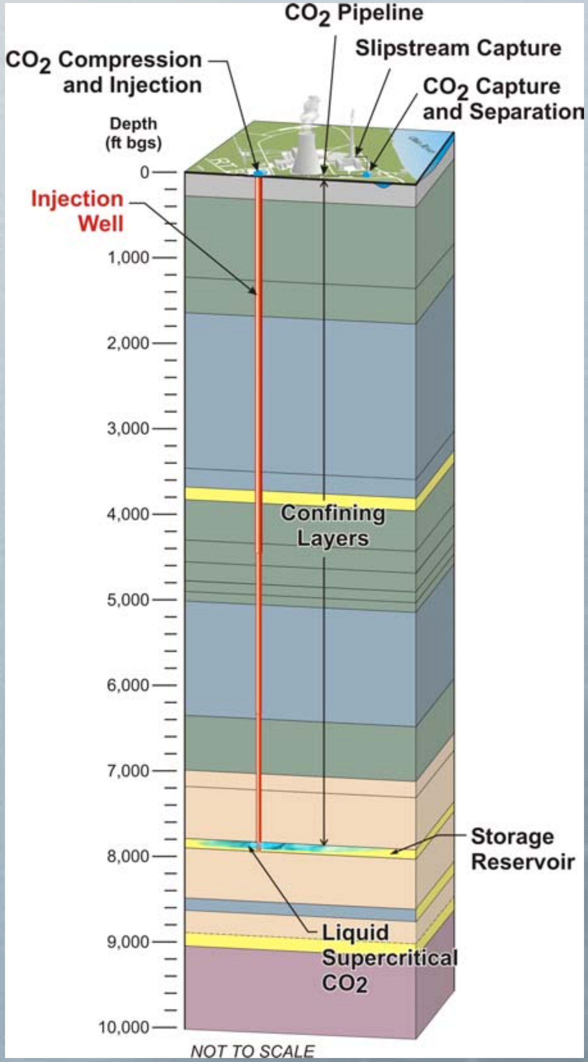
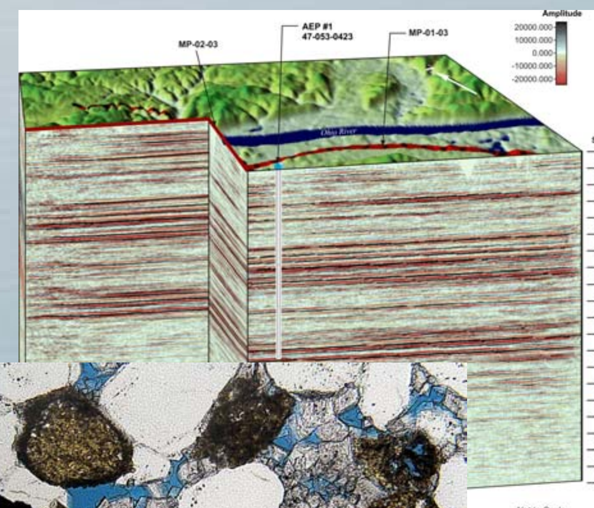
Mountaineer Project Plans/Assumptions

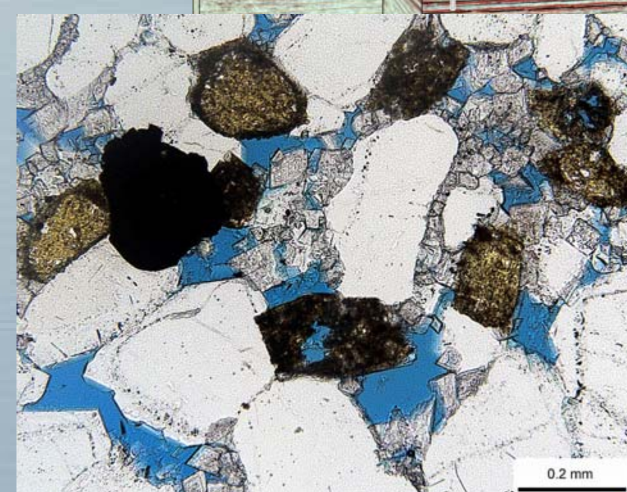
- Develop test-scale integrated carbon capture and storage system.
- Capture and injection of <0.5% plant emissions into deep saline formation (rate depends on slipstream capture specs ~20-100 metric ton CO2/day).
- Several years of continuous injection & monitoring.
- Entire system to be contained on plant site.



Mountaineer Site Characterization

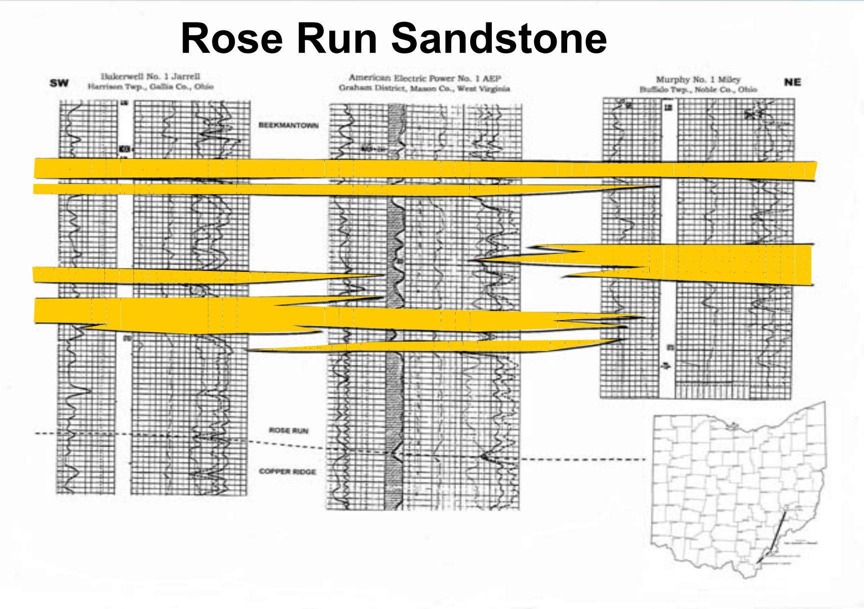
- First CO_2 sequestration test well at active power plant.
- Testing provides extensive suite of quantitative parameters.
- Reservoir testing completed to test injectivity.

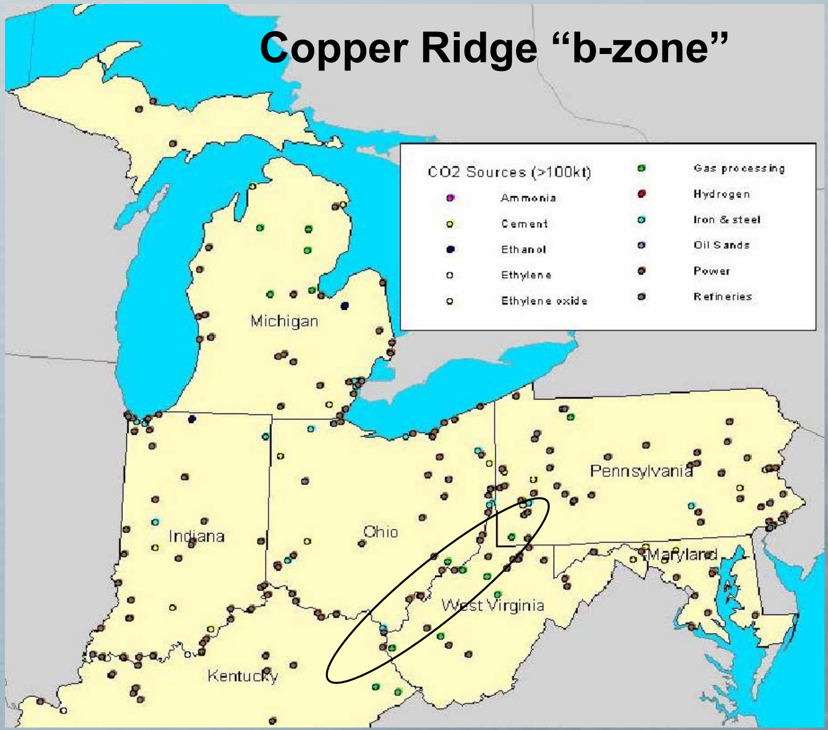




Regional Site Characterization

- Regional data helps define sequestration potential in the region.





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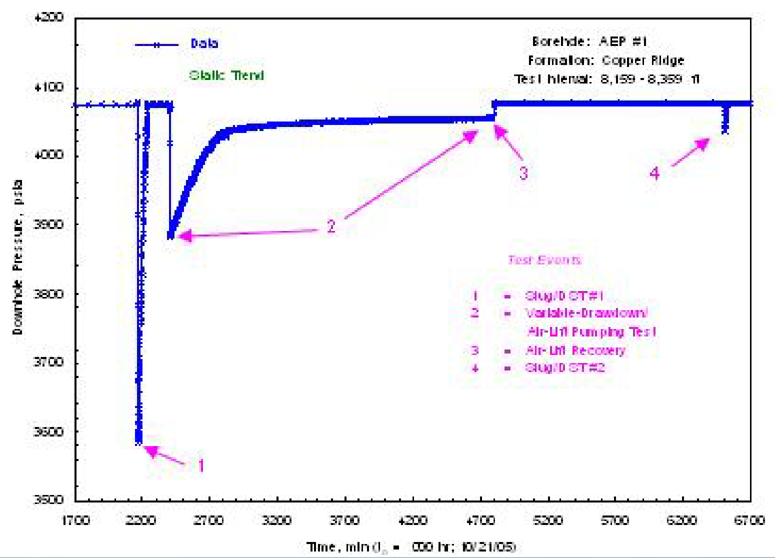
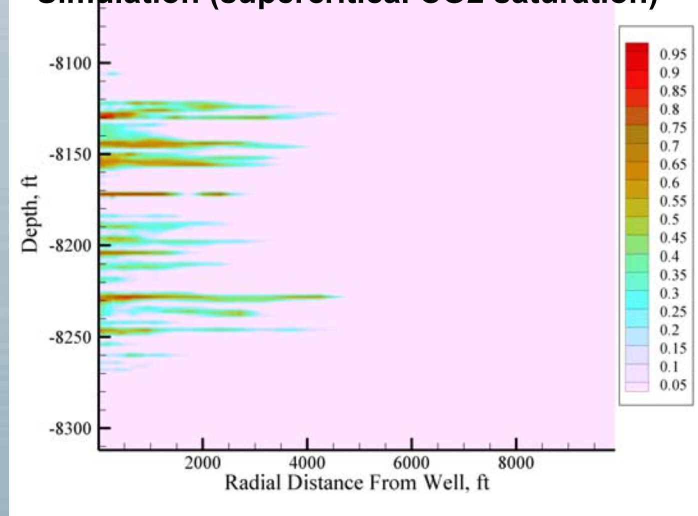
Mountaineer Recent Progress

- Reservoir testing in carbonates (Copper Ridge “b-zone”) indicates permeability up to several hundred mD across 200 ft.
- STOMPCO2 reservoir modeling indicates injection rates of 100s of ktonnes CO2/year possible in both Rose Run Sandstone and Copper Ridge “b-zone”.

Reservoir Tests in Copper Ridge “b-zone”



Copper Ridge “b-zone” STOMPCO2 Simulation (supercritical CO2 saturation)



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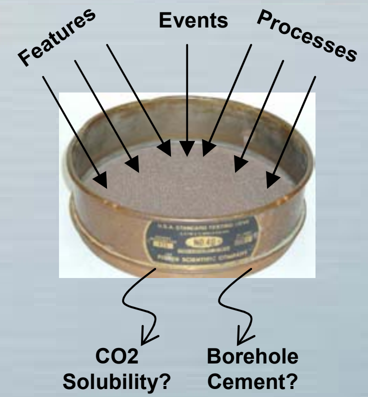
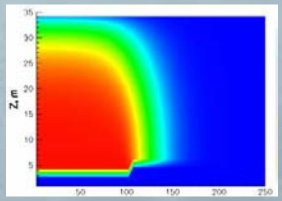
Risk Assessment Methodology

1) ***Features, Events, and Processes (FEP) Performance and Safety Screening***
   – Systematic, qualitative screening
   – High-level effort to identify important items for the project



2) ***Integrated Numerical Modeling Approach***
   – Integrated assessment framework to address risk and consequence
   – Quantitative methods

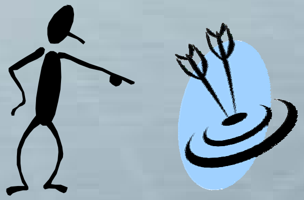


$$\overline{S}_g = \frac{1}{\pi r^2 \phi h} \int_{r=0}^{r=r_s} 2\pi r \phi h S_g \, dr$$

- Comprehensive site characterization provides knowledge base and site-specific parameters for risk assessment.

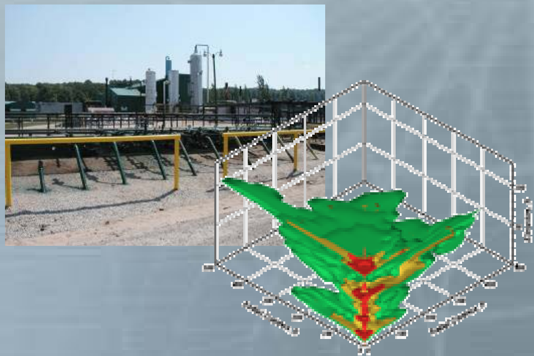
Performance and Safety Screening for the Mountaineer CO_2 Storage Site Using Features, Events, and Processes Database

1. Apply systematic screening procedure to the Mountaineer site for geologic storage of CO_2.



2. Identify potential performance and safety risk items.

3. Provide guidance on injection system design, monitoring program, reservoir simulations, and other risk assessment efforts.



FEP Screening Process

Level 1 Screening (143 Items) → Screen out 69 Items not applicable, policy or legacy issues

↓

Level 2 Screening (74 Items) → Screen out 54 Items addressed by general site conditions and/or site characterization results

↓

Level 3 Screening (20 Items) → Screen out 14 Items accounted for by testing at site and/or system specifications

↓

6 Items (address in design, monitoring, additional testing and analysis)

INTEGRATED MODELING APPROACH FOR RISK ASSESSMENT OF MOUNTAINEER CO2 SEQUESTRATION PROJECT

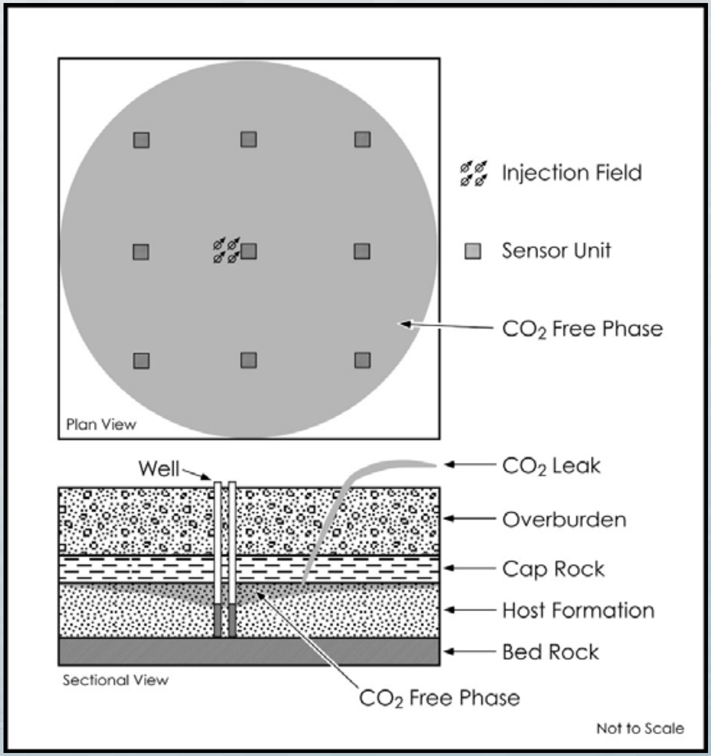
- **Fate and transport models can serve as an effective basis for developing integrated risk assessment and permitting tools for a given site.**

- **We used STOMPCO2, a reservoir-scale numerical model and extended it further, to develop an integrated assessment framework.**

- **This tool can support risk and consequence assessment, monitoring networks design and permitting guidance needs.**

Integrated Assessment Model

An integrated, reservoir scale model can support Engineering Design, Risk & Consequence Assessment, Permitting, Site Monitoring & Verification



Monitoring Networks

Atmosphere

Soil | Water-bodies

Vadose Zone

Overburden & Aquifer

Caprock Integrity | Wells Integrity

Injection, Fate & Transport

Path Forward

- Integrate risk items into MMV program.
- System design for CCS.
- System construction and testing.
- Verification of long-term sequestration.
- Investigate up-scale issues.

Questions to Consider:

- Other risk issues beyond leakage (i.e. system integrity, long-term injectivity, economic risk)?
- Might a CCS system actually reduce risk in some areas (i.e. air emissions from existing power plant)? Example: Mountaineer plant will require SO_X scrubber before CCS is possible. Isn't this a good thing? How does it factor into our risk assessment? Are we ignoring it?
- False positive risks from near surface monitoring?
- Reconciling risk conclusions/recommendations with existing Class I and gas storage applications? Gas storage and waste injection wells generally have lesser risk analysis and MMV.

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Performance and Safety Screening for the Ohio River Valley CO_2 Storage Site Using Features, Elements, and Processes Database

Joel Sminchak, Mark Kelley, and Neeraj Gupta

Battelle Memorial Research Institute, Columbus, OH

Performance and Safety Screening for the Ohio River Valley CO_2 Storage Site Using Features, Elements, and Processes Database

Joel Sminchak, Mark Kelley, and Neeraj Gupta

Battelle Memorial Research Institute, Columbus, OH

Abstract- A systematic screening procedure was applied to the Ohio River Valley Carbon Dioxide (CO_2) Storage site utilizing the Features, Elements, and Processes (FEP) database for geologic storage of CO_2 (Savage et al., 2004). The objective was to identify potential risk categories for the long-term geologic storage of CO_2 at the Mountaineer Power Plant in New Haven, West Virginia, USA. Over 130 FEPs in seven main classes were assessed based on site characterization information gathered in a geological background study, testing in a deep well drilled on the site, and general site conditions. In evaluating the database, it was apparent that many of the items were not applicable to the Mountaineer site based on its geologic framework and environmental setting. Several FEPs were identified for further consideration for the project. These FEPs generally fell into categories related to variations in subsurface geology, well completion materials, and the behavior of CO_2 in the subsurface. Results from the screening were used to provide guidance on injection system design, develop a monitoring program, perform reservoir simulations, and other risk assessment efforts. Initial work indicates that the significant FEPs may be accounted for by focusing the storage program on these potential issues. The screening method was also useful in identifying unnecessary items that were not significant given the site-specific geology and proposed scale of the project. Overall, the FEP database approach provides a comprehensive methodology for assessing potential risk for a practical CO_2 storage application.

Introduction- Concerns about increasing trends in atmospheric greenhouse gases have prompted research into several CO_2 mitigation options. Sequestration in geologic reservoirs has emerged as one of the more viable technologies available to address emissions from large point sources such as power plants, refineries, and other industrial facilities. Experience with natural gas storage, enhanced oil recovery, natural CO_2 fields, and hazardous waste injection demonstrate that injection of CO_2 emissions into deep rock formations is a safe and practical technology, but there is some risk associated with application of geological storage. To address this potential risk, CO_2 sequestration has developed into a storage concept involving monitoring, measurement, and verification of the injected CO_2 to prove that the CO_2 is safely sequestered.

However, a wide range of factors may affect a storage project, and it is difficult to account for all these items in developing a storage and monitoring program. As such, a FEP database was developed by Quintessa to assess safety and performance of geological storage of CO_2 (Savage et al., 2004). The database is an extensive list of possible features, events, and processes that should be considered in a storage project. This systems analysis approach has been used for numerous applications, most notably radioactive waste disposal. A FEP screening approach was selected for the Ohio River Valley CO_2 Storage Project to aid in design and feasibility evaluation for an injection system at the site. The objective of the screening was to identify the main FEPs needed to be considered for the project.

The project itself is aimed at providing an understanding of the viability of carbon capture and sequestration by performing an integrated demonstration of CO_2 capture and geologic sequestration at an active power plant in the Ohio River Valley. This region is a significant energy producer in the United States and has a large potential capacity for geologic storage of CO_2 (Bergman and Winter 1995). Battelle is leading the project with support from DOE's National Energy Technology Laboratory to investigate the feasibility of geologic sequestration of CO_2 in the Ohio River Valley Region. American Electric Power (AEP), BP, the Ohio Coal Development Office (OCDO) of the Ohio Department of Development, and Schlumberger are providing additional sponsorship and technical input.

The site is located just south of New Haven, West Virginia, along the Ohio River at the AEP Mountaineer Power Plant (Figure 1). The plant is a modern 1,300-megawatt coal-fired steam electric generating unit that burns low sulfur coal and is equipped with electrostatic precipitators for particulate emissions control (AEP 1974). The site was selected for investigation in 2002, and a sequential series of characterization tasks were completed to prepare for injection. Initial efforts focused on reviewing the geologic framework of the area as it applies to potential storage reservoirs and caprock (Sminchak et al., 2004). Based on guidelines from this work, a 2,800 m deep well, named "AEP #1," was drilled on the Mountaineer site. The AEP #1 well had dual purposes: 1. an exploratory boring to characterize geologic storage options; and 2. an on-site injection well for a CO_2 capture and storage demonstration for the power plant. Extensive rock core testing, wireline logging, brine sampling, and geomechanical analyses were completed in association with the drilling. A 2-D seismic survey was also performed in two 9 km long transects through the well site (Gupta et al., 2004). Reservoir tests were also completed in the target storage reservoirs and caprock intervals. Risk assessment, public outreach, and reservoir simulations were also included in the project.

The next phase proposed in the program is development of a pilot-scale CO_2 capture and storage system. This step involves design and evaluation of a system to capture a portion of emissions from the plant, separate the CO_2, compress the CO_2 into a supercritical liquid, inject this fluid in an injection well, and monitor the fate of the CO_2 in the storage reservoir (Figure 2). Injection of less than 0.5% of plant CO_2 total emissions per day over a period of approximately 2+ years is the current goal of the design phase (total injection of less than 100,000 metric tons CO_2). A smaller scale of injection was selected to allow for flexibility in optimizing the capture process because this is the first project of its kind at an active power plant. Since the program is in a design and planning stage, a FEP screening was considered constructive to guide future activities.

Methods- The general screening method was used to analyze each item in the generic FEP database against the corresponding site-specific conditions at the Mountaineer site. A conceptual model of the site was developed describing the geologic framework, target storage reservoirs, containment units, brine chemistry, environmental conditions, and proposed injection system. This information was then used in a sequential screening process aimed at identifying the main FEPs that apply to the project.

FEP Database- Screening items were obtained from the "Generic FEP Database for the Assessment of Long-Term Performance and Safety of the Geological Storage of CO_2" (Savage et al., 2004). The FEP database is divided into seven main classes, covering events as broad as neotectonics to microscopic processes such as complexation of CO_2 with heavy metals. Most FEPs are grouped in the CO_2 Properties and Geosphere categories, because these are key topics for CO_2 storage reservoirs. The database only addresses geologic storage, and items related to capture and injection are not included. The FEP database is designed to involve a systematic analysis, but it does not prescribe a numeric value to items. An explanation is supplied for each FEP item, but it is up to some interpretation as to whether it applies to a certain site. To account for this uncertainty, a multi-level screening process was employed for the FEP analysis.

FEP Screening Methods- A stepwise approach was utilized to identify the FEPs that should be considered for the Ohio River Valley CO_2 Storage Project (Figure 2). Screening methods involved the following steps:

1. Compiling characterization data into a site-specific conceptual model
2. Level 1 screening of FEPs for non-applicable or unlikely items
3. Level 2 screening of FEPs that do not apply based on general site conditions and/or site characterization results
4. Level 3 screening using site testing and/or system specifications
5. Providing recommendations on addressing remaining FEPs into system design, monitoring, and application.

Initial screening identified items that were non-applicable, programmatic issues related to CO_2 storage concepts, or legacy issues beyond the scope of a pilot-scale demonstration. The next level of screening examined the remaining FEP items in relation to general site conditions and site characterization results. If site information convincingly eliminated any concerns regarding the FEP, it was removed from further analysis. Level 3 screening was based on more quantitative information from site testing and/or system specifications. The remaining FEP items were compiled and analyzed to determine how they may affect the CO_2 storage project. Lastly, recommendations were made on how system design, monitoring, and storage application may be customized to address the FEPs identified in the screening.

Site Conceptual Model- In the study area, thick sequences of Paleozoic sedimentary rocks form broad basins—the Illinois Basin in the southwest, Michigan Basin in the North, and Appalachian Basin in the southeast—separated by an uplifted Cincinnati Arch region in the Midwestern United States. The study area for this project is located within the Appalachian Basin, where rocks slope toward the southeast. A review of deep wells and wireline logs in the region indicates that the sedimentary rocks are 2,400-3,100 m thick in the immediate vicinity of the study area. The sedimentary rocks overlie dense, metamorphic and igneous basement rocks. The Paleozoic rocks are layered arrangements of shale, siltstone, limestone, dolomite, and sandstone. Rocks dip to the east-southeast in the study area at about 20 m/km. The major geologic structure in the area is the Rome Trough, a failed rift valley that runs southwest-northeast about 40 km to the southeast of the study area (Figure 1). The rock units are otherwise fairly continuous. Earthquake activity in the area is low, and the site is classified as low risk by the United States Geological Survey (USGS) Seismic Hazards Mapping Project (Frankel et al., 2002).

From a reservoir standpoint, the Rose Run Sandstone and Copper Ridge "b-zone" were identified as the most suitable rock formations for CO_2 storage. In the AEP #1 well, the Rose Run Sandstone formation had a total thickness of 35 m in the exploratory boring at a depth interval of 2355-2390 m. The sand layers were interbedded with less permeable dolomite, typical for this formation (Riley et al., 1993). Both wireline logs and core samples indicate that the porosity and permeability in the rock is present as intergranular pore space. In the core samples, the Rose Run was a dense, micro- to very finely-crystalline dolostone, and sandstone intervals were composed of moderately to well cemented, fine to medium grained quartz sand. Porosity ranged from 8-13%.

The seismic survey indicated that the deep sedimentary layers were continuous and followed a gentle regional dip. There was no indication of structures near the site. The Rose Run Sandstone is present mainly in Pennsylvania, Western West Virginia, Eastern Ohio, and New York. The formation does not outcrop at the surface updip of the potential injection well. Thus, the reservoir is contained within the deep rock formations and there is no pathway to the surface. The Copper Ridge "b-zone" was present in the AEP #1 well at a depth of approximately 2491-2539 m. Wireline logs through this zone indicated several intervals of high permeability. The Copper Ridge 'b-zone' is a limited regional feature. In addition, other wells indicated that the "b-zone" may have regional storage capacity (Gupta et al., 2005). Reservoir tests in the AEP #1 well suggest that injection potential in the "b-zone" is greater than the Rose Run.

From a geological storage standpoint, the formations are appealing targets. The reservoirs have sufficient depth for injection of supercritical CO_2. Formation fluids have very high salinity over 300,000 mg/L. The reservoirs are well-confined by multiple, thick, and diverse containment units. Confining formations have very low porosity and permeability that would prevent migration of injected fluid. Trapping mechanisms consist of lithologic trends where the units thin out toward the updip in the central Ohio region. There are no faults, fractures, or other geologic structures that may affect containment. Finally, both formations are isolated, and no other wells penetrate the formation within approximately 40 km. The Rose Run has intergranular porosity, and the injection of CO_2 would be a predictable process. The reservoir is continuous in the study area and has suitable effective thickness for pilot-scale storage. The sandstone mineralogy is fairly inert with respect to any geochemical reactions. The nature of the Copper Ridge "b-zone" is not as well defined, but appears fairly continuous in the area. Over 100 oil and gas wells exist within a 3 km radius of the exploratory well. However, these wells are completed in much shallower rock units.

The injection well is located on an active coal-burning power plant along the Ohio River and provides a useful research location for the entire Ohio River Valley, where many power plants exist. Several towns with populations up to several thousand people are located within 10 km of the site. Infrastructure is fairly well-developed along the river, but less extensive away from the river valley. Land use along the river is a mixture of agricultural, industrial, and residential. The AEP Philip Sporn Power Plant is directly south of the Mountaineer Plant, and an underground coal mine is present west of the site. The nearest residential areas are approximately half a mile north. Climate in the area is temperate with an average yearly temperature of 11.7 ºC.

Level 1 Screening- The objective of the primary screening was to eliminate items not applicable, programmatic issues related to CO_2 storage concept, legacy issues beyond the scope of a pilot-scale demonstration, or other

FEPs that do not apply to the Mountaineer setting. The main FEPs removed in this screening included global climatic factors, biological processes, terrestrial environment, and marine features. Global climate factors were designated as broader policy issues. Effects on terrestrial environment and biological factors were eliminated because the storage reservoir is a very deep saline rock formation isolated from the surface. The site is located many hundred kilometers from any marine environment. While the primary screening removed several obvious items, the majority of the features, events, and processes were carried into the secondary screening.

Level 2 Screening- The secondary screening level compared remaining items to site characterization results. This level comprised the bulk of the screening effort. Many items in this screening can be accounted for with injection regulations, geologic conditions, brine chemistry, and/or the scale of the project. Many administrative issues that may arise from a storage project are addressed by the U.S. Environmental Protection Agency (USEPA) Underground Injection Control regulations. These regulations include such requirements as financial responsibility mechanisms for well abandonment, operational monitoring, and well material workovers. Processes associated with shallow aquifers and terrestrial environments were not included as significant issues since storage will occur in very deep isolated reservoirs with no evident pathways to the surface. Likewise, abandoned gas wells were not included as significant items because no wells penetrate the target reservoirs within 40 km.

Level 3 Screening- The final screening process involved removing items that were addressed with site-specific testing and/or system specifications. Many items associated with the reservoir geology and formation fluids were investigated during the well drilling and testing programs. Reservoir dimensions and character were thoroughly described through core testing, wireline logging, and seismic surveying. However, since there are no nearby wells in the target reservoirs, the uncertainty associated with reservoir heterogeneity was included for further analysis. Similarly, the borehole logging and regional geology demonstrated that extensive, competent containment units are present. FEPs associated with formation fluid chemistry have been investigated through analysis of brine samples from the well, supplemented by brine sample data from the entire region. Initial geochemical modeling shows no significant interaction between formation fluids, minerals in the reservoir rock, and injected CO_2.

Results and Conclusions- The final effort involved a closer investigation of the remaining FEP items. A detailed response to the potential risk presented by the FEP item was developed based on site data and proposed storage specifications. Based on this list, recommendations were developed to address issues in well design, monitoring, further analysis, and system operation.

Final Screening List- Table 1 provides the final list of FEPs that were identified in the screening process and response to these issues. In general, the final list fell into three categories: variations in subsurface geology, well completion materials, and behavior of CO_2 in the subsurface.

Geologic heterogeneities in the storage reservoir were seen as having the potential to affect pressures and fluid migration in the reservoirs. Interlayering of dolomite and sandstone were observed in the Rose Run sandstone; although, the Rose Run is laterally continuous in the seismic survey and regional maps. It is difficult to assess reservoir variations at this site, since there are no other wells within approximately 40 km. Some degree of geologic heterogeneity is expected in every geologic formation, but if these form a limiting boundary they may affect system operation.

Well completion materials were identified as a category that should be considered in the storage project because they may affect containment along the injection well. Since no other wells penetrate the reservoir nearby, this issue mainly applies to the injection well and any future monitoring wells that penetrate the storage reservoir. The proposed injection rate (30-100 metric tons/day) and duration (2-3 years) are such that current well materials should be adequate. Ongoing research is being performed to evaluate well casings and cements that may be integrated into the project.

FEP items related to the properties of CO_2 and interactions of CO_2 were also identified in the screening process. CO_2 solubility and aqueous specification were mainly considered an important process because formation fluids are very concentrated with total dissolved solids of more than 300,000 mg/L. This high salinity indicates low CO_2 solubility in the formation fluids. Consequently, storage mechanisms will likely rely on storage as a separate supercritical phase or residual trapping.

Recommendations for System Design, Monitoring, and Application- Many options are available to address the FEPs identified in the screening study. Geological heterogeneities were investigated with reservoir testing in the AEP #1 well and additional logging through the target reservoirs in wells in the region. The tests did not detect any boundaries in the reservoir. In addition, stochastic reservoir simulations were completed to determine the effects of reservoir variations on injection rates. Operational monitoring of injection pressures will aid in detecting reservoir boundaries. Otherwise, continued regional characterization may address reservoir changes.

Specialized well materials are an effective approach in ensuring the integrity of the well. Acid-resistant cement, alloy injection tubing, and mechanical packers may be used to ensure a competent well. Cement logging and well workovers may also be performed to determine if well materials are degrading; although, these tasks may best be completed at the end of the injection demonstration for this project given the 2-year injection period. Proper design and monitoring of the injection well can also aid in assessing well materials. Measuring pressures in interannulus fluids can provide indication of any degradation in well materials.

