BUILDING A COMMON FEP DATABASE
A workshop organised by IEA GHG
On behalf of BP and the CO_2 Capture Project
London, February 2003

Report Number PH4/17
April 2003

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1. Background

This meeting was the second in a series of planned meetings of technical research groups involved in risk assessment studies on storage of CO_2 in geological reservoirs. The first meeting was organised by BP (on behalf of the CO_2 Capture Project (CCP)) and British Geological Survey (BGS), and was held at the BGS Offices at Keyworth near Nottingham, UK in May 2002. The first meeting was attended by around 30 people from research organisations involved in risk assessment work from North America, Australia, Europe and Japan. One of the key conclusions of the first seminar was that a considered, auditable approach to risk assessment was essential. The research groups agreed to share data, to assist in avoiding duplication and to work towards building a common features, events and processes (FEP) database[1].

To follow up the activities set in motion at Nottingham, a second meeting was organised by IEA Greenhouse Gas R&D Programme (IEA GHG) on behalf of BP and the CO_2 Capture Project – this was held in London in February 2003. The purpose of the meeting was for the participating groups to agree on the development of a single generic FEP database and to decide where and how it would be displayed.

This report provides an overview of the February 2003 meeting and the key outcomes of that meeting.

2. Features, Events and Processes

If CO_2 is to be injected into a geological formation, there will be questions concerning how long the CO_2 can remain in place and what will determine this? Such questions include: will leakage occur, what would be the cause of leakage, what are the leakage pathways and what would be the outcomes of leakage of CO_2 at the surface? Using an established methodology developed for identifying risks associated with the storage of nuclear waste and other hazardous materials, the first step in answering these questions is to create a database of features, events and processes that could affect the successful storage of CO_2. This is a relatively new idea for CO_2 storage. It is intended that the FEP database can be used as a check list by project developers, an auditable process for identifying the risks associated with a particular location. The FEP database is the first step in developing a risk assessment for CO_2 storage. Once a list of features, events or processes has been accepted for a particular CO_2 storage site, they will be used to develop scenarios and release profiles.

An important aspect of the creation of the FEP database, and risk assessment in general, is the dissemination of the concept to a wider audience including understanding whether it would be perceived as a suitable method for the risk assessment of geological storage of CO_2. By using the same methodology to model the characteristics of natural analogues (naturally occurring

[1] A report of the meeting was prepared by BP for the attendees. As an attendee, IEA GHG has a copy and additional copies might be made available by BP on request.

reservoirs of CO_2) it is hoped to demonstrate its thoroughness, establishing it as a suitable method for handling purposeful storage. One of the outcomes of the meeting was the proposal to find a more systematic approach in which those involved in the different research areas, risk assessment and the study of natural analogues, could work together.

3. Meeting Summary

The meeting was attended by 12 people plus one who participated in the meeting by speaker phone. A full delegate list is provided in Appendix 1.

The presentations in the first half of the seminar were as follows:

- Welcome and Introductions, John Gale, IEA GHG.
- A background to the FEP meeting and desired outcome, Tony Espie, BP.
- The EC[2] Weyburn Monitoring Project – FEP database activities, David Savage and Steve Benbow, Quintessa.
- Weyburn Monitoring and Storage Project: Weyburn FEP list, Mike Stenhouse, Monitor Scientific.
- NGCAS FEP activities, William Rodwell, SERCO and Laurence Wickens, ECL.
- SAMCARDS FEP Database Activities, Eric Kreft, NITG TNO.
- Progress on Risk Assessment within the GEODISC Program, Andy Rigg, APCRC.
- SWIFT[3] Activities for UK DTI[4], Mark Vendrig, DNV.

The presentations can be found in Appendix 2.

The presentations showed that two FEP databases have been created, one by Quintessa who are involved in the EC funded portion of the Weyburn Monitoring project, and the other by TNO under the SAMCARDS project sponsored by the CCP. It appears that the approaches of the two are quite different; the question arose as to how these two databases could be consolidated.

The aim of the EC funded portion of the Weyburn Monitoring Project is to develop a web enabled FEP database which will include both generic and project specific data. There have been 150 FEP descriptions prepared for the generic database. The list will be reviewed and refined at a meeting to be held in Orleans in March 2003, organised by the Weyburn project. The generic FEP database will be a generalised list of features, events and processes. The project specific database would be more detailed but it would indicate the cross-relationship with the generic list. It was suggested that this database will help project operators audit themselves and give them the opportunity to address why certain FEPs may have been ignored. Project specific FEPs that did not occur in the generic list can be reviewed to decide whether they should be included. It is thought that the generic database will be continually updated and maintained.

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[2] European Commission
[3] Structured What If Technique
[4] United Kingdom Department of Trade and Industry

The Weyburn database will not be available in electronic format until the end of the year but it was agreed that projects like NGCAS should have access to the Weyburn list of FEPs now so that project reports will match the FEP database design.

The SAMCARDS FEP database has identified 660 FEPs. It includes parameters[5] as FEPs - these have intentionally been excluded in the Weyburn database. It was initially recommended that the more detailed SAMCARDS FEP database could be used as the central database, so that the detail in the SAMCARDS database would not be lost following consolidation with the Weyburn database. However, further discussions suggested that parameters should not be included in a generic FEP database, because they are not necessary for auditing purposes. The detail gained from parameters could be incorporated into higher-level features, events or processes.

It was decided that, in the first instance, the two groups creating the two FEP databases (Quintessa - Weyburn and TNO - SAMCARDS) should compare upper-level information. It was suggested that, as both groups have used the same source information (i.e. FEPs created from the storage of nuclear and hazardous waste and a list of FEPs developed at an earlier meeting in Rome), correlation would be expected at that level. Also, it was thought that careful linking of the two databases would avoid using different terms and that there would be value in consistent use of wording throughout the consolidated FEP database. Removal of the parameters in the SAMCARDS database will considerably reduce the numbers of FEPs and should be done in the first instance to assist in the comparison. It was also acknowledged that each FEP listed should be identified as a ‘feature’, ‘event’ or ‘process’.

Some of the information collected from DNV’s SWIFT studies could be exchanged with the FEP database – it should be quite reliable on the engineering side but can only be a guide and not relied upon on the geological side. The current SWIFT studies were not meant to provide information at the level that the FEP database achieves but they have been requested by the DTI as the first stage in assessing the safety/risks of geological storage for the UK. Engineering FEPs do not feature in the current Weyburn database. There is the potential to extend the generic database by inclusion of engineering FEPs at a later date.

With regards to the use of the consolidated FEP database, it was agreed that project operators would benefit from a list which allowed them the opportunity to compare and contrast. Current projects that can compare results with a consolidated FEP database are GEODISC and NGCAS.

FEPs are not designed to convince anybody as to the safety of geological CO_2 storage but the development of a database is the first step of a longer risk assessment process. Increased transparency could be achieved by the use of a common language with the focus of the FEP database initially aimed at experts and not the general public.

It was suggested that an important point for debate about risk assessment studies would be to define a timescale for the geological storage of CO_2. Should the timescale be, for example, 500 or 10 000 years? Whichever is chosen could set a precedent for all future work. Who would be responsible for, or be in a position to determine, the rationale behind a decision on timescale?

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[5] A parameter is a property of a feature, event or process. For example "water flow" is a process and hydraulic conductivity, fluid viscosity and fluid compressibility are parameters which are variables that can affect it.

The IEA GHG Programme confirmed that, subject to its members' agreement, it was willing to place the database on the www.co2sequestration.info website. Discussions on specific web requirements will continue between the producers of the consolidated FEP database and IEA GHG.

4. Meeting Outcomes

The next step in the development of the consolidated generic FEP database was for TNO and Quintessa to exchange information on the individual FEP databases; this would be instigated by Quintessa in April 2003 after the FEP meeting in Orleans in March. Quintessa would report back to the group on the outcomes of the interaction between themselves and TNO, since this activity would drive the programme for future meetings. It was agreed that the group should aim for another meeting mid-year (2003).

The next experts' meeting would then be followed in the third quarter of the year by a more general meeting that will provide the results and conclusions to a wider audience and start the process of validating the consolidated FEP database.

In addition, Quintessa would send the NGCAS project a paper copy of their FEP database to use as the basis for their risk assessment activities by mid-year, after the further deliberations on its content had taken place.

It was generally concluded that, to aid transparency, best efforts should be made to use a common language in the different FEP databases and that discrepancies between the two databases should be reconciled within the next few months.

APPENDIX 1
LIST OF ATTENDEES

FEP Meeting Delegate List

25th February 2002

Steve Benbow Quintessa Limited Dalton House, Newtown Road Henley-on-Thames Oxfordshire, RG9 1HG UK stevenbenbow@quintessa.org	Lars Ingolf Eide Norsk Hydro ASA Oslo N-0246 Norway lars.ingolf.eide@hydro.com
Tony Espie Senior Reservoir Engineer BP Chertsey Road Sunbury-on-Thames Middlesex TW16 7LN UK espiet@bp.com	John Gale Project Manager IEA Greenhouse Gas R&D Programme Stoke Orchard Cheltenham Glos. GL52 7RZ UK johng@ieagreen.demon.co.uk
Wolf Heidug Shell International E&P P O Box 60 Rijswijk 2280 AB The Netherlands wolfgang.heidug@shell.com	Eric Kreft Netherlands Institute of Applied Geoscience - TNO P O Box 80015 Utrecht 3508 TA The Netherlands e.kreft@nitg.tno.nl
Angela Manancourt Research Officer IEA Greenhouse Gas R&D Programme Stoke Orchard Cheltenham Glos. GL52 7RZ UK angela@ieagreen.demon.co.uk	Andy Rigg Program Manager APCRC GEODISC Program PO BOX 136 North Ryde NSW 1670 Australia a.rigg@petroleum.crc.org.au
William Rodwell Serco Assurance 150 Harwell IBC Didcot Oxfordshire OX11 0QJ UK william.rodwell@sercoassurance.com	David Savage Quintessa Limited 24 Trevor Road West Bridgford Nottingham NG2 6FS UK davidsavage@quintessa.org
Mike Stenhouse Monitor Scientific 3900 S. Wadsworth Blvd. #555 Denver CO 80235 USA mstenhouse@monitorsci.com	Mark Vendrig Senior Scientist DNV Palace House 3 Cathedral Street London SE1 9DE UK mark.vendrig@dnv.com

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APPENDIX 2
PRESENTATION MATERIAL

The EC Weyburn CO_2 Monitoring Project

FEP database activities

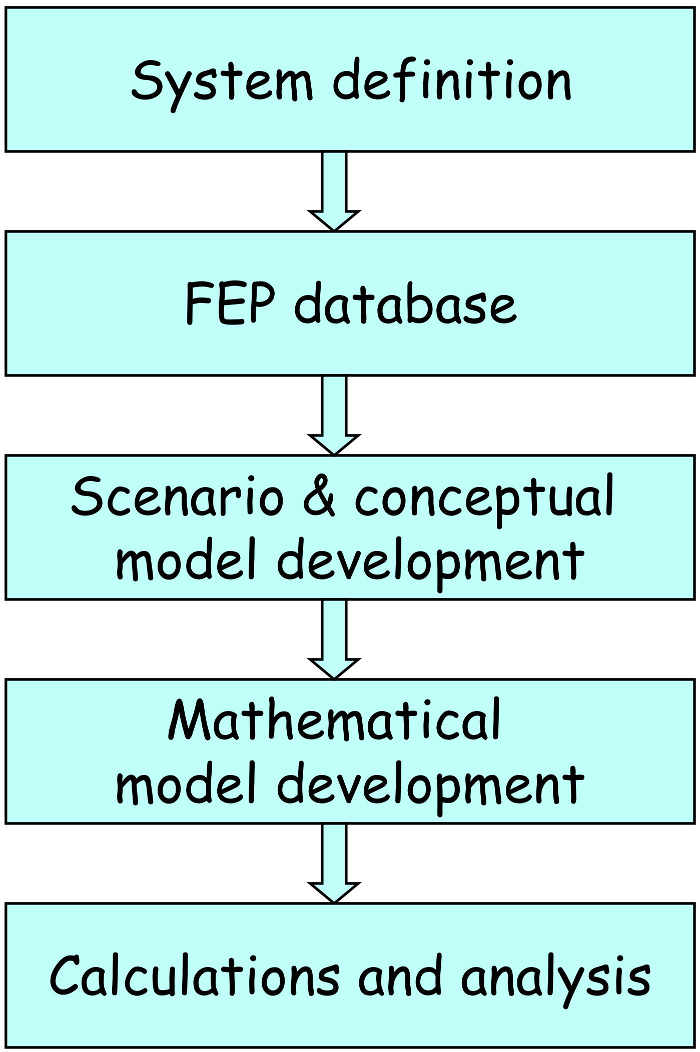
David Savage & Steven Benbow

Quintessa Ltd

Aims

- Construct a generic FEP database as input to the assessment of the safety and performance of geological sequestration of CO_2.
- Make this generic database web-enabled.
- Allow mapping of project-specific databases to the generic version.

Roadmap for safety analysis



FEPs - define 'the sequestration system' as we understand it.

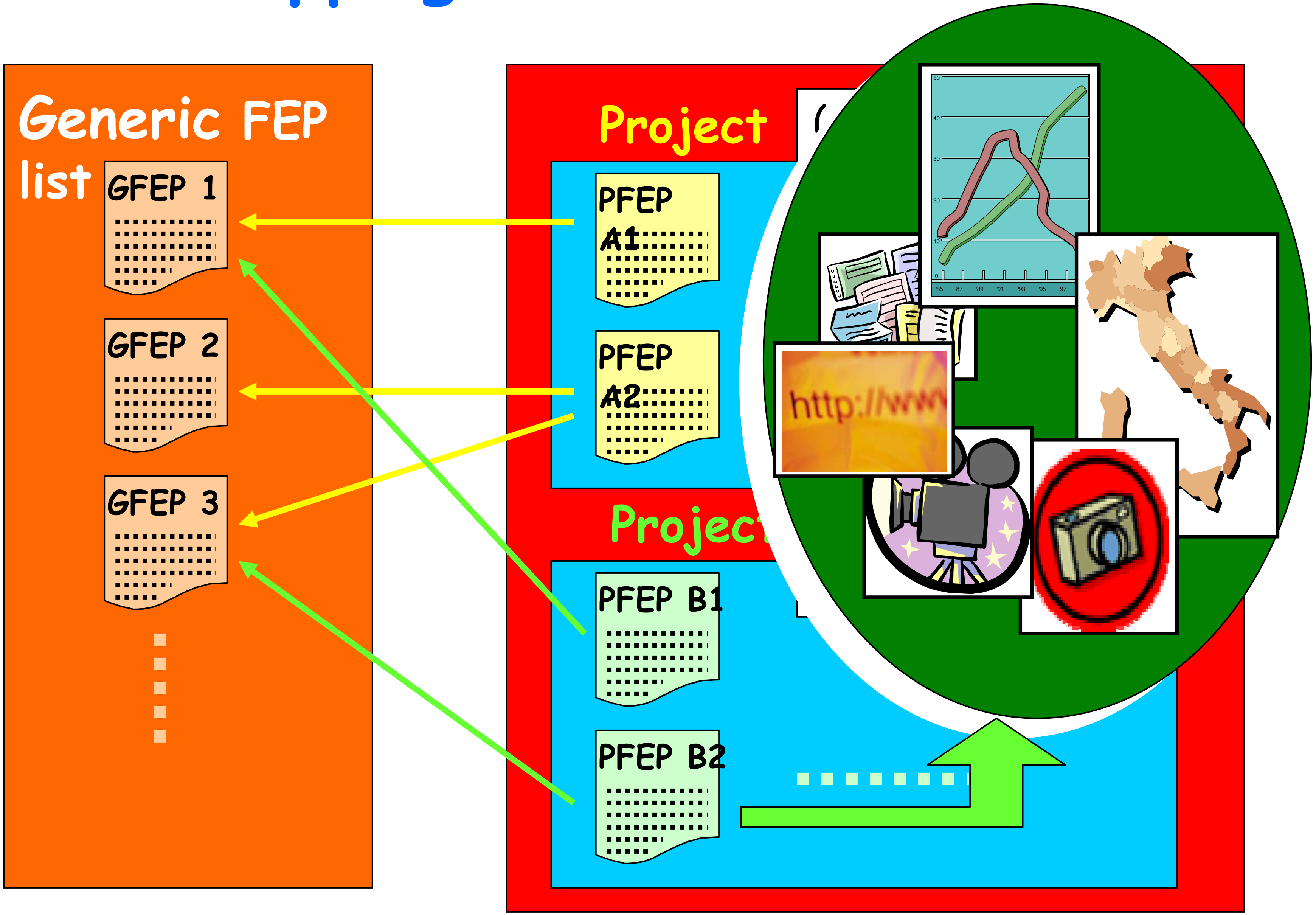
Why have a FEP database?