Given the salinity of the formation brines, storage will occur as mostly separate and residual phase CO_2. Additional monitoring of the CO_2 in the reservoir may be performed to verify sequestration of the injected CO_2. This may involve vertical seismic profiling, reservoir sampling in a monitoring well, or logging in a monitoring well.

FEP Database Applications- The "Generic FEP Database for the Assessment of Long-Term Performance and Safety of the Geological Storage of CO_2" is a useful tool for evaluating a site-specific CO_2 storage project. The database includes an exhaustive list of features, events, and processes that could affect a project. The systematic analysis reduces chances of omitting items which could affect a project. In screening the Ohio River Valley CO_2 Storage Project, it was discovered that the database aided in focusing remaining system design, monitoring, and storage application efforts.

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Savage, D., Maul, P.R., Benbow, S., and Walke, R.C. 2004. *A Generic FEP Database for the Assessment of Long-Term Performance and Safety of the Geological Storage of CO2*, Version 1.0. Quintessa Document # QRS-1060A-1.

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Table 1. Final list of FEPs that were identified in the screening process.

Category	FEP Item	Description	Response
CO_2 Storage	CO_2 Storage Pre-Closure	High injection rates and over-pressuring may affect storage reservoirs and containment units	The injection pressure will be kept under fracture gradients (as determined from fracture testing of reservoir and caprocks). Modeling indicates that injection will not overpressurize the storage reservoir.
CO_2 Properties, Interactions, & Transport	CO_2 Properties	CO_2 solubility and aqueous speciation	Storage will not rely on CO_2 dissolution as most CO_2 is anticipated to remain as a supercritical liquid in place due to highly saline formation fluids. These processes have been addressed with geochemical analysis of brine samples from the well and equilibrium models that predict the effect of introducing CO_2 to the formation fluids.
	CO_2 Transport	-Advection of CO_2 due to injection -Buoyancy-driven flow/migration -Displacement of formation fluids	Movement of the injected CO_2 will be contained in the storage reservoirs as confirmed by injection modeling. The need for a separate monitoring well is being considered for the project, which would be able to monitor migration of injected fluid.
Geosphere	Geology	Reservoir geometry variations and heterogeneity	These features were accounted with stochastic injection simulations to see how they may affect storage over a range of potential conditions such as thickness, permeability variations, and layering.
Boreholes	Drilling and Completion	Durability of well casing and cements	Special cements and tubing are planned for the final well completion, and additional monitoring of the well materials will be built into the project. Injection well design will include interannulus fluid and a surface monitoring system that will automatically detect any damage to the well materials.
	Borehole Seals and Abandonments	Degradation of borehole materials used to abandon the injection well	Acid-resistant cement mixtures were used to complete the proposed injection well. System monitoring will be used to detect any degradation in well materials and well workover may be included to see if well materials altered during the project.

Source = Savage et al., 2004.

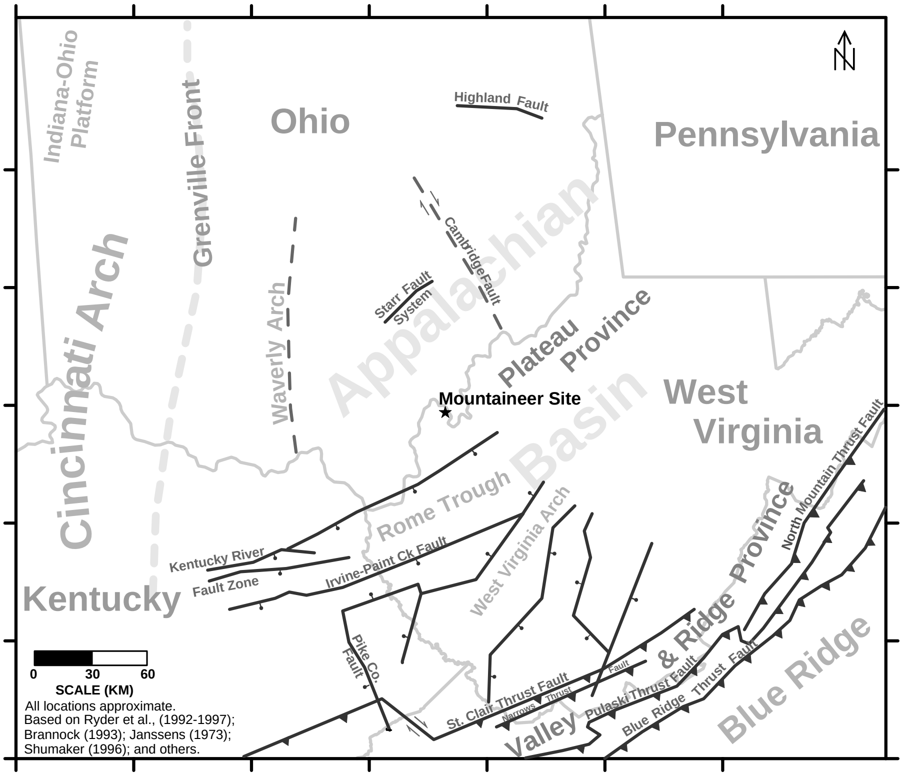


Figure 1. Site location map showing location of the exploratory well at the power plant site and major regional geological features in Paleozoic age rocks.

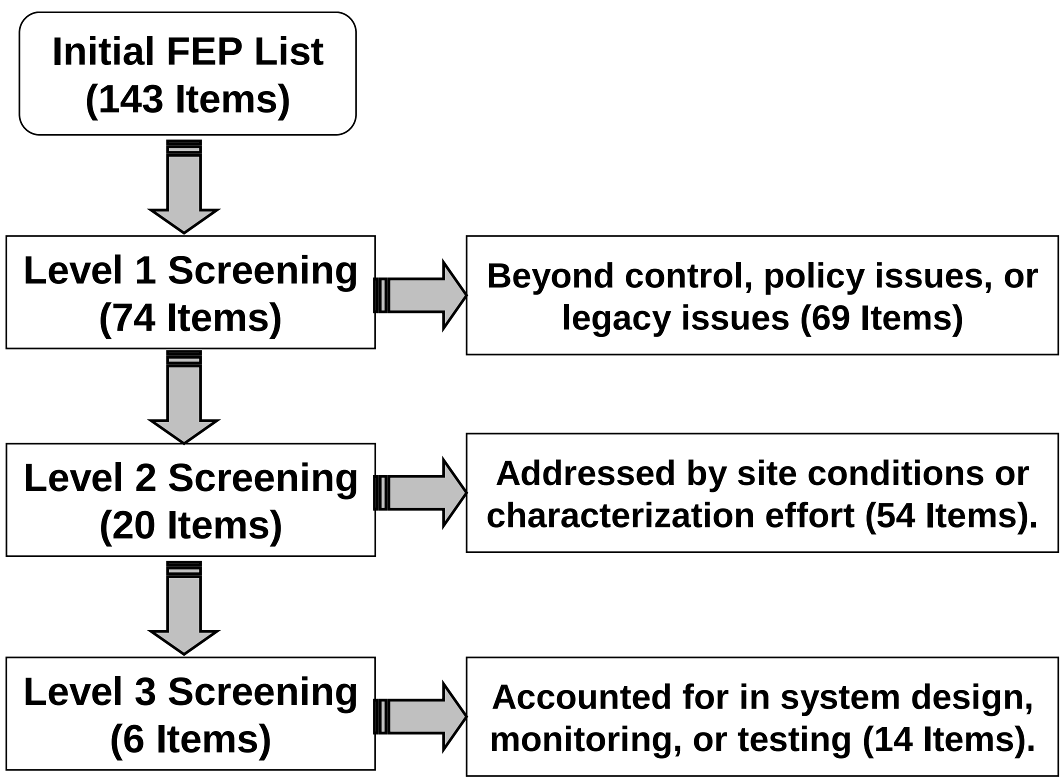
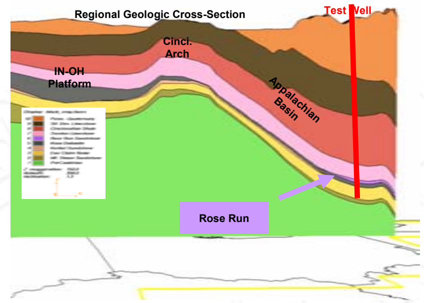


Figure 2. Flow diagram showing the three-level FEP screening process.

Mountaineer Case Study

Breakout Group Feedback

Data set used



- Limited data set, typical for a project at evaluation stage, non petroleum environment
- One full length well through the Precambrian formation of interest
- Very good quality of information

  (core testing, porosity, permeability relative permeability, capillary pressure data for the Rose Run formation and the caprock
- Few additional wells in the general region
- Two seismic lines
- Limited information on depositional system, lateral continuity of the sandstone lenses

Risk Assessment Approach

FEPs analysis for CO_2 storage

- Designed to address the Risk assessment of an experimental injection rather than a full scale project
- Did not address capture or transport issues
- Used the Quintessa database to identify FEPs
- Carried out qualitative FEPs screening, three levels of screening carried out by three independent reviewers
- Identified six main items

- Systematic, comprehensive analysis
- Some subjectivity in the final selection

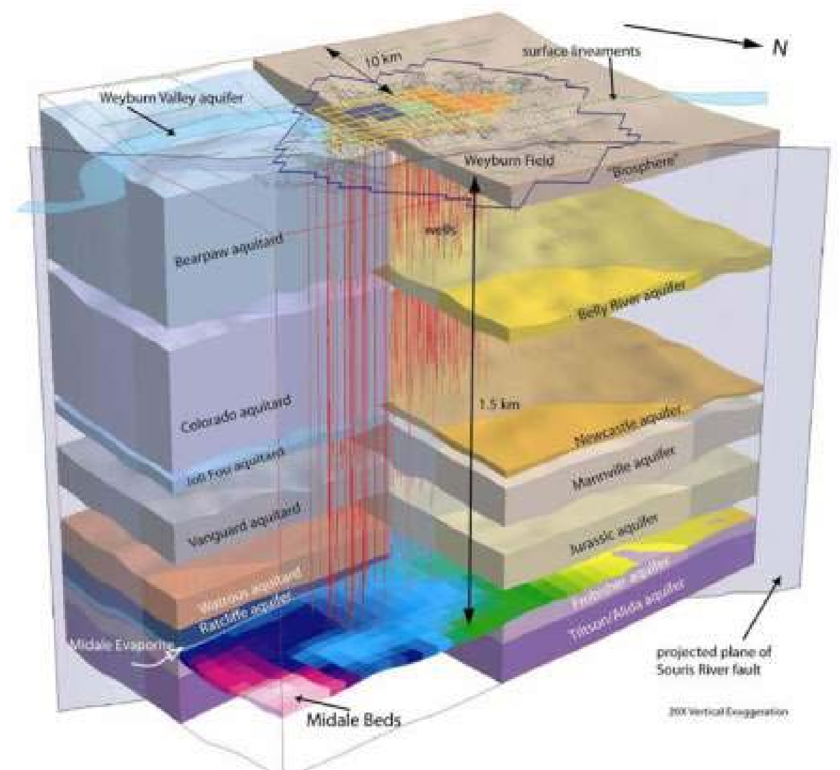
General issues relevant to Risk Assessment and CO_2 storage Confidence Building

- The audience is important in the design of the risk assessment results communication strategy, not in the design of the RA technical approach
- Confidence building involves a lot more than the technical risk assessment
- Impact on confidence when performing ‘what if scenarios that are not supported by the FEP analysis
- Appropriate design of the RA process for the scale of the project perceived.

IEA Risk/Performance Assessment Network Meeting
Lawrence Berkeley National Laboratory
October 5th and 6th 2006

IEA GHG Weyburn-Midale CO_2 Monitoring & Storage Project
FINAL PHASE

Risk Assessment; Storage and Trapping Mechanisms; Remediation Measures; EHS



Malcolm Wilson

Phase 1 RA Activities

- Apply risk assessment techniques to predict the long-term fate of CO_2 within the storage system
  - Identify risks associated with geologic storage
  - Assess ability of oil reservoirs to securely store CO_2 (where CO_2 migrates to and what are the fluxes)
- Derive how much CO_2 is stored in the Weyburn reservoir as a function of time
- Provide input for environmental risk analysis
  - •Global environment
  - •Local environment

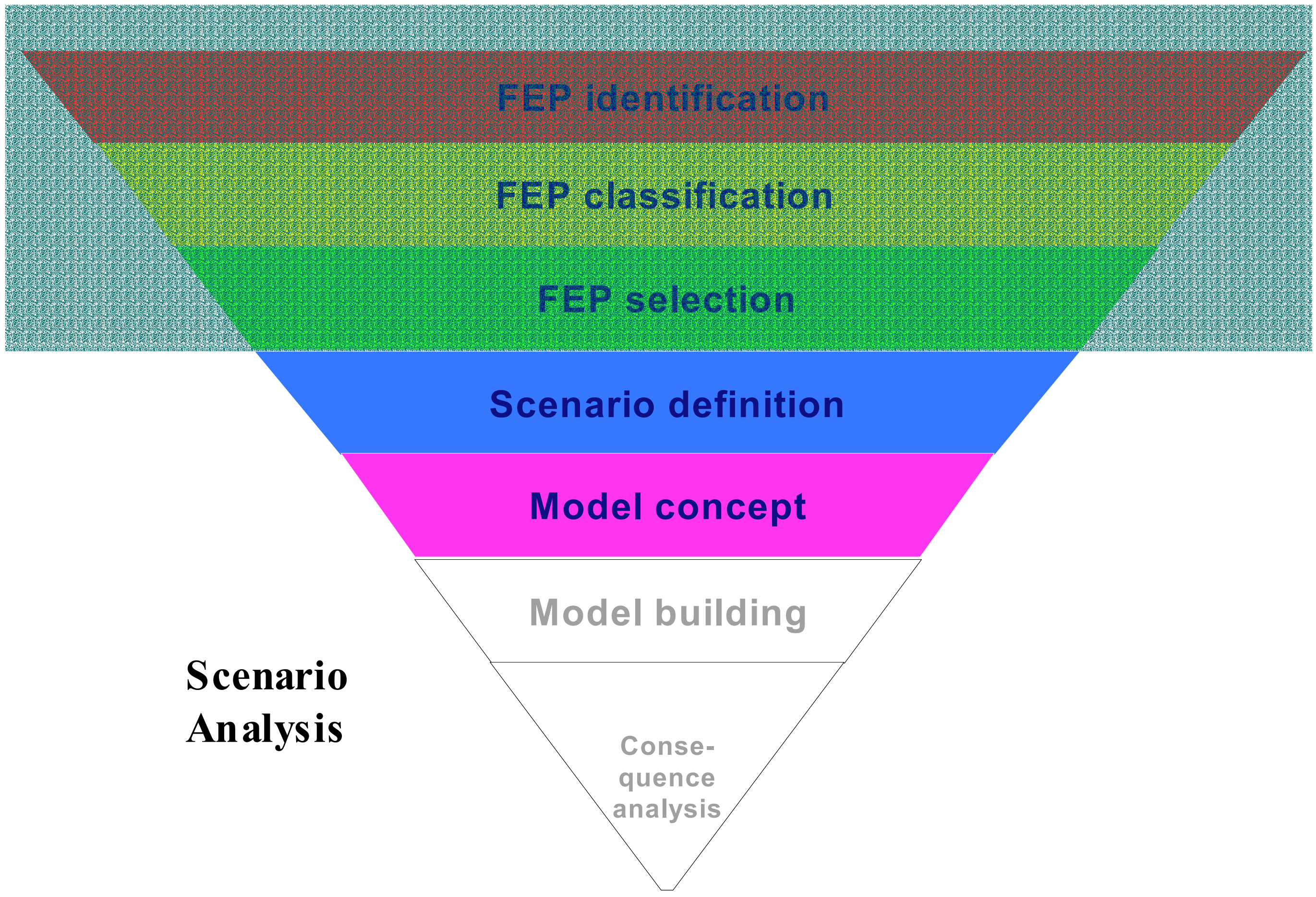
Phased Development of Assessment in response to phased data collection, research, and improved understanding over the course of the Project

- 2001 – 2002: Emphasize systematic performance assessment
  - Scenario Analysis
  - Understand basic processes of CO_2 migration
- 2003: Development of System Model
  - Finalize “Base Scenario” and “Alternative Scenarios”
  - Integration among modeling groups
  - Preliminary system model simulations
  - Probabilistic Risk Assessment
- 2004 plan: 75-pattern model + full geosphere

Systems Analysis / Scenario Development Framework

- Key components of methodology
  - I. Concept of the System - describe/define
  - II. Analysis of Features, Events and Processes
    - What they are, how they interact with each other
  - III. Scenario Development
    - Base Scenario and “What if”scenarios
  - IV. Identify information/data input and modeling / calculational needs and responsibilities

Development of FEPs for the Weyburn System

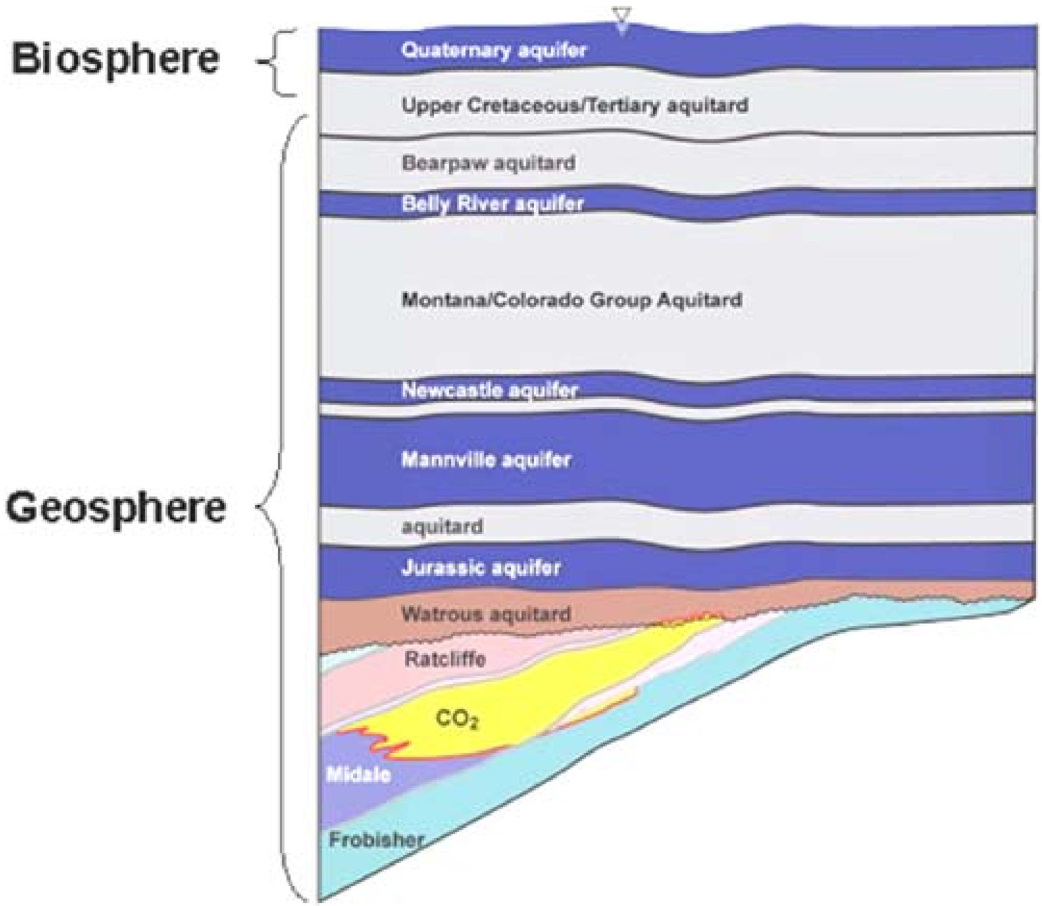


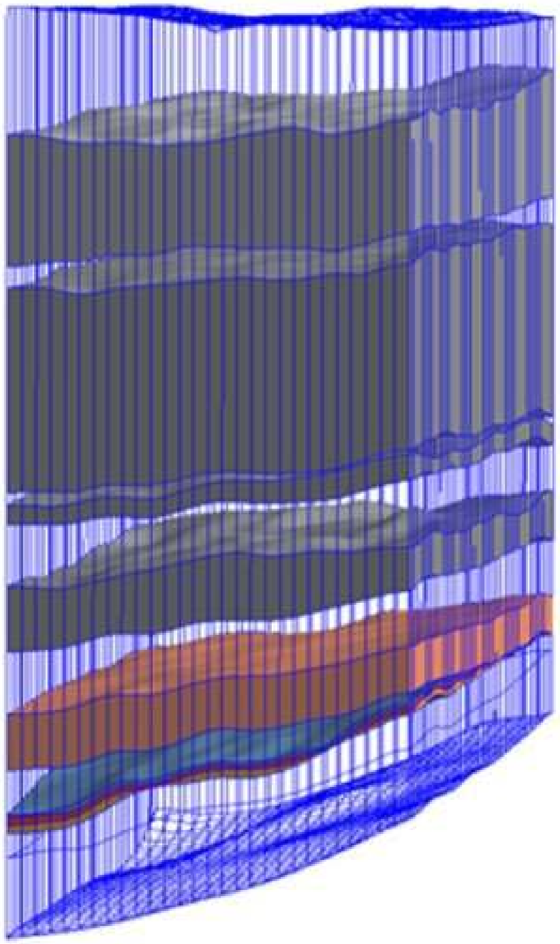
Base Scenario and System Model

- Base Scenario: expected evolution
  - Include FEPs relevant to long-term CO_2 migration
  - Caprock intact and no geological structure failure, but consider natural or man-made (near wellbores) fractures, if any exist
  - All wells are abandoned at the end of EOR, and sealed according to current practice procedures

- System Model for assessment
  - 75 patterns plus 10-km surrounding Midale formations
  - Aquifers and aquitards above and below Midale reservoir
  - All wells within the model domain are considered
  - Time scale: 5000 yrs or 50% loss of CO_2
  - Biosphere: start from the deepest possible potable aquifer

The System Model





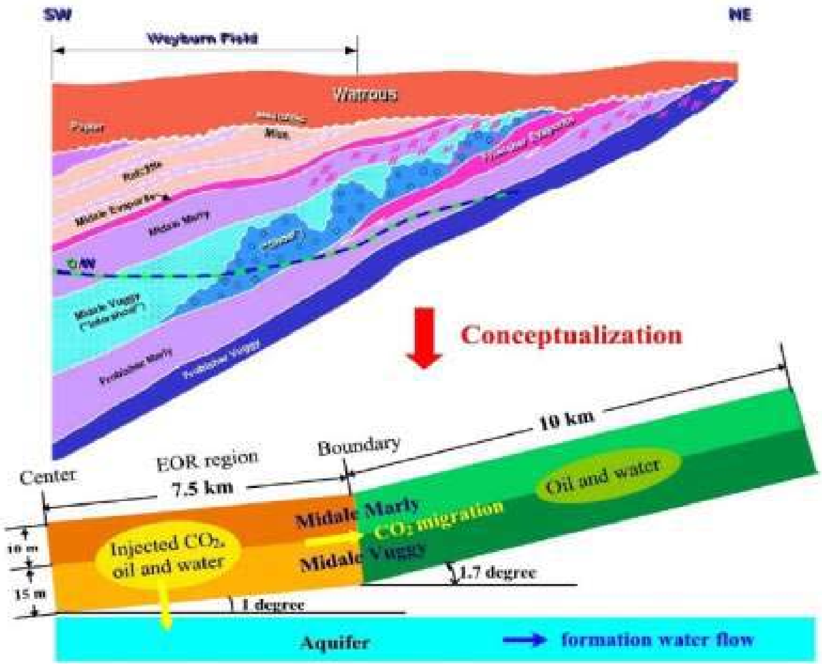
Alternative Scenarios

Alternative Scenario Name	Unique characteristics
Engineering options for EOR (a) Maximize CO_2 storage (b) Water flush at the end of EOR	Option (a) involves larger reservoir pressures; over-pressurisation and caprock fractures are possible problems. Option (b) would result in changes to CO_2 distributions in the reservoir and could also decrease CO_2 storage
Well abandonment options	Emphasis on improved long-term sealing capabilities
Salt dissolution of underlying formations	Dissolution and subsidence may lead to development of fractures
Leaking wells	Involves extreme failures only as the Base Scenario has 'normal' leakage
Fault movement or reactivation, including undetected faults	Could represent a new and fast CO_2 transport pathway; could affect several formations
Tectonic activity	Low probability but possible
Deliberate & accidental human intrusion (a) Destruction of surface casing (b) Resource extraction	Likely scenario involves intrusion into the reservoir in search for CO_2 or petroleum. Option (a) could affect the uppermost seal in one or more wells. Option (b) likely involves extraction of some shallower resource, but could lead to CO_2 blow-out from CO_2 trapped in formations above the reservoir

Modeling: Gradual Towards Comprehensive Assessment

- 2001 model:
  - 2D horizontal cross section
  - 3 components and 2 phases
  - Sensitivity study on diffusion, advection, permeability, and salinity
- 2002 model:
  - 2D cross-section with simple geological features
  - 7 components and 3 phases
  - Sensitivity study on capillary pressure, flow rates of formation water in aquifer below the reservoir
- 2003 model:
  - The System Model with all the digitized geological features
  - 7 components and 3 phases
  - CO_2 source: upscaled 75-pattern and detailed 1 pattern treatments
  - “Unit Cell” abandoned well modeling

Learning's from 2002 Simulations



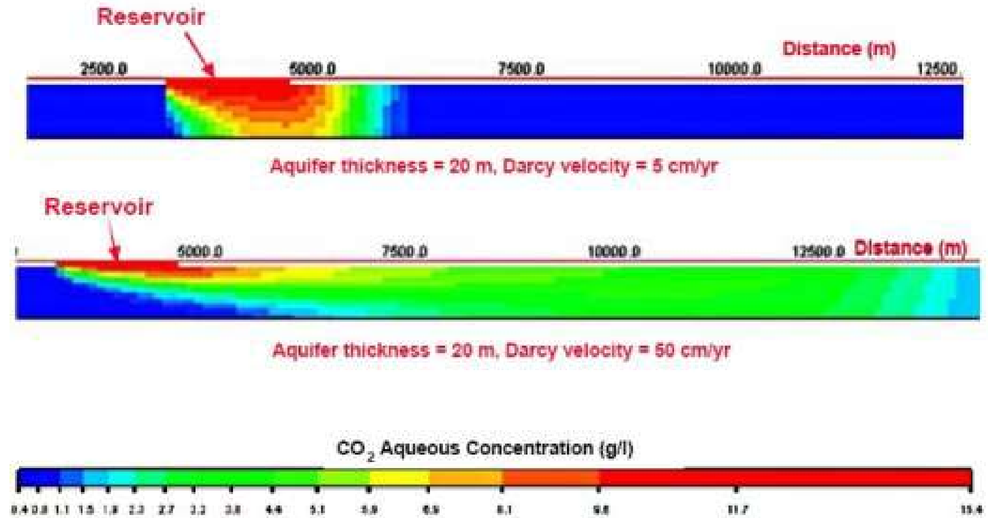
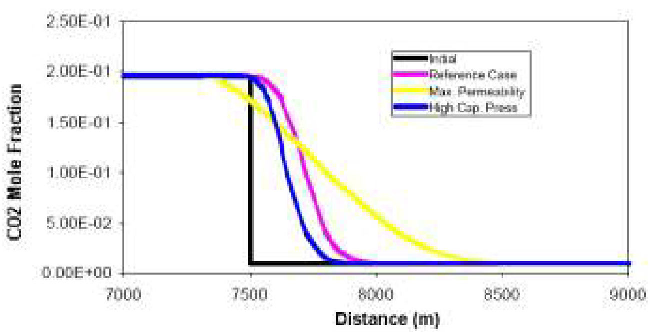
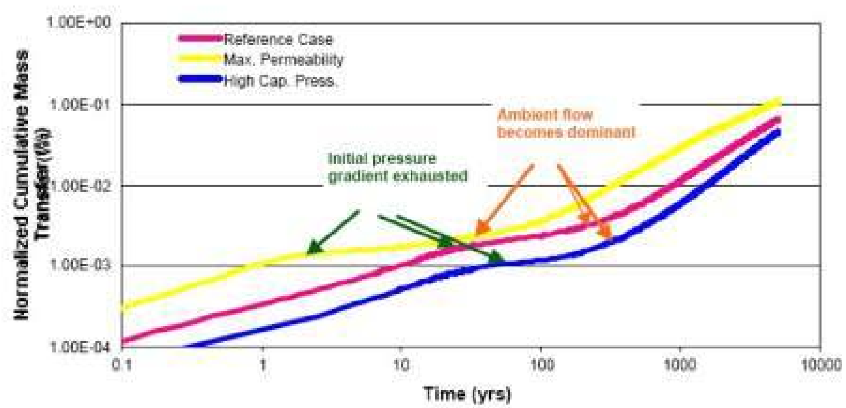


Figure 10: Comparison of cumulative mass transfer of CO_2 from the Weyburn reservoir as a function of time.

Figure 9: Comparison of concentration profiles for CO_2 5,000 years after the end of EOR operations.