- Extent of the FEP database indicates that consideration was given to a large range of FEPs:
  - generates confidence in logic and thoroughness.
- Helps in identifying differences in assessments, e.g. between projects or stages of an assessment:
  - differences in overall scope.
  - differences in treatment of FEPs.
- Helps in demonstrating completeness to regulators, stakeholders, or public.
- Forms a basis for peer review and audit.

Generic and project FEP databases

- Generic FEP (GFEP) list:
  - comprehensive (within defined bounds) master list of GFEPs with descriptions.
  - organised into categories, e.g. biosphere, reservoir, etc.
- Project-specific FEP (PFEP) information:
  - collection of PFEPs with descriptions.
  - each PFEP cross-referenced with (one or more) GFEPs.
  - metadata, links to project documents, images, movies, etc.

FEP mapping



Generic FEP list
GFEP 1
GFEP 2
GFEP 3
Project
PFEP A1
PFEP A2
Project
PFEP B1
PFEP B2
http://www

Approach

- The NEA FEP database for radioactive waste disposal was used as a starting point for structure and content.
- This database was/will be adapted for CO_2 storage through 'FEP Workshops' involving Weyburn and NASCENT project members:
  - Rome, January 2002
  - Orléans, March 2003
- Monitor Scientific have developed a Weyburn project-specific database.

Current database layout

1 EXTERNAL FACTORS			
	1.1 STORAGE AQUIFER/RESERVOIR ISSUES		
		1.1.1 Site investigation	
		1.1.2 Drilling of wells	
			1.1.2.1 Drilling conditions
			1.1.2.2 Drilling fluids/muds
			1.1.2.3 Drilling formation damage
			1.1.2.4 Workover
			1.1.2.5 Sidetracks
			1.1.2.6 Monitoring wells

Current typical FEP entry

FEP name	FEP Description	FEP Number
Accidents and unplanned events	FEPs related to accidents and unplanned events during site investigation, CO_2 emplacement and closure which might have an impact on long-term performance or safety. *Accidents are events that are outside the range of normal operations although the possibility that certain types of accident may occur should be anticipated in operational planning. Unplanned events include accidents but could also include deliberate deviations from operational plans, e.g. in response to an accident, unexpected geological events or unexpected aspects of CO_2 quality and injection arising during operations.* Timescale: short to long term Reference/ source: NEA database Author (s): D Savage Reviewer: M Stenhouse	1.1.11

Potential database structure & layout

Sample

Timetable of development

- 2002: complete first draft of text versions of the 'generic' database.
- March 2003: review content of database and solicit 'extra content'.
- 2003: construct framework for electronic version of the database.
- End-2003: final deliverable for EC.
- Beyond 2003: develop database to include other projects?

In Conclusion…

- A generic FEP database for carbon storage is being constructed through the EC-funded Weyburn project.
- The EC (& DTI) are providing funds through the Weyburn project for this generic database to be web-enabled.
- A possible host for the database is the IEA website.
- It is hoped to continue further development of this database by incorporating information from other projects.

Monitor Scientific LLC

IEA Weyburn CO_2 Monitoring and Storage Project: Weyburn FEP List

Renaissance Hotel, Tuesday February 25th, 2003

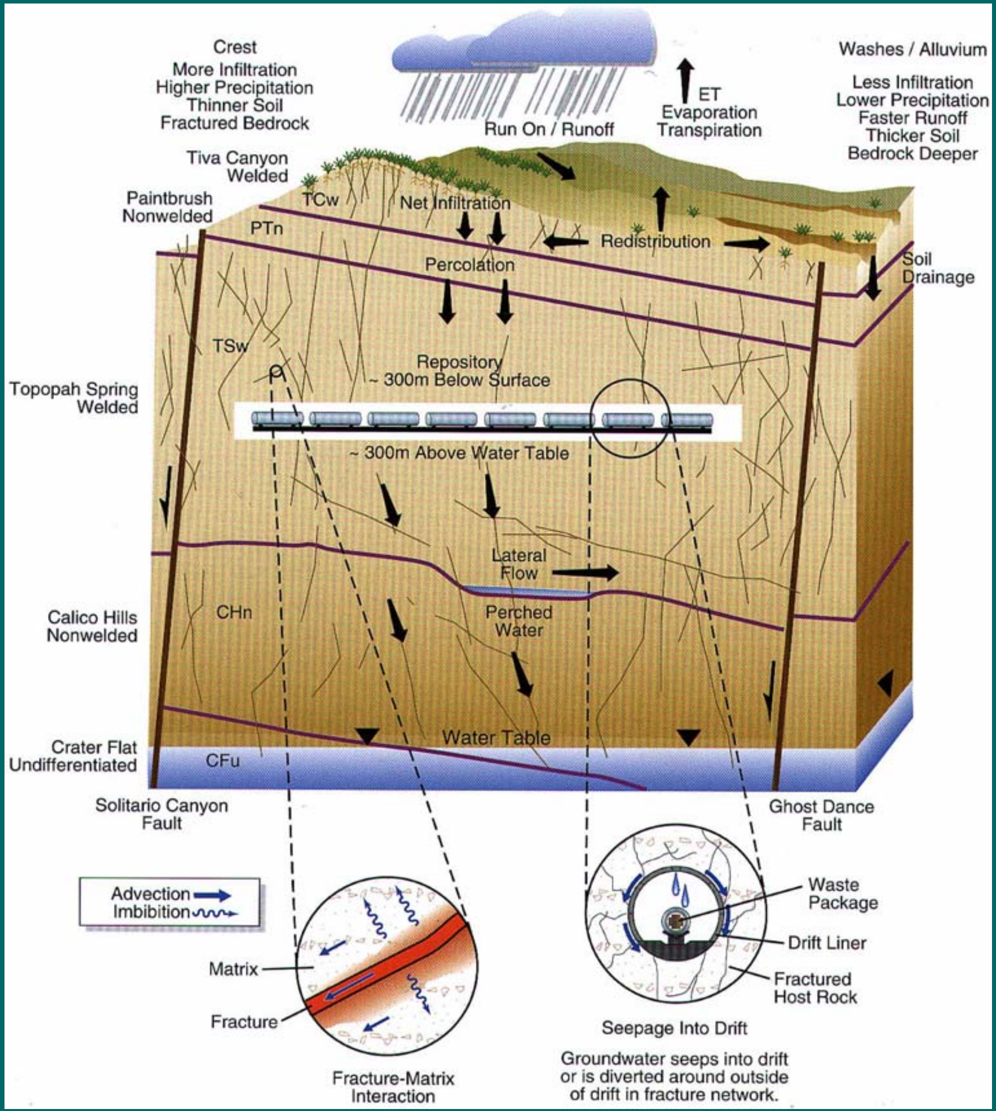
Mike Stenhouse

Monitor Scientific, Denver, Colorado USA
http://www.monitorsci.com

Outline of Presentation

- Brief introduction - MSCI background
- Overview of MSCI approach to long-term assessment at Weyburn
- Specifics
  - FEPs and what to do with them!

MSCI - Background [1]



HLW Repository at Yucca Mountain

- **MSCI staff have been involved in all aspects of quantitative assessments associated mainly with radioactive and hazardous waste disposal**
  - support national waste and regulatory bodies

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MSCI - Background [2]

- **Submitted proposal to DOE in 1998 to develop and carry out generic assessment strategy for geological storage of CO_2**
  - proposal was favorably reviewed but not accepted primarily because of lack of site available for study
- **First Weyburn Workshop, 1999**
  - MSCI expressed interest in carrying out long-term assessment, based largely on the work outlined in the DOE proposal

Methodology: Why Systems Analysis?

- **Systematic and transparent process**
  – Documents the different stages of the assessment, decisions made, and why
- **Fulfils a QA role**
  – Documented, traceable
  – Important for regulatory (environmental) oversight
- **Scales are relevant to long-term CO_2 storage**
  – Spatial (several to tens of km^2) and temporal (hundreds to thousands of years)

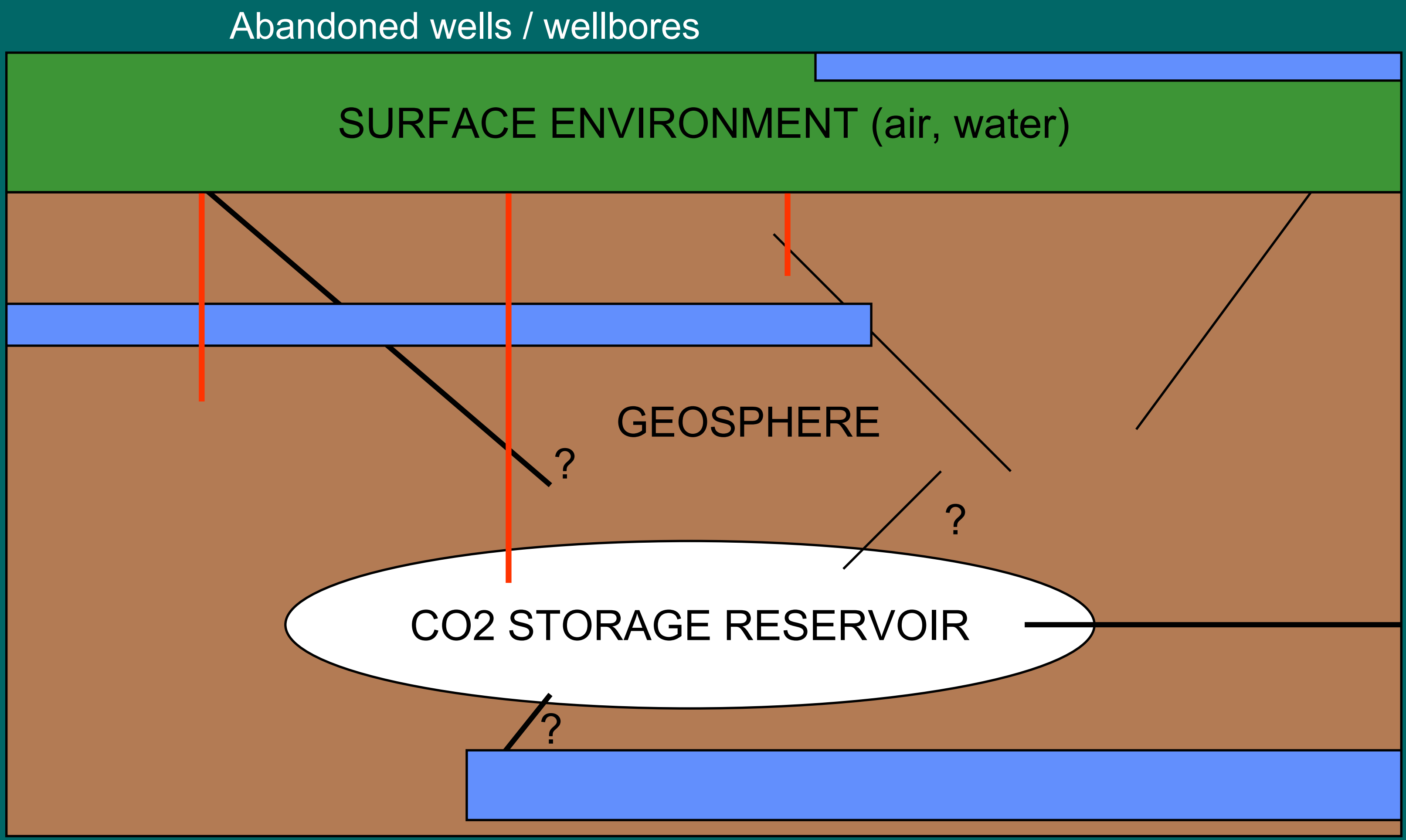
Systems Analysis / Scenario Development Methodology

- **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
    - What if?
  - IV. Identify information/data input and calculational needs and responsibilities for consequence analysis

I. What do We Mean by the System?

- **A physical / conceptual description of what is being assessed (in terms of its safety performance) and its boundaries**
- **Multi-component system**
  - CO_2 storage reservoir + geosphere + accessible environment (air and water)

Concept of CO_2 Storage System



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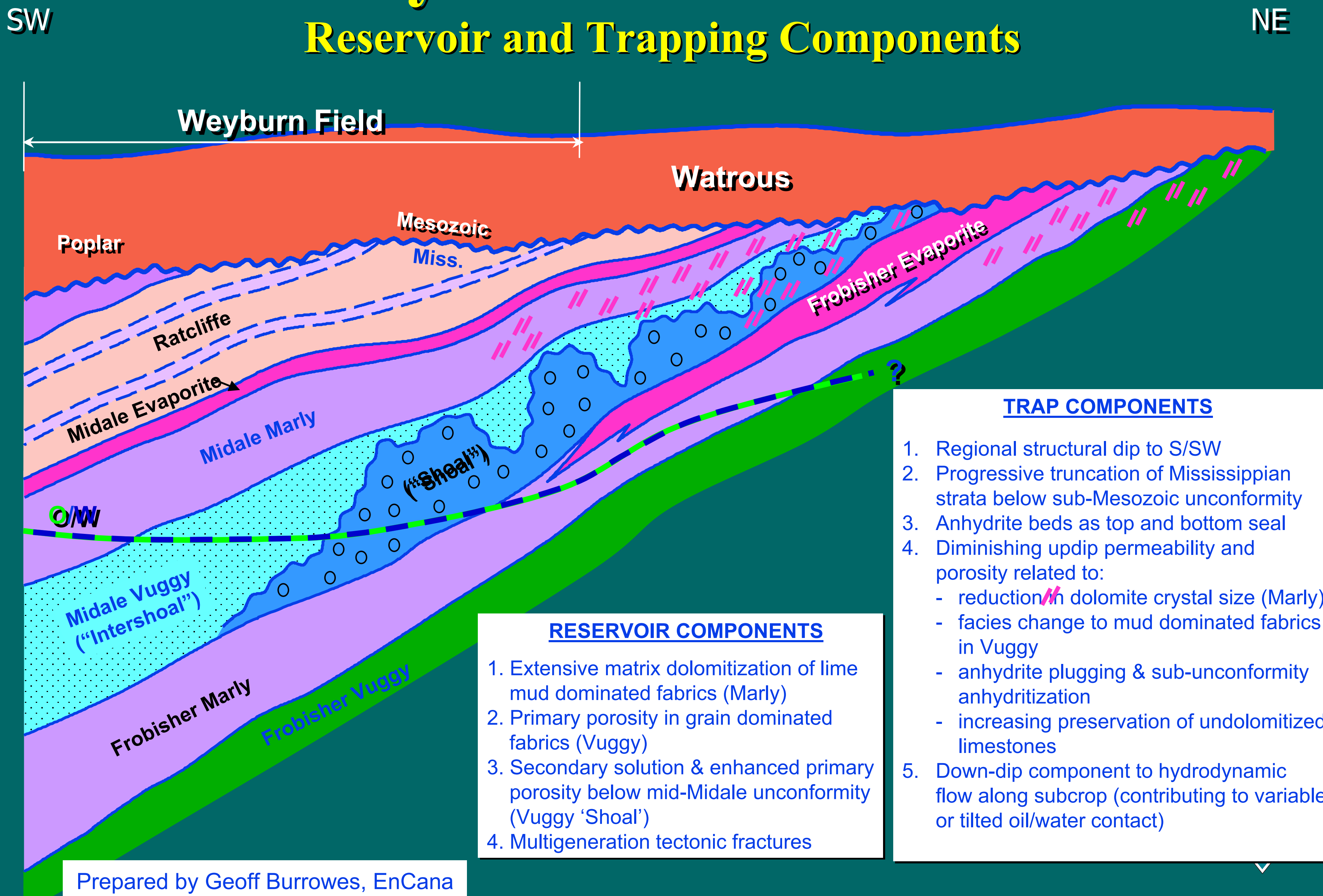
Weyburn Midale Field

Reservoir and Trapping Components



RESERVOIR COMPONENTS

1. Extensive matrix dolomitization of lime mud dominated fabrics (Marly)
2. Primary porosity in grain dominated fabrics (Vuggy)
3. Secondary solution & enhanced primary porosity below mid-Midale unconformity (Vuggy 'Shoal')
4. Multigeneration tectonic fractures

TRAP COMPONENTS

1. Regional structural dip to S/SW
2. Progressive truncation of Mississippian strata below sub-Mesozoic unconformity
3. Anhydrite beds as top and bottom seal
4. Diminishing updip permeability and porosity related to:
   - reduction in dolomite crystal size (Marly)
   - facies change to mud dominated fabrics in Vuggy
   - anhydrite plugging & sub-unconformity anhydritization
   - increasing preservation of undolomitized limestones
5. Down-dip component to hydrodynamic flow along subcrop (contributing to variable or tilted oil/water contact)

Prepared by Geoff Burrowes, EnCana

Considerations for Long-term Assessment: Weyburn [1]

- ***Spatial extent* of System**
  - Affects what geology and hydrogeological regimes are included in the assessment
- **Decision**
  - Focus on 30 km radius around Weyburn (greatest detail), compatible with Task 2 BUT, assessment should drive this decision

Considerations for Long-Term Assessment: Weyburn [2]

- ***Timescale* of assessment**
  - Affects what FEPs are relevant, e.g. geological processes and climate change (glaciation) if timescales are long 1,000's of years)
  - Affects assumptions about future human actions or behavior
- **Decision**
  - Initially, consider hundreds to thousands of years
  - Ultimately, may have to examine timescale of up to 10,000 years if no major geological sink for CO_2

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
    - What if?
  - IV. Identify information/data input and calculational needs and responsibilities for consequence analysis

II. Features, Events and Processes (FEPs)

- ***Features***
  - Physical characteristics or properties of the System (e.g. geological formations, abandoned wells)
- ***Events***
  - Discrete occurrences affecting one or more components of the System (e.g. earthquake)
- ***Processes***
  - Various factors that occur within the System (e.g. precipitation of minerals, groundwater flow)

Concept of 'System' and its FEPs

Combination of Features, Events and Processes (FEPs) that can be used to describe or represent the System's overall behaviour (Internal FEPs)

e.g. **geological, hydrogeological, chemical, geochemical, geomechanical, thermal CO_2 properties and transport**

SYSTEM (=> *Base* Scenario)

FEPs (Events) that are not part of the 'normal' System but can affect it (EFEPs)

e.g. **earthquakes, future drilling**

=> *Alternative* Scenarios

FEP Analysis [1]

- *Identify* FEPs that are relevant to the System
  - Distinguish System FEPs from ‘external’ FEPs
- *Select* FEPs
  - Distinguish those FEPs that are ‘important’ to the performance of the System from those that have negligible effect on its performance
  - Subdivide into arbitrary categories (geological, hydrogeological, chemical/geochemical etc.)
- Mapping exercise

Mapping to NEA FEPs

CODE	NEA FEP CATEGORY / TITLE *	WEYBURN FEP AND/OR COMMENT
NEA0	**ASSESSMENT BASIS**	- - -
NEA0.0	Impacts of concern	*Considered for long-term assessment, but NOT a System FEP*
NEA0.0	Timescales of concern	*Considered for long-term assessment, but NOT a System FEP*
NEA0.0	Spatial domain of concern	*Considered for long-term assessment, but NOT a System FEP*
NEA0.0	Sequestration assumptions	*Considered for long-term assessment, but NOT a System FEP*
NEA0.0	Future human action assumptions	*Considered for long-term assessment, but NOT a System FEP*
NEA0.0	Future human behavior (target group) assumptions	*Considered for long-term assessment, but NOT a System FEP*
NEA0.0	Health impacts	*Considered for long-term assessment, but NOT a System FEP*
NEA0.0	Aims of the assessment	*Considered for long-term assessment, but NOT a System FEP*
NEA0.0	Regulatory requirements and exclusions	*Considered for long-term assessment, but NOT a System FEP*
NEA0.1	Model and data issues	*Considered for long-term assessment, but NOT a System FEP*
NEA1	**EXTERNAL FACTORS**	- - -
NEA1.1	*WEYBURN RESERVOIR ISSUES*	- - -
NEA1.1.	Site investigation	*NOT relevant to long-term assessment (other than existence of borehol*
NEA1.1.	Drilling of injection wells	*Operational FEP; covered by "Source term (CO2 distribution)"*
NEA1.1.	Injection of CO2	*Operational FEP; covered by "Source term (CO2 distribution)"*
NEA1.1.	Closure and sealing of boreholes	Boreholes - unsealed + Incomplete borehole sealing
NEA1.1.	Records and markers, reservoir	*NOT included directly in long-term assessment; related to NEA 1.1.0*
NEA1.1.	CO2 injection pattern	*Operational FEP; covered by "Source term (CO2 distribution)"*
NEA1.1.	Storage concept	*Essentially same FEP as CO2 injection pattern [NEA1.1.06]*
NEA1.1.	Quality control	*NOT included directly; treat QC/QA issues as EFEP*
NEA1.1.	Schedule and planning	*NOT included (more relevant to operational period)*
NEA1.1.	Administrative control, reservoir	*NOT included directly in long-term assessment*
NEA1.1.	Monitoring of reservoir	*NOT included as System FEP; captured in "Monitoring (future)" EFE*
NEA1.1.	Accidents and unplanned events	*NOT included (more relevant to operational period); consider as EFE*
NEA1.1.	Reversibility	*NOT included (more relevant to operational period); consider as EFE*

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Mapping to Rome Workshop FEPs

E	ENGINEERING/BOREHOLE GROUP	WEYBURN FEP AND/OR COMMENT
	MOTIVATION (what are features?)	
E1	Subsurface completion	(covered by) Incomplete borehole sealing
E2	Well lining (present or not?)	(covered by) Annular space (quality/integrity)
E3	Nature of liner (perforated or slotted)	*NOT included explicitly; covered by other FEPs*
E4	Nature of casing (surface/intermediate/production)	*NOT explicitly; covered by other FEPs*
R5	Casing/sealing construction materials (cement, steel)	*NOT explicitly; covered by other FEPs*
E6	Cement curing	*NOT explicitly; covered by other FEPs*
E7	Well records (location, track etc.)	*NOT included: Issue is Loss of records (see R30)*
E8	Borehole logging	*NOT included*
E9	Well orientation (horizontal / vertical)	*NOT considered relevant for post-operational phase*
E10	Drilling conditions	*NOT considered relevant for post-operational phase*
E11	Drilling fluids/muds	*NOT considered relevant for post-operational phase*
E12	Drilling formation damage	*NOT explicitly; capture in EFEP*
E13	Injection/production formation damage (dissolution/precipitation)	*NOT explicitly; covered by other FEPs*
E14	Workover	*NOT considered relevant for post-operational phase*
E15	Sidetracks	*NOT considered relevant for post-operational phase*
E16	Host rock (type, premeability)	Rock properties FEPs
E17	Formation fluids/gases	*NOT explicitly; covered by other FEPs?*
E18	Hydrostatic environment	Hydraulic pressure?
E19	Downhole instrumentation	Monitoring (future)
E20	Well abandonment process	*NOT explicitly; covered by other FEPs*
E21	Monitor wells (adopting old wells, purpose built)	Monitoring (future)
E22	Orphan wells (substandard abandonmnet)	*NOT explicitly; covered by other FEPs*
E23	Orphan wells (distribution)	*NOT included; ADD?*
E24	Human intrusion, future access (accident or deliberate)	Future drilling activities; Mining
	INJECTION (properties, process)	
E25	Quality of CO2	**NOT included; ADD "Purity of CO2"**
E26	Toxic gases	Hazardous nature of other gases
E27	Other gases	Reactive gaseous contaminants
E28	Organics	Organic matter (solid); Dissolved organic material
E29	Bacteria (biological contamination)	Microbial activity
E30	Colloids	Colloid generation

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Weyburn Working List of FEPs

- **Initial Working List**
  - mapped to Quintessa's generic FEP list (2001)
  - mapped to Rome FEP List (January 2002) (engineering/borehole; reservoir; cap rock; biosphere)
  - Calgary Workshop (June 2002)
- **Current Working List (2002/2003)**
  - List now consists of ~ 55 System FEPs

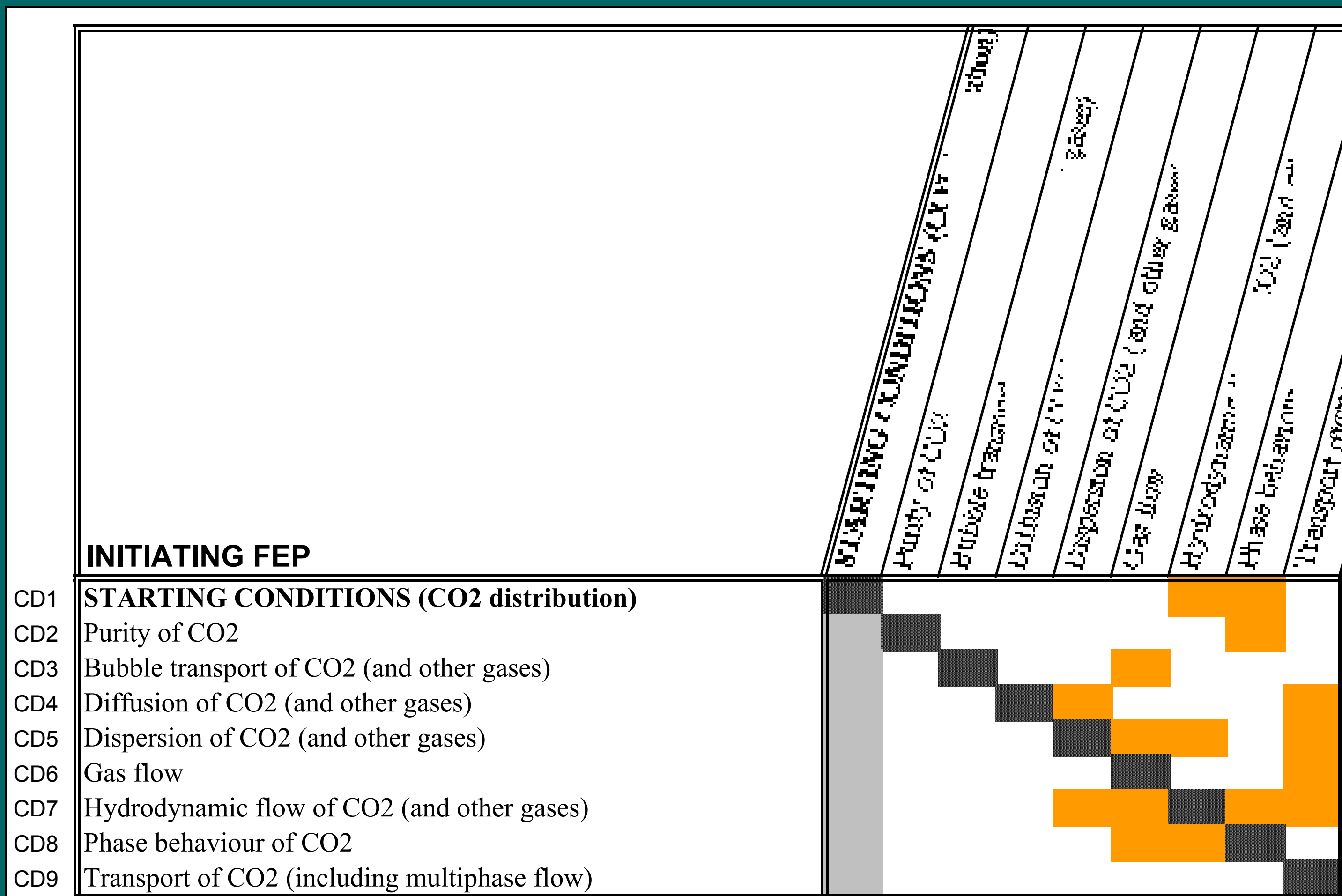
Weyburn FEPs: CO_2 Properties and Transport

- Starting (*i.e.* post-operational) conditions
- Purity of CO_2
- Bubble transport of CO_2 (and other gases)
- Diffusion of CO_2 (and other gases)
- Dispersion of CO_2 (and other gases)
- Gas flow
- Hydrodynamic flow of CO_2 (and other gases)
- Phase behavior of CO_2
- Transport of CO_2 (including multi-phase flow)

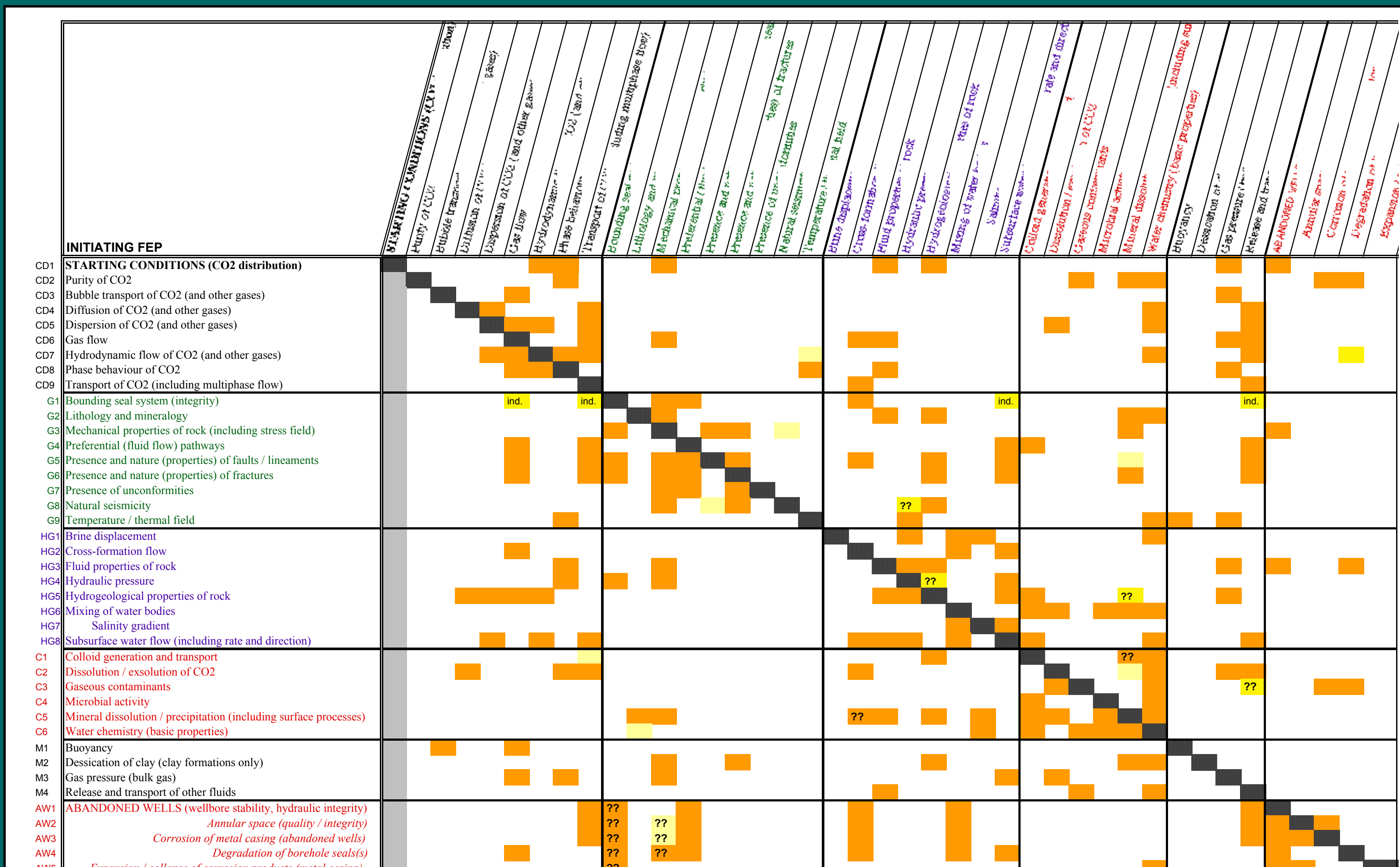
FEP Analysis [2]