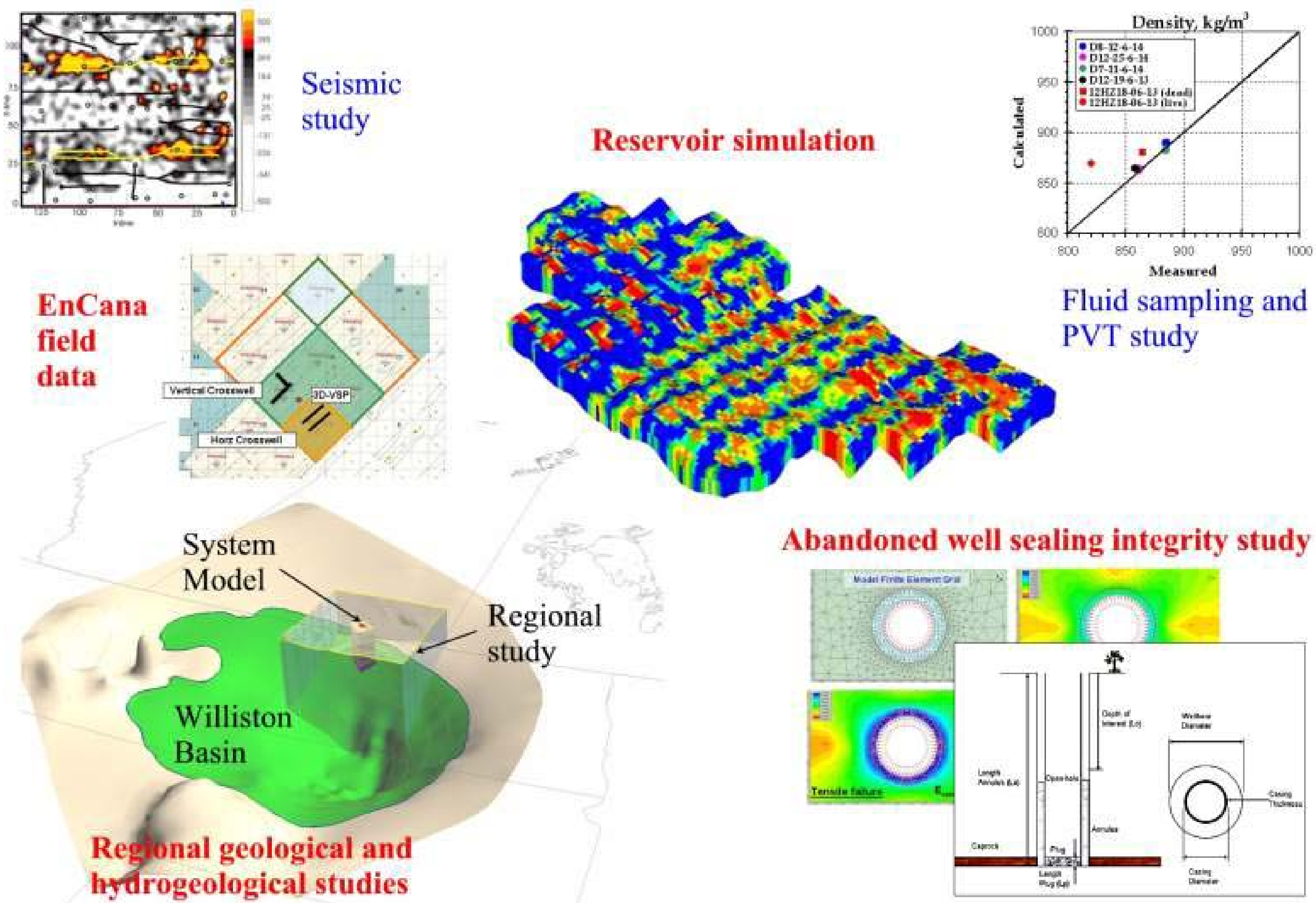




Why Choose E300 as the Modeling Tool? (E300 is developed by Schlumberger)

- No specially-developed tools currently available
- One of the existing tools that can provide the closest approximation to the system: including
  - Previously field applied and tested for CO_2 flood EOR
  - Equations of state and CO_2 dissolution in water
  - Incorporating industry-standard geological data
- Disadvantages include:
  - Unable to couple rock property changes due to geochemical reactions
  - Inaccurate density calculation for water with dissolved CO_2
  - Inconvenient in modeling well leakage
- Available to the modeler and also used by EnCana

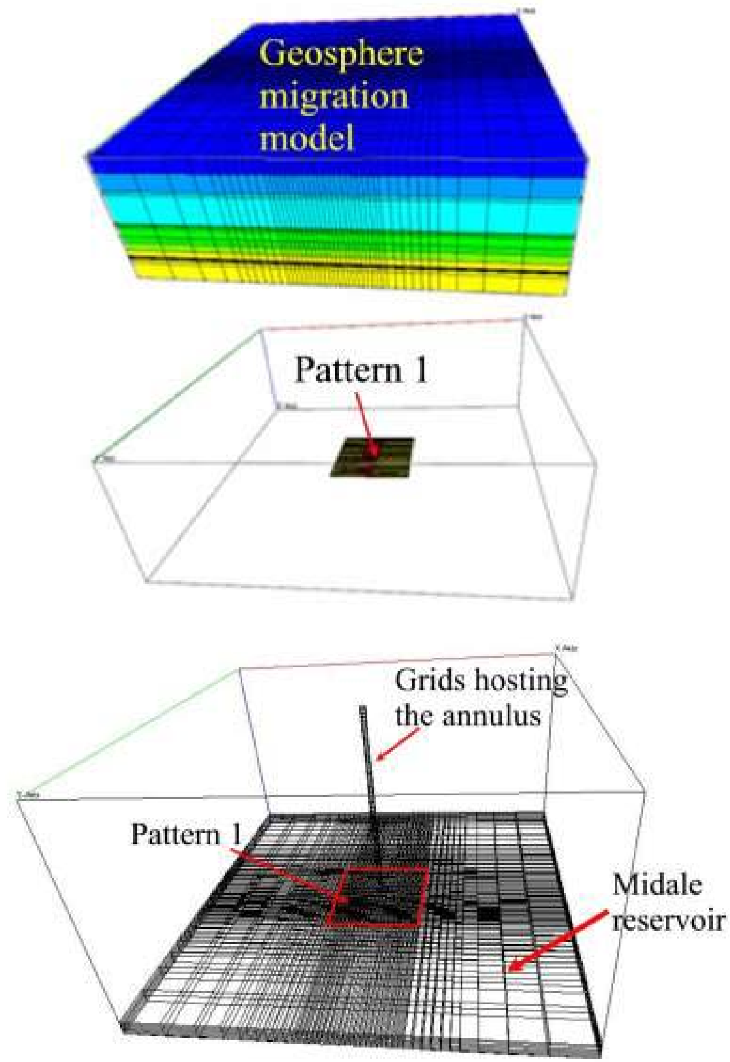
Detailed Studies Provide Key Input to Long-term CO_2 Migration Modeling



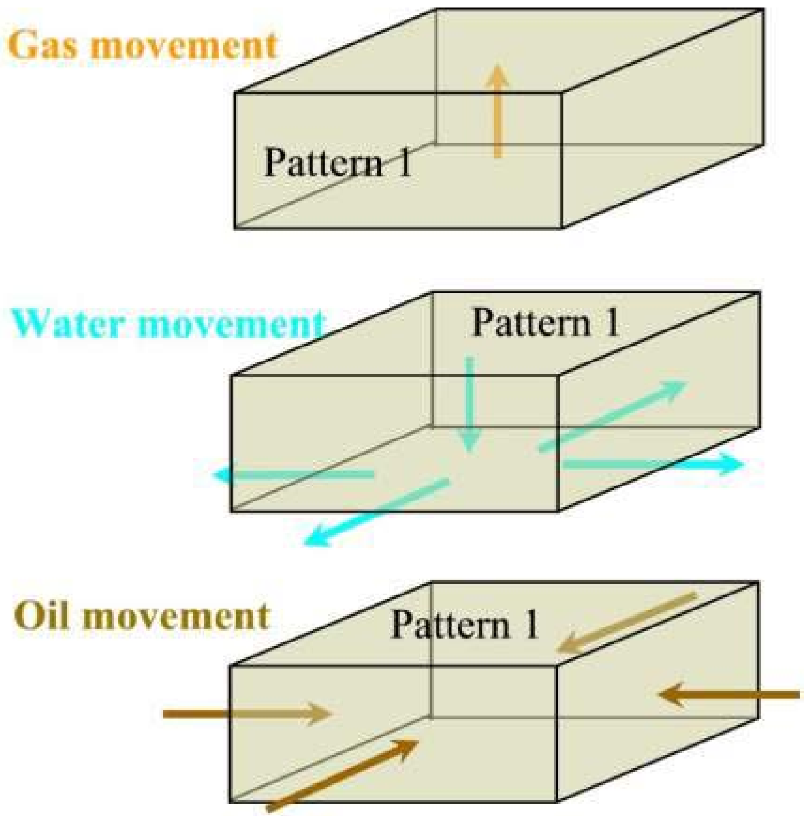
2003 Model: Benchmarking Study

designed to compare the E300 model with CQUESTRA, a simplified model

- Geosphere migration model
  - Understanding basic processes without upscaling of EOR reservoir simulation results
  - Source: EOR Pattern 1 from detailed reservoir study
  - Fictitious geosphere based on the System Model geological profile
- Well annulus leakage model
  - Study processes leading to leakage via well annulus
  - One well in EOR Pattern 1
  - Fictitious geosphere in the Midale reservoir only

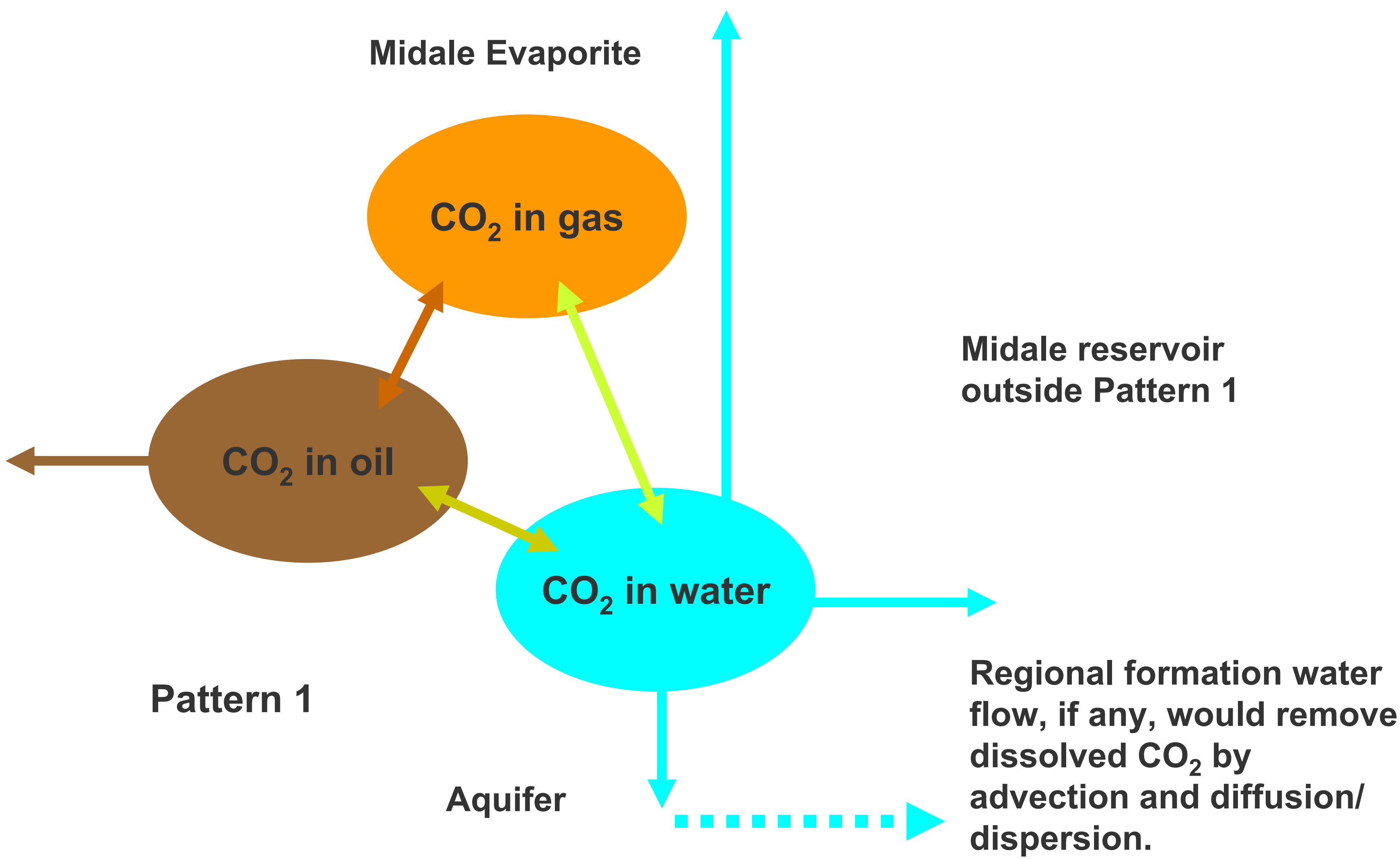


Phase Movement after EOR



- CO_2-rich phase moves up and is trapped in the upper Marly below the caprock.
- Water injected during EOR moves downward and away from Pattern 1 at lower Vuggy, carrying dissolved CO_2.
- Oil outside Pattern 1 with lower CO_2 concentration moves into the Pattern 1 region from lower Marly and upper Vuggy, picking up some CO_2 from gas and water. CO_2 dissolved in oil moves away from Pattern 1 via diffusion.

Mass Transfer Coupled with Fluid Flow and Mass Partitioning



2004 Geosphere Migration Model

- Built based on 2003 Benchmarking modeling experience with increased comprehensiveness
- Use the refined geological System Model
  - Align with 75 EOR patterns
  - Inside each pattern, use the same spatial discretization as the reservoir simulation model
- Petrophysical properties and hydraulic heads are mapped into the model grids
- 75-pattern reservoir simulation results at the end of EOR as initial conditions

Objectives for FINAL PHASE:

Mission of the Project (in PSW) is the following:

Use the IEA Weyburn CO_2 Storage and Monitoring Project (Final Phase) as the "flagship" for developing the necessary technical and operating information to guide regulatory policy on EOR-based CO_2 Geological Storage projects.

OBJECTIVE for proposed RA work program is:

To complete a full field risk assessment of IEA Weyburn Storage site, exploring all relevant storage/leakage mechanisms and describing the ultimate fate of the CO_2.

Project Drivers for RA Activities in the Final Phase

- A recognition that RA is critical for the development of future regulatory activity, but that it had not been completed under Phase I research activities;
- A recognition that inadequate risk assessment methods and risk mitigation measures currently exist for confirming the safety and reliability of geological storage of CO_2; and
- The strong need to rationalize the selection of cost and time-effective methodologies for risk assessment of the long term fate of stored CO_2.
- A second objective of the proposed risk assessment work program is to generate the knowledge necessary to write all relevant sections of the *Best Practices Manual for CO_2 Geological Storage in Association with EOR Projects*.

Project Drivers for RA Activities in the Final Phase

- Methods and management issues
  - Conscious recognition of the various RA methodologies that currently exist and that RA needs to fundamentally address issues of risk management for CO_2 – EOR projects.
- Cost/benefit rationalization of RA programs
  - How extensive (..& expensive) do RA activitites need to be?
- Understanding role of RA in regulatory activity
- “defendable and doable”, minimum dataset required to complete RA,

PSW *Suggested* Work Program:

- Complete the full field risk assessment from Phase 1. All relevant storage and leakage mechanisms should be modeled. Outcomes of significant Features, Events and Processes (FEP) to be completed and documented. **(H*)**
- Describe the ultimate fate of CO_2 in the Weyburn system, the relative volumes in each storage/trapping mechanism, the time to become trapped, and the factors which affect these. This requires the coupling of reservoir simulation with geochemical modeling, especially in determining the degree of CO_2 mineralization/solid storage. **(H*)**
- Determine risk levels for various operations scenarios (e.g. EOR-only, maximize CO_2 volumes stored, impure CO_2 injection, etc.). Identify trade offs (higher water production) and benefits (more oil produced, CO_2 stored) for the different scenarios to support economic analysis for operational decisions and formulation of regulations. **(H)**
- Collaborate with other CO_2 JIP to compare RA techniques. Prepare summary documentation of strengths and weaknesses of each technique. **(H)**

Final Phase Activities –Task 1

- Peer reviewed, formal process to establish 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.
- The intent of this exercise will be to establish a peer-reviewed digital reference database of all input data required for performance assessment modelling, including estimates of uncertainty in all data. It is anticipated this peer review process will be conducted with Theme Leaders and internal RP's within the project, especially those involved in Phase I.

Final Phase Activities –Task 1

- A major component of this task will be the integration of this peer reviewed dataset into the earth science database selected for the project, likely to be Petrel. The inclusion of this data on a common platform will provide a tool for subsequent updating of pertinent data, will provide for effective communication across Theme's and efficient distribution of common datasets amongst RP's. This would also be applicable to reservoir simulation studies.

Final Phase Activities –Task 2

- Conduct 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.

Final Phase Activities –Task 2

- Update and refine the geosphere model based on the latest interpretation of geological and hydrogeological information. The Theme 1 Proposed Work Program highlights the following issues related to this task:
  - The performance assessment model in Phase I was not integrated with 2D and 3D geophysical data;
  - There was a lack of samples in units overlying and underlying the reservoir leading to insufficient parameter characterization of units away from the reservoir;
  - Finer-scale geological barriers were not included in Phase I models; and
  - Potential hydraulic communication between the Midale reservoir and overly Ratcliffe Beds and underlying Frobisher Beds was not included.

Final Phase Activities –Task 3

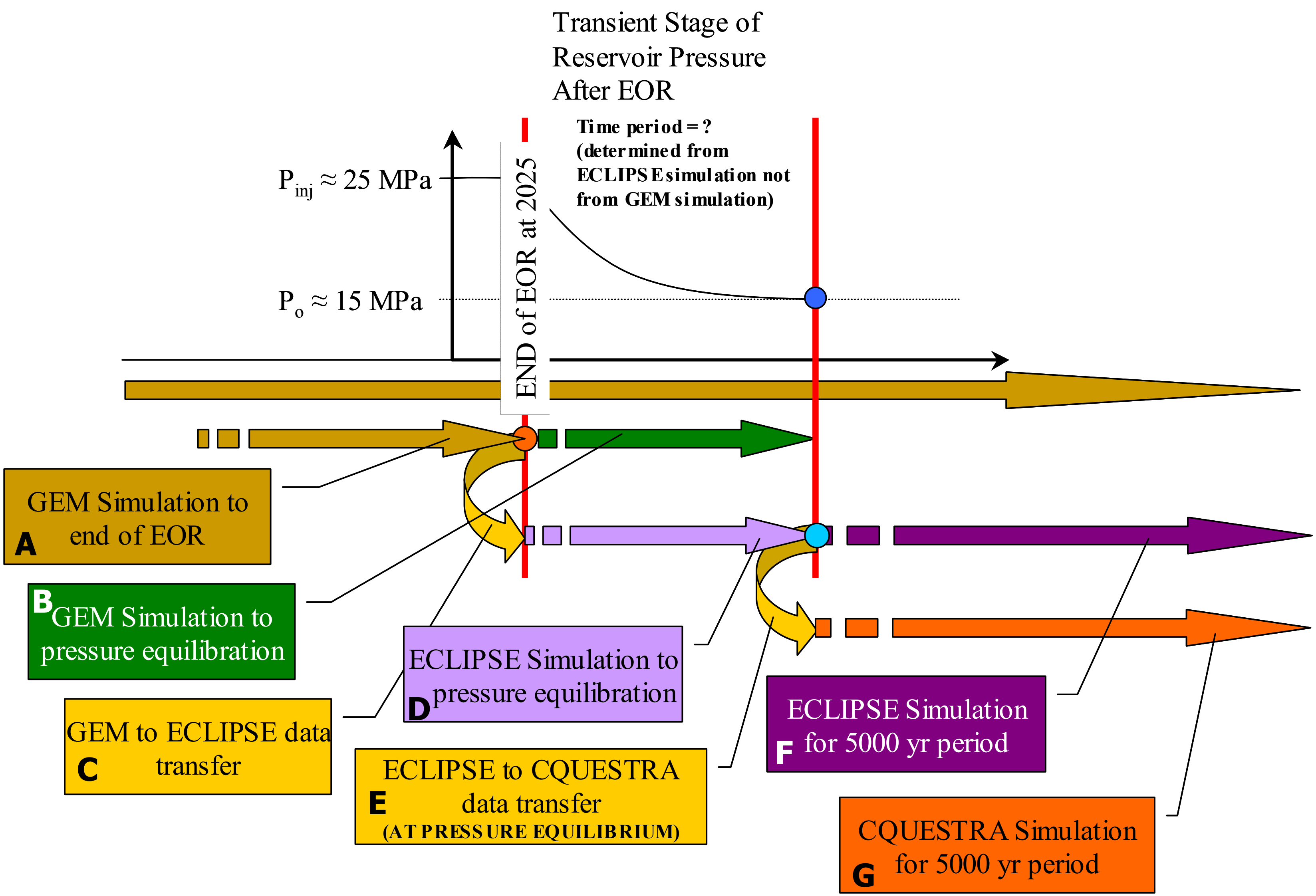
- Development of relevant FEPS and Scenarios for **Apache Midale Field** utilizing established databases for Systems Analysis.
- The Midale field's inclusion in the Project provides a superb opportunity to "test" the FEP's/Scenario database developed in Phase I.
- This can be used to quickly develop a focussed performance assessment program for the Midale field and will assist in developing an effective work program, cost and schedule for the Midale component of the Project.

Final Phase Activities –Task 4

- Reconcile the reservoir-geosphere-biosphere modelling issues.

- Various operational schemes will alter the performance characteristics of the Weyburn (and Midale) geological storage system and must be closely integrated with the simulation methodologies chosen for the risk/performance analyses in order to be assessed.

Integration of Assessment Components



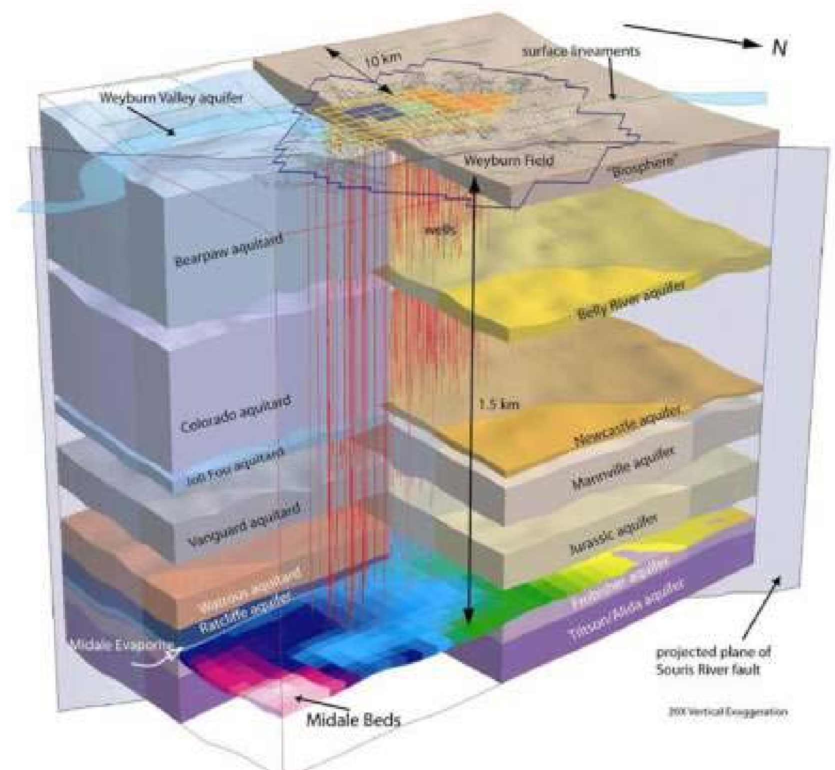
Final Phase Activities –Task 5

- Conduct a semi-quantitative risk assessment for Weyburn and Midale Project. Utilizing the input of an expert panel, conduct a semi-quantitative RA utilizing experts and Phase I work in order to frame the entire risk assessment process for a CO2-EOR project and in particular, the Weyburn CO2-EOR Project.
  - This will engage a multidisciplinary panel of experts and stakeholders for input ranging from reservoir mechanics to hydrogeology to air quality/human health, public policy and regulations.
  - 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.

IEA Risk/Performance Assessment Network Meeting
Lawrence Berkeley National Laboratory
October 5th and 6th 2006

IEA GHG Weyburn-Midale CO_2 Monitoring & Storage Project
FINAL PHASE

Risk Assessment; Storage and Trapping Mechanisms; Remediation Measures; EHS



Malcolm Wilson

IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project

Phase I Project Information

for

Risk Assessment Case Study

October, 2006

Preface

At the conclusion of Phase 1 of the IEA GHG Weyburn CO_2 Monitoring and Storage Project, a detailed review of the accomplishments attained and subsequently, identification of areas where additional technical work was required was completed.

One of the outcomes from this review was the development of a Scope of Work for the Final Phase of the IEA GHG Weyburn-Midale. The component of the workscope related to risk assessment activities is provided below.

A key component of the Weyburn Phase I workflow was the Risk Assessment (RA) for the storage project. The RA brought together much of the work performed in Phase I. Many of the studies, including RA, contribute to the Site Selection process, and the insights gained from the Site Selection (SS) process could heavily influence the developments of storage Best Practices Manual and regulations. A rigorous determination of the data necessary to achieve successful SS is a key outcome of the Final Phase. Weyburn is a natural place to do such an analysis, due to the exceptionally complete data set.

The project drivers identified from the Phase I work to close gaps in knowledge:

- Inadequate risk assessment methods and risk mitigation measures for confirming the safety and reliability of geological storage of CO2.
- Strong need to rationalize the selection of cost and time-effective methodologies for risk assessment of the long term fate of stored CO2.
- Risk Assessment is critical for the development of future regulatory activity, but has not been completed under Phase One.

The suggested technical work program elements that will help close these knowledge gaps include:

- Complete the full field risk assessment from Phase 1. All relevant storage and leakage mechanisms should be modeled. Outcomes of significant Features, Events and Processes (FEP) to be completed and documented. (H*)
- Describe the ultimate fate of CO2 in the Weyburn system, the relative volumes in each storage/trapping mechanism, the time to become trapped, and the factors which affect these. This requires the coupling of reservoir simulation with geochemical modeling, especially in determining the degree of CO2 mineralization/solid storage. (H*)
- Describe the ultimate fate of CO2 in the Weyburn system, the relative volumes in each storage/trapping mechanism, the time to become trapped, and the factors which affect these. This requires the coupling of reservoir simulation with geochemical modeling, especially in determining the degree of CO2 mineralization/solid storage. (H*)
- Determine risk levels for various operations scenarios (e.g. EOR-only, maximize CO2 volumes stored, impure CO2 injection, etc.). Identify trade offs (higher water production) and benefits (more oil produced, CO2 stored) for the different scenarios to support economic analysis for operational decisions and formulation of regulations. (H)
- Collaborate with other CO2 JIP to compare RA techniques. Prepare summary documentation of strengths and weaknesses of each technique. (H)

- Further study natural analogues with respect to leakage and storage integrity. Determine from field data whether mineral trapping can be as significant as theory indicates. (M)
- Study ways to stimulate and accelerate CO_2 mineral fixation (mineralization, mineral trapping) under Weyburn reservoir conditions.(M)

Goal of Weyburn Phase I Case History

- With an understanding of the research and technical work that has been completed or has been underway since the conclusion of Phase I of the IEA Weyburn CO_2 Monitoring and Storage Project (since June 2004) and given the data and information related to the Phase I project, WHAT WOULD BE THE MOST SUITABLE METHODOLOGY OR APPROACH FOR ATTEMPTING TO COMPLETE A RISK ASSESSMENT OF AN ACTIVE CO_2-EOR GEOLOGICAL STORAGE PROJECT?

Project Overview

This CO_2 monitoring and storage project was essentially a field-demonstration made possible by EnCana's CO_2 enhanced oil recovery (EOR) project being carried out at its Weyburn Unit. Located in the southeast corner of the province of Saskatchewan in Western Canada, the Weyburn Unit is a 180 square kilometer (70 square miles) oil field discovered in 1954. Production is 25 to 34 degree API medium gravity sour crude from the Midale beds of the Mississippian Charles formation. The two main reservoir layers in the Midale beds are the Marly zone, a low permeability chalky dolomite overlaying the Vuggy zone, a highly fractured and permeable limestone. The Weyburn field is part of the large Williston sedimentary basin which straddles Canada and the US, Figure 1.

Waterflooding was initiated in 1964 and significant field development including the use of horizontal wells was begun in 1991. In September 2000, EnCana initiated the first phase (Phase 1A) of a CO_2 enhanced oil recovery scheme in 18 inverted 9-spot patterns, Figure 2. The flood is expected to be rolled out in phases into a total of 75 patterns over the next 15 years. The CO_2 is 95% pure and initial injection rate is 5000 tonnes/day (equivalent to 95 mmcfd). A total of approximately 20 million tonnes of CO_2 is expected to be injected into the reservoir over the project life. The CO_2 is a purchased byproduct from the Dakota Gasification Company's synthetic fuel plant in Beulah, North Dakota and is transported through a 320 km pipeline to Weyburn. An operations update for the Weyburn Unit EOR Project operated by EnCana is given in Table 1.

This project summary report is presented in four main "themes" and are the following:

Theme 1: Geological Characterization of the Geosphere and Biosphere
Theme 2: Prediction, Monitoring and Verification of CO_2 Movements
Theme 3: CO_2 Storage Capacity and Distribution Predictions and the Application of Economic Limits
Theme 4: Long Term Risk Assessments of the Storage Site

TABLE 1: OPERATIONS UPDATE FOR THE WEYBURN UNIT EOR PROJECT OPERATED BY ENCANA – FEB. 29, 2004

- CO2 injection into Phase 1a started September 15, 2000
- 98 BCF CO2 injected as of Feb 29th, 2004
- Current CO2 purchase is 105MMscfd
- 25 mmscfd of associated gas and CO2 being recycled
- EOR Operations include Phase 1a(start Sept 2000), Phase 1b(start Oct 2002) and Phase 1c(start June 2003)
- Of the 210 producing wells in the EOR area:
  - 71 producers experienced operational response (CO2 detected in casing gas)
  - 45 producers experienced production response (incremental production)
- Incremental production 9000 bbl/day
- Current Unit production 22,400 bbl/day

Figure 1: Location of the Weyburn Unit

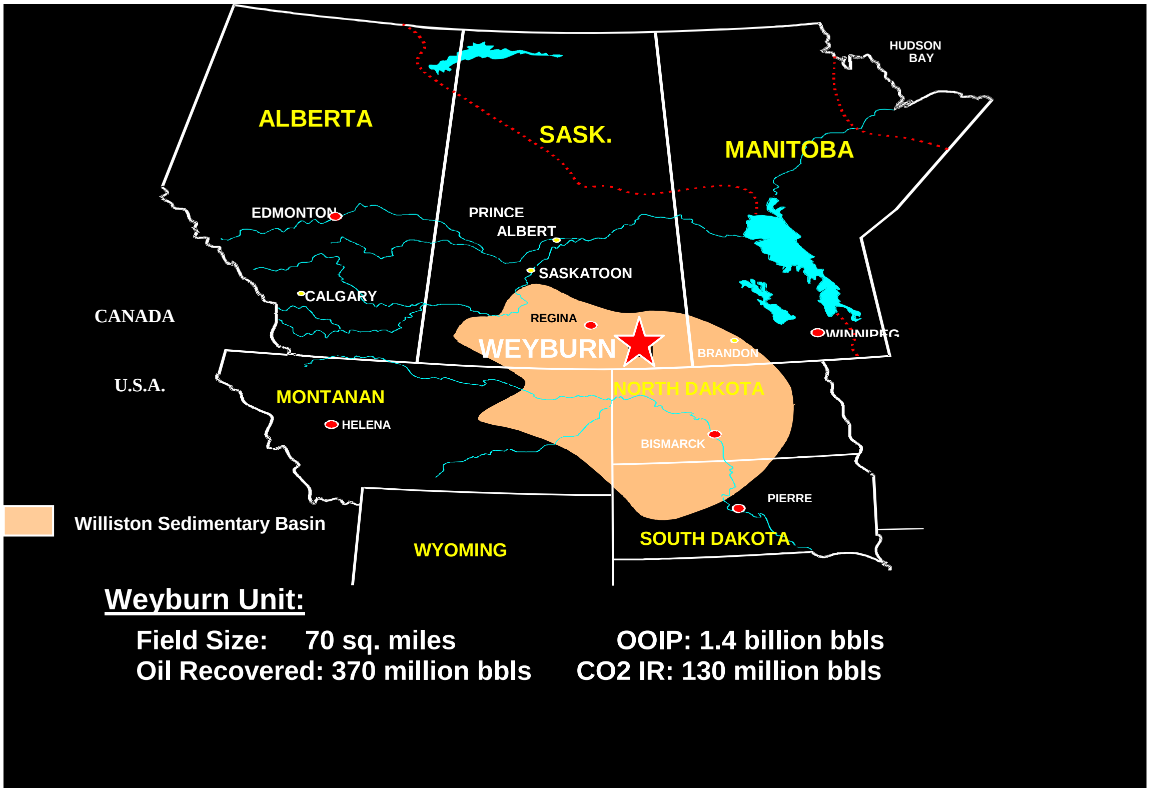
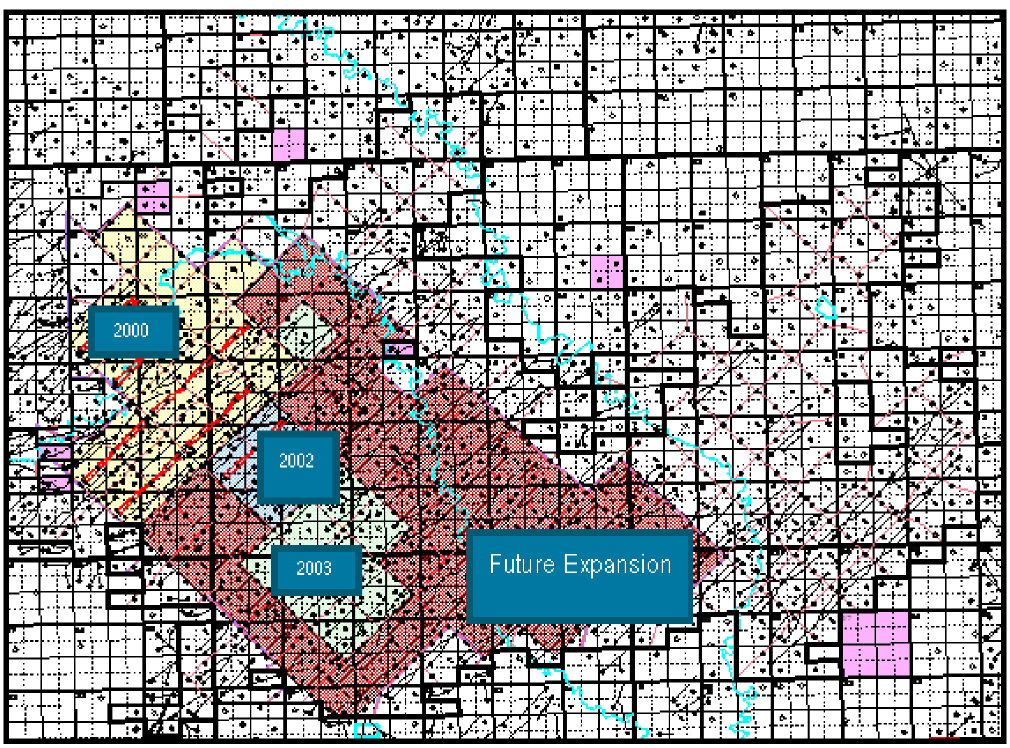


Figure 2: CO_2 Flood Roll-Out Areas (Weyburn Unit)



Geological Characterization of the Geosphere and Biosphere

The Weyburn Oil Pool is a giant oilfield containing about 1.4 billion barrels of oil in place in limestones and dolostones (Midale Beds) of Mississippian age. Carbonates of the Midale reservoir occur at about 1.5 km depth in the northeastern portion of the Williston Basin, a sedimentary basin broadly similar to the Illinois and Michigan basins of North America and numerous intractratonic basins that occur elsewhere around the world.