- **Identify FEP *interactions***
  - 'Binary' interactions, *i.e.* between pairs of FEPs
  - Identify 'important' interactions between FEPs, in particular those impacting CO_2 migration *e.g.* precipitation of carbonate on CO_2 transport
  - Various methods of showing FEP interactions, not many of them are 'transparent'
    - opted for simple FEP interaction matrix

Weyburn: FEP Interaction Matrix: Small Section



Weyburn: FEP Interaction Matrix



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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 <====
    - What if?
  - – IV. Identify information/data input and calculational needs and responsibilities for consequence analysis

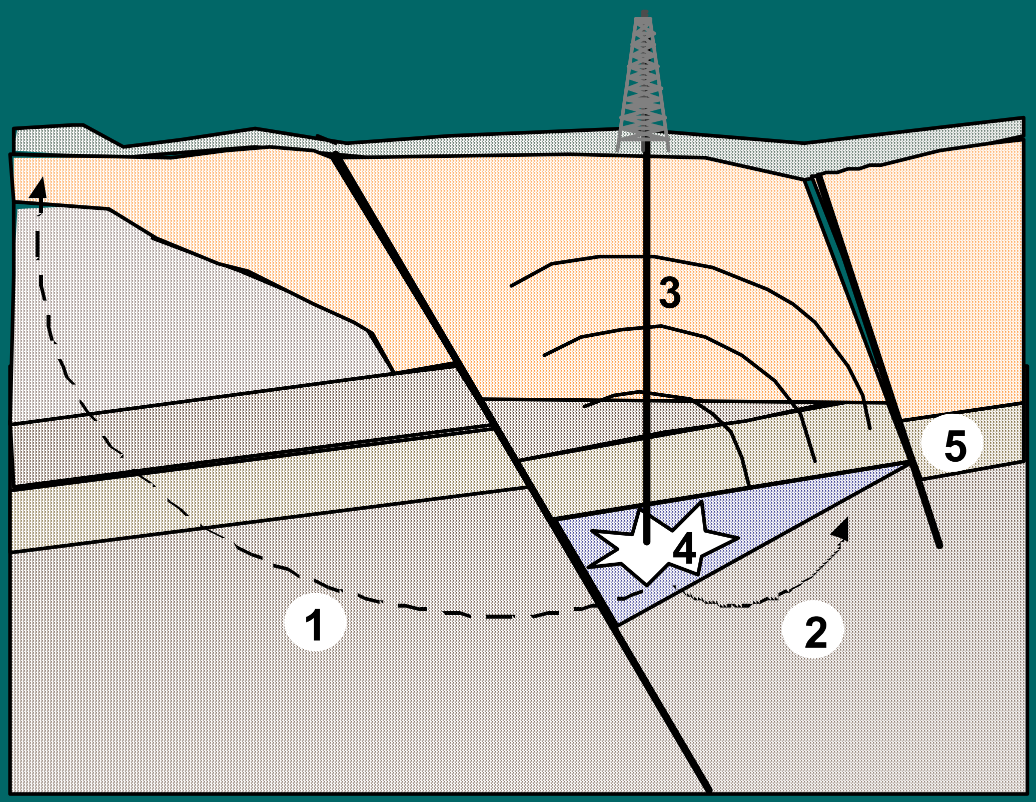
III. Scenario Development

- ***Base*** **Scenario or** ***Reference*** **Scenario**
  - describes the expected evolution of the Weyburn system (reservoir+geosphere+environment) in terms of these FEPs and interactions
- ***Alternative or Perturbation*** **scenarios**
  - Generated by the action of one or more external factors (EFEPs) - FEPs that are not part of the System but have the potential to significantly affect it, *e.g.* an earthquake

Description of Base Scenario

- **Defined as the expected evolution of the Weyburn CO_2 storage system**
  - Majority of CO_2 fluids initially in reservoir
    - CO_2 may exist as supercritical CO_2, CO_2 in water and hydrocarbon phases, and as gas phase
  - Migration *pathways*: combination of *natural* (geosphere) and *man-made* (abandoned wells)
  - Migration *mechanisms*: combination of pressure-driven, density-driven flow, hydrodynamic flow, dispersion, diffusion
  - CO_2-rock-water interactions along flowpath

Scenarios: “What if…?” Events



1. Potential long-term release
2. Rapid “short-circuit” release
3. Induced seismic event
4. Human intrusion (drilling)
5. Release to aquifer

Some Perturbation Scenarios for Weyburn (EFEPs)

- Mining (salt dissolution and other resources)
- Leaking wells (slow, fast)
- Overpressuring of reservoir (EOR phase)
- Alternative techniques for resource recovery
  - "50-year or 100-year soak"
- Tectonic activity and seismic events
- Fault movement/re-activation
- Influence of shallow trapping feature
- Accidental or intentional damage to surface casing
- Future drilling (above, through, to the reservoir)

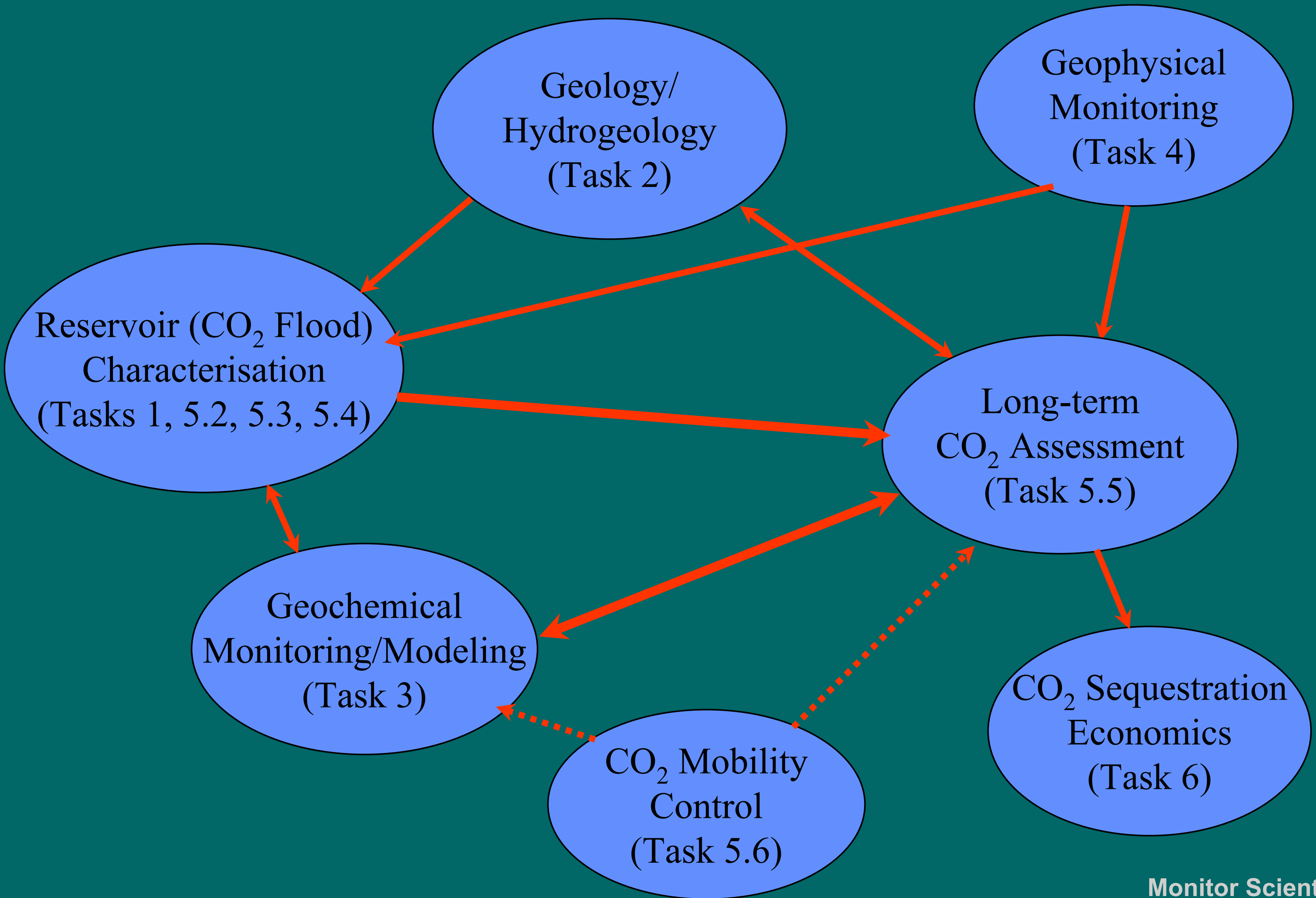
Systems Analysis / Scenario Development Framework

- **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
    - *What if?*
  - IV. Identify information/data input and calculational <== needs and responsibilities for consequence analysis

IV. Assessment Modeling Flowchart / Spreadsheet

- **Identifies what processes and interactions need to be addressed by modeling or other calculational method**
- **Shows the flows of information and data between different participating groups**
  - identifies responsibilities to individuals or groups (= form of accountability)

Key Data Flows for IEA Weyburn Project



Monitor Scientific

Weyburn FEPs: Chemical / Geochemical

- Colloid generation and transport
- Dissolution / exsolution of CO_2
- Gaseous contaminants
- Microbial activity
- Mineral dissolution / precipitation (including surface processes)
- Water chemistry (basic properties)

Weyburn FEPs: Geological

- Bounding seal system (integrity)
- Lithology, lithification and mineralogy
- Mechanical propertes of rock (including stress field)
- Preferential (fluid flow) pathways
- Presence and nature of faults/lineaments
- Presence and nature of fractures
- Presence and nature of unconformities
- Natural seismicity
- Temperature/thermal field

Weyburn FEPs: Hydrogeological

- Brine displacement
- Cross-formation flow
- Fluid characteristics of rock
- Hydraulic pressure
- Hydrogeological properties of rock (basic)
- Mixing of water bodies
- Salinity/density gradient
- Subsurface water flow (including rate and direction)

Weyburn FEPs: Other / Miscellaneous

- Buoyancy
- Dessication
- Gas pressure (bulk gas) / pressure gradient
- Release and transport of other fluids

Weyburn FEPs: Abandoned Well FEPs

- Annular space (integrity/ quality)
- Corrosion of casing metal
- Degradation of borehole seals(s)
- Expansion / collapse of corrosion products

serco

Serco Assurance

NGCAS FEP-Related Activities

William Rodwell
in conjunction with
Laurence Wickens (ECL Technology)

25 February 2003

Content

- **Outline of the approach being followed to assessing risks of CO_2 sequestration in Forties**
- **Describe the use of FEPs and relate to other FEP work**
  - Requirements for a FEP database
- **Progress update on scenario / FEP analysis and structure of safety analysis**
- **Consider that if we want to develop a common approach more is involved than just agreeing a common FEP list**

Analysis of Risks from CO_2 Sequestration in NGCAS

- **Purpose is to identify and quantify the risks from a CO_2 sequestration scheme**
  - Specifically sequestration in the Forties Field
- **Characterise the various “hazards” that might result from a CO_2 sequestration scheme**
- **Identify the scenarios / processes that might give rise to these hazards (FEPs)**
- **Identify the controlling factors that will determine the occurrence of a scenario or the magnitude of an effect (FEPs)**
- **Quantify the risks (or other measures of hazard) and compare with targets for acceptability**

Top Down Approach to Scenario/FEP Analysis in NGCAS

- Structures the analysis in terms of the overall objectives
- Work down from a tractable number of endpoints
- Maintains focus on endpoints
- Incorporates FEPs according to relevance (e.g. quantities that are only parameters in models are not considered until needed)
- FEPs naturally structured into conceptual models
- BUT need to audit for comprehensiveness and unexpected interactions (reference to generic list of FEPs)

Alternative Bottom up Approach to FEP Analysis

- **Draw up list of FEPs (features, events, and processes)**
- **Analysis of interactions**
- **Screening of FEPs & FEP interactions**
- **Development of scenarios as representations of alternative evolutions of the system (e.g. based on alternative assumptions or particular occurrences)**
- **Grouping of FEPs or scenarios with similar consequences**
- **Draw up conceptual models as precursor to numerical analysis**
- **Simplification of analysis to bring out controlling features and make computations tractable**
- **Can be intractable and top-down insights needed for structuring of FEPs**
  - FEP lists need to be structured and/or hierarchical and not be cluttered with low-level parameters

Use of FEPs

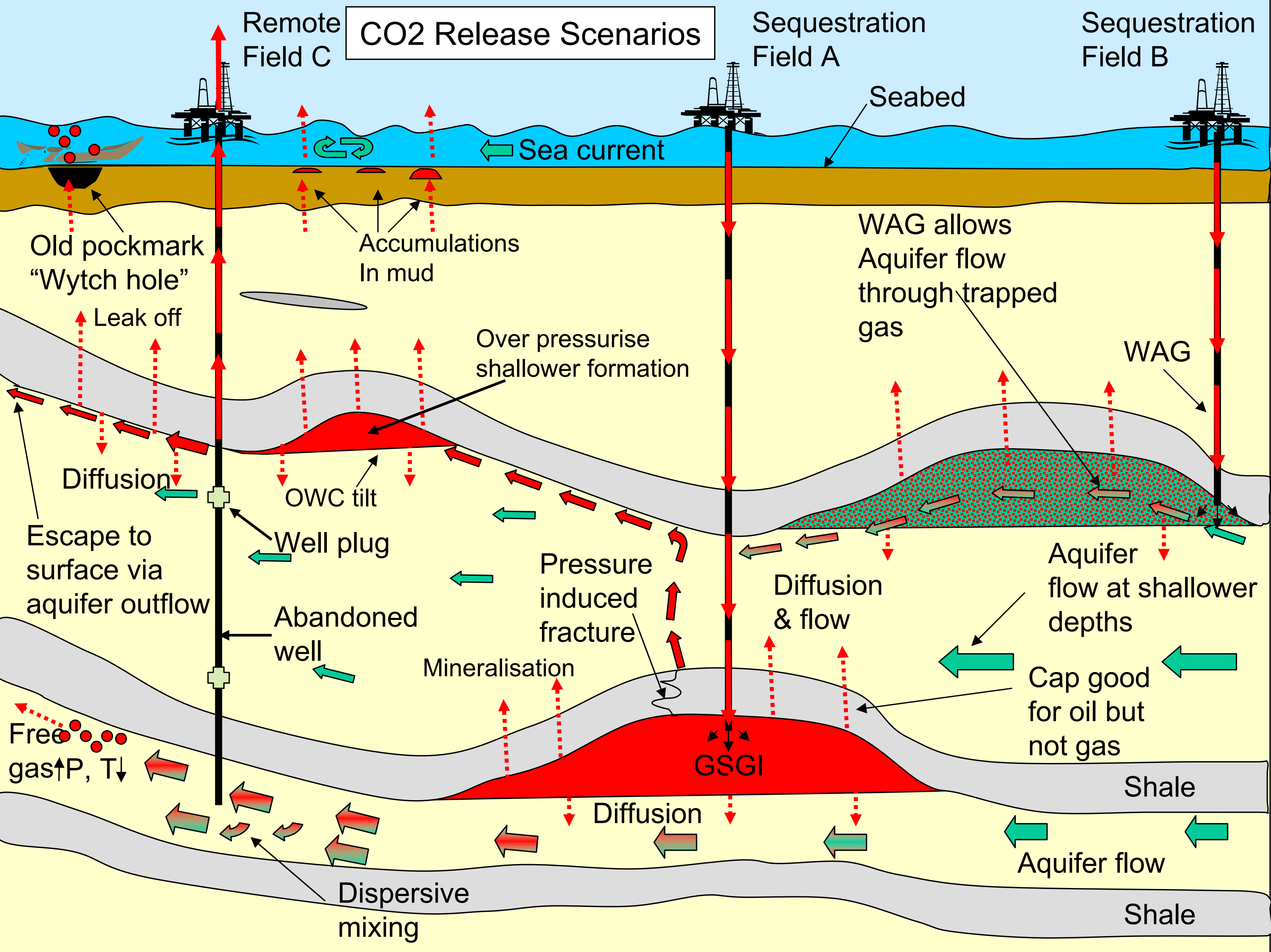
- **Serco / ECL have not set out o produce another FEP list**
  - Lists already being produced by Quintessa and TNO - not cost effective to embark on another
  - FEPs implied by the analysis undertaken
- **Working with other FEP list providers**
  - e.g attendance at the FEP workshop in December
- **Audit our work against generic list**
- **Documentation of FEP coverage in scenarios considered planned as part of final analysis**

Risks from CO2 Storage

- **Accidents during operations?**
  - Outside scope of present study
- **Failure to meet performance targets for containment?**
  - Greenhouse gas abatement criteria? (e.g 0.1% per year)
- **Harm to man after abandonment?**
  - e.g sudden localised releases leading to asphyxiation ?
- **Environmental changes?**
  - Aquatic environment
  - Sub-seabed environment (inconsequential offshore?)
  - Onshore environment (no effect from offshore disposal in Forties)
- **Note that in most cases the key issue will be the leakage of CO_2 to the surface - flux and distribution**

Context in which Risks are to be Quantified

- **Complex and poorly characterised system in which quantification of releases will be difficult**
- **Will not be able to simulate CO_2 migration in the sort of detail deployed within well-characterised reservoirs (e.g. no history matching possible)**
- **Hence adopt conservative approach**
  - Examine "worst case" situations to bound risk; leads to robust case if acceptable risk criteria met
  - Refine assumptions if conservative assumptions are not adequate
  - Highlight controlling factors - demonstrate understanding
- **Criteria needed to bound acceptable magnitudes of effects**
- **Look for analogues that corroborate behaviour**
- **Need to determine timescale of relevance in order to identify scenarios / processes to be considered (e.g. 1000 years)**


CO2 Release Scenarios
Remote Field C
Sequestration Field A
Sequestration Field B
Seabed
Sea current
Old pockmark "Wytch hole"
Accumulations In mud
WAG allows Aquifer flow through trapped gas
Leak off
Over pressurise shallower formation
WAG
Diffusion
OWC tilt
Escape to surface via aquifer outflow
Well plug
Pressure induced fracture
Diffusion & flow
Aquifer flow at shallower depths
Abandoned well
Mineralisation
Cap good for oil but not gas
Free gas↑P, T↓
GSGI
Shale
Diffusion
Aquifer flow
Dispersive mixing
Shale

Primary Escape Routes from Reservoir 1: Through Caprock

- **Existence of Forties Field demonstrates previous integrity of caprock.**
  What's changed?
  - Capillary seal not sufficient with changed capillary pressure and density?
  - Higher permeability to CO_2 than reservoir fluids?
  - Induced fracture (or enhanced permeability path)
    - Overpressurised for CO_2 storage
    - Pressure cycling during production operations
    - Chemical interactions
    - Seismic effects
    - Well perforation induced fracturing
    - …
  - Unidentified pre-existing fracture (changed properties from before field development?)

Primary Escape Routes from Reservoir 2: Via Failed Well

- **Corrosion of well casing**
- **Cement degradation**
- **Migration may occur through annulus or well bore**
- **Migration may be direct to surface or via overlying permeable strata**
  - Connection of high pressure gas to overlying formations may induce fracturing
- **Seismic damage……..**
- **Treat probabilistically**
  - Probability of occurrence will depend on well materials used and abandonment procedure

Primary Escape Routes from Reservoir 3: Escape from Base of Gas Column

- **Solution in groundwater - possibly with subsequent exosolution after movement to region with different P&T**
  - Simple calculations suffice to show that this is insignificant
- **Gas leakage from spill point**
  - Should not occur unless reservoir overfilled

Direct Harm to Man Offshore

- **Asphyxiation from CO_2 accumulation on rig**
  - Accumulation of a CO_2 cloud around platform or in confined spaces on platform
  - Depends on leakage rate, air conditions rig geometry, etc
  - Distinguish sea-bed escape from platform-level escape
    - Consider transport in the water column for the former
  - Escape from wells in neighbouring fields requires quantification of any lateral migration
  - Key issue will be characterising (probabilistically), leakage rates from wells
- **Hazard to shipping from sudden gas release**
  - Release from accumulation below sea-bed sediments
  - No evidence that has ever occurred on a sufficient scale to be a problem in North Sea

Harm to Environment

- **Geological structure ensures all release will be subsea**
  - No need to consider onshore releases
- **Harm to aquatic environment**
  - Acidification of sea water and effect of carbon dioxide on marine communities
  - Mobilisation of toxic elements which discharge to sea bed
  - Need to understand mixing / dilution processes in North Sea
  - Understanding of effect on marine organisms insufficient for definitive definition of acceptable concentrations - de minimis arguments may suffice

Greenhouse gas mitigation performance

- Need to sum over all releases
- Need only measure(s) of likely performance (if one sequestration scheme falls short of expectation the effect may not be significant if the average performance for all such schemes does meet targets - need unbiased measures)
- Need consensus on targets and timescales

Example Components of assessments

- **Quantification of leakage through dissolution in underlying aquifer - insignificant**
- **Screening out of seismic risk to cap rocks and wells**
  - Very low risk of significant quake in region
- **Preliminary calculations of risk from release to platform**
  - e.g. 200 MMscf/day (~5.7 10^6 m^3d^{-1}) only gives a 10 cm thick layer of CO_2 on a platform
- **For comparison, traffic at a busy US freeway junction produces 2 MMscf/day per 50m**

Summary

- **Scenarios identified for risk analysis of sequestration in the Forties Field**
  - Preliminary identification of controlling factors
  - Implies underlying relevant FEPs
  - Base-case and variant scenarios defined
- **Off shore location limits number of relevant FEPs**
- **Would be useful to audit current scenarios / FEPs against definitive list of generic FEPs**
  - Generic FEP lists most useful if appropriately structured
- **Assessments are concentrating on simple bounding calculations and screening of processes**
  - Iterative process
- **Awaiting results from flow modelling being carried out by other NGCAS partners**
- **Need agreement on certain criteria to establish a common approach**

Progress and status

SAM CARDS FEP Database Activities

Netherlands Institute of Applied Geoscience TNO
- National Geological Survey

Eric Kreft, Geo-Energy

Objectives of SAM CARDS (CCP)

- Develop a method and tools for HSE risk assessment of geological CO_2 sequestration
- Apply methodology in a performance assessment of two sequestration scenarios, i.e. injection in an onshore depleted gas field and an offshore aquifer trap