Characterization of the Weyburn geological system for CO_2 storage targeted the delineation of primary and secondary trapping mechanisms and the identification of any potential pathways of preferential CO_2 migration. To place these components within a regional, or basinal, context, the geological framework was constructed for a region extending 200 x 200 km around the Weyburn Field that includes portions of Saskatchewan, North Dakota and Montana. Large-scale studies such as this more effectively reveal basin hydrogeological flow characteristics and the underlying tectonic framework that can greatly influence depositional patterns of sedimentary packages and fracture development. Increased detail was focused within an area extending 10 km beyond the limits of the CO_2 flood that forms the basis for the system model used in risk assessment (Figure 2).

Lithostratigraphic mapping identified over 140 individual surfaces from the Precambrian basement to ground surface. The lithostratigraphic units were used to define larger flow packages, or hydrostratigraphic units, that were mapped and characterized using extensive data analysis to provide fundamental information on fluid behavior within the basin as required by performance assessment. Much of the 2000 km of 2D seismic data processed to refine the characterization of subsurface features and basement tectonics was integrated with high-resolution aeromagnetic data to augment fracture and regional fault delineation. Detailed geological studies performed on primary seals (those in contact with the reservoir) and secondary seals (barriers to flow higher in the stratigraphic column) include core descriptions, petrography, isotope geochemistry and fluid inclusion studies. Shallow hydrogeological surveys defined the distribution and continuity of potable aquifers in near-surface sediments of the study region. Remotely sensed imagery analysis was used to determine whether structural elements observed in the deep subsurface are related to linear surface features identified through air photo and satellite imagery. Soil gas surveys, designed to transect some of the linear surface features, are performed regularly around the Weyburn Unit to monitor for changes in CO_2 fluxes in soils that may be due to potential anthropogenic CO_2 migration. Other specialized studies undertaken include obtaining cores from selected strata above the reservoir for petrophysical measurements, till sampling for soil gas characterization, shallow aquifer demarcation, and natural analog comparisons. Integration of these diverse data has provided a coherent and representative geological model that can be tailored for use in risk assessment.

Primary seals enclosing the reservoir (including the overlying Midale Evaporite and a highly anhydritized altered zone and the underlying Frobisher Evaporite) are observed to be highly competent and exhibit only rare discontinuities; most of which formed shortly after deposition, are completely healed and exhibit no visual evidence of fluid conductance (Figure 3). In addition, as part of the primary sealing package, the Lower Watrous Formation forms a regionally extensive aquitard that effectively separates a deep hydrogeological system (including the Midale Beds) from a shallower hydrogeological system (Figure 4). Overlying the Watrous Formation is over 1 km of predominantly clastic strata that contain several thick and regionally extensive aquitards providing additional barriers to upward fluid migration. Aquifers present within the shallow hydrogeological regime may have high flow velocities (m/yr) and are important for scenario analysis of CO_2 leakage. Within the Midale Beds however, low flow velocities (cm/yr) and favourable flow directions suggest formation water is unlikely to be an effective transport mechanism for dissolved CO_2. Fracture zones and regional tectonic elements are present within the study region, yet none were found to exhibit evidence of fluid conductance or influence over hydrogeological components. Salt dissolution also has occurred within the risk assessment study region and may have induced fracturing of overlying rocks, although with no apparent compromise of the geologic container (Figure 5). Overall, one of the most important results from this work is the development of a tremendous geoscience dataset pertinent to understanding geological storage of CO_2 in the Williston Basin and other sedimentary basins.

Figures

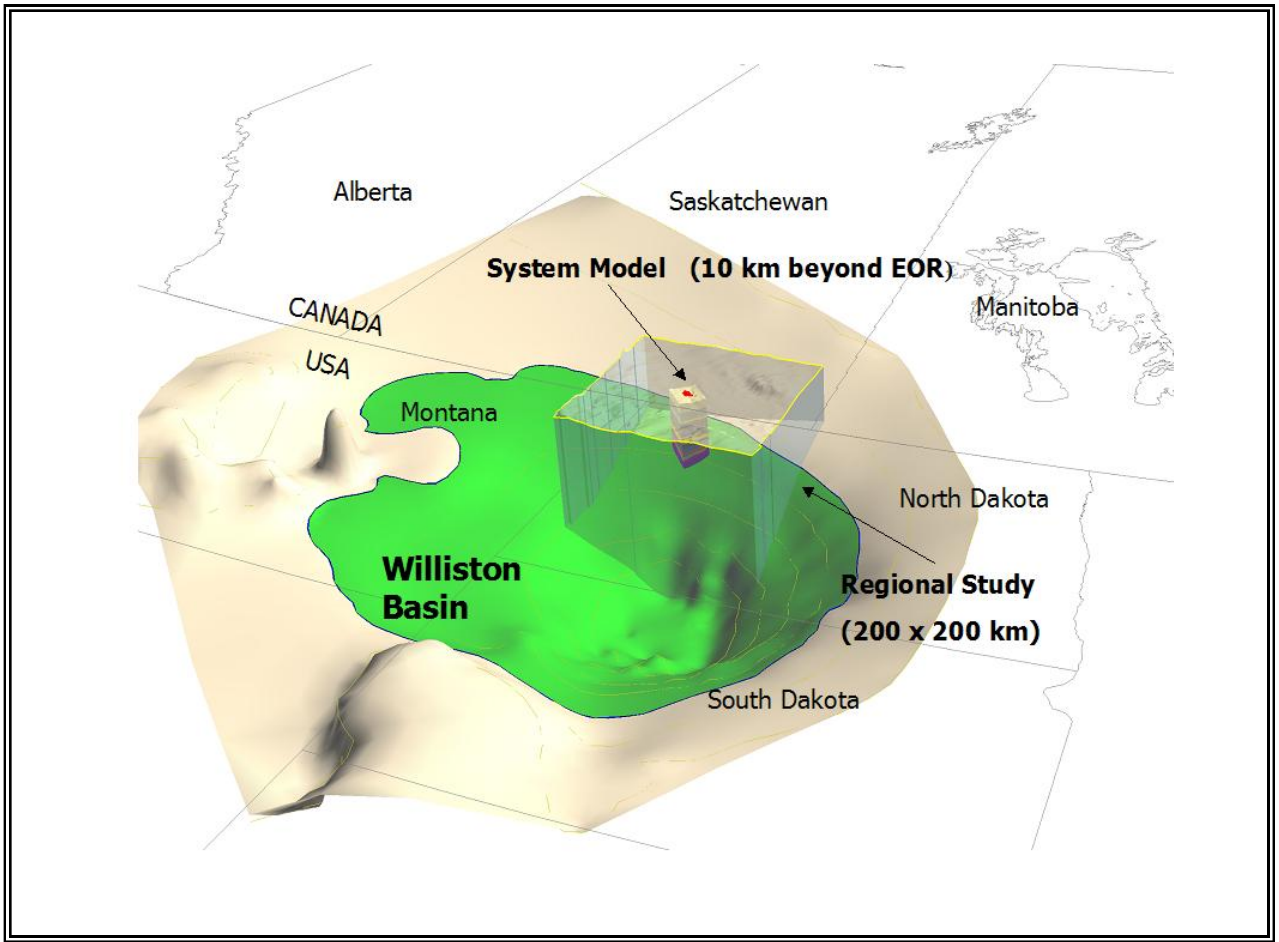


Figure 1: Location of the IEA Weyburn CO_2 Monitoring and Storage Project in relation to the Williston Basin. The geological framework was determined for an area 200 x 200 km that ranges from about 1.5 to 4 km deep, or approximately 100,000 km^3. A more detailed study was focused on a region extending 10 km beyond the limits of the CO_2 EOR flood to construct a system model for use in risk assessments. The geoscience framework region straddles the Canadian and United States border and includes parts of Saskatchewan, North Dakota and Montana. The Williston Basin is representative of intracratonic sedimentary basins of which many will be considered to contain potential sites for CO_2 injection and storage.

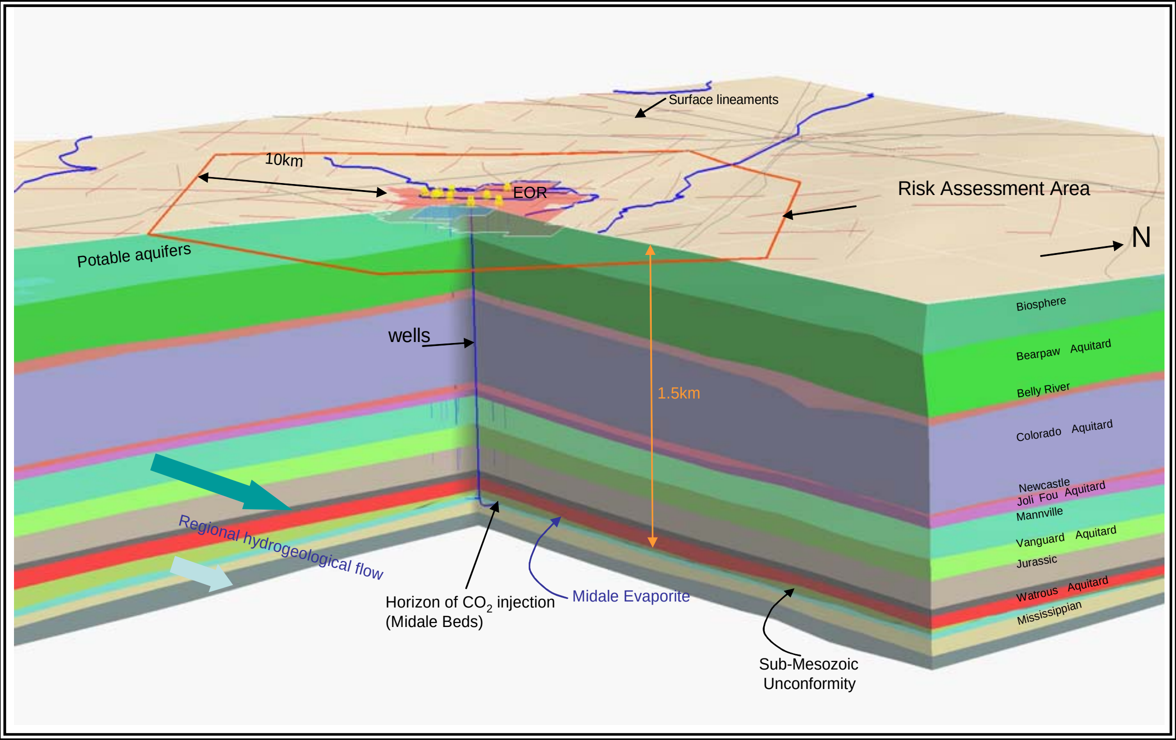


Figure 2: The System Model used in risk assessments includes geological and man-made features. Geological features of the model include structures, truncation surfaces, primary and secondary seals, and the lithostratigraphy upscaled into hydrostratigraphic units defining major aquitards and aquifers and their respective transport properties all within a spatially accurate framework. The current system model considers strata to about 150 m below the reservoir, but can easily be modified to include or exclude any geological data available. The output from the geological model may run directly within flow simulators for performance assessment. Data for probabilistic analysis may also be derived from the model.

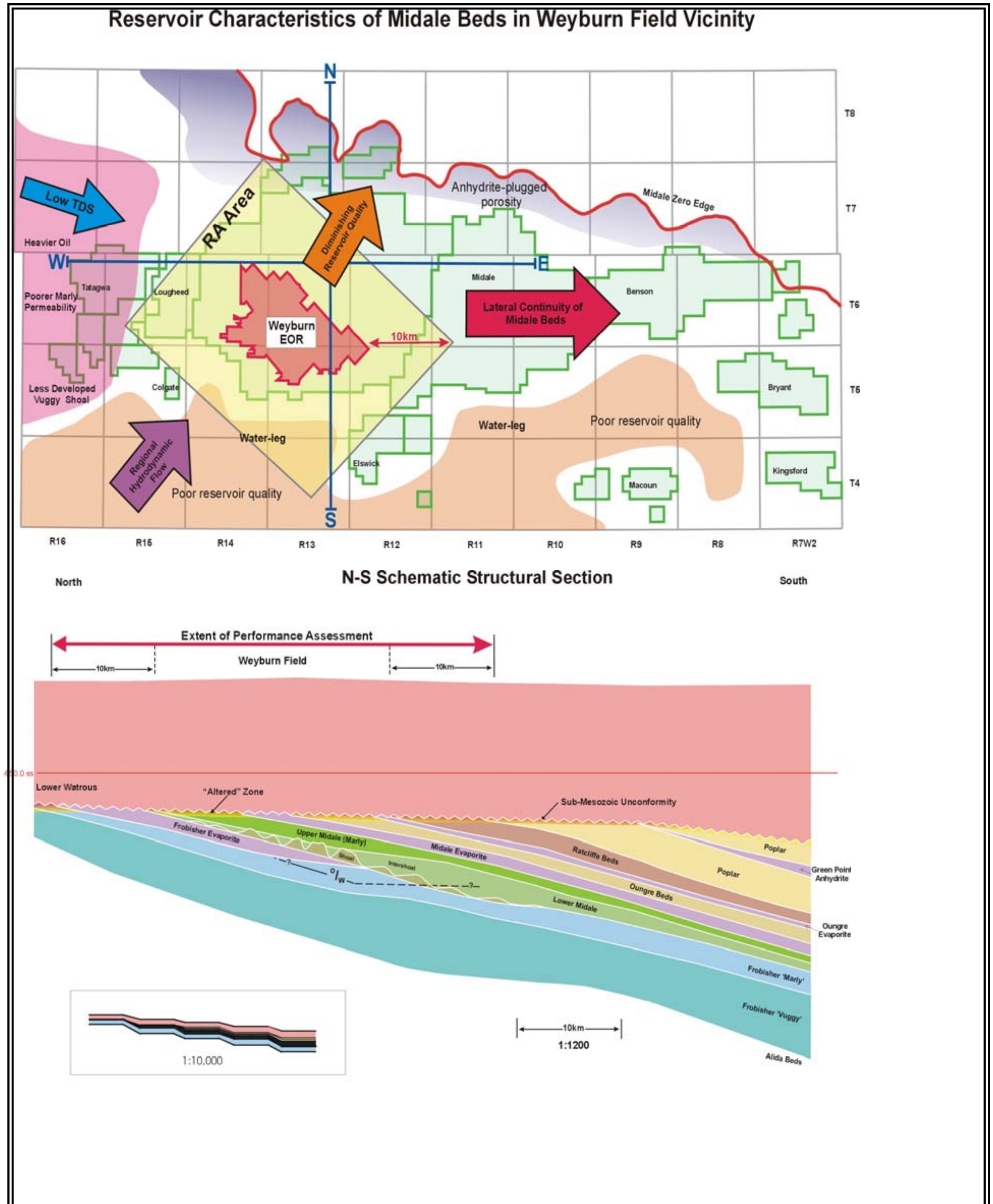


Figure 3: Bounding conditions of the Mississippian Midale Beds of the Weyburn Unit are shown in plan view in the upper diagram. A north – south cross-section through this map is shown in the lower diagram which depicts the spatial relation of the primary sealing units, the Midale Evaporite, the altered zone, the Frobisher Evaporite and the Lower Watrous Formation, to the Midale Beds. The Midale Beds consists of an upper dolostone unit (Marly), which is where CO_2 is currently being injected, and a lower limestone unit (Vuggy) from which most previous oil production was obtained.

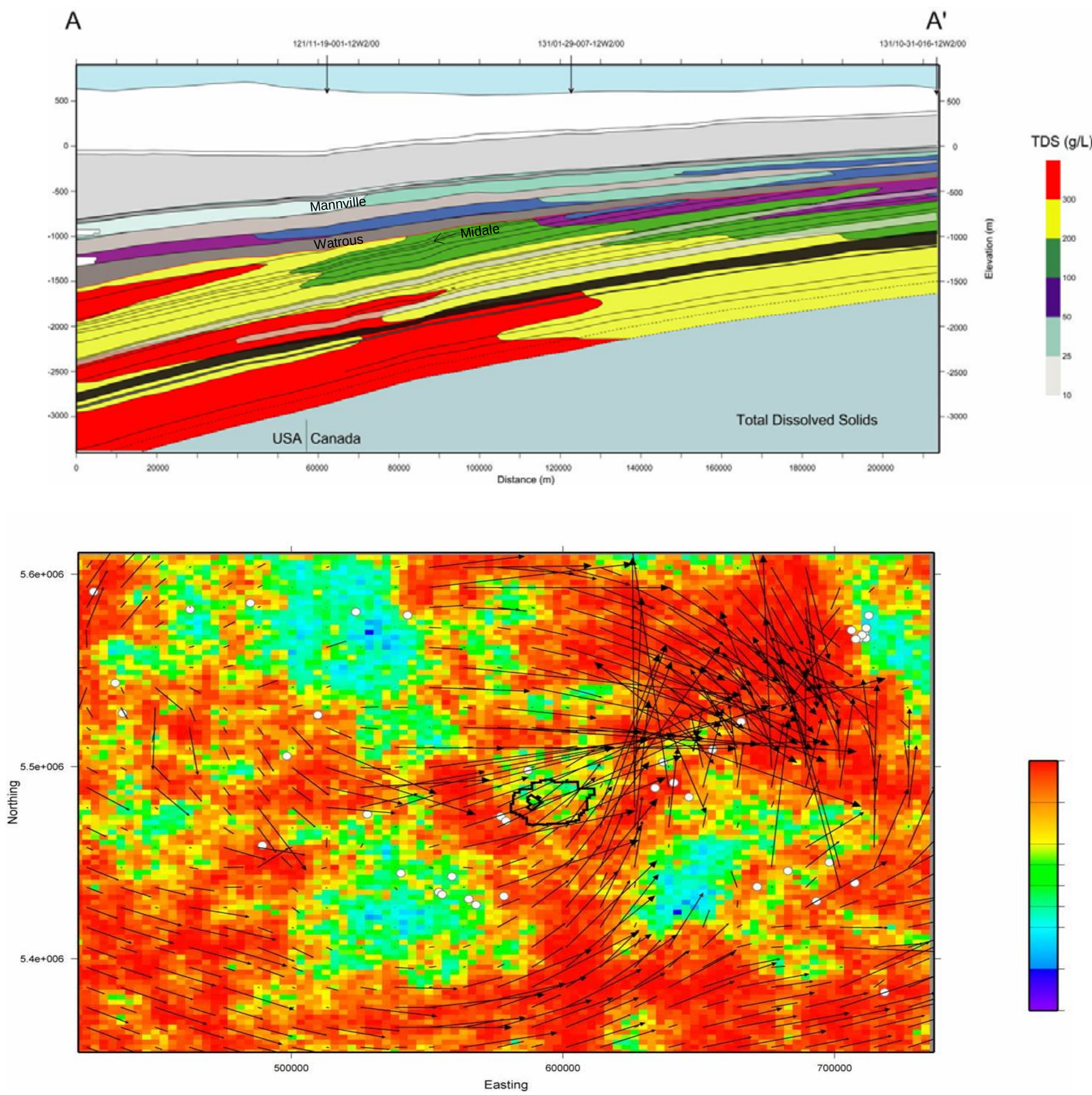


Figure 4: Upper figure is a north-south hydraulic cross-section of total dissolved solids across the entire Weyburn Study area. This diagram indicates the lower, more saline hydrogeological system is isolated from the shallower, fresher hydrogeological system. The Midale reservoir is found at the uppermost part of the lower system and is overlain by the non-flow Lower Watrous Formation.
Lower figure is a plan view of the simulated permeability field of the Mannville aquifer (Cretaceous), a hydrogeological unit overlying the Mississippian reservoir having the greatest permeability and fastest flow velocities. Arrows indicate nodal velocities that average near 8.5 m/yr above the Weyburn reservoir, and which may approach 50 m/yr within the larger study area.

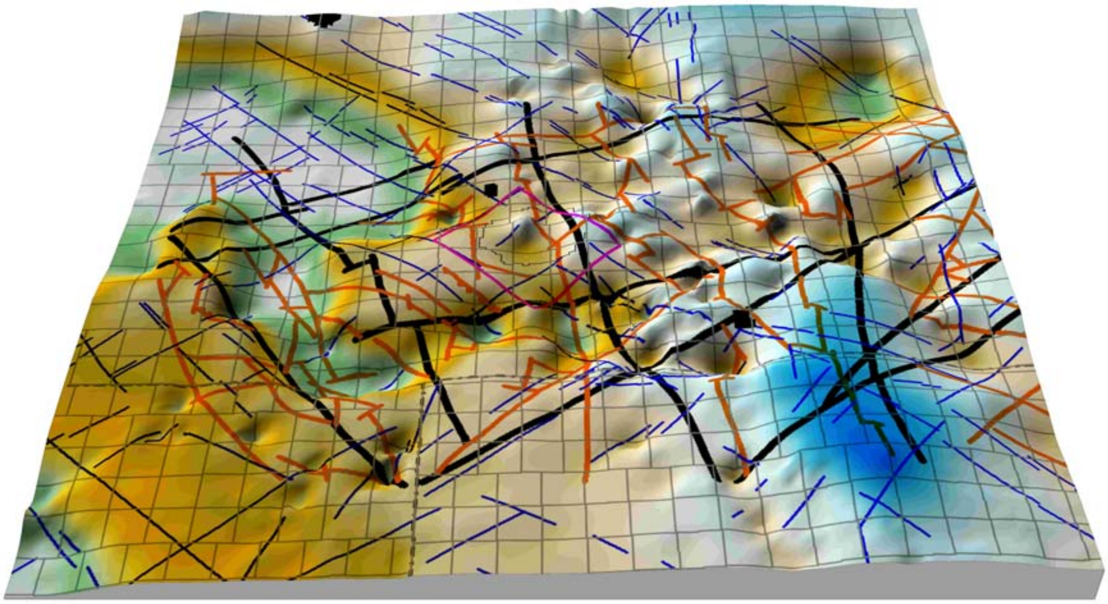


Figure 5: Thickness variations of the Devonian Prairie Evaporite Formation that occurs more than 1 km below the Mississippian Midale reservoir. Superimposed on the thickness variations, which are due mainly to subsurface salt dissolution, are numerous tectonic and surface features identified within this project. The dark heavy lines are major tectonic elements within the basin; the thinner red lines are fractures and faults interpreted to occur at various depths within the sedimentary column; and the thin blue lines are lineaments identified on ground surface through satellite imagery. The influence of the tectonic elements is apparent in depositional and erosional patterns of strata from basement to surface. The dynamics of salt dissolution within basins has greatly affected trapping potential and is an area requiring further work.

CO_2 Storage Capacity and Distribution Predictions

(Note: The simulations described below should be viewed as the type of simulation required to support risk assessment studies. The simulations completed in Phase I, while attempting to closely model operational conditions, was not meant to replicate specific field development options.)

Technical Approach

GEM, a multi-phase, multi-component compositional reservoir simulation model was used to predict the CO_2 storage capacity in the Weyburn Unit reservoir. The approach taken in modeling the size and complexity of 75 EOR patterns was to start with fine-grid single-pattern simulations and end with a coarse-grid 75-pattern simulation. The process involved three levels of upscaling: (1) from a detailed geological model of the Weyburn reservoir to a fine-grid reservoir simulation model; (2) from 3 fine-grid single-pattern models to coarse-grid models of the same patterns; and (3) from 3 coarse-grid single-pattern models to a 75-pattern model using the same grid resolution.

Laboratory measurements of oil properties and CO_2-oil phase equilibrium behaviour using oil samples collected periodically from different wells provided information to tune the equation-of-state (EOS) parameters in the PVT model used in the reservoir simulation. The reservoir simulation model was validated by both lab-scale and field-scale simulations. In the lab-scale simulation, CO_2-coreflood experiments conducted with different oil samples were history-matched while in the field-scale simulation, field production histories in 3 different patterns with different CO_2 injection strategies (i.e., “simultaneous but separate water and gas injection” (SSWG), “Vuggy water-alternating gas” (VWAG), “Marly, Vuggy water-alternating-gas” (MVWAG)) were history-matched. Then, the reservoir simulation model was used to predict the CO_2 storage performance during the EOR period, first in the 3 single patterns and then in the entire 75 EOR patterns. EnCana’s operating strategies was followed as closely as possible. This was labeled the Base Case. Alternative CO_2 storage cases after EOR were also investigated with a focus on promoting additional CO_2 storage.

Using the predicted CO_2 distribution in the reservoir at the end of EOR, a geochemical model was used to provide a preliminary assessment of the amount of CO_2 that will be stored in the reservoir through different trapping mechanisms (solubility, ionic and mineralogical trappings). The geochemical modeling also used formation and injection fluid compositions, detailed mineralogical assessment of each of the major flow units in the reservoir, and evaluation of mineral kinetic data.

The performance of both CO_2 storage and EOR depend on achieving maximum sweep efficiencies (conformance) and that can be improved through conformance control techniques. The Weyburn reservoir pay zone is a fractured-carbonate with large permeability contrasts, which allows the injected CO_2 to finger and bypass a significant fraction of the recoverable oil. Laboratory evaluation of commercially available technologies for conformance control such as CO_2-foam, gel and gel-foam processes were conducted to select the most suitable options for the Weyburn reservoir. Well production histories provided by EnCana have been analyzed to select candidate wells with high production GOR for future conformance control field trials. The analysis included reservoir simulation modeling using existing fine-grid single-pattern simulations to design the field trial and predict the field trial performance.

With the prediction of CO_2 storage capacities and EOR performance, an economic model was used to apply economic constraints to the CO_2 storage cases. This Storage Economic Model has the capability to calculate CO_2 capture, transportation and storage costs in addition to the conventional economic evaluation of an EOR process. The model can be run either for stand-alone CO_2 storage options (e.g. depleted oil or gas reservoirs, saline aquifers, etc.) or storage in conjunction with CO_2 EOR projects. The objective of the Storage Economics Model is to guide geological storage decisions where not only estimates of the maximum amount of CO_2 that can be physically stored is required, but also how much of that CO_2 is actually economically stored, under different gas credits assumptions.

Results and Conclusions

Figure 1 shows locations of the oil sample wells in the Phase 1A area. All oil samples have densities ranging from 858 to 903 kg/m^3, which represent oil at the lightest end and near the field average, respectively. Based on the analysis of these oil samples, a 7-component PVT model (CO_2; C_1 & N_2; C_2, C_3, & H_2S; C_4 to C_6; C_7 to C_{12}; C_{12} to C_{30}; and C_{30+}) was developed and continuously fine-tuned. The measured oil properties such as viscosity, density, saturation pressure, gas-oil-ratio (GOR) and minimum miscibility pressure (MMP), agreed well with predictions from the PVT model. Viscous fingering was found to be a dominant mechanism in the core floods as shown in Figure 2. Further validation of the simulation model was carried out in 3 detailed fine-grid single-pattern simulations in the Phase 1A area as shown in Figure 3. Examples for successful history-match of the field production histories are shown in Figure 4 for a full pattern and an individual well, respectively. Figure 5 shows qualitative comparison between numerical prediction of CO_2 distribution and seismic observation. Predictions were then made for the CO_2 distribution and storage capacity at the end of EOR (2033) for these single patterns with different CO_2 injection strategies of SSWG, VWAG and MVWAG. This final CO_2 distribution at the end of EOR provided the initial conditions for the risk analysis model of the geosphere to assess the potential CO_2 leakage and migration, including from near wellbore zones.

Fine-grid single-pattern simulations were up-scaled to coarse-grid simulations of the same patterns. The three coarse-grid single-pattern simulations were used as building blocks to carry out simulations of the entire 75 patterns. Figures 6 and 7 show the CO_2 inventory and CO_2 distribution at the end of EOR (2033), respectively for the entire 75 patterns, following EnCana's field operating guidelines as closely as possible. It is found that an estimated of 23.2 million tonnes (MT) of CO_2 can be stored in the reservoir at the end of EOR, of which 7.08 MT (30.5%), 10.25 MT (44.2%) and 5.87 MT (25.3%) would be stored in the gaseous, oleic and aqueous phases, respectively. Performance of alternative EOR and CO_2 storage cases are shown in Table 1. Alternative CO_2 storage cases II and IIa consider continuous injection of CO_2 after EOR with all the production wells shut-in until the reservoir reaches the maximum pressure of 29.5 MPa. Alternative CO_2 storage cases III and IIIa consider continuous injection of CO_2 after EOR with production wells shut-in when GOR exceeds 1,500 m^3/m^3.

Detailed mineralogy of the Weyburn reservoir is provided from microscopic examination, X-Ray Diffraction (XRD) results, and LPNORM analysis of approximately 100 samples that establish the presence and abundances of minerals for each of EnCana's reservoir flow unit. Results show that even in a carbonate reservoir such as at Weyburn, silicate minerals are present in sufficient quantity to react with CO_2-charged fluid. Using estimates of the porosity and the volume of each of the flow units and the reactions determined through the geochemical modeling, the maximum potential amount of trapping in each flow unit can be estimated as shown in Table 2. Integrating these results over the entire reservoir yields a total of approximately 45.15 MT with 22.65 MT, 0.25 MT and 22.25 MT of CO_2 potentially stored through solubility, ionic and mineralogical trapping mechanisms, respectively. The most critical assumptions in this calculation are that there is sufficient supercritical CO_2 for reaction in each of the flow units and that complete/significant reaction of the silicate minerals will occur over 5,000 years. Subject to the assumptions inherent in this approach, the reservoir simulation estimates of CO_2 distribution in the reservoir can be combined with the geochemical modeling long-term reactions to obtain a "Rev 0" estimate of the CO_2 distribution in the Weyburn reservoir after 5,000 years. Based on the CO_2 storage capacity of 23.2 MT for the Base Case, approximately 10.25 MT will be in the oleic phase, 6.50 MT and 0.07 MT through solubility and ionic trappings in the aqueous phase, respectively and 6.38 MT through mineral trapping as shown in Figure 8. There will not be a free supercritical CO_2 gas phase present in the reservoir after 5000 years.

Conformance control experiments indicated that gel systems developed for Weyburn are able to block the flow of both water and CO_2 very effectively. Therefore, gel treatments can be considered a viable option for improving CO_2 conformance in the Weyburn field. Figure 9 shows the residual resistance factor (RRF), a measure of the degree of reduction in original permeability to the injected water and CO_2 after gel placement. In selecting well candidates, 20 high GOR wells were identified out of 600 wells. Reservoir simulation was used to design a gel placement field trial involving a horizontal injection well in Pattern 1 (P1612614). The simulation predicted the performance of two near-by horizontal producers. A total pore volume (PV) of 80,000 m^3 was assumed to be treated with 1,000 m^3 gel, as gel placement is limited to fractures which are approximately 1% PV. Such a gel treatment would cost CA$200,000 to $500,000. Figure 10 shows predicted oil and gas production rates for one of the production wells before and after the gel treatments. The simulation indicated an incremental oil recovery of 20,000 m^3 corresponding to a 10% increase in oil recovery without a gel treatment. Based on additional void space available from the incremental oil recovery, an additional 28,000 tonnes of CO_2 can be stored. If this preliminary estimate is extended over the entire field (75 patterns) and assuming a 10% increase in total oil recovery and that only 20% of the EOR patterns undergo gel treatments, it is estimated that an additional 1.83 MT of CO_2 could be stored.

A demonstration case of the Storage Economics Model is presented here. The case is predicated on continued CO_2 injection in the Weyburn Unit past the economic limit of the EOR operation. The economic drivers, in this case, are the incremental oil recovered by the additional CO_2 injected as well as the granting of gas credits. Figure 11, depicts the oil production rate and CO_2 injection rate profiles for both the EOR and the post-EOR phases. The EOR phase allows 23.2 MT of CO_2 to be physically and economically stored. The post-EOR phase allows for up to an additional 31.6 MT of CO_2 to be physically stored. However, the portion of the 31.6 MT that can be economically stored will depend on the amount of the CO_2 credits received and the desired rate of return for the operation, Table 3.