Involved R&D institutes

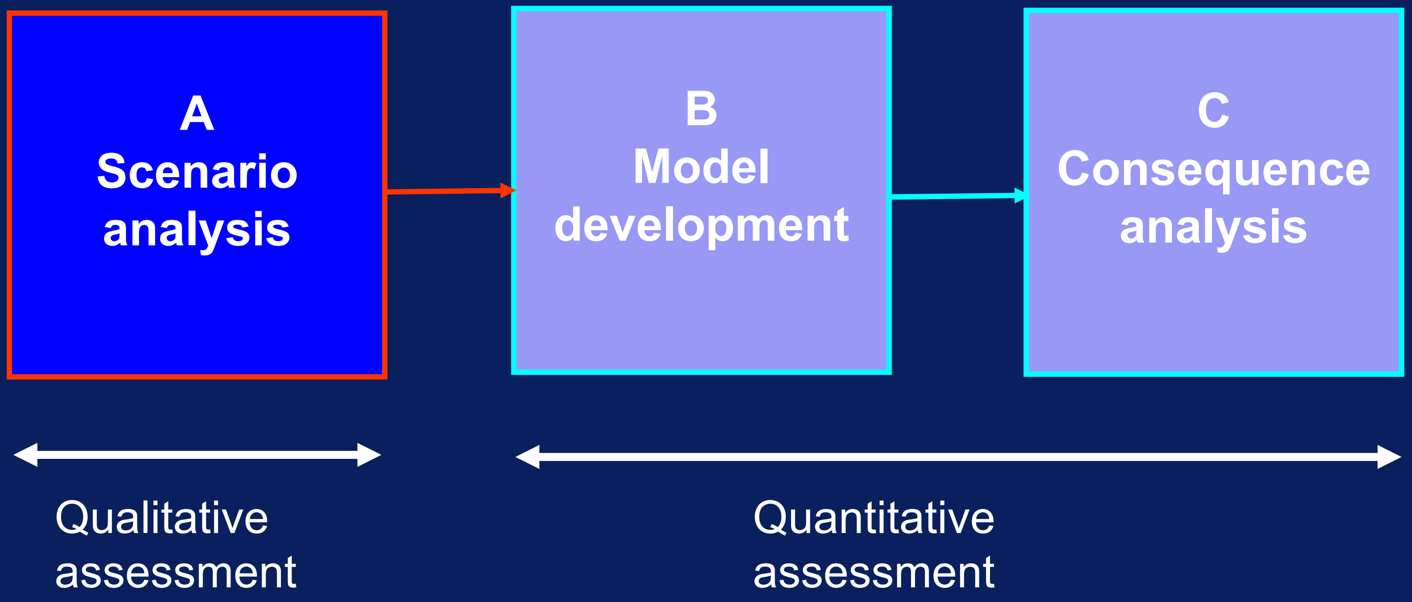
TNO

BRGM

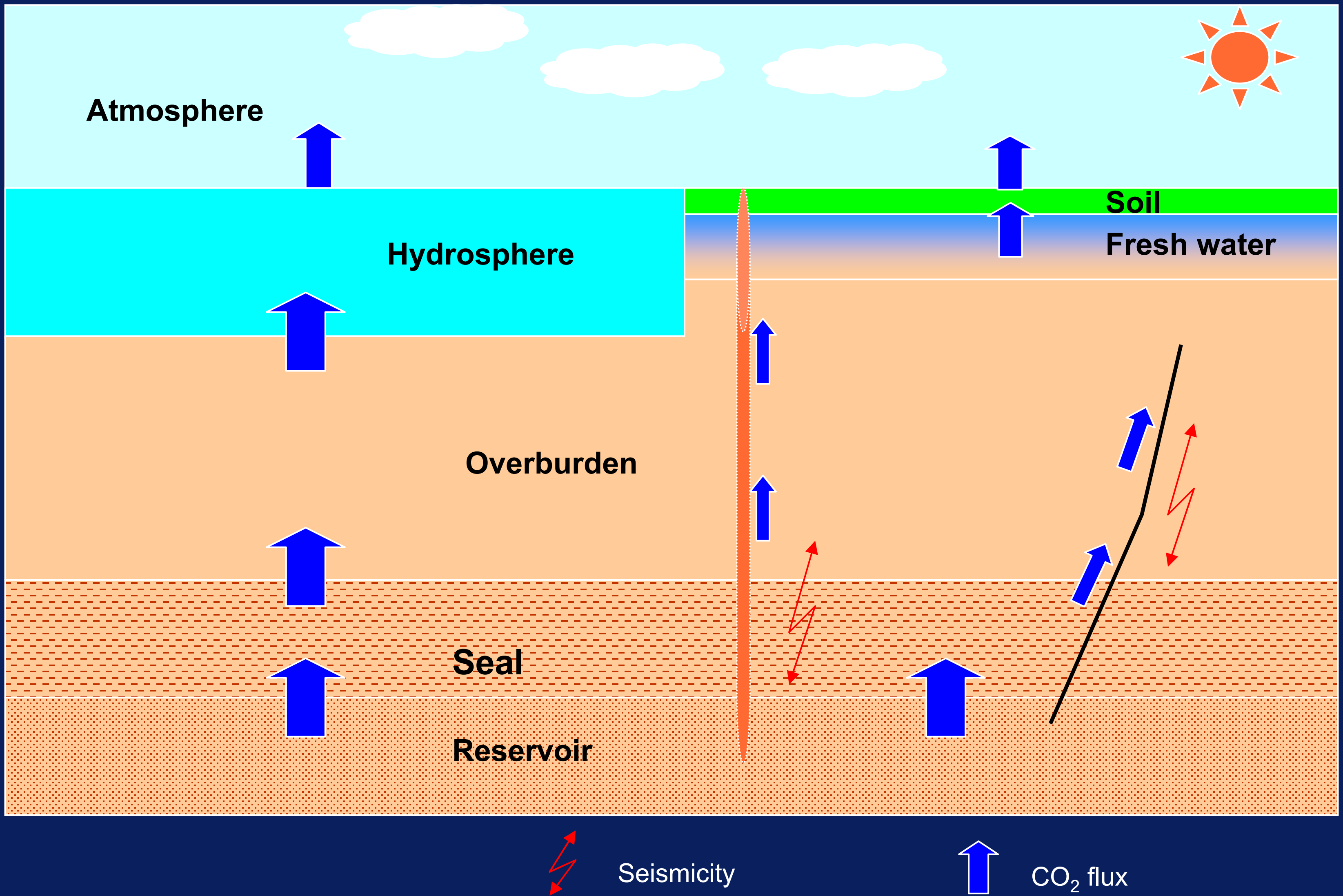
WAGENINGEN UNIVERSITY

WL | delft hydraulics

Basic components of safety assessment method



Major spatial entities



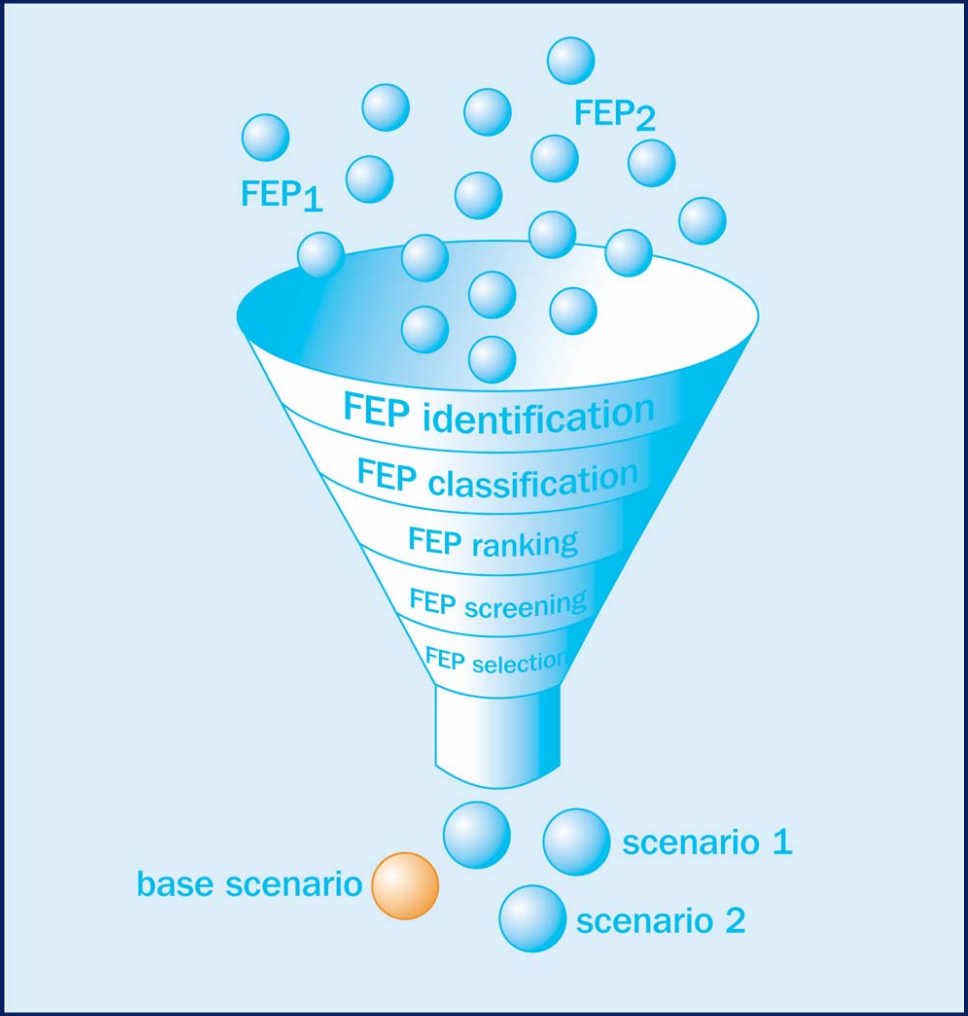
Scenario analysis (qualitative assessment)

- Comprehensive
- Traceable
- Transparent and accessible

A
Scenario
analysis

Scenario analysis (qualitative assessment)

A Scenario analysis



Scenario building (2003)

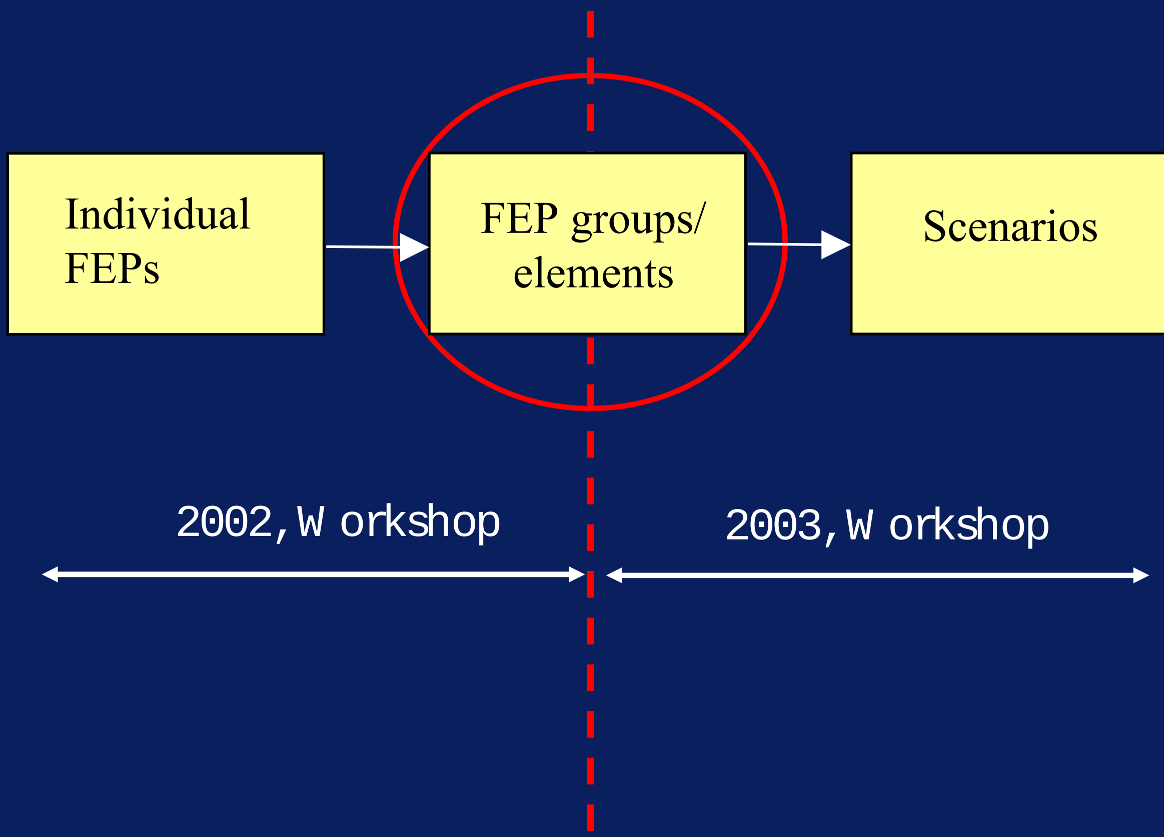
- Identify scenario-defining FEPs
- Assign FEP-groups to a scenario element (= compartment)
- Combine scenario elements to scenarios
  - Base scenario (unit probability FEPs)
  - Alternate scenarios (uncertainty)

Final result of scenario analysis

- Shortlist of interacting FEPs
- Grouped in restricted number of criticical scenarios
  - Base scenario
  - Alternate scenarios

Current status scenario analysis

A Scenario analysis



Current developments

- interaction matrix within MS-Access
- Baysian network software (Java) around MS-Access

Current status FEP database

- 660 FEPs related to CO_2 sequestration
- in an MS Access database
- that is used for scenario analysis support (CTT)

Example of single FEP

Identification

ID	5
Expert name	EK & FvB
Name	Reactivation of faults
Description	Reactivation of existing faults, caused by natural/man induced seismicity, changes in stress regime
FEP relation to safety	An increase in fault transmissibility attacks the storage/sealing capacity of reservoir, seal and overburden
Source/references	
Date of last mutation	10/1/02
Mutation by	EK

Classification

Type of FEP	process/event
Natural/Man induced	Natural + Man in
Sequestration specificity	Generic
Compartments	☑ Basement, ☑ Reservoir, ☑ Seal
Effect on	☑ Matrix, ☐ Fluid, ☐ Sequestered CO_2
FEP character	☑ Mechanical, ☑ Transport, ☐ Chemical
Spatial scale	☑ <= 100 m, ☑ 1 km, ☐ 10 km
Time scale	☐ <= 100 years, ☑ 100-1000 years, ☑ >= 1000 years

Ranking

Relevance for assessment:	possible effects: fault opening. Shear offset. With as a result leakage. 2nd effect is Induced seismicity noticabe at surface. Likelyhood is depenmdent on case specifics (assessmemt base)
Probability:	likely
Potential impact:	significant
Potential risk	
Name evaluator	
Date_of _evaluatioı	

Comments

FEP sources

- NEA FEP international database
- Weyburn project FEP workshop Rome (January 2002)
- SAM CARDS FEP workshop Utrecht (December 2002)
- Literature (PROSA, IWACO, SKI, Joule II)

FEP classification attributes

- F, E, or P
- Natural/man-induced
- Compartment(s) involved
- Fluid/matrix related
- Chemical/mechanical/transport/thermal/biological
- Spatial scales
- Temporal scales

F, E or P

- Features
  - System /model parameters
  - System describing factors
- Events
  - Future occurences
  - Changing features
- Processes
  - System /model processes
  - Non-model processes indicating change

Static model description, base case FEPs

Change to model, scenario defining or base case or negligible FEPs

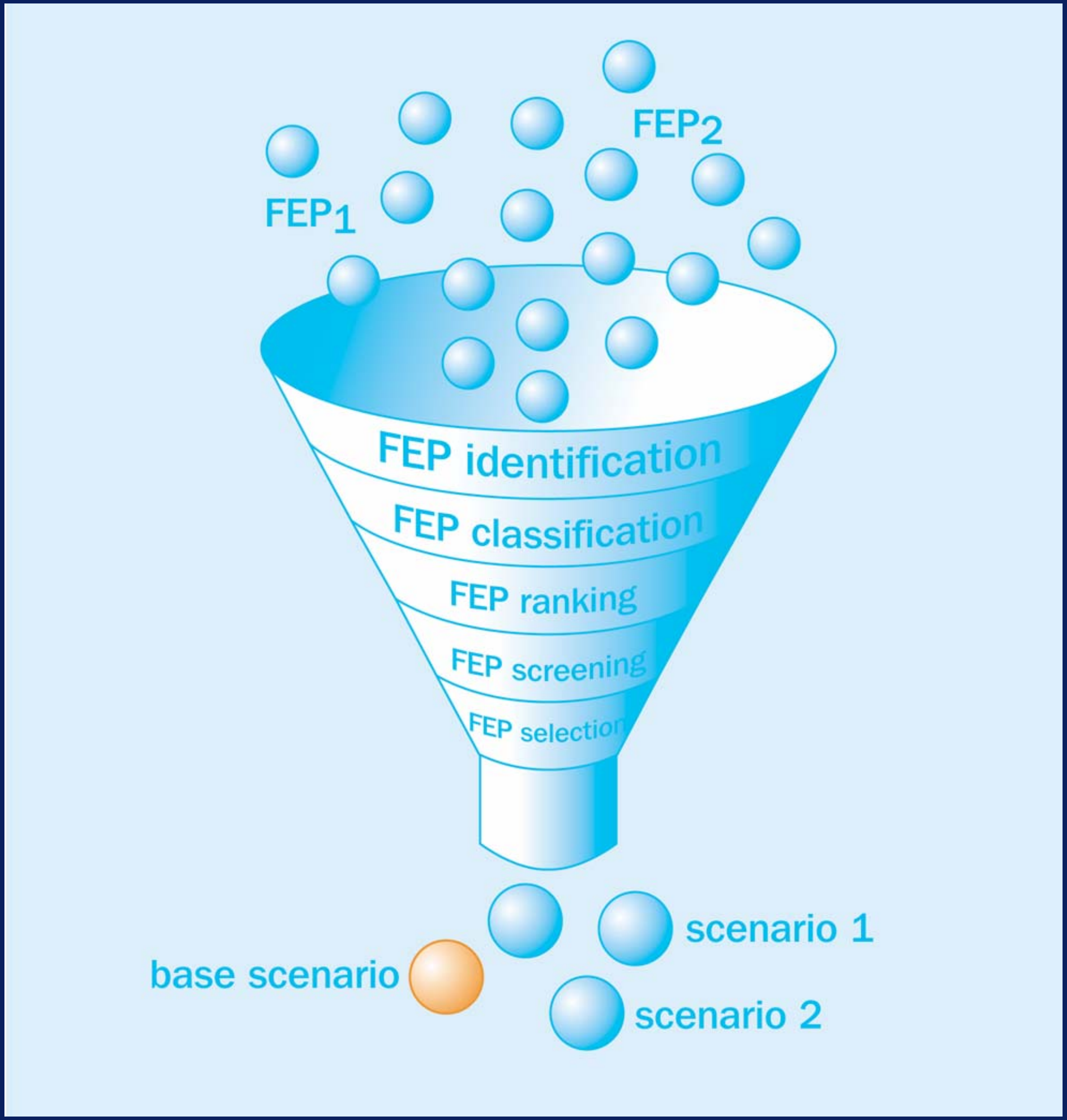
Conclusions SAM CARDS

- 660 FEPs stored in MS Access database
- 20+ attributes per FEP
- database also used as a tool to record all relevant steps and decisions during scenario analysis procedure
- TNO-NITG currently developing support-tools
- workshop to be organised in May/June 2003

TNO-NITG

- Seeking alliance to present FEPs as Baysian networks
- How can we combine FEPs and natural analogues?

FEP Workshop 2002



Objectives

- Assure that NITG's list of FEPs is comprehensive
- Examine the applicability of the proposed method

Workgroup Session Goals

- Reduce the number of FEPs
- Define base-case and scenario defining FEPs

FEP Ranking

Probability	*Semi-quantitative*
Description	**Probability** (example)
very likely	>0.9
likely	0.1-0.9
unlikely	0.0001-0.1
very unlikely	<0.0001

Impact
Description
significant
marginal
negligible

Results Workshop

- Reduction of number of relevant FEPs from 660 to 46
- Time schedule not met, 46 remaining FEPs have not been grouped

Conclusions Workshop

- FEP database nearly complete, new FEPs relate to marine and atmospheric compartment
- FEP analysis process not efficient because of ambiguous nature of some of the FEP descriptions
- TNO-NITGs methodology seems promising in terms of FEP reduction, number of scenario defining FEPs (46) could be reduced further by grouping
- More accent on EPs of the FEPs
- More attention to scientific argumentation of FEP ranking

GEODISC

CO2CRC

AUSTRALIAN PETROLEUM COOPERATIVE RESEARCH CENTRE

APCRC

a joint venture between government, industry and universities

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Progress on Risk Assessment within the GEODISC Program

Andy Rigg

Program Manager

GEODISC Research Program

IEA/CCP-JIP Risk meeting London 25th February 2003

Background-Pre June 2002

- The group allocated to undertake Risk Assessment within GEODISC is **CSIRO-Perth**
- The group was dominated by mathematicians during the period from early 2000 to late 2001
- Initially took a very complex theoretical approach dominated by **"Juniper"** program and technology
  - Managing uncertainty in decision making process
  - Using hierarchical modelling of processes
  - Sees how uncertainties propagate through decision making
  - Allows uncertainties to be ranked
  - Involves use of a rich calculus developed from Interval Probability theory and relates to Baysian probability
- Greatest problem was explanation of Juniper methodology to researchers (let alone public); loss of credibility
- But……………Juniper is of some interest to sponsors

Post June 2002

- GEODISC (Andy Rigg) and URS (Adrian Bowden) attend Risk workshop in Nottingham
- Adrian reviews URS "Risque" program and proposes a revised risk management framework for Geological Storage for consideration (next slide)
- General discussions (post meeting) conclude that substantial benefit might result from GEODISC taking an alternate approach to "FEP path" being followed by many other researchers, despite strong conviction that the approach is supportable
- Reviewed with CSIRO personnel on return including new players (Robert Johnson-ex PSTI, Baolei Han, and Jiayan Pang-ex Santos)
- CSIRO was already investigating using software which utilised the Australian-New Zealand risk-analysis standard
- Selected "KnowRisk" software-for evaluation using Petrel Sub-basin technical evaluation.