Table 1: Numerical prediction of CO_2 storage capacity and EOR performance for Base Case and Alternative Cases

	Baseline EOR Case (2000 – 2033)		Alternative EOR Case (2000 – 2033)	
CO_2 Injected, %HCPV	45.9%		59.7%	
CO_2 Recycled, % Injected	58.2%		56.9%	
CO_2 Stored, million tonnes	23.21		30.05	
Oil Recovery after water flood, %OOIP	26%		26%	
Oil recovery after EOR, %OOIP	47.2%		50.3%	
Net CO_2 Utilization Ratio, m^3/m^3	416		496	
	Alternative Storage Cases (2033 – 2055)		Alternative Storage Cases (2033 – 2055)	
	Case II	Case III	Case IIa	Case IIIa
CO_2 Stored (Additional), million tonnes	29.08 (5.87)	54.85 (31.64)	37.14 (7.09)	60.65 (30.60)
Oil Recovery @2055 (Additional), %OOIP	----	54.3% (7.1%)	----	54.7% (4.4%)
Net CO_2 Utilization Ratio, m^3/m^3	----	1,462	----	2,585

Table 2: Estimates of long-term (5000 years) maximum CO_2 trapping potential

Flow Units	Trapping Mechanisms in Each of Flow Units in Weyburn Reservoir			
	Solubility (million tonnes CO_2)	Ionic (million tonnes CO_2)	Mineral (million tonnes CO_2)	% Mineral Trapping
m0	1.22	0.0128	1.87	60%
m1	3.57	0.0452	3.90	52%
m3	4.14	0.0347	5.73	58%
v1	3.65	0.0426	2.97	45%
v2	3.87	0.0683	1.51	28%
v3	1.40	0.0155	1.44	50%
V4	2.38	0.0206	2.90	55%
V6	2.42	0.0175	1.93	44%
Total	22.65	0.2572	22.25	49%

Table 3: Economic evaluation of rate of return for a CO_2 storage process

Rate of Return given Credit for CO_2 Stored (C$/tonne) $0.25 million/well cost at 2033 ($67 million initial capex in year 2033)																	
Year of Post EOR	Credit for Stored CO_2																Additional Post EOR CO_2 Storage (MT)
	$5	$7	$8	$9	$10	$11	$12	$13	$14	$15	$16	$17	$18	$19	$20	$25	
20	< 0	< 0	11%	14%	16%	19%	21%	23%	25%	27%	29%	30%	32%	34%	36%	45%	29.9
19	< 0	7%	11%	14%	16%	19%	21%	23%	25%	27%	29%	30%	32%	34%	36%	45%	28.7
18	< 0	7%	11%	14%	16%	19%	21%	23%	25%	27%	29%	30%	32%	34%	36%	45%	27.5
17	< 0	8%	11%	14%	16%	19%	21%	23%	25%	27%	29%	30%	32%	34%	36%	45%	26.2
16	< 0	9%	12%	14%	17%	19%	21%	23%	25%	27%	29%	30%	32%	34%	36%	45%	24.7
15	3%	10%	12%	15%	17%	19%	21%	23%	25%	27%	29%	30%	32%	34%	36%	45%	23.2
14	5%	10%	13%	15%	17%	19%	21%	23%	25%	27%	29%	30%	32%	34%	36%	45%	21.6
13	6%	11%	13%	15%	17%	19%	21%	23%	25%	27%	28%	30%	32%	34%	36%	45%	20.0
12	6%	11%	13%	15%	17%	19%	21%	23%	25%	26%	28%	30%	32%	34%	36%	45%	18.4
11	7%	11%	13%	15%	17%	19%	21%	22%	24%	26%	28%	30%	32%	34%	36%	45%	16.9
10	6%	11%	12%	14%	16%	18%	20%	22%	24%	26%	28%	29%	31%	33%	35%	45%	15.4
9	6%	10%	12%	14%	16%	17%	19%	21%	23%	25%	27%	29%	31%	33%	35%	44%	14.0
8	4%	8%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%	30%	32%	33%	43%	12.6
7	2%	6%	8%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%	30%	32%	42%	11.2
6	< 0	1%	3%	5%	8%	10%	12%	14%	16%	18%	20%	22%	24%	27%	29%	39%	9.9
5	< 0	< 0	< 0	< 0	< 0	2%	4%	6%	9%	11%	13%	16%	18%	20%	23%	34%	8.5

Figures

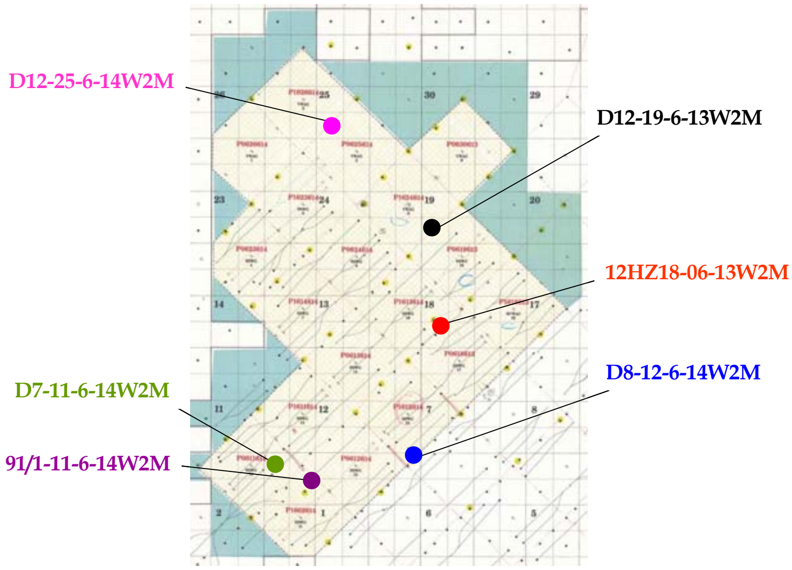


Figure 1: Locations of oil sample wells

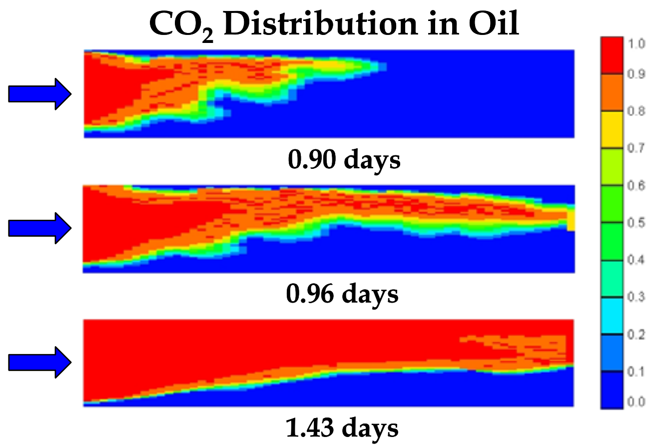


Figure 2: Numerical prediction of CO_2 distribution of a coreflood experiment using oil sample collected from well D7-11-6-14W2

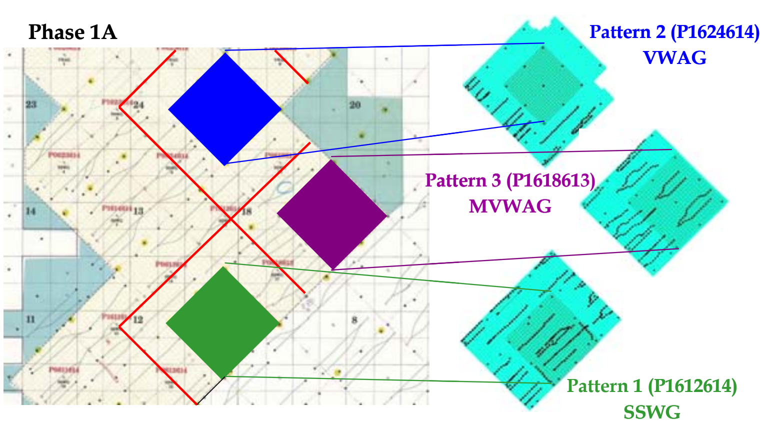
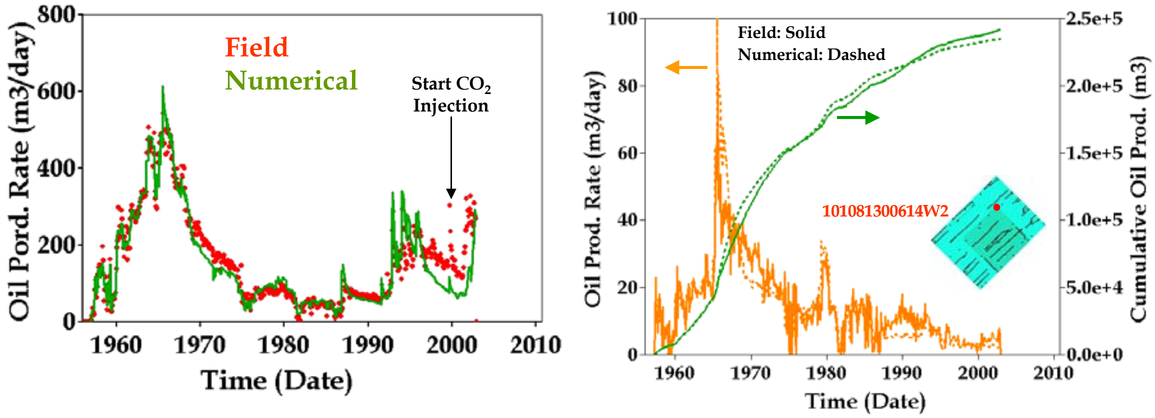


Figure 3: Locations of 3 single-pattern simulations in Phase 1A area



(a) Pattern 1 (P1612614) (b) Well D8-13-6-14W2M

Figure 4: Comparison of numerical prediction and field production history

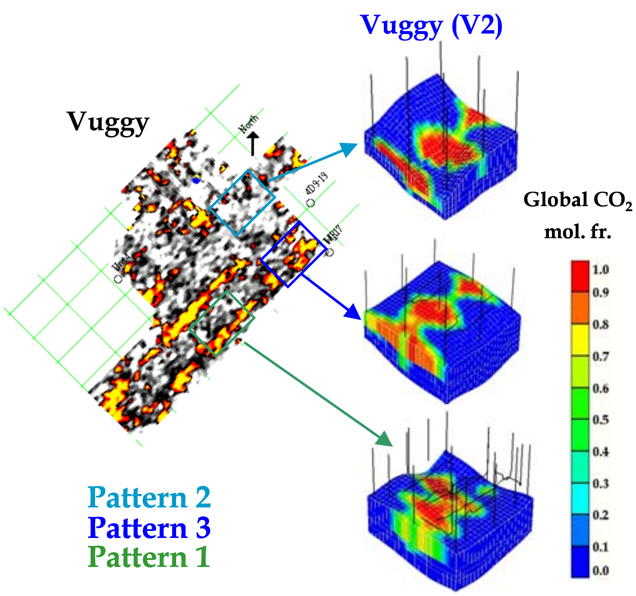


Figure 5: Comparison of numerical prediction of CO_2 distribution and EnCana's 3D 4C surface seismic (CO_2-related anomalies) after 2 years of CO_2 injection (2002)

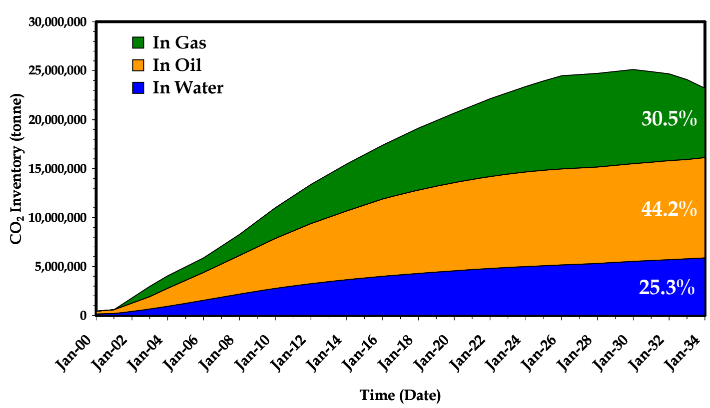


Figure 6: CO_2 inventory for 75 patterns (Base EOR Case)

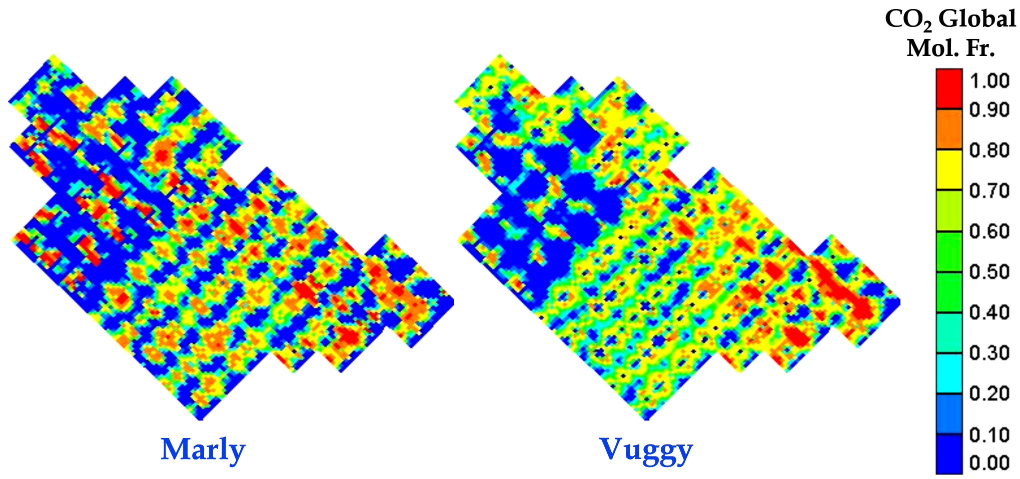


Figure 7: CO_2 distribution at end of EOR (2033) for 75 patterns (Base EOR Case)

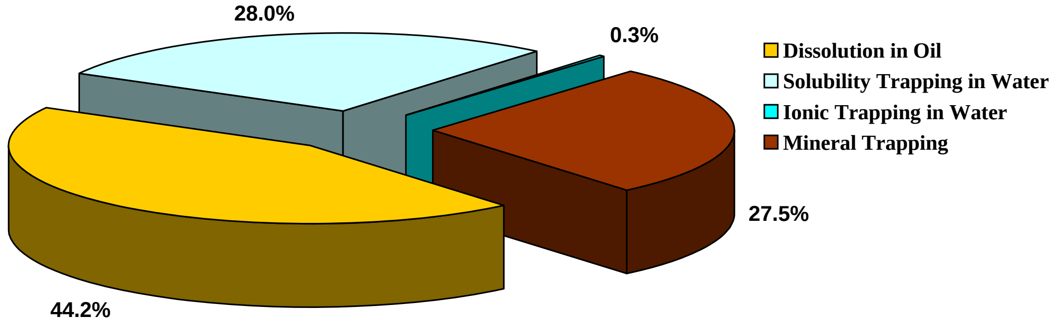


Figure 8: "Rev 0" estimation of the CO_2 distribution in Weyburn reservoir after 5,000 years based on geochemical modelling (Base EOR Case of 23.2 million tonnes)

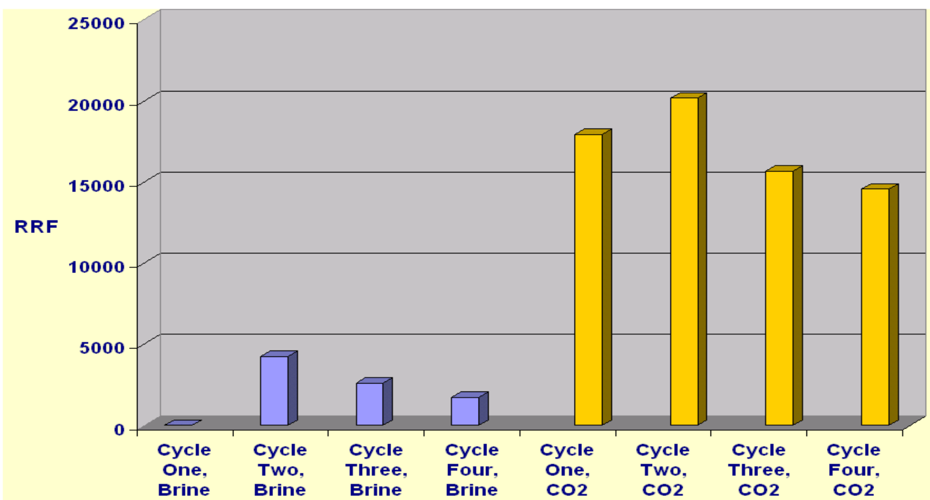


Figure 9: Residual resistance factors for the post-gelation permeability measurements for several cycles of experiment

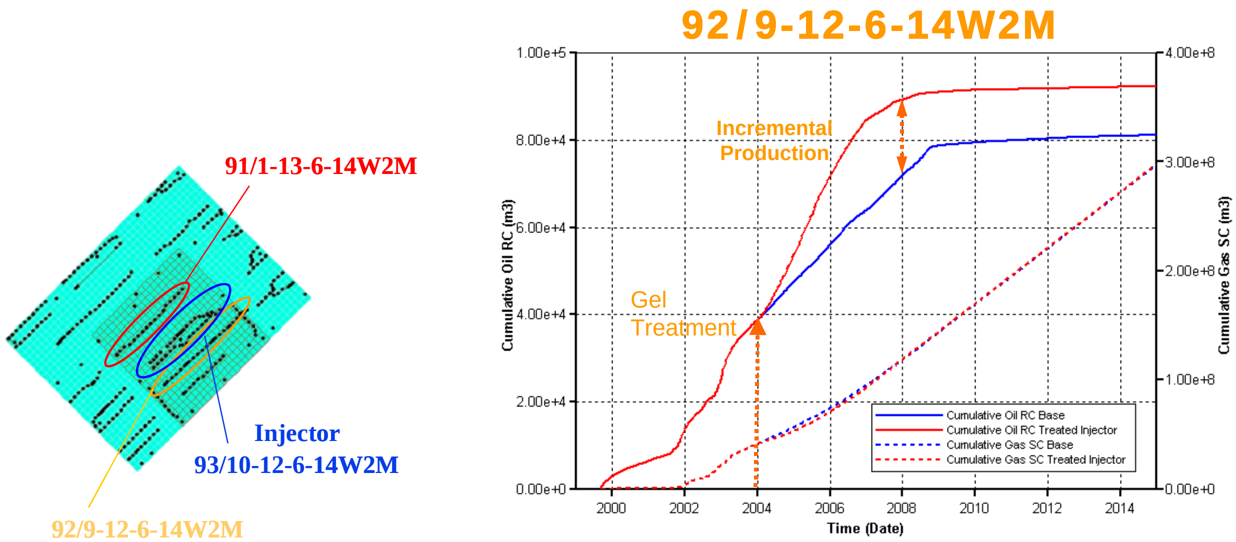


Figure 10: Predictions of gel treatment performance in Pattern 1 (P1612614)

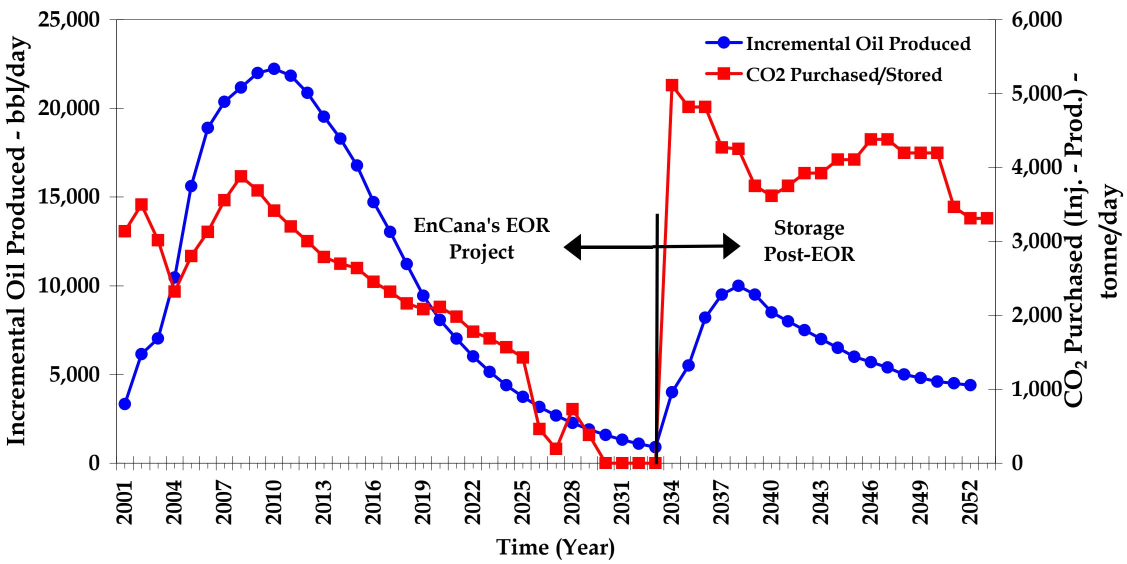


Figure 11: Profiles of oil production and CO_2 purchased used in economic evaluation

IEA GHG Weyburn – Midale CO_2 Monitoring and Storage Project

Expert Review Meeting

PTRC, Regina, Canada

1st to 2nd Feb 2006

Review Meeting Aims

- To review the technical work programme for the project
  - PTRC, Theme Leaders
    - The guidance of the project sponsors and Technical Steering Committee (TSC).
- To identify any gaps in the work programme
  - Suggest additional areas of research that could complement the work programme.

Outcome

- A report for dissemination within the Weyburn Monitoring Project.
  - Conclusions from expert review
  - A statement on the technical integrity of the proposed work programme
  - Identification of any further research needs.
    - Assist the selection of new projects to cover any gaps identified in the technical programme

Project Strengths

- High quality data set
  - Unique
- High quality research staff
  - Recognise the need for integration
    - Theme leaders driving this - don't under estimate this task
- Phase 1 made some significant progress on a number of CO_2 storage areas
  - Monitoring, risk assessment, geological modelling etc.,
- Scientifically sound basis to move to the final phase

Project Objectives

- Build on results from Phase 1?
  - Somewhat ambiguous
  - Yes based on what has been presented will do that
  - But can this objective be tightened?
- Might be better to focus on key research issues identified in Phase 1 and build upon that work
  - More tangible outcome from the final Phase

Final Project Objective

- Focus on developing sound scientifically based data to answer key technical issues
- Many times over two days response was we don't know. Examples:
  - Faults/fractures are they transmissive
  - Partitioning of CO_2 in the reservoir
  - Unresolved issues over seismic interpretation
  - Differences between two RA models
  - Well bores leakage potential

Final Phase Focus

- Identify key research issues in each theme
- Focus on resolving these issues in this phase
- Scientifically sound and qualified data set
- Confidently go out and engage the regulators and public
- Does not mean tearing up research programme you have
  - Re-evaluating it
  - Some refocusing of individual project submissions

Making best of What You Have

- A lot of discussion about acquiring new data
- Seems a lot of work can be done with existing data to improve its quality and understanding
- Help focus where they need to collect new data
- Helps overcome new data acquisition issues

Theme 1

- Identified key issues:
  - Fractures, above and below seals, hydrogeology
- Focus should change to developing a predictive model to assist verification of CO_2 storage
  - Not to develop more and more models
  - Ground truthed model used in RA programme
- Data – a lot of data already

Theme 1

- Data – a lot of data already
- Could focus on getting new targeted data
  - New wells across faults to study transmissibility
- Reconcile existing data
  - Stress measurements need to be looked at

Theme 2

- Plan sound
- Problem highlighted was access to wells on site
- Consider alternative strategy to gain data they need
  - Wells outside Weyburn field
  - Trying to do everything but should consider co-operating with other projects to gain access to data
  - Benefit in involvement in Well bore integrity network to help focus and target research work for this theme
  - Need to mine database – might find holes in data
    - Use to screen wells outside Weyburn
- Consider looking a issues related top background fluids and not just CO_2

Theme 3 - Geophysics

- Programme sound
- Need to pull together all the data sets
  - Understand inconsistencies
  - Recognised in plan
- Look carefully at modelling predictions
  - Find out what you can add
- Consistencies between data sets and models to be resolved
- Improve confidence in existing seismic data set and models

Theme 3 - Geochemistry

- Unique data set
- Need to maintain the data collection – this is unique to Weyburn (soil gas and geochemical)
- Analyse the data to determine quality of data
- Modelling – is the data collected the right data?
- Partitioning of CO_2, phase of CO_2 in the reservoir

Theme 3 - Geophysics

- Consider taking a small pattern and resolve uncertainties either with existing first or by acquiring new seismic data
- Drill new instrumented wells to gain additional data to understand seismic anomalies
- Look at existing seismic and determine what they need to do to understand
  - May be new lab data, geochemical modelling
- Make better use of pressure transient data in hydrogeological context

Theme 4

- Not risk assessment – really performance assessment
  - Weyburn core skill not risk assessment
  - For RA develop quality data set give that to RA specialists
  - But they need to be ground truthed
- Theme sits as central pillar which other themes hang from
- Theme becomes integrator for whole project

Theme 4

- Modelling discrepancies is a big loose end that needs to be sorted out
- Recommend they resolve discrepancies in the models
  - Understand data used/applied in both models
  - Identify key pieces of the models and understand why models give different outputs
  - Then allows models to be compared
  - If not completed undermines credibility of modelling approaches

Theme 4

- Theme needs to commence as soon as possible
  - Step 1 - peer review of data from phase 1
    - Well defined exercise
  - Step 2 – development of new performance assessment framework
    - Helps address uncertainity and highlight data needs
    - Feeds in to other themes to define data requirements
    - Scheduling issue

Theme 5

- Merge this activity into Themes 3 & 4
- Geochemical modelling important to develop understanding of fate in reservoir
  - Long term predictions

Best Practise Manual

- Stated as projects key deliverable
- Important outcome of this Final Phase
- A lot of mention in individual presentations
- Did not get any details on its scope/content
  - Would have been useful to have a presentation on this
  - Outline contents available?
- Written at project end
  - Not clear how that was going to be achieved
  - Need an identified person to take lead and pull it all together – could be a separate theme?

Best Practise Manual

- Project should reconsider BPM process
- Considerable value in producing a version 0, BPM now
  - Could be part of Quick Start programme
  - Help focus future research activities
  - Get people thinking about what they need and where there are gaps
    - Interact with other projects to see what they need
- Undertake the research programme at Weyburn and refine BPM
- In parallel apply at Midale – again help refine BPM
- Have a good tested BPM for CO_2 storage in oil fields
  - Some generic features – apply again in subsequent aquifer project

Feedback Loop

- Recommend a feed back loop from project to expert reviewers
  - Valuable to keep ER's appraised of progress and problems
- Suggest 6 monthly progress summary
  - Discuss issues with PTRC, Project Integrator
  - Focus experts on issues
    - Might be value in expanding ER on certain issues
- Hit the ground running for future reviews.

Comments on Non Technical Programme

- Regulatory Process
  - Discussions to date focused on 5 key components
    - Site characterisation (Theme 1)
    - Monitoring (Theme 2)
      - Before and after injection
    - Risk Assessment (Theme 3)
    - Predictive modelling (Themes 1, 3, 4 and 5?)
      - History matching from monitoring
    - Remedation plans (Theme 2)

Comments on Non Technical Programme

- Communication
  - Public
    - How safe is it?
    - Where does the Co2 go when its stored and does it stay there?
  - Regulators
    - Confident it is contained
    - Projects to assist in regulatory development
- Need to verify how much has been stored to get credits

Comments on Non Technical Programme

- Hard to see how you can confidently engage public and regulators with the uncertainties in the underlying data
- Difficult to see how you can apply for credits for CO_2 storage with the uncertainties in the project data
- Essential to come to closure on the key research topics from Phase 1

Reccommendations

- Concentrate on CO_2 storage
  - Adapt existing research programme
- Concentrate on resolving key outstanding issues in the project data
  - Need to build confidence in the data set which is essential for Non Technical Programme
- Start the BPM development now rather than leave it to the end

Thank You

- PTRC hosting us
- Theme leaders for their openess and active involvement
- Expert reviewers for their time and effort
- Useful learning exercise for all concerned

“The Schweinrich structure”, a potential site for industrial scale CO_2 storage and a test case for a safety assessment in Germany

Eric Kreft, Rickard Svensson, Robert Meyer, Arie Obdam, Rob Arts, Christian Bernstone, Sara Eriksson, Pierre Durst, Irina Gaus, Bert van der Meer, Cees Geel

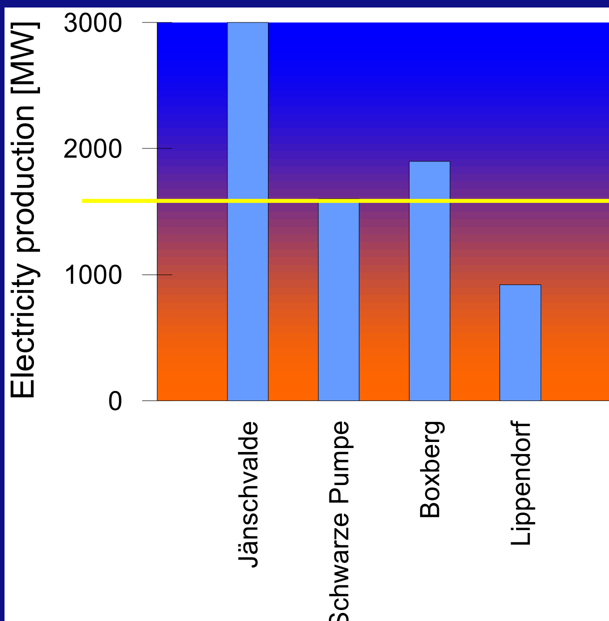
TNO | Knowledge for business

Rob van Eijs

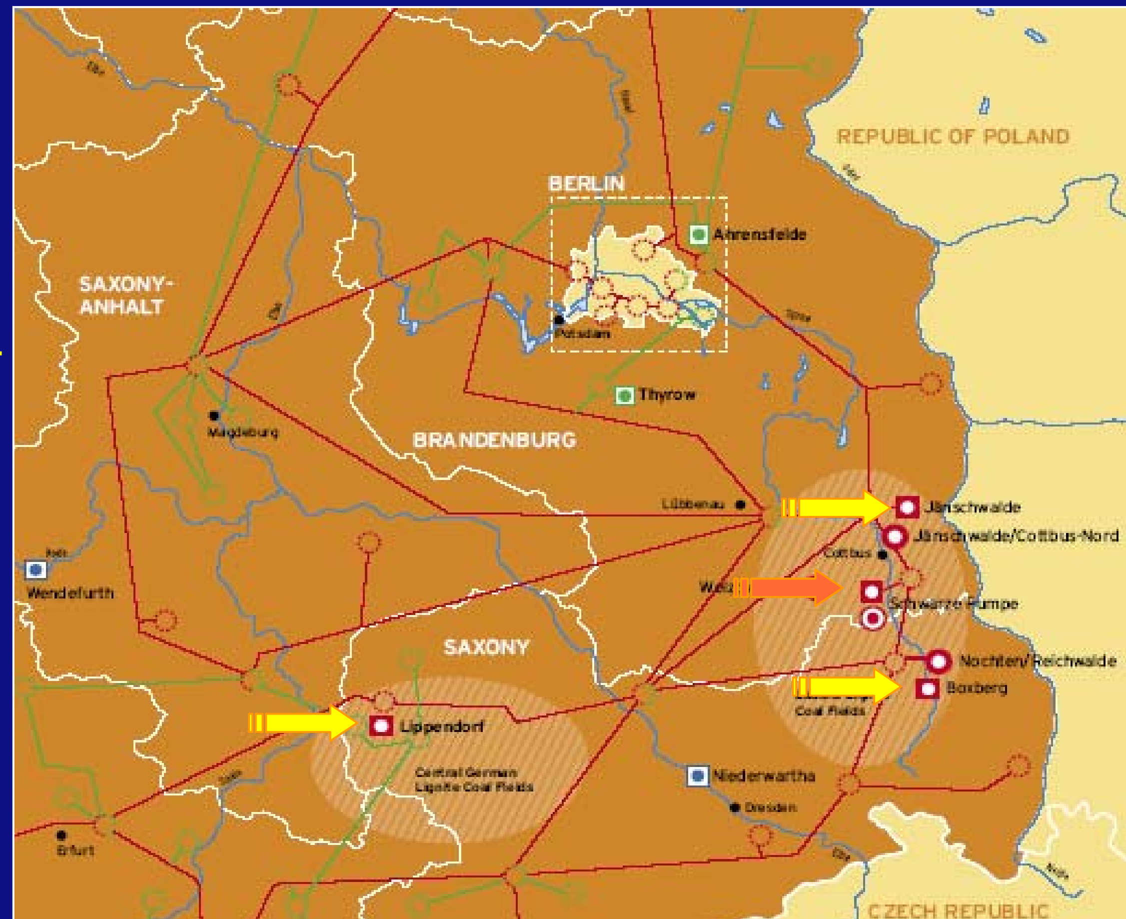
CO2STORE Study Sites

Major power plants operated by Vattenfall

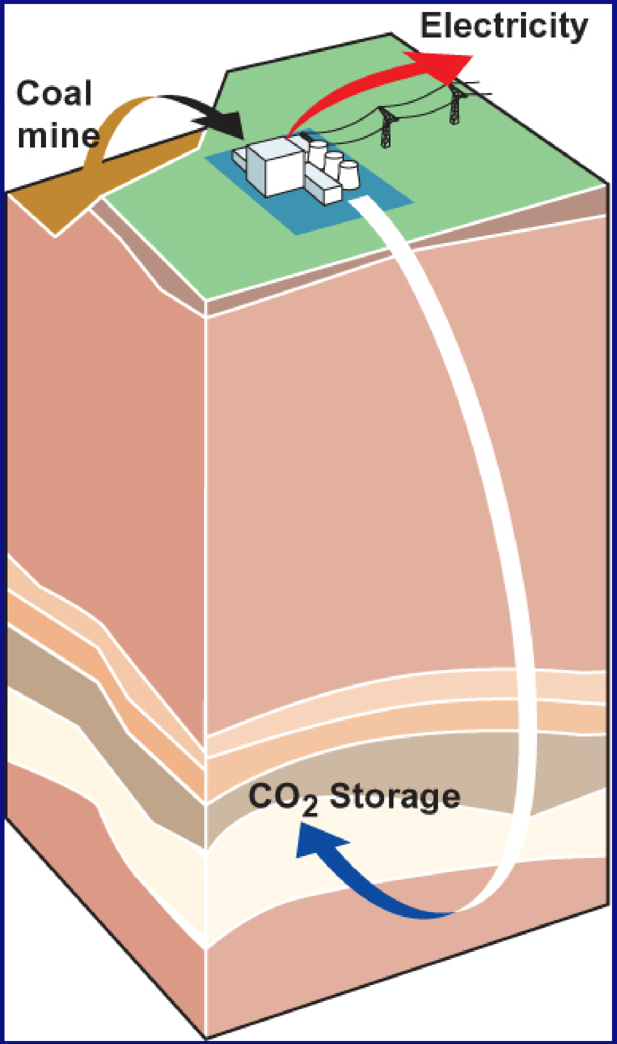
Schwarze Pumpe Power plant: Representative size