GEODISC

CO2CRC

OVERALL RISK MANAGEMENT FRAMEWORK FOR CO_2 GEOLOGICAL STORAGE

FLOWCHART	**Geological / Engineering Failure Type Analysis** →	**Consequences Analysis (Triple Bottom Line style)** →	**Qualitative Risk Assessment** →	**Develop forward strategy for Project** →	**Implement Strategy (Reduce CO_2 emissions)** →	**Regular Review (demonstrate attainment of goals)**
WHO	Project managers; Panel including Geologists, Engineers, Modellers, Soil Scientists	Project managers; Panel including Geols, Engs, Soils, Economists, Legal, Financial, External Stakeholders	Project Managers, Risk Analysts	Project Managers; Expert Panels; External Stakeholders	Project Managers; Stakeholders	Project Managers; Expert Panels; Stakeholders
TASKS	Clearly identify and differentiate between risk events, costs, benefits. **Perform FEP/pathway analysis**, technical modelling, Identify failure types and their likelihoods	Clearly identify full range of impacts of all Failure Types. Identify pathways to material consequences. Estimate likelihoods and costs ($ and loss of life)	Derive probabilistic estimates of risk cost, risk quotients, benefit-cost relationships. Generate simple but sound outputs.	Use simple outputs to make choices and develop forward strategy. Focussed program of; further study, pilot project, permitting, funding, monitoring	Wider stakeholder engagement, eg. Community consultation, Regulator buy-in	Review performance of project. Refine information. Set new goals. Communicate to all stakeholders, Demonstrate -safe, measurable, verifiable, total community benefit

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Australian/New Zealand Risk Analysis Standard
The Standard to be used for GEODISC

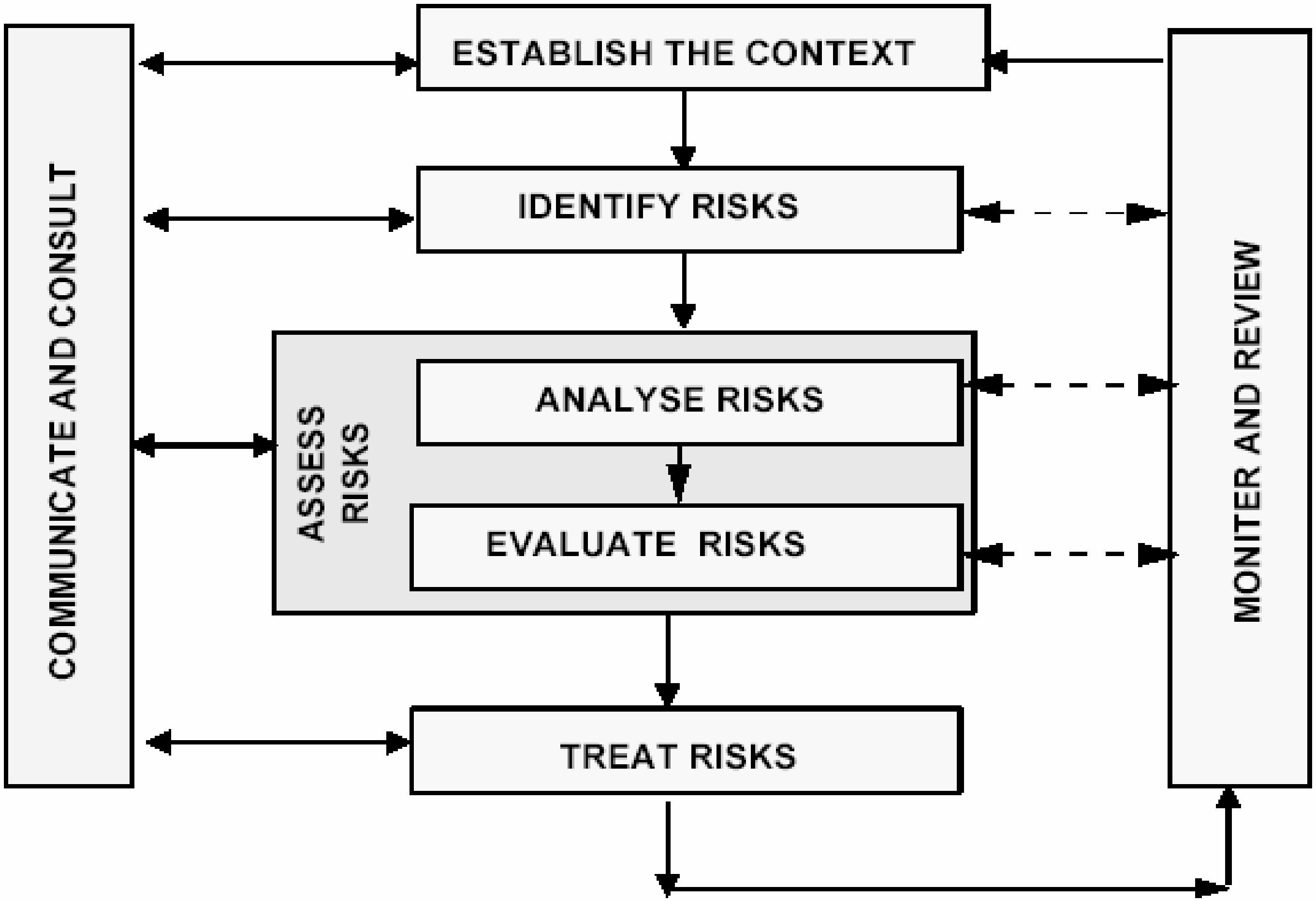
- AS/NZS4360 is the first risk management standard anywhere in the world
- The standard is a generic guide for the establishment of the risk management process
- *'the systematic application of management policies, procedures and practices to the tasks of identifying, analysing, evaluating, treating and monitoring risk'*

  Tom Beer, CSIRO Environmental Risk Network

The Risk Management Process

- Managing risks involves a series of logical steps (from AS/NZS4360)
  - Establish Context
  - Identify Risks
  - Risk Analysis
  - Risk Evaluation
  - Risk Treatment
  - Monitoring and Review
  - Communication and Consultation

The AS/NZS4360 Framework



Core Risk Management - Model 1

- Identify Risks (R) & Consequences (Q) Without Controls and
- Assess Likelihood & Consequence

Risk Assessment:

Likelihood X Consequences —— gives → Risk Rating (Level of Risk)

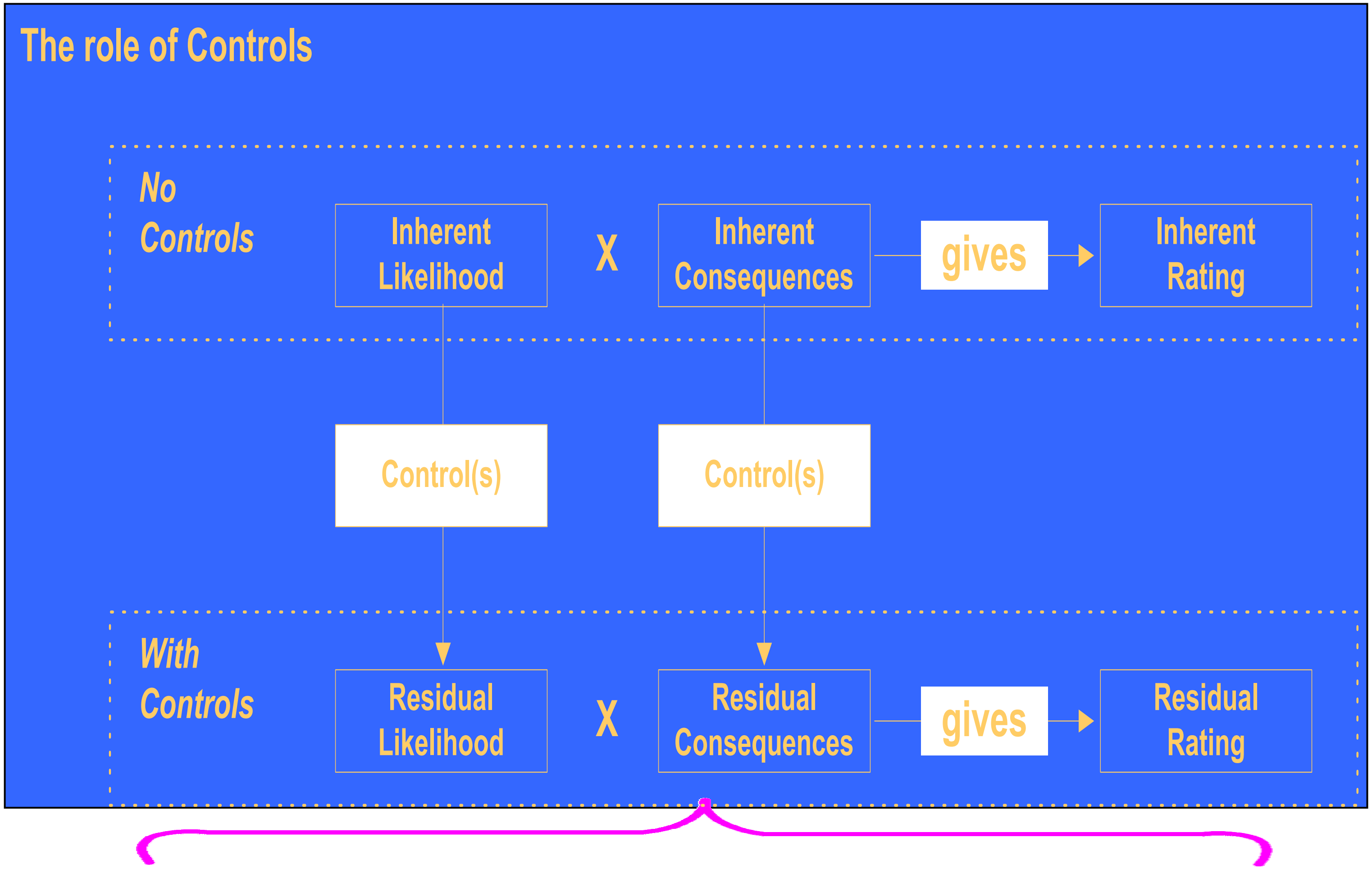
Inherent Risk

Core Risk Management - Model 2

- Next prioritise risks i.e.
  - If Risk Rating is at a high level and if
    - Likelihood is “more likely”, it may require preventative controls
    - Consequence is “larger impact”, it may require corrective controls

Core Risk Mgt Model 3

Identify **Controls;** Assess Effectiveness (reduction in risk rating)



Residual Risk

"KnowRisk" - The Tool for GEODISC

- "KnowRisk" is an information technology risk management template set based on AS/NZS4360
- We use "KnowRisk" to:
  - Identify the risks of CO_2 geological sequestration,
  - Evaluate and analyse risks, Select risk management methods, and then
  - Reduce the risks or their impacts.
- The "KnowRisk" process brings together team members and managers to discuss project risks.
- Develop a 'knowledge base' to support systematic data collection and knowledge utilization in projects and businesses.

The Risk Management Model of “KnowRisk”