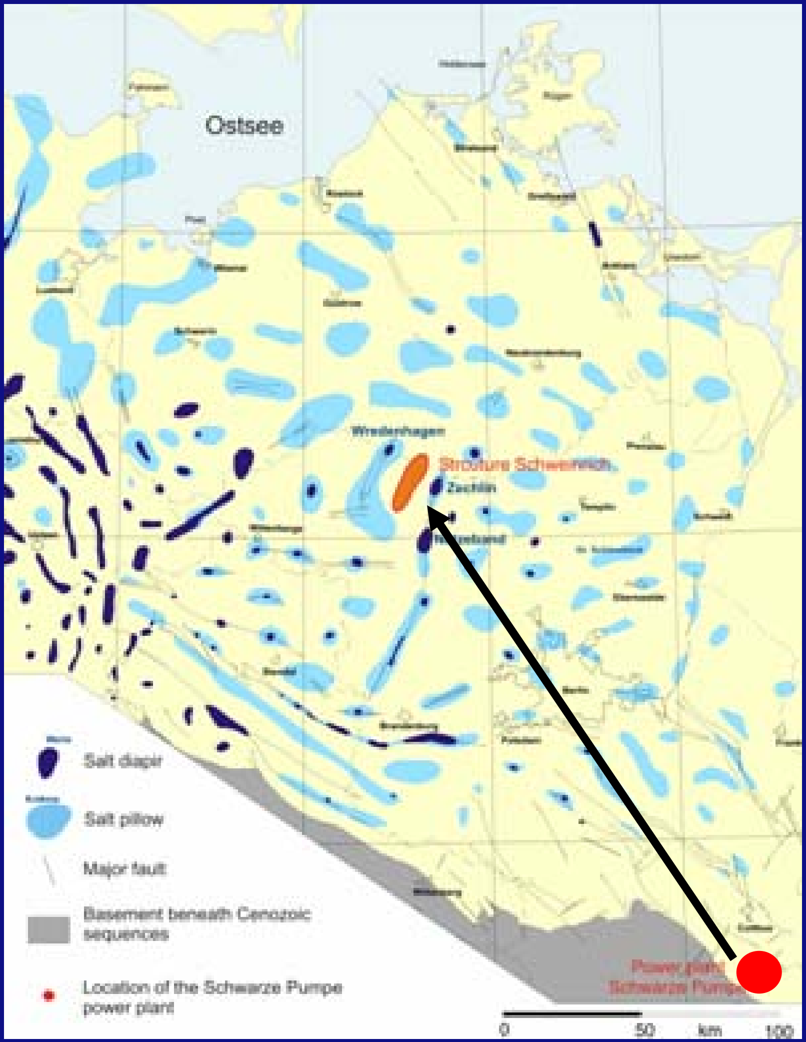
10 Mton CO_2 / year



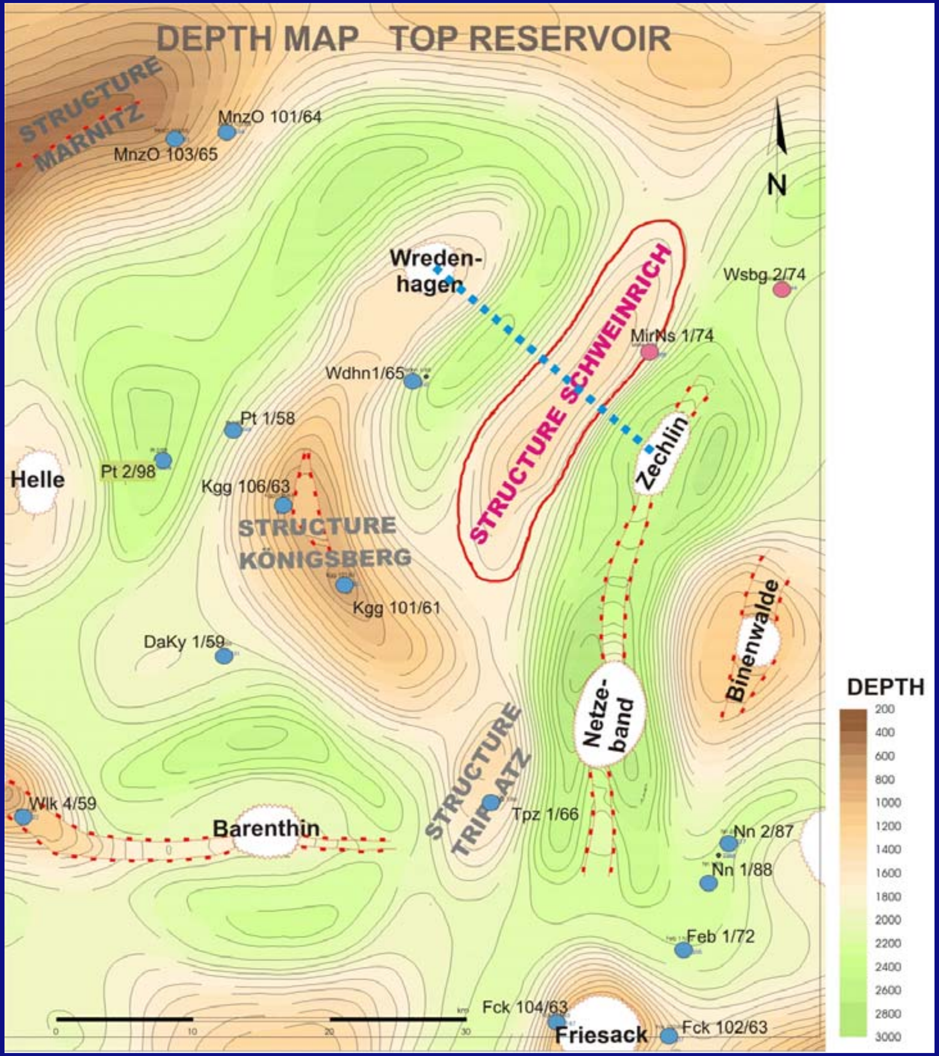
Vattenfall CO_2 free power plant project

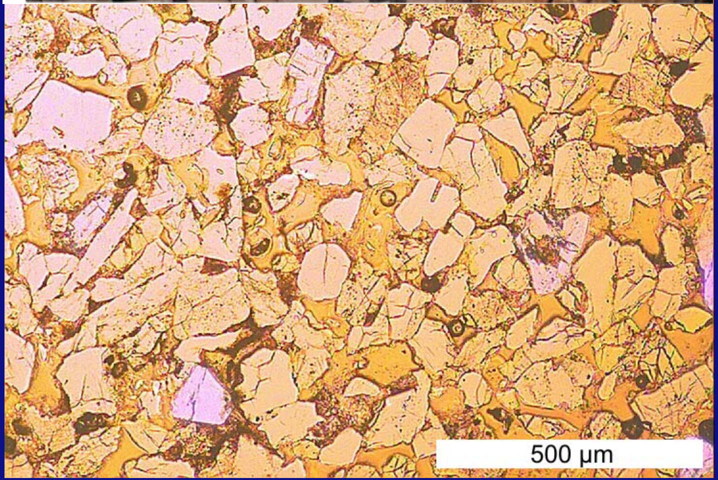


Location of Schwarze Pumpe Power Plant

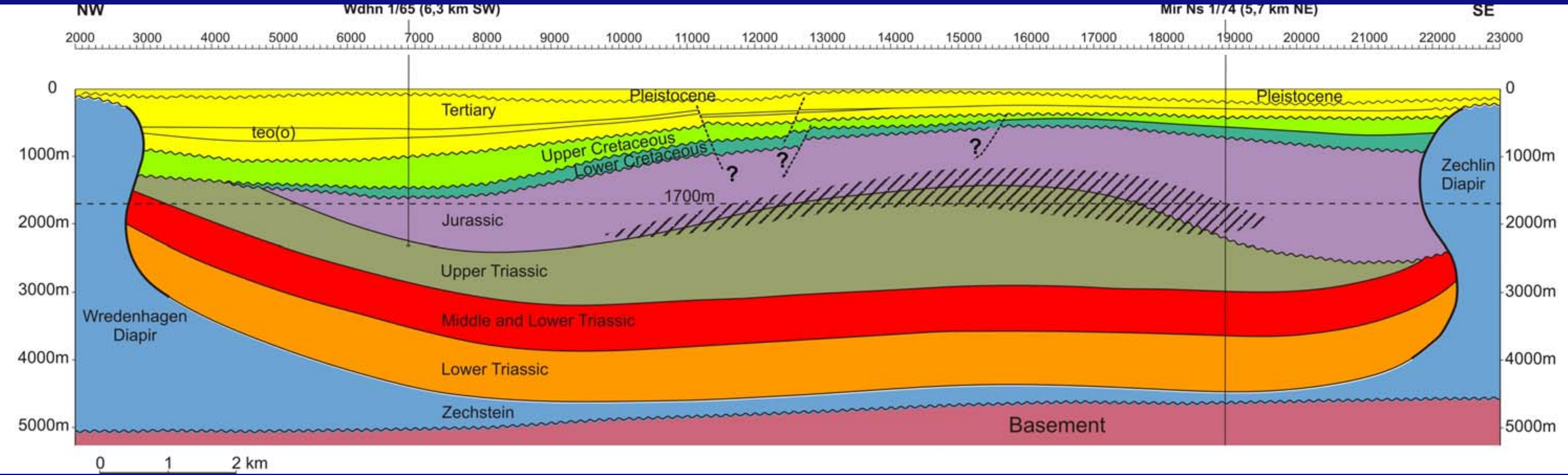


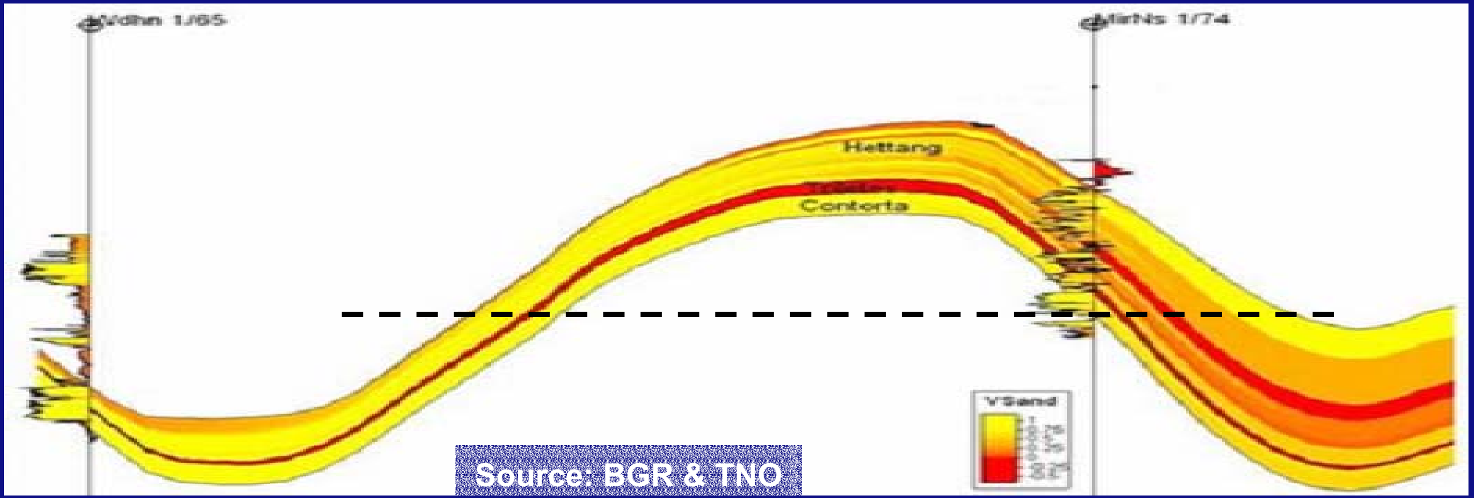
CO_2 injection in the Schweinrich deep saline aquifer



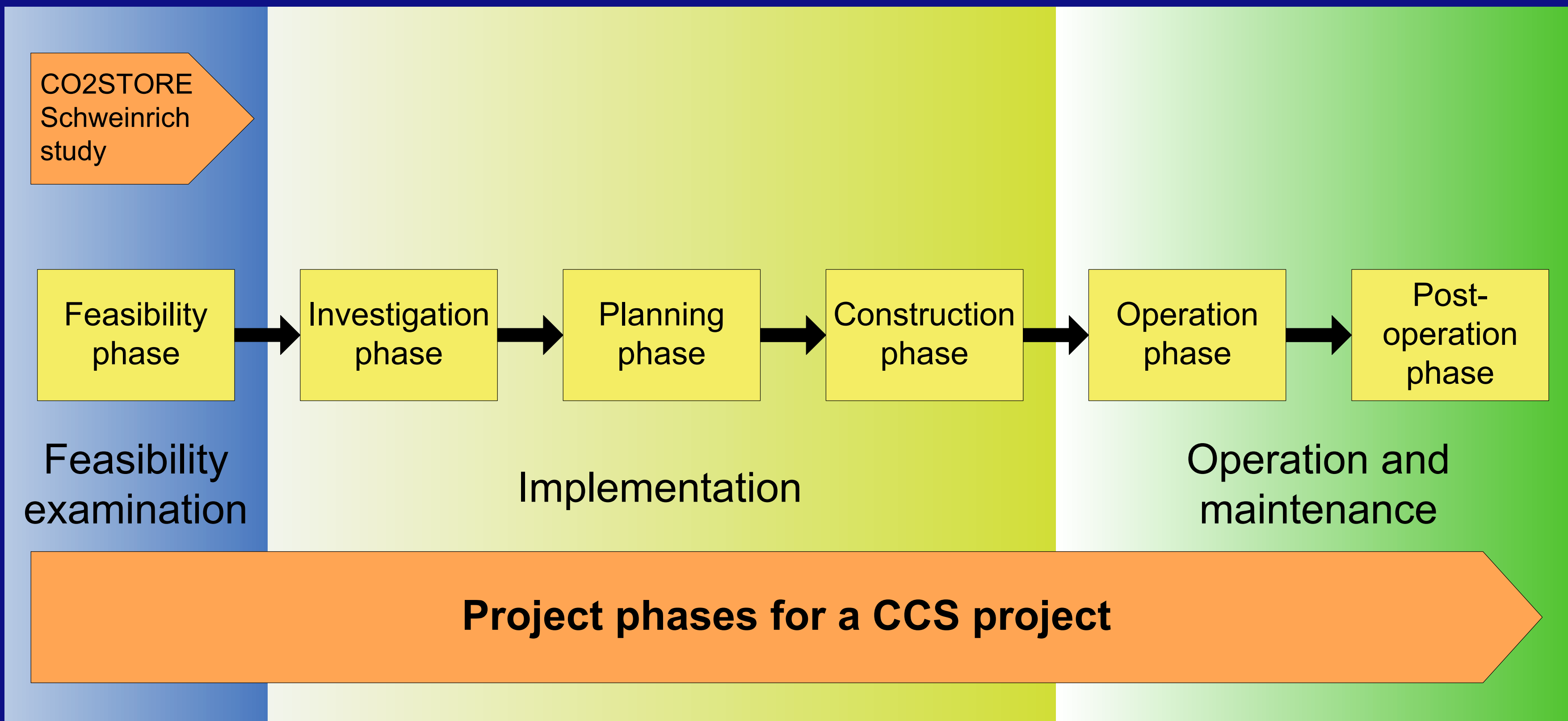


W – E Cross Section





Process chain safety assessment CCS projects



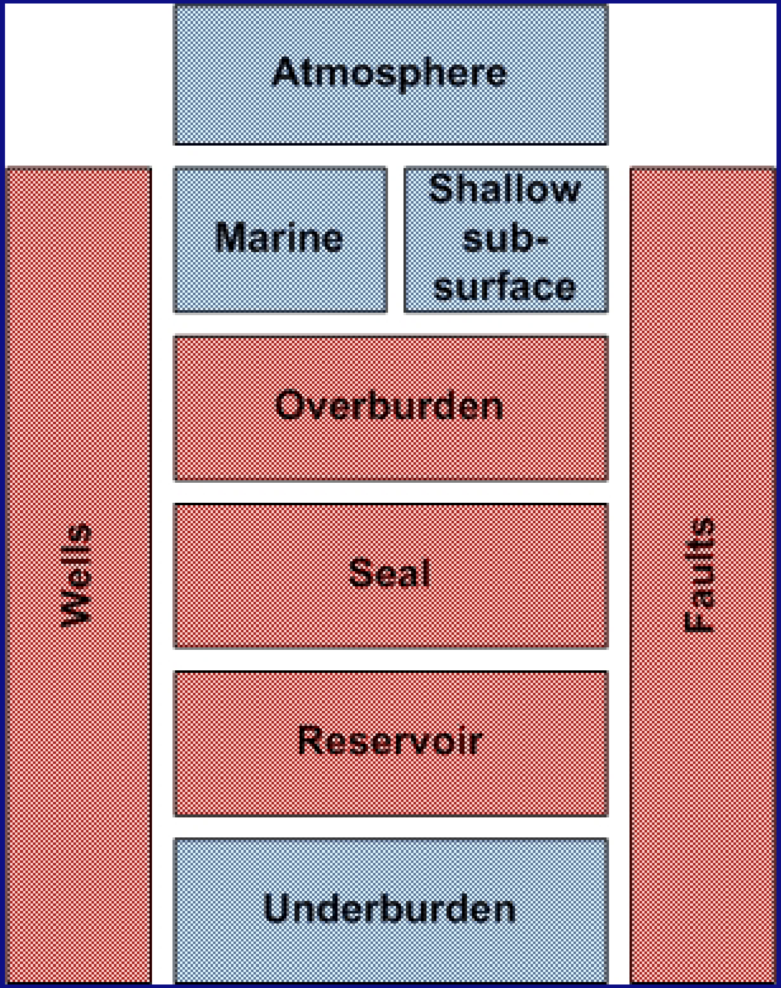
- Safety evaluation
  - based on SAMCARDS methodology + tools
  - assessment of shallow subsurface NOT included
  - stochastics without CO_2 dissolution

Vocabulary

- RISK MANAGEMENT
  - RISK ASSESSMENT
    - RISK ANALYSIS
      - SOURCE IDENTIFICATION
      - RISK ESTIMATION
    - RISK EVALUATION
  - RISK TREATMENT
    - RISK AVOIDANCE
    - RISK OPTIMISATION
    - RISK TRANSFER
    - RISK RETENTION
  - RISK ACCEPTANCE
  - RISK COMMUNICATION

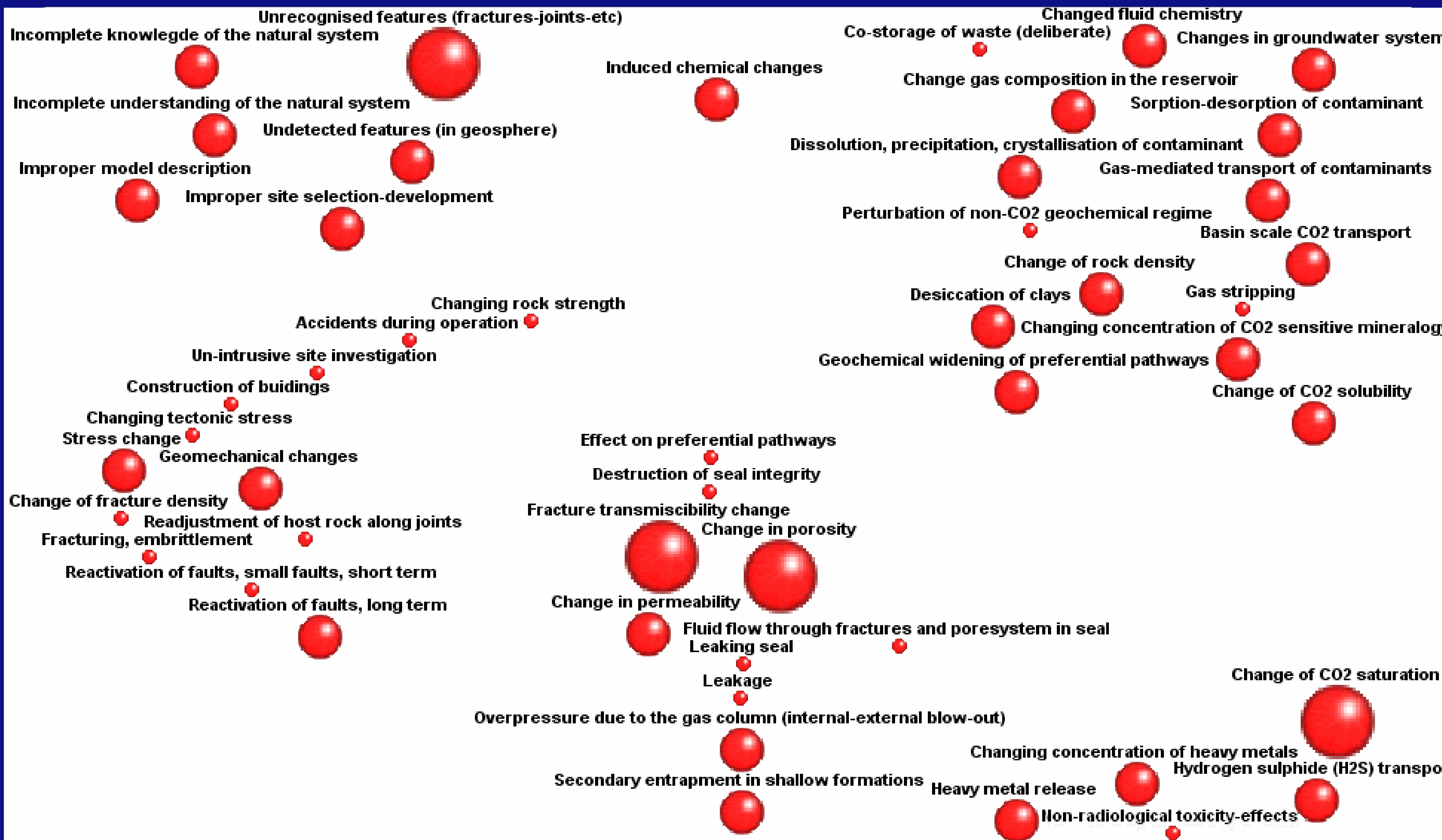
- Risk analysis – Systematic use of information to identify hazards and to estimate the risk.
- Risk evaluation – process of comparing the estimated risk against given risk criteria to determine the significance of the risk.
- Risk assessment – Overall process of risk analysis and risk evaluation.

Evaluation of spatial entities

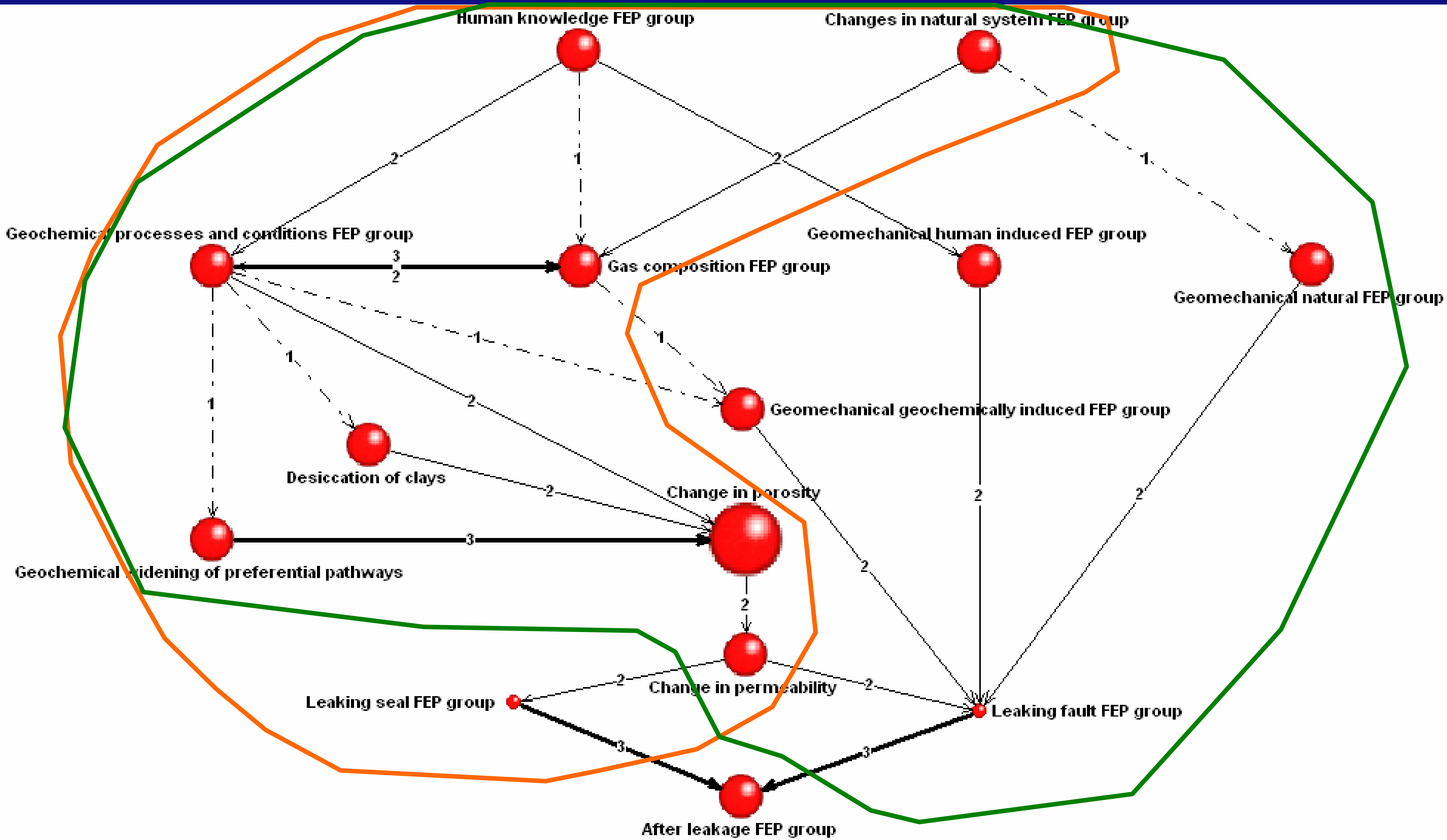


- 1: Reservoir
- 2: Seal
- 3: Overburden
- 4: Faults
- 5: Wells

Safety assessment



Safety assessment



Four scenarios

- 1: Leaking seal scenario
- 2: Leaking fault scenario
- 3: Leaking well scenario
- 4: Reference scenario (base case)

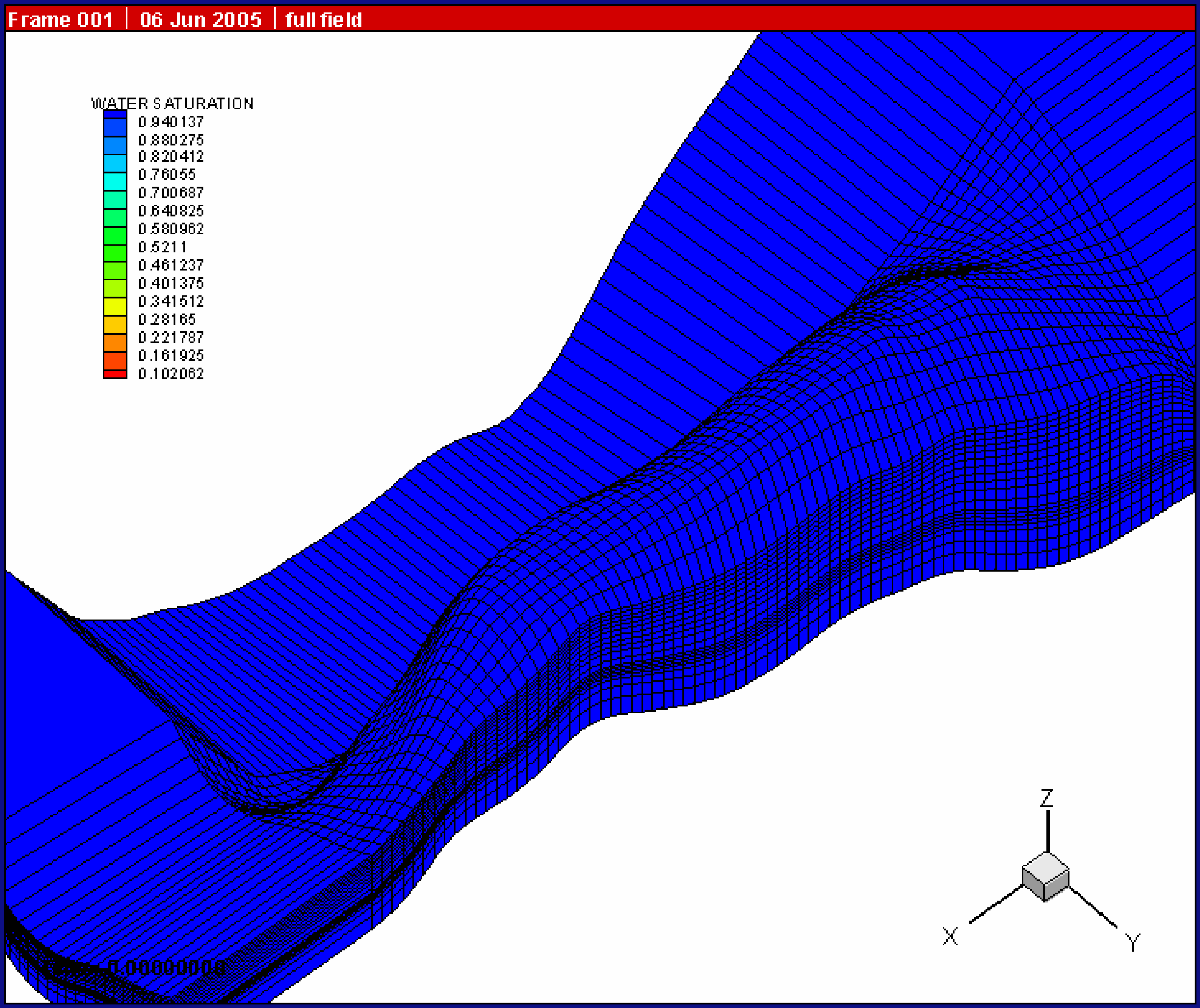
Procedure probabilistic modeling approach (per scenario)

- Calibrate simplified models to fine scale model
- Generate a long list of X stochastic input variables
- Generate 10^X input files (SIMED-II)
- Execute 10^X input files in batch mode
- Analyse results
- Assess CO_2 in Pleistocene sediments
- Evaluate / compare with risk criteria

Calibration to fine scale model

- Similar (upscaled) input variables
- Similar CO_2 spread in time
- Similar reservoir pressures in time