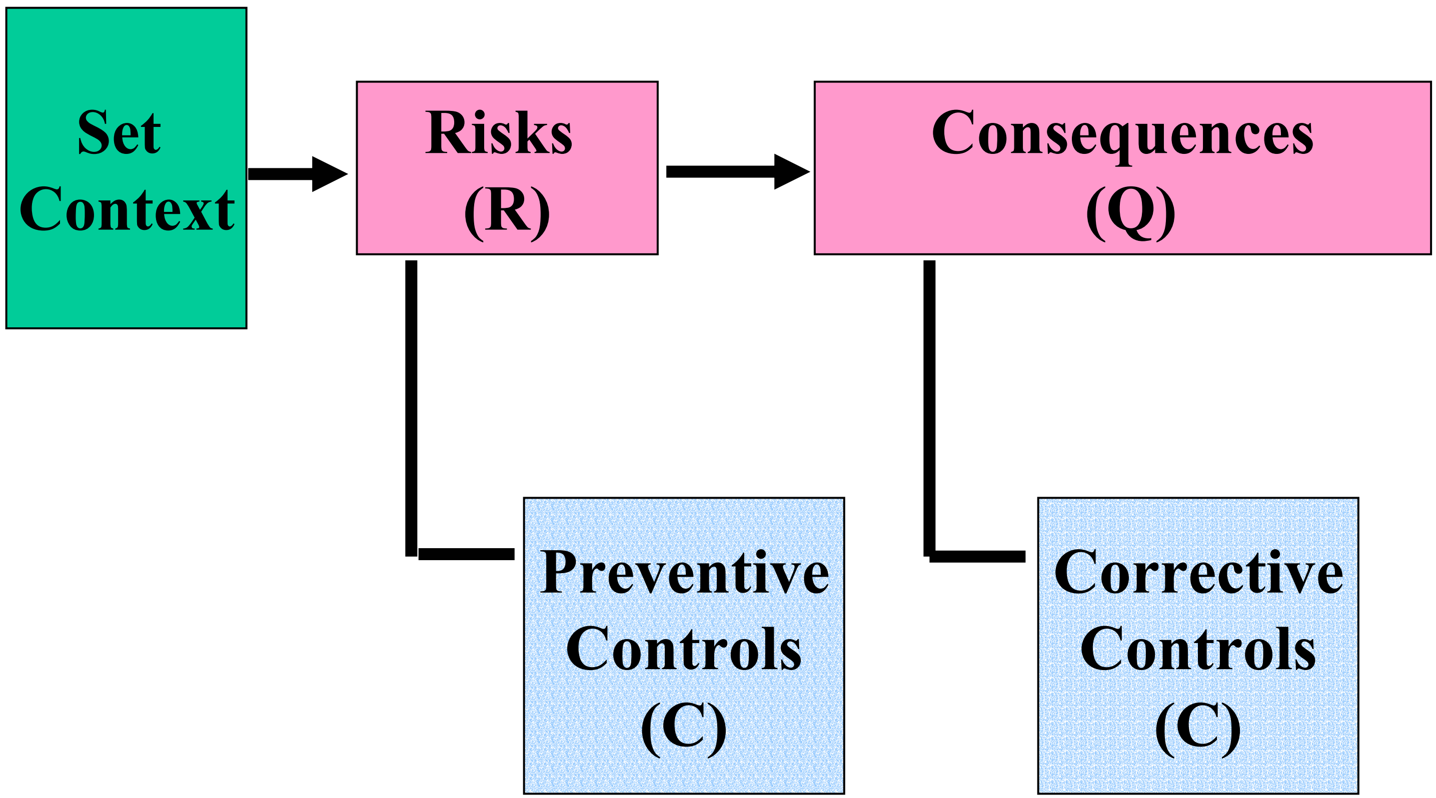


Image of a fully linked “KnowRisk” Window

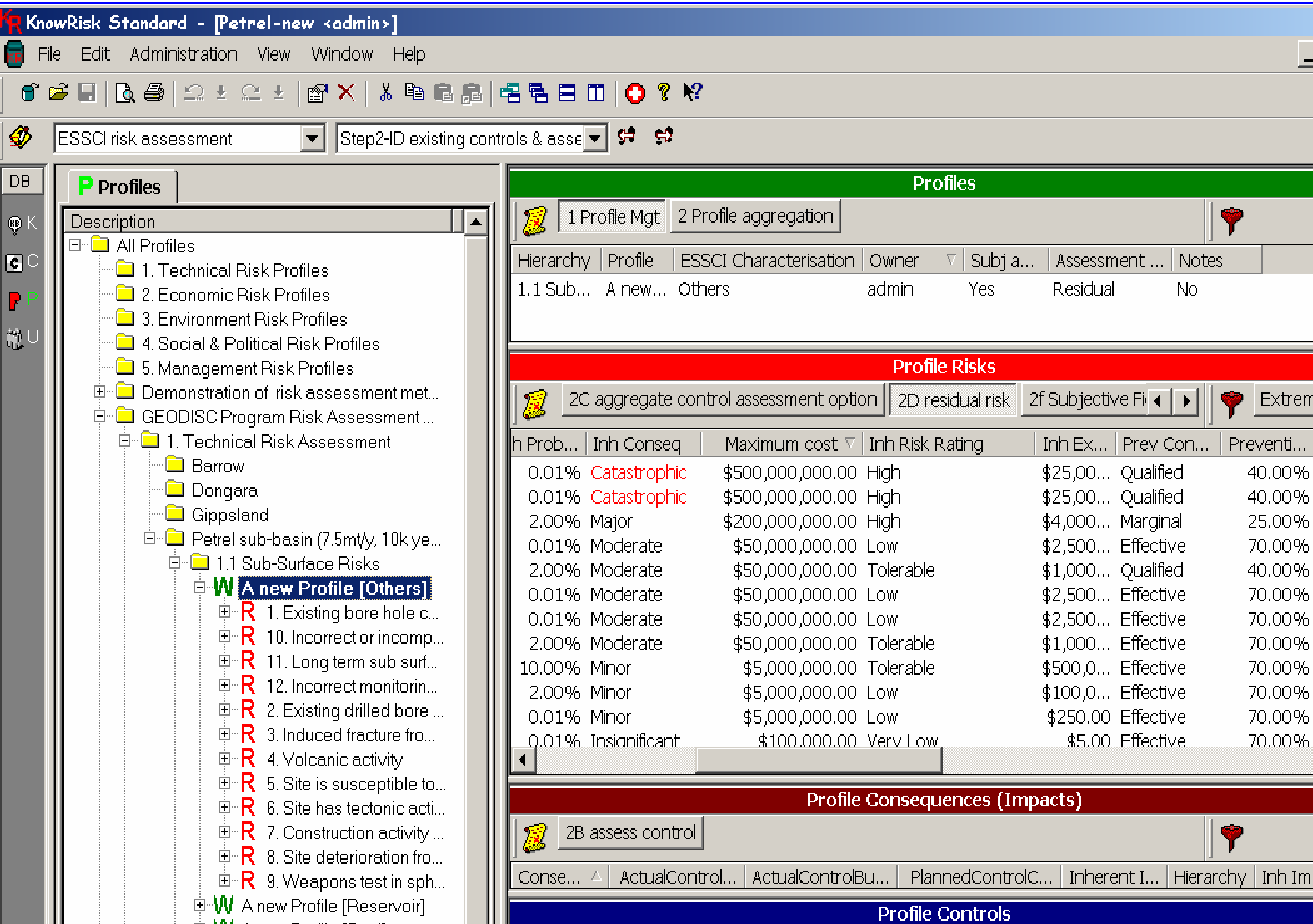
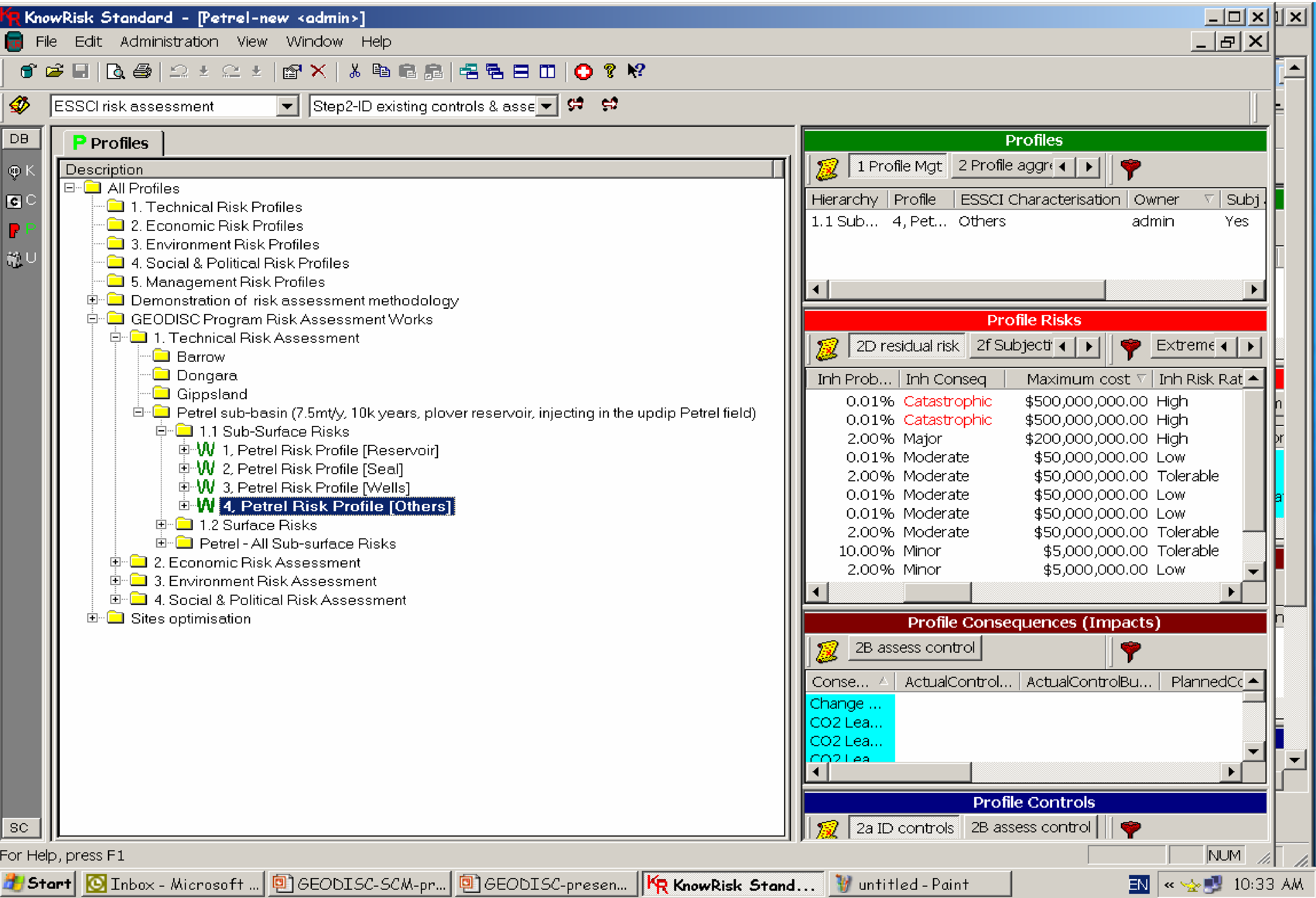


Image of the risk profile of GEODISC



Current Status

- Series of meetings held with researchers using the Petrel Sub-basin work as a template; gathering "KnowRisk" and "Juniper" information concurrently. High level risks and impacts identified.
- Still some difficulty with researchers in coming to grips with process and especially the quantification of risk
- Some evidence that "KnowRisk" software is assisting in the process of discussion and prioritisation of risks and impacts; BUT no direct evidence yet that this is any better than the earlier undertaken (simplistic) Risk vs. Impact mapping
- Will be running series of "KnowRisk" models for Petrel to identify impact of "researcher bias" where individuals either over or under emphasise the risks and their potential impacts in their technical area
- Preparing report covering an assessment of non-technical risks i.e. social (public perception, social action), technological development risk, political risk, economic risk (micro, national, global)

Geological Sequestration
Increased Public Awareness

- In Australia, we are seeing rapid increase in public awareness especially in the print media, promoted by both new CRC applications (CO2CRC) as well as brown coal tenders and recent Clean Coal Technology Mission to the US and the US-Australia Climate Action Partnership-the “BBQ test” questions all relate to “will it leak”

SWIFT as a tool for determining risk in geological sequestration (Work in progress)

Mark Vendrig
DNV London

MANAGING RISK DNV

What Is SWIFT

- Structured What If Technique
- Systematic team-oriented technique for hazard identification (HAZID)
- SWIFT considers deviations from normal operations identified by brainstorming
- SWIFT relies on input from the expert team to identify and evaluate hazards.
- The Swift facilitator's function is to structure the discussion.
- The SWIFT recorder keeps an on-line record of the discussion on a standard log sheet.

The Expert Team

- It must be balanced. Greenpeace and FOE for the concern approach, and the engineers for the solution approach.
- Everyone must have technical insight into the work
- Must have a factual basis and not a representation of personal and political agendas

The objectives of the SWIFT review

- To identify hazards that may result in leaks of CO_2 from various possible types of geological structures, and the safeguards that are planned to minimise the risks.
- To evaluate the likelihood and consequence of CO_2 leaks by comparing the hazards and safeguards to those present in conventional natural gas production (and, if possible, injection and storage).
- To evaluate the relative importance of the different hazards in contributing to the total expected quantity of CO_2 leaking during the reservoir life.

SWIFT Protocol

1. Define reservoir types. Consider each in turn.
2. Brainstorm possible hazards, e.g. “What if...?”, “How could...?”
3. Structure the hazards into a logical sequence for discussion.
   Start with the major ones, so that escalation of initiating ones can be cross-referenced.
4. Consider each hazard in turn.
   Consider possible causes of the event.
   Consider possible consequences if the event occurs.
   Consider safeguards that are planned to be in place to prevent the event occurring.
   Consider frequency and consequence relative to natural gas production
5. Record discussion
6. Reconsider whether any hazards have been omitted
7. Use checklists and previous accident experience to check for completeness.
8. Rank each hazard for importance within CO_2 sequestration.

What is Risk ?

- Hazard
- Frequency
- Consequence

Risk = Frequency of hazard x consequence

Hazard Brainstorm

- Ice Ages and ice sheet loading
- Well bore failure during operational/abandonment phases
- Blow out
- Casing failure
- Cap rock failure
- Earthquake
- Lateral migration and CO2 movement around seals
- Natural pathways/ factures/faults9Intervention by drilling or mining
- Chemical failure of well bore
- Over pressurisation
- Ship collision/Iceberg collision
- Operator error
- Terrorist attack/sabotage
- Unrecognised geological structures
- And 18 more

Top Hazards

- Well bore failure
- Chemical interaction at the well bore
- Physical interaction at the well bore
- Geomechanical effects
  - Micro seismicity
  - Stress and micro fractures due to:
    - Injection rate/volume
    - Injection pressure (pressure changes and stress)
    - Injection fluid temperature (thermal stress)
  - Fault lubrication by CO_2 (causes slipping)
  - Fluid-CO_2 interface stress
  - Tectonic activities
  - Extraction of oil changes reservoir shape and stresses
  - Corrosion cracking (rock dissolution)

DELPHI

- What frequency of leaks would you expect from the sequestration reservoirs?
- What distribution of initial release rates would you expect in the above leaks?
- What distribution of release duration would you expect in the above leaks?
- What reduction in release rates would you expect during the above duration?

The Model

$$QL = F \times Ro \times D \times M \times L$$

where:

Q = quantity of CO_2 leaked (tonnes) in lifetime

F = frequency of significant leaks (per reservoir year)

Ro = initial release rate in leaks (tonnes per day)

D = overall release duration (days)

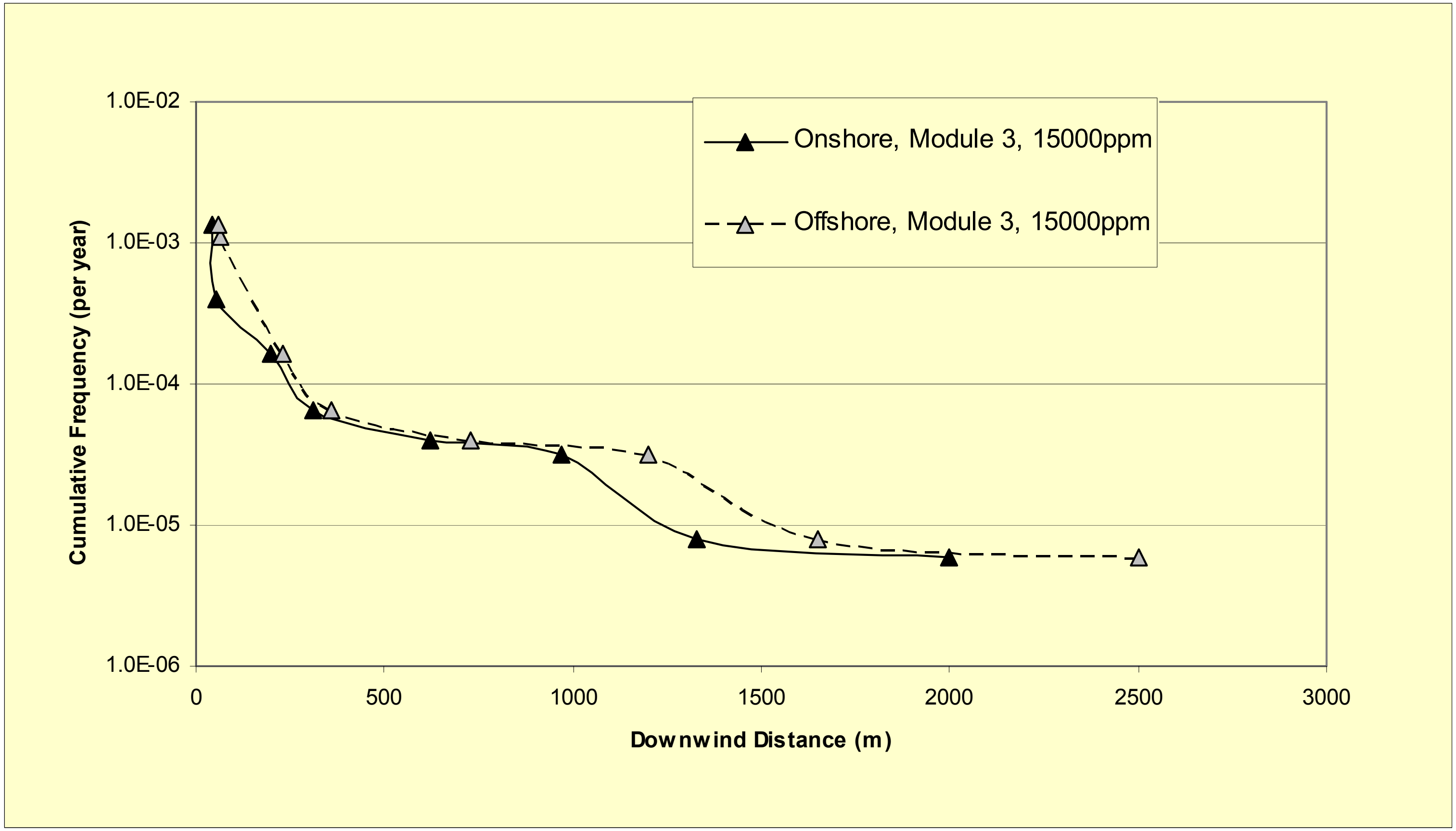
M= modification reflecting the reduction in release rate over the duration

L = reservoir design lifetime (years)

The Engineered System

- 2000 and 15000 ppm identified as key CO_2 risk concentrations for environment and people (conforms with the Saripalli estimates)
- Based on these, 30m to 5km zones will be impacted by CO_2 leaks depending on where the leak occurs in the system

The Engineered System Model Outputs



Is it providing results ?

- The consequence review matches the Saripalli paper
- The plume profiles as in the previous slide match expected plumes from the oil and gas industry and demonstrate the individual risk
- The engineered system can be modelled and impact zones of up to 5 km are described
- The geological system is still in progress but the SWIFT identified the key issues. The experts are now feeding back their estimates. Experience shows this give accurate ranges.

The Saripalli findings

Summary of consequences and concentrations in various environments (after Saripalli *et al,* 2002)

Media*	**Consequences**		
	Severe [1]	**Moderate [0.5]**	**Low [0.1]**
Air (280 ppm)	Lethal, habitat loss (>10%)	Injuries (> 5%)	Discomfort (> 1%)
Buildings (280 ppm)	Injury, evacuation (> 5%)	Irritation, discomfort (> 2%)	Noticeable, no harm (> 1%)
Ground water (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; .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%)