Fine scale model Schweinrich

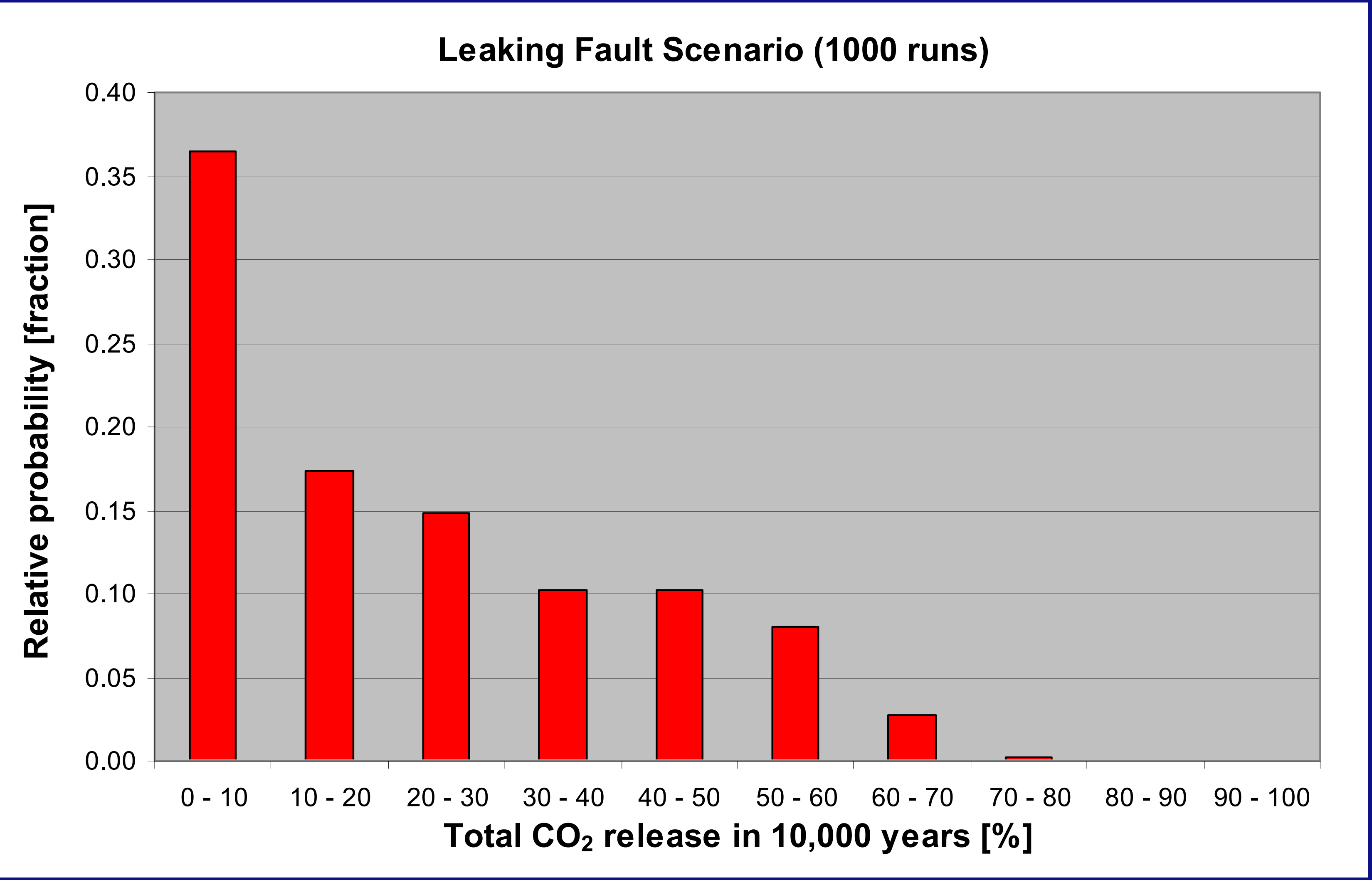


Simplified Layer cake models

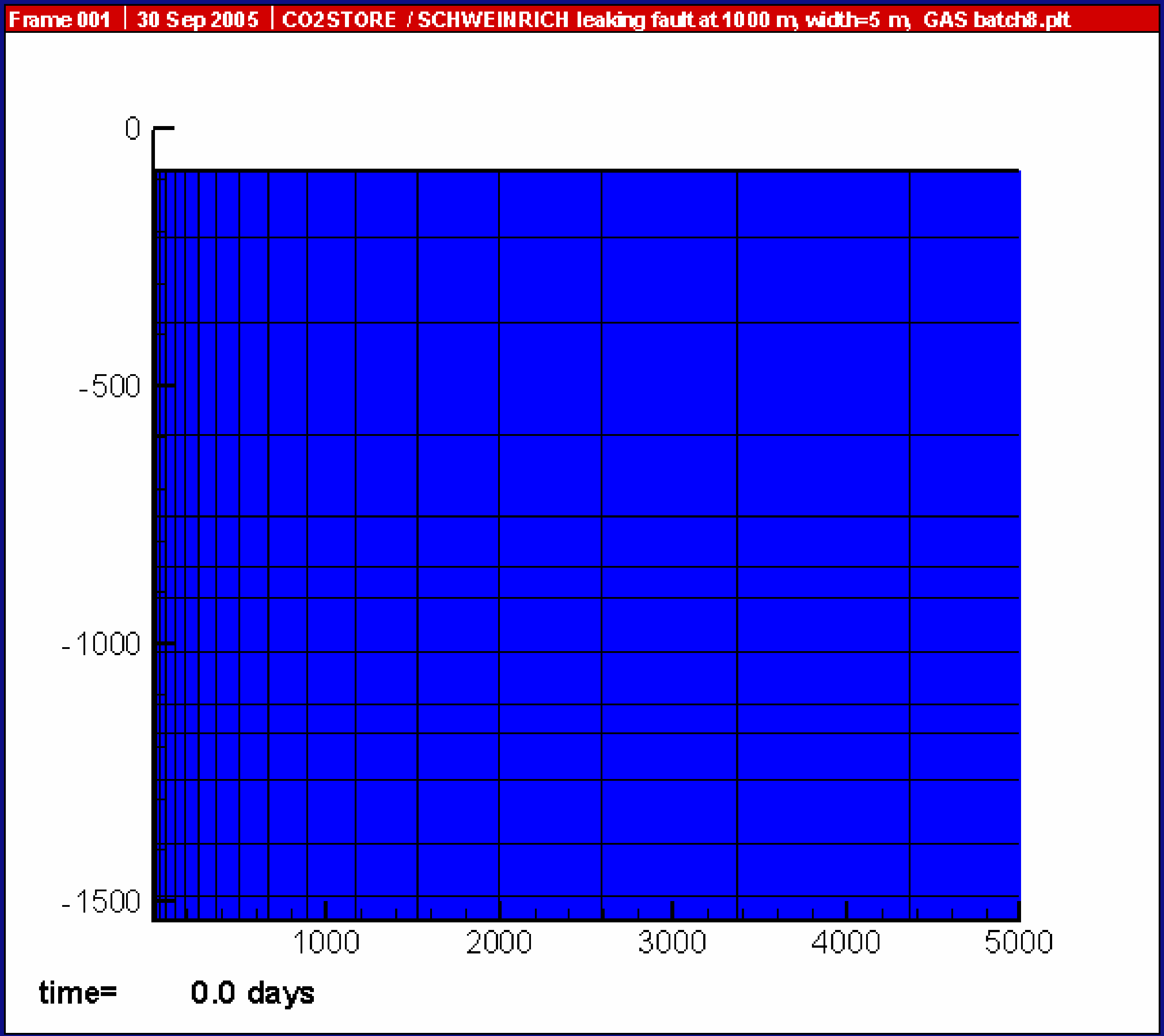
Layer	top	bottom	thickness	rocktype	k_hor	k_vert	porosity	
[#]	[meters]	[meters]	[meters]		[mD]	[mD]	[fraction]	
1	0	164	164	RT5	500	0.01	0.08	Pleistocene mix of gravel, sand, silt, clay and till
2	164	260	96	RT2	500	50	0.25	Tertiary clean sands
3	260	490	230	RT6	1E-05	1E-05	0.03	Tertiary claystones
4	490	700	210	RT5	100	0.01	0.1	Cretaceous limestones
5	700	802	102	RT2	500	50	0.25	Cretaceous sands
6	802	896	94	RT4	250	0.001	0.06	Middle Jurassic siltsones
7	896	925	29	RT2	500	50	0.25	Middle Jurassic sandstones
8	925	1108	183	RT4	250	0.001	0.06	Lower Jurassic siltstones
9	1108	1130	22	RT2	500	50	0.25	Lower Jurassic sandstones
10	1130	1220	90	RT3	1	0.001	0.05	Lower Jurassic siltstones
11	1220	1308	88	RT6	1E-05	1E-05	0.03	Lower Jurassic claystones
12	1308	1466	158	RT1	500	5	0.15	Lower Jurassic sandstone
13	1466	1509	43	RT3	1	0.001	0.05	Uppermost Triassic siltstones
14	1509	1564	55	RT1	500	5	0.15	Uppermost Triassic sandstones

Reservoir (orange)
Interpolated thickness of top of Schweinrich anticlinal structure (yellow)

Analysis of results



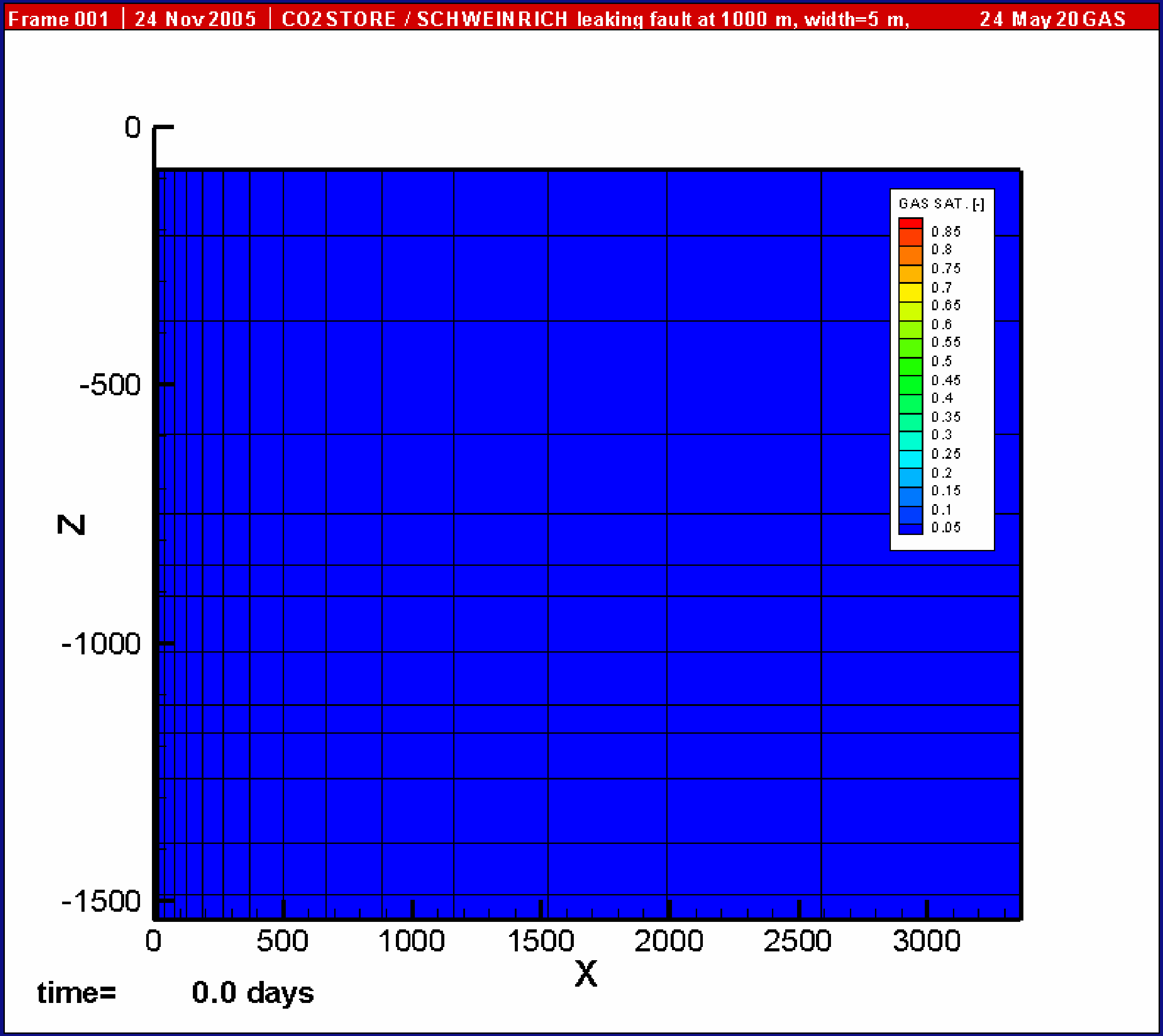
Reference scenario



Reference scenario

- No leakage / release from seal
- No safety hazard

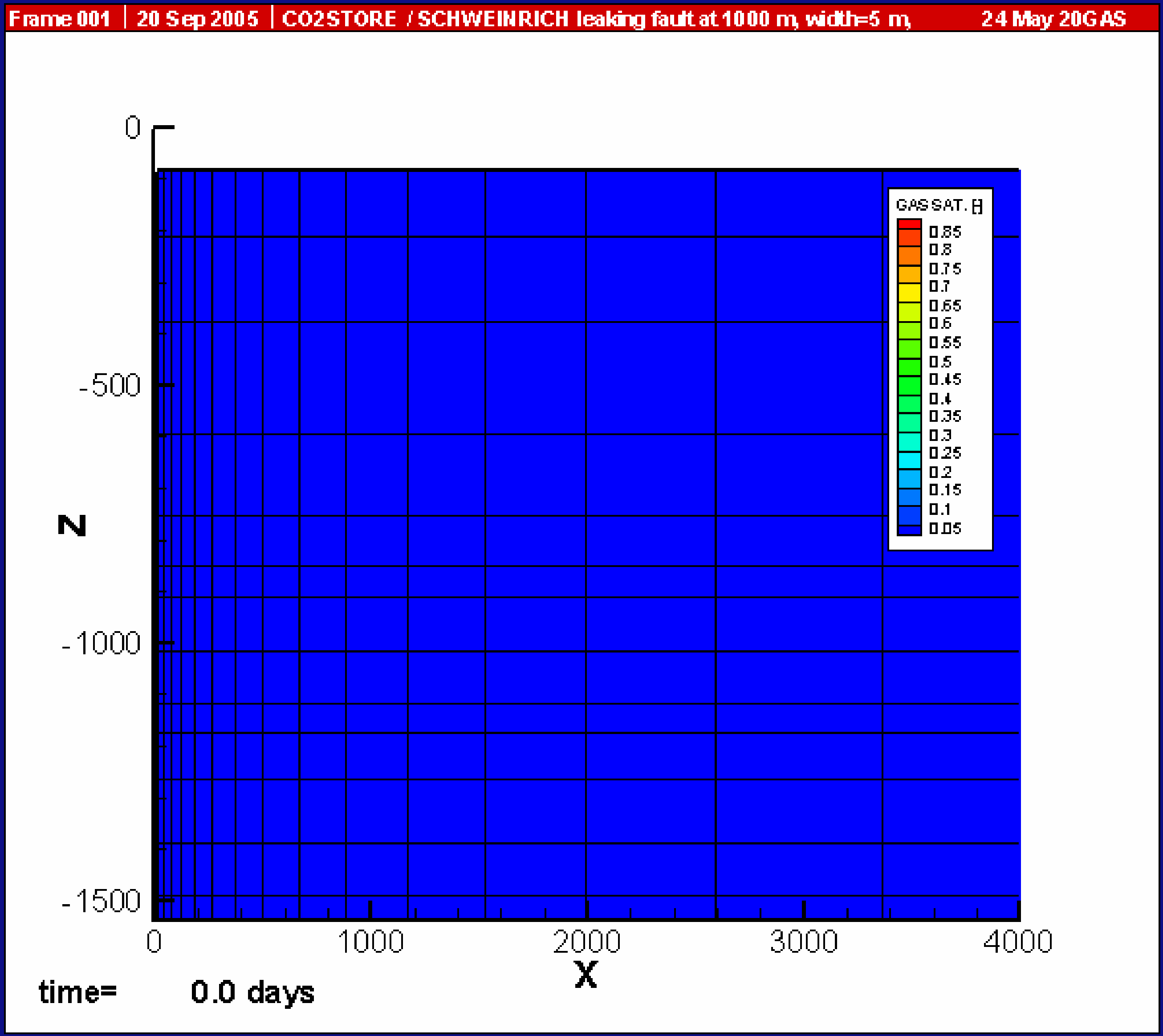
Leaking seal scenario



Leaking seal scenario

- Release from reservoir into overburden
- However CO_2 does not reach shallow subsurface
- No safety hazard

Leaking well scenario

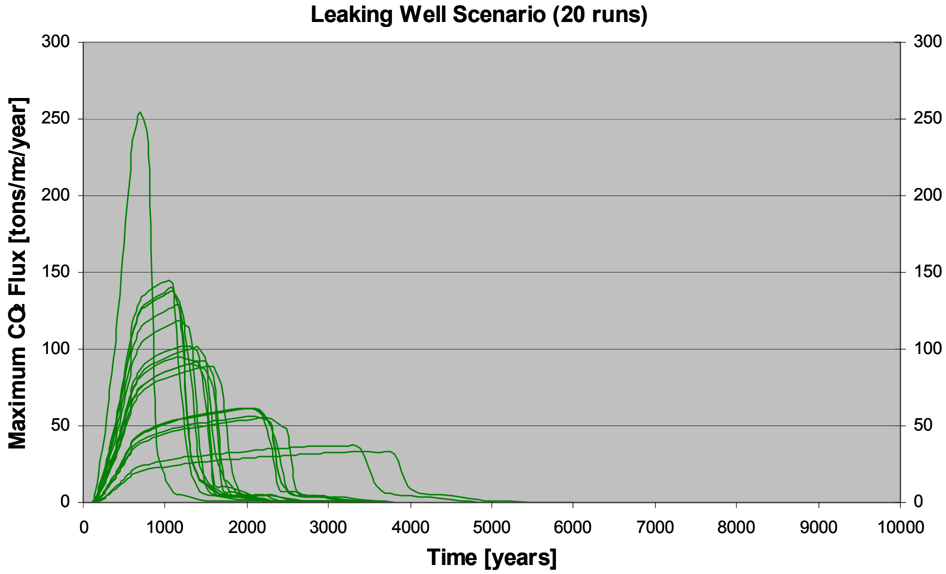


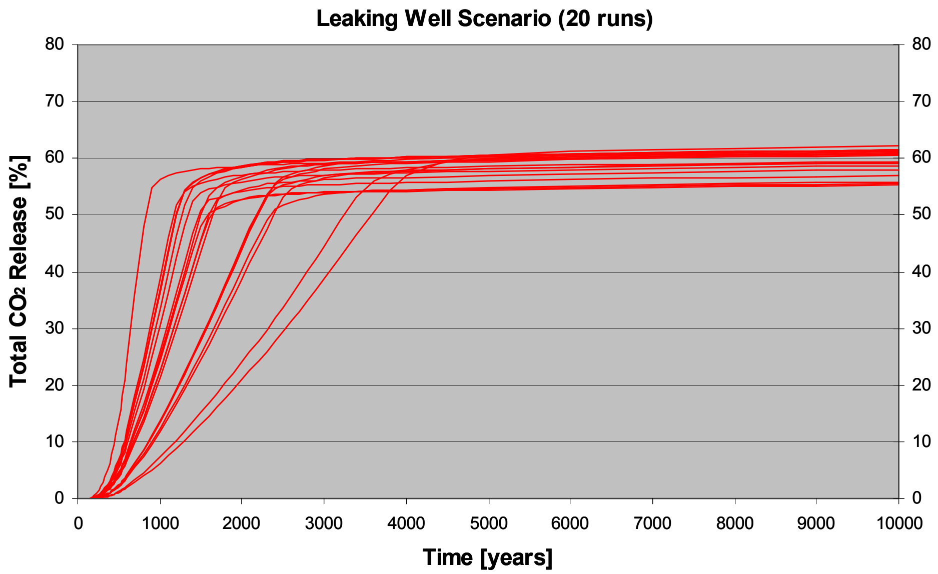
Leaking well scenario

- High leakage rates / fluxes
- About 60 % released in 3000 years

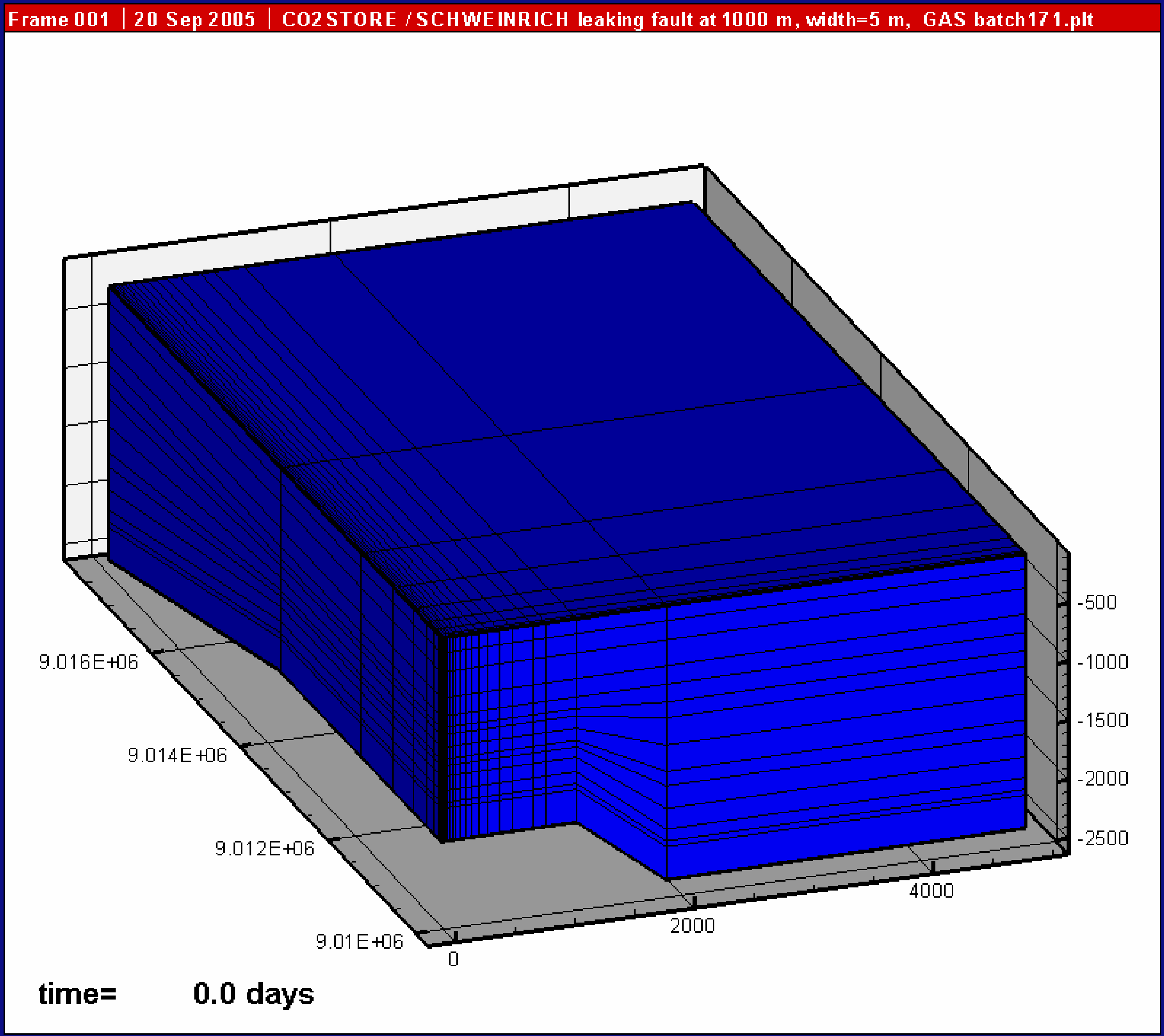
BUT:

- No existing/historical wells penetrate the reservoir
- Injection wells can be constructed with latest technology
- In reality mitigation measures will be taken at early stage

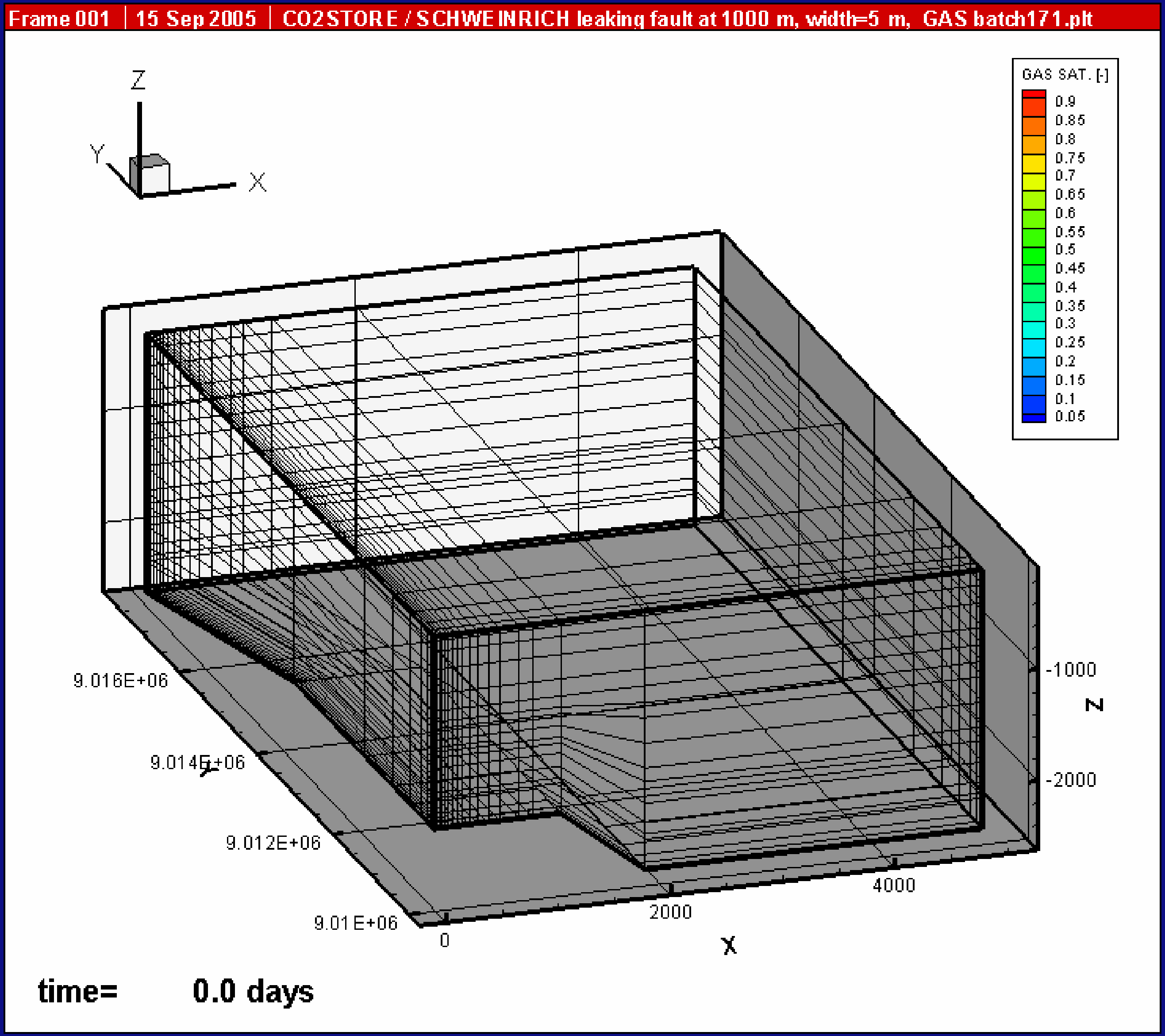




Leaking fault scenario



Leaking fault scenario

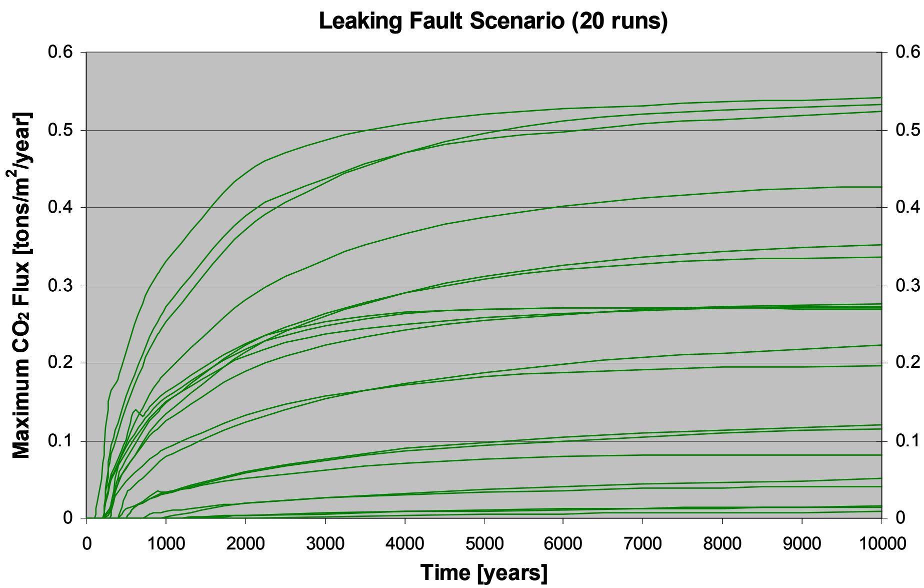


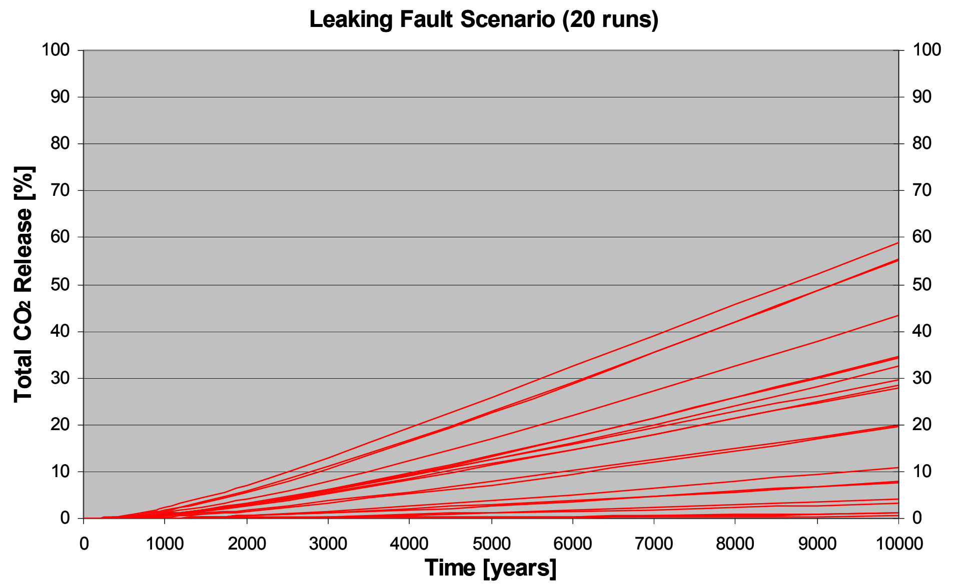
Leaking fault scenario

- High variability in outcome / results
- Intermediate leakage rates / fluxes
- Fluxes compare well to natural analogues (Streit & Watson, 2004)

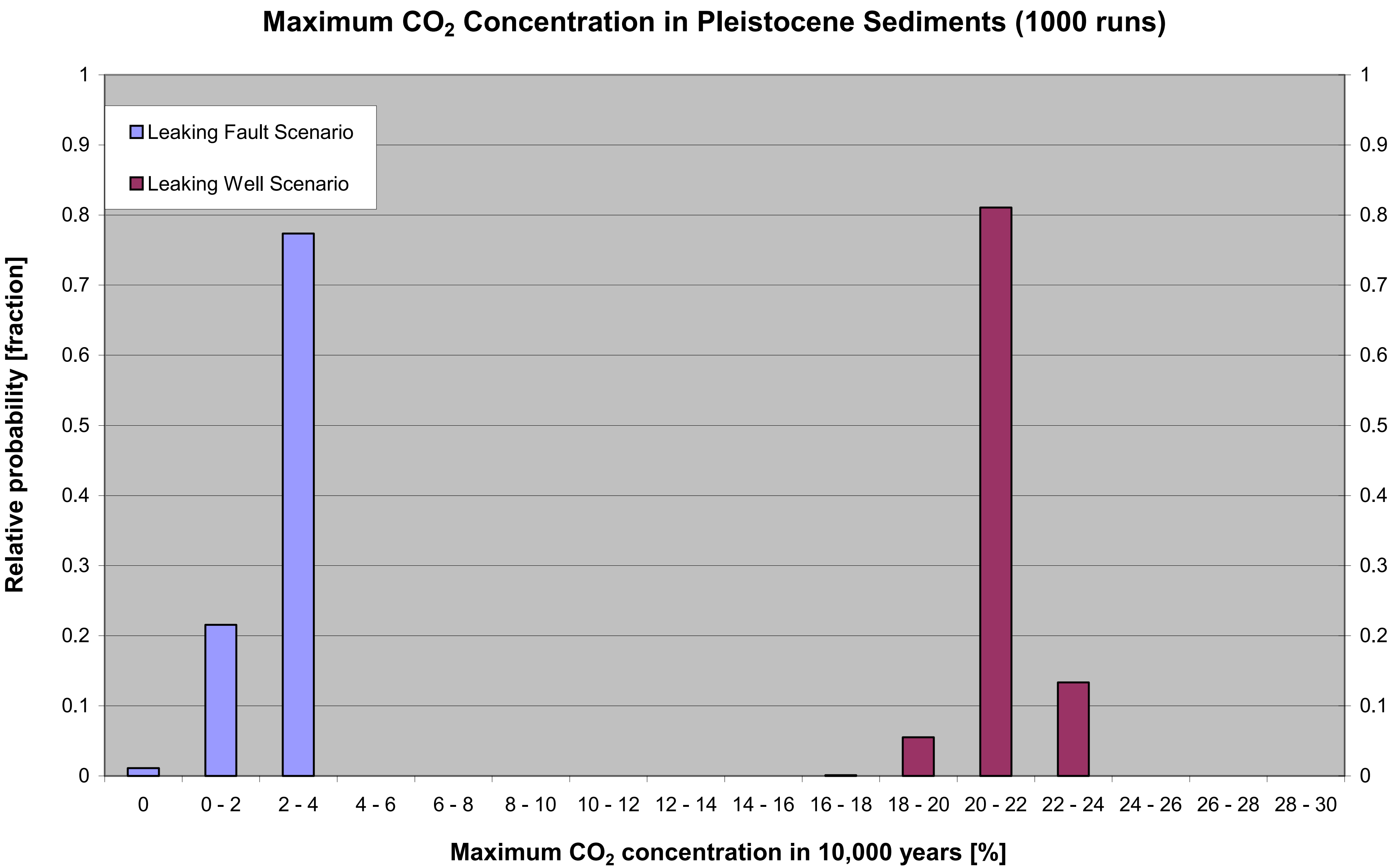
BUT:

- No proven faults from reservoir to surface
- Sealing properties of faults unknown (too large range applied)





Safety evaluation (I)



Safety evaluation (II)

Saripally et al. (2002):

TABLE 1. CONSEQUENCE VALUE TABLE FOR HAZARDS.
((X) IS CONCENTRATIONS OF CO_2 ; [X] IS MAGNITUDE OF CONSEQUENCE)

Media*	*Consequences*		
	Severe [1]	**Moderate [0.5]**	**Low [0.1]**
Air (280 ppm)	lethal, habitat loss (>10%)	Injuries (> 5%)	Discomfort (> 1%)
Bldgs (280 ppm)	Injury, evacuation (> 5%)	Irritation, discomfort (> 2%)	Noticeable, no harm (> 1%)
Groundwater (10^{-4} M or 0.2%)	Acidity, well corrosion, irrigation loss (> 6%)	Mild acidity and corrosion (> 2%)	Elevated, low acidity without significant impacts (> 0.2%)
Surface water (10^{-5} M; 0.022%)	Acidity, CO_2 explosion, fish kills (> 2%)	Higher acidity, mild toxicity Effect on irrigation (> 1%)	Elevated, low acidity with no significant impacts (> 0.022%)
Soils (1-2%)	Low pH, tree kills, animal deaths (> 8%)	Moderate acidity, tree/ crop/soil cover loss (> 3%)	Mild suppression in pH with no significant impacts (> 2%)
Biota (10^{-5} M)	O_2 depletion, lethal (>4%)	Injure life functions (> 2%)	Mild toxicity (> 0.5%)

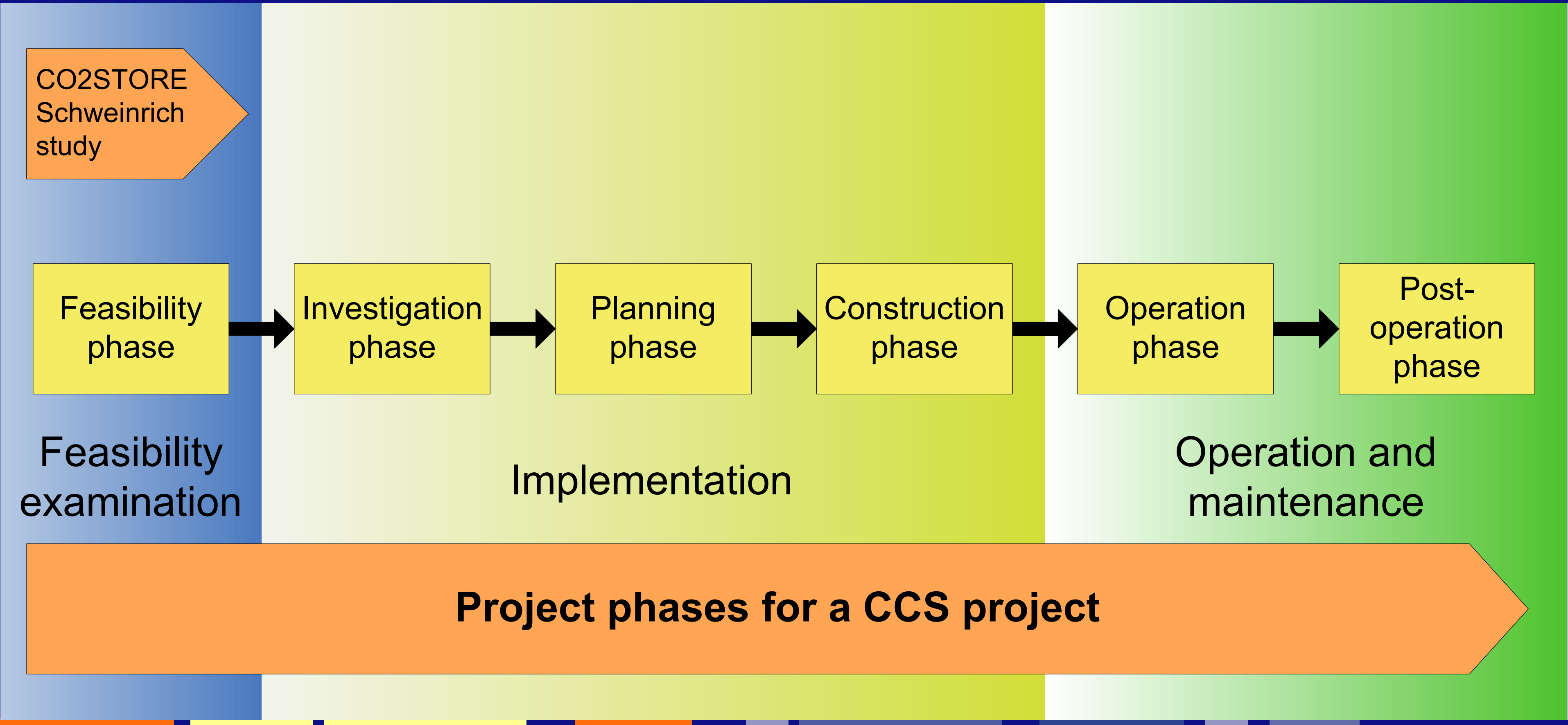
*Normal concentration shown for each medium within ( ).

Conclusions from safety analysis

- Adverse effect for leaking fault scenario
- Severe / lethal effects for leaking well scenario
- BUT:
  - Leaking well scenario unrealistic
  - Range of model input parameters too large
  - Faults need further investigation
    - Location
    - Vertical extent
    - Properties

Upcoming work

- Injection strategy
- Fault characterization



Acknowledgements

- EU CO2STORE project and its partners, in particular:

- Vattenfall
- BGR
- BRGM
- TNO
- BGS

"The Schweinrich structure", a potential site for industrial scale CO_2 storage and a test case for a safety assessment in Germany

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Abstract

This paper reports on the first step towards a health, safety and environment (HSE) performance assessment of the potential future storage of CO_2 in the aquifer anticlinal structure Schweinrich, located in Germany. The performance assessment was conducted under the European 5[th] Framework project CO2STORE, as one of the demonstrations of best practices related to geological storage of CO_2.

The identification of risks associated with geological storage of CO_2 requires methods that can analyse and assess the hazards. The purpose for this study has been to evaluate the performance assessment methodology as a suitable method to use for the safety assessment of CO2 storage projects, i.e. evaluation of the Health, Safety and Environmental (HSE) effects with CO_2 storage. For this reason the methodology has been applied to the case study Schwarze Pumpe. Being a case study restricts the work from a feasibility study point of view, *i.e.* to identify the key safety factors that could be examined further in the case an actual CO_2 storage project would be considered at structure Schweinrich. Evaluation criteria for the study were CO_2 leakage levels from natural analogues. The study is based on the current available data, gathered in prior surveys, and on the use of simplified models. Results should be interpreted as preliminary, however, the results point out clearly which additional data should be gathered related to the long-term storage performance in case the site would be investigated further.

Introduction

The assessing and managing of risks with geological storage of CO_2 is a relatively new area of research. Thus, no thorough knowledge base to extract experiences from exists. This has put focus on learning from studies conducted for other substances with similar but still different risks. From such studies a thorough safety assessment method called performance assessment has been adopted. However, based on the experiences from natural gas storage, several HSE risks associated with subsurface storage can be managed with strict regulations on matters as site selection and well construction. Thus, in addition to the performance assessment evaluation, it is also important to establish guidelines for matters that can be included in a future safety standard for CO_2 storage.

The methodology has been applied to the case study Schwarze Pumpe, with the potential storage Schweinrich. This structure is located in the northeastern region of Germany, about 100 km north-west of Berlin, at a depth of approximately 1,600 m. It was selected as the most suitable candidate site in the Northeastern German Basin for underground storage of 400 Mtons of CO_2. This corresponds to the amounts emitted from a large power plant such as Schwarze Pumpe during a period of 40 years. The Schwarze Pumpe plant is located in Brandenburg (Niederlausitz) 150 km southeast of Berlin and operated by Vattenfall Europe Generation.

The Schweinrich structure covers an area of about 100 km^2 and its estimated storage potential is between 500 and 840 Mt CO_2 ([1]). Its anticlinal structure (Figure 1) contains two main reservoirs: the shallowest in the Lower Jurassic (Lias, Hettang) and the deepest in the Upper Triassic (Keuper, Contorta). The total reservoir thickness ranges between 270 and 380 m and consists of several layers of fine-grained, highly porous sandstones. The sandstones are overlain by several hundred metres thick, Jurassic, clayey formations that form the cap rock of the storage system.

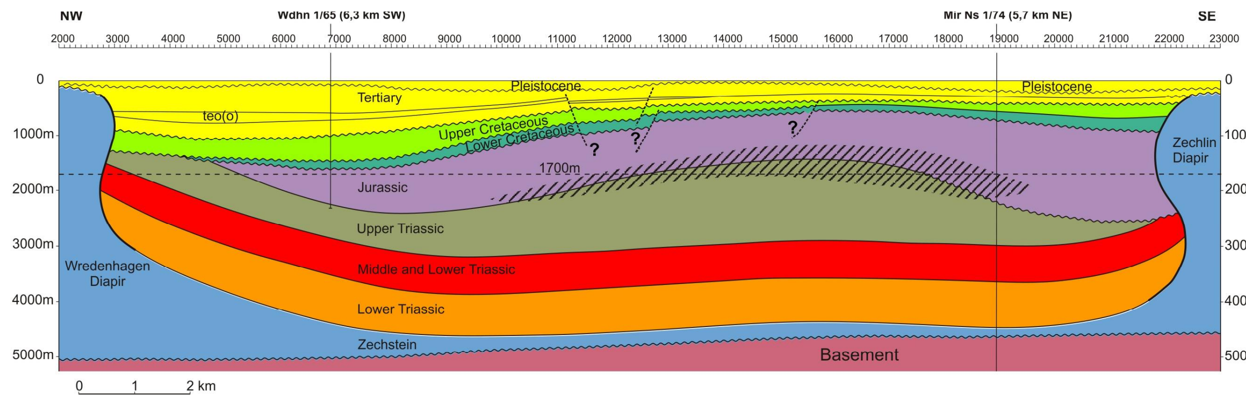

Figure 1. Cross-section of the Schweinrich anticline between two salt diapirs. The hatched area indicates the reservoir and storage position.

The current geological model of Schweinrich is based on the available information from 2D seismic lines, mostly gathered in the early 70's, and exploration wells near the structure. No wells penetrate the anticline. Refinement of the model combined with new data as it is gathered will continue throughout the performance assessment process. Considered as an example, the structure Schweinrich has been used as a representative, generic model, also valid for other potential storage sites in Northeast Germany.

Methodology

The purpose for the performance assessment study has been to evaluate the methodology as a suitable one to use for the safety assessment of CO_2 storage projects, i.e. evaluation of the Health, Safety and Environmental (HSE) effects with CO_2 storage. Moreover, the HSE effects from CO_2 storage have been evaluated from a feasibility point of view, thereby identifying and evaluating the key safety factors at an early stage. These safety factors could then be examined further in a follow-up project. Hence, for the study presented here, the results from the simulation models are compared against the CO_2 leakage levels from natural analogues (*e.g.* reported in [2]),.

The FEP analysis of the Schweinrich structure evaluates potential HSE factors within the next 1000 years after start of CO_2 injection. However, as hazards may occur as a consequence of the identified safety factors, the simulations are run for additional 9000 years. The outcome of the safety scenarios was expressed as the maximum concentration and maximum flux of CO_2 in the pore system in the shallow subsurface, Pleistocene sediments. The Pleistocene is represented by the topmost subsurface layer in the simulation models. No outcome was given with respect to groundwater deterioration and mobilisation of heavy metals, since no modelling of the flow and fate of CO_2 in the shallow groundwater compartment was conducted. This is planned for the next phase of the performance assessment.

Identified Safety Scenarios

Four safety scenarios were identified through combinations of FEPs.:

1. *Reference scenario*: No failure to the containment zone occurs. This scenario, considered to be the most likely, reflects the CO_2 injection process and the flow and fate of CO_2 in the reservoir after abandonment of the site.
2. *Leaking-seal scenario*: The leaking seal scenario reflects the CO_2 injection process and the flow and fate of CO_2 through the caprock due to geochemical deterioration. The reason for possible release of CO_2 through the caprock might be due to small amounts of carbonates and thin marl layers in the shale layers that form the caprock.
3. *Leaking-fault scenario*: The leaking fault scenario reflects the flow and fate of CO_2 through a fault system running from the caprock to the shallow subsurface. The interpretation of the existing seismic lines over the Schweinrich structure are not conclusive due to the poor data quality, but the existence of fault systems in the Mesozoic and Caenozoic overburden cannot be ruled out (Figure 1).. At this moment, the constituency of such a fault system and its permeability are simply unknown and require additional data acquisition.
4. *Leaking-well scenario*: The leaking well scenario reflects the CO_2 injection process and the flow and fate of CO_2 along the well trajectory due to several events and processes. The drilling and completion schedule of the wells were unknown at the time of FEP evaluation. Therefore a ”generic” abandoned old well safety scenario based on a previous study was applied ([3]). This scenario was chosen mainly to evaluate the differences in outcome with the above scenarios. It must be noted, that no abandoned wells penetrate the Schweinrich structure and that all possible precautions can still be taken for future injection wells making the occurrence of leaking wells highly unlikely.

Model Development

The safety scenarios present the possible future flow and fate of CO_2 for 10,000 years after injection. The scenarios are represented with simplified 2D and 3D models with stochastically varied input parameters using the multi-component flow simulator SIMED-II. The advantage of using simplified models is their limited run time, allowing a large number of stochastic input combinations to be modelled (Table 1). The simplified models have been calibrated to a detailed, deterministic, fine-scaled model of the Schweinrich structure over an injection period of 40 years (Figure 2). The driving force for CO_2 to ascend is mainly buoyancy.

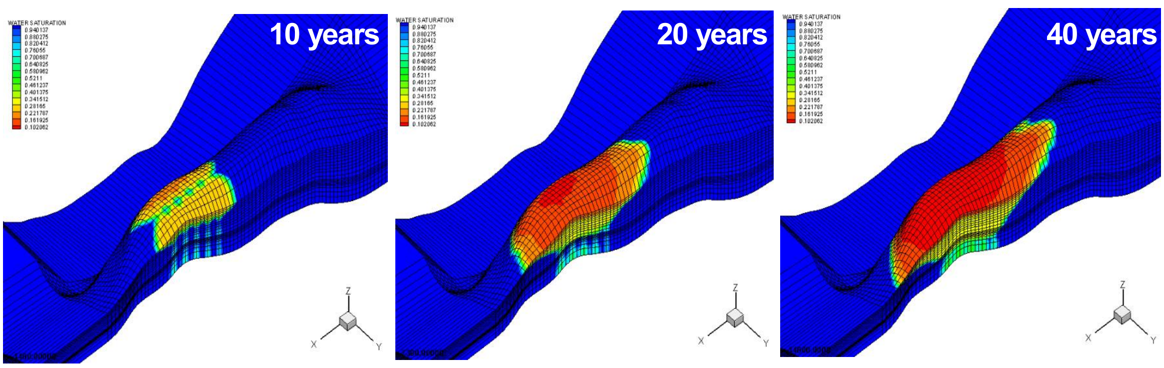

Figure 2. Development of the CO_2 Gas saturation in time (3D deterministic model).

Table 1: Number of grid blocks of different Schweinrich simulation models

	# grid blocks X	# grid blocks Y	# grid blocks Z	Time per run
Simplified radial model (2D)	25		16	22 seconds
Simplified cartesian model (3D)	20	21	17	20 minutes
Deterministic 3D model	84	40	22	2 days

Thousand simulations were carried out for each safety scenario. The variation of the stochastic input parameters, such as permeability, was constrained based on related studies ([4] and [5]). In case of uncertainty on input parameters that were not varied stochastically, generally worst case values were selected. Moreover, the CO_2 dissolution in the aqueous phase as well as capillary entry pressures were not taken into account. A few sensitivities were run including CO_2 dissolution in order to evaluate the effects on model outcome. Changes in flux and concentration with respect to the case without CO_2 dissolution varied between 2 and 25% in flux and between 0 and 7% in concentration for high and low release rates respectively. For these reasons the outcome expressed as the maximum flux of CO_2 in the shallow subsurface Pleistocene sediments are biased towards the worst case scenarios.

Simulation Results

The reference scenario and the leaking-seal scenario show no increase of CO_2 in the Pleistocene sediments in 10,000 years. The CO_2 escaping from the seal is sufficiently held up and spread over time so as not to reach the shallow subsurface (Figure 3).

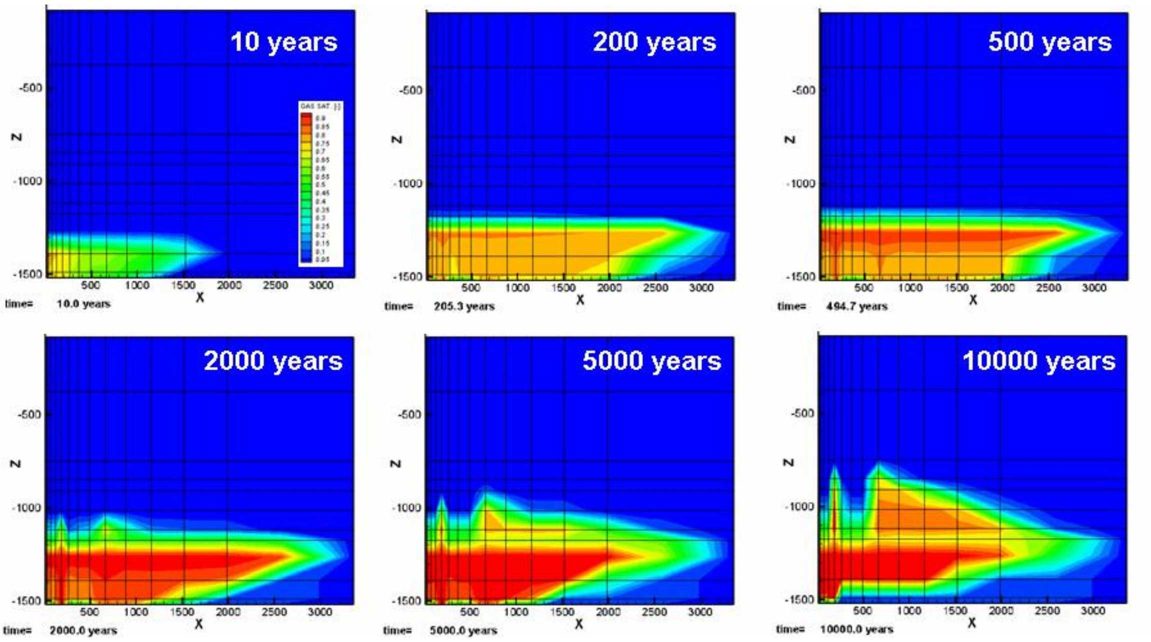

Figure 3. Cross-sections of the simplified 2D flow model presenting subsurface CO_2 saturation in the leaking-seal scenario. The CO_2 injection is positioned on the left-hand side of the sections.

The leaking-fault scenario, i.e. where it is assumed that the anticipated fault extends from the caprock to the shallow subsurface, shows a relatively slow migration process of CO_2 along the fault plane. An example of one of the simplified model runs is presented in Figure 4. Maximum CO_2 fluxes vary between 0.00025 and 0.62 tonnes/year/m^2 in the Pleistocene sediments (Figure 5). These values are comparable to leakage rates from natural CO_2 accumulations in Europe and Australia ([2]). The maximum CO_2 concentration in the groundwater of the shallow subsurface Pleistocene sediments is less than 4% at a depth of 80 meters. This is close to the lower limit of deleterious effects on plant health and yield of 5 % CO_2 ([6]). The effects of the fluxes and concentrations on the shallow subsurface ecosystem will be investigated in a later phase.

The ranges in outcome show that further research on the existence of the faults through the caprock is required. Such a study would be a prioritised task in the case an actual CO_2 storage project would be considered at structure Schweinrich. The location of the faults can be investigated by running a 3D seismic survey, and the fault properties can be determined by conducting a specialist study on the local fault permeability. Note that the simulation results should be interpreted as worst case scenarios, especially since the presence of faults cutting the caprock has not been established yet.

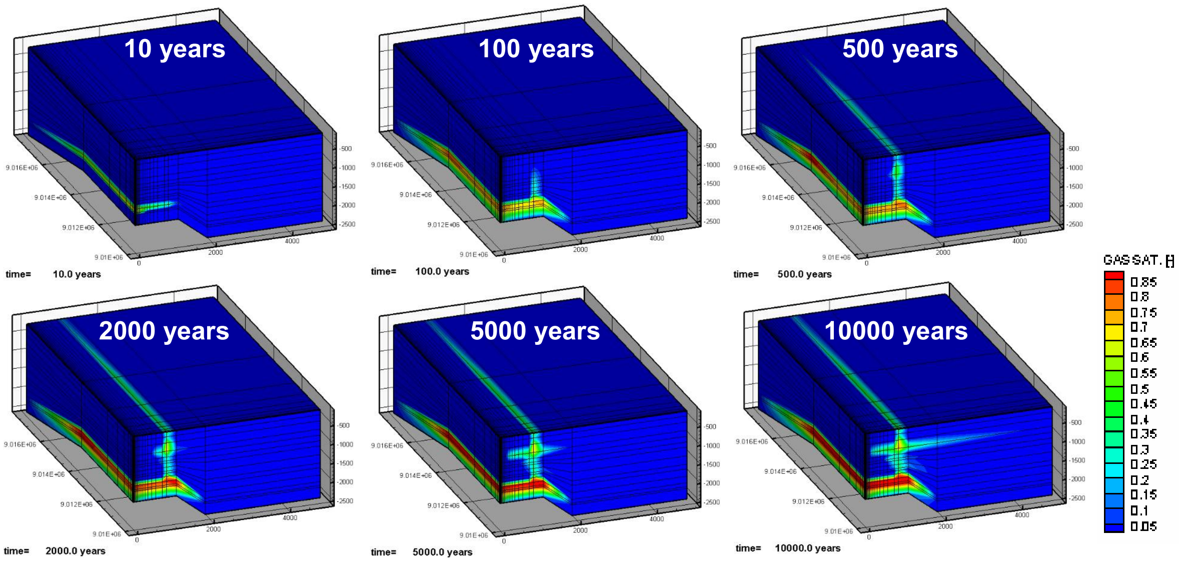

Figure 4. Quadrant of the simplified 3D flow model presenting subsurface CO_2 saturation in the leaking-fault scenario. The CO_2 injection is positioned in the lower left corner. Note that this scenario assumes that a permeable fault from the caprock to shallow subsurface is present, which can NOT be confirmed at this stage. More data (i.e. seismic data) is needed to explore the extent of the fault system.

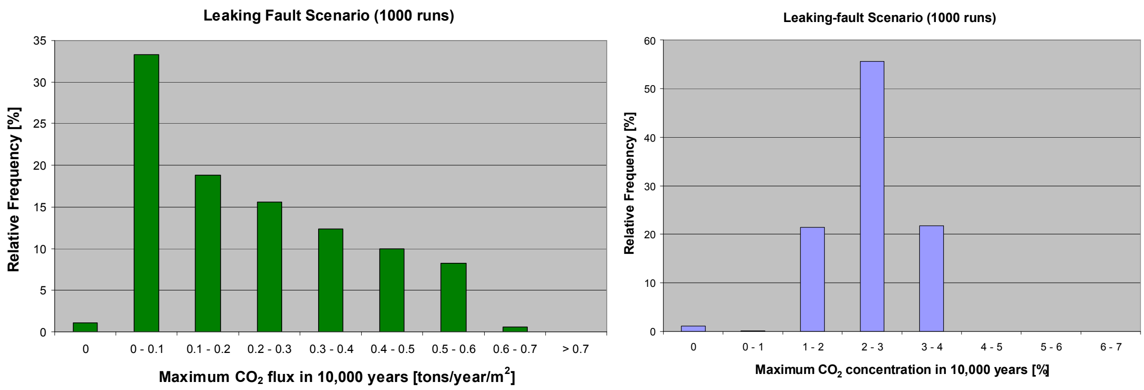

Figure 5. Simulated maximum fluxes and maximum concentrations in local groundwater for the leaking-fault scenario (assuming there is a leaking fault). Results were acquired without modelling CO_2 dissolution in the aqueous phase.

The leaking-well scenario (Figure 6) is the most dramatic, with average release percentages of 60% of the total amount of injected CO_2. The release of CO_2 is directly proportional to the permeability of the well zone, which increases in time as a result of various FEPs that apply specifically to this scenario. To be noted is that the study is based on data of an existing abandoned old well, i.e. not the quality to be expected from a purpose designed abandoned CO_2 injection well.
Maximum fluxes in the Pleistocene vary between 15 tonnes/year/m^2 and 350 tonnes/year/m^2 .This scenario is unrealistic since new wells at Schweinrich would have a better design. Also, high leakage rates in the well zone could be detected early. In that case mitigating actions could be taken to avoid further leakage. Most likely, the injection wells would be placed at the lower flanks of the Schweinrich structure. As mentioned previously, this scenario was run mainly to evaluate the differences in outcome with the above scenarios.

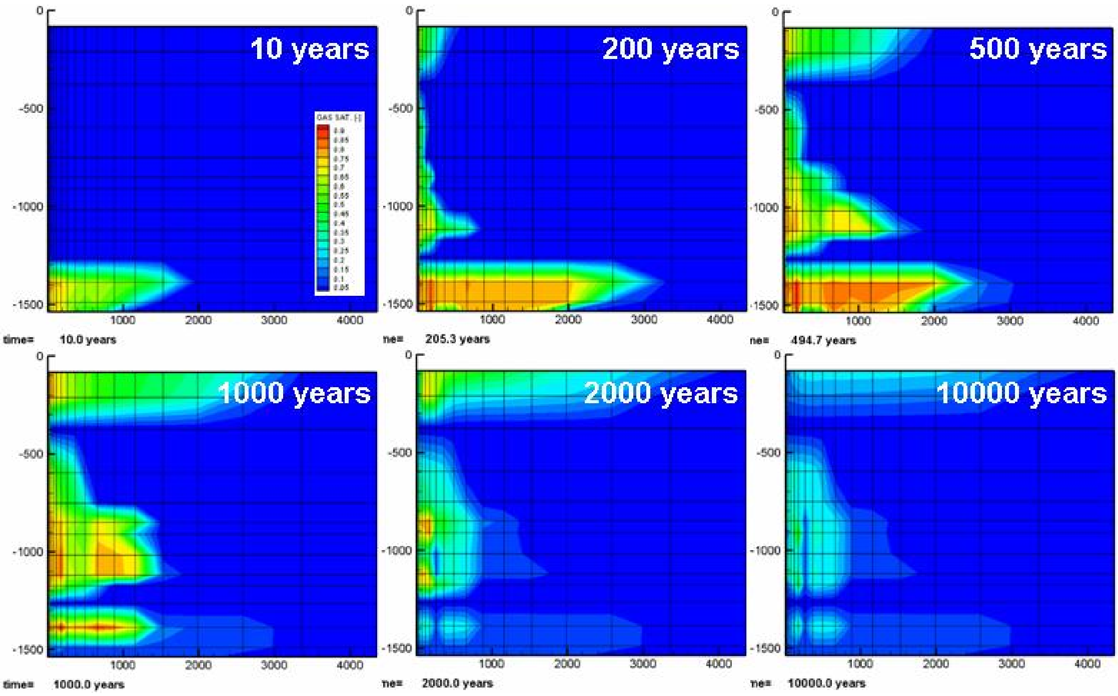

Figure 6. Cross-sections of the simplified 2D leaking-well scenario, presenting the subsurface CO_2 saturation.

Conclusions

The methodology evaluation points out that the performance assessment methodology is a powerful tool for use in safety assessments of CO_2 storage projects. This first HSE performance assessment of the Schweinrich structure was conducted on the basis of existent and limited inputdata, available before a commercial site exploration. Using simplified models, the reference scenario and some worst case scenarios have been analysed. The outcome is biased towards worst case scenarios because of the uncertainty on the input parameters and the use of simplified models. The results are preliminary, given the ongoing data-gathering process and refinement of the geological model. The performance assessment points out clearly which additional data should be gathered related to the long-term storage performance in case the site would be investigated further.

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Schweinrich Case Study

Breakout Group Feedback

Case Studies

- Four performance assessment studies to review
  - Gippsland, Latrobe Valley, Australia
  - Mountaineer, Ohio, USA
  - Weyburn, Saskatchewan, Canada
  - Schweinrich, Germany
- Review in breakout groups

Aims of Case Study Review

- Assess each case study
  - How robust is the data base used?
  - How robust is the approach used?
  - How robust are the assumptions used?
  - How confident are we in the results?
- What we can confidently say about the performance assessments
- How we can use the results to build confidence in the long term storage performance

Gippsland	Mountaineer	Weyburn	Schweinrich
Andy Rigg	Joel Sminchak	Malcolm Wilson	Rob van Eijs Sara Eriksson
Wim Turkenburg	Larry Myer	Sevket Durucan	Tony Espie
Jonathan Pearce	Anna Korre	Elizabeth Scheehle	John Gale
Ferhat Yavuz	Nerraj Gupta	Mike Stenhouse	Olivier Bouc
Karou Koyama	Scott Truesdale	Rajesh Pawar	Kenneth Bogden
Tom Grieb	Jean Phillipe Nicot	Robert Budnitz	Dick Rhudy
Brian McPherson	Brent Lakeman	Carolyn Preston	Curt Oldenburg
Norio Shimada	Yingqi Zhang	Michael Cox	Natalia Quisel
David Keith	Tsukasa Kumagai	Christian Hermanrud	Kenshi Itaoka
Preston Jordan	Hiroyasu Takase	Jens Birkholer	Ilka van Dalwigk
Andrea Cortis	Grant Bromhal	Dorothy Peterson	Makoto Akai
			Yuri Leonenko

Schweinrich Case Study

Breakout Group Feedback

Opening Comments

- Not a full risk assessment
- Actually a scoping study
  - Testing of concepts
  - Learning by doing
- Good first step
- Next step to acquire more data to do a performance assessment

Robustness of Data Set

- Data set limited but typical for a saline formation in Europe
  - Existing “old’ sub surface geological data used
    - not designed for this purpose
  - No data on hydrology etc.,
  - Major uncertainties about seal integrity
  - Basis for uncertainty ranges could not be evaluated

Robustness of approach

- Approach good based on data available
  - FEPs too complex at this stage?
  - QA of FEP selection?
  - Disconnect in FEP detail and model needs at this stage of an assessment
  - Do we have the knowledge to develop a smaller FEP sub set?
- Set of scenarios were plausible
  - Base cases as well as worst cases to give balance
- Modelling approach appropriate

Robustness of Assumptions

- Assumptions may not have been physically feasible
  - Well bore case in particular
- Worst case scenarios assumed rather than taking probabilities of events into account

Confidence in Results

- Scenario analysis to test feasibility
- Identifies need to collect more data
- Achieved desired purpose

What can we communicate?

- Only a scenario analysis and we need to take care when communicating results
  - Beware of presenting quantitative numbers
  - Need to add caveats clearly when presenting results

Confidence Building

- Identified the issues that need to be addressed in a structured appraisal programme

Next steps

- Presentations on members web site
- Report for public dissemination
- Next meeting
  - London, Imperial College
  - Date: TBC

Actions Arising

- Terminology
  - IEA GHG action to initiate a discussion
- Site characterisation
  - Joint or separate network?
  - Working group to discuss
- Ecological analysis
  - Propose joint IEA GHG/CO2GeoNet workshop
    - Spring 2007
- Confidence building
  - Consider next steps – working group
  - Discussion board?